TRIPLE-POROSITY/PERMEABILITY FLOW IN FAULTED GEOTHERMAL RESERVOIRS: TWO-DIMENSIONAL EFFECTS

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ABSTRACT

An essential characteristic of some fractured geothermal reservoirs is noticeable when the drilled wells intersect an open fault or macrofracture. Several evidences observed, suggest that the fluid transport into this type of systems, occurs at least in three stages: flow between rock matrix and microfractures, flow between fractures and faults and flow between faults and wells. This pattern flow could define, by analogy to the classical double-porosity model, a triple-porosity, triple-permeability concept. From a mathematical modeling point of view, the non-linearity of the heterogeneous transport processes, occurring with abrupt changes on the petrophysical properties of the rock, makes impossible their exact or analytic solution. To simulate this phenomenon, a detailed two-dimensional geometric model was developed representing the matrix-fracture-fault system. The model was solved numerically using MULKOM with a H_2O+CO_2 equation of state module. This approach helps to understand some real processes involved. Results obtained from this study, exhibit the importance of considering the triple porosity/permebility concept as a dominant mechanism producing, for example, strong pressure gradients between the reservoir and the bottom hole of some wells.

INTRODUCTION

For more than thirty years the naturally fractured media have been the object of multiple studies. Models of diverse complexity have been created to explain their behavior in different fields: groundwater, geothermal reservoirs and, above all, in petroleum engineering. The essential difficulty in the realistic modeling of fractured media continues to be the partial ignorance about the dimensions, spatial distribution and interconnections of the fractured network. Being even possible to write and solve transport equations into the matrix and in the fractures, there are many unknown parameters in any fractured region. From the fluid thermodynamics point of view, the fractures in the matrix blocks are rock discontinuities, while from a mass flow point of view, there are no discontinuities and the problem is essentially geometric.

Observations carried out in volcanic faulted reservoirs, (Los Azufres & Los Humeros, Mexico), showed singular behavior of wells intersecting open faults. Almost all producing wells crossed, at different depths, extremely high permeability zones (1-10 darcys,Suárez et al,1992), that does not correspond to fresh volcanic rock permeability (~ 1 microdarcy), neither to microfractures permeability (~ 100 milidarcys). This property, linked to other evidences observed, suggests that fluid and heat transport in such systems occurs in three stages: matrix-fractures-fault, implicating strong contrasts in the petrophysical parameters of each medium. Our purpose is to introduce some numerical results supported by real data, about what could happen in a medium of triple porosity and triple permeability flow at a detailed scale, representing real dimensions of faults and fractures. The focus of the proposed problem is essentially practical. We want to show some difficulties inherent to the understanding of real geothermal fractured reservoirs behavior with conductive faults, and the usefulness of its interpretation under the triple porosity/permeability concept.

DOUBLE POROSITY MEDIA

The media with double porosity behavior constitutes a classical topic in the literature on fractured reservoirs. The primal analytical and semianalytical models for flow of slightly compressible liquid emerged in the 60's. According to this idea, the matrix blocks surrounded by fractures, could be of any size, with scarce fractures or intensely fractured. The original concept of double porosity was stated for the first time by Barenblatt, Zheltov and Kochina (1960). Considering stationary flow in the matrix and ignoring storage in the fractures, those pioneers formulated a liquid flow equation in each medium. The interaction parameter between matrix and fractures was the mass flow passing at every second, per unit of volume of fractured rock. This term resulted to be proportional to density and to the pressure difference between both mediums and in inverse proportion to liquid viscosity: $q=\alpha\rho\ (p_m-p_f)\ /\mu$, where α was a dimensionless constant only relied to the geometry of the block-fracture boundary.

The model initially exposed by Warren & Root (1963) contains as essential parameters ω (quotient of fractures storativity with respect to total storage) and λ which is a resistance factor indicating the intensity of matrix-fractures interaction. These authors also considered a pseudostationary flow in the matrix, this hypothesis originates erroneous approaches for short simulation times. Nevertheless, this simplification conformed well to petroleum fields' data containing important differences between matrix and fracture permeabilities, because in those conditions there is a certain retard in matrix-fracture transfer. Subsequently, de Swaan (1976) considered the real transitory flow and, later, Cinco Ley & Meng (1988) included the effect of finite conductivity faults.

Similar double porosity problems were introduced in hydrothermal reservoir engineering (Cinco et al., 1979); but the complex processes involved in phase change and the non-linearity of parameters in the basic equations, made the analytic solutions very scarce. The double porosity model in geothermal reservoirs was generalized by Pruess & Narasimhan (1985) and solved numerically by means of the Multiple Interacting Continua concept (MINC). A numerical model published recently (Zimmerman et al.,1993), treats matrix-fractures transient flow in semianalytical form.

TRIPLE POROSITY BACKGROUND

Closmann (1975) extended for the first time the double porosity concept, describing a fractured medium composed by two distinct types of matrix, one with lower permeability and minor porosity than the other, but considering only flow within the fractured network. Abdassah & Ershaghi (1986) used a model that they called of *triple porosity*, when remarking abnormal changes in the graphs of some well tests during the transitory period. Liu & Chen (1990) introduced an exact solution for an isothermal, cylindrical reservoir saturated with slightly compressible fluid, with a centered well in a multiple porosity, multiple permeability medium. Under this concept, N continua porous media interact between themselves; having each one its own pseudostationary interporosity flow and its own parameters. This model makes up the widest generalization of the original concept created by Barenblatt and coauthors.

In geothermal reservoirs with phase changes, the transitory period within the matrix cannot be neglected. Precisely, during the transfer between matrix and fractures, the medium's discontinuity causes abrupt changes in flow thermodynamics because geothermal fluid is extremely sensitive to geometrical changes of the flow conduits in the reservoir. The original idea of Barenblatt and coauthors, and the derived models, couldn't work fine for a fluid that changes from liquid to two-phase because density and viscosity are discontinue spatial functions.

In the aforementioned fields, we have observed wells that initially had a strong depression. When interrupting extraction during some period, and after reopening them, the production attained almost the same previous level after certain time. Thermal inversions also have been observed in some wells producing 100% steam from zones that correspond to compressed liquid conditions. For 12 years, some few wells maintained in permanent production, do not show any noticeable change in their thermodynamic characteristics. Zones of high permeability have been detected, coexisting with almost impervious close zones. The triple porosity/permeability concept unifies all these phenomenons.

GENERAL CONCEPTION OF THE TRIPLE POROSITY / PERMEABILITY MEDIUM

The triple porosity/permeability concept we are introducing, is based on experimental observation of fractured reservoirs traversed by big open faults or macrofractures, where the intensity of fissuring is high near to the fault, intermediate in the fractured network and where a remarkable permeability contrast exists between matrix blocks, microfractures and faults. Figure 1 is a photocopy of a 10 cm diameter core, cutting a 1.5 cm thickness fault of the Los Azufres geothermal field at 2680 m depth. In the picture is visible the intense network of fractures around the fault. The micro-fractures show an average opening of 0.1 cm. The behavior of some non producing wells suggest that fissuring decreases faraway from the faults at any depth (Suárez et al,1992). This observation implicates that after some distance to the fault, matrix blocks increase their size and only isolated sparse microfractures can be found.

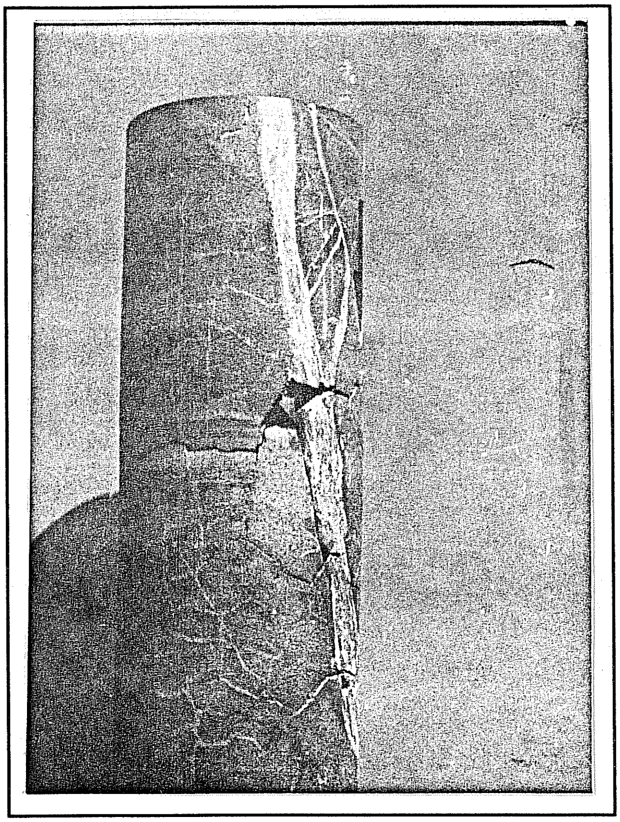

Fig. 1.- Core of andesite extracted from well Az-48 in Los Azufres geothermal field, at 2680 m depth.

From a practical point of view, is useful to consider the effect of the fissuring around the fault, only when the matrix blocks are sufficiently spaced between them, that is to say, when the middle distance between parallel fractures is greatter than a minimal value δ_m (Gringarten & Witherspoon, 1972). Otherwise it wouldn't be possible to distinguish between pressure/temperature averages in the fractured medium and those in the porous simple medium. The matrix-fractures interaction speed in mediums intensely fractured, with distances shorter than this minimal spacing compensates, in average, the effective pressure/temperature differences between both continua (Suárez,1990). Close to the fault, the medium could be considered of simple porosity with high permeability, constituting a transition zone between blocks of fractured matrix and the fault.

The concept of "triple porosity" we are proposing, considers that diffusivity attains its largest values in the conductive fault and is much larger in the fractured network than in the matrix. Flow toward the wells occurs in such a way that the initial response in the extraction zone is immediately detected in the fault; then is noticed in the fractures and, much later in the matrix. The three mediums, matrix, fractures and fault are considered, under this concept, as three interacting continua exchanging mass and heat through special transport functions which depend on the form and size of blocks, on fissuring intensity and on the communication with the fault. The transfer among matrix-fractures-fault is transitory and must depend on many factors including tortuosity and mineralization.Our triple porosity medium is formed by three continua interconnected, having different petrophysic and thermodynamic characteristics, which coexist in a single physical space overlaid by the cartesian axis. A medium of triple porosity/permeability containing simple water, could be represented theoretically by two pseudo-vectorial equations:

$$\frac{\partial(\rho_j \phi_j)}{\partial t} + div(\rho_j \vec{v}_j) = q_{ij} \qquad [mass] \ldots (1)$$

$$\frac{\partial e_j}{\partial t} + div(\rho_j h_j \vec{v}_j - K_j \cdot \vec{\nabla} T_j) = q_{ij} h_j \quad [heat] \ldots (2)$$

Subindex j=m, f, F represents the respective medium's equation: matrix, fracture, Fault; thus a total of six scalar equations. The nomenclature is common: ρ_j is density, ϕ_j porosity, v_j speed of flow, e_j is the total energy rock+fluid, h_j means specific enthalpy of the fluid, K_j is thermal conductivity tensor and T_j ,the temperature in each medium. All terms are functions of time and space. Parameter q_{ij} represents mutual interchange among the three continua. The preceding equations are considerably simplified for a triple porosity reservoir initially saturated with liquid. Assuming petrophysical parameters approximately constant in each medium:

$$\frac{\partial \vec{p}}{\partial t} = \mathbb{N} \cdot \nabla^2 \vec{p} + \vec{q}\,; \quad \mathbb{N} = (\eta_{jk}) = \begin{pmatrix} \eta_m & 0 & 0 \\ 0 & \eta_f & 0 \\ 0 & 0 & \eta_F \end{pmatrix} \quad \ldots (3)$$

$$\vec{p} = (p_i)\,; \left\{\eta_i = \frac{k_i}{\phi_i C_i \mu_i}\right\}, \left\{q_i = \frac{q_{ij}}{\phi_i C_i}\right\}; \ for\ i = m, f, F$$

∇^2 is the laplacian operator, p_i is fluid pressure in each medium, η_i is the diffusivity coefficient, k_i ,permeability, C_i , compressibility and μ_i , viscosity. Data measured in a fault zone of the Los Azufres geothermal field shows strong diffusivity contrast: $\eta_m \sim 0.003$, $\eta_f \sim 0.3$, $\eta_F \sim 1$ (m^2/s). These equations could be solved in some simplified cases. For example, in a very big reservoir with radial flow from the fractured net toward the fault, the general dimensionless equation which describes the flow motion is:

$$\omega \frac{\partial P_{fD}}{\partial t_D} = \frac{1}{r_D} \frac{\partial}{\partial r_D} \left(r_D \frac{\partial P_{fD}}{\partial r_D}\right) - \Omega \int_0^{t_D} \frac{\partial P_{fD}}{\partial \tau} \psi(t_D - \tau)\, d\tau \ \ldots (4)$$

The flow function ψ (t_D - τ) is attached to the geometry of flow between fractures and fault (or matrix and fractures). The variable Ω is a time independent, dimensionless coefficient that describes the geometric characteristics of fractures-fault contact. Similarly if a spherical, radial or linear flow is considered between matrix and fractures, another similar equation could be coupled for any of these flow geometries between matrix and fractures. Several analytic and semianalytic solutions can be found in the literature (see references). As a comparative illustration, the solution for equation 4 in Laplace space is:

$$\mathcal{L}[P_{fD}](r_D, s) = \frac{K_0(\sqrt{s\theta}\, r_D)}{s\sqrt{s\theta}\ K_1(\sqrt{s\theta})} \qquad \ldots\ldots\ldots \quad (5)$$

Where $\theta = \Omega\Psi(s) + \omega$ and $\Psi(s)$ is the Laplace transform of ψ (t_D), K_0 and K_1 are the modified second kind Bessel functions of 0th and 1st order respectively, s is the image in Laplace space of dimensionless time t_D. This formula can be numerically inverted to obtain, in real-time space, numerical values for dimensionless pressure (Cinco et al.,1979). As a general comment, it is remarked that pressure decrement in the fault, as calculated with this model, is much more smoother than that observed in real geothermal reservoirs. Thermodynamic properties may vary softly within the matrix; while in fractures variations are abrupt with discontinuities in the pressure/temperature gradients. These variations are emphasized into the faults being, in fact, open rough channels where, probably, Darcy's law is not valid. Because of lack of space we did not include a graphic comparison between this solution and the following approach.

NUMERICAL APPROXIMATION TO THE TRIPLE POROSITY/PERMEABILITY FLOW

General stated equations of mass and energy are contained in MULKOM's code (Pruess, 1988). The general ideas sketched before, were included in a two-dimensional model defining approximately the geometry of each continuum (Fig. 2). The model was solved numerically with MULKOM for an H_2O+CO_2 equation of state. We carried out the calculations for different initial states with fluid extraction in the fault and various boundary conditions. Fault thickness was simulated explicitly for an opening of 0.01 m (Fig. 1). The fractured network is heterogeneous and intense in the immediate vicinity of the fault within a radius of 5 meters. Close to the macrofracture there is a 10 meters transition zone with fewer fractures and lower permeability, connected to regular matrix blocks of increasing diameter, starting from 20 m until a distance of 100 m to the fault. In the fault's plane (X,Z) there are 43 elements in the X axis and 20 elements in the Z axis.

Distances between different elements forming the mesh, were constructed according to a normalized geometric succession: $d_N = d_{N-1} \cdot \sqrt[5]{10}$, $d_1 = d_0 \cdot \sqrt[5]{10}$. Initial parameter d_0 is equal to 0.01 m in the fault, and 1.0 m in the fractured zone. In this way we could cover rapidly very short distances, passing to big distances without following a regular proportion. This technique influences positively the efficiency of the solution method. We perform several series of numeric experiments with the parameters indicated in table 1. With the purpose of forcing a rapid answer in the zone of extraction, there is no recharge of mass nor of heat through any boundary. Fluid was extracted supposing different initial states in the system: liquid and two-phase. The reservoir's portion around the fault is limited by two impervious boundaries located 100 m (right and left). A brief synthesis of results is described next.

EXTRACTION FROM A SINGLE VERTICAL FAULT

(a)- **Initial State: Liquid** (Figs.3,4,5,6).
Reservoir initial conditions correspond to compressed liquid, which is extracted in the fault. Depressions in fault and fractures are observed immediately; pressure decrement appears slowly in the matrix. During the short simulated time thermodynamic changes are isothermal in the matrix, starting at 15 m distance to the fault; consequently, single liquid remains as the dominant phase in the matrix blocks. Main changes are observed in the vicinity of the fault, where temperature and pressure draw down are homogeneous. Steam saturation and carbon dioxide partial pressure,change abruptly at matrix-fractures and fractures-fault interfaces after some days. Fluid expansion in the fractured network provokes the production of vapor within a limited radius up to 18 m distance. At matrixfractures interface, steam saturation reaches a maximum that goes falling down toward the fault. Such phenomena occur because the fault receives a liquid contribution from deeper zones. CO_2 partial pressure swoops rapidly inside the fault and fractures and remains constant in the matrix.

(b).- **Initial State: Two-Phase** (Figs. 7,8,9,10)
Initial steam saturation is 30%. The behavior of pressure and temperature is different from previous case. Depressions happen now faster but attenuate at less distance, while temperature decays up to 25 meters within the matrix, then it remains constant until the next impervious boundary. Steam saturation reaches 100% between the fractured zone and some near blocks; in the matrix vapor grows, but not so much between the boundary and this zone. CO_2 partial pressure falls rapidly and smoothly near the fractured network and increases abruptly in the fault, remaining almost constant in the matrix blocks near to the border. Triple porosity effect is appreciated in both variables. The fault and the fractured network are clearly distinguished. The lower quantity of vapor in the fault is explained the same as in the previous case.

Extracting fluid from two parallel faults presents combined effects, similarly to the cases previously discussed. Whether considering two faults inclined and parallel, intersected by the same well (Fig. 2), is equivalent to have two horizontal production zones of high permeability interacting through the well. In this case pressure fall off and temperature decrement occur precisely in the high permeability zone. When traversing a lower zone of high permeability, the temperature exhibits an inversion, that is to say, a sudden decrement at this depth; afterwards it increases again. Pure steam can coexist with a two - phase vertical zone or even with a compressed liquid region below or up to the production zone. Something similar occur with noncondensible gas. It can coexist with very low values in the zone of high permeability and higher values outside.

Fig2.-GEOMETRICAL MESH SHOWING CHARACTERISTICS OF: FAULTS, FRACTURED NETWORK AND MATRIX BLOCKS.

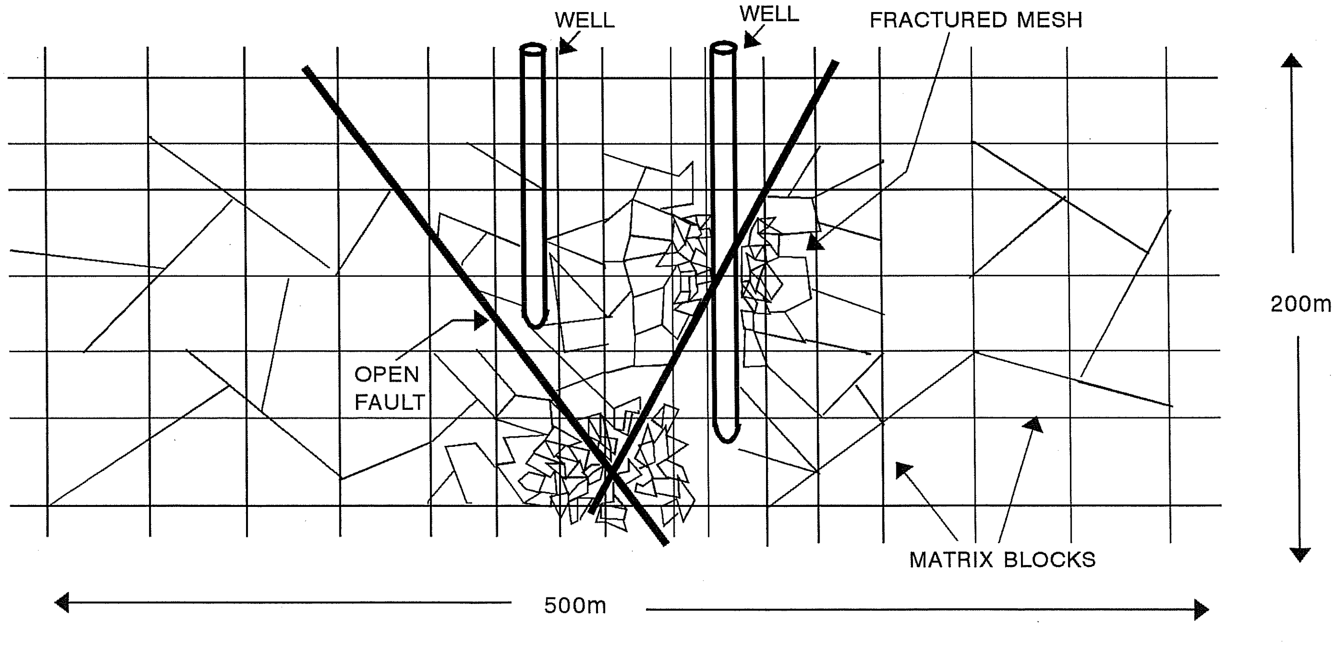

TABLE 1.- SOME PARAMETERS USED IN THE SIMULATIONS. {T_1 holds for initial liquid state; T_2 for two-phase. Initial vapor saturation is 0.3 and $P(CO_2)$=5 bar (all cases)}

Rock Type	ρ kg/m^3	ϕ	k_X (m^2)	k_Z (m^2)	K_T W/m/C	C_P J/kg/K	P bar	T_1 (°C)	T_2 (°C)	η_i m^2/s
FAULT	1355	0.75	10^{-11}	10^{-11}	0.62	3528	55	250	264	0.900
FRACT	2000	0.35	10^{-13}	10^{-13}	1.52	1992	55	250	264	0.300
MATRX	2251	0.01	10^{-16}	10^{-18}	2.00	1165	55	250	264	0.003

CONCLUSIONS

The main aim of this paper has been to present numerical results, obtained from a two-dimensional model, developed to simulate flow in a triple porosity/permeability faulted, naturally fractured geothermal reservoir. This work was motivated from the essential characteristic of some reservoirs where producing wells intersect a fault. From results of this study, the following conclusions can be made:

1.- Fluid transport from the formation to the wells occurs in three stages: flow between matrix and fractures, flow between fractures and fault, and last flow to the well mainly through the fault.

2.- Pressure and temperature measured in wells represent average values, resulting from multiple interactions among the macrofracture, the microfractures and the matrix.

3.- The effect of the fault presence results in important reservoir behavior differences with respect to conventional double porosity model behavior.

4.- These differences are emphasized with regard to the abrupt discontinuities in the gradient of thermodynamic properties, ocurring at the interfaces between the pairs of systems. These differences also include abrupt variations of the mass and energy production and of the spatial steam and CO_2 distribution in the reservoir. Total flow of heat is dominant in the faults and very poor in the matrix.

5.- The changes detected in the principal variables could have a wide variety of forms and behaviors. The effect of triple porosity is appreciated in the distribution of vapor and of carbon dioxide at fault's neighborhood.

6.- In fact what we are measuring in terms of "*reservoir pressure*" and "*temperature of the formation*", is an average value resulted from the multiple interaction between porous rock, microfractures and fault in the the zone immediately affected by extraction or by drilling and the word "*reservoir properties*" should be considered only as an ambitious euphemism in this class of systems.

REFERENCES

-Abdassah, D. & Ershaghi, I.; (1986). "*Triple Porosity Systems for Representing Naturally Fractured Reservoirs*". SPE Formation Evaluation, I(2), pp. 113-127.

-Barenblatt, G., Zheltov, Y. & Kochina, I.; (1960). "*Basic Concepts in the Theory of Seepage of Homogeneous Liquids in Fissured Rocks*". J.Appl.Math.Mech., No. 24, pp. 1286-1303.

-Cinco Ley,H., Brigham,W., Economides,M., Miller,F., Ramey,H., Barelli,A. & Manetti,G.; (1979). "*A Parallelepiped Model to Analyze the Pressure Behavior of Geothermal Steam Wells Penetrating Vertical Fractures*". SPE 8231, 54th Annual Tech.Conf.

-Cinco Ley, H. & **Meng, H.Z.** (1988). "*Pressure Transient Analysis of Wells With Finite Conductivity Fractures In Double Porosity Reservoirs*". SPE 18172.

-Closmann, P.J.; (1975). "*An Aquifer Model for Fissured Reservoirs*". Soc. of Petroleum Engineers Journal, Vol. 15, No. 5, pp. 385-398.

-De Swaan, A.; (1976). "*Analytical Solutions for Determining Naturally Fractured Reservoir Properties by Well Testing*". SPE Journal, Vol. 16, pp. 117-122.

-Gringarten, A. & Witherspoon, P. (1972). "*A Method of Analyzing Pump Test Data from Fractured Aquifers*".Proc. of the Symp. on Percolation Through Fissured rock. Stuttgart, Ger.

-Liu, M.X. & Chen, Z.X. (1990). "*Exact Solution for Flow of Slightly Compressible Fluids Through Multiple-Porosity, Multiple-Permeability Media*". Water Res. Research, Vol. 26, No. 7, pp. 3393-1400.

-Pruess, K. & Narasimhan, T.N. (1985). "*A Practical Method for Modeling Fluid and Heat Flow in Fractured Porous Media*". SPE Journal pp. 14-26, February 1985.

-Pruess, K. (1988). "*SHAFT, MULKOM, TOUGH: A Set of Numerical Simulators for Multiphase Fluid and Heat Flow*". GEOTERMIA - Revista Mexicana de Geonergía, Vol. 4, No. 1, pp. 185-202.

-Suárez, M.C. & Mañón, A.; (1990). "*Injection of Cold Water and Air into a Two-Phase Volcanic Hydrothermal System*". First TOUGH Workshop, Lawrence Berkeley Laboratory, Preprints, Sep. 13-14, Berkeley, California.

-Warren, J.R. & Root, P.J.; (1963). "*The Behavior of Naturally Fractured Reservoirs*". Soc. of Petroleum Engineers Journal, Vol. 3, No. 3.

-Zimmerman, R.W., Chen, G., Hadgu, T. & Bodvarsson, G.S. (1993). "*A Numerical Dual-Porosity Model With Semianalytical Treatment of Fracture/Matrix Flow*". Water Resources Research, Vol. 29, No. 7, pp. 2127-2137. July 1993.

Fig. 3– PRESSURE EVOLUTION AT FAULT NEIGHBORHOOD (initial liquid)

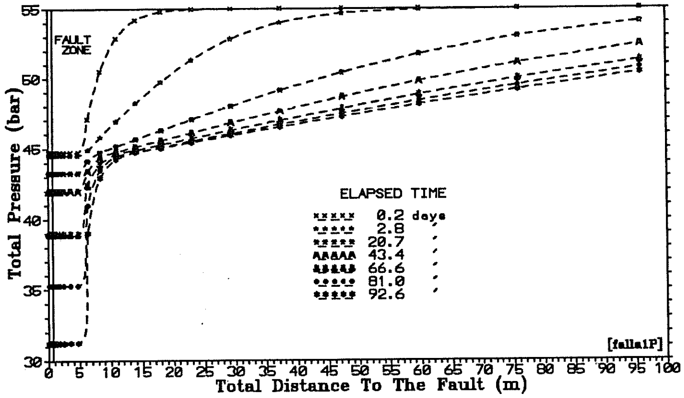

Fig. 4 – TEMPERATURE EVOLUTION AT FAULT NEIGHBORHOOD (initial liquid)

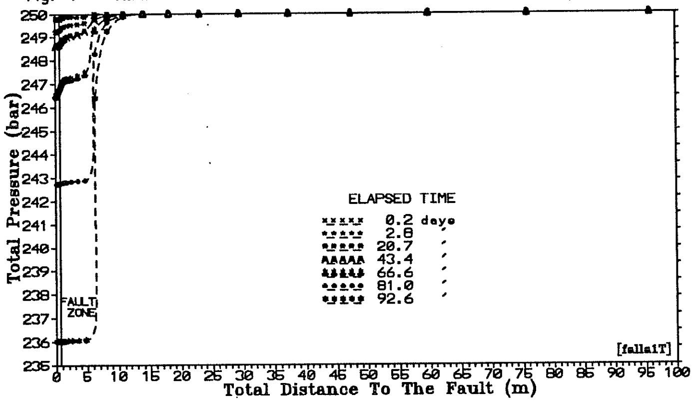

Fig. 5 – STEAM SATURATION AT FAULT NEIGHBORHOOD (initial liquid)

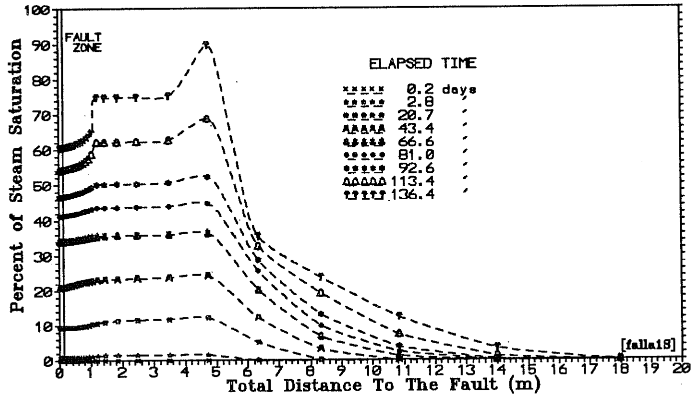

Fig.6–CO_2 PARTIAL PRESSURE AT FAULT NEIGHBORHOOD (initial liquid)

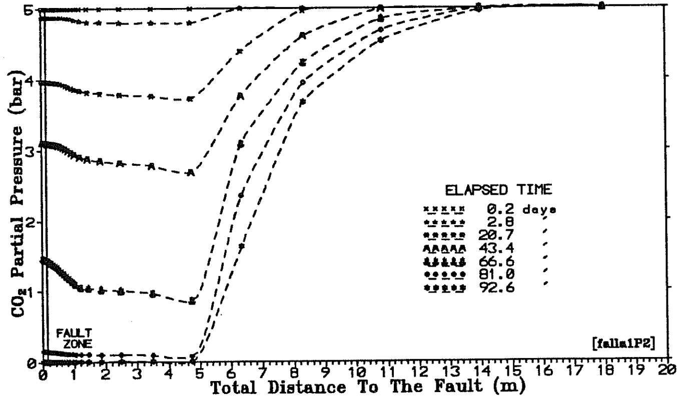

Fig. 7 – PRESSURE EVOLUTION AT FAULT NEIGHBORHOOD (initial 2–phase)

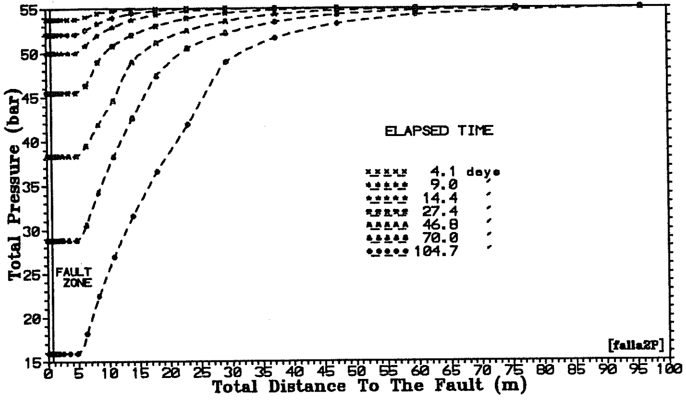

Fig.8 –TEMPERATURE EVOLUTION AT FAULT NEIGHBORHOOD (initial 2–phase)

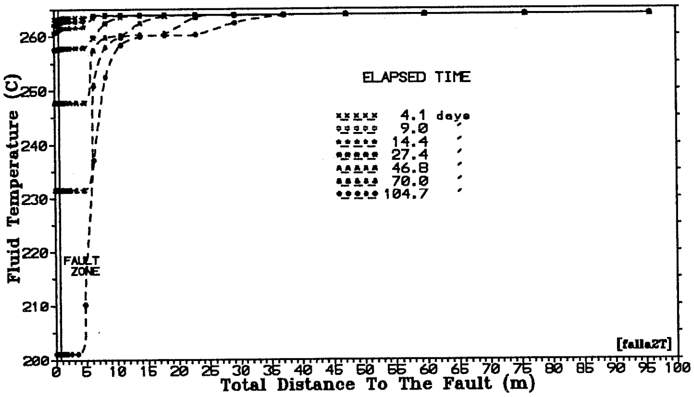

Fig. 9 – STEAM SATURATION AT FAULT NEIGHBORHOOD (initial Sv = 0.3)

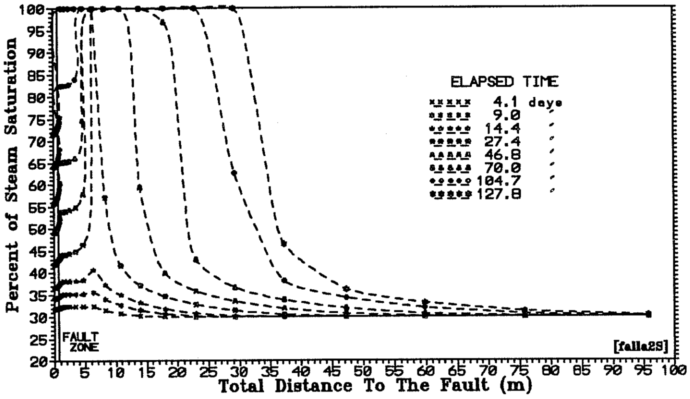

Fig.10– CO_2 PARTIAL PRESSURE AT FAULT NEIGHBORHOOD (initial 2–phase)