RESULTS OF GEOTHERMAL SURFACE EXPLORATION ON THE ISLAND OF GRANDE COMORE, UNION OF COMOROS

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ABSTRACT

Geothermal surface exploration has been conducted on the island of Grande Comore, Union of Comoros. This included geochemical gas and liquid sampling and analysis. A CO_2 flux survey was also undertaken. Geophysical surveys include gravity and magnetotellurics, although only preliminary results of the latter are available at the time of paper submission.

Thermal features are found in the caldera at the summit of the active Karlatha volcano and in a rift to the north of the caldera. There is little geochemical or geophysical evidence for an exploitable resource within the caldera. However, the northward rift contains a solfatara which has fumaroles with gas chemistry indicative of a high temperature (300°C) potential resource. The resistivity pattern at depth beneath the solfatara is consistent with the possibility of a resource a depth.

As Grande Comore is a hot spot volcanic island the potential resource there may be analogous to the Puna development in Hawaii. Early power estimates of 48 MWe are adequate for the planned initial development of 10 MWe.

1. INTRODUCTION

A consortium between the Government of Comoros, The United Nations Development Program (UNDP) and the New Zealand Ministry of Foreign Affairs (MFAT) has explored the potential for a geothermal resource on the island of Grande Comore in the Union of Comoros. With the assistance of New Zealand Government funding technical assistance, further funding was secured from the East African Geothermal Risk Mitigation Facility (GRMF) in 2015 to carry out surface exploration with the goal of establishing a possible resource for a geothermal development of an initial 10 MWe.

Grande Comore is the westernmost and largest island of the Comoros archipelago (Figure1), encompassing 1024 km^2. It is also has the highest elevation and is the most recent in geological terms, its high point being the summit of the Karthala volcano (2361 m above sea level). Karthala volcano is a basaltic shield volcano with an active hydrothermal system on its flanks (Savin et al., 2001 and Chaheire and Chamassi, 2012). It has multiple nested calderas at its summit (Strong and Jacquot, 1970) and rifts aligned to the NNW and to the SE in which fissure eruptives are found (Bachelery and Coudray, 1993). The presence of a rift system with fissure eruptives associated with a major shield volcano is similar to that exploited by the Puna geothermal project in Hawaii (Speilman et al., 2006) and therefore could host thermal activity at depths suitable for targeting by drilling. The presence of fumaroles, hydrothermal alteration and a solfatara on Karthala's upper northern flank in the rift support this.

In November 2014, Jacobs and the Bureau Géologique des Comoros (BGC) undertook geochemical, soil CO_2 flux and shallow temperature surveys at Karthala, with magnetotelluric (MT) and gravity surveys carried out in July 2015. The overall impression of the thermal activity at Karthala is of a young magmatically-driven geothermal system recharged by meteoric water with no clear evidence of seawater input.

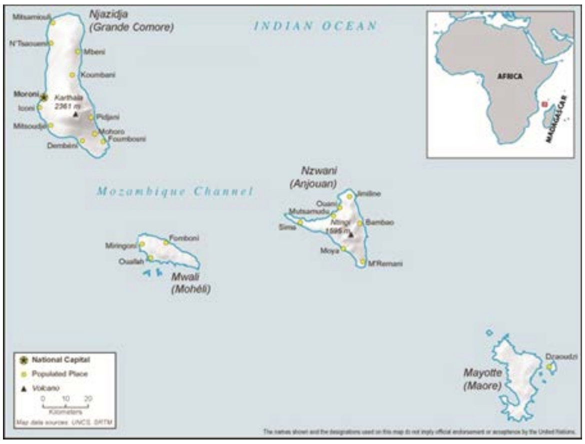

Figure 1: Location Map

2. GEOLOGY AND VOLCANOLOGY

The main island of Grande Comore is comprised of two volcanic massifs: Le Grille and Karthala volcanoes (Esson et al., 1970). La Grille, forming the northern portion of the island, has not been active for the last 1,300 years. Karthala, on the other hand, is the only presently active volcano in the Comoros archipelago. This basaltic shield volcano forms the southern two-thirds of Grande Comore Island and hosts an active hydrothermal system.

Bachelery and Coudray (1993) distinguished three main stratigraphic units for the Karthala volcano:

- Old Karthala - with active rift zones, large collapse structures and relatively large volumes of lavas that represent the main growth stage of the volcano and corresponds structurally to the volcanic shield-building stage.
- Recent Karthala - considered to post-date the formation of the 'primitive' caldera of Karthala.
- Present Karthala - corresponds to the youngest lava flows, emitted during the past few hundred years. The still high magma production rate and

multiple collapse structures associated with these two last phases of activity suggest that they may also be regarded as part of a main shield-building phase.

Karthala lavas are mostly saturated to slightly undersaturated basalts, picrobasalts and trachybasalts (SiO_2 contents between 45 to 49 wt %) with an average of 4 wt % normative nepheline (Bachelery and Coudray, 1993). The Old Karthala lavas exhibit an olivine–clinopyroxene–plagioclase phenocryst association and rarely contain dunitic, wehrlitic and gabbroic cumulate xenoliths (Bachelery and Coudray, 1993). The olivine–clinopyroxene phenocryst association is the only one observed in the Recent Karthala lavas and they are free of xenoliths (Bachelery and Coudray, 1993).

Trace element and isotope data is interpreted to indicate that Karthala lavas were produced in an upwelling mantle plume from partial melts derived from an amphibole-bearing garnet-lherzolite mantle source (Class and Goldstein 1997; Class et al. 1998; Claude-Ivanaj et al. 1998), with negligible evidence for shallow contamination.

Only two K–Ar ages are available for Karthala (Hajash and Armstrong, 1972; Emerick and Duncan, 1982). These K–Ar ages indicate that volcanic activity has persisted for at least the past 130,000 years. Radiocarbon dating of charcoal found in La Grille and Karthala indicate ages < 1300 and <5045 years for recent activity, respectively (Bachelery and Coudray, 1993). At least fourteen eruptions have been experienced by Karthala during the last 100 years (Smithsonian, 2015), most of them being predominantly effusive although more violent phreatic explosions in 1918, 1948, 1952, 1991 and 2005 have also been recorded. Almost all the eruptions were located along two rift zones, which are well defined with both topographic features and distribution of eruptive fissures. The north rift zone extends over 25 km to the north of the central caldera, and the southeast rift zone is about 12 km long.

The Karthala caldera is roughly elliptical, with a N-S length of 3.5 km and an E-W length of 2.8 km (Bachelery and Coudray 1993). The greater caldera results from the coalescence of at least seven smaller calderas (Strong and Jacquot, 1971). A 300-m deep crater complex, Choungou-Chahale, formed during repeated episodes of collapse and effusion, occupies the center of the caldera. At least four individual craters can be identified within the Choungou-Chahale complex. The most recent of these craters is located in the southern part of the Choungou-Chahale complex and was formed as the result of the July 1991 phreatic eruption (Bachelery and Coudray 1993).

Choungou-Chagnoumenl is the most northern of the calderas. It is the source of a major lava flow in 1972 that left behind a lava lake and produced a small cone with which much of the current thermal activity is ascoaited.

3. THERMAL FEATURES

Most of the surface manifestations are found in the nested summit calderas of the Karthala volcano (Figure 2). The strongest activity is on the southern and eastern rim of the 1972 volcanic eruption crater in the most northern caldera. There are also areas of steaming ground on the eastern rim of the southern caldera.

Outside of the nested calderas there is a notable group of thermal features in the La Soufriere area to the NNW where a rift is found (Figure 3). The main La Soufriere solfatara covers an area of about 300 m^2. This includes hydrothermal alteration, steaming ground and fumaroles. Sulphur is actively depositing around the fumaroles (Figure 4) forming euhedral crystals. This type of sulphur is typical of that formed by atmospheric oxidation of H_2S. At about from 80 to 170 m to the SE are found eight smaller areas of altered hot ground that are aligned in this direction, which is parallel to the mapped fissure eruptions on the geological map (Figure 5). This provides an important link between the areas structure and thermal activity.

There are cold springs and wells at low elevations, but no clear indications of geothermal fluids are present although some wells contain significant Cl concentrations, due to seawater contamination. There are also bicarbonate spring waters that have a temperature a few degrees in excess of ambient.

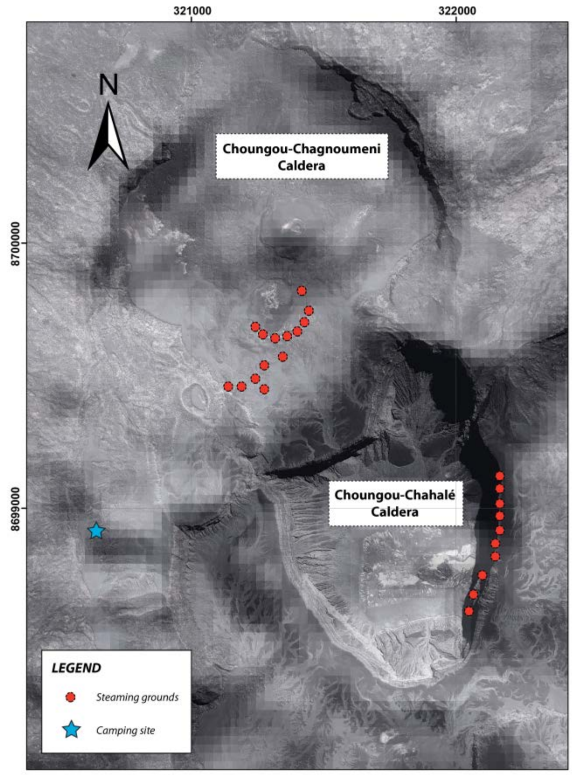

Figure 2: Thermal activity location in the calderas.

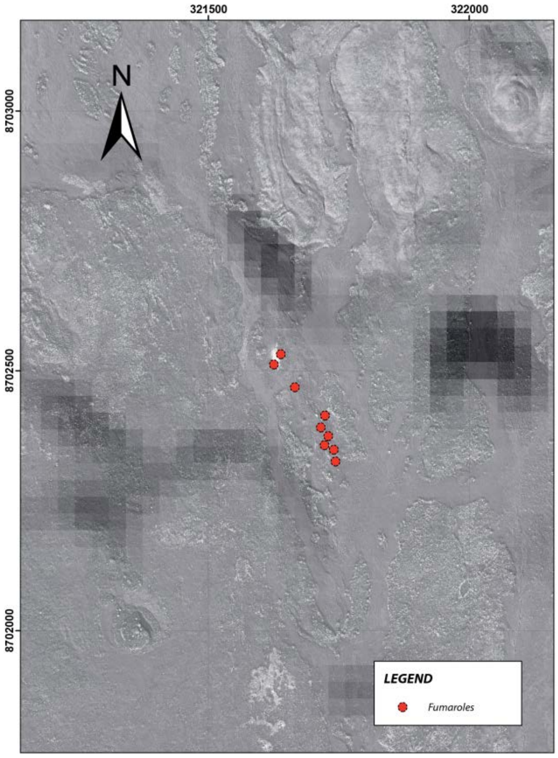

Figure 3: Thermal activity locations associated with NNW rift. La Soufriere solfatara is the white patch at the northernmost of the thermal features.

Figure 4: Gas sampling of a fumarole at La Soufiere; note the yellow coloured sulphur depositing on the outside of the fumarole.

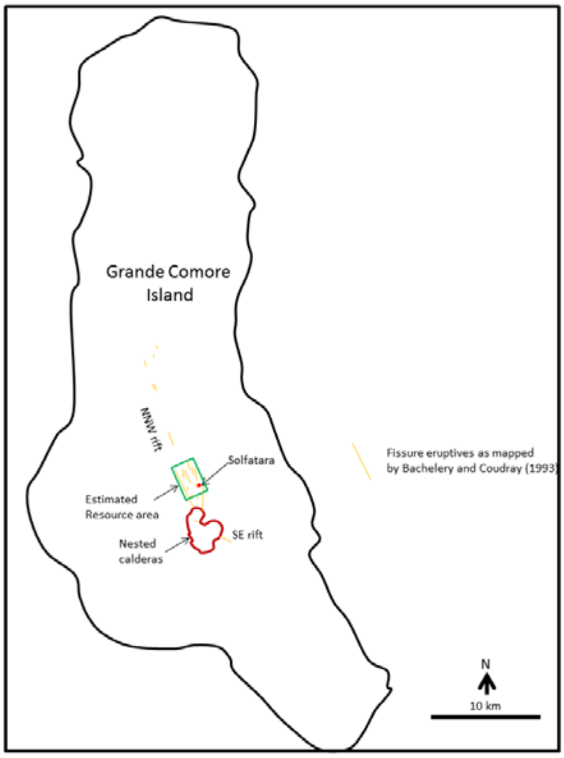

Figure 5: Location of fissure eruptives indicative of rifts.

4. GEOCHEMISTRY

The surface fluid chemistry at Grande Comore includes HCO_3-rich cold springs, saline Na-Cl waters from cold bores located near the coast, and fumaroles and steaming ground associated with Karthala volcano (Figure 6).

4.1 Water Chemistry

The chemistry and the isotopic composition of the HCO_3 (up to 190 mg/kg) waters along with low temperatures (<24.7°C) indicates that they are groundwater (Shvartsev, 2008). Some of the temperatures are possibly slightly higher than ambient and it is possible that the CO_2 precursor for the bicarbonate could be ultimately sourced from a geothermal resource or from magmatic gases from the Karthala volcano.

The relative high Cl/B molar ratios of the Na-Cl waters (up to 1210) and their Na-K-Ca-Mg proportions indicate that these waters are a mixture of seawater (<5%) and meteoric water (>95%), without the participation of any geothermal or magmatic components.

4.2 Gas Chemistry

Air free analyses could only be obtained from fumaroles in the La Soufiere solfatara. The gas (other than atmospheric) from the steaming ground in the caldera is mainly CO_2.

The air free fumarole chemistry is consistent with a geothermal resource at depth, but with more reducing conditions than that for andesitic type systems addressed by Giggenbach (1987). Thus, the D'Amore and Panichi (1980) geothermometer has been used rather than the Giggenbach (1991) Ar based geothermometers, to calculate a reservoir temperature of around 300°C.

Condensate samples collected from the caldera steaming ground and La Soufriere areas have pH's higher than 4 and low Cl and F contents, indicating that magmatic acid forming gases (SO_2, HCl and HF) are not present; at least at the surface.

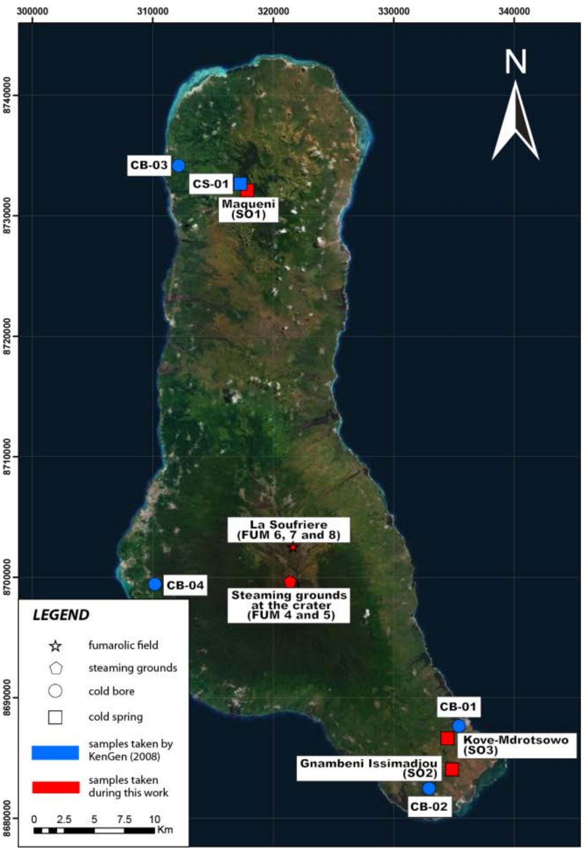

Figure 6: Distribution of geochemical sampling points. Kengen (2008) refers to Muchemi et al. (2008) in references.

4.3 CO_2 Flux Survey

Comparison of CO_2 flux and soil temperature at Karthala showed that higher CO_2 fluxes and soil temperatures were only measured in areas with known thermal features (fumaroles and steaming grounds) and decrease rapidly with distance from each feature. Thermal features and, therefore, high CO_2 fluxes and soil temperature, are spatially controlled by fractures that were recognised in the field. These fractures have a main orientation coinciding with the direction of the proposed rifting system affecting the northern flank of Karthala volcano. The observation of localised high CO_2 flux suggests that structural permeability is controlling surface emissions at Karthala.

The CO_2 fluxes measured in other areas, such as further along the proposed major rift zone and where inferred lineaments were mapped, are in the range of CO_2 flux values produced by biologic activity. This could be explained by the very low permeability of the lithology that composes the volcanic structure at Karthala (i.e. basaltic lava flows, ash deposits), which prevents the CO_2 from escaping to the surface. The latter does not exclude the possible existence of fault-fracture meshes in these areas at depth, but if the faults exist they are not open conduits for transport of deep degassing to the surface.

5. MAGNETOTELLURICS

Of the geophysical surveys undertaken, only preliminary MT results are available at the time of paper submission; so only generalised descriptions can be provided.

The preliminary results show a shallow layer of very high resistivity in most of the basaltic volcanic pile, as expected. Within it is a layer with slightly lower resistivity, interpreted to be associated with a groundwater aquifer. A zone of very low (<2 Ωm) resistivity is found immediately beneath the caldera, but doesn't extend downslope in any direction let alone towards the solfatara. This very low resistivity zone is interpreted to be where magmatic volatiles are condensing into ground water and forming smectite by interaction with the rock. These condensed volatiles can't be particularly acidic, otherwise kaolinite would be the main clay with expected resistivities closer to 20 Ωm and the main volatile is likely to be CO_2.

A similar shallow low resistivity zone occurs near La Soufrière, separate at shallow levels from the low resistivity anomaly in the crater, but the two anomalies join up at deeper levels, with the resulting low resistivity layer deepening and thickening towards the north (along the rift) and the west, as its resistivity becomes progressively higher. This may be indicating geothermal resource below the base of the low resistivity layer, in the area between La Soufrière and the crater. Since a basaltic pile is present, the location of the base may equate with the 240°C isotherm in the zone between La Soufriere and the crater, similar to what has been found in Icelandic fields (Haraldsdottir et al., 2012).

3. CONCEPTUAL MODEL

Rifts are found in oceanic hot spot volcanoes (Carracedo, 1999) such as Karthala. These rifts form due to the gravitational instability of the volcanic pile rather than being a regional tectonic feature. This instability is due to the island initially growing as a submarine seamount. In which case it will have a steep angle of repose as the volcanic pile is being supported by the seawater. Once the volcano grows above the sea the added weight can no longer be supported by the steep pile and the island will start splitting up. If there is a magma body present the magma can enter the newly created open space and with cooling "cement up" the island; although if there is too much magma it is possible that it may actually trigger a collapse. With successive movement of the gravity fault and injection of magma the rift forms and will be infilled with dykes.

The most similar developed field analogue to Karthala is the Puna geothermal field on the Big Island of Hawaii. They share the same setting of an oceanic island hotspot and have rifting off an active basaltic volcano. Even so there are significant variations. At Hawaii the eruptive centre (Pu'u' O'o), associated with the rift on which Puna is located, is not the main eruptive centre on the island. The Pu'u' O'o eruptive centre rift that hosts the geothermal reservoir is initially orientated to the SE, but moving further along the rift the orientation changes to the NE. There have been major fissure eruptions from the NE section of the rift that have produced voluminous lava flows over 43 km of the rift; some in the vicinity of the Puna development were erupted in 1959 (Spielman et al, 2006). The NE part of the rift has relief from 990 m asl to sea level and continues out to sea. The Puna geothermal development is located about

30 km from the eruptive centre at an elevation of 320 m asl. The immediate area at Puna has a structural complexity in that it is at a 600 m transverse step-over in the rift; although wells were mainly targeted into the main rift fractures. Recharge waters include both meteoric waters and seawater. The average well at Puna produces 20 MWe. Well failures have been to drilling problems (including encountering magma; Teplow et al., 2009), scaling and corrosion rather than lack of permeability or temperature.

In contrast Karthala is the main active eruption centre on the island of Grande Comore. There are numerous fissure eruption centres that mark the location of the rifts, but they have produced only minor volcanic features. The main rift has a relief of 2250 m to 930 m asl.

A major similarity however is that thermal features are limited in extent and in the immediate Puna area the resource is essentially blind. This may reflect high permeability in the rifts above a clay alteration layer. The clay layer limits the amount of upward movement of steam and gas and what does get through is absorbed by overlying groundwater before it reaches the surface.

A second major similarity is that the time frame of these systems is very short in comparison to volcanic arc exploitable geothermal systems where dating studies suggest that the fields may be 100 000s of years old whereas in this case it may be just 100s as the fissure eruptives at Karthala cut historically dated lava flows (Bachèlery and Coudray, 1993). This may only be possible because hot spot volcanism in comparison to arc volcanism has overall lower gas contents and lower amounts of gases that upon condensation can form acidic waters (Giggenbach, 1992). This may be accentuated in oceanic rifts because much of the magmatic gas will be lost from the magma in the main eruptive centre before the magma moves laterally into the rifts. This means that even though oceanic rift geothermal systems are very young they need not have acidic reservoir waters.

Thus the conceptual model in this case does not include a large convective system that will take a significant time from initiation until an exploitable field is present. The model involves long, relatively narrow geological features (the rifts) where permeability is both concentrated and highly inhomogeous along with long and thin heat sources in the form of young dykes. The nature of the permeability will evolve with time. The rift will propagate through normal faulting, but initially these faults may be filled with magma and lose their permeability. Since the rift will still be under tension more normal faults will form when the dykes solidify and may preferentially form along the dyke contacts which may in turn be filled with magma. This process will continue until either there is no more mobile magma available or the dykes are cooled sufficiently to develop cooling fractures which should be orientated at right angles to the normal faults. This means that a network of permeable fractures will form in and around the dykes allowing efficient heat transfer from them to the reservoir water.

The dykes may be so young that there is still molten magma at their base (as found at Puna; Teplow et al., 2009). As the dykes are being cooled, geothermal reservoir waters and permeability are being generated by contraction fractures caused by meteoric waters entering the rifts. In the case of Karthala the rifts terminate prior to reaching sea level and there is unlikely to be seawater recharge as at Puna. The recharge is considered to be rain water which has fallen on the highest northern slopes of Karthala and then percolated down the upper part of the rifts thus providing sufficient hydraulic head that the water is pushed along the rift (Figure 7). Initially the geothermal reservoir will be dynamically constrained by the presence of the overlying ground waters that originated at lower elevations. However, temperatures will be high enough for steam to form, which upon condensing into the overlying ground waters alters the rock to form the clay cap that excludes the shallow ground waters. The clay cap should propagate down the rift with time. Once it does the amount of cold water coming into the rift will be restricted to that coming from higher elevation. This will slow cooling of the rift particularly since where the rift terminates at lower elevation onward flow to outside the rifts may be restricted by the lack of normal faulting.

6. RESOURCE ASSESSMENT

A final interpretation of the MT results is required before a more definitive resource assessment can be made. Thus the potential resource area has been defined geologically as that in which young fissure eruptives are abundant in the area of the solfatara and to the NNW (Figure 3). An average temperature of 280°C is taken as the most likely case for a stored heat calculation as it takes into account the cooler margins away from the solfatara that gas geothermometry was obtained. Other input data for the most likely case for a stored heat calculation have been conservatively estimated given the sparseness of the data. A P50, most likely case, gives 43 MWe. Given the 10 MWe proposed size of the development the estimate looks promising.

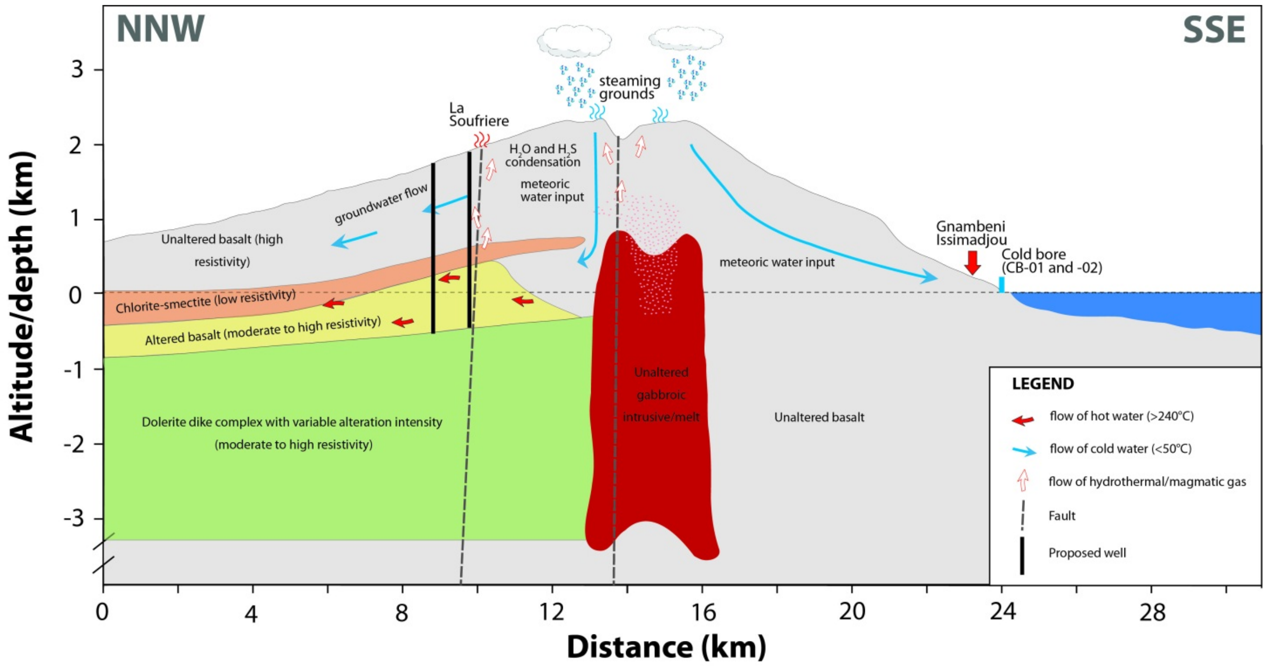

Figure 7: Schematic conceptual model along the rift hosting known thermal activity.

4. CONCLUSIONS

Geothermal exploration was undertaken in 2014 and 2015 on Grande Comore of the Comoros Islands. The majority of the thermal features are directly related to the caldera of Karthala volcano, but with little geochemical or geophysical support for there being an exploitable geothermal system beneath the caldera.

A solfatara on the upper northern flanks of the volcano within a rift has both gas chemistry and the resistivity pattern of a potential resource at depth. It may be analogous to the successfully developed resource at Puna, Hawaii.

Further interpretation of the geophysics is required to firm up the potential resource size. However, there is a reasonable expectation that a 48 MWe resource may be present. This is sufficient to meet the planned initial development size of 10 MWe.

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