Proceedings Australian Geothermal Energy Conferences 2013
Brisbane, Australia, 14-15 November 2013

Modelling the stability and performance of ductile reservoirs: fault reactivation, reservoir compaction instabilities and sand production

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Keywords: compaction, fault zone

ABSTRACT

Geothermal reservoirs are characterized by high temperatures and unlike conventional petroleum plays have often long passed the threshold for ductile deformation of the involved minerals. In this environment traditional -brittle- concepts of failure and stimulation techniques have limited performance, usually short-lived. The reason for this is the nature of ductile deformation, with the rate of deformation (time) erasing brittle features in time. Hence, ductile reservoirs are prone to ductile instabilities, which in turn determine their stability and performance. In this study we summarize recent findings for shear failure and compaction instabilities under high temperature environments. We show that these reservoirs are formed by strong interactions of chemical reactions and long time scale creep processes and their geological fingerprint cannot be described by classical reservoir mechanics.

1. INTRODUCTION

Ductile deformation is rate-, temperature- and pressure dependent. The plastic flow rule can be adequately described by the traditional ductile relation

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \left(\frac{\sigma'}{\sigma'_0} \right)^m e^{-\frac{T_0}{T}} \tag{1.1}$$

Where $\dot{\varepsilon}_0, \sigma'_0, T_0$ are reference values for the plastic strain rate $\dot{\varepsilon}$, the effective overstress σ' and the temperature *T*, respectively. The exponent *m* is the rate sensitivity coefficient. In a dry material the effective overstress is equal to the total stress, whereas in a fluid saturated medium it is relaed to the pore fluid pressure *p* through Terzaghi's principle, $\sigma' = \sigma + pI$ (*I* being the unity matrix).

A frequently used criterion for material bifurcation of the solid to mechanical loading was given by Issen and Rudnicki (2000) as an extension of the bifurcation theory used by Rudnicki and Rice (1975). According to this criterion, material bifurcation in the form of localized deformation takes place in a rate-independent elasto-plastic material obeying a standard stress-strain incremental response with an elastoplastic modulus D_{ep}

$$\dot{\varepsilon} = D_{ep}\, \dot{\sigma}' \tag{1.2}$$

when the determinant of the acoustic tensor is zero. This criterion provides the necessary conditions for D_{ep} so that localized shear and compaction failure to emerge. As ductile deformation extends past the initial failure, this criterion is necessary but not sufficient to characterize material failure under ductile conditions (Regenauer-Lieb et al, 2013a,b). In this realm materials exhibit multiphysical instabilitites that do not necessarily coincide with the classical rate-independent ones.

These instabilities are significant as they determine the post failure evolution of the reservoir, affecting its stability and productivity. In this work we therefore summarize the key aspects of these multiphysical features, relevant to geothermal industry. Hence, shear failure is studied for its direct connection to fault reactivation, whereas compaction bands are put under the spotlight as the key features governing reservoir compaction and sand production near the wellbore (Katsman et al., 2009).

2. SHEAR FAILURE

The theory of shear failure under dry conditions was presented by Veveakis et al. (2010) and extended to fluid saturated conditions recently (Alevizos et al., 2013 and Veveakis et al, 2013a). In this case the deformation is due to shear, hence Eq. (1) is written in terms of the shear strain rate, $\dot{\gamma} = \dot{\varepsilon}$.

The response of a creeping fault under constant stress τ_n is summarized in Figure 1. We notice that 3 areas of stability can identified with respect to the logarithmic strain rate and the normalized applied stress τ_n / τ_0. According to these, at low loading stresses ($\tau_n < \tau_n^{cr}$) the fault creeps stably, whereas pass the critical point it enters an oscillatory regime. In addition, for elevated strain rates a third regime arises, where the fault exhibits single instability events.

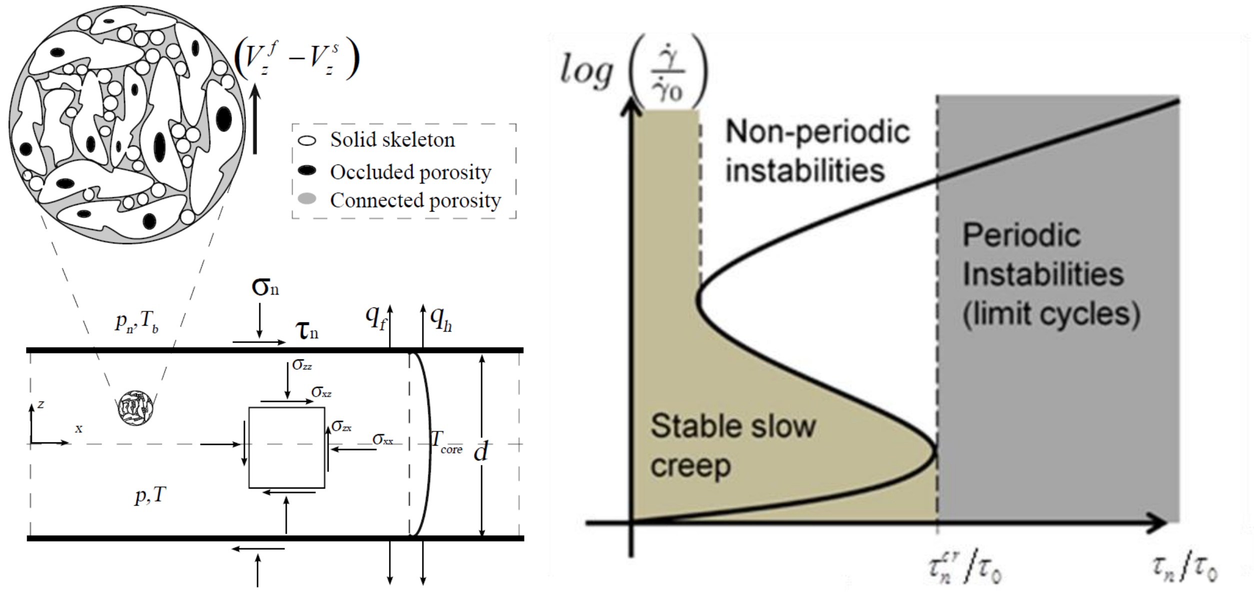

Figure 1: Summary of ductile shear failure and fault reactivation. Left: a fluid saturated shear zone (fault) of thickness *d* is deforming under constant load. The solid skeleton is allowed to change phase to fluid and vice versa. Right: Stability diagram of the fault, where 3 areas of stability are identified with respect to the logarithmic strain rate and the normalized applied stress τ_n/τ_0 . According to these, at low loading stresses ($\tau_n < \tau_n^{cr}$) the fault creeps stably, whereas when it passes the critical point it enters an oscillatory regime. In addition, for elevated strain rates a third regime arises, where the fault exhibits single instability events.

The critical point τ_n^{cr} is a function of the physical parameters of the fault (thermal conductivity, reaction characteristics, boundary and loading conditions) as calculated by Veveakis et al (2010). Hence, increasing either the shear loading or the strain rate (equivalently increasing the pore pressure or temperature) would lead to reactivating the fault in the ductile regime.

3. COMPACTION INSTABILITIES

Similarly to shear instabilitites, compaction bands are traditionally approached by Rudnicki and Rice's (1975) criterion. This criterion cannot explain the formation of periodic set of compacion bands, especially in the ductile regime (Figure 2). The theory for ductile compaction bands (DCBs) was recently developed (see Regenauer-Lieb et al, 2013b and Veveakis et al., 2013b) and calculates that the formation of DCBs in a fluid saturated medium depends on the dimensionless parameter

$$\lambda = \frac{\dot{\varepsilon}_0 \, \mu_f}{k \, \sigma_n'} H^2 \tag{1.3}$$

Where μ_f is the fluid viscosity, *k* the permeability of the solid matrix, σ_n' the loading effective stress and *H* the height of the specimen (Figure 2c). It is deduced that there is a critical value of *λ* ($\lambda_{cr} = 13$), above which periodic compaction bands emerge, with their number N_C being a function of *λ* (Figure 3).

Hence, in the ductile realm DCBs emerge as a function of the loading conditions and the hydromechanical parameters of the problem at hand. We notice that higher values of λ correspond to more DCBs, thus deducing that higher applied strain rates, higher pore fluid pressures or less permeable solid rocks promote instabilities.

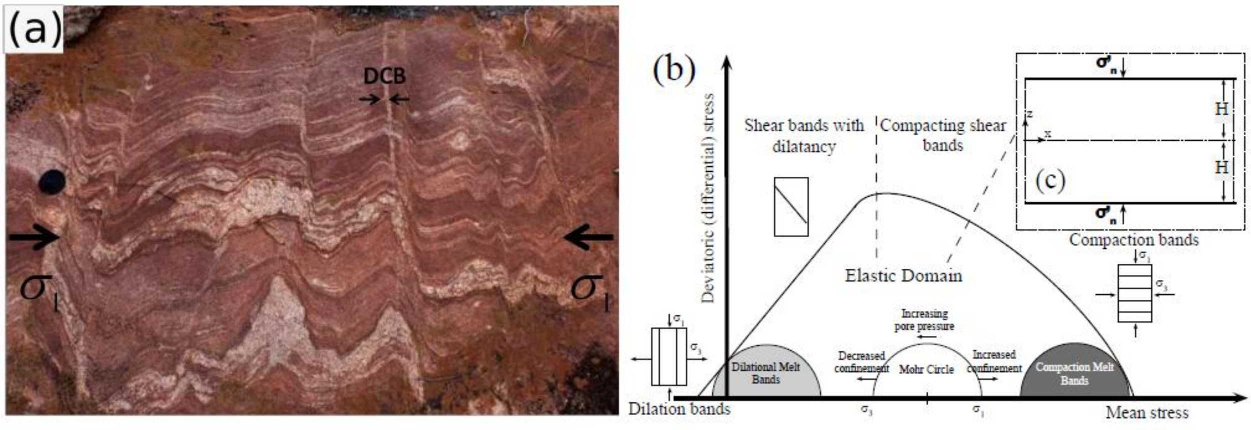

Figure 2: (a) Banded and folded ductile Archean gneiss with layer-parallel pegmatite intrusions (horizontal white bands). Folds have axial planar leucosomes (crystallized melt) oriented N-S across the photograph. We interpret these as Ductile Compaction Bands (DCBs) forming at right angle to the maximum compressive stress, oriented E-W. The orientation of the maximum compressive stress is inferred by the folding patterns and the absence of evidence for high pore pressures. Note the 20-50 cm spacing between leucosome (melt channels) bands of 10 mm thickness. Outcrop from the Yalgoo Dome, Yilgarn Craton, West Australia. (b) Traditional concept of failure from solid mechanics, where compaction bands are formed in the area of high mean (confining) stresses (Issen and Rudnicki , 2000). In this area compaction bands are formed perpendicular to the maximum compressive stress. Note that dilational instabilities only form at low confining pressures, with dilation bands forming at low angles to the maximum compressive when σ3 is tensile either due to tensile loading or due to high pore pressures. (c) 1D approach to the study of the formation of horizontal (perpendicular to the maximum compressive stress) compaction bands pattern in the ductile regime.

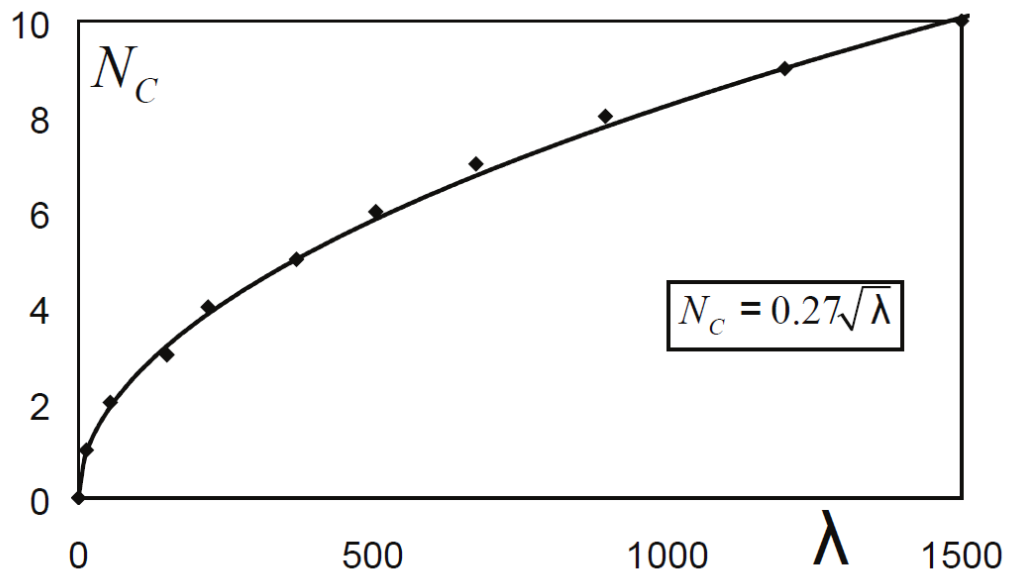

Figure 3: Number of DCBs N_C as a function of λ.

4. CONCLUSIONS

We have summarized recent advances in ductile instabilities relevant for geothermal reservoirs. We postulate that these reservoir cannot be modelled by classical mechanical concepts as these solutions only apply to short time scale processes. The geological architecture of geothermal reservoirs are, however, formed over millions of years. We have briefly discussed ductile instabilities that also emerge on short engineering time scale such as compaction bands. Since fault reactivation and reservoir compaction are of paramount importance in the viability and performance of a geothermal reservoir we expect that these simple criteria would be of wide applicability to the geothermal industry.

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