Is enhanced heat and tracer transfer by intermittent porous flow an important process in deep geothermal systems?

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PROCESSES IN ENHANCED GEOTHERMAL SYSTEMS

In enhanced or engineered geothermal systems (EGS) a fluid is pumped into a fractured reservoir through an injection well and is extracted again in a production well (Fig. 1). During this process, the fluid interacts with the rock and exchanges heat and in many cases mass (by dissolution and re-precipitation of minerals; Fig. 2). In addition, fluid flow through pores and fractures alters the stress field and mechanical behaviour of the rock. Variations in pore pressure may lead to brittle failure and opening of fractures (Fig.3 and Fig. 4).

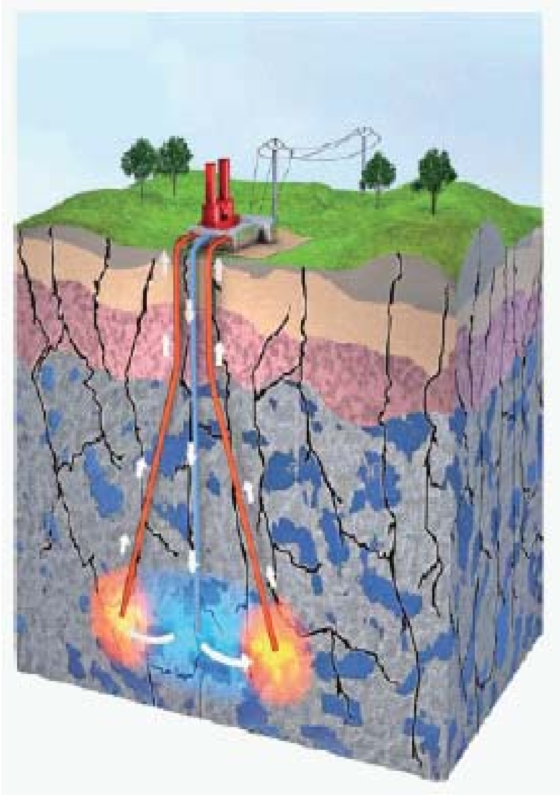

Fig. 1: Schematic drawing of the EGS at Soultz-sous-Forrêt, France, from Genter et al., 2009.

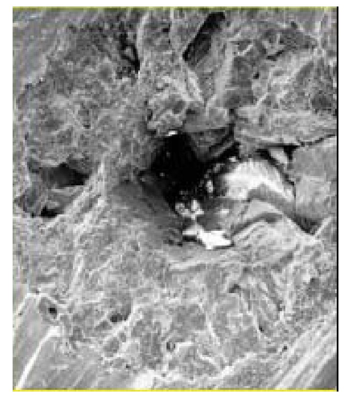

Fig. 2A: Precipitation of previously dissolved minerals (e.g. carbonates, silica, clays) in a pore or micro-fracture (picture from Portier & Vuataz, 2008).

Fig. 2B: Example of mineral deposition at Soultz: Dissolution of material in the reservoir and re-precipitation at shallower levels may reduce flow in the reservoir close to the well and in the well and tubing and can cause serious damage to the equipment.

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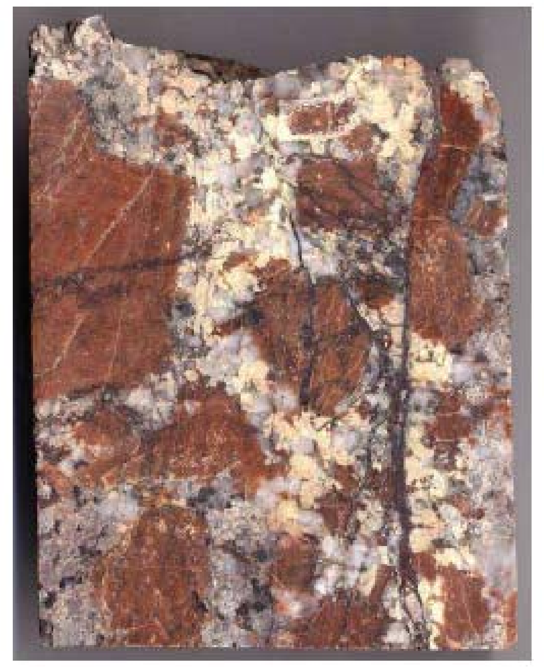

Fig. 3: Fractures in altered granite from a core taken at the EGS at Soultz-sous-Forret (Genter et al., 2009). Results from Soultz indicate that hydraulic stimulation enhanced permeability by opening previously closed weakness zones and fractures, not by creating a new network of mode-I hydraulic fractures.

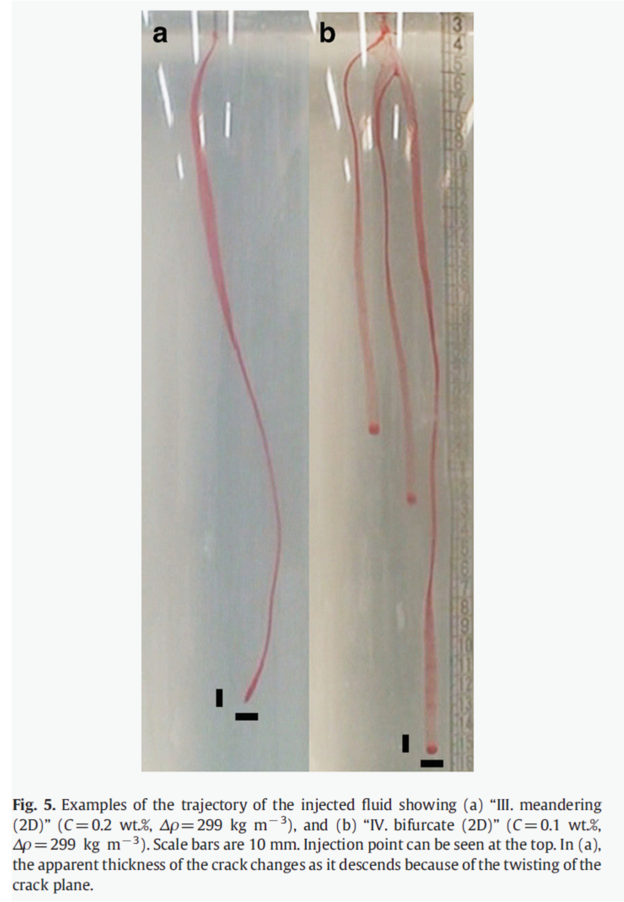

Fig. 4: Fractures created in a visco-elastic medium in an analogue experiment (Sumita & Ota, 2011).

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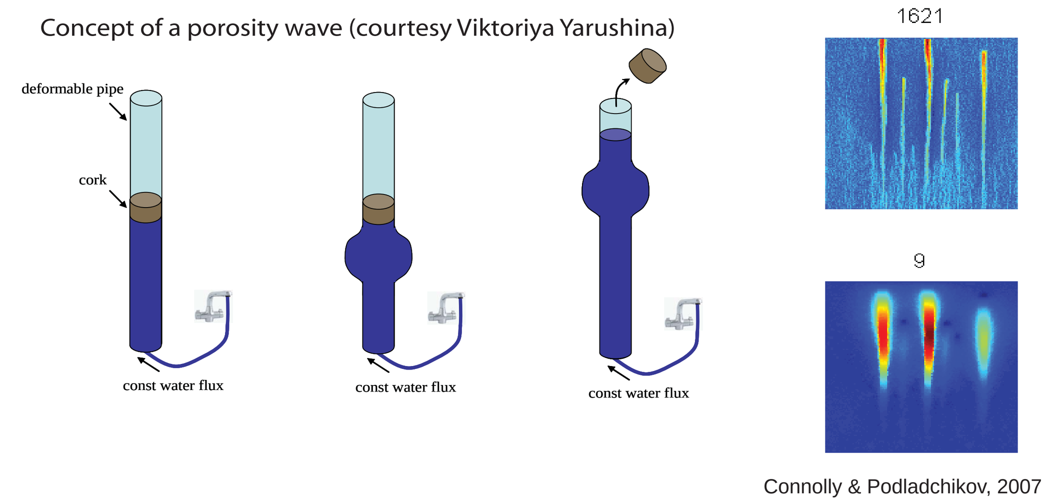
INTERMITTENT POROUS FLOW: SOME MORE EXPLANATIONS

Increase of fluid pressure leads to (plastic opening of pore space. Dissolution and precipitation of minerals under stress leads to effectively viscous compaction and closure of pore space and fractures (Fig. 5 and 6). These processes, combining reactive fluid flow through a porous rock with dynamically changing porosity and permeability can be modelled using the concept of porosity waves (Connolly & Podladchikov, 2007; Fig. 7).

Porosity waves

Porosity waves develop due to viscous compaction of the matrix. They may be purely viscous, visco-elastic or visco-(elasto-)plastic. Their shape varies depending on rheology. In two dimensions, they form elongated chanels of enhanced porosity with a high pressure head and a low pressure tail. In three dimensions, they form tubes.



Porosity waves lare pulses of strongly focused flow. Tranport of heat and mass can be significantly faster than Darcy flow through the background porosity.

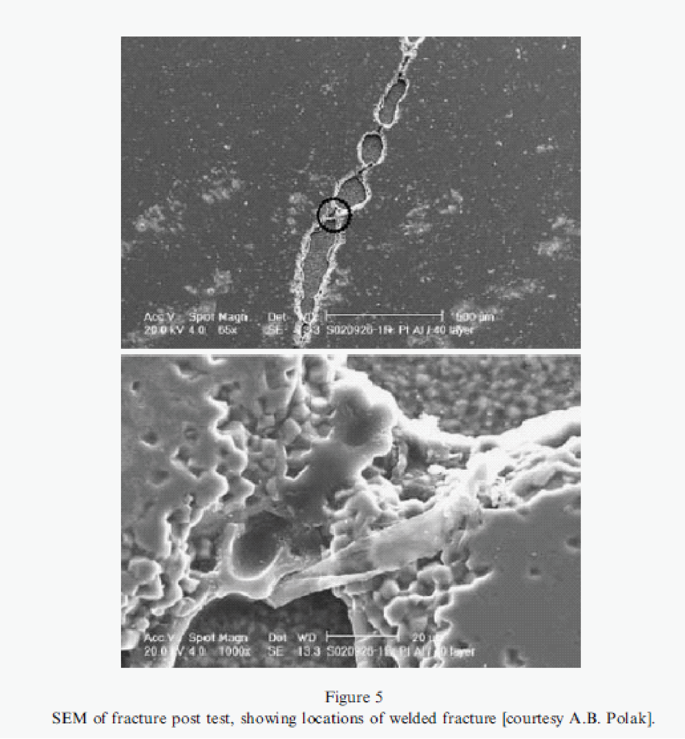


Fig. 5: Reactive flow under experimental conditions comparable to EGS through a fracture in novaculite under load resulted in closure of the fracture and permeability decrease under net dissolution (Elsworth & Yasuhara, 2006).

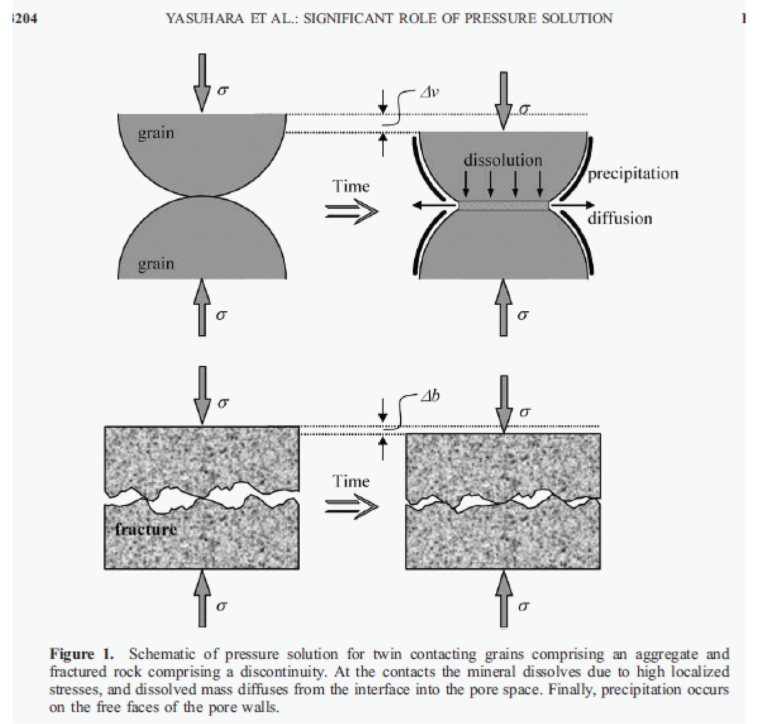


Fig. 6: Conceptual model for permeability reduction due to reactive flow under a load, explaining the observations in Fig. 5. Healing of the fracture is due to pressure solution, causing viscous compaction (Yasuhara et al., 2004).

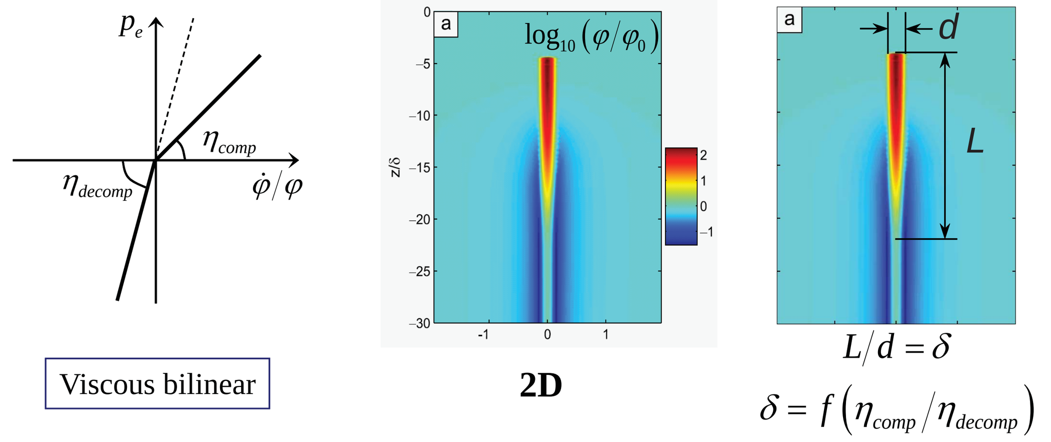
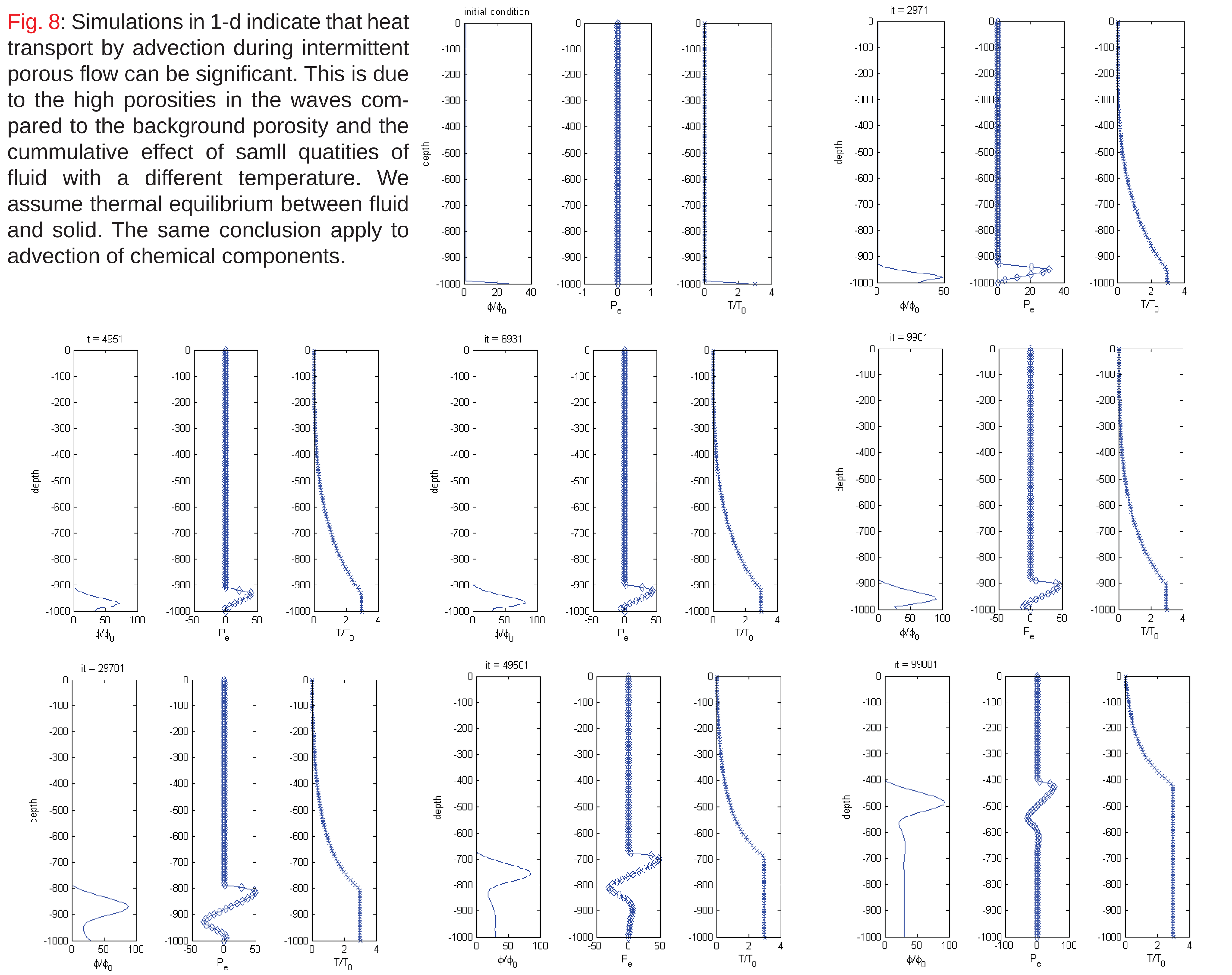


Fig. 7: The dual viscosity model reflects that the resistance to (plastic) opening of pores (decompaction) is much smaller than the resistance to viscous compaction. This description of the rheology leads to strong focusing of the fluid into high porosity chanels in 2-d. The width of the chanel depends on the ratio of the two viscosities (Connolly and Podladchikov, 2007).

PRELIMINARY RESULTS

Porosity waves are predicted to constitute an important fluid focusing and transport mechanism. They create transient or dynamic permeability in the reservoir and may allow for the rapid and focused transport of fluids, heat and mass in and out of the area close to the well without invoking the existence of an additional connected network of open fractures (Fig. 8).

Fig. 8: Simulations in 1-d indicate that heat transport by advection during intermittent porous flow can be significant. This is due to the high porosities in the waves compared to the background porosity and the cummulative effect of samll quantities of fluid with a different temperature. We assume thermal equilibrium between fluid and solid. The same conclusion apply to advection of chemical components.



Equations

Effective pressure
$$\frac{\partial P_e}{\partial t} = \frac{1}{\beta(\varphi)}\left(\frac{\partial \varphi}{\partial t} - \frac{P_e}{\eta(\varphi)}\right)$$

Porosity , visco-elastic compaction
$$\frac{\partial \varphi}{\partial t} = -\frac{\partial}{\partial z}\left(\frac{k(\varphi)}{\mu_f}\cdot\left(\frac{\partial P_e}{\partial z} + \Delta\rho g\right)\right)$$

Temperature
$$\frac{\partial T}{\partial t} = \kappa_T \frac{\partial^2 T}{\partial z^2} - q\frac{\partial T}{\partial z}$$

Flux q
$$\frac{\partial \varphi}{\partial t} = -\frac{\partial q}{\partial z}$$
$$q = \frac{k(\varphi)}{\mu_f}\cdot\left(\frac{\partial P_e}{\partial z} + \Delta\rho g\right)$$

with $k(\varphi) = k_0 \cdot \left(\frac{\varphi}{\varphi_0}\right)^n$, $n = 3$; $\beta(\varphi) = \varphi^b \cdot \beta_0$, $b = 1/2$ and $\eta(\varphi) = {\eta_s}/{\varphi^m}$, $m = 1$.

OUTLOOK

Further studies have to be carried out in 2-d to account for the effect of focusing.
The conditions under which significant advection of heat and mass occurs have to be studied in detail and parameters need to be constrained.
The numerical models have to be tested against laboratory experiments and field data, which is challenging. However, numerical results can be used to indicate and constrain the length and time scales at which we may expect these processes to occur in nature.