Proceedings 5th African Rift geothermal Conference
Arusha, Tanzania, 29-31 October 2014

Asal-Fialé geothermal field (Djibouti republic): A new interpretation for a geothermal reservoir in an actively spreading rift segment

Jacques Varet
Geo2D
j.varet@geo2d.com

Keywords: Feasibility, Asal, Rift, Caldera, magma chamber, geothermal reservoir, sea water

ABSTRACT

A new interpretation is proposed for the Fialé geothermal site located in the active Asal Rift, the first emerged segment of the Aden-Red Sea rift entering in the African continent through the Gulf of Tadjoura (Republic Djibouti). While a feasibility study is being engaged by the national company Electricity of Djibouti (EDD) with the support of a consortium of Public Banks lead by the World Bank, including 4 deep wells drilling and testing with the objective of further development for a 50 MWe plant through IPP, a new Fialé geothermal field model is proposed. This is based on detailed analysis of the seismo-tectono-volcanic event which affected the axial part of the Asal-Ghoubbet active rift in the period 1978-2005 and its consequences on the hydrogeology and heat source evolution. This hypothesis is presented here in view of enlightening the stakeholder as it has a direct impact on the geothermal drilling program to be engaged in the coming months.

1. INTRODUCTION

The aim of this paper is to present a new interpretation of the Asal geothermal field while a feasibility study is presently being carried out on the Fialé site, designed to release the remaining risks before a commercial program of electricity production can be implemented through an IPP under favourable economic conditions. The Asal site is located 120km away from the capital of Djibouti (World Bank, 2011). Note that while Djibouti is a small country, with a total population of less than one million inhabitants, the port of Djibouti is very active and fast growing as it is the main connection to the outside world economy for Ethiopia, a fast growing country with 80 million inhabitants. In addition to the present asphalted road and an old railway line (the century old "Chemin de Fer Franco-Ethiopien" now out of use), a new electric railway line is being built connecting Addis-Abeba Dire-Dawa and Djibouti. This ambitious geothermal program (totalizing US$32M and lasting about 3 years) is financed by a public banking consortium led by the World Bank (with the OFID, AfDB and AFD). Evidence of 4 deep, deviated wells, productive and long lasting certified tests of the reservoir(s) are deemed necessary in convincing investors to further develop the geothermal power projectof 50MW, in response to the needs of the base load of the Djibouti electric distribution network.

2. BACKGROUND

It was shown byTazieff et al. 1972, Barberi et al. 1970, Varet, 1975, 1978 that Asal is the easternmost axial basaltic ranges of the Afar depression, (including from NW to SE: Erta Ale, Alayta, Manda-Harraro, Manda-Inakir and Asal, Figure 1) where the present spreading mechanism operating in the Arabian-African plate separation – with a 2 cm per year average speed - is visible at the earth's surface. This early basic geological work facilitated the geothermal exploration program engaged by BRGM (1970, 1973) in Djibouti and the quick identification of the Asal Rift as a target of major interest. Geological, hydrogeological and geophysical surveys enabled proposing a model in which the shallow anomalous hot mantle along the Asal-Ghoubbet Rift was to provide an efficient heat source with additional supply from a shallow magma chamber underneath the central part of the Asal shield Volcano.

Deep exploration drilling have been engaged in 2 phases (BRGM 1975a,b; AQUATER 1989), so that altogether six deep wells were drilled in the Asal rift with depths ranging from 1137m to 2105m. A1, A3 and A6 are in the same area, located on the SW faulted block inside the rift but away from the active volcanic axis and sea water regularly flowing from the marine gulf of Goubbet to lake Asal (-155masl) through the open faults of the tectonic axis (Figure 2). A4 and A5, located toward the central part of the rift, encountered the superficial underground sea water flow towards Asal between 250m and 280m followed by a rapid temperature increase in the hydrothermalized caprock, but did not reach any productive geothermal reservoir. A3 and A6 temperature profiles are almost similar (Figure 3), with one intermediate medium temperature reservoir and one deep high temperature reservoir. The deep high temperature reservoir was of 263.5°C and 280°C respectively. No deep reservoir was encountered by A4 and A5, despite greater depths, and rather low permeability was encountered, with bottom-hole temperatures reaching 345°C and 359°C, respectively.

It appears that all the six wellsencountered a similar strong increase in temperature at depths ranging from 240m to 600m. This was followed deeper by lower temperature increase indicating the convective behaviour of a geothermal reservoir as seen in Figure 3. The geophysical data correlates with the well logs in suggesting a certain continuity of that impermeable horizon, a clay dominated conductive layer that constitute the cap of a reservoir present in the whole Asal rift area (Fig. 4), which is not the case for the deep reservoir (CFG 1993; ENEL 1990; ORKUSTOFNUN 1988; Jalludin 1992). Despite the fact that this reservoir was never properly tested, its salinity was estimated to be around 50g/l. (ENEL 1990)

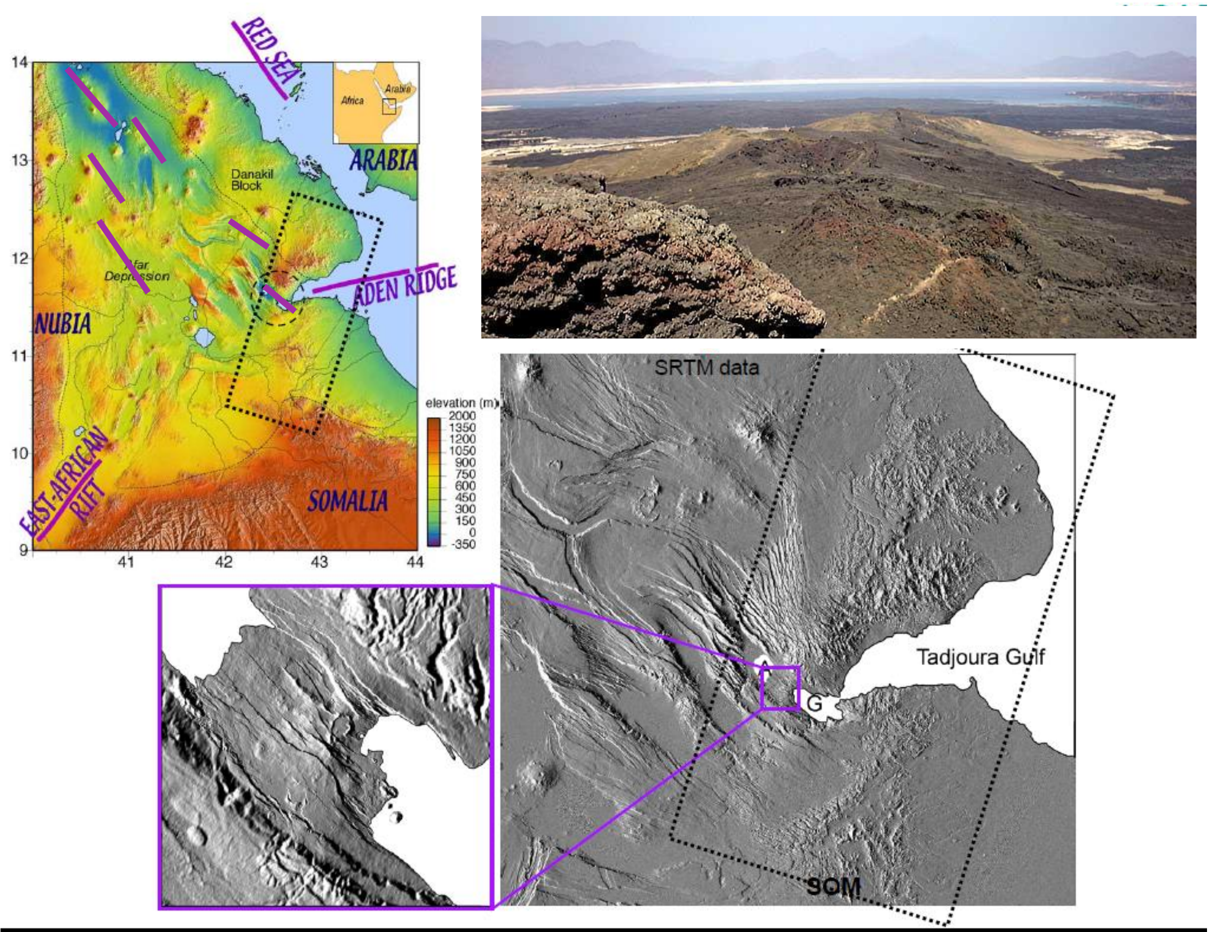

Fig.1: Location of the Asal geothermal site at the first emerged rift segment in SE Afar, where the axial volcanic ranges (in violet) meet the Aden ridge through the Gulf of Tadjoura and the Ghoubbet Bay (G). Photo: the Ardoukoba craters and fissure eruption.

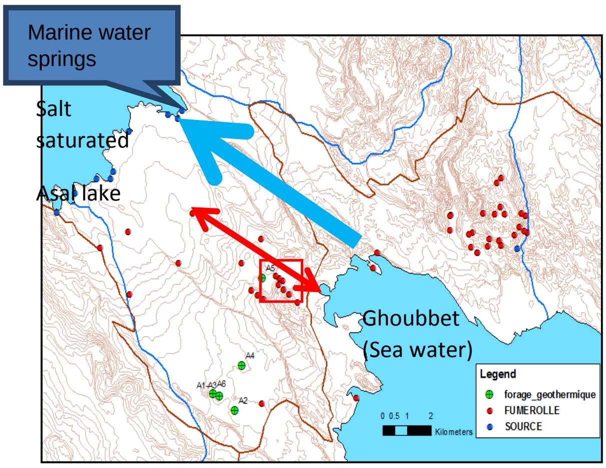

Figure 2: Location of the drilled sites (in green, numbered) and main fumaroles of the Asal rift on the topographic map. The first wells (A1 to A3) and later A4 et A6 were drilled on the SE side of the rift, at a fair distance from the active volcanic axis of the rift (double red arrow) as well as from the sismo-tectonically active along which an important ground sea water flow cross through from Ghoubbet to lake Asal (blue arrow). The site of the present feasibility project is the red square.

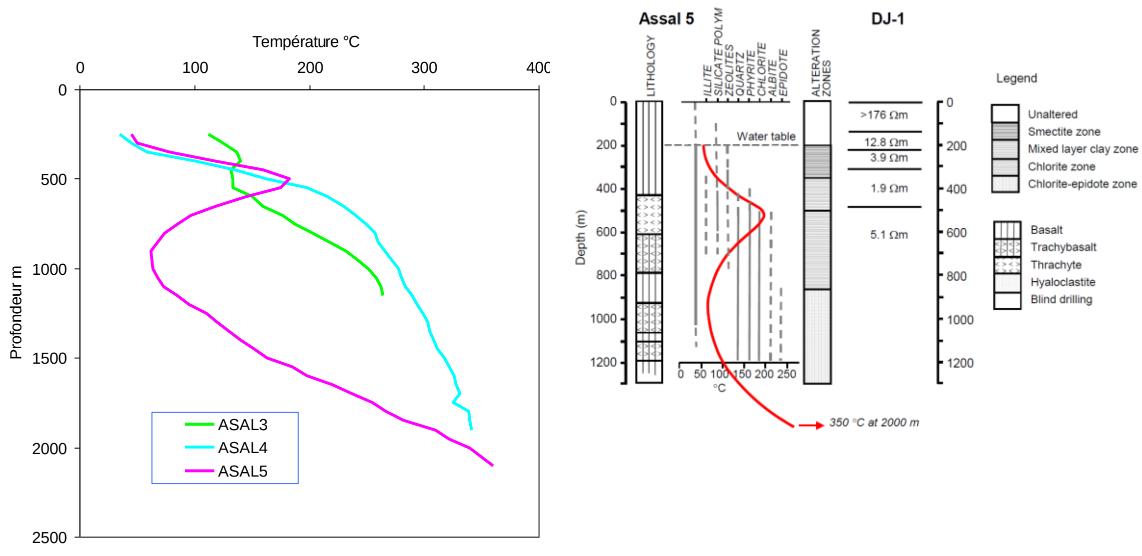

Figure 3: Temperature profiles measured in the Asal wells A3 to A5. Note the inversion of temperature observed in the A5 well drilled in 1988 immediately NW of the Fialé caldera (Source: Jaludin, 2003). Note also that the hydrothermal mineral sequence matches the resistivity profile but not the temperature profile indicating an inflow of cold sea water as observed by Anarson & Flovenz, 1995)

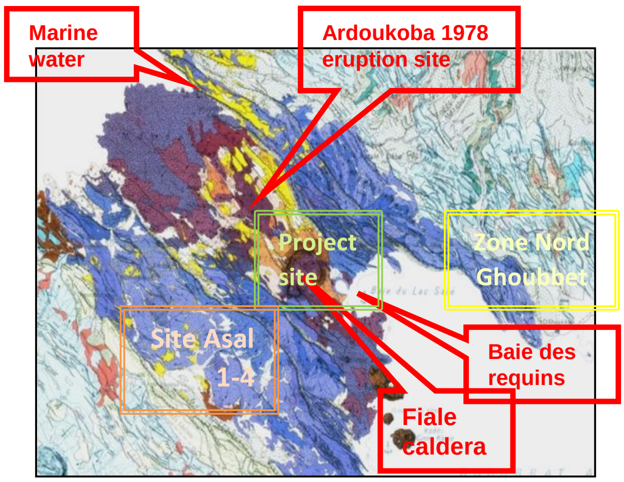

Figure 4: Geological map of the Asal Rift (Stieltjes, 1978); hyaloclastites are in orange, recent basalts in deep blue and violet whereas early rift basalts (300.000 - 100.000 y.) are in pale blue; the stratoid series (3 to 1 My) is in very pale blue colour. Lacustrine deposits (diatomite) in yellow.

A new geophysical survey combining TDEM and MT methods engaged by ISOR for Reykjavick Energy Invest (2008) enabled the elaboration of a new conceptual model taking into consideration available data including the results from the previous deep drilling. This allowed for siting the 4 exploration wells in the central part of the rift axis within Fiale caldera and its immediate surroundings. After REI withdrew its interest in the project. the programme was taken as a base of reference for the World Bank to propose the feasibility study presently being engaged. Following these references, the 4 wells have been planned to be drilled up to a depths of 2800m with large production diameters (9 inches) and deviated in the reservoir (below 2000m) in order to maximise the chances to intersect open productive fissures supposedly vertical in this axial part of the rift.

3. OBSERVATION OF THE RESULTS OBTAINED AT A5

Since well A5 is the only one drilled yet in the Fialé caldera and its immediate surroundings, it is of interest to have a further look at the results obtained there. This well was drilled in 1988 by Aquater and display a particular profile, with a strong temperature inversion. While the temperature increases sharply between 300 and 500m, reaching 185°C, it decreased to circa 60°C down to 1000m from where it increased again to 359°C. The well was terminated at 2105m, as there were no deep reservoir encountered.

A striking fact is that the hydrothermal mineral assemblage is in good agreement with the measured temperatures in all wells (Zan et al. 1990), except for A5. This well show a high temperature chlorite-epidote assemblage in the area subjected to the important temperature inversion (Fig. 3). This can be interpreted as the invasion of cold sea water in a pre-existing, well developed, high temperature reservoir, which should have existed at a depth of 500 to 1000 metres. Another point of observation is that between 1100m and 2105m, the increase of the temperature is rather linear, ranging from 100 to 259°C, which leaves no room for a deep geothermal reservoir as the basaltic magma chamber is known to be at shallow depth as shown by the precise 3D mapping of the seismic events encountered in the period 1978-2001 (see Fig.9 and 10 below).

4. DISCUSSION OF THE FIALE GEOTHERMAL SITE MODEL IN LIGHT OF THE SISMOVOLCANIC CRISIS (1978-2005)

The Asal volcanic and tectonic range display a typical rift structure with a shield volcano dissected by faults having emitted a continuous petrologic series from tholeiitic basalts to ferrobasalts by crystal fractionation of olivine and bytownite at shallow depth (Stieltjes et al.1976) indicating possible presence of a magmatic heat source at shallow depth. De Chabalier & Avouac (1994) showed that the Asal shield volcano was built in the last 300,000 years and was subjected to successive rifting episodes, the extension of 17 to 29 mm / year along a 40° North direction being regularly compensated by magma injection.

Whereas a precision levelling of 200 benchmarks was established in 1973, along a 100 Km traverse across the rift, no deformation was observed until the 1978 tectono-volcanic event, a seismic crisis including strong faulting (Fig. 5) and the eruption of Ardoukoba volcano along the axis of the rift (Demange et al. 1979,). The central part of the traverse was measured again in 1979 just after this event and did show an opening of 1.9 metres in the inner part of the Asal graben (Ruegg et al., 1979). In the winter of 1984-1985, new sets of geodetic measurements were carried (Ruegg & Kasser, 1987) which did show that continuous extension occurred at a rate of 6 cm a year during the following decade. Further measurements showed that since 1987 the rift opening speed drastically decreased to 1cm a year (fig.6).

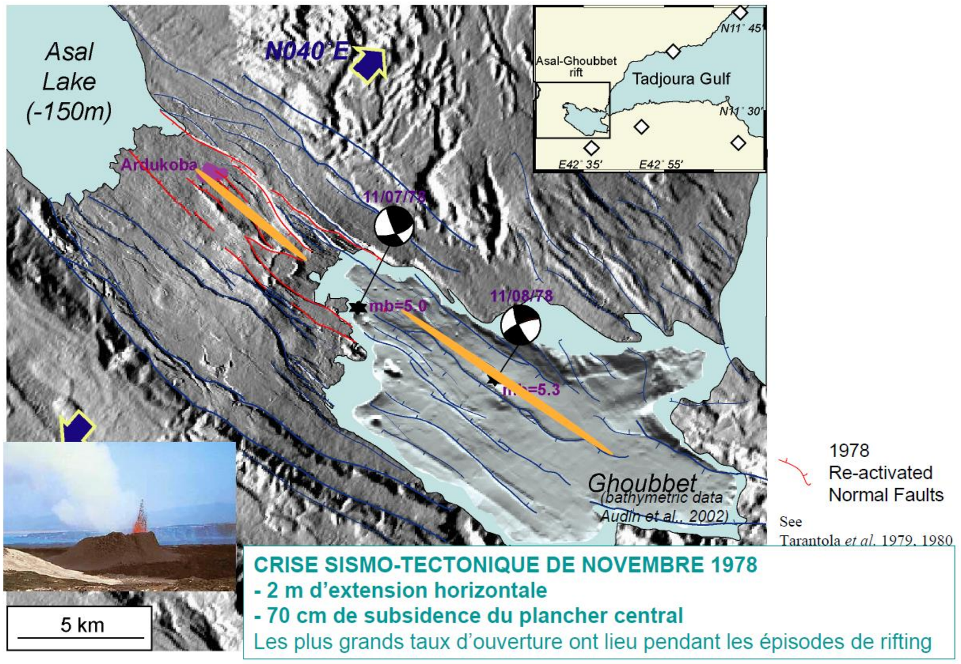

Fig. 5: The sismo-tectonic crisis of November 1978: 2 metres of horizontal extension occurred along the Asal emerged rift segment as well as along the Ghoubbet gulf (shown in yellow). Fissures and faults along the inner rift (in red) were reactivated (after Doubre, 2006)

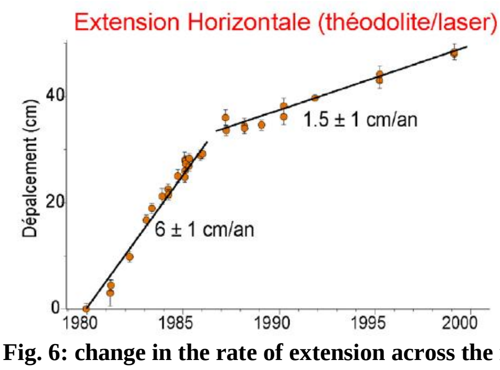

Fig. 6: change in the rate of extension across the rift occurring in 1988-1989, as shown by successive theodolite/laser measurements across the rift axis (Vigny et al. 2006)

GPS measurements were also carried which did confirm these data and précised the deformation occurring in the rift, with an uplift of the rift northern shoulder at a rate of 5-7 mm/year (Vigny et al., 2006). Within the rift floor, a contrasting behaviour was observed with the sinking at a rate of 2-4 mm/y, located in the “petit rift”, that is the tectonic axis north of the volcanic axis, whereas the central part of the volcanic axis at a mid-distance between Lake Asal and the Ghoubbet was shown to inflate at a rate of 8 mm/y.

It was also shown by Ballu et al. (2003) that the gravitational acceleration decreased in the central part of the rift axis between 1985 and 1999. This can be interpreted either as resulting from an uplift of the bedrock or as the result of a decrease of the density due to magma up-rise, and most probably for both reasons. These observations were confirmed by further radar interferometry studies using RADARSAT imagery covering the period 1997-2005 (Doubre, 2006). The processing of these images did show the uplift of northern shoulder of the rift and the downthrows of the normal faults that limit the inner rift floor. The inner part of the rift appears relatively stable except on the Fialé caldera western margin where an uplift movement is visible (Fig.7).

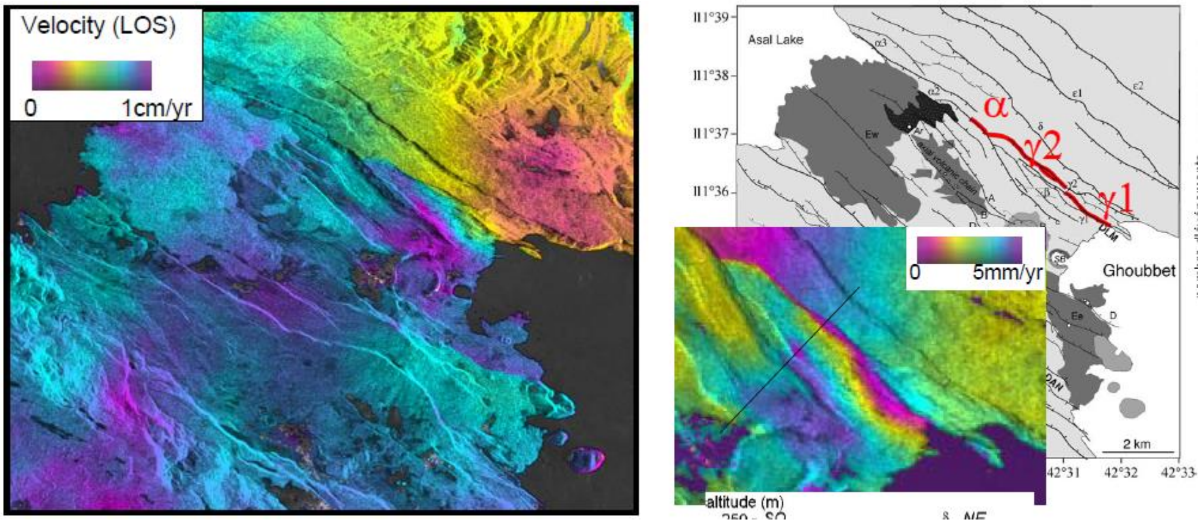

Fig. 7: Cumulative displacement measured by interferometry in the period 1997-2005 using RadarSat data (90 images). Observe the uplift of northern block, the sinking of the central floor (on the left) and the measured displacements on “petit rift” fault NE of volcanic axis (after Doubre, 2006)

This can be related to the seismic data which confirm the activity of the faults north of Fialé and show a spectacular concentration in the caldera itself in the period 1987-2001 whereas very few events were recorded in the 10 previous years following the Ardoukoba eruption (Fig.8).

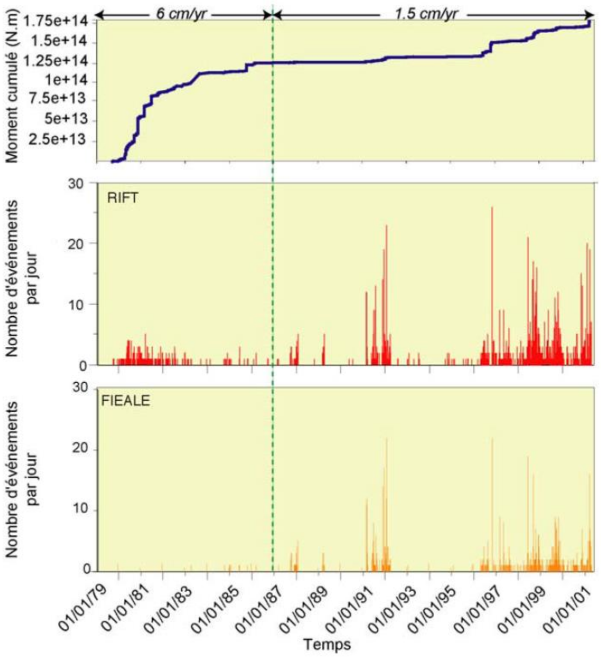

Fig. 8: Record of the seismic activity in the Asal rift in the period 1979-2001 following the 1978 sismo-tectono-volcanic crisis. Note that the change of seismic behaviour in 1987 corresponds with the change in the spreading rate (or cumulative moment) measured (Doubre et al. 2006)

One should underline here the two distinctive events which affected the Asal inner floor and more precisely the Fialé site during the last 40 years, and their consequence in terms of water circulation and heat release, of interest for us in view of its geothermal exploration and exploitation:

- The first period includes the Ardoukoba event and the following 10 years period (1978-1987):
    - It allowed for a modest basaltic eruption near to the NW extremity of the rift opening, showing a basaltic magmatic diking along the rift axis,
    - It mainly allowed for the brutal opening of the rift axis up to 2 metres in width at the level of the caldera;
    - This distensive tectonic event continued during the following 10 years at a rate of 6 centimetre a year allowing for more fissures to open;
    - As a consequence, the axial part of the rift floor, notably between the "petit rift" and the Ardoukoba-Fiale-Baie des Requins volcanic axis, was continuously filled by an accelerated flow of cold sea water descending from the golf of Ghoubbet towards the Asal lake 155 metres below.
- The second period is the Fialé caldera seismic event:
    - It occurred progressively in a distinct period, lasting 14 years, between 1987 and 2001;
    - It can be interpreted as resulting from the new infilling of magma underneath the "lava lake" of the caldera;
    - It allowed for a renewed magmatic heat source to become available at shallow depth.

Let us now specify the characteristic of this rather shallow seismic activity as observed on Fig. 9. It can be interpreted as resulting from the influx of sea water. Several elements support this interpretation:

- No seismic activity is recorded below 3 Km depth below the "lava lake", the recent surface volcanic feature which occupies the caldera floor,
- Whereas the depth of this aseismic roof tend to increase along the caldera walls and the caldera margins.
- The seismic activity is confined in a 1 to 2 Km depth interval, which can be interpreted as a zone of direct interaction between the hot rising magma and a faulted layer intruded by sea water.
- No seismic activity is recorded at shallow depth (less than 1 Km), eventually indicating a plastic (clay zone) hydrothermal cap.

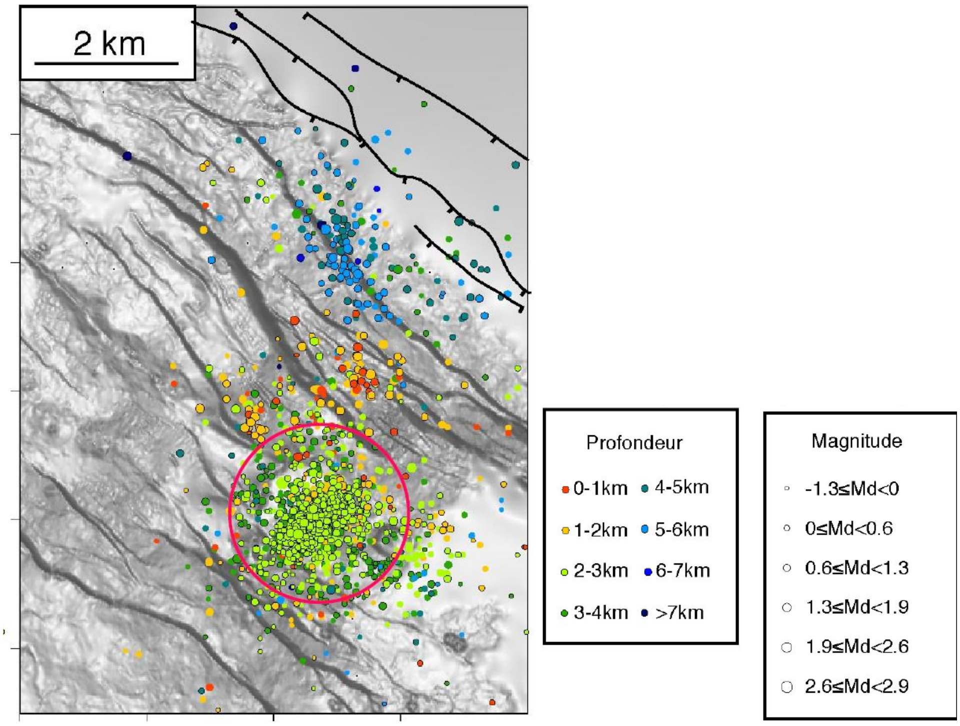

Fig. 9: Seismic activity observed in the Asal rift in the period 1987-2001. Whereas in the period 1978-1987, that is during the 10 years following the Ardoukoba event very limited seismic activity was observed in the Fialé caldera, this recent axial volcanic unit show a an important activity. Whereas very few events are recorded at shallow depth (0-2 Km) in the caldera centre where intense activity is measured in the 2-3 Km depth interval, the depth of the events appear to be deeper (3-4 Km) along the caldera walls and margins shallow events being observed N and E of the caldera. The absence of deep events below 3Km in the inner part of the caldera can be interpreted as resulting from the presence of a magma chamber below that depth. (Note that a distinct deeper set of events is observed along the fault bounding the rift margin where important vertical displacements are observed; differing from Fialé, this area was continuously active since 1978).

When the chronology of the seismic events is more precisely observed (Fig.10) it is possible to deduce that the brittle roof of the ductile aseismic mass migrated as a consequence of 5 events that can be interpreted as resulting from the displacement of the magma in the chamber. This correspond to a step-by-step up-rise of the basaltic magma, successively hitting the lower part of the sea-water table that did massively flow through the newly opened fissures of the rift axis during the first – dominantly tectonic – 1978-1987 period:

- The first of these events occurred in 1991 and affected an area located in the central part of the caldera at a depth of 3,5 to 2,5 Km and did hit and migrated up the caldera SW wall.
- The next (1996) event was located at a similar depth but affected and migrated up the NE side of the caldera.
- The 1998 event was located at the same depth in the central part of the caldera.
- In 1999, the brittle zone migrated upward, at a depth ranging from 2.2 to 3 Km maximum only
- The last event recorded in 2001 did show both a shallower depth (less than 2 Km) along the SE wall of the caldera and beyond toward Baie des Requins, as well as deeper events on the NW margin on the caldera and beyond in the A5 area.

The fact that the Fialé caldera is apparently presently quiet since the last 9 years indicates that the magma did cease to rise, and is in a process of slow cooling, with a surrounding high temperature magma-water contact zone that is now stabilized. As a consequence, important amount of heat is being dissipated in the surrounding rocks and geothermal reservoir(s). The reservoir that was invaded by cold water during the 1978-1987 period, as observed in A5 in 1988, has encountered several events of abrupt heating for 10 years (1991-2001) due to the vicinity of magma injection and is still subject since another 13 years to important heat dissipation from the huge mass of basaltic magma injected in that period.

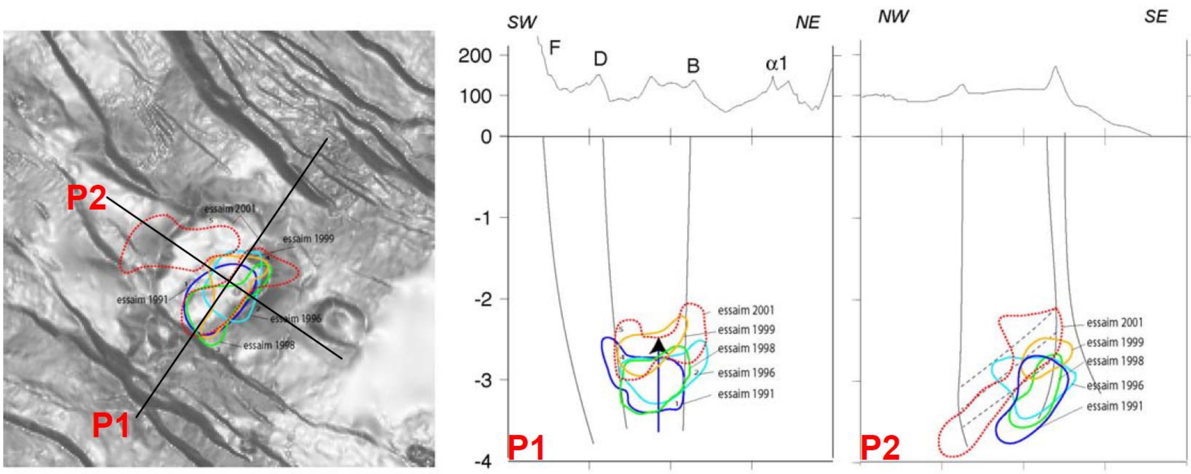

Fig.10: a detailed mapping of the chronology of the main seismic events having occurred at Fialé caldera in the period 1991- 2001 show a general movement of rise of the seismic activity which can be interpreted as a rise of the magma chamber, the upper part of which having migrated from 3.5 to 2.0 Km depth with a displacement of the events towards NW where the uplift was also observed from radar interferometry (from Doubre, 2006)

Considering the complementary surface investigations needed for locating the exploration wells and establish a drilling strategy, the seismic tomography developed by Doubre et al (2006) should allow to correlate with new DTDEM and MT sounding, as the activity continued since these surveys were undertaken by Arnarson and Flovenz before 1995, with consecutive changes in the reservoir conditions (Fig.11).

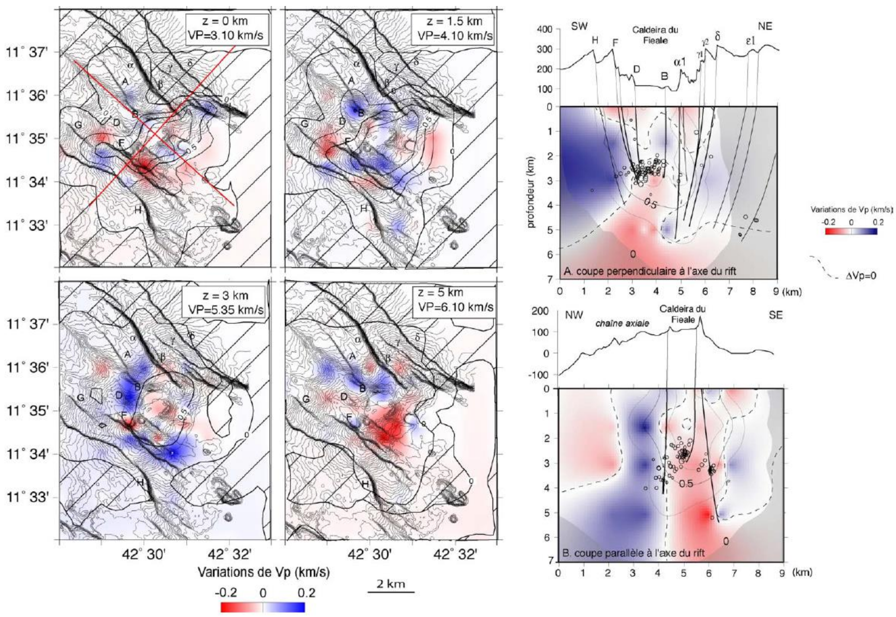

Fig. 11: Seismic tomography of the Asal-Fialé (Doubre et al. 2006)

5. CONSEQUENCE FOR THE DRILLING PROGRAM TO BE IMPLEMENTED IN THE COMING MONTHS

If this interpretation is correct, it has a direct impact on the conception of the drilling program to be engaged in the next few month as part of the feasibility study.

1. The first action to be undertaken should be to revisit the A5 well and engage a new thermal logging of this well. If we remember that it was drilled in 1988, which means that it just encountered the rapid cooling of the pre-existing reservoir during the 1978 event and the following active distensive phase that lasted ten years until 1997. We can infer from the profile that it was previously at a temperature of 200 to 300°C at a depth of 500 to 1000 metres. Although the extension of the fissures was decreasing in 1988, the reservoir was not yet affected by any new heating event before 1991 when the first magma injection occurred in the centre of Fialé caldera. Note that it is the event of 2001 magmatic injection phase that had the most effective influence on the geothermal reservoir at A5 location. Therefore, a new efficient heat source has been effective for the last 24 years. As a consequence, one should expect that the A5 reservoir in the interval 500 to 1.000 metres hopefully displays at present all the characteristics of an economic geothermal reservoir, with a suitable temperature (eventually above the previous range of 200 to 300°C), a good fracture permeability and a moderate salt content (sea water composition slightly concentrated due to vapour leakage, as observed along open fissures at the surface of the lava lake).
2. Secondly, the reservoir has to be searched for at a shallow depth in the caldera surroundings, avoiding the NE margin where cold sea water flow is still intense due to the active nature of the "petit rift", whereas no magmatic injection occurred in that part of the Asal rift floor.
3. Thirdly, the drilling programme previously established by REI and taken for granted by the World Bank and associated banking consortium should be revisited. The deep wells planned at a depth of 2,500m and deviated at a depth of 2,000m up to 2,800m length may not only miss the target but also be at risk, as the chance to encounter magma in this depth range is rather high, as also shown by Houmed et al. (2012), following the presentation of Vergne et al. in 2012 at the Afar Rift Symposium held in Addis Abeba.
4. Fourthly, a shallower drilling program should consider much earlier deviation (to be initiated at 500m depth) in order to cross the maximum of open fissures in the reservoir at depth of 500 to 1500m.

THANKS

I thank Cecile Doubre for her personal communications, the geothermal PMU at EDD in Djibouti and the AFD for allowing for this new insight of Asal data, Getahun Demissie for fruitful discussions, Susan Onyango for edits, and Peter Omenda for his revision and help in publishing this paper.

REFERENCES

Abdallah A. Gérard, A., Varet, J. : Construction d'un modèle synthétique du champ géothermique d'Asal. BRGM/82-SDN-951-GTH (1982) 25p. 10 cartes

Arnarson, K., & Flovenz, O.G.: Geothermal Exploration by Tem-Soundings in the Central Asal Rift in Djibouti, East Africa. World geothermal Congress (1995)

Arnarson, K.: The Asal Geothermal Field, Djibouti. Geophysical Surface Exploration. ISOR (2008)

AQUATER: Geothermal exploration project. Republic of Djibouti.Final Report. ISERST (1989) 159p.

Ballu, V., Diamant, P., Briole, P., & Ruegg, J.C.: Gravity field variations across the Asal rift: insight on vertical movements and mass transfer. Earth plant. Sci. Lett. **208** (2003) 41-49.

Barthes V., Gérard A., Varet J. : République de Djibouti, Champ géothermique d'Asal, synthèse des données disponibles au 1er juin 1980 BRGM/80-SGN-525-GTH42 p. 13 photos, 14 cartes (1980)

Battistelli A., Rivera J. and Ferragina C.: Reservoir engineering studies at the Asal field: Republic of Djibouti. Geothermal Resources Council Bulletin (1991) 280-289.

Barberi F., Borsi S., Ferrara G. Marinelli G., Varet J.: Relationships between tectonics and magmatology of the Northern Afar (or Danakil) depression. Symp. Royal Soc., March, 1969, Philos. Trans. Royal Soc. London **A 267** (1970) 293-311

Barberi F., Ferrara G., Santacroce R. and Varet J.:Structural evolution of the Afar triple junction. Afar Depression of Ethiopia, Bad Bergzarben, Germany, April 1-6 1974. A. Pilger and A. Rösler 1 (1975)38-54.

Barberi F. & Varet J.: Volcanism of Afar: small scale plate tectonics implication. Bull. Géo. Soc. Amer. **88** (1977) 1251-1266.

Battistelli A., Rivera J. and Ferragina C.:Reservoir engineering studies at the Asal field: Republic of Djibouti. Geothermal Resources Council Bulletin (1991) 280-289.

Banon, J.C., Correaia, H., Fabriol, R., Herbrich, B.: Projet géothermique Asal-Nord-Ghoubbet Avant-projet de faisabilité. BRGM/83-SGN-629-GTH (1983) 68p

Bosch B., Deschamps J., Lopoukhine M., Marce A. et Vilbert C. : La zone géothermique du lac Asal (TFAI). Résultats de terrain et études expérimentales. Bull. BRGM. II4 (1974) 367-383.

BRGM : Reconnaissance géothermique du TFAI. BRGM/70-SGN-GTM. (1970) 59p.

BRGM : Etude géothermique de la région du lac Asal, campagne 1972-1973. BRGM73-SGN-144-GTH (1973) 22p.

BRGM : Territoire Français des Afars et des Issas: rapport de fin de sondage: résultats des premiers essais de production. BRGM75-SGN-442-GTH (1975a) 18p.

BRGM : Territoire Français des Afars et des Issas: rapport de fin de sondage, interprétation des données géologiques de Asal 1 et Asal 2. BRGM75-SGN-443-GTH. (1975b) 19p.

BRGM : Report on project DJI78/005. Testing on geothermalfluids. Lac Asal (République de Djibouti): Phase 1. BRGM80-SGN-400-GTH (1980) 27p.

BRGM : Reconnaissance géothermique par prospections gravimétrique-électrique, audio-magnétotellurique dans la région du

Cattin, R., Doubre, C., DeChabalier, J.B., King, G., Vigny, C., Avouac, J.P., & Ruegg, J.C. : Numerical modeling of quaternary deformation and post-rifting displacements in the Asal-Ghoubbet rift (Djibouti, Africa). Earth & Pys. Sc. Let. **139** (2005) 352-367.

CFG : Champ géothermique d'Asal. Djibouti. Synthèse des données. 93CFG06. (1993) 87p.

Correia, H., Demange, J., Fabriol, R., Gérard, A., Varet, J. : Champ géothermique d'Asal. Synthèse des données disponibles au 1er janvier 1983. BRGM/83-SGN-022-GTH 71p. 10 cartes (1983)

Dauteuil, O., Huchon, P., Quemeneur, F., Souriot, T.:Propagation of an oblique spreading centre : the west Gulf of Aden. Tectonophysics **332** (2001) 423-442.

De Chabalier J-B. & Avouac J-Ph. : Kinematics of the Asal Rift (Djibouti) determined from the deformation of Fiale volcano.Science265 (1994) 1677-1681

Demange J., Stieltjes L., & Varet J., L'éruption d'Assal en novembre 1978. Etude pétrologique et considérations pétrogénétiques. Hawaii symposium, IAVCEI (abstract) (1979)

Doubre, C. Peltzer, G., Manighetti, I., Jacques, E. : Recording of Seismicity during the last Rifting Event. J. Geoph. Res. (2006)

Doubre C., Manighetti I., Dorbath I., Dorbath C., Bertil D., Delmond J.C.: Crustal structure and magmato-tectonic process in an active rift (Asal-Ghoubbet, Afar, East Africa): 2. Insights from the 23-year recording of seismicity since the last rifting event. J. Geoph. Res. **12**, B05406 1029 (2007) 32p.

Doubre C. & Peltzer G.: Fluid-controlled faulting process in the Asal Rift, Djibouti, from 8 year of radar interferometry observations. Geology **35** (2007) 69–72.

ENEL: Djibouti geothermal project. Report on the state of mining knowledge on the Asal zone. Proposals and recommandations. (1990) 28p.

FICHTNER : Projet d'évaluation des ressources géothermiques : Etude d'Impact Environnemental et Social (EIES) Projet N°610-1175, 9 chapitre, 9 annexes. (2012)

Fouillac C., Fabriol R. et Lundt F. : Champ géothermique d'Asal. Synthèse des données disponibles au 1er janvier 1983. Rapport BRGM83-SGN-022-GTH, (1983) 71 p.

Hjartarson, G., Gisladottir, V., Gislason, G., Olafsson, K.: Geothermal Developemnt in the Assal Area, Djibouti. Proceedings World Geothermal Congress, Bali (2010) 8p.

Houmed, A.M., Haga, A.O., Abdilahi, S. & Varet, J.: The Asal geothermal site, Djibouti Republic (model update, 2012). Argeo C4 conference, Nairobi (2012)

ISOR The Asal geothermal field, Djibouti. Rapport CERD (2008).

Jalludin M. : Synthèse sur le réservoir géothermique superficiel du rift d'Asal. Rapport CERD (1992)

Jalludin M. : Interprétation des essais de production et des essais hydrodynamiques sur les forages géothermiques du rift d'Asal. Rapport CERD, 47 p.(1996)

Manighetti, I., Tapponnier, P., Gillot, Y., Jacques, E., Courtillot, V., Armijo, R., Ruegg, J.C. and King, G.: Propagation of rifting along the Arabia-Somalia plate boundary Into Afar. J. Geoph. Res.103 (1998) 4947-4974

Manighetti, I., P. Tapponnier,V. Courtillot,Y. Gallet, E. Jacques, and Y. Gillot: Strain transfer between disconnected, propagating rifts in Afar, J. Geophys. Res. **106** (2001) 13,613– 13,665.

Marinelli G. et Varet J.: Structure et évolution du Sud du "horst Danakil" (TFAI et Ethiopie). C.R. Acad. Sci., **D276** (1973) 1119-1122.

ORKUSTOFNUN: Geothermal resistivity survey in the Asal rift in Djibouti. Vol. I and Vol. II. (1988)

Richard, O. et Varet, J.: Study of the transition from a deep oceanic to emerged rift zone: Gulf of Tadjoura, République de Djibouti. Int. Symp. Geodyn.Evols. Afro-Arabian System, Roma, (1979)

Ruegg J.C., Lépine, J.C., Tarantola A.: Geodetic measurements of rifting associated with a seismo-volcanic crisis in Afar. Geoph. Res. Lett. **6** (1979) 817-820.

Ruegg, J.C. & Kasser, M.: Deformation across the Asal-Ghoubbet Rift. Djibouti, uplift and crustal extension 1979-1986. Geoph. Res. Lett., **14** (1987) 745-748

Ruegg, J.C., Briole, P., Feigl, K., Vigny, C. Abdallah, A., Bellier, O., Huchon, S., Al Khirbash, S., Laike, A., d'Oreye, N. & Prevot, M. : First Epoch Geodetic GPS Measurements Across the Afar Palte Boundary zone; Geoph. Res. Lett., **20** (1993) 1899-1902

Sanjuan B., Michard G. et Michard A. : Origine des substances dissoutes dans les eaux des sources thermales et des forages de la région Asal-Goubhet (République de Djibouti). Journal of Volcanology and GeothermalResearch, **43** (1990) 333-352.

Stieltjes, L.: Carte géologique du rift d'Asal, République de Djibouti, Afar, East Africa, CNRS, Paris, BRGM, Orléans (1980)

Stieltjes L., Joron J.L., Treuil M. Varet J. : Le rift d'Asal, segment de dorsale émergé, discussion pétrologique et géochimique. Bull. Soc. Géol. France **18, 4** (1976) 851-862

Tapponnier P. et Varet J. : La zone de Makarassou en Afar: un équivalent émergé des "failles transformantes" océaniques. C.R. Acad. Sc. Parist. **278 D** (1974) 209-212

Tazieff H., Barberi F., Giglia G., Varet J.: Tectonic significance of the Afar (or Danakil) depression. Nature **235** (1972) 144-147

Varet J.: Carte géologique de l'Afar central et méridional, CNR-CNRS, 1/500 000 Géotechnip (1975)

Varet, J.: Geology of central and southern Afar (Ethiopia and Djibouti Republic), 1/500.000 map and report. CNRS, Paris (1978) 124p.

Vergne, J., Doubre, C., Mohamed, K., Dujardin, A., Leroy, S.: The lithospheric structure beneath mature continental rifts : New insights from a dense seismic profile across the Asal---Ghoubbet Rift (Djibouti). Addis Ababa Afar Rift Symposium, (2012)

Vigny, C., eChabalier, J.B., Ruegg, J-C., Huchon, P., Asfaw, L., Khanbari, K.: 25 years of geodetic measurements along the Tadjoura-Asal rift system, Djibouti, East Africa. J. Geophys. Res. (2006)

Walpersdorf, A.C., Vigny, C., Ruegg, J.C., Huchon, L., Asfaw, & Al Kirbash, S.: 5 years of GPS observations in the Afar Triple Junction Area. J. of Geodyn. **28/2-3** (1999) 225-236.

Zan L., Gianelli G., Passerini P., Troisi C. and Haga A.O.: Geothermal exploration in the Republic of Djibouti: thermal and geological data of the Hanlé and Asal areas. Geothermics **19, 6** (1990) 56.