Tetra-Porosity Models of Geothermal Reservoirs With Faults

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ABSTRACT

Several fractured geothermal reservoirs have wells that are completed in the neighborhood of open faults. Large numbers of field=s evidences observed, strongly suggest that fluid transport in such type of systems, occurs in a very complex way. This phenomenon could be ideally represented by four stages: flow between rock matrix and microfractures, flow from micro fractures to fractures, flow between fractures and faults and flow from faults to wells. This pattern flow could define, by analogy to the classical double-porosity model, a tetra-porosity and tetra-permeability concept. To simulate this phenomenon, a detailed two-dimensional geometrical model was developed representing a matrix-fracture-fault system with high petrophysical heterogeneity. The model is solved numerically using Tough2 with a H_2O+CO_2 equation of state module. This approach helps to understand some real processes involved. The preliminary results obtained from this study, show the importance of considering a triple or better, a tetra - porosity/permebility flow as a dominant mechanism producing, for example, the strong pressure gradients between the reservoir and the bottom hole of some wells.

Introduction

For more than forty years naturally fractured media have been object of multiple studies. Diverse models have been created to explain their behavior in different fields: groundwater, geothermal and petroleum reservoirs. The essential difficulty to create realistic models 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 the transport equations for the matrix and for 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 the mass flow point of view, the problem is essentially geometric.

Observations carried out in two volcanic faulted reservoirs, (Los Azufres and Los Humeros in Mexico), showed singular behavior of wells intersecting open faults. Almost all production wells crossed, at different depths, zones of high permeability (1 to 10 darcys), that does not correspond to fresh volcanic rock permeability (-1 microdarcys), neither to microfractures permeability (-100 milidarcys). This property suggests that the fluid transport in those systems occurs in three different stages or frames: matrix-fractures- fault, implicating strong contrasts in the petrophysical parameters of each medium. Fluid transport from matrix blocks to production wells in fractured reservoirs with open faults, can be accurately represented by appropriate permeability averages at the interfaces among media. The main purpose of this paper is to introduce some numerical results supported by real data, about what could happen in a tetra porosity/permeability medium 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 tetra 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 models for flow of slightly compressible liquid emerged in 1960. According to this concept, 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 is proportional to density and to the pressure difference between both mediums and in inverse proportion to the 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 the total storage) and λ which is a resistance factor related to the intensity of the interaction matrix-fractures. These authors also considered a pseudostationary flow in the matrix; hypothesis that originates erroneous approaches for short simulation times. Nevertheless, this simplification conformed well to petroleum fields' data when there are important differences between matrix and fracture permeabilities, because in those conditions there is a retard in the 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; but due to both, the phase change processes and the non-linearity of parameters in the basic equations, the analytic solutions are very scarce. The model of double porosity in geothermal reservoirs was generalized by Pruess & Narasimhan (1985) and resolved numerically by means of the Multiple Interacting Continua concept (MINC). A numerical model treating the transient flow matrix-fractures in semianalytical form was published nine years ago (Zimmerman, *et. al.*, 1993).

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 minor 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 they remarked abnormal changes in the graphs of some well tests during the transitory period. Liu & Chen (1990) introduced an exact solution in an isothermal, radially heterogeneous cylindrical reservoir with a well located in the center, saturated with slightly compressible fluid. They considered this a multiple porosity and multiple permeability medium. Under this new concept, N porous continua interact, each one has its own interporosity pseudostationary flow and its own parameters. This model constitutes the widest generalization of the original concept of Barenblatt and coauthors. In geothermal reservoirs with phase changes, the transitory period within the matrix cannot be neglected. Precisely in the transfer functions between matrix and fractures, the discontinuity of the medium causes abrupt changes in flow thermodynamics because geothermal fluid is extremely sensitive to geometrical changes of the flow conduits in the reservoir. The original concept of Barenblatt and coauthors, and the derived models, couldn't work fine for a fluid that changes from liquid to two phases because density and viscosity are discontinuous spatial functions.

In the aforementioned fields, there are some wells presenting initial strong pressure drawdown. When extraction is interrupted and, after some period, the well is reopened, its production attains almost the same initial level after certain time. Thermal inversions also have been observed in some wells producing 100% steam from zones that correspond to compressed liquid conditions. In other few cases, wells maintained under permanent production conditions during 12 years, do not show any noticeable change in their thermodynamic characteristics. Zones of high permeability that coexist with very almost impervious zones, are also observed. The triple and tetra porosity/permeability concepts unify all these phenomenons.

The Tetra Porosity - Permeability Concept

Any medium that exhibits well differentiated discontinuities in its distribution of porosities must be considered as a multiple porosity continuum. Under the concept of Tetra porosity, four continuous porous media interact with each other (Figure 1). Each one has its own parameters and its own interporosity flow. The saturating fluid can be non isothermal, in one or two phases or with multiple components. Double porosity models can be classified as special cases of this general theoretical concept. The non-isothermal multiple porosity-permeability model describes an interconnected global phenomenon that also produces multiple effects on other interdependent phenomena at a larger scale.

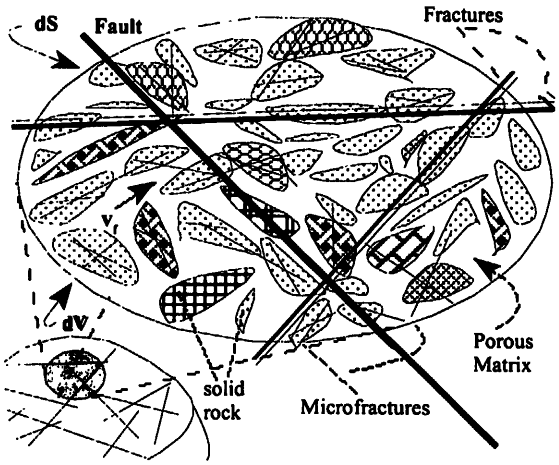

Figure 1. Differential volume of a tetra-porosity medium showing a fault (10^{-11} m^2), fractures (10^{-13} m^2), microfractures (10^{-15} m^2) and matrix (10^{-18} m^2).

This is the more general concept applicable to all-class reservoirs, conforming the highest degree of complex system in geothermal engineering. However, it is not possible to give a unique practical definition of this idea. Volcanic reservoirs can contain more than two systems of this type. Direct observations of geothermal fields with large faults, show that fracturing intensity is higher close to the fault than in a distant fractured network. A remarkable permeability contrast coexists among the matrix blocks, the fractures and the faults (Table 1). This model is based on the fact that the initial response to fluid extraction is detected immediately in the fault, then after a while it becomes notorious in the fractures and much later in the nonfractured rock. The system's global permeability depends inversely on the distance to the fault.

The observation on the microscope of thin sections of cores and cuttings extracted from volcanic fields show, visible fractures apart, the existence of microfractures connected to the matrix and to the fractured network. The net of microfractures conforms another continuum overlapped to the previous ones and has intermediate permeability values. It is the case of volcanic reservoirs with matrix-microfracture-fracture-fault flow. This model describes wide areas of the Los Azufres and of the Los Humeros, Mexico geothermal fields. The interporosity flows are transitory and depend on several factors including tortuosity and mineralization. The behavior of some non producer wells show that the fissuring decreases faraway from the faults at any depth. This observation implicates that after some distance to the fault, matrix blocks increase their size and only isolated sparsed microfractures can be found.

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 the pressure/temperature averages in the fractured medium from those in the porous simple medium. The speed of interaction (matrix-fractures) in mediums intensely fractured in distances lower than this minimal spacing compensates, in average, the effective pressure/temperature differences between both continua (Suárez, 1996). Close to the fault, the medium could be considered of simple porosity with high permeability, constituting a zone of transition between the blocks of fractured matrix and the fault.

A Triple Porosity - Permeability Mathematical Model

The concept of "tetra porosity" considers that diffusivity attains the largest values in the conductive fault and is much larger in the fractured network than in the matrix. The flow toward the wells occurs in such a way that the initial response in the zone of extraction 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 that depend on the form and size of blocks, on fissuring intensity and on its communication with the fault. The transfer matrix-fractures-fault is transitory and it should depend on many factors including tortuosity and mineralization.

A triple porosity medium is formed by three continua interconnected, with different petrophysic and thermodynamic characteristics, coexisting in a single physical space overlaid by the cartesian axis. Inside this medium transitory flows of mass and energy take place. A medium of triple porosity/ permeability containing simple water, could be represented theoretically by two vectorial equations:

Equation 1.

$$\frac{\partial}{\partial t}\int_{V_n}(\phi\,\rho_L\,S_L+\phi\,\rho_V\,S_V)\,dV+\int_{V_n}(\vec{\nabla}\bullet\vec{F}_L+\vec{\nabla}\bullet\vec{F}_V)\,dV=\int_{V_n}(q_L+q_V)\,dV=\int_{V_n}q_F\,dV$$

Equation 2.

$$\frac{\partial}{\partial t}\int_{V_n}\phi\,\rho_F\,e_F\,dV+\frac{\partial}{\partial t}\int_{V_n}(1-\phi)\,\rho_R\,h_R\,dV=-\int_{V_n}\vec{\nabla}\bullet\vec{F}_E^2\,dV+\int_{V_n}q_U\,dV$$

Subindex n = m, f, F represents the respective equation for each medium: matrix, fracture, Fault; thus a total of six scalar equations. The nomenclature is common (j = L for liquid, V for vapor): ρ_j is density, ϕ_j porosity, S_j liquid saturation, F_j mass flow; e_j is the total energy rock+fluid, h_R means specific enthalpy of the rock, F_E is total energy flow (F for fluid, R for rock) in each medium. All the terms are functions of time and space. The parameter q_i represents the mutual exchange of flow among the three continua. Thermodynamic properties vary softly within the matrix; while in fractures those same properties vary abruptly with discontinuities in the pressure/temperature gradients. These variations are emphasized into the faults that are, in fact, open rough channels where probably the law of Darcy is not valid. Data measured (Table 1) 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).

Table 1. Some Petrophysical Properties of Heterogeneous Reservoirs. [@]

Well	Depth (m)	Density (kg/m³)	Porosity (%)	Permeability (milidarcy)	K_{Ter} (W/m/EC)	C_P (J/kg/EC)
H-18	1750-1753	2340	14.7	0.01	2.42	921.1
H-02	616-619	2160	19.7	0.02	1.54	1046.7
H-19	1769-1771	2460	11.5	0.15	1.91	1172.3
H-26	1810-1813	2670	4.5	1.87	1.95	1004.8
H-24	2844-2847	2450	12.7	3.83	1.62	1046.7
Az-33	1350	2355	12	247.6	1.93	1165
H-28	1200	2430	12.3	101.3 H10³	1.99	1069

[@]Petrophysical data were measured in a Terra-tek lab (Contreras et al., 1990) in liquid saturated cores at p=100 bar and T=25°C. Permeability values in the last two rows of this table were deduced from analysis of pressure tests. Wells H - are in the Los Humeros and Az-33 is a well in the Los Azufres geothermal field.*

Numerical Approximation To the Triple Porosity Flow

The general stated equations of mass and energy are contained and solved in TOUGH=s code (Pruess, 1988). The general ideas sketched before, were included in a two-dimensional model defining approximately the geometry of each continuum (Figure 2). The model was solved numerically with TOUGH for an H_2O+CO_2 equation of state. Calculations were carried out for different initial states with extraction in the fault and various boundary conditions. Fault thickness was simulated explicitly for an opening of 0.01 m (Figure 1). The fractured network is heterogeneous and very intense in the immediate vicinity of the fault within a 5 meters radius. Close to the macrofracture there is a 10 meters transition zone with less fractures and minor 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.

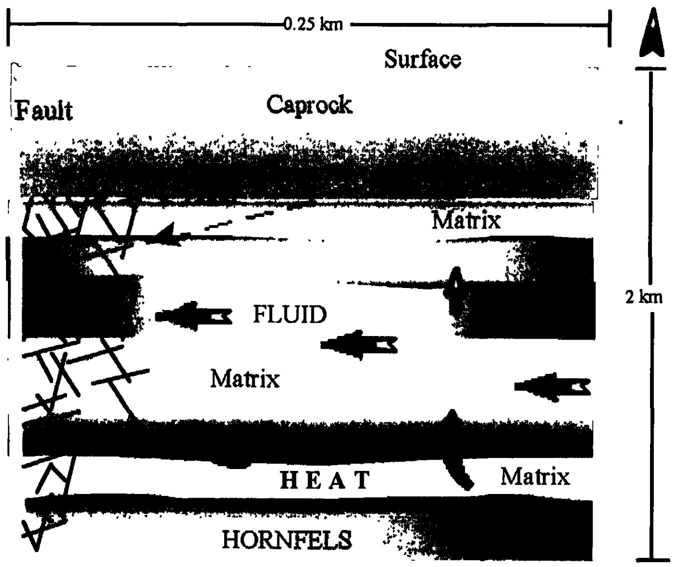

Figure 2. Idealized 2D hydrothermal zone with an open fault, fractured network and matrix blocks.

Distances between elements forming the mesh were constructed according to the 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 it is possible to 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. There is no recharge of mass nor heat through any boundary, with the purpose of forcing a rapid answer in the zone of extraction. Fluid was extracted supposing different initial states in the system: liquid and two phases. There is an impervious boundary located 100 m to the right. A brief synthesis of results is described next.

Extraction From a Single Vertical Fault

(Initial State: Liquid, Figures 3, 4, 5 & 6)

Reservoir initial conditions correspond to compressed liquid, which is extracted in the fault. Pressure decline in fault and fractures are observed immediately; pressure falloff appears slowly in the matrix. During the short simulated time thermodynamic changes are isothermal in the matrix, starting from 15 m distance to the fault. For this reason, 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 drawdown 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 from that zone. At matrix-fractures interface steam saturation reaches a maximum that declines toward the fault. Such phenomena occurrs because the fault receives a contribution of liquid from deeper zones. CO_2 partial pressure decreases rapidly inside fault and fractures and remains constant in the matrix.

If the initial steam saturation is not zero , the behavior of pressure and temperature is slightly different than in previous case. Pressure decline happens a little faster but attenuates 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 slightly between the straight border and this zone. CO_2 partial pressure falls rapidly but smoothly near the fractured network; remaining almost constant in the matrix blocks. Triple porosity effect is appreciated in both variables. The fault and the fractured network are distinguished clearly. The lower quantity of vapor in the fault is explained the same as in the previous case.

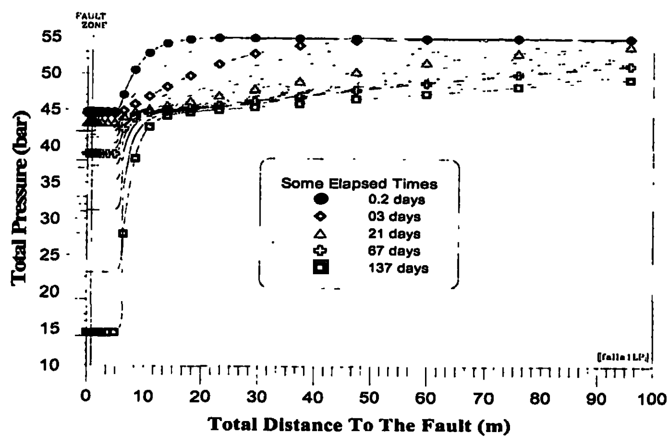

Figure 3. Pressure Evolution at Fault's Neighborhood (initial liquid phase, impervious right boundary at 250m).

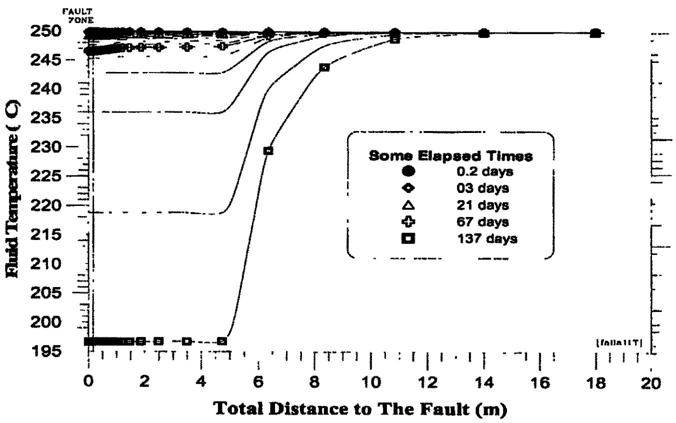

Figure 4. Temperature Evolution at Fault's Neighborhood (initial liquid phase, impervious right boundary at 250m).

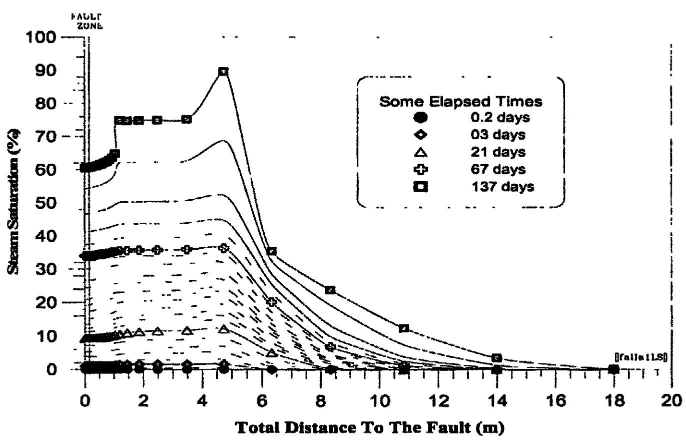

Figure 5. Steam Saturtaion at Fault's Neighborhood (initial liquid phase, impervious right boundary at 250m).

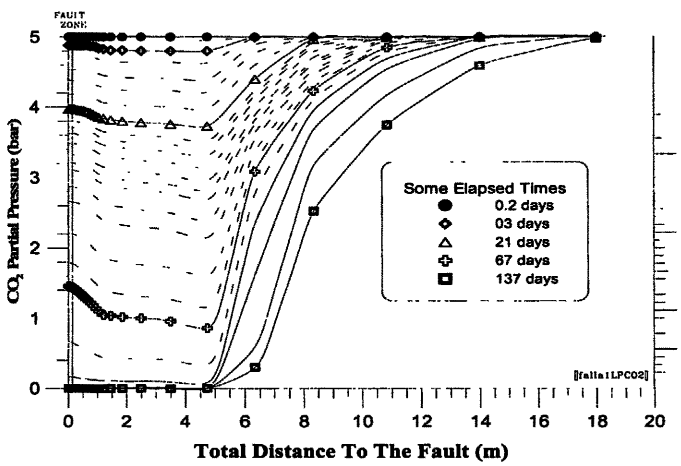

Figure 6. Carbon Dioxide Partial Pressure at Fault's Neighborhood (initial liquid phase, impervious right boundary at 250m).

Conclusions

There are essential differences in the behavior of fractured systems with faults. Upon analyzing the initial answer of geothermal wells finished in fractured volcanic zones with faults, the initial effect of faults and fractures in the thermodynamic behavior of the well has an immediate influence. As a matter of fact what one is 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 immediate vicinity of the well. This value represents consequently only the average about what is happening in the zone immediately affected by the extraction.

The abrupt changes remarked in the fault zone, is compatible with the simultaneous existence of matrix blocks that remain in almost static conditions. Large amounts of noncondensible gases in the matrix can coexist with very low presence of gas in the producing faults and in the zones of extraction. The total flow of heat is dominant in the faults and very poor in the matrix. Due to the internal geometry of the region (boundaries among the matrix blocks, the fractures and the conductive faults) where the processes of transport take place, the thermodynamic variables change abruptly introducing discontinuities in the gradients of those functions. The changes detected in pressure as the principal variable could have a wide variety of forms and behaviors. These changes do not occur only in pressure and temperature, but they are also translated to abrupt variations of mass and energy flows, in the steam distribution and CO_2 evolution. The effect of triple porosity is appreciated in the distribution of the vapor and of the CO_2 in the vicinity of the fault.

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