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CHEMICAL HYDROFRACTURING OF THE HOT DRY ROCK RESERVOIR

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ABSTRACT

The experimental study of the water-rock interaction shows that the secondary mineral assemblage depends on the water composition. For example, granite-pure water interaction produces zeolites (relatively low-dense, Mg-poor minerals), whereas seawater yields chlorites (high-dense, Mg-rich minerals). The reactions have volumetric effects from several % to 20 % in magnitude. Volume deformations in the heterogeneous matrix cause uneven mechanical strains. Reactions with the effect of about 0,1 vol.% may cause strains of the order of 100-1000 bars being enough for destruction of rocks. Signs and magnitudes of local volume changes depend on the mineral composition of the secondary assemblage. Hence, one can provide either healing or cracking of primary fractures, as desired, by changing the composition of water in the water-felsic rock system where some elements (Mg, Fe) are in lack. The techniques of "chemical hydrofracturing" looks promising as applied to a granite HDR massif. One can regulate the permeability of fractured flow paths by changing in concord the composition and pressure of the injected water. This approach should promote efficient extraction of the petrothermal energy.

INTRODUCTION

High permeability of the Hot Dry Rock (HDR) reservoir is a necessary precondition for the efficient heat extraction by the circulating water. If the initial permeability of rocks is low, permeable paths are commonly created by the hydraulic fracturing of the HDR massif between two boreholes by injecting the water into one of them under a high pressure. Afterwards water circulates from this borehole to other one through the fractured flow path.

Field experiments made by R.W.Charles with co-workers (1981) showed that during exploitation of the HDR system, a secondary flow path may suddenly appear. Mechanism of this phenomenon was taken no notice of by those researchers. But such a phenomenon should encourage heat extraction, and it is worth to reveal this mechanism in order to use it for proficient heat extraction.

This work is devoted to a physical-chemical model of water-rock interaction being able to cause fracturing of the Hot Dry Rock reservoir.

EMPIRICAL AND THEORETICAL BASIS FOR CHEMICAL HYDROFRACTURING OF ROCKS

Chemical reactions in the water-rock system are a well-known factor of mechanical strains and fracturing of host rocks. In particular, stress corrosion provides subcritical crack growth (Atkinson and Meredith, 1987), whereas precipitation of solids serves to crack-seal (Engelder, 1987). T.Engelder believes that intermittent cracks growth is a result of stress cycling when stress repeatedly exceeds tensile strength of the crack healing cement. These observations provoke us to turn to a new theoretical model of mechanical processes coupled with chemical reactions (and temperature variations, as well) in the water-rock system (Yakovlev and Borevsky, 1994a; Yakovlev, 1995).

The model shows the water acting as a universal agent of mechanical strains, heat-mass transfer, and chemical reactions. In general, interrelationship (coupling) of these processes is described by a continuity equation deduced for the water-rock system from the Mass Conservation Law:

$$\beta\frac{\partial P}{\partial t}+\frac{1}{\rho}\nabla(\rho\vec{u}) = w_c + w_t\,, \qquad (1)$$

where P is pressure in bars; t is time in s; β is the coefficient of isothermal compressibility of the system due to pressure variations (bar^{-1}); ρ is density of the water-bearing rock; $\vec{u}$ is the flow velocity in m/s; w_c and w_t denote the specific volume production (s^{-1}) due to the chemical reactions and thermal expansion/contraction, respectively. In the given study, the chemical effects are of primary interest. The term "chemical volume production" w_c expresses the total relative volumetric effect of chemical reactions per time unit:

$$w_c = \frac{\partial \varepsilon}{\partial t}, \qquad (2)$$

where ε denotes the sum of specific volumes of reactants at the given time moment t including all of the solid phases of the rock matrix, water, and dissolved species in the given local volume of the water-rock system (see below).

For a closed system ($u = 0$) at constant temperature, equation (1) is re-written in a common form:

$$\beta \Delta P = \Delta \varepsilon, \qquad (3)$$

where symbol Δ denotes the parameter increment per a time period Δt, namely: ΔP is the piesometric effect caused by the total relative volumetric effect $\Delta\varepsilon$ of the rock alteration per the time period Δt;

$$\Delta\varepsilon = \Delta V / V_1 = (V_2 - V_1) / V_1, \qquad (4)$$

where V_1 and V_2 are, respectively, initial and final volumes of the given local fragment of the water-rock system. Note, that in general case, the total volumetric effect $\Delta\varepsilon$ differs from one $\Delta\varepsilon^s$ calculated only for solid phases (matrix), as follows:

$$\Delta\varepsilon^s = \Delta V^s / V_1^s = (V_2^s - V_1^s) / V_1^s, \qquad (5)$$

where V_1^s and V_2^s are, respectively, initial and final volumes of solid matrix in the given fragment of the water-rock system. The effect $\Delta\varepsilon^s$ defines only a change of porosity having no influence (!) on the pressure change.

The coefficient β in (3) ranges from 1.3×10^{-6} to 9.4×10^{-5} bar^{-1} for the main types of rocks (Yakovlev and Borevsky, 1994a). By substituting in (3) the coefficient β with these typical values we find that

$$\Delta P \cong (10^5 - 10^6)\, \Delta\varepsilon. \qquad (6)$$

The relation (6) implies a fundamental result: when the volumetric effect of chemical reactions is only about 10^{-3} (i.e., 0.1%), pressure changes by a critical value of the order of 100 to 1000 bars. Such pressure variations easily create stresses exceeding the strength of atomic bonds at the sharp ends of fractures and near the contacts of mineral grains. Therefore, the noted value of the chemical specific volumetric effect is considered as the "critical" one - $\Delta\varepsilon_{crit.} \cong \pm10^{-3} = \pm0.1\%$ - characterizing conditions of rocks' destruction.

In fresh rocks subjected to alteration the critical volumetric effect is reached very quickly. We have calculated the effects for a set of typical hydration/dehydration reactions of basic rocks subjected to greenstone metamorphism (Yakovlev and Borevsky, 1994b; Yakovlev, 1995). The set of reactions describes appearance of Ca-zeolites (laumontite, lawsonite and wairakite), epidote and Mg-chlorite due to dissolution of Ca- and Na-plagioclases, Mg-pyroxen and SiO_2 re-distribution in the matrix. A similar set of reactions may take place in felsic (Mg-poor) rocks (granite, dacite, etc.) when aqueous solution brings Mg-ion fixed in chlorites. The volumetric effects $\Delta\varepsilon$ of the above reactions vary from several to 20 vol.% being by 2-3 orders of magnitude more than the critical value (~0.1%). Therefore, the reactions proceeding in closed or almost closed pores with the mean volumetric effect of $\approx$10%, the host rock is destroyed when only 1/1000 to 1/100 portion of its matrix has been altered. Of special interest for the current study is that the chemically induced fracturing should happen just after the water having contact with fresh rock.

The volumetric effects $\Delta\varepsilon$ depend on the set of mineral phases contacting with water in local micro-volumes of geological space (individual pores, etc.). In general, very pronounced positive volumetric effect takes place when the secondary minerals (some zeolites, etc.) are relatively low-dense, whereas marked negative effect is a result of relatively high-dense secondary minerals appearing like Mg- and Fe-chlorites. Heterogeneity of the composition and properties of rocks leads to spatially uneven mechanical strains: some pores are expanded (ΔP>0) whereas others ones are collapsed (ΔP<0) - so, hydraulic fracturing may be very intensive. Micro-fractures joint forming fractured zones that can widely spread throughout an initially monolithic rock massive.

For example, the Kola Superdeep hole passed such a zone of hydraulic destruction of metamorphic rocks (Borevsky et al., 1984). Besides, widely spread post-volcanic greenstone belts of the Earth, both ancient ones (in the Canada, Ural, etc.) and young (in the Caucasus region, Japan, etc.), demonstrate that large massifs of basic igneous rocks may be transformed entirely into "green schists" as a result of the above mechanical and chemical processes, and unexpected hydrodynamic phenomena, as well (Yakovlev, 1992; Yakovlev, Borevsky, 1994b).

At the same time, massifs of felsic rock as usual retain almost unaltered for a geologically long time. In fact, felsic rocks does not contain components need for creation of high-dense secondary minerals like chlorite. When the fresh felsic rock contacts with Mg-poor water (of meteoric origin), only low-dense secondary minerals (zeolites, carbonates, clays, etc.) are precipitated. They heal flow paths and the rocks are "conserved" impeding to further alteration. At the same time, the felsic rocks contacting with Mg-rich water (e.g., seawater), the mentioned chemical and mechanical processes may occur like in the basalt-water system. This circumstance is essentially interesting in a view of possible ways for regulating the permeability of felsic Hot Dry Rock reservoirs.

Field and laboratory research of the granite-water interaction (Charles et al., 1981; Charles and Bayhurst, 1982; Savage et al., 1989, etc.) showed the water composition controlling the phase composition of secondary mineral assemblage. Stream or distilled water percolating through the fractured granite produces mainly zeolites (like laumontite), sulfates and carbonates replacing feldspars and silica. At the same time, seawater (donor of Mg) passing through the granite produces principally chlorite-type mineral or smectite-like clay phase containing chlorite interlayers. These two types of water-rock interaction are schematically described below and their volumetric effects are calculated by using the relations (4-5) (mole volumes of reactants in cm^3 are subscribed under their formulae):

(A) granite - stream water

$$\underset{\substack{\text{anortite}\\100,79}}{CaAl_2Si_2O_8} + \underset{\substack{\text{quartz}\\2\times22,69}}{2SiO_2} + \underset{\substack{\text{water}\\4\times18,07}}{4H_2O} \rightarrow \underset{\substack{\text{laumontite}\\205,43}}{CaAl_2Si_4O_{12}\cdot 4H_2O}$$

Volumetric effects of reaction A:
- total one
  absolute - $\Delta V = +10,20$ cm^3,
  relative - $\Delta\varepsilon = +5,2$ %;
- one calculated for solid phases:
  absolute - $\Delta V^s = +82,20$ cm^3,
  relative - $\Delta\varepsilon^s = +66,7$ %.

(B) granite - seawater:

$$\underset{\substack{\text{anortite}\\100,79}}{CaAl_2Si_2O_8} + \underset{\substack{\text{quartz}\\22,69}}{SiO_2} + \underset{\substack{\text{aqueous solution}\\8\times18,07 \quad 5\times0,69}}{(8H_2O + 5Mg^{++})} \rightarrow \underset{\substack{\text{chlorite}\\208,2}}{Mg_5Al_2Si_3O_{10}(OH)_8} + \underset{\substack{\text{aqueous solution}\\2,45 \quad \approx0}}{(Ca^{++} + 8H^+)}$$

Volumetric effects of reaction B:
- total one
  absolute - $\Delta V = -60,84$ cm^3,
  relative - $\Delta\varepsilon = -22,4$ %;
- one calculated for solid phases:
  absolute - $\Delta V^s = +84.72$ cm^3,
  relative - $\Delta\varepsilon^s = +68,6$ %.

Mole volumes of minerals and H_2O are taken for these calculations from (Karpov et al., 1976). Mole volumes of aqueous species are accepted with regard to the structure of aqueous solutions of electrolytes considered theoretically by O.Ya.Samoilov (1957). This theory shows that proton ions do not occupy any notable space of the structured solution since they are distributed at negative poles of water molecules. Therefore, we can accept that contribution of H^+-ion to the reaction's volumetric effect is near zero. Contribution of aqueous Ca^{++} and Mg^{++} ions depends on their "hydration number". But they have almost equal hydration numbers, about 4 (Samoilov, 1957). So, their pure crystal-chemical volumes were taken into account, calculated from their radii: 0,99A for Ca^{++} and 0,65A for Mg^{++}, after L.Pauling (Voitkevich et al., 1977).

By comparing the reactions A and B one can see their total volumetric effects differing significantly. Reaction A causes total expansion of the "stream water-rock" system squeezing the water (added to zeolites) out of fractures, whereas reaction B causes total contraction of the "seawater-rock" system associated with the absorption of water in chlorites. At the same time, the volumetric effects of these reactions calculated for solid phases have a uniform and marked positive magnitudes : 67-69%. So, the both reactions serve to the common healing of fractures despite of different signs of mechanical strains caused by them.

In the course of reaction A, the total expansion is superimposed on the matrix expansion (fracture healing). This makes a major contribution to the above mentioned "crack-seal" (Engelder, 1987) with contemporary squeezing the water out of the pore spase. So, reaction A will be interrupted rather quickly and the initial fracture growth will be suppressed. In the case of reaction B, contraction of the closed system induces inflow of the solution through the halo of secondary minerals in spite of the crack healing. It serves to the crack growing by the stress corrosion of fresh minerals near its ends (Atkinson, Meredith, 1987). Moreover, even if such crack has being sealed entirely near its inlet zone due to an additional outer load on the host matrix, it would not prevent its further growth, since the sealed crack behaves like an autoclave with pronounced strains being caused in the host matrix and increasing locally up to critical values. This is also an aid to the fracture further growth.

Therefore, these examples show that in felsic rocks, the crack growth - with total spreading the fractured zone - may be either stimulated or suppressed chemically - depending on the solution composition. This circumstance looks quite promising in a view of man-controlled hydrofracturing of crystalline rocks used for heat extraction or other practical purposes.

CHEMICAL HYDROFRACTURING OF FELSIC HOT DRY ROCKS

Let us consider a possible way for man-controlled "chemical hydrofracturing" of HDR reservoir according to the above behavior of granite-water system. The procedure proposed (Fig.) consists of repeated technological cycles including three stages.

At the 1st (short-time) stage, Mg-rich water is used for the hydraulic fracturing of felsic hot rock massif by injecting the water under a pressure $P^{1}_{inj.}$ exceeding the lithostatic load $P_{lith.}$ The newly-formed fractured system consists of the main flow path and branch cracks off it. A thin halo of secondary minerals rapidly covers the walls of fractures. The halo contains chlorite-type minerals.

At the 2nd (relatively long-time) stage the fractured system is filled with pure (stream) water under a lower pressure $P^{2}_{inj.}<P^{1}_{inj.}$. The stream water being injected replaces seawater along the main permeable channels, but in the branch fractures relatively stagnant conditions will prevail, especially near their ends away from the main channel. So, near the inlet zones of branch fractures chemical reactions like A will prevail aid to sealing of thin fractures by zeolites and accompanying phases. The thin halo of chlorite-type minerals covers fresh minerals near the inlet zones. Nevertheless, it is unlikely that this halo may impede essentially further granite-stream water interaction as it infers from the experimental study of the seawater-rock interaction (Crovisier et al., 1987; Eroshchev-Shak, 1992). At the same time, at the ending zones of sealed branch fractures reactions like B continue to go promoting further replacement of matrix with secondary minerals.

At the 3d stage, the stream water is injected under a pressure $P^{3}_{inj.}$ being low enough to provide the branch fractures seal due to the lithostatic load pressing the thicker part of halo (near the inlet zone) into a tight stopper. The sealed fracture behaves as a closed system (like an autoclave) that encourages its growth. The halo of zeolites in the inlet zone may serve as protector covering fresh minerals if the halo was compressed enough after the crack-seal. At such conditions reactive solution should not contact with fresh minerals near the inlet zone, therefore the branch fracture can grow only at the expense of lengthening its peripheral zone.

After the fractures growth is suspended (e.g., because of lack of reactants), one can repeat step-by-step the above injection cycle trying to create new flow paths or, maybe, to heal the existing unwanted fractured zones, as desired.

CONCLUSIONS

In the Earth's interior composed of dry impermeable rocks, even small changes of rocks' composition in contact with water act as a powerful regulator of mechanical strains and easily cause destruction of rocks.

Theoretical speculations and empirical data allowed us to propose a method for the man-controlled chemical hydrofracturing of granite HDR reservoir by coordinated changing the composition and pressure of the injected water.

Here we paid the attention only to some of the principal features of the man-disturbed water-rock system. Many other questions remain to be answered. Field and laboratory experiments (in particular, in the framework of HDR projects) should verify validity and clarify white gaps of the technique proposed.

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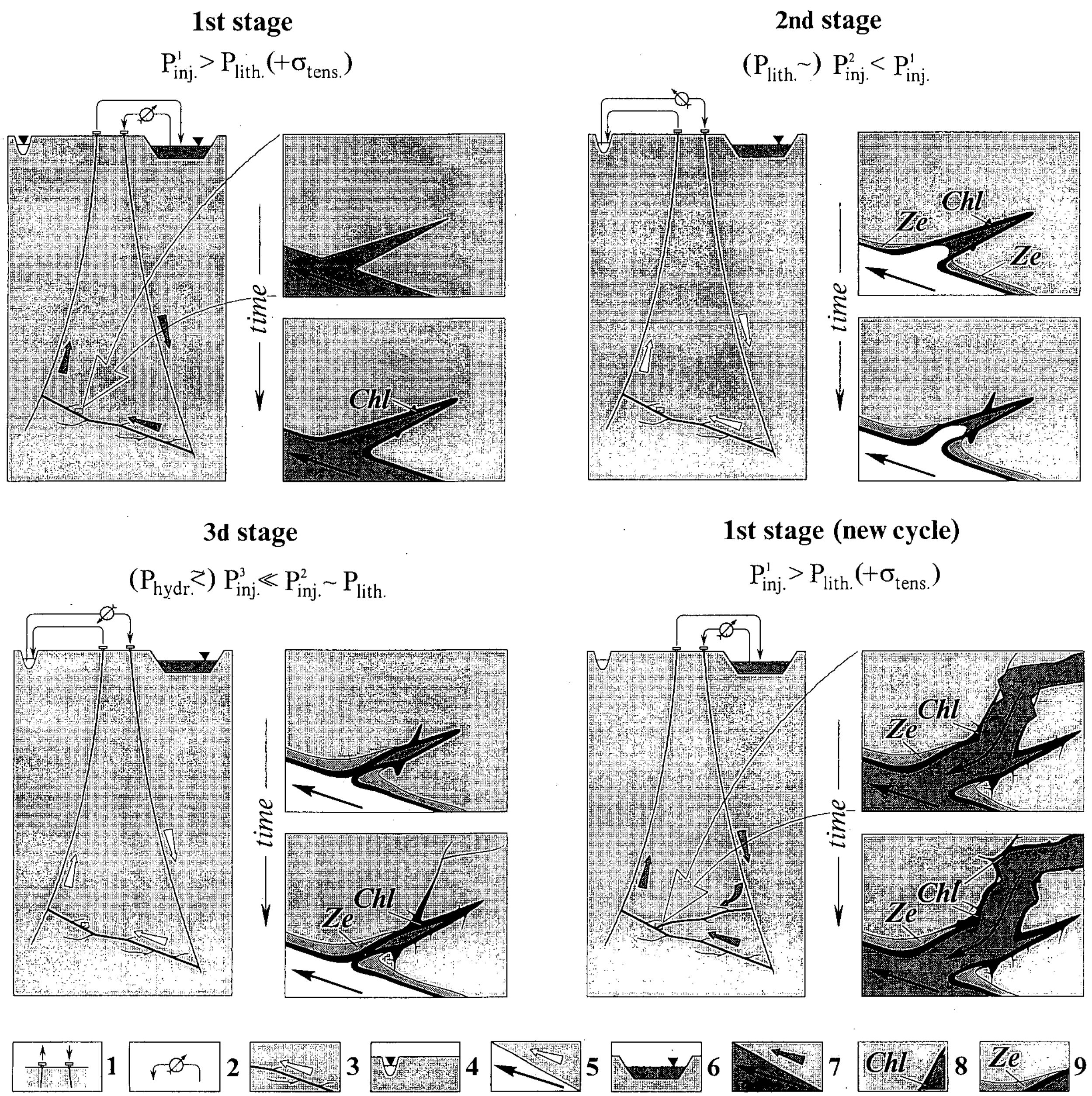

1st stage

$P^1_{inj.} > P_{lith.}(+\sigma_{tens.})$

2nd stage

$(P_{lith.}\sim)\ P^2_{inj.} < P^1_{inj.}$

3d stage

$(P_{hydr.}\lesssim)\ P^3_{inj.} \ll P^2_{inj.} \sim P_{lith.}$

1st stage (new cycle)

$P^1_{inj.} > P_{lith.}(+\sigma_{tens.})$

Figure. Scheme of the artificial chemical hydrofracturing of felsic Hot Dry Rock reservoir. 1 - boreholes; 2 - direction of the injected water movement and manometer showing relative pressure of injection; 3 - fractured flow path; 4 - source of pure (stream) water; 5 - directions of the stream water movement at different scales; 6 - source of Mg-rich water; 7 - directions of the Mg-rich water movement at different scales; 8 - halo containing secondary chlorite-type (relatively high-dense) minerals; 9 - halo containing secondary zeolites (relatively low-dense minerals). (See the text).

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