characteristics of the produced fluids and interference effects between wells have also been detected (Truesdell et al., 1984).

The usefulness of fluid geochemistry and reservoir engineering studies, as well as electrical resistivity, passive seismic, precision gravity, and ground-surface deformation surveys, for monitoring the behavior of the Cerro Prieto geothermal field under production has been discussed by Lippmann et al. (1983).

SUMMARY

Great advances have been made toward understanding Cerro Prieto. We hope that many of the studies initiated under the 1977–1982 DOE/CFE agreement will continue and add important new information as the field is expanded. For example, more needs to be known about the hydraulic properties of the sandy and shaly layers; the hydrogeologic model should be updated as new results and field data become available; and the general monitoring of the behavior of the field should continue, especially as new areas come under production.

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DEPOSITIONAL ENVIRONMENTS IN THE CERRO PRIETO GEOTHERMAL FIELD, MEXICO

*S.E. Halfman, M.J. Lippmann, and J.A. Gilreath**

Mainly on the basis of dipmeter log data, Halfman et al. (1984a) have modified and updated their geologic model of the Cerro Prieto field. The depositional environment of the geologic units controlling the subsurface flow of geothermal fluids has been established, and new faults and uplifts (contemporaneous or postdepositional) have been identified.

GEOLOGIC SETTING AND RECENT HISTORY OF THE AREA

The Mexicali Valley is part of the Salton Trough, an actively developing structural depression that resulted from tectonic activity that has created a series of spreading centers and transform faults that link the East Pacific Rise to the San Andreas fault system. The Cerro Prieto field is associated with one of these spreading centers, where the crust is being pulled apart by right-lateral stike-slip movement along the Cerro Prieto and Imperial Faults (Lomnitz et al., 1970; Elders et al., 1972).

During the early Pliocene (about 5 Ma b.p.), the present configuration of the Gulf of California began to develop by major crustal extension, splitting Baja California from the Mexican mainland (Saunders et al., 1982). At that time, the waters of the Gulf extended northward to about the present Salton Sea area. The propagation of the Colorado River delta into the Cerro Prieto area began in mid- to late Pliocene (Ingle, 1980).

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By late Pliocene, the southwesterly advance of the delta was essentially complete, resulting in the conversion of the Salton basin to a nonmarine depositional basin (Lyons and van de Kamp, 1980). By mid-Pleistocene time, the marine connection between the Gulf of California to the south and the Imperial Valley to the north was severed (Ingle, 1980).

GEOLOGIC AND HYDROGEOLOGIC MODELS OF THE CERRO PRIETO

Halfman et al. (1984a) have developed five geologic cross sections for Cerro Prieto (e.g., Figs. 1 and 2) showing the distribution of sandstone, sandy-shale, and shale lithofacies. After superimposing temperature profiles and well production intervals on these cross sections, they were able to identify two geologic units that largely controlled the subsurface flow of the geothermal fluids: Shale Unit O and Sand Unit Z. Shale Unit O is a thick, relatively impermeable, low-porosity body that locally forms a cap rock for the geothermal reservoir. This unit is classified mainly as a shale lithofacies group. Sand Unit Z, underlying Shale Unit O, contains thick, permeable, high-porosity sandstone beds that allow fluid circulation; it is the main stratigraphic unit of the geothermal reservoir.

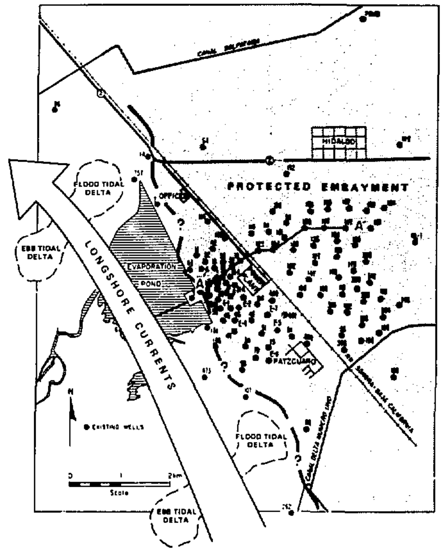

Figure 1. Schematic paleoenvironmental map for the deeper part of the Cerro Prieto section. Location of wells and cross section A-A'. [XBL 835-1804C]

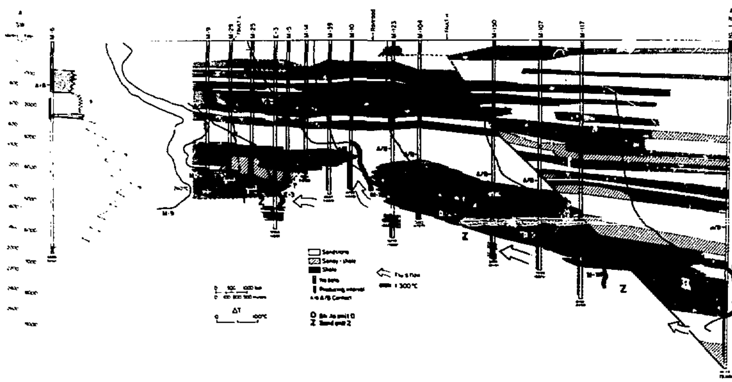

Figure 2. Lithofacies cross section A-A', showing well locations, lithofacies groups, faults, temperature profiles, producing intervals, A/B contacts, Shale Unit O, Sand Unit Z, and arrows indicating direction of fluid flow. On the temperature profiles, the points corresponding to 300°C are placed under the location of the respective wells. The parts of the temperature profiles shown by heavy lines indicate temperatures of 300°C or greater. [XBL 828-10945A]

The hydrogeologic model discussed by Halfman et al. (1984a) shows that under natural conditions the geothermal fluids enter the Cerro Prieto field from the east at depths greater than 3000 m through Sand Unit Z. The fluids move westward through this unit, rising to shallower depths through fault zones and sandy gaps in overlying Shale Unit O. In the thick sandstones along the western margin of the producing field (west of well M-9), the geothermal fluids either mix with cold groundwaters or discharge to the surface as hot springs, mud volcanoes, and fumaroles.

DEPOSITIONAL ENVIRONMENT OF CERRO PRIETO RESERVOIR ROCKS

Critical to understanding the nature and characteristics of the geologic units governing to a large extent the flow of geothermal fluids in the reservoir, in particular Sand Unit Z and Shale Unit O, is an understanding of the depositional environment of these rock units. This environment controls largely the overall lithology of the units and the continuity, thickness, and intercalation of their sandstone and shale beds, all of which determine the hydraulic properties of the units.

Most researchers have first attempted to interpret the depositional environment of the unusually thick sandstones (> 900 m) penetrated by wells M-96, M-3, M-6, and S-262 drilled along the western margin of the field (Mañón) et al., 1977; Prian, 1978; and Lyons and van de Kamp, 1980).

A careful analysis of available dipmeter logs from 26 wells showed that the depositional environment of the thick sandstones, Shale Unit O, and Sand Unit Z was once part of a coastal system (Halfman et al., 1984b). Along a west-to-east line, one would find, in succession, longshore current, shoreline, and protected embayment deposits (Fig. 1). The significant sandstone thicknesses penetrated in the western part of the field are associated with northward-flowing longshore currents in an actively subsiding basin. The subsidence of this basin probably continues today, as Cerro Prieto is located on an active spreading center, mentioned earlier (Lomnitz et al., 1970; Elders et al., 1972). Lyons and van de Kamp (1980) have shown from petrographic studies that the thick sandstones were derived from Colorado River sediments. Therefore, longshore currents must have been carrying sediments northward to the Cerro Prieto area from an ancient Colorado River delta located to the south of the field.

Interpretation of the dipmeter logs shows that at Cerro Prieto many of the deposits associated with the longshore currents were formed in flood-and-ebb tidal deltas. The dipmeter patterns corresponding to those deltaic deposits are similar to the distributary front patterns described by Gilreath and Stephens (1975). The dip patterns characteristically show high-angle dips decreasing to lower ones (about a 10–20° span) over a depth interval of about 15–30 m. A good example of an ebb-tidal deltaic deposit is shown between 1143 and 1150 m in the dipmeter log for well M-96 (Fig. 3). The long axis of this deposit is oriented in a west-northwest direction. The general direction of the longshore currents is to the north, as evidenced by the northward dip patterns between 1128 and 1143 m and between 1173 and 1211 m (Fig. 3). Also shown in this figure are tidal flat deposits between 1158 and 1173 m. Other types of dipmeter patterns for these thick sandstones indicate shallow water (Gilreath et al., 1969) and river deposits (Schlumberger Limited, 1981) associated with a longshore current environment.

Once the depositional environment for the thick sandstones found in the western region of the field was established, it became easier to identify the environment of deposition of the sediments of Shale Unit O. The dipmeter log for well M-150 from 1524 to 1859 m illustrates some of the typical patterns for Shale Unit O (Fig. 4). These dips show a repeating pattern of high- to lower-angle dips, indicative of foreset bedding resulting from southwest- to northeast-flowing currents. The very orderly pattern shows that little if any reworking of the sediments occurred. To preserve the foreset beds, rapid deposition and burial must have occurred. The gamma-ray log for Shale Unit O indicates typical thin

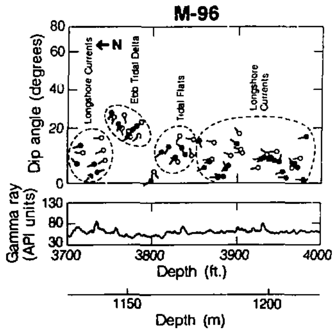

Figure 3. Dipmeter log for well M-96, representing an ebb-tidal delta (1143–1150 m), tidal flat (1158–1173 m), and longshore current (1128–1143 m and 1173–1212 m) deposits. [XBL 842-9592]

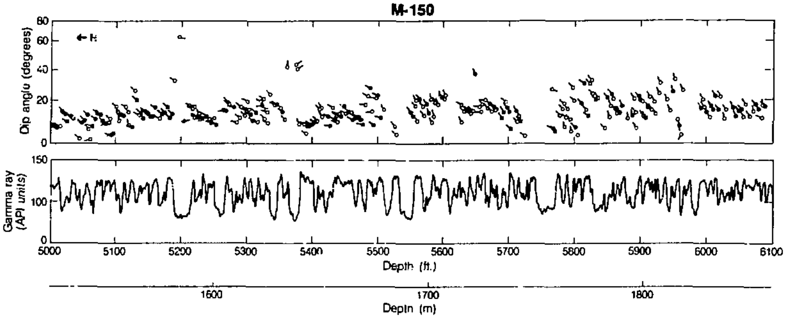

Figure 4. Dipmeter log for well M-150, representing foreset beds from 1524 to 1859 m. [XBL 842-9595]

interbedded sandstone and shale layers. Considering that this unit was deposited in an area between the longshore currents to the west and the mainland to the east and that its thin interbedded sandstone and shale layers were laid down in a very quiet and undisturbed environment, it can be inferred that the sediments were probably deposited in a protected embayment, as shown in Fig. 1.

Sand Unit Z is also composed mostly of foreset beds deposited in a protected embayment. However, the sandstone and shale beds of the upper portion of Sand Unit Z are generally much thicker than the beds of the lower portion of Shale Unit O. The source of sediments for both units was the Colorado River (Lyons and van de Kamp, 1980). Moreover, the dipmeter patterns of both units indicate that the energy of the currents transporting the sediments into the protected embayment must have been similar. Therefore, the greater thickness of the sandstone and shale beds may be due to alternating high and low energy conditions of the Colorado River over longer periods of time and/or to erosion by the Colorado River through thicker sandstone and shale source rocks.

By establishing the characteristics of the coastal environment of deposition of the sedimentary rocks forming the Cerro Prieto geothermal reservoir and its (discontinuous or local) cap rock, it is easy to explain the sandier nature and eventual disappearance of Shale Unit O in the western part of the field. The sandier western portion of Shale Unit O (from well M-10 to M-9) represents the beginning of a transition from protected embayment deposits (to the east) to longshore current deposits (to the west). The sandy-shale group within Shale Unit O (between wells M-5 and M-29) is permeable enough to allow some geothermal fluids to flow westward through it.

The thick and highly permeable deposits associated with longshore currents bounding the reservoir to the west lets westward-moving hot fluids mix with (colder) groundwaters, thus limiting the horizontal extent of the geothermal reservoir. Therefore, new wells should be drilled east to these thick sandy deposits, preferably south and southwest of NL-1, which is near the geothermal heat source.

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THE KRAFLA GEOTHERMAL FIELD, ICELAND: A MODELING CASE STUDY

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Lawrence Berkeley Laboratory, in cooperation with the State Electric Power Works of Iceland (SEPW) and the Icelandic National Energy Authority (NEA), conducted a comprehensive modeling study of the Krafla geothermal field in Iceland. The study consisted of four tasks: analyzing the well-test data, modeling the reservoir system in its natural (unexploited) state, determining the generating capacity of the different reservoir regions, and modeling the well performance on the basis of different exploitation schemes.

For detailed modeling of a geothermal system, one must know or estimate many parameters that characterize the system. One of the most important parameters is the transmissivity, kH, of the reservoir, which represents the relative ease of fluid movement within the reservoir. The existing well-test data from Krafla wells were analyzed to yield the transmissivity distribution in the reservoir. A modeling study of the natural state of Krafla reservoir was undertaken, because this can provide important constraints on reservoir parameters.

The final two tasks deal with the generating capacity of the reservoir and the well performance. We develop a simple lumped-parameter model for approximate estimation of the generating capacity of the field, which allows for natural recharge and reinjection. Numerical methods are then employed in a two-dimensional areal simulation of the Krafla system. Finally, a quasi-three-dimensional model is developed in which all wells are represented individually. The model achieves an approximate match of past production rates and enthalpies of the wells. It is then used to predict future well behavior (flow rates and fluid enthalpy) and overall reservoir depletion under various reservoir management schemes.

The present article gives a rather brief summary of the modeling work; a more complete description is given in Bodvarsson et al. (1983a).

THE KRAFLA GEOTHERMAL FIELD

The Krafla geothermal field is located in the neovolcanic zone in northeastern Iceland. The zone is characterized by fissure swarms and central volcanoes. The Krafla field is located in a caldera (8 × 10 km) with a large central volcano, named Krafla. The field has been under development for the past decade. At present, 23 wells have been drilled at the Krafla field (Fig. 1). In the "old" wellfield (west of the Hveragil gully), the wells have encountered two major reservoirs (Fig. 2); the upper reservoir (200–1000 m depth) contains single-phase

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