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ON THE DEFORMATION OF FRACTURES AND MICROFRACTURES IN POROELASTIC ROCKS

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ABSTRACT

Some volcanic hydrothermal systems contain portions of rock where fractures and microfractures appear closed. This phenomenon could have two origins: the first one is self-sealing by mineral deposition during water-rock interactions. The second one results from the combined action of both fluid-rock compressibility and rock geomechanical deformation. Under geothermal conditions the rock can be dry, wet or completely saturated. From experimental results and direct observations in cores it is well known that the cohesive structure of rocks is weakened by the presence of liquid in the pores. The mechanical parameters of fractured volcanic rock are also influenced by its cohesion and directly affected by both pressure and composition of the fluid located in pores, fractures and microfractures. In some type of volcanic systems the fluid could be scarce since the beginning of its formation, producing a natural closure of fissures. In this paper we develop a practical explanation and a theoretical description of such geomechanical phenomenon of closure of fissures on the basis of some fundamental poroelastic equations. Recent studies carried out on a prototype of this type of systems (Los Humeros, México) allow to conclude that at the moment of being formed, out of unknown reasons, this reservoir was unable to store abundant fluid as in other similar reservoirs. Our central hypothesis is that such lack of fluid caused the collapse and closing of fractures and faults in some portions of the reservoir, originating a global permeability drop and permitting, at the same time, the coexistence of strong pressure gradients between the matrix blocks and the few open fissures. The lack of liquid and the poor global permeability are also supported by geochemical evidence, because in most drilled zones in this reservoir chemical equilibrium between water and rock has not been attained.

Keywords*: Poroelasticity, fractures, fracture elasticity, fractures collapse, hot dry or wet rock, low permeability, geothermal systems, Los Humeros reservoir, Mexico.*

In geothermal reservoirs the rocks are poroelastic and their geomechanical properties are affected by the presence of fluid inside the pores. The different values between dry and saturated rock parameters are determined by the amount of liquid saturation, porosity, permeability, pressure and temperature (Farmer, 1968). Compared with gases, liquid water has very low compressibility. This property tends to reduce rock elasticity and stiffness, but saturated rock density and the magnitude of wave propagation are increased, while strength is reduced. In other words, the presence of water in a rock always makes its fracture easier. Such effects are well known in porous materials since 1943. This is generally called

INTRODUCTION

It is well known that fluid extraction from simple underground porous media, can produce subsidence because of the reduction of the internal pore pressure and of the effective pores' diameter. A similar event occurs in naturally fractured reservoirs that had intense tectonic activity in their remote past and where the original fracturing was higher. Nevertheless, some volcanic hydrothermal systems contain portions of fractured rock where many fractures appear closed. This phenomenon could be caused by autosealing during water-rock chemical interactions at high temperature. Fractures in volcanic systems can also be closed because of fluid lost by natural means or through human activity. In both cases the deformation differences between dry rock and saturated rock play an important role.

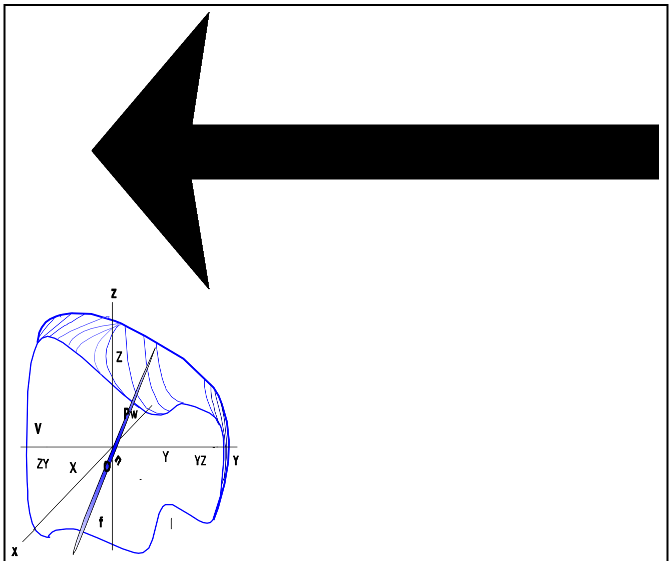
Rocks forming volcanic systems are discontinuous not only on the small scale of pore spaces, but also on local and regional scales they present fractures and faults or major discontinuities. If at the moment of its formation the reservoir was unable to store abundant water, such lack of fluid could cause the collapse and closing of many fissures, fractures and even faults, originating a global drop on permeability and permitting, at the same time, the coexistence of very strong pressure gradients between the matrix blocks and the residual open fractures. If the rock is accepted to be poroelastic, then we have to accept also that fractures aperture has some variability and the related permeability is also affected by fluid extraction and by liquid injection, the rock acting as a solid sponge. Volcanic reservoirs contain fractures and microfractures. We freely employ the term fissure to refere to both of them. In this paper we present a simple fissure-poroelastic model to estimate fissure deformation. As a concrete example of this phenomenon, we apply the model to the Los Humeros, México geothermal field, a fractured volcanic reservoir with high energy and low permeability.

EFFECTS OF FLUID ON GEOTHERMAL ROCK PROPERTIES

the *pore-water* effect, which affects more or less the whole rock thermo-mechanical behavior. In the study of fractured rock, we have to extend those concepts to include new notions such as *fissure-water* effect and *fissure elasticity*. On the basis of the classical poroelastic theory we can calculate approximately how internal stresses and deformations are affected by the fluid in a fractured rock matrix. There are two extreme cases to consider: dry rock and totally saturated rock.

A QUASI-PLANAR 3D MODEL FOR THE ISOTHERMAL DEFORMATION OF FRACTURES

Let V be a rock portion of a geothermal reservoir that can be dry or saturated with water in liquid state. This portion of rock is confined and crossed by a single fracture **f** in the plane YZ. The fissure has an inclination ? with the vertical axis Z (Fig. 1). The water saturating the region V has very low compressibility and the pore-water pressure is almost equal to the hydraulic pressure p_f, represented by a spherical tensor p_f $d_{i\,j}$ (the unit tensor is $d_{i\,j}$). A compressive tensor stress **S** is applied to V. The plane YZ is orthogonal to the plane of failure.



The tensorial stress in the fissure can be represented in a simpler system of coordinates (**i**, **t**, **n**), where **t** is a unit vector parallel to **f** and **n** is a unit vector orthogonal to **f.** In the reference frame XYZ, we perform a positive rotation of axes $\mathbf{U}^T\ \mathbf{S}\ \mathbf{U}$, around OX in the direction of ?. **U** is the rotation matrix and **S** is the total stress tensor:

$$U^T\ \Sigma\ U = \begin{pmatrix}1 & 0 & 0\\ 0 & \sin q & \cos q\\ 0 & -\cos q & \sin q\end{pmatrix}\begin{pmatrix}s_X & 0 & 0\\ 0 & s_Y & s_{yz}\\ 0 & s_{yz} & s_Z\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \sin q & -\cos q\\ 0 & \cos q & \sin q\end{pmatrix} = \begin{pmatrix}s_X & 0 & 0\\ 0 & s_T & s_{TN}\\ 0 & s_{TN} & s_N\end{pmatrix} = \Sigma_U$$

Each component of tensor $\mathbf{S}_U$ is:

$$s_T = s_Y \sin^2 q + s_Z \cos^2 q + 2\, s_{yz} \sin q \cos q = \frac{s_Y + s_Z}{2} - \frac{s_Y - s_Z}{2} \cos 2q + s_{yz} \sin 2q$$

$$s_N = s_Y \cos^2 q + s_Z \sin^2 q - 2\, s_{yz} \sin q \cos q = \frac{s_Y + s_Z}{2} + \frac{s_Y - s_Z}{2} \cos 2q - s_{yz} \sin 2q$$

$$t = s_{TN} = (s_Z - s_Y) \sin q \cos q + s_{yz} (\sin^2 q - \cos^2 q) = \frac{s_Z - s_Y}{2} \sin 2q - s_{yz} \cos 2q$$

We can further simplify the system of equations (2) by assuming that vectors (**i**, **j**, **k**) correspond to principal directions of the state of stress around the fissure. Let us assume that X, Y, Z are the principal axes and that V is subjected to the principal stresses s_X, s_Y and s_Z as shown in figure 1. The main effective stresses are contained in the plane YZ, s_X , s_Y are the lateral confining stress and s_Z is the vertical stress, minimum and maximum respectively, having a zero shear stress on this plane $s_{yz} = 0$. If the rock is dry, the tangential stress s_T , the normal stress s_N and the shear stress $t = s_{TN}$ acting in the direction ? of the fracture are given by the following parametric equations:

$$s_T = \frac{s_Y + s_Z}{2} - \frac{s_Y - s_Z}{2} \cos 2q$$

$$s_N = \frac{s_Y + s_Z}{2} + \frac{s_Y - s_Z}{2} \cos 2q$$

$$t = \frac{s_Z - s_Y}{2} \sin 2q$$

On the other hand, in saturated porous rock the effective stresses acting in the rock will be decreased by the pore-water pressure p_f . This effect was discovered by Terzaghi in 1943 when he showed experimentally that the stress tensor s_I acting in saturated rocks is reduced by $s_I - p_f$ in every principal stress axis (I = X, Y, Z). Similarly, in a fissured rock the effective stress acting on the solid framework and controlling its behavior, is the difference between each principal stress and the fissure-water pressure. Replacing these effective stresses in equation (3) we obtain the tensor stress $\mathbf{S}_w$ acting in the

$$s_{Tw} = \frac{(s_Y - p_f) + (s_Z - p_f)}{2} - \frac{s_Y - s_Z}{2} \cos 2$$

$$s_{Nw} = \frac{(s_Y - p_f) + (s_Z - p_f)}{2} + \frac{s_Y - s_Z}{2} \cos 2$$

$$t_w = \frac{(s_Z - p_f) - (s_Y - p_f)}{2} \, sen\, 2q = t$$

The Los Humeros geothermal system is a high energy reservoir. Its measured temperatures are between 260°C and 400 °C. It is located between the states of Puebla and Veracruz in Mexico, toward the eastern portion of the TransMexican

$$\_ = \frac{1+n}{\mathrm{E}} \Sigma - \frac{n\,\mathrm{s}}{\mathrm{E}} (d_{\mathrm{ij}})$$

Volcanic Belt (Fig. 2). This reservoir is inside a collapsed caldera, forming part of a larger system of other volcanic calderas. It contains mainly andesites, with fluid transported through open fractures and lithologic contacts. Most of the faults in this geothermal field do not exceed 1200 meters

$$\__N = \frac{1-n}{2E}(s_Y + s_Z) + \frac{1+n}{E}\frac{(s_Y - s_Z)}{2} \cos$$

fissure saturated with water:

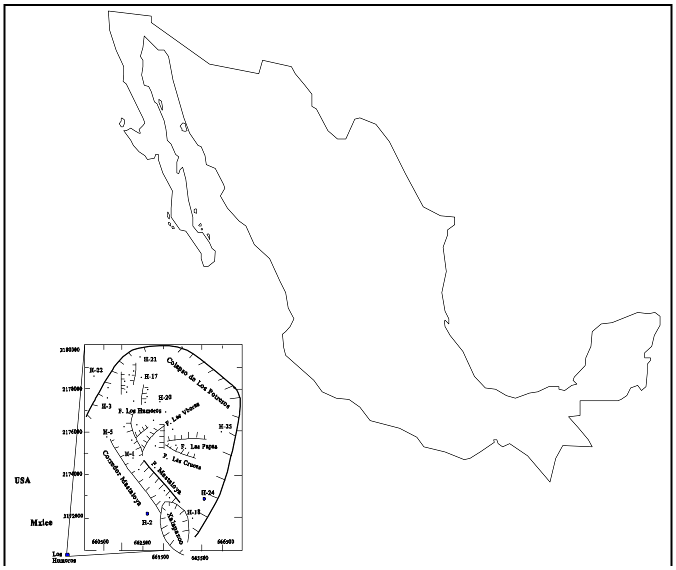
$$\__{Nw} = \frac{1-n}{2E}[(s_Y - p_f) + (s_Z - p_f)] +$$

$$\frac{1+n}{E}\frac{(s_Y - s_Z)}{2} \cos 2q - \frac{n(s_X - p_f)}{E}$$

In a vertical fracture ? = 0° and $s_{Nw} = s_Y - p_f$. If the fracture is horizontal ? = 90° and $s_{Nw} = s_Z - p_f$. If the fracture is inclined at ? = 45°, $s_{Nw} = (s_Z + s_Y)/2 - p_f$. In the principal reference frame (**i**, **j**, **k**) the strain tensor **e** is given by:
Where E is the modulus of elasticity and *v* is the Poisson ratio. In the rotated frame (**i**, **t**, **n**) the components of the elongation tensor $\mathbf{e}_U$ have similar expressions as in equations (3). We only need the normal strains to estimate the fissure deformation. In dry rock it is given by:
The normal elongation in saturated rock is directly obtained by replacing equation (4) in equation (5):
Equations (4), (6) and (7) corresponds to a quasi-planar model to estimate the fissure deformation.

APPLICATION TO THE ROCK OF THE LOS HUMEROS RESERVOIR

depth. This is particularly important because the existence and communication of widely fractured zones closely depend on faults with great penetrability. The Los Humeros reservoir is fractured, but its global permeability is small. With some important exceptions, it has little communication among fractured sections and many existent fractures are totally or partially sealed (Suarez, 1995). The current measured porosity in some wells is quite high at different depths. However, this



system should be classified as a hot “wet” rock system, because its essential problem is the deficiency of liquid. There are no evidences of any important recharge of water entering the reservoir in spite of the existence of some aquifers around the field. On the field's surface there are neither thermal springs nor boiling muds, but exclusively steaming grounds.

The field has an installed capacity of 35 MWe, 37 wells whose depths vary from 1450 to 3250 meters. There are 25 producers, mostly producing dry steam; two wells are injectors. The total amount of fluid extracted from the field is composed by 645 T/h of vapor and 210 T/h of liquid. The average fluid rates are 26 T/h/well of steam and 8.4 T/h/well of liquid, for a global steam quality of 75.4%. On the surface it can be observed that the spacing between open fractures varies from 1 to 5 cm, with a minimum opening of 1 mm. In some areas the fractures appear every meter without presenting openings. The high fracturing appears to be associated to partial penetrating faults, defining an area of influence with good secondary permeability. When increasing the distance to this zone of influence, the frequency of fracturing diminishes and, consequently, the permeability decreases.

Los Humeros turns out to be a reservoir with low water content and low permeability, but with high energy. There is an effective caprock formed by ignimbrites, and the chemical composition of the geothermal fluid is far from the meteoric line (Tello, 1992). Isotopically the water of the springs at Los Humeros is above the meteoric line, indicating its recent infiltration. The average production of liquid is 4.6 T/h/well, with the only exception of well H-1, while the average steam rate is 26 T/h/well. Therefore, only a small amount of liquid arrives to production zones. Reservoir fluid geochemistry corresponds to geothermal clorude-sodic water. Water of the few springs around the field is bicarbonate-sodic water, not of geothermal type. There is no geochemical equilibrium between the rock and the fluid, indicating that there was not enough liquid *in situ* to interact with the rock. The natural discharge of the reservoir only occurs through fumaroles and steaming grounds related to some faults and consequently, the possible recharge could only be equal to those discharges (Suárez, 1995). There is no evidence of the existence of any communication between the hydrothermal system and the scarce springs surrounding the field. All this characterizes a reservoirs with global poor permeability and scarce liquid.

Petrophysical Properties

In 1988 several measurements of petrophysical properties were carried out in cores from the Los Humeros reservoir (Contreras et al., 1990). The analyzed cores consisted of 18 samples divided in 39 fragments from 15 wells, in a range of depths between 616 m and 2847 m. Densities of rock, porosities, absolute permeability, rock compressibility, modules of elasticity, specific heat, thermal conductivity and thermal diffusivity were measured in the laboratory in both, dry rock and water saturated rock. The measurements were done at ambient temperature, but under confining pressures between 100 and 400 bar. The reported results show the great heterogeneity of the rock forming the reservoir. Pressure tests showed low values of *kh* products, between $1.0 \cdot 10^{-13}$ and $5.22 \cdot 10^{-13}$ m^3. Rock compressibilities were measured by uniaxial and triaxial tests. The purpose of triaxial testing was to determine the core specimens behavior under confining pressures similar to those found in the reservoir stress field.

In order to illustrate an application of this model to the concrete case of the Los Humeros reservoir, we consider its general properties and use some averaged parameters. At a depth of 1500 m the rock density is $?_R = 2620$ kg/m^3 , we have estimated a pore-fissure-water pressure $p_f = 125$ bar; the corresponding temperature is 310 °C and the liquid density is 700 kg/m^3. The numerical values of the principal stresses s_X, s_Y and s_Z are given by the confining lateral pressures and the lithostatic load respectively:

$$s_Z = r_R g z + p_0 = 386 \text{ bar}$$

$$s_X \_ s_Y = 0.7 r_R g z = 270 \text{ bar}$$

Where $g = 9.8$ m/s^2 is the acceleration of gravity, $p_0 \approx 1$ bar is atmospheric pressure, z =1500 m represents depth and a = 0.7 is an experimental correction coefficient which generally ranges between 0.5 and 0.9 (Farmer, 1968). Its first value corresponds to rock with high porosity while the second one is for rock with little porosity. Assuming an angle ? =60° for the fracture's inclination and the preceding numerical values in dry rock, we obtain from equation (3):

$$s_N \_ 328 - 58 \cos q = 357 \text{ bar}$$

$$s_{Nw} \_ 357 - 125 = 232 \text{ bar}$$

The same data applied to equation (4) for saturated rock give: Average modulus of elasticity and Poisson's ratio are equal to $E = 2.0 \times 10^{5}$ bar and v = 0.23 (Contreras et al., 1990). Elastic strain is also different in each case. For the practical purpose of estimating fracture deformation in the orthogonal direction we define dz = h e_n , where dz is the small normal compression experimented by the fissure relative to the direction **n**. We also assumed that fractures are separated by a distance h = 1 m. We obtain from the application of result (9) to equation (6) for dry rock:

$$\_{N} \_ 1.44 \_ 10^{-3} \_ dz = 1.44 \text{ mm}$$

Substituting result (10) in equation (7) we obtain for the case

$$\_{Nw}\ \_\ 7.93\ \_\ 10^{-4}\ \_\ dz = 0.8\ mm$$

of saturated rock:

In the previous example we are assuming that elasticity modulus E will not be affected by the presence of water. But practical experience shows that in porous rocks, liquid saturation affects the value of E. The effect of pore-water pressure p_f on the elasticity of the rock would lead to an equivalent decrease in strain (Farmer, 1968; Blès & Feuga, 1986). Thus, it is necessary to introduce an experimental correction to preceding value (12). Some authors (*ibid*.) have found a decrease in strain of 50%. Therefore the corrected value of e_{Nw} for andesites will be an effective normal elongation between 0.4 and 0.8 mm.We infer that in dry, low porous rocks, natural fissures present a clear tendency to be closed by normal lithostatic stresses. Under the same loading conditions, fractures filled with water will not collapse because of the presence of a pore-fissure-water pressure opposing the normal stress.

This analysis is also supported by other experimental results obtained by different authors. For example, Colback & Wiid (1965), measured a strength reduction of 50% in saturated sandstone. Rocks with low porosity contain small amounts of absorbed water and have a mechanical behavior very similar to that of dry rocks. Whereas a high porosity saturated rock will be considerable weakened even at low pressure, facilitating the formation of fractures. This is the case for geothermal rocks having porosities greater than 10%. The Rehbinder effect postulates that all phenomena due to p_f are caused by a reduction of the cohesive structure of the rock, because it is weakened by the presence of liquid in the pores. Since all deformation and failure characteristics are influenced by this cohesion, they will be affected in proportion to the amount and pressure of the liquid present; strength and elastic modulus being decreased.

There are another important thermo-mechanical effects in geothermal reservoirs. High pressure and temperature increase ductility and lowering yield point of the rock. The effects of high confining pressure is to induce plastic flow. We have observed that fissures, fractures and microfractures are more numerous in the vicinity of large or regional faults. The same has been reported by several authors (Blès & Feuga, 1986). This phenomenon occurs because when a fault is generated within massive rocks, original stress distribution is modified around the fault, producing the development of different tension fractures, specially near the end of the fault.

Faults and fractures in volcanic geothermal systems were produced by one or several tectonic events, during discontinuous deformations that arrived beyond the limit of elastic strain, specially in volcanic rocks, composed of brittle materials. The main natural mechanisms forming the faults and fractures are compression, extension, shearing and shortening . These mechanisms all act together and are also influenced by the previous presence of stratification, cleavage or joint of fractures (Blès & Feuga, 1986). Fissures and faults derived from an earlier tectonism can already be present as rock discontinuities and become active in a new tectonic event. That is why in volcanic reservoirs very complex structural systems can be developed.

Fissure-poroelastic deformation also influences reservoir thermodynamics. The volcanic matrix in Los Humeros has low natural permeability. As consequence the fluid flashes in the formation before it enters the wells and the two-phase enthalpy becomes larger than the reservoir’s enthalpy. A triple porosity mechanism (Suarez & Samaniego, 1995) explains why, when extraction starts up, pressure differences are introduced between the reservoir and the well's feeding point. Pressure gradients induce the creation of a boiling front starting at matrix-fractures interface. Apparently a parallel mechanism of phase segregation appears, allowing the migration of more vapor toward the well, even if the reservoir's natural state corresponds to compressed liquid. The segregation of phases occurs because of the different densities of liquid and vapor. Liquid phase is heavier than steam, so it experiments a delay in its vertical ascent. At the same time, because of the different viscosities of both phases, vapor moves easier than liquid inside the fractures roughness. Consequently, segregation enriches the fluid with more vapor before entering the well. This explains why an extraction zone in natural compressed liquid conditions can produce high quality steam.

The mechanism will be accented if porosity is poor, permeability is low or if there is few liquid in the pores. Taking 1 mm as a typical fracture aperture, we can estimate its

$$k_f\ \_\ \frac{b^3}{12\ H} = \frac{10^{-9}}{12\ x\ 1200} = 7\ x\ 10^{-14}\ m^2$$

permeability using the cubic law:

On the other hand, measured permeability in a core with one open fissure (Contreras et al., 1990) is 0.147× 10^{-15} m^2. From

$$b = \sqrt[3]{k_f\ x\ 12\ x\ 1200} = 0.13\ mm$$

the cubic law we deduce a fracture aperture:

The lowest measured core permeability in this field was equal

$$b = \sqrt[3]{10^{-18}\ x\ 12\ x\ 1200}\ \_\ 0.02\ mm$$

to 1 microdarcy. After the cubic law:

Both experimental values are of the same order of magnitude of results predicted by our model.

CONCLUSIONS

- There exist natural systems, such as the Los Humeros geothermal reservoir, that contain small amounts of liquid water and low permeability, but high temperature. This geothermal area had intense tectonic activity in its remote past and consequently fracturing should be equally intense. In this reservoir original permeability was high.

- However, the shortage of fluid allowed the collapse and closure of fissures because internal stresses could not compensate the lithostatic load, due to the lack of hydraulic support. Under these natural conditions every fissure, with less than two milimeter aperture, could be closed by the vertical compression it supports.

- Water-rock interaction propitiated the selfsealing of faults and fractures, specially in shallow strata. At the same time, the high temperature and water shortage caused the detachment of corrosive gases such as HCl.

- Diverse evaluations of the potential energy contained in Los Humeros reservoir point out the feasibility of installing up to 80 MWe in order to generate electricity for 25 years. Given the aforementioned characteristics, it is expected that most of the producing wells will evolve to superheated steam in the short term. The biggest risk for the longevity and commercial exploitation of this field, resides in possible abrupt depressions because of lacking liquid and the poor communication among fractured sections.

- An evident, practical and simple solution for these problems consists simply in injecting plenty of external water into the reservoir. The andesite is a brittle rock, easily fractured. Upon increasing rock permeability wide portions of the reservoir would communicate with the injection zones improving production. The increase of available liquid will dilute the HCl alleviating its aggression to the wells.

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