THE DARAJAT GEOTHERMAL FIELD CONCEPTUAL MODEL, A VAPOR DOMINATED SYSTEM

Julfi Hadi

Resource Exploitation Department, Amoseas Indonesia Inc.
Gedung Sarana Jaya, Jl. Budi Kemuliaan I no. 1, Jakarta 10110, Indonesia

ABSTRACT

Integrated geology, geochemistry and geophysics data shows numerous reservoir characteristics at Darajat that are similar to other known vapor geothermal systems. The Darajat surface manifestations are characterized by the appearance of fumaroles, mud pools and steam condensate fed springs only, with the absence of the typical sodium chloride hot springs. Analysis of thin sections and temperature dependent alteration minerals showed that the vapor field first started as a water dominated system with reservoir temperature exceeding 280^o C and has cooled to the current 240^o C vapor reservoir. Intrusive rocks, temperature dependent alteration minerals, gas ratios, and top of reservoir contours suggested that the magma bodies that supply heat to the previous liquid and the current vapor systems are apparently centered in the same vicinity. MEQ data and seismic tomography modeling suggested that the younger intrusive bodies that supply heat to the vapor system must be situated deeper than 4 km from the current surface. Argillic (illite-smectite) and silicic alteration product deposited near the top of the previous liquid reservoir, capped and sealed the current vapors reservoir. The increasing gas/steam, CO_2/H_2S and CO_2/NH_3 ratios observed with commercial steam production support the idea of liquid water in the rock matrix (boiling). Gas ratio contours overlap with the current top of the reservoir identify the up flow and out flow zones. No convincing geochemistry data indicate any natural recharge from the reservoir margins (sides) or input from deep chloride brines. Cores, cuttings and thin sections work showed that alteration clays and minerals deposited by the up flowing fluids from the past liquid system have a significant control on the plumbing and fluid path of the current vapor reservoir. Numerous veins, voids and vugs in the rock matrix are filled and sealed with alteration minerals. Formation Micro Scanner data suggest that major permeable zones in the vapor reservoir may be characterized by young, unmineralized, high density minor fractures or fractures where the deposited minerals have been leached by downward flowing steam condensate.

1. INTRODUCTION

1.1. Background

The largest producing geothermal systems in the world, which comprises approximately ten percent out of the entire population of world known geothermal systems, are vapor dominated. The Darajat and Kamojang geothermal fields, two out of the five producing vapor fields today, are located in West Java, Indonesia **(Figure-1** (insert)). In 1996 Amoseas Indonesia Inc. started a major drilling program in the Darajat geothermal field to both increase the proven reservoir area and to provide steam for a second, possibly third power generation unit. Part of the overall work program was to create an integrated model by combining geology, geophysics and geochemistry. The finished model was then compared to other well studied vapor geothermal system, such as the Geysers and Larderello. One aim of this study is to help better understand conceptually the occurrence of this vapor system in Indonesia for future exploration.

1.2. Geological Framework

The geological history of Indonesia, especially the presently active Sunda-Banda Arc region, which extends from the northern most tip of Sumatra, through Java, west and east Nusa Tenggara, Banda Arc and north Sulawesi, is dominated by subduction zones and arc magmatism (Carlile and Mitchell, 1994). Geothermal systems found in Indonesia are normally volcano hosted and related to these subduction zones. The Darajat field is situated along a range of volcanic centers nearly 30 km in lengths. These Quaternary volcanics include active volcanoes at Gunung Papandayan (last erupted 1772) and Gunung Guntur (last erupted 1840). The volcanics are predominantly of intermediate to mafic composition, except the Kiamis obsidian flows and pyroclastic deposits erupted from vents situated between Darajat and Kamojang fields. Although several individual eruptive centers are distinguishable, the Darajat area is dominated by partially collapsed remnants with no obvious associated cone. Due to the lack of exposure in the Darajat field, structures can be recognized generally only from topographic evidence. The dominant lineament directions in the region are the NE-SW and NW-SE trending faults. The most visible structural features on aerial photographs are the Kendang and Gagak faults **(Figure-1**).

1.3. Surface Thermal Activity

The Darajat surface activity is generated mainly by steam rising from depth, which has formed steaming ground, acidic sulfate pools, superheated fumaroles and outflows of steam condensate on the surface. Unlike liquid dominated system typical sodium chloride hot springs are absent. There is only one main surface manifestation in the Darajat field, the Kawah Darajat thermal area **(Figure-1**). These features are interpreted to be associated with an up flow zone. Three outflows of steam condensate have been found, one along the Cibeureum stream and the other two around 3 to 4 km east of Darajat. Areas of surface hydrothermal alteration are mainly found in the Kawah Darajat thermal area and along a few major known surface structures.

2. CONCEPTUAL MODEL

2.1. The Heat Source and evolution to the vapor system

Core and cutting shows that several wells both on the north and south side of the Gagak Fault penetrated shallow intrusive bodies interpreted to be microdiorite **(Figure-2**). Down hole P-T surveys indicated that this microdiorite is too cool to be the heat source for the present day geothermal system. However, these intrusive bodies correlate well with shallowest appearance of epidote contour, top of reservoir contour and up flow zones found by gas ratio. This suggests that the current heat source must be located in the same vicinity and may have evolved from the same shallow intrusive bodies. Recent MEQ data shows seismic events occurring 4 km below the surface. The velocities of seismic shock waves propagated by earthquakes through the mantle are controlled by physical properties of the material - the denser the material, the higher the seismic wave velocities (Francis, 1994). From the surface to 4 km depth, where the crustal earthquakes nucleate, the crust is probably associated with a brittle dense rock where heat loss is governed by convection and conduction. The partial melts of magma (heat source) that supplies heat to the present system may be considered to occur below the deepest earthquakes, or at least 4 km below surface. This is in agreement with similar depths obtained in other geothermal fields and volcanic areas (Foulger, 1995)(**Figure-2).** This interpretation is supported by seismic tomography modeling of a low Vp/Vs ratio zone occurring 4 km from the surface (Geosystem, 1997).

Different groups of hydrothermal minerals have been found from cuttings and core samples. Hydrothermal minerals found include silica, clays, carbonates, sulfates, calc-silicates, feldspars, sulfides and minor iron oxides. Alteration suites occur primarily as a result of host rock interaction with hot, near neutral pH, alkali chloride fluids (Hadi, 1997). The occurrence of directly deposited fluid precipitated silicate minerals such as laumontite, wairakite, prehnite and epidote suggest that the Darajat geothermal field is associated with a liquid dominated environment in the past. Multiple cross cutting quartz veins in the lava indicated different events of hydrothermal activiy. Transformation of smectite to illite at shallow depths and the occurrence of amphibole in thin section (both in disagreement with down hole temperature) reveal the presence of multiple geothermal events in the history of the Darajat field associated with a heat source of more than 280^o Celsius (Hadi, 1997). The lower current down hole temperature suggests that the system is cooling at the present time. Argillic (illite-smectite) and silicic alteration products deposited near the top of the previous liquid reservoir, correlate well with the elevation of first steam entry in wells drilled into the vapor system. These clays are generally situated just above the current reservoir and interpreted to cap and seal the vapor reservoir **(Figure-2)**.

2.2. Fluid Paths (Up flow – Out flow)

Two well studied models (White et. al., 1971 and Truesdell, 1991) were reviewed to interpret the up flow and out flow zones of the Darajat system. These models show several characteristics of a vapor system based on studies at the Geysers and Larderello fields:

1. Main reservoir contains steam stored in fractures
2. Liquid water stored in the rock matrix and small fracture
3. Underlying zone of boiling liquid, assumed to be brine
4. Zone of condensation at the top of the vapor dominated reservoir and forming condensate which drains back to the bottom

The first five years of geochemistry of gas and isotopic patterns at Darajat appear to follow a chemical sequence depending on solubility in steam (Truesdell, 1991)(**Figure-3**). With distance from the up flow zone, ratios of gas/steam, and CO_2/H_2S increase, while oxygen-18 decrease **(Figure-3)**. Steam flowing laterally away from up flow zone partially condenses (soluble constituents move to liquid phase) as heat is conducted to the surface and the condensate drains downward. In general, gas/steam, CO_2/H_2S and Oxygen-18 contours show a good association with an interpreted up flow zone in the center of the field over the Gagak fault and extending north to the S-1 well **(Figure-4)**. Increasing gas ratios and a decrease of oxygen-18 to the east, north and south is interpreted as lateral steam movement to the margins, represented by progressive condensation **(Figure-4)**. The elevation of top of reservoir (elevation of first steam entries) and the patterns of these gas ratio contours showed similarities and formed an integrated model which identified a common main up flow and out flow of the current vapor system **(Figure-4)**.

2.3. Steam in Fracture and Immobile fluids in the Matrix

As Darajat wells discharge only vapor, to study the existence of liquid boiling in the matrix, an analysis using gas ratios was conducted. Boiling of liquid in the matrix was assumed to be a response to the lowering of pressure in nearby fractures. The steam resulting from this process then flows down gradient through fractures into the producing well. Gas ratios such as CO_2/H_2S, CO_2/NH_3 and gas/steam were plotted against time and wellhead pressure (WHP). All ratios of CO_2/H_2S, CO_2/NH_3 and gas/steam show a decrease with time, suggesting an increase in soluble constituents, NH_3 and H_2S, due to boiling with commercial production **(Figure-5)**. CO_2/H_2S, CO_2/NH_3 and gas/steam data were also plotted against WHP. The result showed decreasing of the ratios at lower WHP, suggesting an increase of NH_3 and H2S with increasing of flow **(Figure-5)**. In ideal conditions, at low flow rates (high WHP), where reservoir pressures are not drawn down significantly, a well may produce entirely from in situ reservoir steam, while at high flow rates (low WHP) additional steam flow may be produced from boiling of immobile formation liquid (Kingston Morisson, 1996). Both of this analysis suggested the existence of liquid water in the matrix.

Cores, cuttings and Formation Micro Scanner (FMS) data shows that the Darajat reservoir consisted of a low porosity matrix composed of andesite, microdiorite and pyroclastics, with open fractures. Thin section study showed the occurrence of many fractures and veins in the reservoir filled by hydrothermal minerals precipitated directly from fluid during the previous liquid dominated system. Integrated fracture data such as FMS, drilling data and spinner logs from large fracture in the reservoir was correlated against steam zone data, which indicated that major permeability in the reservoir is characterized by high density minor fractures. These producing fractures are interpreted as young fractures or fracture s where the deposited minerals has been leached by flowing steam condensate (Truesdell pers. comm., 2000).

2.4. Natural Recharge

Isotopic data from both the Larderello and Geysers vapor fields shows input of natural recharge to the reservoir from the margin of the field (Calore et. al., 1982)(Truesdell, 1991). Recent Darajat tritium and chloride data suggest no input is observed from the margins or postulated deep brines.

3. RESULT AND DISCUSSION

Integrated geology, geochemistry and geophysics data show numerous similarities in the characteristics between Darajat and other known geothermal system. Similar to the Geysers, the Darajat vapor system evolved from a liquid dominated environment with a heat source of more than 280^o Celsius and has cool to the present temperature of 240^o Celsius. Petrography work showed that alteration clays and minerals deposited by the up flowing fluids from the past liquid system have significant control on the plumbing and fluid paths of the vapor system. Several conclusions may be deduced from the study concerning the Darajat conceptual model (**Figure-6**):

1. The young magma body that is supplying heat to the current system may have evolved from the same intrusive(s) that supplied heat to the liquid system
2. Argillic (illite-smectite) and silicic alteration products deposited near the top of the previous liquid reservoir capped and sealed the current vapor system
3. Gas ratios correlate well with the top of reservoir map, show an up flow zone over the Gagak Fault extending to the S-1 well and lateral steam flow to the east, south and north (margin), represented by progressive condensation
4. Gas ratios show the main reservoir contains steam stored in fractures
5. Gas chemistry against time and WHP show the existence of liquid water in the rock matrix
6. Isotopic and chloride data give no indication of natural recharge from the margins
7. Integrated fracture data indicate that the major permeability in the reservoir is characterized by young high density minor fractures or fractures where the deposited minerals has been leeched by down flowing steam condensate

Many surface features of frontier geothermal systems in Indonesia have characteristics of vapor domination: moderate-steep topography with limited surface activity and the absence of chloride springs or outflows. Geology and geophysical tools that were commonly used to explore for liquid dominated systems are not effective in assessing a vapor system. These tools primarily will detect and interpret relict alteration from the previous liquid system instead of the present vapor system. This study show that gas ratios, combined with the top of reservoir data which has been proven to be effective in interpreting vapor system in the Larderello and Geysers fields, can also be used to evaluate up flow zones, fluid movement, and boiling associated with a vapor system in Indonesia.

4. ACKNOWLEDGEMENTS

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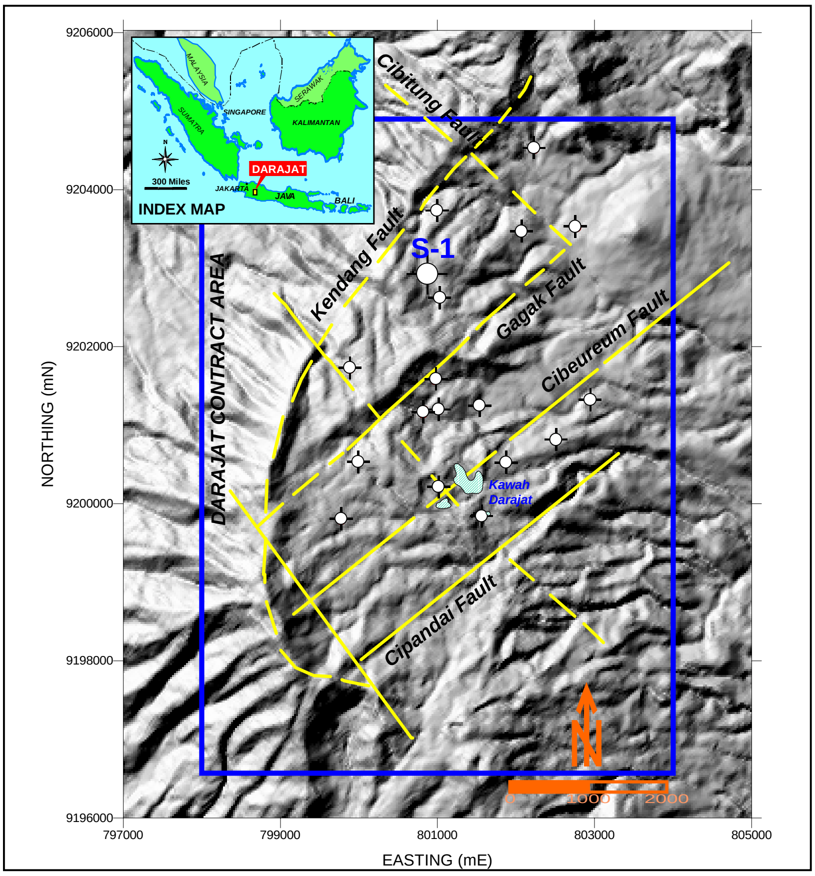

Figure 1.
Physiography of the Darajat Geothermal field showing major NW-SE and NW-SW lineaments, the Kendang ridge, Gagak fault, S-1 well and Kawah Drajat.

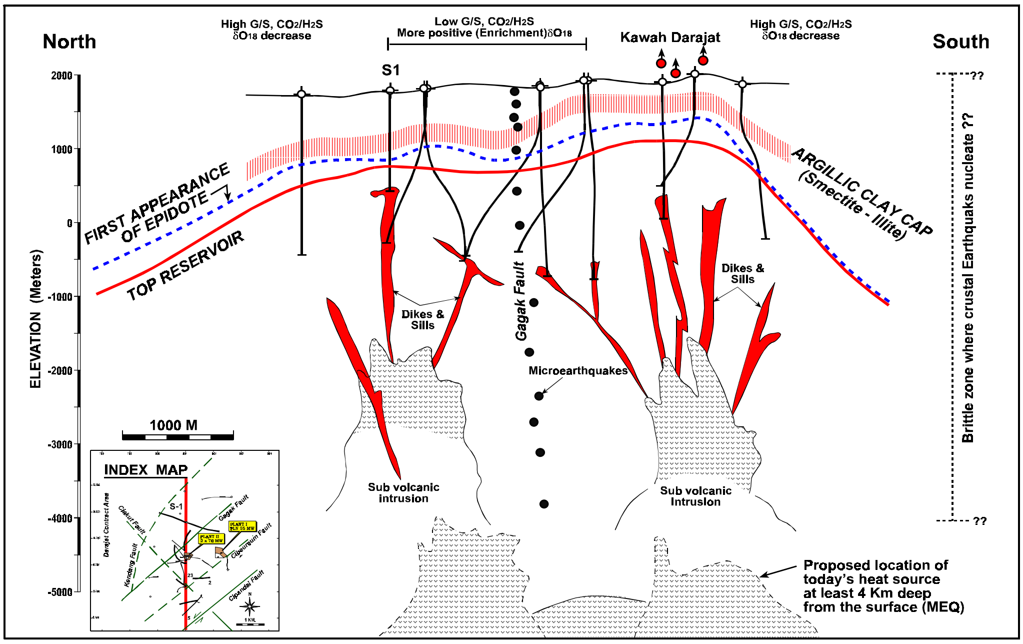

Figure 2.
Schematic N-S diagram showing ; (1) The relationship between sub-surface intrusive rock and the first appearance of epidote, smectite–illite and top of reservoir (2) Location of deepest MEQ 4 km below surface suggest semi-brittle zone and partial melting (current heat source) deeper than 4 km

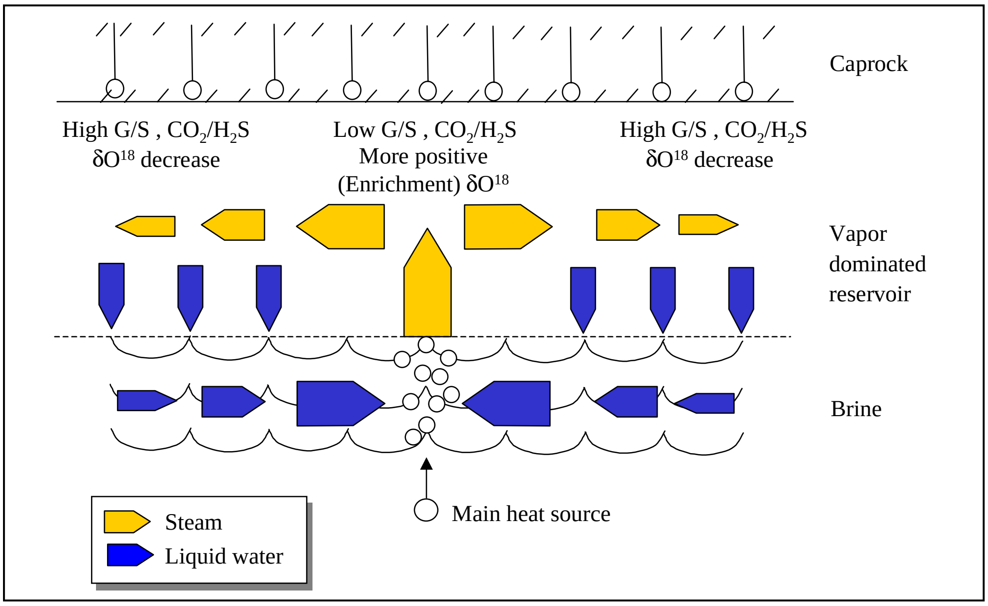

Figure 3.

Schematic model of fluid flow, boiling, and lateral steam movement to the margin near the top of reservoir showing low gas/steam, CO_2/H_2S and more positive $\delta^{18}O$ near up flow and high gas/steam, CO_2/H_2S and more negative $\delta^{18}O$ on the margins (progressive condensation) (D'amore and Truesdell, 1979)

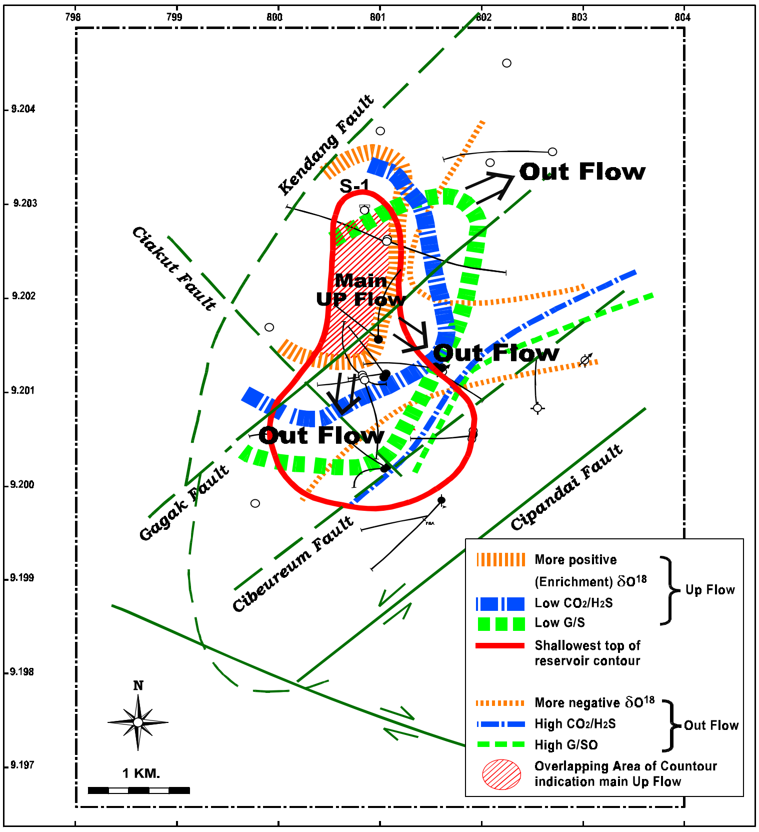

Figure 4.

Map showing location of overlapping area of low gas/steam and CO2/H2S, and a more positive $\delta^{18}O$ contour indicating main up flow zones and steam laterally flowing to the margins near the surface represented by high gas/steam, CO2/H2S and more negative $\delta^{18}O$

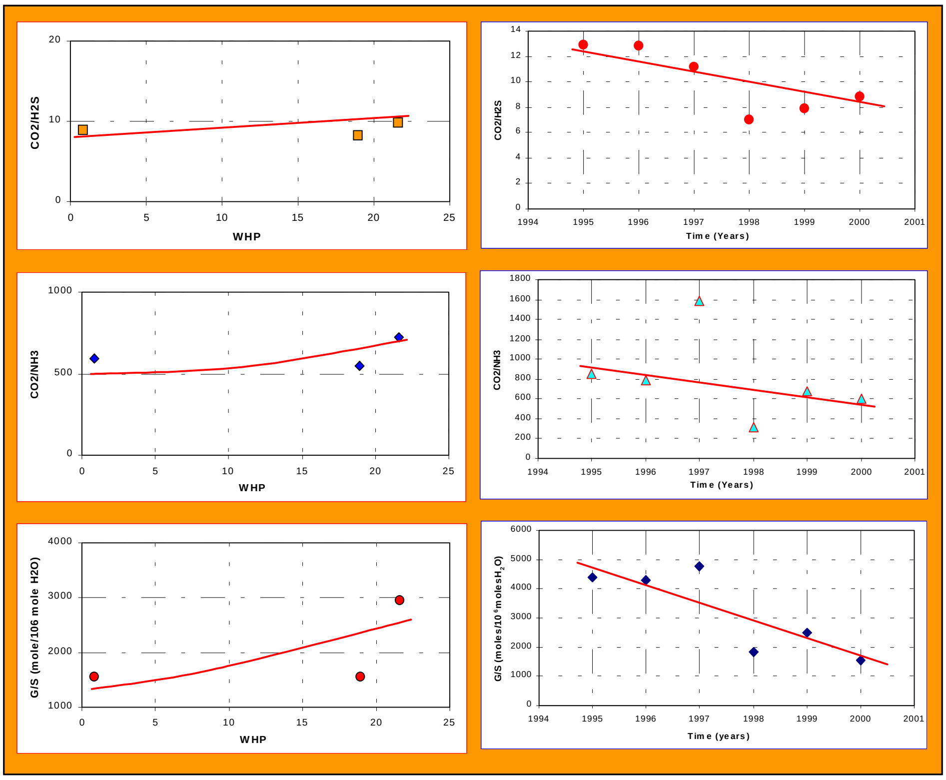

Figure 5.
Example of gas ratio variation from DRJ-10 well showing an increase of soluble constituents such as H2S, NH3 and steam with time and lowering of WHP indicating boiling of immobile fluids in the matrix

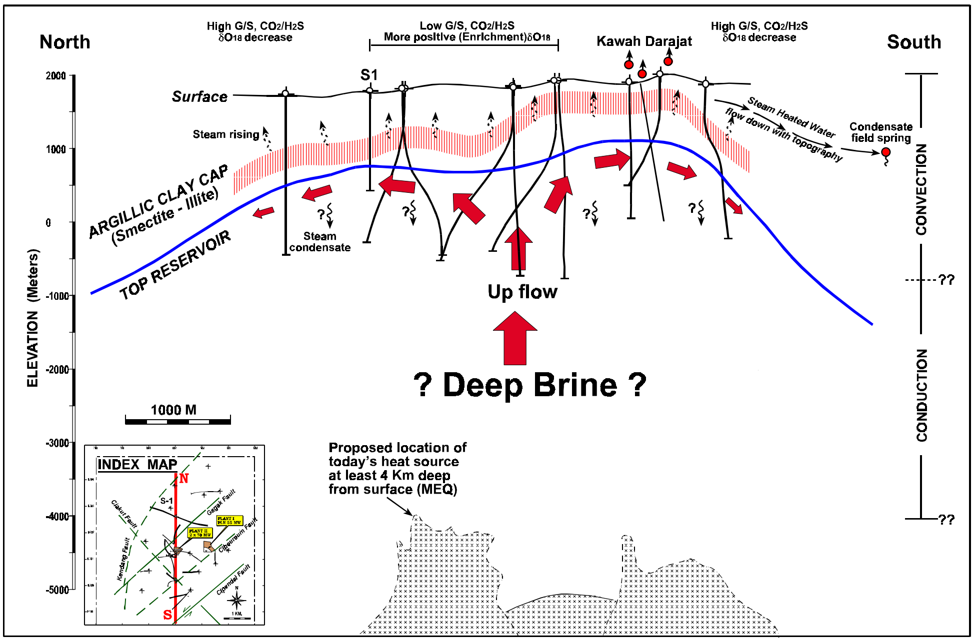

Figure 6.
N-S cross section of the reservoir showing up flow and lateral steam movement (progressive condensation) to the margin, steam rising upward and condensate flowing downward ? , and proposed location of current heat source