In-Situ Stress in Australia and Subsurface Fluid Flow

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IN-SITU STRESS IN AUSTRALIA

The *in-situ* stress field is a key variable in any geothermal development, principally because of its control on the direction of subsurface fluid flow. Data on the *in-situ* stress field of Australia have been derived from a variety of sources including relatively shallow engineering methods often associated within mining activities (sampling up to a few hundred metres depth); from deeper petroleum wellbores (sampling up to a few kilometres depth); and from earthquake focal mechanism solutions (sampling up to seismogenic depths, typically up to 20 km in Australia). Data on stress orientations within Australia have been compiled within the public domain Australian Stress Map database (www.asp.adelaide.edu.au/asm).

The Australian Stress Map comprises 331 reliable (A-C quality) indicators of horizontal stress orientation within the Australian continent (Figure 1). The map reveals distinct stress provinces

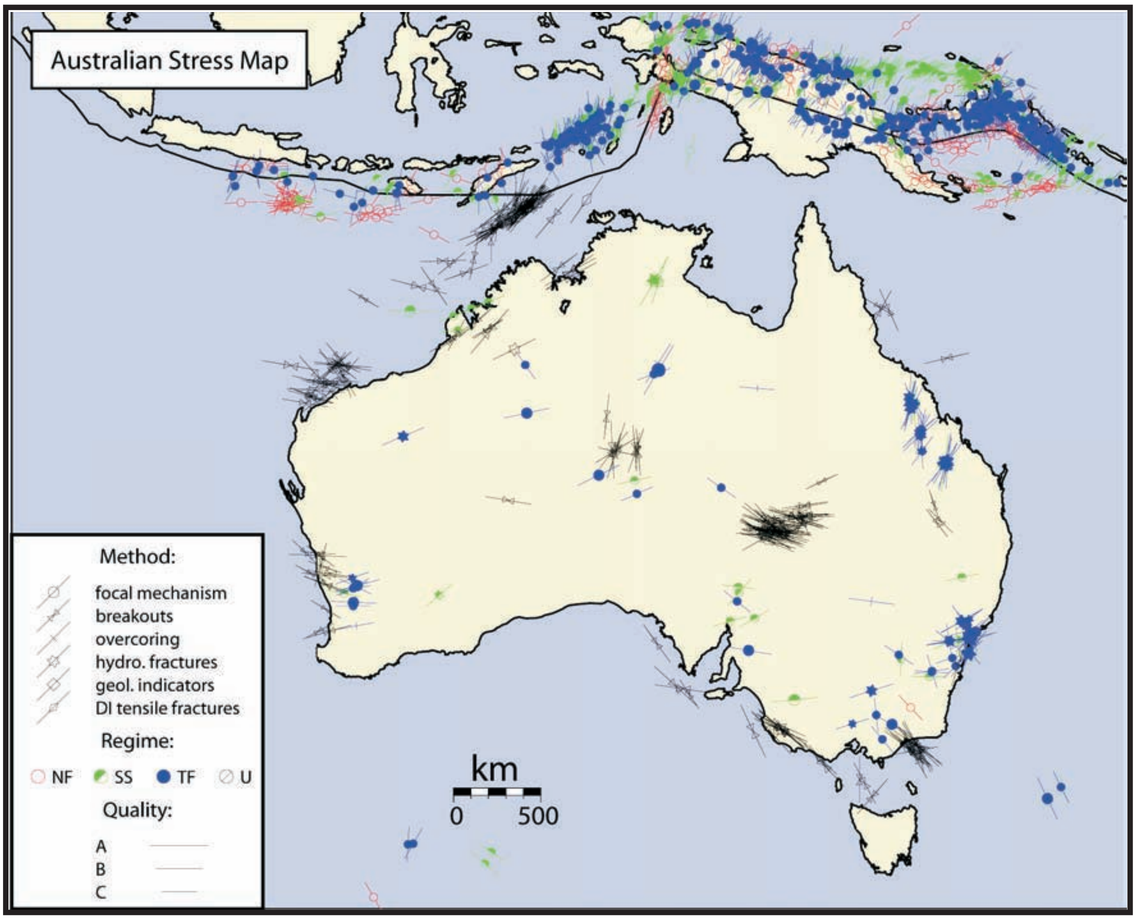

Figure 1. Australian Stress Map (A-C quality data).

(~500 km-scale) within which stress orientations are consistent. However, unlike in many other continental areas, stress directions within Australia change significantly between different provinces and do not parallel the direction of absolute plate motion. The Australian Stress Map data also reveal that stress orientations are generally consistent with depth, i.e. different techniques, sampling different depths in nearby locations yield consistent stress orientations.

The Australian Stress Map data do not support the often-made assertion that the Australian crust is everywhere one consistent with reverse faulting ($s_H>s_h>s_v$) such that the vertical stress (s_v) is the minimum principal stress. The reverse faulting regime is widely considered favourable to the development of engineered geothermal reservoirs because the stimulation zone is horizontal to sub-horizontal in such an environment and can potentially be exploited using horizontally offset vertical injection and production wells.

Earthquake focal mechanism solutions are approximately evenly divided between those of reverse faulting nature ($s_H>s_h>s_v$) and those of strike-slip nature ($s_H>s_v>s_h$). Extensive measurements of the minimum principal stress in petroleum exploration wells suggests that in sedimentary basins in Australia the minimum principal stress is generally horizontal. Even in the Cooper Basin, where the sub-horizontal orientation of the stimulated zone at Habanero suggests a reverse faulting regime in the granite basement, shallower data from the overlying basin suggest a strike-slip fault regime

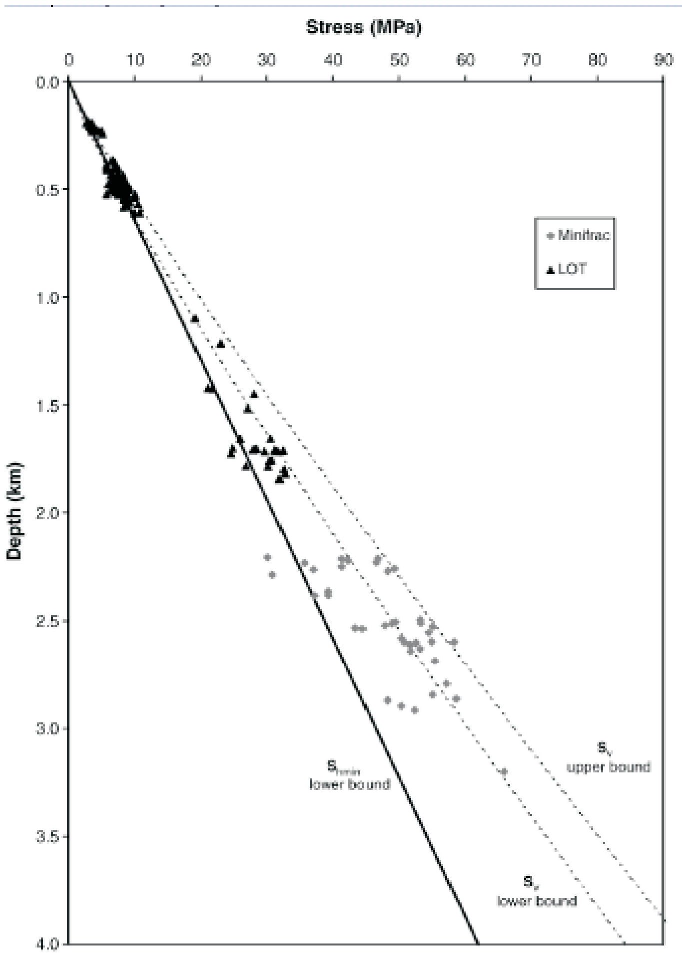

Figure 2. Stress magnitude data from the Cooper-Eromanga Basins. Both leak-off tests (LOT) and minifracs provide estimates of the minimum horizontal stress, the latter generally being more reliable. Note that there is considerable scatter in the magnitude of minimum horizontal stress and only in the minifrac data deeper than 2.5 km does the minimum horizontal stress approach and possibly exceed the vertical stress (from Reynolds et al., 2006).

(Figure 2). It should thus not be assumed that stimulation zones in geothermal reservoirs in Australia will be horizontal, especially within sedimentary basins. In situ stress analysis and measurement is required on a site-by-site basis.

IN-SITU STRESS AND FLUID FLOW IN NATURAL FRACTURES

Numerous field examples illustrate that (unstimulated) fluid flow along natural fractures in the subsurface tends to be focused on fractures that are suitably aligned for failure within the *in-situ* stress field (e.g. Barton et al., 1995). Flow is focused on fractures suitably oriented to be tensile fractures (orthogonal to the minimum principal stress) and/or on those suitably oriented to be conjugate shear fractures (inclined ~30° to the maximum principal stress and intersecting in the intermediate principal stress direction). There is, however, some debate regarding whether tensile or shear fractures play the key role.

It should also be recognised that some fractures are more stress-sensitive than others and partial bridging by cements may lead to fractures remaining open and hydraulically conductive in otherwise unfavourable stress conditions (Laubach et al., 2004). The likelihood of pre-existing fractures being hydraulically conductive within the *in-situ* stress field is best assessed using the fracture susceptibility diagram which can combine information on the orientation and nature of pre-existing natural

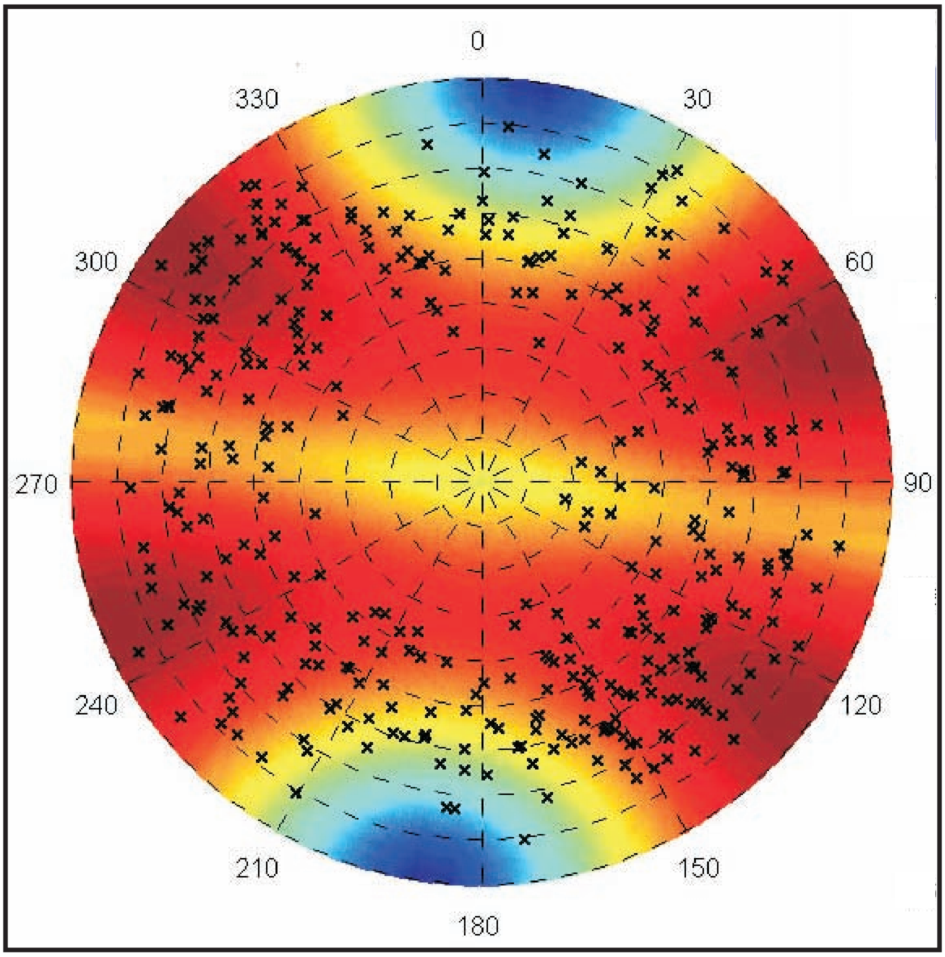

Figure 3. Fracture susceptibility diagram for a strike slip stress regime ($s_H>s_v>s_h$) where s_H is only slightly larger than s_v. The plot is a lower hemisphere projection polar plot of normals to planes. Colours show propensity of a fracture orientation to be open and hydraulically conductive within the in-situ stress field (red most likely to be open) and crosses show the orientation of fractures mapped from image logs.

fractures with information on fracture orientations most likely to be open and hydraulically conductive within the *in-situ* stress field (Figure 3). This presentation will outline the fracture susceptibility methodology.

IN-SITU STRESS AND FLUID FLOW IN STIMULATED FRACTURES

Experience from waterflooding during enhanced oil recovery operations demonstrates the key role of *in-situ* stress on subsurface fluid flow with fluid injection. The influence of *in-situ* stress on fluid flow in stimulated fractures is even stronger than its influence on fluid flow in natural fractures, because new fractures are created and/or pre-existing fractures reactivated dependent on their orientations within the *in-situ* stress field. Figure 4 summarises preferential fluid flow directions of

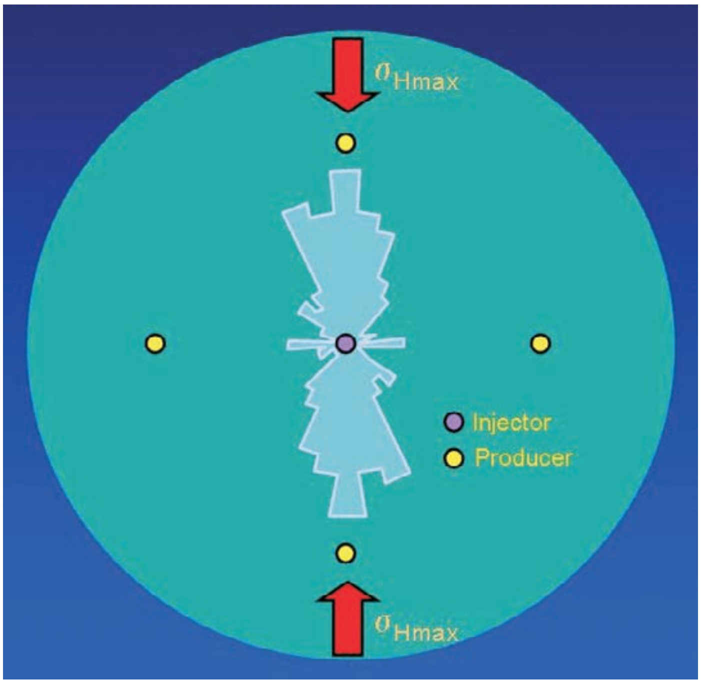

Figure 4: Preferential fluid flow direction in enhanced oil recovery operations in over 80 oil fields. Fluid breakthrough directions from a variety of different injection/production well patterns and a variety of different stress orientations have been normalised to a five spot pattern with maximum horizontal stress as indicated.(from Heffer and Lean, 1993).

injected fluids from over 80 field cases of enhanced oil recovery in North America, North Sea, continental Europe, Middle East & China showing the very strong influence of *in-situ* stress with fluid flow focused in the sH direction. This presentation will present examples of the control of *in-situ* stress on stimulated fluid flow both from oil field and geothermal examples.

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