Characterisation and modelling of stress-dependent permeability and flow in shallow fractured rock aquifers

Luke Mortimer
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A groundwater observation well at the Wendouree Winery, Clare Valley, South Australia.

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Summary

In situ stress can exert a significant control on fluid flow patterns in fractured rocks with relatively low matrix permeability. In addition to overall reduction in rock mass permeability, fracture deformation results in preferential flow along fractures oriented orthogonal to the minimum principal stress direction (due to low normal stress) or inclined ~30° to the maximum principal stress direction (due to dilation). As fracture void geometries and the connectivity of a flow network change in response to changing *in situ* stress, the storage, permeability and flow pattern should also be expected to change in magnitude, heterogeneity and/or anisotropy. These influences of *in situ* stress on the absolute and relative magnitudes and spatial distribution of the components of the permeability tensor are well documented for applications at depth but have received little attention at shallow to near surface settings. Groundwater flow modelling of shallow (<200 m) fractured rock aquifers is typically conducted under the assumption that permeability is independent of the stress state i.e. fluid flow is taking place within an effectively non-deforming medium. The potential influence of stress on fracture permeability at shallow depths might also be considered weak owing to the relatively low overburden pressures. This is perhaps the main reason why the effects of stress fields are largely ignored in shallow depth hydrogeological investigations. The question as to what extent this assumption holds at shallow to near surface depths is the main focus of this body of research.

Stress-related effects on groundwater flow at shallow depths are difficult to identify and characterise due to the complex interactions between all of the inherent properties of a fractured rock aquifer. These properties include the factors that dominantly control groundwater flow: fracture network density, geometry, connectivity and infill. Furthermore, surface processes such as weathering, erosion and unloading alter the original hydraulic nature (connectivity, transmissivity) of fractured rock masses resulting in higher degrees of spatial heterogeneity within shallow flow systems. These processes and interactions often mask the influence of *in situ* stress fields on fracture network permeability and groundwater flow. The multitude of the influential factors means that no one method can adequately map the spatial distribution of hydraulic properties that control advective groundwater flow at shallow depths. Therefore, any stress-dependent fracture permeability investigations require a multi-parameter, multi-disciplinary methodology including hydromechanical (HM) modelling.

This research began with a detailed geological and hydrogeological characterisation of fractured rock aquifers within the Clare Valley, South Australia. The study area is situated within a near horizontal, WNW-ESE directed regional compressional stress field that is seismically active and undergoing uplift and erosion. This area was the subject of several previous geological, geophysical and hydrogeological investigations that provided invaluable background field observations which improved model constraints and reduced the level of uncertainty. This research built on these previous studies through an integrated analysis of local area fracture networks from outcrop mapping, geotechnical drill core logging, surface and borehole geophysical surveys, borehole groundwater flow analyses and representative HM models. It demonstrated how *in situ* stress affects groundwater flow in shallow (<200 m) fractured rock aquifers and to what extent fracture hydraulic aperture distributions, fracture network connectivity and groundwater flow rates are modified via fracture deformation processes. The inclusion of representative HM models was important as field techniques such as outcrop mapping, borehole hydraulic and geophysical surveys do not fully account for sub-surface fracture deformation and HM response of a fracture network as a whole. In particular, comparison between deformed (stressed state) and undeformed (zero stress state) HM models enabled the effects of *in situ* stress to be qualified and quantified through evaluation of the measurable changes in the groundwater flow system of the original (pre-existing) versus deformed (contemporary) state of a fracture network.

This research adopted a unique philosophy and approach that demonstrates how to generate information complementary to standard hydrogeological observations, especially in areas where field hydrogeological data are limited. This concept was extended to preliminary fault stress state modelling to improve the probability of identifying zones of enhanced fault permeability, which in turn, could potentially increase productivity and reduce the uncertainty in locating fault-related fluid production targets, particularly in early stage exploration projects or in areas of unknown or complex geology.

Ultimately, this research contributes to the knowledge and understanding of the role *in situ* stress plays and of its interactions with other influential factors in determining groundwater flow in fractured rock aquifers. It also provides guidance on what are the critical datasets and how they can be measured and practically applied in the field as well as incorporated within groundwater flow models over local to regional scales.

Declaration of Originality

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any University; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text

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Luke Mortimer

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1 Introduction

1.1 Objectives

In situ stress fields are ubiquitous within the Earth's crust regardless of geological setting. Stress (σ) arises at all scales in the Earth's crust from several sources including the weight of overlying rocks, tectonic forces, fluid pressures, thermal loading and other geological phenomena such as volcanic activity, igneous intrusions etc (Engelder 1993, Hobbs *et al.* 1976, NRC 1996). In general, stress fields are inhomogeneous and defined by three mutually orthogonal principal axes of stress, which generally lie in the vertical (σ_V) and the maximum (σ_H) and minimum (σ_h) horizontal planes. In practice, far-field crustal stress regimes are classified using the Andersonian scheme, which relates the three major styles of faulting in the crust to the three major arrangements of the principal axes of stress (Anderson 1951). These stress regimes are: (a) normal faulting ($\sigma_V > \sigma_H > \sigma_h$); (b) strike-slip faulting ($\sigma_H > \sigma_V > \sigma_h$); and (c) reverse faulting ($\sigma_H > \sigma_h > \sigma_V$).

Stress acting on a fracture plane can be resolved into normal and shear stresses, which are the components of stress that act normal and parallel to a plane, respectively. In a fractured rock mass, these stresses are highly coupled and can cause fractures to deform. It is well documented that these processes occur at depth, in the order of kilometres, under conditions of high confining pressures and are often accounted for in petroleum, geothermal, nuclear repository and rock engineering studies (e.g. Barton *et al.* 1995, Finkbeiner *et al.* 1997, Gentier *et al.*, 2000; Hillis *et al.*, 1997; Hudson *et al.* 2005; Rutqvist and Stephansson 2003). However, the potential rate of fracture deformation is considered to be greatest at shallow depths where lower confining pressures result in a lesser amount of contact between fracture walls (fracture stiffness) (NRC 1996). This concept of nonlinear fracture stiffness implies that stress-dependency of fracture permeability may be expected to be greatest at shallow depths where groundwater is typically extracted. Whether this dependency would result in discernible changes in fracture permeability at the relatively low stresses prevailing at shallow depths is a complex issue that has largely been ignored in hydrogeological investigations. Presently, groundwater flow modelling of shallow fractured rock aquifers is typically conducted under the assumption that permeability is independent of the stress state (i.e. fluid flow is taking place within a non-deforming medium) but this assumption at shallow to near surface depths remains to be fully investigated.

The influence of *in situ* stress on groundwater flow in shallow fractured rock aquifers is difficult to characterise due to the inherent complexities in fracture network geometries, densities, connectivity, infill and weathering. These intrinsic factors dominate and may, in some cases, mask any evidence of the effects of the stress field at least at depths of <200 m below the surface. The multitude of the influential factors means that no one method can adequately map the spatial distribution of hydraulic properties that control advective groundwater flow at shallow depths. Therefore, this research investigated stress-dependent fracture permeability at shallow depths through a multi-parameter, multi-disciplinary methodology including hydromechanical (HM) modelling.

This research project is based upon the fractured rock aquifers of the Clare Valley, South Australia. This is an ideal field site as it is situated within a near horizontal, WNW-ESE directed regional compressional stress field that is seismically active and undergoing uplift and erosion. Importantly, this area has been the subject of several previous geological, geophysical and hydrogeological investigations that provided invaluable background field observations which improved model constraints and reduced the level of uncertainty.

The research described in Chapters 2 and 3 demonstrate how the effects of *in situ* stress is ubiquitous and always plays some role in the behaviour of groundwater systems at shallow (<200 m) depths. Specifically, Chapters 2 and 3 are based on the same detailed integrated analysis of local area fracture networks, borehole geophysical logs, borehole groundwater yields and HM models that demonstrate that *in situ* stress does affect groundwater flow in shallow (<200 m) fractured rock aquifers by altering fracture hydraulic aperture distributions, fracture network connectivity and groundwater flow rates via fracture deformation processes. Critically, field observations are explained through the use of representative, stochastic, HM models which characterise the key physical processes involved. A comparison between deformed (stressed state) and undeformed (zero stress state) HM models enabled the effects of *in situ* stress to be qualified and quantified through evaluation of the measurable changes in the groundwater flow system of the original (pre-existing) versus deformed (contemporary) state of a fracture network. Both chapters present a logical and robust basis for identifying, measuring, modelling and quantifying the effects of *in situ* stress at shallow depths from single well- to regional-scale datasets.

The research outcomes of Chapters 2 and 3 benefitted from the fact that their respective investigations were based upon one fractured stratigraphic unit located at one well instrumented field site. Chapter 4 builds upon these outcomes by further applying the concept of mechanical stratigraphy to an intercalated fractured sedimentary sequence to describe how stress-dependent fracture permeability differs within individual stratigraphic units and how, ultimately, this affects local groundwater flow behaviour. This is achieved through an analysis of outcrop data in conjunction with a conceptual, stochastic HM model which differentiate between the influences of the primary (or inherent) fracture network versus that of the present-day *in situ* stress field and their respective effects on bulk rock mass permeability.

This research developed a unique philosophy and approach that demonstrated how to generate structural and geomechanical information complementary to standard hydrogeological observations, especially in areas where field hydrogeologic data are limited. Chapter 5 shows how this methodology may be practically applied to preliminary fault stress state modelling that aims to improve the probability of identifying zones of enhanced, stress-related, fault permeability. Although this particular chapter focuses on a practical application of this methodology to the specific problem of geothermal fluid exploration it is just as applicable for any subsurface fluid regardless of depth.

This research contributes to the knowledge and understanding of the role *in situ* stress plays in determining groundwater flow in fractured rock aquifers through:

1. Specifically answering the complex question to what extent *in situ* stress affects groundwater flow in shallow (<200 m) fractured rock aquifers.

2. Identifying the critical datasets and how they can be best measured, practically applied and numerically modelled.
3. Differentiating the role of the inherent fracture network permeability (e.g. fracture orientation, spacing etc) versus the modifying effects of secondary processes such as subsurface fracture deformation, weathering, uplift and unloading.
4. Applying the concept of mechanical stratigraphy to describe contrasting HM effects on groundwater flow within an intercalated fractured sedimentary sequence.
5. Developing a methodology based upon structural and geomechanical datasets complimentary to standard hydrogeological field data which has many practical benefits in areas of unknown or complex geology irrespective of geological setting or depth below the surface.

This thesis is comprised of three journal papers (Chapters 2, 3 and 4) and one conference proceeding (extended abstract; Chapter 5). Each chapter contains pertinent literature reviews within their introductory sections. In their chapter order these publications are referenced as follows:

Mortimer L, Aydin A, Simmons CT, Love AJ (2011) Is *in situ* stress important to groundwater flow in shallow fractured rock aquifers? Journal of Hydrology, 399 (3-4): 185-200 [Chapter 2].

Mortimer L, Aydin A, Simmons CT, Heinson G and Love AJ (2011) The role of *in situ* stress in determining hydraulic connectivity in a fractured rock aquifer. Hydrogeology Journal, DOI 10.1007/s10040-011-0760-z [Chapter 3].

Mortimer L, Aydin A, Simmons CT, Love AJ (in prep.) Role of mechanical stratigraphy in determining groundwater flow in fractured sedimentary successions. Submitted to Hydrogeology Journal 30 June 2011 [Chapter 4].

Mortimer L, Aydin A, Simmons CT, Love AJ (2010) Targeting Faults for Geothermal Fluid Production: Exploring for Zones of Enhanced Permeability. Proceedings Australian Geothermal Conference 2010, November 16-19, 2010, Adelaide, Australia [Chapter 5].

1.2 Outline of remaining chapters

The following abstracts, directly extracted from their respective journal and conference papers, provide an outline of the content from each of the five chapters.

Chapter 2: Is *in situ* stress important to groundwater flow in shallow fractured rock aquifers?

In situ stress affects the permeability tensor of fractured rock masses at depth but its effect on shallow to near-surface fractured rock aquifers has received little attention. This is partly because stress-related effects on groundwater flow at shallow depths are difficult to identify and characterise due to the complex interactions between all of the inherent properties of a fractured rock aquifer. These properties include the factors that dominantly control groundwater flow: fracture network density, geometry, connectivity and infill. Furthermore, surface processes such as weathering, erosion and unloading alter the original hydraulic nature (connectivity, transmissivity) of fractured rock masses resulting in higher degrees of spatial heterogeneity within shallow flow systems. These processes and interactions often mask the influence of *in situ* stress fields on fracture network permeability and groundwater flow. In this study, an integrated analysis of local area fracture networks, borehole geophysical logs, borehole groundwater yields and hydromechanical models demonstrate that *in situ* stress does affect groundwater flow in shallow (<200 m) fractured rock aquifers by altering fracture hydraulic aperture distributions, fracture network connectivity and groundwater flow rates via fracture deformation processes. In particular, a comparison between representative models of deformed (stressed state) and undeformed (zero stress state) fracture networks showed that below 100 m depth, groundwater flow rates could decrease several fold under the influence of the contemporary stress field. This prediction was highly consistent with the field observations. In contrast, groundwater flow modelling of shallow fractured rock aquifers is typically conducted under the assumption that permeability is independent of the state of stress. A key finding of this study is that *in situ* stress may be a more important control on both local and regional scale shallow groundwater flow systems than previously recognised. The methodology applied in this study also offers an alternative approach to investigating groundwater flow in fractured rock masses where field hydrogeological data are limited.

Chapter 3: The role of *in situ* stress in determining hydraulic connectivity in a fractured rock aquifer.

Fracture network connectivity is a spatially variable property that is difficult to quantify from standard hydrogeological datasets. This critical property is related to the distributions of fracture density, orientation, dimensions, intersections, apertures and roughness. These features that determine the inherent connectivity of a fracture network can be modified by secondary processes including weathering, uplift and unloading and other mechanisms that lead to fracture deformation in response to *in situ* stress. This study focussed on a fractured rock aquifer in the Clare Valley, South Australia, and found that fracture network connectivity could be discriminated from several geological, geophysical and hydrogeological field datasets at various scales including single well and local- to regional-scale data. Representative hydromechanical models of the field site were not only consistent with field observations but also highlighted the strong influence of *in situ* stress in determining the distribution of fracture hydraulic apertures and the formation of hydraulic chokes that impede fluid flow. The results of this multi-disciplinary investigation support the notion that the hydraulic conductivity of a fracture network is limited to the least hydraulically conductive interconnected fractures, which imposes a physical limit on the bulk hydraulic conductivity of a fractured rock aquifer.

Chapter 4: Role of mechanical stratigraphy in determining groundwater flow in fractured rock successions.

Fractured sedimentary rock successions can be subdivided in terms of mechanical stratigraphy, which defines a subdivision of rock into discrete intervals according to the mechanical properties which determines the deformational behaviour of each interval to an applied force. This study focussed on fractured rock aquifers of the Clare Valley, South Australia, and found that the key determinant of groundwater flow is the inherent permeability of the mechanical stratigraphy and to a lesser extent the effects of *in situ* stress. Conceptual hydromechanical modelling demonstrated that mechanical stratigraphy governs subsurface fracture deformation processes which ultimately results in a reduction in the magnitudes of the permeability tensor of individual mechanical stratigraphy units and accordingly the bulk rock mass permeability. Mechanical decoupling and poor hydraulic connection between significantly contrasting mechanical stratigraphy could potentially modify and even inhibit cross-bed flow. Methods that map and subdivide fractured rock aquifers which capture relative fracture network permeability and heterogeneity from structural and geomechanical datasets have many practical benefits in terms of the targeting of wells and management of catchment-wide groundwater resources.

Chapter 5: Targeting faults for geothermal fluid production: exploring for zones of enhanced permeability.

Faults can potentially deliver increased geothermal fluid production by boosting the bulk permeability and fluid storage of a production zone. However, the hydromechanical properties of faults are inherently heterogeneous and anisotropic, thereby, making it challenging to distinguish between permeable and impermeable faults. This discussion paper outlines the key features that determine fault permeability and shows how the probability of locating zones of enhanced fault permeability can be improved by preliminary fault stress state modelling. It is proposed that such modelling (with appropriate level of complexity commensurate with the availability, nature and quality of data) can reduce the uncertainty and risk of exploring for fault-related geothermal targets, particularly in early stage exploration projects or in areas of unknown or complex geology.