GEOTHERMAL EXPLORATION BY TEM-SOUNDINGS IN THE CENTRAL ASAL RIFT IN DJIBOUTI, EAST AFRICA

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ABSTRACT

In 1988 the National Energy Authority of Iceland (NEA) made a resistivity survey in the Asal Rift in Djibouti, East Africa. The survey was a part of a geothermal exploration of the Central Asal Rift. Because of the arid conditions a central loop transient electromagnetic (TEM) method was applied. The survey revealed a rather complex but clear resistivity structure, which correlates with the geological structure of the area. The level of the highly saline groundwater was mapped with great accuracy. A hydrological barrier that was observed in the active rift zone is most naturally explained by effective self sealing due to mineral deposition at the margins of the geothermal system. The water table, under Lava Lake, is found to be locally above sea level, probably reflecting an upwards convecting plume of geothermal fluids. The resistive basement found in the survey area is locally absent under Lava Lake, most likely due to higher porosity in the geothermal upflow zone.

INTRODUCTION

In 1988 the National Energy Authority of Iceland (NEA) made a resistivity survey in the Asal Rift in Djibouti, East Africa. The Asal Rift is a rift zone in the landward extension of the bay of Ghoubbet al Kharab, which is a westward extension of the Gulf of Tadjura (see Fig. I). The objective of the survey was to locate possible geothermal resources and drilling targets in the active part of the rift. The surface in the prospect area is very dry so that conventional Schlumberger soundings or other direct current methods are not applicable. The central-loop TEM method, which couples inductively to the ground, was therefore selected. Further details about the survey in Djibouti are given in Arnason and Flóvenz (1995).

GEOLOGICAL SETTING

The Asal Rift is located on the eastern border of the Afar depression, at the junction of three major tectonic structures in East Africa: the African Rift Valley, the Gulf of Aden, and the Red Sea. The rift, which opened during the Pleistocene, is a westward extension of the Gulf of Aden-Tadjura spreading axis. It extends about 11 *km* to the northwest from the bay of Ghoubbet al Kharab to Lake Asal, which is 155 *m* below sea level. The

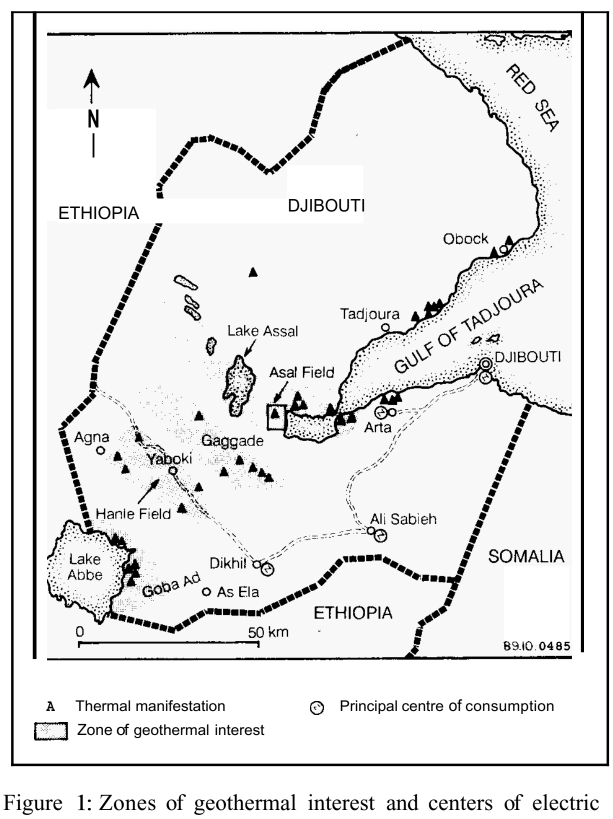

Figure 1: Zones of geothermal interest and centers of electric power consumption.

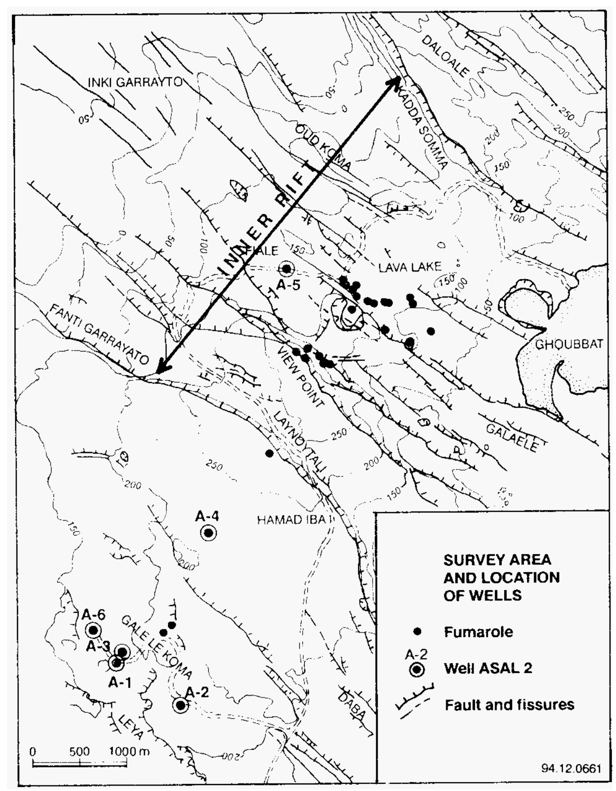

Figure 2 Overview of the central Asal Rift.

rift is about $10 km$ wide and is characterized by extensive faulting and volcanic activity with the latest eruption occurring in 1978.

The spreading rate of the Asal Rift has been estimated to be about $1.5\ cm/year$ (Delibrias et al., 1975). The rift is often divided into an "external rift", characterized by large normal faults, and an "inner rift", characterized by vertical faults and fissures. The present rifting and volcanic activity is confined to the inner rift.

The main geological units in the Asal rift area are of basaltic origin. The rift is surrounded by the Dalha basalts (6-8 *Mu)* and the basaltic Stratoid series (1-4 *Mu*). A basaltic lava shield (Asal series), with a center close to Lava Lake in the southeastern part of the inner rift, covered most of the rift at one time. This shield, which is now broken by large faults, mostly covers hyaloclastite that is found inside the southern part of the external rift (see Fig. 2). In the inner rift phreatic tuff mostly underlies recent lava flows. The Lava Lake is a large phreatic crater whose bottom is covered with recent basaltic lava.

Geothermal surface manifestations, warm springs and fumaroles, are found in the Asal Rift. Warm springs, with temperatures ranging from 30°C to 80°C, are abundant along the east side of Lake Asal. In the rift between Lake Asal and the Gulf of Ghoubbet, the water table is well below the ground surface so only fumaroles appear on the surface. These are found in two areas: in a NW-SE elongated area in the external rift around wells Asal-1, 2, 3, and 6, with a maximum temperature of 66°C; and in the southern part and to the south of Lava Lake in the inner rift, with a maximum temperature of 99°C (see Fig. *2).*

Prior to the TEM survey, six 1146-2013*m* deep wells had been drilled (see Fig. 2), only one of which was located within the inner rift. They all showed high temperatures, up to 345°C. Few permeable zones were found, however, and and these yielded high salinity brine, which caused intensive scaling and rapid reduction in mass flow. The exploration of the presently active inner rift was motivated by the possibility of finding higher permeability formations and lower salinity fluids than hitherto.

DATA ACQUISITIONAND INVERSION

The central-loop TEM sounding method has been described in many publications (for a pedagogical description see e.g. Fitterman and Stewart, 1986; Árnason, 1989; Arnason and Flóvenz, 1992). A loop of wire (transmitter loop) is placed on the ground and a magnetic field is built up by transmitting current into the loop. The current is abruptly turned off and the decay rate of the magnetic field is measured by a receiver coil placed at the center of the transmitter loop. The decay rate is dependent on, and can be inverted in terms of, the resistivity structure of the Earth under the transmitter loop.

The decaying magnetic field at the surface is much less affected by local inhomogeneities than the electric field. This makes TEM soundings much less sensitive to local resistivity variations at the sounding site than magnetotelluric and direct-current soundings, such as Schlumberger soundings. The central-loop TEM method is therefore, in many respects, superior to the conventional Schlumberger soundings. Data collection is cheaper and faster, and since no current is injected into the ground, this method makes many areas, which are practically unaccessible by Schlumberger soundings, easily accessible for geothermal and ground water exploration.

The field work took place from late May to the beginning of July. Data acquisition took 25 days, resulting in a total of 45 soundings. The locations of the soundings are shown in Fig. 3. The equipment used in the survey was an EM37-3 set from Geonics Ltd., and usually the transmitter loop was a $300 \times 300\ m^2$ square loop. The transmitted current was usually in the range of 20-23*A*, and the transient signal was recorded in the time interval of 0.087-70.4 *ms* after the current turn-off. The electromagnetic noise level in the prospect area turned out to be low, and the data were generally of good quality.

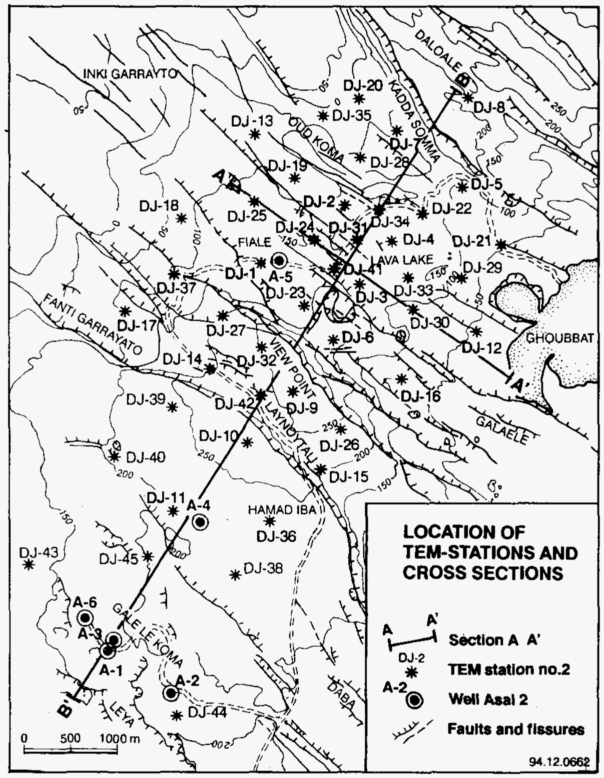

Figure 3: Location of TEM-stations and cross sections.

The sounding curves were turned into resistivity models by one-dimensional inversion. To this end a non-linear least-squares inversion program developed at NEA was used (Árnason, 1989). The program can be run either on personal or mainframe computers.

A model with four or five layers gave the best inversion fit for most of the soundings. The average deviation between measured and calculated apparent resistivity values was normally about 1%. The least resolved parameter in the models is the resistivity value of the uppermost high-resistivity layer, which is present in all the models. The resistivity value of a resistive layer appearing underneath very low resistivity, which is found in nearly all the soundings, is likewise poorly defined. The best determined model parameter is the depth down to the boundary where a high resistivity is underlain by a very low resistivity. This depth is determined to an accuracy of the order of 1%. The intermediate layer parameters, resistivities and thicknesses, are calculated with a probable accuracy of 20-30%.

THE RESISTWITYSTRUCTUREOF THE CENTRALASAL RIFT

Resistivity cross sections have been made perpendicular (Fig. 4) and parallel (Fig. *5)* to the rift. The locations of the sections are shown in Fig. 3. Both sections show a resistive surface layer $(\rho > 100 \Omega m)$ with a variable thickness, ranging from about hundred to several hundred meters. This can be explained as partially saturated or unsaturated basaltic rocks. The layer is underlain by a low resistivity layer $(\rho < 7$ *), the top of which is considered to correspond to the ground water level. Higher resistivity appears underneath the low resistivity layer within the inner rift, except below Lava Lake. The nature of this resistive layer is discussed later, but it denotes most likely reduced porosity due to secondary mineralization.

The cross section on Fig. 4 extends to boreholes Asal-1, 3, and 4. The upper boundary of the low resistivity layer is displaced in the SW part of this section. This displacement, with a downthrow of

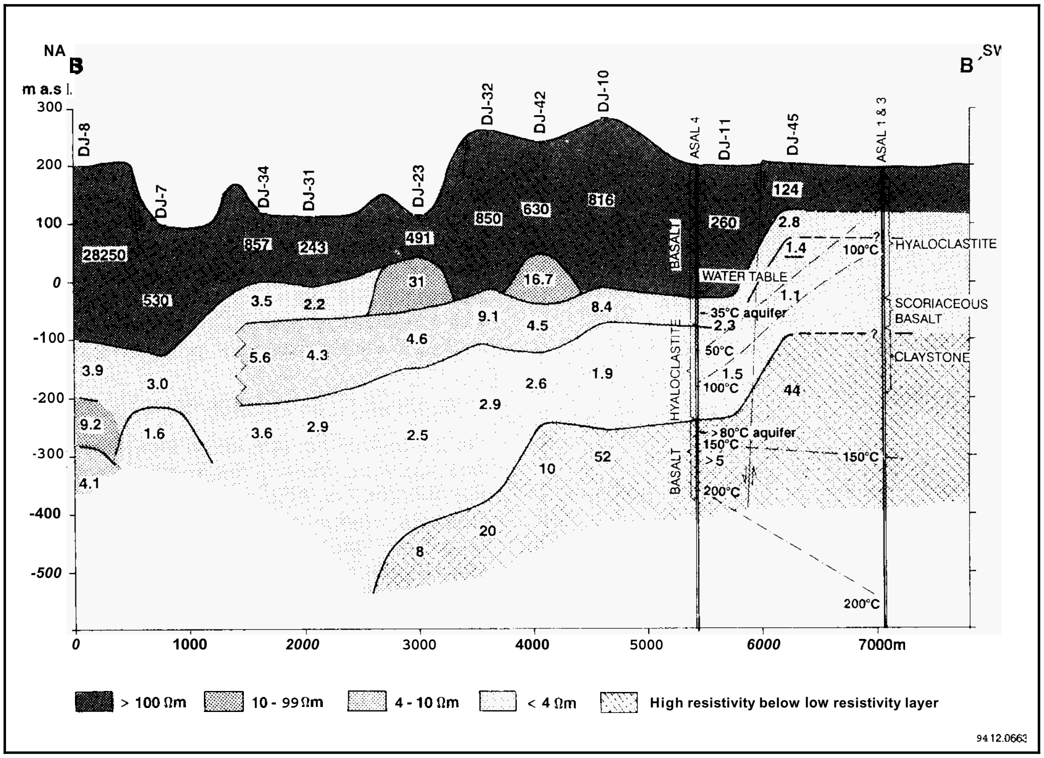

Figure 4: Resistivity cross section across the rift.

about 175 *m* to the **NE** (between soundings DJ-11 and DJ-45), coincides with a fault that can be seen on the surface. Lithological sections from wells Asal-3 and Asal-4 show that the boundary between the Asal series and the underlaying Stratoid series is some 200 *m* lower in Asal-4 than in Asal-3 (Aquater, 1989). Some data from these wells are shown in Fig. **4.** It is seen that the lower boundary of a thick hyaloclastite series, belonging to the Asal series, is about 200 *m* deeper in well Asal-4 than in Asal-3.

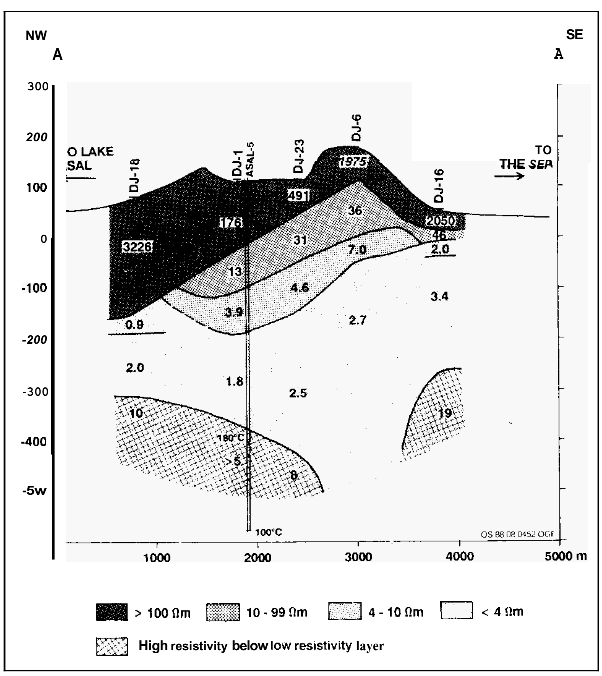

Figure *5:* Resistivity cross section along the rift.

The resistivity cross-section parallel to the rift (Fig. 5) shows that the depth to the conductive layer increases substantially from **SE** towards ***NW.*** The upper boundary of the layer is close to sea level at the **SE** end of the sections but drops rather steeply to about 150 *m* below sea level on the ***NW*** side of a zone running through Lava Lake and perpendicular to the rift. This must be interpreted as a sudden drop in the water table and indicates a hydrological barrier across the inner rift.

The section parallel to the rift shows another interesting feature. In places where the upper boundary of the low-resistivity layer dips from about sea level down to about 150 *m* below sea level (i.e. above the hydrological barrier), layers appear with intermediate resistivity values (Fig. *5).* The intermediate resistivity appears in most of the soundings as two layers: a layer of 10-80 Ω*m* and an underlying layer of 4-7 Ω*m*. These layers are found in an area bordering Lava Lake to the south and west. The 4-7 Ω*m* layer is thickest around the fumaroles in the southern part and to the south of Lava Lake. It is thought to be just below the water table, and its extension coincides roughly with the barrier in the central rift. The relatively high resistivity values in this layer below the water table are probably caused by extensive mineral deposition or boiling close to the water table.

The 10-80 Ω*m* layer could reflect partially saturated rocks. There is a large pressure drop across the barrier, and hot water that migrates through the barrier is likely to flash. The partially saturated layer is thought to reflect condensation of updrafting steam from the boiling.

The resistivity values in the low-resistivity layer seem to show a rather consistent variation. The lowest resistivity values are about 2 Ω*m* at the end of the bay of Ghoubbet, and could correspond to seawater saturated rocks. The values are lower than 1.5 Ω*m* to the **SW** of well Asal-4, and also in the ***NW*** part of the inner rift, which fits with the ultra high salinity of the fluids in wells Asal-1, 3 and *6.* The highest values within the low-resistivity layer (> 2 Ω*m*) are observed in a zone of similar spatial extension as the hydrological barrier. This might be explained by reduced porosity and permeability due to mineral deposition within the barrier.

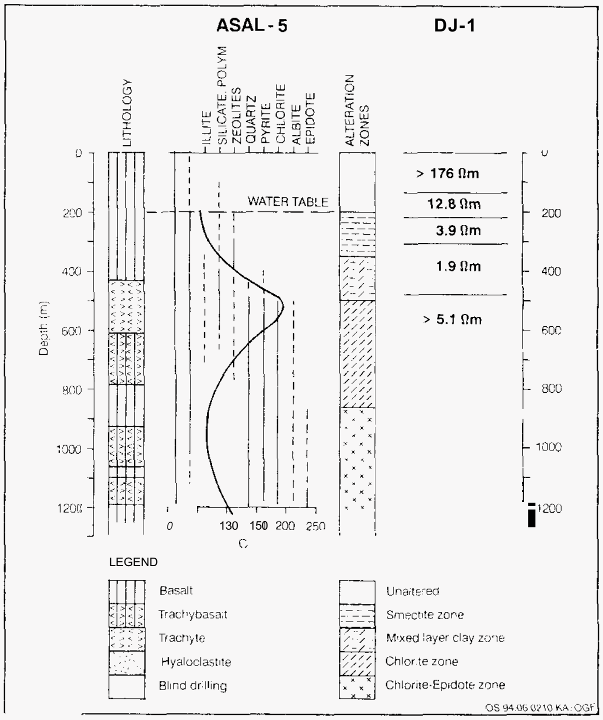

Figure 6: Comparison of data from well Asal-5 and TEM-sounding DJ-1.

COMPARISON WITH WELLDATA

In order to facilitate the interpretation of the resistivity structure in geological terms, two soundings were made close to wells **Asal-5** and Asal-4 (DJ-1 and DJ-11, respectively).

Figure 6 shows a comparison of the data from well Asal-5 with the layered model for TEM sounding DJ-1. The figure shows a lithological section, the distribution of alteration minerals, and the temperature in the uppermost 1200m in the well. The resistivity model for DJ-1 includes five layers. **A** resistive surface layer is underlain by a layer of intermediate resistivity (about 13 Ωm). The boundary between this intermediate layer and an underlying layer of about 4 Ωm coincides with the water table in the well. Below the 4 Ωm layer there is a layer of about 2 Ωm extending to a depth of about 475 m. There the resistivity increases again and is higher than 5 Ωm. The lower boundary of the low-resistivity layer is close to the boundary between the mixed-layer-clay zone and the chlorite zone. This boundary is defined as the depth where chlorite becomes the dominant clay mineral and the degree of alteration and mineral deposition increases considerably (quartz and pyrite become abundant).

The comparison of DJ-11 with data from the well Asal-4 is similar. The boundary between the resistive surface layer and a layer **of** resistivity about 2.3 Ωm coincides with the water table in the well. Beneath this layer there is a layer with resistivity of about 1.5 Ωm extending down to about 450 m. At this depth the resistivity increases again and is higher than 3.6 Ωm. Again the increase in resistivity is close to the transition to the chlorite zone.

The comparison with borehole data shows that the uppermost high-resistivity layer found in all soundings reflects unsaturated rocks. In most of the survey area the resistivity drops sharply from values higher than 100 Ωm to values of about 3Rm or lower. The comparison of DJ-11 with Asal-4 shows that this sharp transition defines the water table. The definition of the water table is not as obvious in the areas where the layers of intermediate resistivities ($10 < \rho < 80 \Omega m$ and $4 < \rho < 10 \Omega m$) are present. The comparison of sounding DJ-1 with well Asal-5 (Fig. 6) suggests that the water table is to be found where the resistivity drops below 8 Ωm.

Figure 6 shows that the present temperatures in well Asal-5 are not in equilibrium with the alteration, and that the rocks around the well have been cooled down. Logs from Asal-4 show temperatures close to the boiling curve below the water table. The comparison between the resistivity layering and well data does not show any obvious correlation between resistivity and temperature, except that the basement resistivity is probably somewhat lower at **Asal-4** than at **Asal-5,** which is consistent with higher temperatures at depth. The resistivity variations below the water table seem to be mainly related to variations in porosity and salinity. The low-resistivity layer at Asal-4 coincides roughly with a hyaloclastite layer. This **is** probably due to higher porosity in the hyaloclastite than in the basalt above and below.

*INTERPRETATION **OF** THE RESISTWITYSTRUCTURE*

On the basis of the comparison between resistivity models and well data some inference can be made about the subsurface conditions in the **Asal** Rift. Figure 7 shows the elevation of the water table in the survey area, defined as the upper boundary **of** resistivity lower than 8 Ωm. The figure shows some interesting features. The water table is well above sea level in the borehole area in the **SW** part of the external rift. It drops sharply to about sea level at the fault just **SW** of well Asal-4, indicating that the fault acts as a hydrological barrier for ground water flow from the south. The water table is close to sea level to the NE of this fault and to the **SE** of a line running perpendicular to the rift, through Lava Lake and the area around well Asal-4. NW of this line the water table drops suddenly to the level af Lake **Asal.**

This sharp drop of the water table must mean that there is a hydrological barrier across the rift. Such an effective barrier in the active rift implies that there must be extensive mineral deposition that rapidly clogs steadily opening flow paths. This must be caused by precipitation of secondary minerals, such as calcite and anhydrite, from a geothermal system.

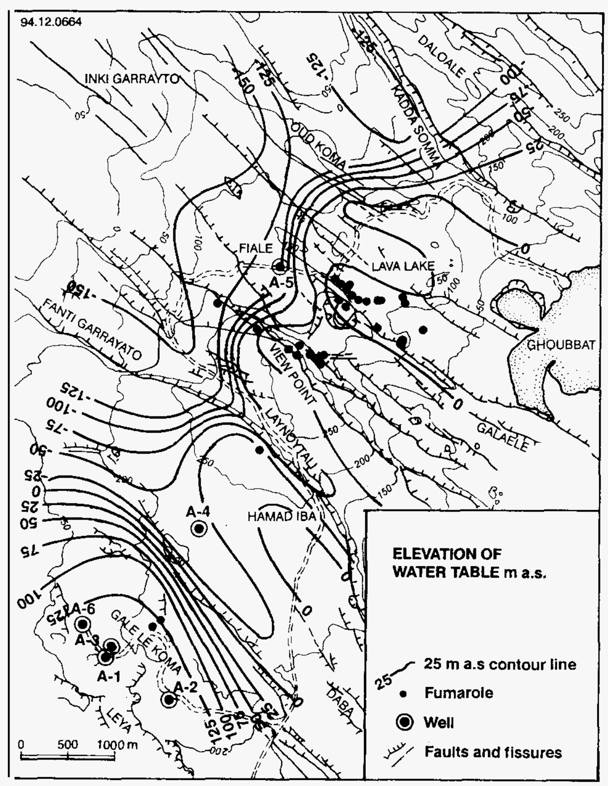

Figure 7: Elevation of water table in m above sea level.

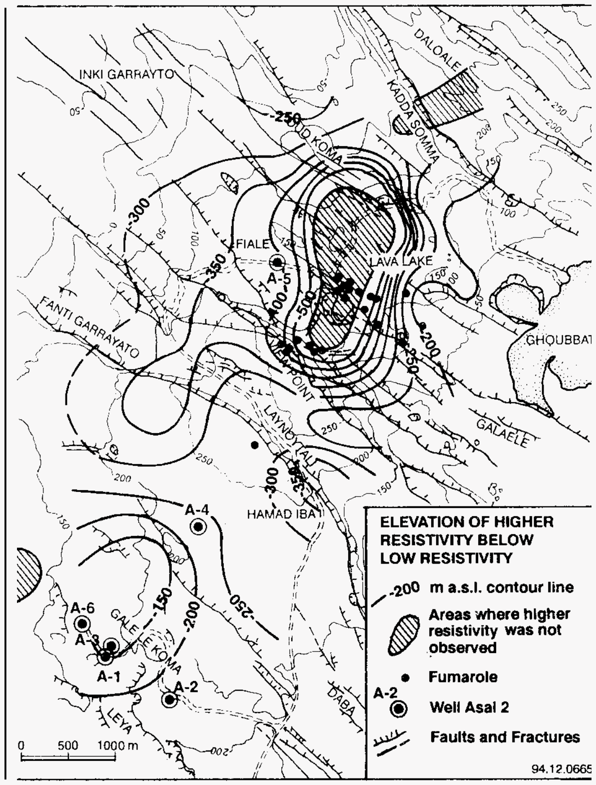

Figure 8: Elevation of higher resistivity below low resistivity.

Figure 7 shows some interesting details. Areas where the ground water table is considerably below sea level extend from the NW into the barrier along the fault **SW** of well Asal-4 and along the great fault at the **SW** margin of the inner rift. This shows that these faults provide flow paths to drain the ground water towards Lake Asal. In the inner rift the barrier seems to be less interrupted by faults despite higher tectonic activity. This is probably due to more intense geothermal activity and mineral deposition in the inner rift. The water table is generally above sea level under and to the south of Lava Lake, except for a narrow tongue with lower water level extending from the **NW** into Lava Lake. This tongue coincides with a heavily fractured zone in Lava Lake. The rise of the water table above sea level is most naturally explained by an underlying, upwards convecting, plume of geothermal fluid. The fumaroles in the southern part of Lava Lake are found in the area where the water table is highest (Fig. 7), lending further support to this hypothesis. The tongue with water level below sea level, running from **NW** and into Lava Lake, probably reflects transient leakage through the barrier along recently activated faults and fractures.

Comparison of well data with resistivity models shows that the higher resistivity below the low-resistivity layer correlates with changes in alteration mineralogy, and the increase in resistivity with depth reflects reduced porosity due to mineral deposition. Figure 8 shows the elevation of the resistive basement. The basement is found under most of the survey area. It is above 200 m below sea level in the wellfield in the **SW** external rift and at the end of Ghoubbet, but at about 300 m below sea level in the **NW** part of the inner rift. The depth increases rather sharply towards an anomaly under and to the south of Lava Lake, where the basement is found to be absent.

The absence of the resistive basement is not likely to be due to greater depth to the chlorite zone. More probably, it is due to higher porosity and permeability. Tectonic activity in the inner rift probably maintains relatively high permeability in the upflow zone. At the margins of the geothermal plume, on the other hand, mineral deposition is intense enough to keep permeability low despite the active rifting. The anomaly is therefore thought to delineate an upwards convecting plume of geothermal fluid. This hypothesis is supported by the fact that the anomaly correlates with the fumaroles at the surface. The absence of fumaroles over the northern part of the anomaly could indicate that the convecting geothermal plume is locally disturbed by a flow of relatively cold seawater from Ghoubbet and through the barrier.

CONCLUSIONS

On the basis of the resistivity structure discussed above, the geological structure of the Asal Rift, and experience from investigations of high-temperature geothermal fields in the rift zones of Iceland, the following model is proposed for the geothermal activity in the central **Asal** Rift.

In the area between Ghoubbet al Kharab and Lake Asal, there is a general underground flow of seawater towards Lake Asal along the rift zone, driven by the pressure difference between the sea level and the level of Lake Asal. Below Lava Lake this general flow is interrupted by a local upflow of geothermal fluid, mainly along open fissures connected to the active faults. This upflow creates an anomaly in the water level causing it to rise above the sea level. The conclusion of an upflow zone in Lava Lake is supported by the presence and the distribution of fumaroles, and by the absence of high resistivity at depth.

The impermeable barrier **just** west of Lava Lake is thought to be due to precipitation of secondary minerals from geothermal fluid. There is a large pressure drop across this zone. Hot water migrating through the barrier along fractures is likely to flash, due to the pressure release, causing precipitation of minerals that further strengthen the barrier. The steam from the flashing will move upwards, condense, and create a partially saturated layer, which appears as a layer of intermediate resistivity.

Above the upflow zone there will also be precipitation of minerals from the ascending geothermal fluid, reducing the porosity of the rocks. Since the rift is tectonically active, secondary porosity and permeability are probably maintained along faults and fissures, however. The mineral deposition is much more intense at the margins of the upflow zone and manages to maintain low permeability around the plume in the active rift, by a process known as self sealing.

Finally, the following explanation is suggested for the observed nonequilibrium between the alteration and the present temperature in well Asal-5: In the geologically recent past, perhaps until approximately 200,000 years ago, the main activity in the Asal Rift was associated with volcanic axes that do not necessarily coincide with the present axis (the inner rift). One of those is represented by hyaloclastite formations in the vicinity of wells Asal-1, 2, and 3. At that time the fossil alteration in the inner rift, as revealed by well Asal-5, was already present, and the top of the smectite alteration zone was close to the surface, as in wells Asal-1, 3, and **6.** When the inner rift opened up with intense fracturing, the area affected was cooled down by the flow of cold water (during pluvials) or seawater (during interpluvials) along these fractures between Ghoubbet al Kharab and Lake Asal. The area subsided and new basaltic lava was formed on the surface, which is represented by the uppermost unaltered rocks in well Asal-5.

As time passed, the volcanic activity, reaching its maximum at Lava Lake, led to a formation of a convective geothermal system, probably in response to a localized concentration of intrusions. The upflow part of the system is below Lava Lake, and a self sealing process, caused by precipitation from geothermal fluid, has created a hydrological barrier around the upflow zone. Crustal movements in rifting episodes cause the barrier to break **up** along some of the faults and allow some geothermal fluid to escape. The temperature maximum at 500 m depth in well Asal-5, as well as the narrow tongue of low water level running from **NW** and into Lava Lake, are considered to be due to such leakage along faults through the barrier.

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