The review helps people gain insight into the science and mechanics of the technique, and looks into the documented findings of other studies

Geomechanics of hydraulic fracturing

Environmental effects in the Australian context

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A decade ago, the greater public had not heard of hydraulic fracturing and today, many people outside the resources sector consider it to be a recent technical innovation. Although it's true that the broad application of hydraulic fracture stimulation for gas recovery in tight and low-permeability shale is comparatively recent, the technique has been utilised in the oil sector for more than 65 years for well stimulation, to enhance recovery from conventional petroleum reservoirs.

Perhaps the best known geophysicist in the world during the post-war period, M. King Hubbert[1], together with co-author David G. Willis, summarised early work on the subject in their seminal 1957 paper '*Mechanics of Hydraulic Fracturing*'. At the time they said:

"The hydraulic-fracturing technique of well stimulation is one of the major developments in petroleum engineering of the last decade. The technique was introduced to the petroleum industry in a paper by J. B. Clark of the Stanolind Oil and Gas Company in 1949. Since then its use has progressively expanded so that, by the end of 1955, more than 100,000 individual treatments had been performed."

This one statement alone, made almost half a century ago, demonstrated that hydraulic fracturing stimulation was recognised as a critical and widely adopted technique for the petroleum industry from the outset.

Despite the passing of decades since the widespread adoption of the method, it is clear, based on the nature of public debate, that only a small percentage of opinion in the public and media discourse is founded on a reasonable technical understanding of the technique. Few media commentators are likely to comprehend the nature of geomechanics and how rocks behave under the hydraulic stress of fluid injection.

To help address this, a technical discussion is presented on the hydraulic fracturing of rocks, and a brief consideration of some of the environmental effects.

[1] Marion King Hubbert (1903-1989) was a geophysicist and world authority on energy resource estimation, predicting as early as 1949 that the fossil fuel era would be short, and later predicting with remarkable accuracy the decline of US oil production from the 1970s. Described as brilliant but short-tempered, Dr Hubbert made important advances in petroleum geology, hydrogeology, and fluid pressure in faulting.

The mechanics and application of hydraulic fractures in rocks

Early work

Although research had been previously published on the nature and propagation of pressure fractures in rock, the application as a process for well stimulation was first presented in 1949 by William Clark in the Transactions of the American Institute of Mining, Metallurgy and Petroleum Engineers (AIME). A common early interpretation was that injected fluid pressure causes fractures to propagate in rock along bedding planes, and in doing so, required that pressure must exceed that of the overburden weight. In turn this can be calculated from the density and overlying thickness of the rock. However this notion had been queried during the 1940s due to the recognition that hydraulic pressures required to initiate fractures could be less than indicated by the overburden weight.

In a 1953 paper, Hubbert showed in fact that fracturing pressures were related to the stress field within the rock, and that in tectonically relaxed areas, fracturing should be vertical and achievable with pressure below overburden. Research continued through the 1940s and 1950s, culminating in Hubbert and Willis' seminal 1957 paper, '*Mechanics of Hydraulic Fracturing*'. In this paper, the relationship between the pre-existing underground stress state and the nature and direction of fracturing under pressure, was demonstrated through both geomechanical theory and applied experimental methods.

This important work underpinned the basic science and application of hydraulic fracturing as a practical technique.

Fundamentals of hydraulic fracturing

In the classic well-stimulation scenario, hydraulic fracturing occurs when the pressure of fluid injected into a formation is sufficient that the force generated exceeds the tensile strength of the rock, as Hubbert had postulated. Failure of the rock allows fractures to propagate along the path of least resistance; this path is primarily influenced by the three-dimensional stress state within the rock. In order to understand how fractures develop, an understanding of stress in the Earth's upper crust is essential.

In a simplified form, the stress regime within the Earth's crust at some material depth can be resolved into three orthogonal force vectors: a vertical stress component and two horizontal stress components commonly denoted as S_V, S_{Hmax} and S_{Hmin}. These are referred to as the three principal stresses. Vertical stress arises primarily as a function of the weight of overburden whereas the horizontal stresses result from tectonic effects, such as crustal compression or extension caused by plate movements.

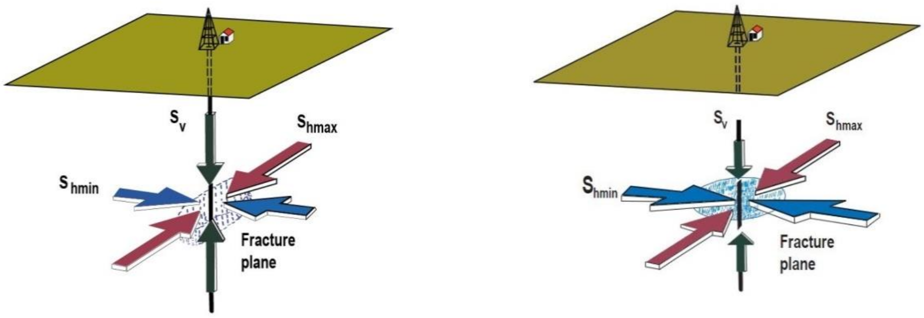
Although simple hydrostatics would suggest that these three stresses might be equal, the long history of mobility and deformation in the Earth's crust (folding and faulting) demonstrates that this cannot be the case. To account for such deformation, there must be substantial differences between the three principal stresses (Hubbert and Willis, 1957).

Under this paradigm of unequal stress, it follows that pressure injection of fluid will cause the rock to fail in a plane perpendicular to the direction of the least principal stress (Hubbert and Willis, 1957). Because S_{Hmax} is by definition greater than S_{Hmin}, the least principal stress is necessarily either S_{Hmin} or S_V[2].

It is useful to visualise the hydraulic fracturing scenario referred to above in terms of the pressurised planar fracture pushing apart the rock. It is evident that this will occur in the direction of the lowest stress, thereby constraining the path of least resistance for fracture propagation irrespective of what the orientation of bedding or cleavage planes might be. Figure 2.1a below shows an example with S_{Hmin} as the least principal stress and Figure 2.1b shows an example with S_V as the least principal stress.

Figure 2.1 Stress and fracture plane development

A) **B)**



Based on this theory, and an understanding of the relative magnitude of these stresses, we can confidently predict the orientation of hydraulic fractures. So, in the case where S_{Hmin} is the smallest of the three stresses, it follows that fractures must develop in a vertical plane as in the case for Figure 2.1a, whereas if S_V is the smallest stress then fracturing must occur in a horizontal plane as illustrated in Figure 2.1b.

This is consistent with studies and experiments such as Warren and Smith's work in 1985, showing that whilst pre-existing structures such as faults and fractures can have some influence on initial hydraulic fracture development, the overall fracture propagation trajectory is controlled by the orientation of the least principal stress - either S_{Hmin} or S_V - as predicted by Hubbert and Willis (Zoback, 2007).

Although the preceding discussion is focussed on the intentional hydraulic fracturing of rock, it should be noted that fracturing can also occur unintentionally. An example of this is during drilling operations if the drilling mud density is allowed to rise excessively for the depth of the uncased formation. It can also occur during waste water injection if flow rates and pressures are high enough. Hydraulic fractures also occur naturally and are thought to propagate as a result of critical pressurisation of pore fluid (Osborne and Swarbrick, 1997).

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[2] It is of course possible in some circumstances for $S(_{Hmax})$ and $S(_{Hmin})$ to be equal.

Fracturing pressure

The minimum injection pressure required to initiate hydraulic fracturing should notionally be equal to the least principal stress[3], although a higher rupture pressure may be necessary initially. This will be dependent on the tensile strength of the rock and how near or far any existing discontinuities lie from the point of injection. There can be other cases where the initial pressure is somewhat greater or lower than that indicated by the least principal stress.

For example, greater pressures might be required in cases where the hydraulic fracturing is being made through a perforated and cemented wellbore/casing, and the resulting tortuosity of the hydraulic path between the well bore and the formation introduces frictional loss. Lower pressures might be indicated where pre-existing drilling-induced tensile fractures exist, in which case no additional pressure may be required to initiate them (Zoback, 2007). In addition, the initial behaviour of fractures is also affected by the type of fluid, whether penetrative such as used in 'slickwater' hydraulic fracturing or non-penetrative, such as gel type hydraulic fracturing fluid.

Following fracture initiation, the pressure required to keep the fracture open in the case of a non-penetrating fluid, is equal to the stress-field normal to the fracture plane (Hubbert and Willis, 1957) which must be the least principal stress. To further propagate the fracture will require pressure only slightly above this. However as the fracture extends, fluid frictional loss will limit its extent and therefore increasing pressure over time will be required to continue extending the fracture.

The extent of hydraulic fractures

We see from the previous discussion that hydraulic fractures must propagate in a plane perpendicular to the least principal stress, and that in regions where S_V is the least principal stress, fractures must propagate in a horizontal plane. Where S_V is not the least principal stress, fractures must propagate in a vertical plane. The physical extent of the fracture is however not a function of rock stress as commonly thought, but instead is dependent on the duration of time where the pressure is high enough to keep the fracture open and sufficiently high for propagation at the fracture tip (Davies et al., 2012).

Because of this, the ultimate extent of the fracture is a function primarily of pressure and injected volume, and individual well stimulation events are typically conducted for controlled short time periods, typically measured in hours. Detection and measurement of the microseismic events that occur during propagation using microseismic arrays and surface tilt-meters, can help establish the fracture extent. It should be noted that the extent of fracturing can also be affected as the fracture propagates and encounters formations of varying confining stress or increased permeability which allows fluid to bleed off (Davies et al., 2012).

[3] The tensile strength of the rock mass is assumed to be effectively zero, due to the presence of discontinuities such as pre-existing fractures.

As a result, to develop vertical extensive fracture systems, high pressure fluid injection is needed across long periods of more than a day. Multiple steps in the fracture stimulation may also be required to break through boundaries such as permeable beds.

In a recent study of the vertical extent of hydraulic fractures, it was found that greater potential for taller fractures exists in shallower strata, with the maximum propagation recorded at ~588 m in the Barnett Shale, in the United States (Davies et al., 2012). In that study, the data demonstrated that the probability of fractures having vertical extent greater than 500 m is less than 1%.

Crustal stress and faulting

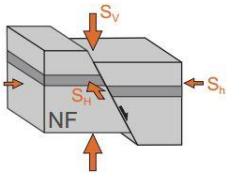
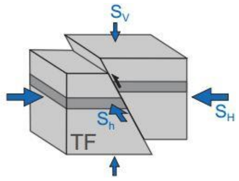
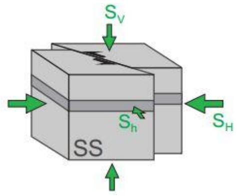
Understanding crustal stress

With an understanding of the geomechanics of rock fracturing, an interpretation can be made of the potential environmental effects of hydraulic fracturing. This is provided site-specific or regional knowledge of the stress state within the Earth's upper crust is also understood.

Stress exists throughout the crust and is universally compressive, due to the low tensile stress of rocks. Given that the mechanics of hydraulic fracturing and geometry of fracture development are controlled by stress, it's crucial to the interpretation of potential environmental impacts that these stresses (as they exist within the deep sub-surface) can be determined.

In classical faulting theory, as presented by Anderson (1951), the relative magnitudes of the three principal stress components are correlated with the three principal faulting modes observed within the Earth's crust. Observation of earthquake activity provides important information describing the state of stress with depth (Meissner and Strehlau, 1982). Table 3.1 presents the primary fault modes which are correlated with the relative magnitude of the vertical stress (S_v) in relation to the two observed horizontal stresses and specific tectonic settings.

Table 3.1 Fault modes, principal stress relationships, and tectonics

Fault mode	Relative stress magnitude	Tectonics	Concept
Normal	$S_v > S_{Hmax} > S_{Hmin}$	Extensional	
Reverse	$S_{Hmax} > S_{Hmin} > S_v$	Compressional	
Strike-slip	$S_{Hmax} > S_v > S_{Hmin}$	Neutral	

We see that, for example, when S_v is the least principal stress that compressional tectonics (associated with reverse faulting) is the prevailing crustal regime.

Causes and measurement of crustal stress

The primary mechanism for the development of horizontal stress within the crust at depth is tectonic forces such as plate boundary motion, lithosphere flexure due to density differential and thermo-elastic forces in, for example, cooling oceanic crust (Zoback et al, 1989).

Vertical stress as previously noted, arises primarily from the overlying weight of rock above the point of measurement, and can be calculated readily with an understanding of the integrated or mean density (r) of rock with depth (z) and gravitational acceleration (g) (Jaeger and Cook, 1971):

$$S_v = \int_0^z \rho(z) g dz \approx \bar{\rho} \, gz \qquad \text{eqn.1}$$

Assuming an integrated or mean rock density of 2,300 kg/m^3, and that vertical stress is normal to the Earth's surface, equation 1 results in S_v of approximately 23 MPa/km (in imperial units, 1 PSI per foot is a common approximation). More precise determination of S_v can be calculated from field density data, such as obtained from borehole density logs.

Characterisation of the magnitude and orientation of horizontal stresses (S_{Hmax} and S_{Hmin}) is less straightforward. Nevertheless, reliable data can be determined through a range of technical methods, including wellbore observations and tests, earthquake analysis and interpretation of structural geology.

Global tectonic studies demonstrate that most intraplate regions are characterised by compressional stress, with extensional regimes limited mainly to regions of thermal uplift, such as ocean-ridge spreading boundaries. It's concluded that the stress state throughout the upper brittle crust is regionally consistent, enabling the definition of regions in which stress magnitudes and orientations are generally consistent (Zoback et al, 1989). This has important implications for prediction of the fracture behaviour during well-stimulation.

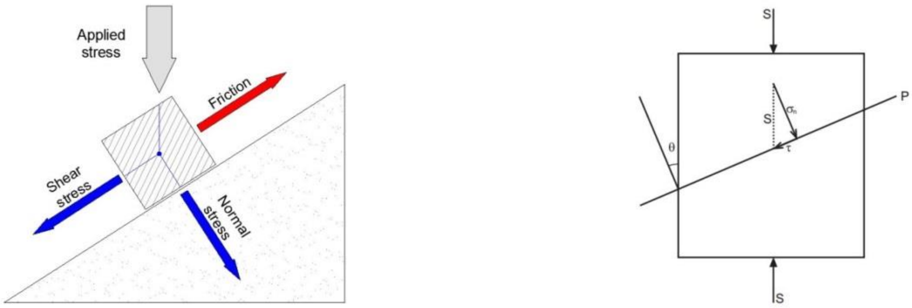
Failure equilibrium and faulting

Although it might be considered that the upper limit of the maximum horizontal stress (S_{Hmax}) in the crust would be limited to the compressive strength of rock, Zoback (2007) points out that a more realistic upper limit for S_{Hmax} will be the frictional strength of previously faulted rock, because essentially all rocks are fractured and/or faulted other than at very small scales. Amontons' Law (equation 2 and Figure 3.1a) describes the material property of friction (co-efficient of friction: µ) as the ratio of shear stress (t) to normal stress (s_n):

$$\mu = \frac{\tau}{\sigma_n} \qquad \text{eqn. 2}$$

Through extensive experimental work, Byerlee (1978) showed that the coefficient of friction within faults is largely independent of rock type and surface roughness. Values for µ between 0.6 and 1.0 are typical for deep stress measurements (Townend and Zoback, 2000). To represent the forces acting on a fault, figure 3.1b illustrates how stress is resolved into a shear component (parallel to a plane) and a normal component.

Figure 3.1 a) Frictional components of Amontons' Law
b) stress (S) resolved into shear (t) and normal (s_n) components



a) **b)**

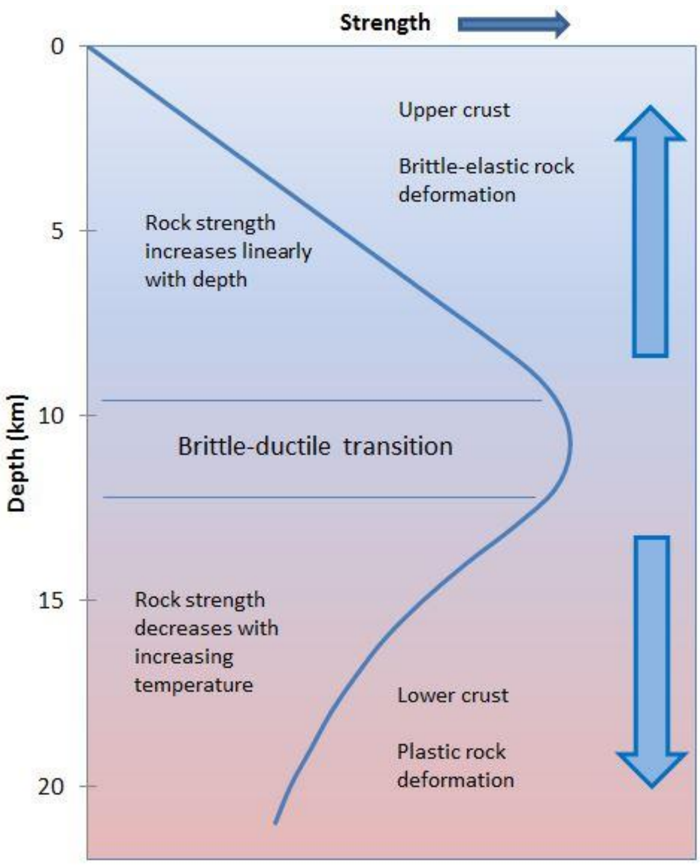
Stress and crustal strength

Measurements of actual crustal stress at depth are consistent with the hypothesis that stresses are controlled by the frictional strength of pre-existing faults, and that the Earth's crust appears to be in a state of frictional failure equilibrium (Zobeck, 2007). Interestingly, Townend and Zoback (2000) present data that support this hypothesis and show that critically stressed faults on the one hand limit crustal strength, whilst at the same time (counter-intuitively) keep the crust strong by maintaining high crustal permeability and keeping pore pressures close to hydrostatic at depth.

Within the lithosphere, rock strength varies according to depth (Figure 3.2) with a maximum strength generally below 10 km depth[4], where the brittle upper crust transitions to the ductile lower crust. Within the upper crust, rock strength increases linearly with increasing vertical stress and hence depth. However rock strength also decreases with temperature, and because temperature increases with depth, the rock becomes progressively more ductile (above approximately 400º) and less prone to fracturing under applied stress.

The relationship between rock strength and depth is conceptualised in Figure 3.2, and is typical for continental crust, where felsic[5] rocks dominate. Oceanic crust, by way of contrast, is dominated by higher density mafic[6] rocks and a different depth-strength relationship.

Figure 3.2 Brittle-ductile transition and rock strength with depth



Tectonic force results in a continual steady-state creep within the ductile rock of the lower lithosphere (Meissner and Strehlau, 1982). The mechanism for build-up of crustal stress is thought to result from these plate-driving forces in the ductile lower crust and upper mantle (Zoback, 2007). Because the brittle upper crustal rock cannot deform in a plastic manner, elastic strain accumulates and this energy is periodically released through slippage on faults which manifest as

[4] The actual transition depth varies from region to region, due to factors such as crustal lithology and thermal gradient.
[5] Rocks dominated by feldspar and silica, such as granite and rhyolite.
[6] Rocks rich in magnesium and iron minerals, such as basalt and dolerite.

earthquakes. As a result of this, the upper crust is maintained in brittle-failure equilibrium. Even within intraplate regions, where earthquakes are relatively infrequent, this equilibrium will exist, and the reduced seismic activity in those regions simply reflects a lower ductile strain rate within the lower lithosphere (Zoback, 2007).

In comparing theoretical curves of crustal yield strength versus depth with the depth-frequency distribution of earthquakes, Meissner and Strehlau (1982) found a strong consistency between theory and observation, and that the peak strength achieved in the crust is primarily related to the rock temperature and water content, and not the properties of particular layers, such as lithology

Tectonic stress in continental Australia

The contemporary tectonic stress field in Australia is observed to be complex. Zhao and Müller (2001) showed that the main forces acting on the Australian continent included mid-ocean ridge push from the south, subduction-zone push from the east and an easterly push direction from offshore to the west of the continent. In particular, to the north of the continent, plate boundary interactions between the Australian plate and the Eurasian and Pacific plates are complex and subduction dominates (Zhao and Müller, 2001). However despite this complexity, the available data indicates that the Australian continent is predominantly in a compressional tectonic state (Hillis et al., 1999; Zhao and Müller, 2001).

Hillis et al. (1999) compiled a range of in situ stress data from eastern Australia, including the seismically active Sydney Basin and the relatively aseismic Bowen Basin, both of which are prospective unconventional gas exploration regions. The Bowen Basin data indicated that the rock failure condition in the uppermost 1000 m of crust is predominantly reverse faulting, with a small strike-slip component. Normal faulting was only represented by 3% of the Bowen measurements. The Sydney Basin data indicated even greater reverse faulting tendency than the Bowen Basin, with only 2% of data representing normal faulting condition.

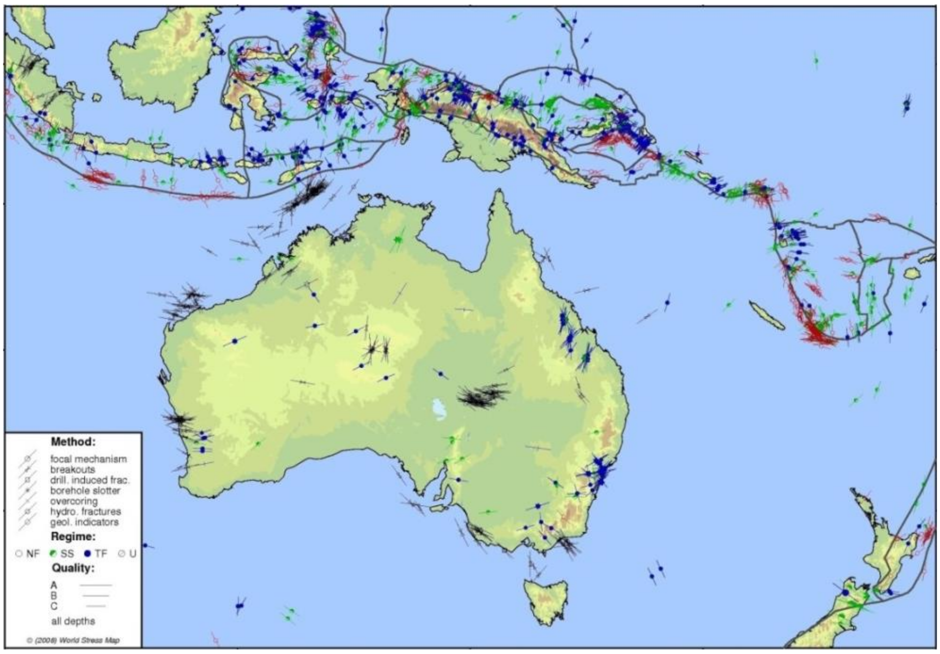
Hence, these results from Hillis et al. (1999) strongly support the conclusion that eastern Australia is tectonically compressive, consistent with expectations based on plate boundary forces. However it is interesting to note, that while the Bowen data indicate a broadly consistent north-south orientation of S_{Hmax} throughout as predicted based on plate boundary-force models, the Sydney Basin data in contrast does not indicate a dominant stress orientation. Continental margin and local structural effects are proposed to explain the Sydney Basin data (Hillis et al., 1999).

Despite the indicated stress orientation anisotropy, the reverse faulting regime nevertheless indicates that compressive tectonic forces are at play.

Contemporary Australian stress regime

Figure 3.3 shows tectonic stress within the Australian region, based on data from the World Stress Map database (WSM, 2014). The WSM database comprises a compilation of measurements of the present-day stress field of the Earth’s crust, and includes academic, industrial and government data (WSM, 2014).

Figure 3.3 Tectonic stresses within Australia and region



Stresses across the Australian continent are observed to be consistent with a compressional intraplate crust, with extensional stresses limited mainly to offshore plate margins. The data available are consistent with the findings in Zoback et al. (1989) that most intraplate regions are characterised by a compressional stress regime, with extensional tectonics limited almost entirely to regions of thermal uplift.

The important conclusion here is that the tectonic stress region in continental Australia, being primarily compressive, implies horizontal fracture development during hydraulic fracturing. This has implications for the understanding of environmental effects, as discussed below.

Environmental effects of hydraulic fracturing

A good deal of public debate and media focus on the environmental effects of 'fraccing' has led to a groundswell of 'grass root' movements opposed to both hydraulic fracturing and the development of unconventional petroleum resources in general. The flow on effect has politicised regulation and management of onshore petroleum exploration in Australia and in some states bans or moratoria have stifled exploration, citing environmental concerns. Two of the key concerns raised are induced earthquakes, and impacted water supplies due to migration of fracturing fluids.

Human induced seismicity

Intense public awareness has focussed on the potential for well stimulation activity to trigger earthquakes. Induced seismicity (earthquakes resulting from human activity) has been recognised for a long time. Well known triggers include the filling of large dams and injection of waste water into aquifers. In Australia, there are many examples of moderate magnitude induced seismic events that result from reservoir filling, where a significant increase in mass loading occurs near the surface of the crust together with deep seepage of water through fractures in underlying rock. This results in increased pored pressure at depth and distance from the reservoir, leading to slippage on critically stressed faults.

In the case of hydraulic fracturing, fluid injection not only creates new fractures, but can also introduce pressurised fluid into existing fault zones and trigger seismicity (Davies et al., 2013). Revisiting Amonton's Law (equation 2), it is clear that a reduction in normal stress (σ_n) must reduce the coefficient of friction. This occurs because injection of fluid into an existing stressed fault will provide a fluid pressure force acting normal to the plane of the fault, reducing the normal stress between the fault surfaces. If the fault is critically stressed, it follows that the reduction in co-efficient of friction may trigger a fault slip movement.

The question of how to establish whether any given seismic event is a result of well stimulation is a fundamental problem in understanding induced seismicity. Seven generally accepted criteria that must be met before fault activation is considered to be human induced are listed in Davis and Frohlich, 1993 (cited in Davies et al., 2013):

1. Are these events the first known earthquakes of this character in the region?
2. Is there a clear correlation between injection and seismicity?
3. Are epicentres near wells (< 5 km)?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic structures that may channel flow to sites of earthquakes?
6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?
7. Are changes in fluid pressures at hypocentral distances sufficient to encourage seismicity?

A recent comprehensive study (Davies et al., 2013) considered 198 published cases of induced seismicity, ranging up to a magnitude of M_w 7.9[7].

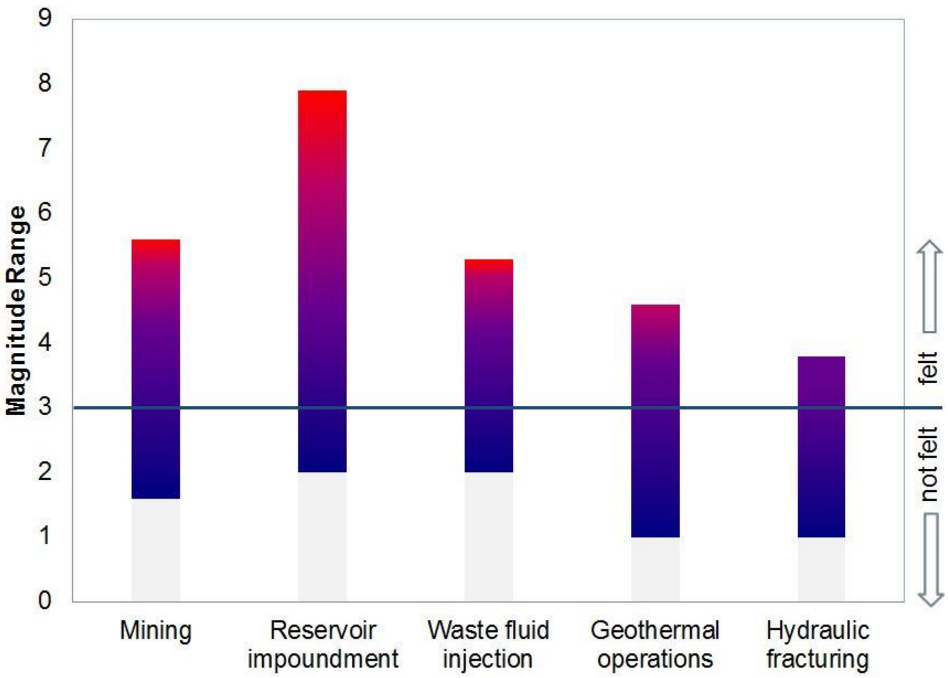
The study found that hydraulic fracturing of shale usually generates very small magnitude seismic events, compared to processes such as reservoir impoundment, oil and gas reservoir depletion and waste water injection.

Events associated with mining ranged from M_w 1.6 to M_w 5.6, for reservoir impoundment from M_w 2.0 to M_w 7.9, and for waste water injection from M_w 2.0 to M_w 5.3 (Figure 3.4). These magnitudes are significantly greater than those found for hydraulic fracturing, which were found to range from M_w 1.0 to M_w 3.8 (Davies et al., 2013).

[7] M_w = moment magnitude, a measure of earthquake intensity used by seismologists that supersedes the Richter scale (M_L) and is based on energy released by the event.

In comparison, many cases of significant reservoir induced seismicity are documented in Australia. Examples include Eucumbene Reservoir (M_L 5, 1959), Warragamba Dam (M_L 5.5, 1973) and Thomson Reservoir (M_L 5.0, 1996) Gibson (undated).

Figure 3.4 Magnitude of induced seismic events



Although reactivation of existing faults cannot be ruled out in practice, it is noted that after hundreds of thousands of well stimulation operations, only three examples of felt[8] seismicity had been documented. A study by The National Research Council of the National Academy of Science (Washington) identified only one incident globally - in Blackpool, England - where hydraulic fracturing caused induced seismicity exceeding M_w 3 (NRC, 2012).

Even though demonstrated impacts are low, the risk due to hydraulic fracturing can be even further reduced if suitable investigations are undertaken to ensure a comprehensive understanding of the geological environment is made.

Mobility and fate of fracturing fluid

The potential for contamination of water supplies from hydraulic fracturing fluid is the single greatest public concern surrounding hydraulic fracturing and the development of unconventional gas in general. In particular, unsubstantiated claims abound that hydraulic fracturing events have led to contamination of shallow groundwater aquifers and surface water supplies. Although a review of the literature will confirm that there is little real or demonstrated evidence for

[8] It is commonly accepted that some earthquakes between M_w 2.5 to 2.9 may be felt; at M_w 3.0 or greater (KGS, 2013) earthquakes will be generally felt. Damage usually does not occur for quakes below M_w 4 or 5 (USGS, 2015).

this, it is nonetheless of value to consider the potential mechanisms for such impacts.

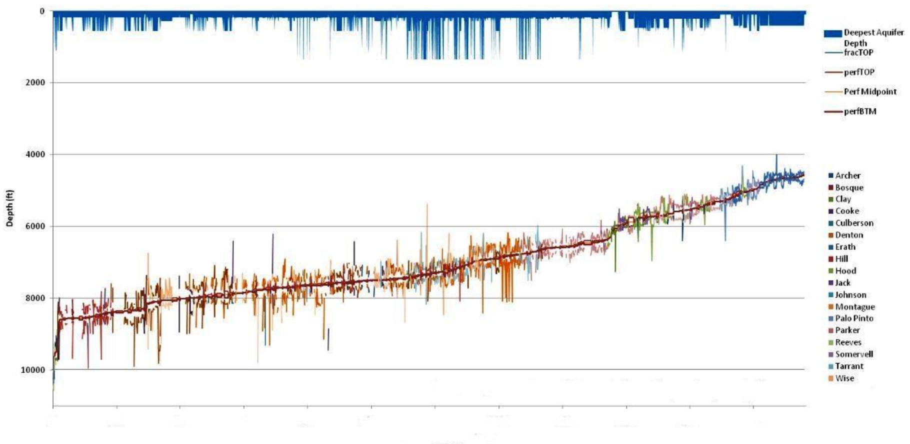
Notwithstanding environmental releases that might arise from well casing failure or containment loss at the surface, pathways for contamination of water supplies due to hydraulic fracturing events are restricted to those that would allow for the migration of fluid under pressure from the target formation to the surface. The following potential mechanisms can be considered:

- Direct hydraulic migration within a newly created fracture
- Migration via Darcian[9] or density driven flow through porous media formations between the target formation and the surface
- Migration via an existing permeable feature, such as an existing geological fault

The direct fracture migration mechanism requires that fractures from hydraulic fracturing propagate sufficiently to impact the water resource. Where the resource is a surface water system or shallow aquifer, vertical fracturing is necessary and of sufficient extent to intersect the resource. In the previous discussion it was shown that the Australian stress regime, being compressive, is counter to this notion and favourable for horizontal fracture development. A typical structural setting where vertical fracturing is favoured would be an extensional tectonic regime, such as the Barnett Shale, a significantly developed unconventional gas target in Texas.

Figure 4.1 provides a plot of Barnett Shale fracture height on a chart with comparison to reported aquifer depths and indicates that generally there is no practical evidence that fractures can intersect and impact on those aquifers. This relationship is likely to apply generally for shale gas targets and certainly the deeper CSG formations (shallower CSG targets are generally not required to be stimulated, as greater intrinsic permeability is present due to structural unloading).

Figure 4.1 Barnett Shale fracture height and aquifer depth (Fisher and Warpinski, 2011)



[9] Flow that arises due to a hydraulic gradient and permeability, in accordance with Darcy's Law.

In the case of migration through porous media under Darcian or density flow processes, Flewelling and Sharma (2014) show that the proposed rapid upward migration of brine and hydraulic fracturing fluid resulting from well-stimulation activity does not appear to be physically plausible, and that unrealistically high estimates of upward migration are the result of invalid assumptions about both hydraulic fracturing and the hydrogeology of sedimentary basins.

It may be possible to demonstrate some potential for transport through permeable features such as existing faults in cases where a hydraulic fracture intersected such a feature. It is worth considering that to realise this pathway, a very substantial volumetric increase in injected fluid must occur than otherwise would be required and planned for during the well stimulation event. In practice it is reasonable to expect that firstly, hydraulic indications such as flow and pressure of such leakage would be obvious and apparent. Secondly, the logistics of the hydraulic fracturing operation would not include sufficient fluid to allow for such a pathway, if it existed, to be completed sufficiently for an impact to eventuate.

If it is postulated that hydraulic fracturing at shallow depths might pose a greater risk, then risk reduction can be gained by expending additional effort to better characterise the target area’s structural geology, in particular to identify the presence of permeable faults.

Summary

Hydraulic fracturing is widely adopted in the oil and gas sector for well stimulation, and has been applied to conventional petroleum reservoirs for more than 65 years. Although the physics are complex, the technical issues are well understood and tested in both theory and practice. The historical evidence gained over a long period of widespread application of hydraulic fracturing in the petroleum sector demonstrates a very low risk of environmental impact directly arising from field application of the method.

The nature of fracture development under hydraulic pressure observes the laws of geomechanics and is highly predictable providing a competent understanding of the stratigraphy, structure and stress field is available. In most Australian basin settings the compressive stress field predicates horizontal fracture development, however in any case, the performance of hydraulic fracturing in extensional environments shows that even this factor is not problematic.

Modern investigation techniques such as 3D seismic surveys are available to effectively and reliably characterise structural settings and faults, and a range of methods are available to test and confirm sub-surface stress fields. Microseismic arrays can also be used to measure and control the development of fractures in real-time during a stimulation event.

The risks due to hydraulic fracturing induced seismicity are low, with few events of any note being attributed to hydraulic fracturing. To date, there have been no reports of any events that resulted in damage, despite the many thousands of well stimulation events conducted. Risks attributed to other human induced activities, such as mining, reservoir construction and waste fluid injection in contrast, can be higher. In this regard, waste fluid injection associated with wellfield development is of concern, however the potential for impacts due to this can be readily mitigated through the recycling of fracturing fluids, minimisation of waste injectables and by ensuring that brine injection wells, if used, are distal from potentially active faults.

Finally, the risk of transport of hydraulic fracturing fluids to surface water or near-surface resource aquifers, arising from out of zone fracture development, is low. Claims to the contrary are inconsistent with the evidence.

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