PROCEEDINGS, Fifteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 23-25, 1990
SGP-TR-130

GEOTHERMAL SYSTEMS IN SEDIMENT-FILLED RIFT VALLEYS: HYDRODYNAMIC AND GEOCHEMICAL CHARACTERISTICS.

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We have compiled detailed geophysical, hydraulic and geochemical data from numerous major liquid-dominated geothermal fields in order to develop a generalized hydrodynamic and geochemical model for typical geothermal systems which are found in sediment-filled rift valleys.

The location of these geothermal fields is determined by their tectonic framework and associated structures like spreading ridges, subduction zones, and continental rifts. This study is dominated by the extensive data available on moderate to high temperature geothermal fields which are typically found within continental rifts or where oceanic spreading ridges extend onto the continent. Representative examples of this common type of geothermal systems are the East Mesa, Salton Sea (both USA), Cerro Prieto (Mexico), and Olkaria field (Kenya).

THERMAL STRUCTURE

Rift valley-associated geothermal fields are usually located in regions with anomalous surface heat flow. The geothermal fields of the Imperial Valley have a surface heat flow above 200 mW/m^2 (Lachenbruch et al., 1985). This flux is similar to those reported from other fields and approximates a lower limit to surface heat flow of these systems. The upper extreme is found in high temperature systems like that at Salton Sea where the local heat flow exceeds 2500 mW/m^2 (Newmark et al., 1986).

The pattern of the geothermal-gradient varies considerably within each field, depending on the location of the convective or conductive heat flow zones. The maximum of the near surface geothermal gradient is commonly between 0.83 $^oC/m$ (Salton Sea; Newmark et al., 1988) and 0.18 $^oC/m$ (East Mesa; Combs, 1971). Laterally within one field, the near surface gradient can vary widely.

Newmark et al., 1988 report, for example, a rise of the shallow geothermal gradient from near regional (0.09 $^oC/m$) to an extreme value of 0.83 $^oC/m$ laterally over 2.5 km across the Salton Sea geothermal field.

Within the thermal cap above geothermal reservoirs, the gradient is also highly variable, for example, from about an average value of 0.38 $^oC/m$ for the Salton Sea (Elders and Cohen, 1983) to 0.14 $^oC/m$ for the Heber geothermal field.

Below the cap in the reservoir, representative gradients of the Cerro Prieto or Salton Sea geothermal field are 0.08 to 0.1 $^oC/m$ and in the Heber geothermal field with 0.015 $^oC/m$ (Lippmann and Bodvarsson, 1985).

A relatively high geothermal gradient for a reservoir with moderate temperatures is 0.06 $^{o}C/m$ within the East Mesa geothermal field (Elders and Cohen, 1983). The ranges indicate clearly that hydrothermal systems with high maximum reservoir temperatures, like the Cerro Prieto and Salton Sea geothermal fields, have also the highest temperature gradients in the three thermal zones. The pertinent depth range for these temperature gradients depends mainly on the variability of the reservoir geometry from field to field, as discussed next.

RESERVOIR GEOMETRY

Rift valley-associated geothermal fields can be best described lithologically by three or four different depth zones: over-laying sediments, caprock, reservoir and basement.

The caprock is commonly of sandstone with interbedded shales and extends down to a minimum of 350 m in the Salton Sea field (Randall, 1974) to a maximum of approximately 2,500 m in the Cerro Prieto field (Elders, 1979). However, an average thickness of 500 to 700 m (within the Dunes, East Mesa, Heber and Salton Sea geothermal field) seems to be more representative.

The thickness of the reservoir ranges typically from 600 to 2,500 m. Fluid flow is restricted below 3,000 to 3,500 m depth due to the increasing influence of the porosity-reducing alteration of the upper greenschist facies in the hotter, deeper rocks. In this kind of reservoir, the production interval is typically in the 600 to 1,800 m depth range and reflects the relative large permeability in the upper and middle part of reservoirs.

Surface evidence like hot springs, fumeroles, and sinter terraces, or data on contours of reservoir temperatures indicate typical areas of 25 to 55 km^2 and an area of approximately 35 km^2 seems to be representative (e.g. Olkaria; Grant and Whittome, 1981). However, resistivity measurements suggest that geothermal systems are larger, such as in the Olkaria field (Kenya) field with an approximate area of 80 to 100 km^2 (Grant and Whittome, 1981). Similar uncertainties affect estimates of reservoir volumes or calculations using data from Lippmann and Bodvarsson (1985), and Salveson and Cooper (1981). The approximation indicates that the Heber field near 35 km^3 is one of the smaller reservoirs. Maximum volumes of larger geothermal systems, like the Salton Sea system have a range of 70 to 100 km^3.

SALINITY OF GEOTHERMAL SYSTEMS IN RIFT VALLEYS

Both maximum reservoir temperature and the characteristic variation in salinities are plotted in Fig. 1. Included are salinities from six different fields in sediments in comparison to salinities from ten geothermal fields located in a volcanic dominated rift-valley (Taupo zone, New Zealand). A representative range for total dissolved solids in the sediment dominated type is 4,000 ppm (East Mesa; Hoagland,1976) to 270,000 ppm (Salton Sea; Elders and Cohen, 1983). The deep, hypersaline brines within some of these systems are mainly the product of downward percolation and partial evaporation of lake or groundwater (Rex, 1985). The large variability within high and low temperature reservoirs is illustrated by the Salton Sea

(T.D.S.: 50,000-270,000 ppm) and East Mesa systems (T.D.S.: 1,500-24,000) (Mc Kibben et al, 1988; Coplen, 1975).

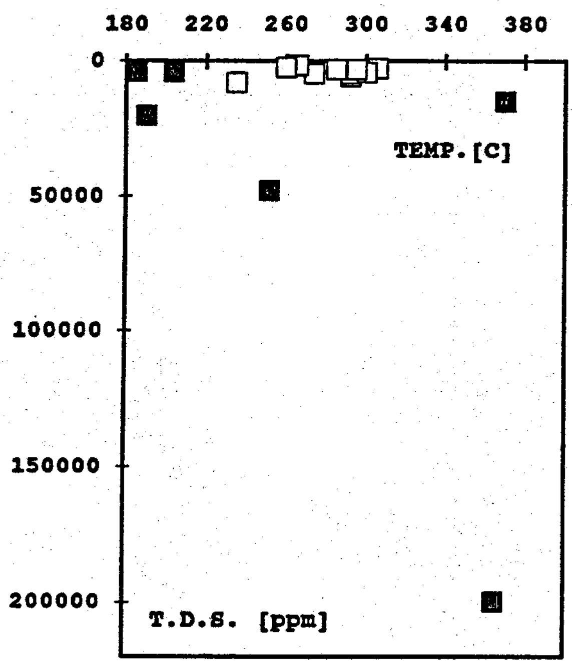

Figure 1: ■ sediment-associated fields
□ volcanic dominated fields

This range is considerable larger than that within the fields of the Taupo zone (data from Ellis, 1979), where total dissolved solids are below 10,000 ppm.

POROSITY CHARACTERISTICS

For the evaluation of reservoir behavior, we must approximate the rock porosity as it varies with depth. This exercise is complex because of the effects on pore space of alteration reactions and various dissolution and precipitation processes. Representative data on some geothermal fields are given in Table 1.

These values are only estimations. Note that of all samples with a porosity near 5 %, their number increases

Table 1: Reservoir Porosities

Location	Porosity (%)
Salton Sea System	
1. Base of Caprock	15 - 20
2. Upper Reservoir	~ 30
3. Lower Reservoir	19
4. Lower Reservoir	11
5. Reservoir Average	14
Cerro Prieto System	
6. Near Surface	40
7. 2,000 m Deep	5
8. Reservoir Average	10
Heber Field	
9. Caprock	15 - 30
10. Lower Reservoir	10
East Mesa Field	
11. Caprock	33
12. Reservoir Average	23

Source

1.	Mc Dowell and Elders, (1980)
2.	Schroeder et al., (1976)
3.-5.	Calculated here from McDowell and Elders, (1980), Tewhey, (1976) and others.
6.-7.	Lyons and van de Kamp, (1980)
8.	Elders et al., (1982)
9.-10.	Ershaghi and Abdassah, (1983)
11.-12.	Calculated here from well logs in Pearson, (1976).

significantly in wells deeper than 1,400 m.

Data in Table 1 and from other fields indicate that reservoir porosities vary usually between 40 and 3 %.

PERMEABILITY RELATIONS

Few permeability data or estimates are published for these geothermal fields. Permeability increases are quite common due to fracturing in the lower reservoir zones and are reported from several fields. In fractured zones, measured well permeabilities are approximately five to ten times higher than in measurements on cores.

Table 2 Reservoir Permeabilities

Location	Permeabilities (md)	
Salton Sea System	horiz.	vert.
1. Upper Reservoir Sandstones	~500	---
2. Reservoir Shales	---	0.1-1.0
3. Reservoir	100-500	---
East Mesa Field		
4. Average	170	45

Source

1. Schroeder et al., (1976)
2. Morse and Thorsen, (1978)
3. Morse and thorsen, (1978)
4. Calculated here from wire log data in Pearson, (1976)

Own calculations (Table 2) based on well logs from East Mesa (Pearson, 1976) seem to be consistent with published permeabilities from core and well tests.

Similar permeabilities reported from other fields, like Cerro Prieto and Heber (Lippmann and Bodvarsson, 1985; Elders et al., 1984), fall also in a range between 600 to 50 md horizontal permeability and 100 to 0.1 md vertical permeability, representative of this hydrothermal environment.

PERMEABILITY AND POROSITY: EFFECTS OF HYDROTHERMAL REACTION ON THE EAST MESA FIELD

Detailed porosity and permeability data, derived from well logs and core logs (Pearson, 1976) are shown in Fig. 2, 3 and 4. They represent averaged intervals of 250 m (820 ft.) and combined porosity and permeability values from eight geothermal wells from East Mesa and four nearby non-thermal wells.

The caprock, 610-762 m thick (2,000 - 2,500 ft) is mainly unconsolidated sediments, which extend to a depth of 848 m (2,780 ft) (Coplen, 1976).

The relatively large porosities and permeabilities of the caprock show

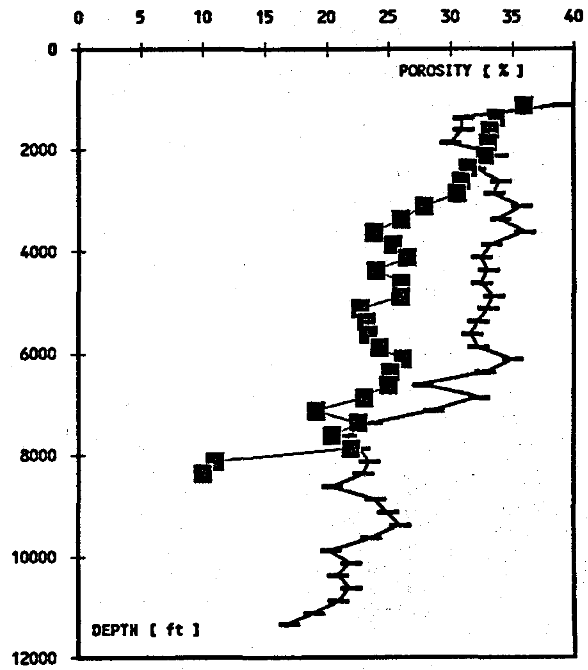

Figure 2: ■ hydrothermal wells
- non-thermal nearby wells

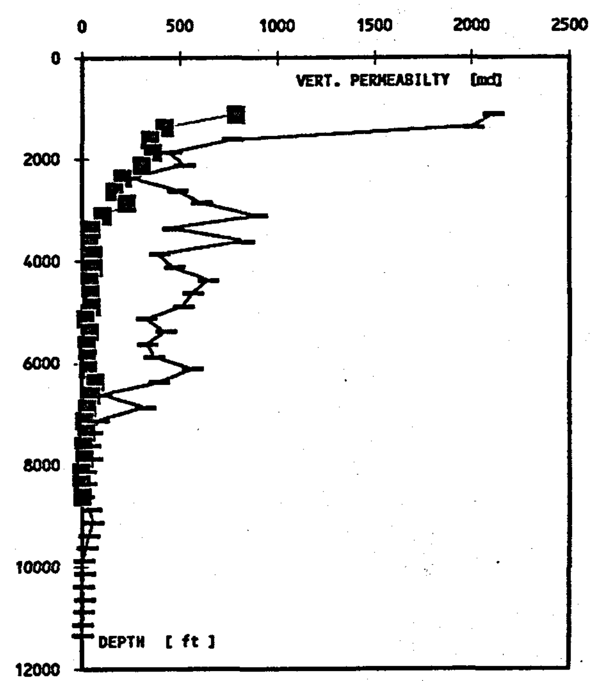

Figure 3: ■ hydrothermal wells
- non-thermal nearby wells

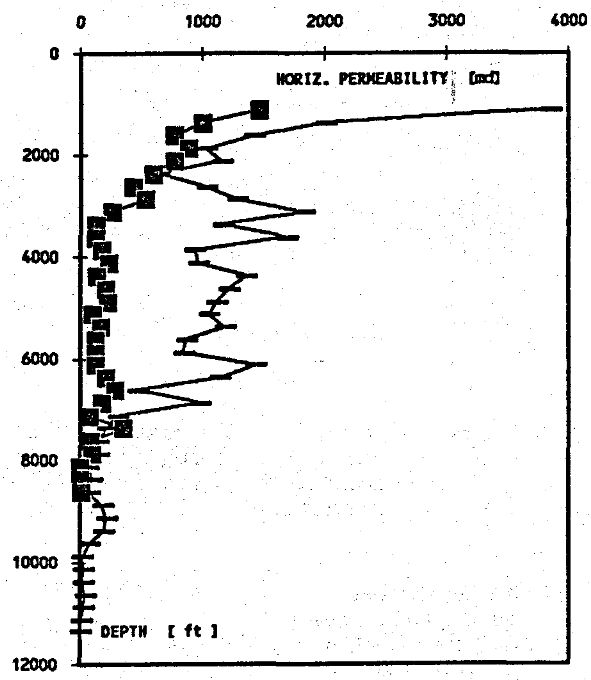

Figure 4: ■ hydrothermal wells
- non-thermal nearby wells

that it is relative permeable. Lower permeability and intensely cemented sandstones occur first at a depth near 640 m (2,100 ft) Hoagland (1976).

The initial porosity of the rock section (Fig. 2) varies over 30 and 38% and indicates no significant decrease due to compaction within the upper 1,800 m (5,900 ft).

Fig. 2-4 show that in the reservoir (about 600-2,340 m (2,000-7,700 ft)), the average porosity and permeability are significantly reduced compared to the initial rock values. This trend reflects the increased alteration and cementation, which decrease the permeability even at moderate geothermal temperatures. The vertical permeability (Fig. 3) drops within the reservoir to about 15 md near 990 m (3,250 ft) limiting major fluid transport below this depth to horizontal flow or flow along fractures. However, significant fracturing with resulting permeabilities of about 100 to 150 md, which would allow significant flow along fractures, was mainly found in deeper parts of the reservoir (Howard et al., 1978).

The general oscillatory decrease of these parameters with increasing depth may be a result, either of the initial shale content or more thoroughly cemented zones as reported by Hoagland, (1976).

FLOW RELATIONSHIPS

There is a large variation in surface discharge of this type of geothermal systems. The maximum, in the Cerro Prieto field is 5 x 10^6 m^3/y (Truesdell et al., 1984). Moderate temperature systems, like the Westmoreland or Dunes fields, usually show no surface discharge.

A specific flow of 3.6 x 10^6 m^3/y through the Cerro Prieto reservoir (Truesdell et al., 1984) is apparently a maximum rate.

Calculations for the low temperature reservoir of East Mesa (Kassoy, 1975) and the high temperature reservoir of the Cerro Prieto field show that the specific discharge is approximately 0.6 m/y, an order of magnitude representative of other fields of this type.

The surface discharge can change quickly. For example the present discharge of the Salton Sea field 3.9 x 10^4 m^3/y was considerably larger in the last century (Muffler and White, 1980). There are strong indications that the fluid flow within the Cerro Prieto reservoir changed significantly over time in this relative young (approx. 16,000 to 10,000 years) fields. McKibben et al., (1988) demonstrate that now the Salton Sea geothermal field is characterized by a dynamic flow stage during which hot fluid rises along highly permeable zones from the deep recharge aquifers to the upper reservoir. The brine residence time of 10^2 to 10^3 y, (Zukin et al., 1987) reflects the present rapid flow.

Similar flow and time relationships may be indicated by the temperature development of the Cerro Prieto reservoir where around 10,000 y have been necessary to reach reservoir temperatures of 160 to 200 °C (Elders et al., 1984). However, the extreme high temperatures of 350 to 370 °C were probably reached in a considerably shorter period. The apparently major variation in flow rates of a reservoir occurs over intervals short in comparison to the life of a geothermal system. For the well documented Wairakei system, Ellis (1979) deduced the static or minimum flow stage lasted 10^4 to 10^5 y and the dynamic stage for 10^4 to 10^2 y representing general intervals for various types of geothermal systems.

In Fig. 5 is a generalized cross section through a geothermal system in a sediment-filled rift valley (across the principal flow direction) including typical values of some parameters.

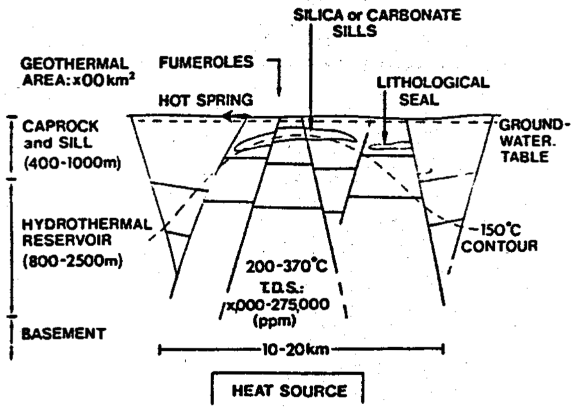

Figure 5: Generalized cross section through a geothermal system across the principal flow direction.

This research was supported by the Gas Research Institute under contract no. 5088-260-1746.

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