THE ASAL GEOTHERMAL FIELD (REPUBLIC OF DJIBOUTI)

H. Correia, C. Fouillac, A. Gerard and J. Varet

B.R.G.M. — Energy Division
B.P. 6009
45060 Orleans Cédex France

ABSTRACT

The Asal region is located along the rift connecting the Red Sea to the Gulf of Aden through Afar. It is a typical segment of the rift valley characterized by active tectonic, seismic, volcanic and hydrothermal activity. For this reason it was selected by BRGM in 1970 as a target for geothermal exploration. Data collected during exploration and drilling of this area have enabled us to draw a model of the geothermal system. A tholeiitic magma chamber at a temperature of 1,200 °C located at a depth of 5 to 8 km is overlain by a fractured system where brine circulates in chemical equilibrium with the basalt. This system is locally overlain by dry steam zones in the most fractured central part of the system. Superficial water of meteoritic origin circulates in the upper part of the system, on the margins of the rift, whereas sea water circulates along the open fissures of the rift axis from the Ghoubbet to Lake Asal.

The Asal geothermal field can support an installed capacity of several tens of MW, far above the needs of the Republic of Djibouti. Preliminary production tests show that separation conditions can be found allowing us to master silica and sulphide scaling problems. Cu, Zn, Pb and Ag deposited by the fluid may also have an economic value.

INTRODUCTION

Asal was described as a segment of the world oceanic rift system by earlier investigators. Its geothermal potential was then studied by BRGM through geo-volcanological (Stieltjes, 1973), geochemical and geophysical techniques (Lopoukhine, 1973; Stieltjes and others, 1976), and drilled by deep wells. One of the wells (Asal 1) encountered a productive geothermal reservoir of 260 °C at 1,020 m depth. New geophysical and geochemical surveys have been performed in the area since the 1979 Ardoukoba eruption (Anis and others, 1979), enabling us to draw a model of the geothermal system. Production tests carried out since allow precise representation of the chemical characteristics, origin and conditions-of-production of the fluid.

GEOGRAPHY

The Asal geothermal system is located in the isthmus between Lake Asal and Ghoubbat al Kharab (Figures 1 and 2) at a distance of about 120 km from Djibouti. Altitudes range from -151 m at Lake Asal to +300 m at the highest point of the rift valley floor. The area is bounded by the high plateaus of Dalha to the north (above 1,000 m high) and by 400 to 700-m-high plateaus to the south, which separate Asal from the Gaggade and Hanle sedimentary plains.

The region is arid and desertic, with an average rainfall of 79 mm per year. Hydrogeological studies of the region show a general ground flow of water towards Lake Asal, which is the lowest point of the area and is occupied by a salt lake saturated in sodium chloride and calcium sulfates (Lopoukhine, 1973). The area is controlled by faults of northwest-southeast direction, with well expressed young tectonics, still active at present (Ruegg, Lepine and Vincent, 1980).

Geothermal exploration was performed within the rift, considering:

- the high heat flow expected near the rift axis due to geodynamic and volcanological considerations,
- the intense distensive fracturing affecting the area, which increases the permeability of a young basaltic crust already permeable, and
- the number and intensity of hydrothermal activity (hot springs, hot grounds, fumaroles and steam vents) in the area.

GEOLOGY

The Asal area constitutes a typical rift valley of oceanic type, with a much developed graben structure displaying axial volcanism (Barberi and Varet, 1977; Barberi and others, 1975; Stieltjes and others, 1976). It is exclusively built of volcanic materials, dominantly tholeiitic basalt flows, with minor occurrences of scoria and hydroclastic cones (Stieltjes, 1984). Lavas range in composition from transitional basalts to iron-rich differentiates, with abundant porphyritic lava, rich in large-size bytownites, among the youngest products of the rift axis (including the Ardoukoba eruption of 1979) (Figure 3). Mineralogical and petrological studies performed on these rocks show that crystal fractionation occurred at a depth of 5 km and a temperature of 1,200° C (Bizouard, Clochiatti and Marinelli, 1980) in a magma chamber located on the rift axis (Figure 4).

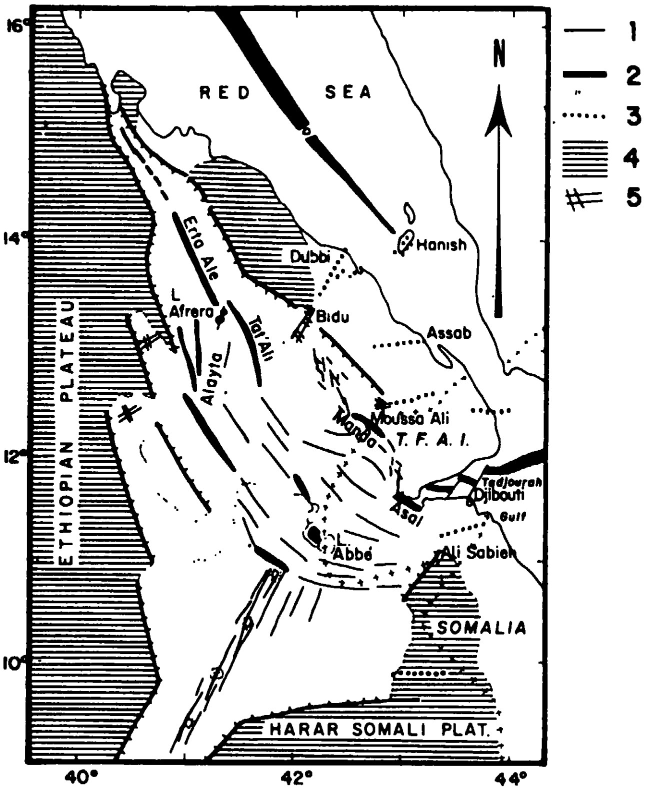

Figure 1. Structural scheme of the Afar region, with location of the Asal rift. 1=major faults; 2=axial volcanic ranges of tholeiitic affinity; 3=transverse volcanic ranges of alkaline affinity; 4=out-cropping crystalline basement (thinned crust); 5=crustal volcanoes located at the intersection of tectonic directions

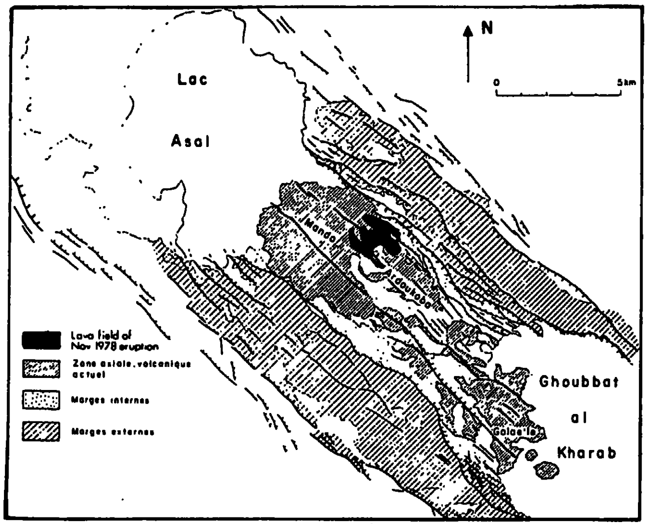

Figure 2. Simplified geological map of the Asal rift showing the various volcanic units of the rift floor younger than 1 million years (after Stieltjes and others, 1976)

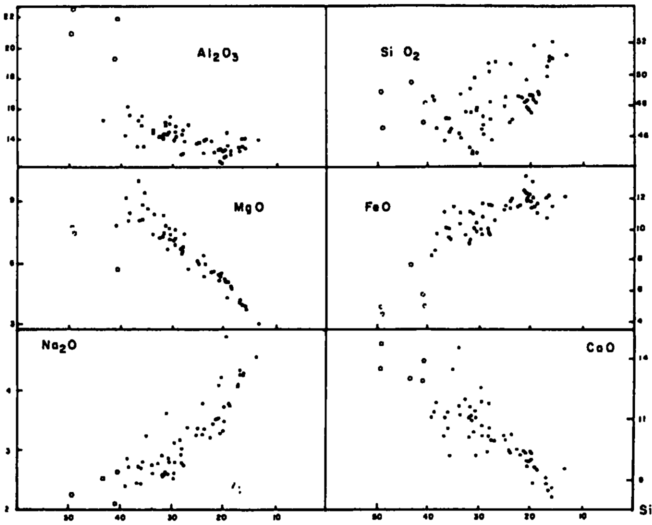

Figure 3. Chemical variation of the lavas of the Asal rift floor; major elements are plotted versus the Solidification Index (Steiltjes and others, 1976)

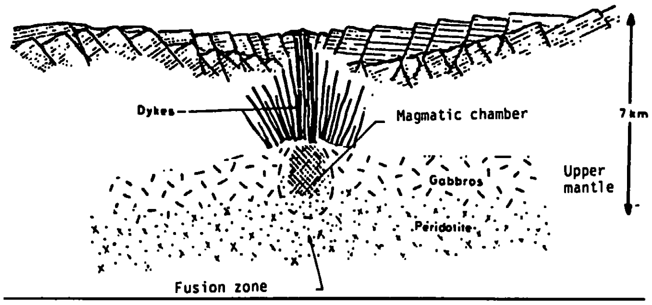

Figure 4. Schematic of the volcano-tectonic system of the Asal geothermal field (Steiltjes and others, 1976)

Geology also indicates that the area is undergoing a dome-like deformation visible both along and across the rift axis (Stieltjes, 1973). Recent geodetic measurements confirm that this movement is still active at present and corresponds to a center of deformation located 5 to 8 km deep.

Extensive tectonics affect the whole valley in the floor, with well-developed open fissures and normal faults. The high permeability of the area is also shown by the intercalations of fractured basalts and scoria visible along recent fault scarps.

GEOCHEMISTRY

Several hot waters issue in the rift area. Their emergence temperatures range from 40 to 80 °C. Some very low discharge vents of dry air and steam, heated to 140° C by underground circulation, can also be sampled. Chemical and isotopic studies have been performed on the spring samples the locations of which are shown in Figure 5.

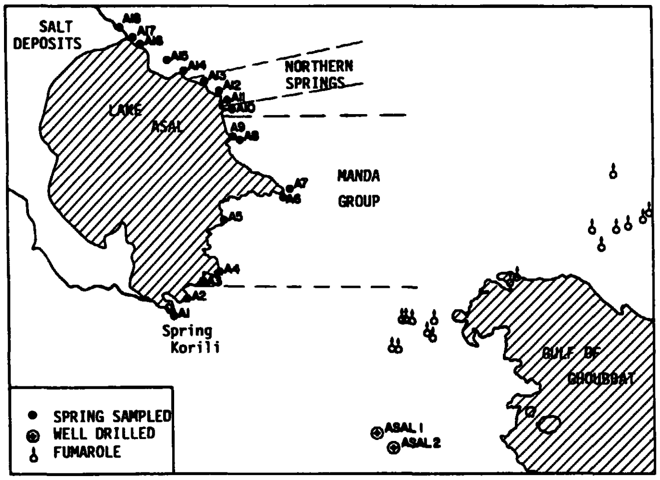

Figure 5. Locations of geochemical samples

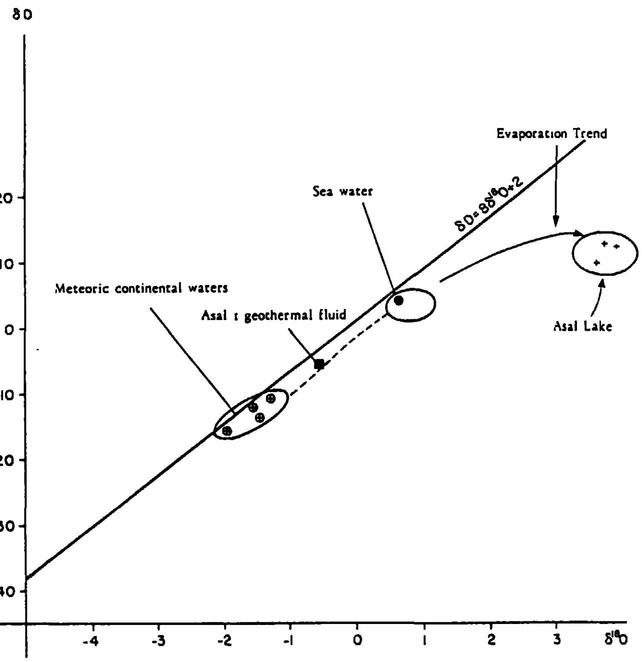

Figure 6. Oxygen isotope composition of the Asal hydrothermal system (Lundt and Fouillac, in preparation)

Complete analyses of the deep geothermal brine discharge at 120 Tons/hour at Asal 1 have been performed during well tests in 1981 (Table 1). The isotopic properties of the various water types are summarised in Figure 6.

On the basis of their chemical and isotopic composition, the natural springs can be classified into three groups:

(1) The Manda group (samples A3 to A9) is almost normal seawater coming from the Gulf of Ghoubbat and being slightly heated by circulation through the intensely fractured basalts,

(2) The northern springs (samples A11 to A13) are of continental origin, as evidenced by their isotopic composition. Their very high TDS content is supposed to be gained by leaching of evaporitic deposits randomly occurring in the area. Chemical geothermometry gives fairly consistent estimates near 200° C,

(3) Sample A1 is also a water of continental origin, with a TDS value slightly less than that of sea water.

The other spring samples of the area seem to be formed by the mixing of two of the pure end members defined above or by mixing between one pure end member and the Lake Asal alkali-chloride brine. The origin of Asal 1 geothermal brine can be predicted using the δ D-δ^{18}O diagram of Figure 6:

— the geothermal fluid is not produced by the evaporation of sea water as is the Asal Lake Na-Cl brine

— the geothermal fluid could not have been produced by the mixing of sea water and Asal Lake.

On the contrary all the geochemical-correlation tests that we have drawn suggest that Asal geothermal fluid originates by mixing of sea water and high-TDS continental water of meteoritic origin. In the absence of a significant ^{18}O positive shift, considering the high temperatures involved (260° C), we can consider that the fluid-to-rock

Table 1. Chemical and isotopic composition of representative waters from the Asal area (values are in millimoles per kg)

Samples	Temp. °C	Na	K	Ca	Mg	Li	Cl^-	SO_4^-	HCO_2^-	SiO_2	δD ‰	δ^{18}O ‰
Lake ASAL	32	4,120	121	61.6	472	0.8	5,190	44.1	2.05	1.1	(4)	(4)
Spring A1	81	413	11.3	77.3	16.3	0.3	581	3.12	0.47	0.28	-1.18	-1.6
Spring A12 (1)	80.3	1,000	56.5	254	36.6	1.24	1,610	16.7	0.40	1.6	-1	-1.3
Spring A7 (2)	30.5	552	12.4	14.1	56.8	0.03	632	3.3	31.2	0.30	0.37	0.9
ASAL Fluid (3)	255	1,240	125	410	0.98	1.9	2,200	0.21	0.32	8.57	-5.5	-0.6

(1) Spring A12 is representative of northern springs
(2) Spring A7 is representative of Manda springs
(3) Deep fluid chemistry recalculated taking steam separation into account
(4) Values variable depending on sampling depths and location

ratio is high in the reservoir. The chemical composition of the brine reflects chemical equilibrium at temperatures between 249 and 260°C, in close agreement with the measured bottom hole temperatures (250 to 260°C).

INTERPRETATION OF WELL-TEST DATA

A more detailed study of the physico-chemical properties of the fluid discharged by Asal 1 under different well-head conditions revealed the following points:

(1) The heavy metal content of the brine (Fe, Mn, Cu, Zn, Pb and Ag) is high.

(2) When operating the discharge with different diaphragm diameters, the recorded well-head temperature and pressure vary. As temperature drops, the concentration factor of dissolved species caused by flashing, and possibly variation in the pH of the liquid induces metal sulfide scaling according to:

$$Me^{2+} + S^{=} \rightleftarrows \underset{\downarrow}{\underline{Me\,S_2}}$$

The following Me sequence is observed, with decreasing temperature: Pb, (Cu, Zn), Fe.

(3) For the higher diaphragm diameters, corresponding to the lower temperatures, heavy silica scaling is observed.

The various drill tests have clearly shown that, provided a sufficient well-head pressure (15 bars) and temperature (180°C) are maintained, neither sulfide nor silica scaling will occur in drill pipes. It is then possible to maintain long-term production and operate mineral-deposition equipment at the surface.

Technical and economic interest in the mineral recovery from the brine should now be checked.

GEOPHYSICS

Geophysical surveys were performed on the Asal geothermal field between 1973 and 1982. They are of two types: regional surveys (airborne magnetometry, gravimetry, seismicity) and local surveys (E.M., D.C. resistivity, HF and LF magnetotellurics). Magnetic and gravimetry anomalies clearly show a magnetised and heavy intrusive axis going from Ghoubbat to Asal lake (Figure 7 and 8) with its southern part a possible transverse zone of faulting associated with the known reservoir.

Deep Surveys (magnetotellurics, D.C. resistivity mapping with 14 km long injection line) show a huge conductive structure, located on Figure 9. Interpretation of magnetotelluric soundings suggests that the mean depth to the top of the last conductive discontinuity is roughly 5 to 6 km. This is interpreted as the basaltic magma chamber, in good agreement with observed geothermal gradients (20 and 25°C/100 m) and with surface deformations.

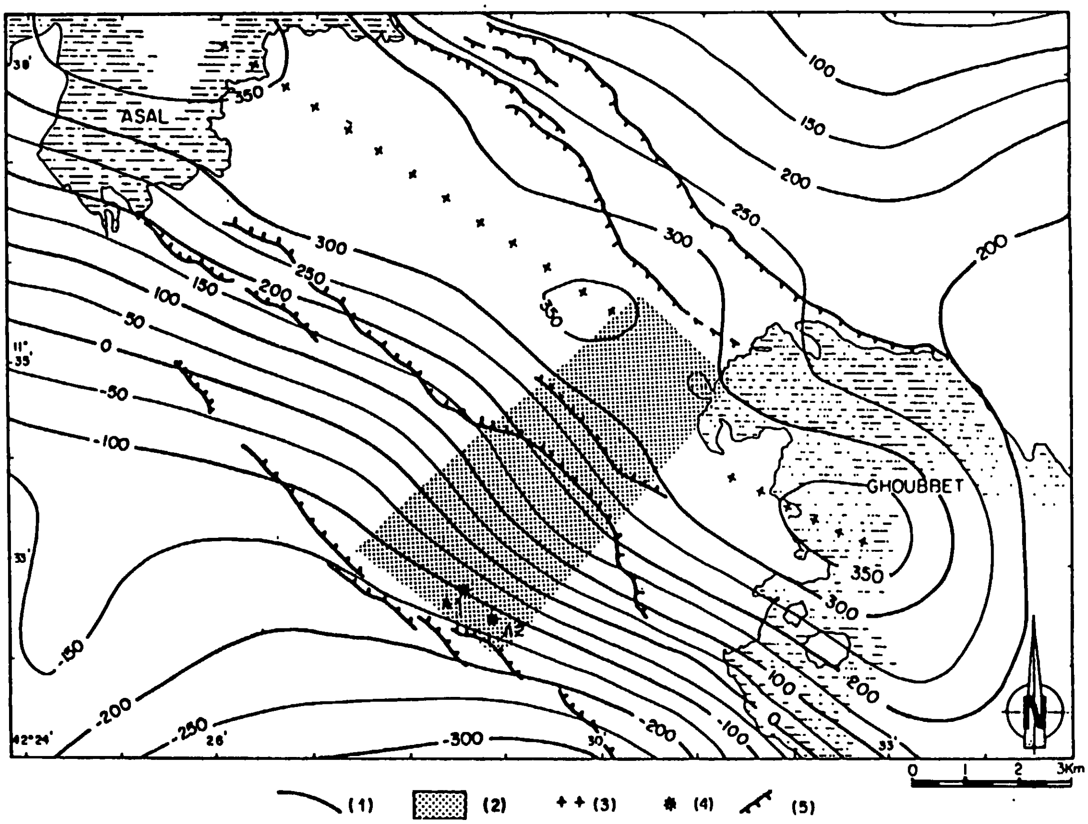

Figure 7. Aeromagnetic map of the Asal area, reduced to the pole. 1 = isogam curve (in nT); 2 = probable transverse fractured zone; 3 = axis of main magnetized structure; 4 = location of Asal 1 and 2 geothermal wells; 5 = major fault scarps.

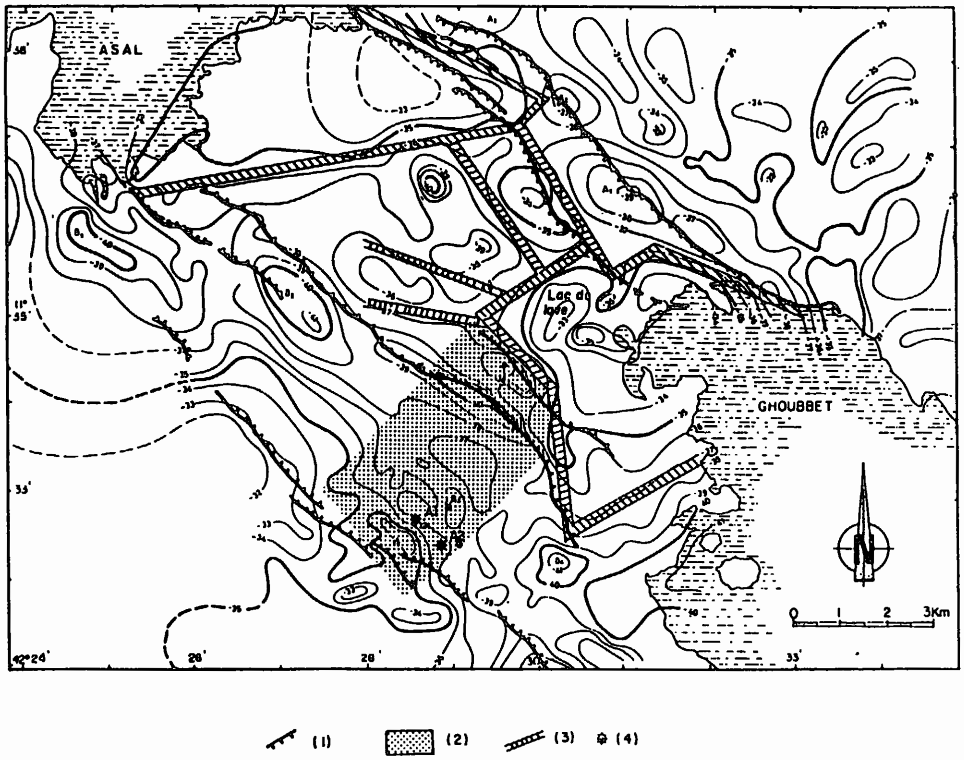

Figure 8. Bouguer gravity map of the Asal area (density 2.67). 1 = major fault scarps visible at the surface; 2 = zone of probable transverse fractures; 3 = limit of the heavy compartments inside the rift; 4 = location of Asal 1 and 2 geothermal wells.

Shallow Surveys (E.M. -Melos system-, Audio-MT) are strongly limited in penetration by the very conductive line induced by circulated sea water.

SYNTHETICAL MODEL

Having observed in boreholes Asal 1 and 2, hydrostatic level 200 m deep, a first high-temperature reservoir at shallow depth (150° C, 500 m) and a deeper brine reservoir at a depth of 1,000 m, which shows that these boreholes are located on the southern flank of the deep conductive body found by D.C. resistivity and MT, a maximum geothermal gradient of 35 °C/100 m can be expected in the central part of the conductive anomaly, with reservoir temperatures of 300° C at depths of 800 to 1,000 m.

Occurring in a very fractured medium (gravity data show a negative anomaly of -2 mgals associated with the main superficial fractures), such high thermic conditions favor the occurrence of a dry steam reservoir in the central part of the Asal geothermal field (pressure being between 60 and 80 bars at 800 m, and water boiling at 285° C under 70 bars).

The model in Figure 10 shows that the geothermal reservoir encountered at Asal 1 extends and thickens towards the rift axis where dry steam may be encountered at accessible depth.

CONCLUSIONS

Asal 1, although allowing commercial production of steam after separation of brine and solid deposits above the well-head, is not representative of the more favourable production conditions that should be encountered in the more central part of the Asal geothermal field where more productive reservoirs displaying better characteristics, including dry steam, are shown to occur.

Economic considerations show that Asal geothermal field is capable of a production of electricity at a price competitive with fossil-fuel alternatives either for local industrial developments or for replacement of presently oil-driven electricity in the Djibouti capital.

ACKNOWLEDGEMENTS

The Asal geothermal exploration programme was funded by BRGM, French Ministry for Foreign Affairs, Cooperation and Development State Secretariat and UNDP. We thank ISERST, Dr. Anis Abdallah and Djibouti authorities for their sustained interest in geothermal developments.

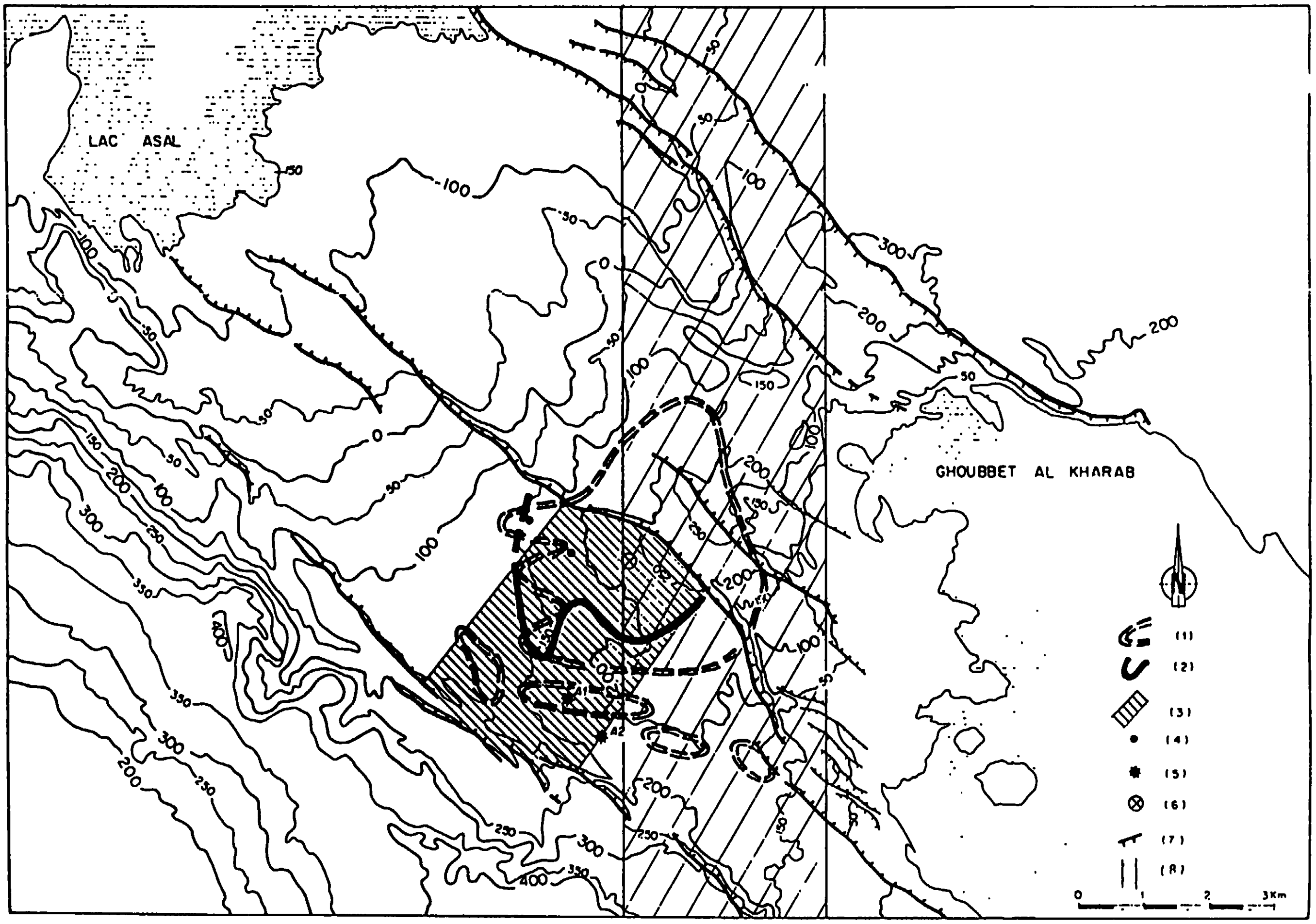

Figure 9. Contours of major geophysical structures, reported on IGN topographic base (50 m contours). 1= contours of the main conductor (rectangle method); 2= contours of the main MT 5 ex conductive anomaly; 3= transverse fractured zone deduced from magnetic and gravity anomalies; 4= phreatic water; 5= Asal 1 and 2 geothermal wells; 6= proposed site for the next geothermal well; 7= major fault scarps visible at the surface; 8= area of major seismic activity.

REFERENCES

Anis, A.M., and others, 1979, Nature, v. 282, p. 17-23.

Barberi, F., Ferrau, G., Santaccroce, R., and Varet, J., 1975, Schweizebart, Stuttgard, p. 38-54.

Barberi, F., and Varet, J., 1977, Geological Society of America Bulletin, v. 88.

Bizouard, H., Clochiatti, R., and Marinelli, G., 1980, Bulletin Soc. Geol. Fr., v. 22, p. 845-850.

Lopoukhine, M., 1973, BRGM Report 73 SGN 139, GTH.

Ruegg, J.C., Lepine, J.C., and Vincent, C., 1980, Bulletin Soc. Geol. Fr., v. 22-6, p. 917-924.

Stieltjes, L., Joron, J.L., Treuil, M., and Varet, J., 1976, Bulletin Soc. Geol. Fr., v. 22, p. 837-844.

Stieltjes, L., 1973, Thesis, Orsay University.

——— 1985, Geological map of Asal rift (1:50,000): BRGM (in press).

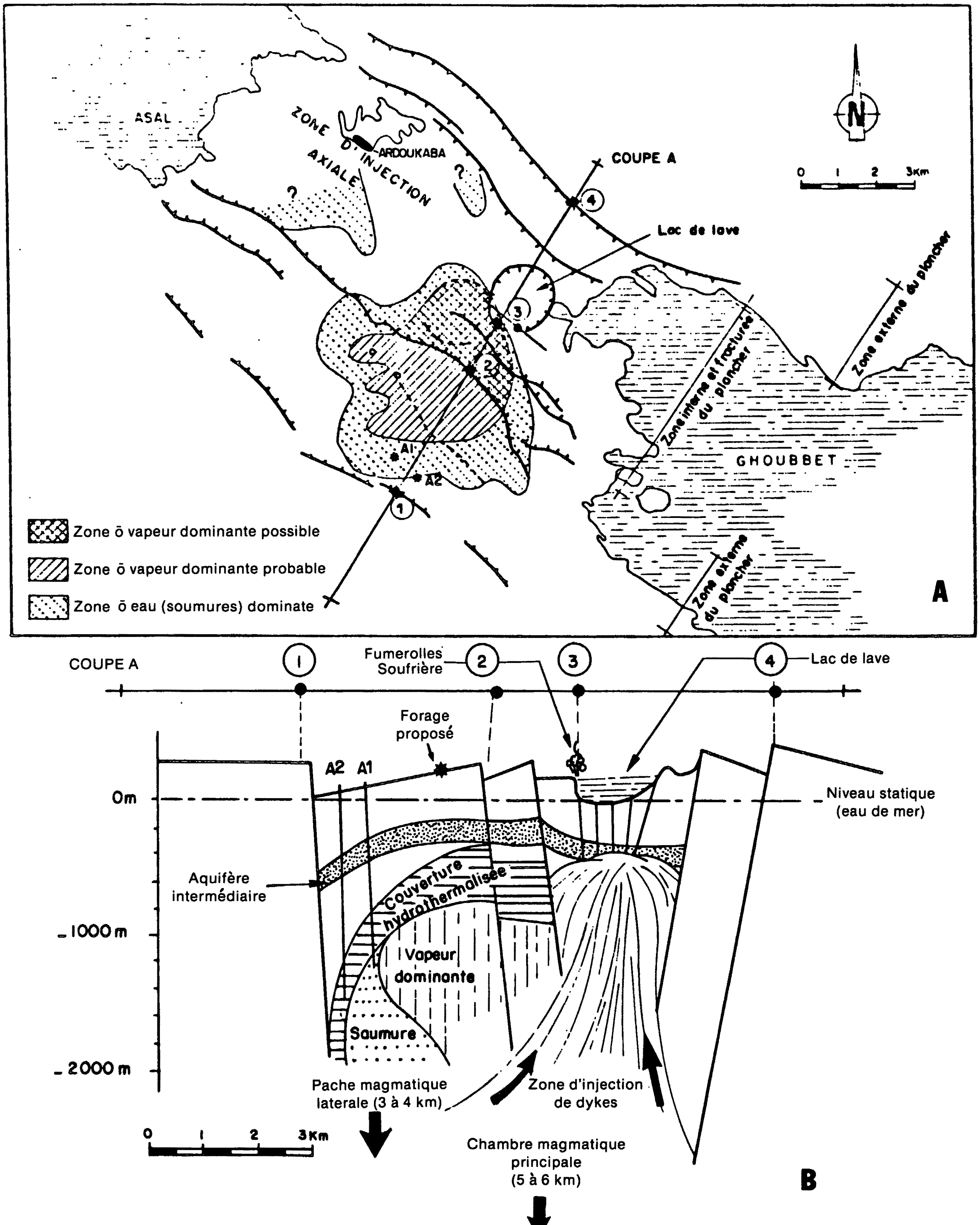

Figure 10. Model proposed for the Asal geothermal field. (A) Map of the geothermal reservoir, with brine dominant (dotted pattern) and steam dominant (diagonal pattern) areas. (B) Cross section of the geothermal field, with location of Asal 1 and 2 geothermal wells, and of proposed future exploration well.