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Updating of the Descriptive Conceptual Model of the Paipa Geothermal System, Colombia

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ABSTRACT

Based on the integration of a 3D geological model constrained by potential fields geophysics, a magnetotelluric 3D inverse model, and updated geological and geochemical information, a new descriptive geothermal model is proposed for the Paipa geothermal system. The system is hosted in a sedimentary environment, where it coexists with a sodium sulfate saline water circulation circuit and with rocks enriched in radioactive elements. The sedimentary sequence is intruded by two dome complexes (Alto Los Volcanes and Alto Los Godos) and hypabyssal rocks and is partially covered by pyroclastic deposits from the volcanic activity. Sodium sulfate saline hot springs, with temperature up to 76°C, with abundant gas discharges are concentrated in two zones structurally controlled. The proposed conceptual model describes a main magmatic heat source and the possible radiogenic heat contribution from igneous rocks enriched in 238U, 232Th and 40K. The main recharge zone comes from the outcrops of sandstones from a Cretaceous sedimentary formation (Une) from the east and southeast in the Tibabosa-Toledo Anticline. A deep recharge (to the basement) would occur towards the north from the circulating water through the Une formation, which, in the valley where the system occurs, underlies the younger sedimentary sequence by following extensive structures as faults, crosses between faults and the contact planes of igneous intrusions with rocks from the basement and the sedimentary cover. A sedimentary reservoir is located in the Une formation from the geothermal fluid up flow, between the dome complexes. The proposed cap rocks consist of clayish levels from the sedimentary sequence. The discharges zones are known as La Playa and ITP-Lanceros sector. La Playa sector and consists of few low flowrate hot springs (~0.2 l/s), one of which has the highest temperature in the system, and one low pressure and low temperature (70°C) steam vent. The ITP-Lanceros is shaped by several springs of higher flowrate (up to 6 l/s) and temperature up to 72°C. Two sodium sulfate low temperature springs with the highest total dissolved solids concentration in the area represent the endmember of a mixing process experienced by the hot water along its path to the surface. The mixing process causes a chemical and isotopic masking of the geothermal water composition. The alkaline geothermometers are not reliable. A simple enthalpy-silica model suggests a maximum temperature around 230°C. The hydrothermal alteration in xenolites points out temperatures up to 320°C. The high 3He/4He ratios suggest the contribution of a magmatic gas source.

1. INTRODUCTION

Geological frame.

The Paipa's geothermal system is located in the Eastern Cordillera Sedimentary Basin, about 180 km NE from Bogotá, in a compressive tectonic environment, controlled by Boyacá and Soapaga regional faults. The local structural features include thin skin and low angle faults and thick skin and high angle faults. (Fig. 1). The northwest zone is dominated by low skin-reverse faults as El Hornito, Canocas, Santa Rita, El Tuno, El Bizcocho, El Batán and Buenavista. Towards the east and south of the area, thick faults prevail, some of them normal as Paipa-Iza, Cerro Plateado and Las Peñas and some of them reverse as Lanceros and Aguatibia faults (Velandia, 2003). The geological map in scale 1:25.000 describe a basement formed by metamorphic rocks (filites, schists and gneises) and Paleozoic sedimentary rocks. The sedimentary cover consists of Cretaceous rocks which sequence from bottom to top is formed by Tibasosa, Une, Churuvita, Conejo, Plaeners, Los Pinos, Labor y Tierna and Guaduas, Paleogene rocks as Bogotá formation, Neogene rocks as Tilatá formation and the Quaternary (alluvial, lacustrine and fluvial-lacustrine deposits, as well as a hydrothermal breccia (Fig. 1B). The rocks from the sedimentary sequence consist of levels of sandstones, claystones and siltstones excepting by Labor y Tierna and Plaeners formations which consist of quartz.sandstones and fractured siliceous lidites. In addidtion, Guaduas formation presents coal mantles, Tilatá formation has layers of lignite, the formations Tibasosa, Churuvita, Conejo and Los Pinos, present limestone levels and Tibasosa, Churuvita and Conejo formations, levels of shales (Velandia, 2003).

In the middle zone from the geothermal area pyroclastic deposits and domes related with Paipa Volcano, were mapped by Cepeda & Pardo (2004). In this report the authors verified the volcano composition as rhyolitic – trachytic with alkaline affinity composition and, based on the deposit's characterization, defined the volcano activity in 14 eruptive units.

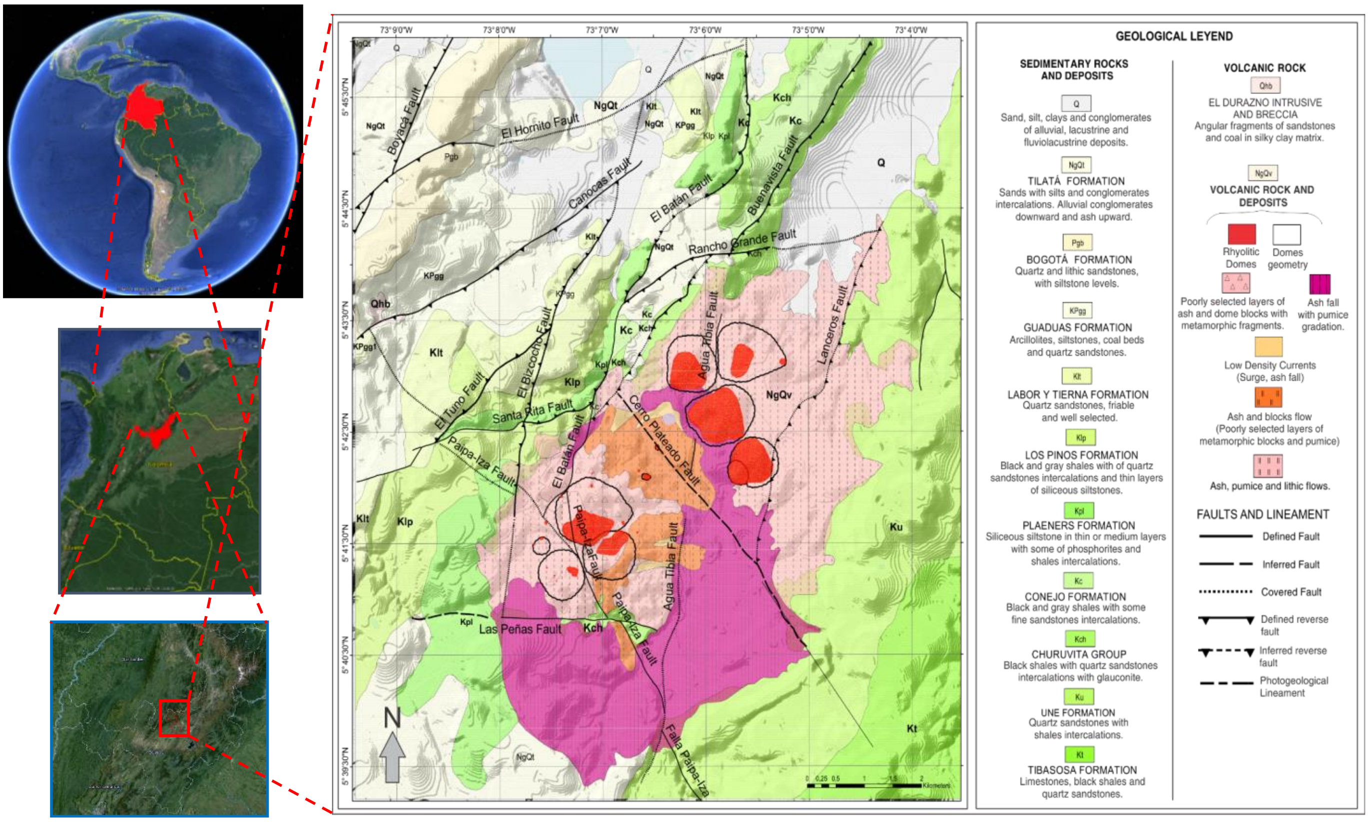

Figure 1: Paipa's geothermal Area. A. Regional tectonic frame (Velandia, 2003). B. Geological map scale 1:25.000 (Velandia, 2003); vulcanites map (Cepeda&Pardo, 2004); domes' map (Rueda-Gutierrez, 2016).

Background on Paipa's geothermal system

The geothermal system of Paipa, and more specifically its hot springs, was reported since the first half of the XIX Century when researchers from Europe toured South America in scientific trips (Boussingault & Roulin, 1849). Navia & Barriga (1929) registered relevant geological descriptions including the identification of extrusive igneous rocks and carried out a detailed geochemical study. Many years after, through the geothermal reconnaissance study (OLADE, ICEL and Geotérmica Italiana, 1982), the chemical analysis of the hot springs was updated, rocks from one of the igneous domes was dated in 2.5 Ma and the system was classified as medium-high priority as a geothermal prospect. Subsequent work has been integrated to formulate at least four (4) conceptual models, which are briefly described next. Ferreira & Hernández (1988) conducted geologic observations and chemical characterization of hotspring waters, from which posited a geothermal system being formed by a heat source derived from an intrusion magma, inferred from the presence of bodies volcanic; a reservoir of primary permeability probably stayed in the Une formation, with geochemical temperature of more than 200°C; a cap rock formed by claystones from the Churuvita formation and a recharge area associated with outcrops of the Une formation and, a deep fluids discharge conducted by normal NE-SW normal faults.

Lozano (1990) integrated a geoelectric study to the geological information of Olade, ICEL & Italian Geothermal (1982) and proposed a system with a heat source related to volcanism present in the area, located between 3 and 5 km deep, in two reservoirs. The first reservoir, housed in the Guadalupe group (shaped, in this zone, by the formations Plaeners and Labor y Tierna) would be shallow and small and would have the Guaduas formation as the cap rock. The second one, located deeper into the Churuvita and Une formations, would be thicker and would have Conejo formation, made of impermeable rocks, as the cap rock. The most interested zone was defined in terms of resistivy towards the north of the geothermal area, between 10 and 20 $\Omega{\cdot}$m, in an elongated NE polygon which includes the artificial Sochagota Lake and a NE structure named as El Salitre Fault.

Alfaro et al. (2005) proposed a conceptual model based on the integration of results from some studies carried out as a part research of this geothermal area: geology map and structural model in scale 1:25.000 (Velandia, 2003), study of the volcanites (Cepeda & Pardo, 2004), geochemistry and isotopes of hot springs (Alfaro, 2002a; Alfaro, 2002b), as well as preliminary studies of hydrothermal alteration (Alfaro, 2005a), gas geochemistry (Alfaro, 2005b), radon emmanometry (Alfaro & Espinosa, 2004) and geoelectrical study (Vásquez, 2005). According to this model, the geothermal system is located inside a volcanic caldera formed by Paipa Volcano, at the end of the first of two eruptive epochs. The heat source of the system is the cooling magma intrusion younger than 2.5-2.1 Ma. The local recharge zone has secondary permeability and is defined by circular structures left around the igneous intrusions (domes) and fractures from the siliceous lidites belonging to the Plaeners formation. A deep reservoir in fractured rocks would be located around extensive basement faults (Paipa-Iza and Cerro Plateado) which are also considered as possible magma conduits. Shallower reservoir(s) would stay in primary permeability levels from the sedimentary sequence, where lateral extension would allow the geothermal water to flow towards the recharge zone to the north of the area. The hydrothermal fluid would have reached around 320°C and it is likely that at present it mantains high temperature conditions (above 225°C). The fluid flow goes from south to north to the discharge zone which is controlled by faults, crosses, and extensive zones related to tectonic block rotation. The main discharge zone occurs in the sector known as ITP-Lanceros in the cross between El Bizcocho and El Hornito faults. There, a thermal spa, property of the mayoralty, and a hotel were built. The deep fluid experience mixing processes with a high salinity sodium sulfate source that masks chemical and isotopes composition of the geothermal fluid. This is why the discharged fluids are not representative of the reservoir. On the other hand, the gas composition indicates the contribution of an organic source, possibly coming from the sedimentary sequence.

Within the frame of the same research from the SGC, complementary surface studies were carried out: surface hydrothermal alteration (Valentino, 2008), inventory of water point inventory (Ortiz & Alfaro, 2010), a preliminary assessment of the meteoric water isotope composition (Alfaro, 2012), gravity and magnetic study (Vásquez, 2012), prospection by geoelectric method (Franco, 2016) and preliminary modelling of the resistive structure by magnetotellurics (Moyano, 2013). In addition, the SGC, through the Energetic Resources Exploration Group conducted a uranium exploration study to the South of Paipa locality (González, et al., 2008). From the integration of these complementary studies some adjustments were done to the previous conceptual model (Alfaro et al., 2012): The regional recharge comes from the Anticline Tibasosa-Toledo through Une formation, where it outcrops in a large extension. The geological body mapped it as a hydrothermal breccia (Fig. 1B), actually it is an intrusive body highly altered with anomalous ^{238}U, ^{232}Th and ^{40}K concentrations, whose radioactive disintegration could provide complementary heat to the system. The hot fluid reservoir would stay in the sedimentary sequence between the resistive basement and a very conductive layer shaped by cap rocks and the circulation of saline sodium sulfate fluids (Alfaro et al., 2012).

2. NEW EXPLORATION STUDIES

In addition to the mentioned studies other studies were carried out as part of the research of Paipa's geothermal system: domes mapping, characterization of core samples from holes drilled in El Durazno intrusive body, 3D geological model constrained by gravity and magnetic data, 2 and 3D final magnetotelluric models, shallow temperature surveys and updating of the geoelectrical study. These studies are described next.

2.1 Domes mapping

From observations and analysis of new outcrops and revision of precedent studies (Hernández & Osorio, 1990; Valentino, 2008), the volcano structure hypothesis was rethought. The existence of two volcanic complexes was confirmed in the geothermal area. They were called Alto Los Volcanes and Alto Los Godos. Between them the valley of the Quebrada Honda creek and smaller domes of similar composition are located (Rueda-Gutierrez, 2016). See Fig.2.

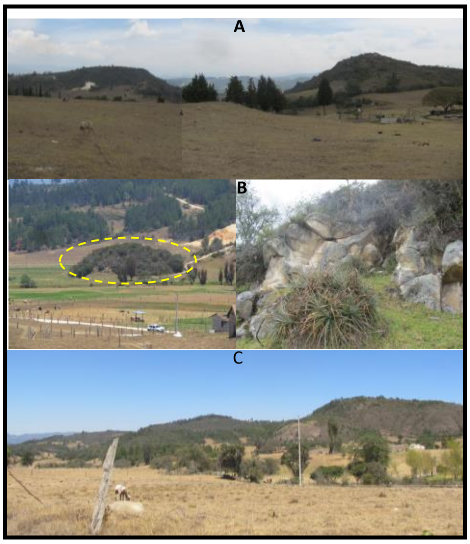

Figure 2: Overview of igneous domes in the geothermal area of Paipa. A. Alto Los Volcanes dome complex. B. Dome of the Quebrada Honda valley. C. Alto de los Godos dome complex. Taken from Rueda-Gutierrez (2016).

Rueda-Gutierrez (2016) compiled and reported new dating on igneous rocks from Paipa geothermal area, as follows: the pyroclastic deposits of the area range between 1 to 9.9 Ma dated by fission tracks' method. Rocks from the Alto Los Volcanes dome complex were dated in 1.0± 0.25 and 2.6±0.7 Ma by fission tracks' method and in 1.76± 0.002 Ma by the Ar-Ar method. The dome of Quebrada Honda's valley was dated in 1.81±0.024 Ma by Ar-Ar method and, by using the same method, the Alto Los Godos dome complex was dated in 2.6 ±0.0021, 2.71 ±0.0025 and 2.80 ±0.031 Ma.

2.2 Radiogenic heat estimation in El Durazno igneous intrusion

At least three anomalies of radioactive elements were found in Paipa's geothermal area (González et al., 2008). The biggest one was found in the El Durazno intrusion (Figure 3) where 4 holes, 50 to 100 m deep, were drilled with core recovery from top to bottom. Rodríguez-Ospina & Alfaro-Valero (2015) characterized those core samples by a macroscopic description, mineralogical analysis and gamma spectrometry analysis. The highest ^{238}U, ^{232}Th y ^{40}K concentrations are 370 ppm, 130 ppm y 8%, respectively. Based on the average concentrations, the radiogenic heat was estimated for the four holes in 9.6, 12.5, 9.7 y 8.3 Wm^{-3}. A wider description of this work is presented in a separate paper at this conference (World Geothermal Congress 2020).

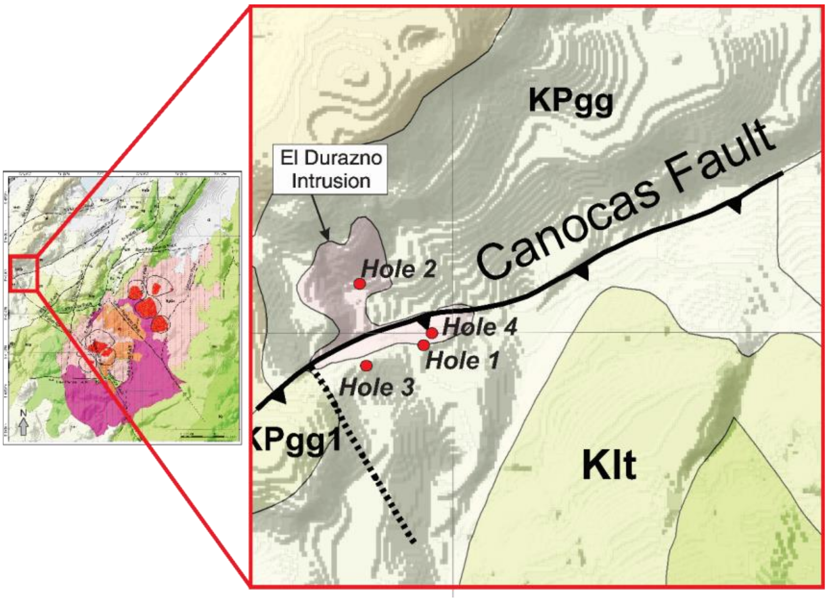

Figure 3: Location of drilled holes in El Durazno intrusion. Taken from Rodriguez-Ospina & Alfaro-Valero (2015).

2.3 Geological 3D model constrained by gravity and magnetic data

As a result of the stochastic inversion of a 3D direct geological model (Figure 4), the geophysical gravity and magnetics data (Figure 5), by using the software Geomodeller, a 3D lytho-constrained model was obtained (Figure 6) (Llanos et al., 2015). Other products from the modelling include density and magnetic susceptibility 3D models. According to the density model interpretation (Alfaro, et al., 2017), the densities of the basement rocks and the magmatic intrusions are comparable. They remarkably contrast with the rocks from the sedimentary sequence and define the geometry of a possible sedimentary reservoir between them, originated from the geothermal fluid upflow.

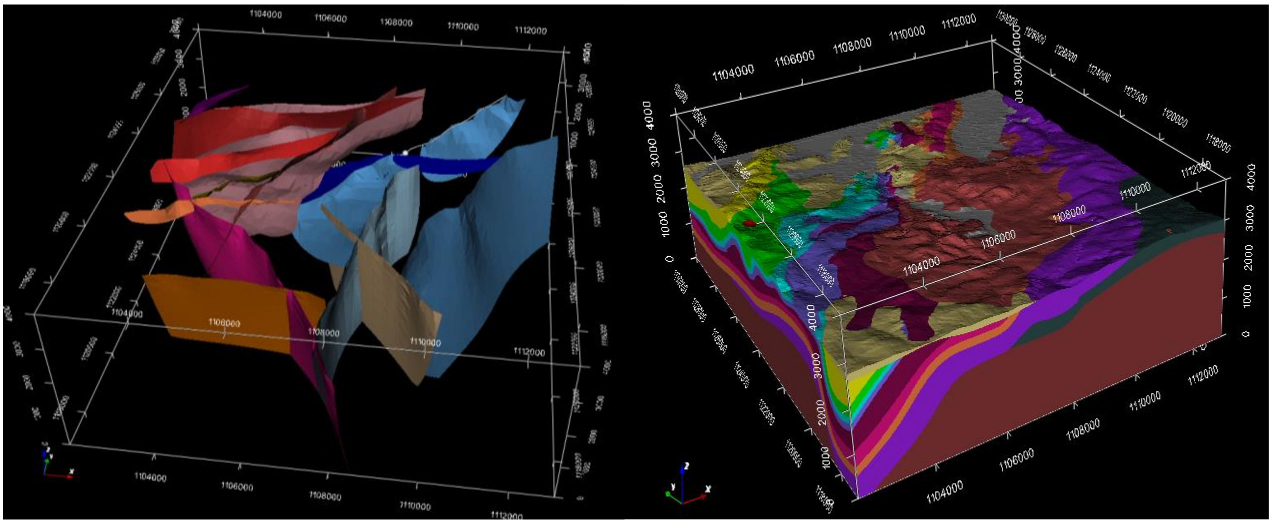

Figure 4: 3D direct models. Left: faults. Right: geology. Taken from Llanos et al., (2015)

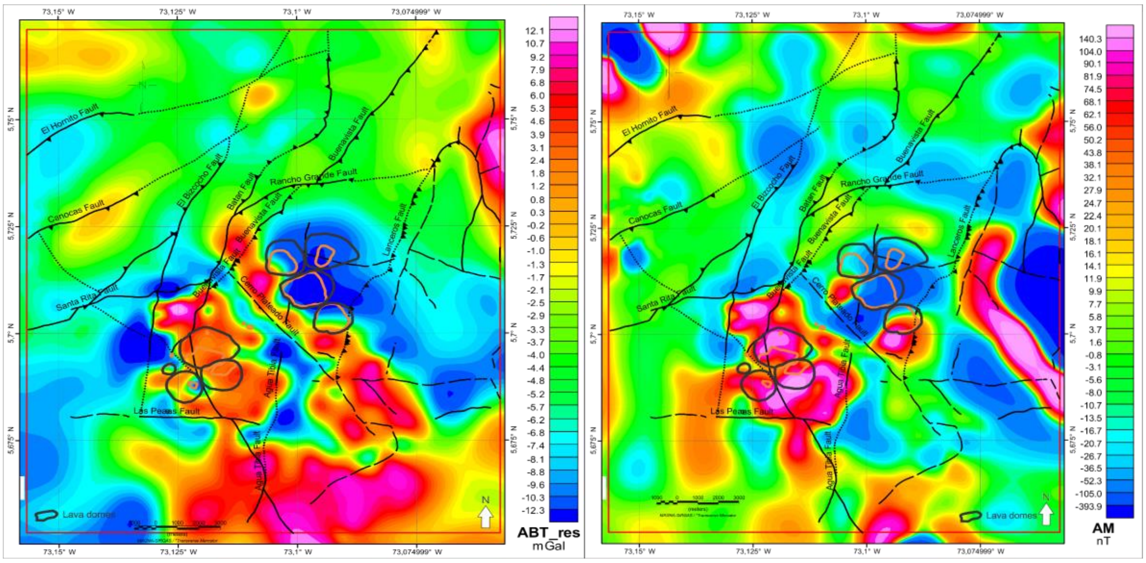

Figure 5: Geophysical grids used for the stochastic inversión. Left: Residual Bouguer's anomaly. Right: Total magnetic intensity field. Taken from Llanos et al., (2015). Structural model, taken from Velandia (2003).

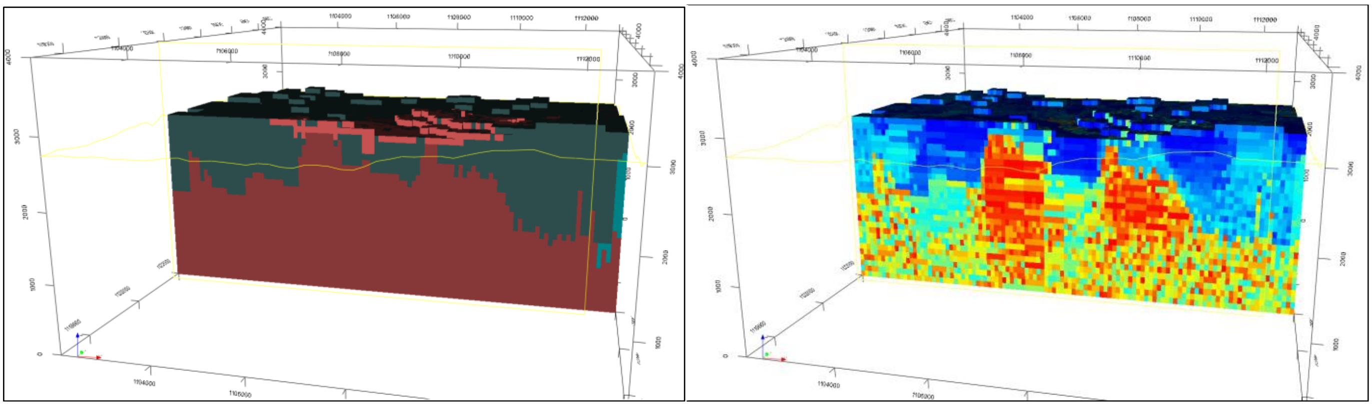

Figure 6: Products of the 3D inversion. Left: 3D geological model (lytho). Right: 3D density model. The low density zone (in blue) between high density rocks (in red) is posted as a shallow sedimentary reservoir.

2.4 Magntetotelluric 2 and 3D models.

From magnetotelluric soundings, 2 and 3D resistive structure models were obtained for Paipa's geothermal area (González-Idárraga & Rodríguez-Rodriguez, 2017; Siripunvaraporn, 2016). Three main resistive zones were defined: between 300 and 1000 Ω.m, towards the east of the area down to the modelling depth (4 km) bellow the anticline Tibasosa-Toledo; <10 Ω.m, mainly to the west and northwest down to 2-3 km deep and, between 1 and 300 Ω.m, in the rest of the area. They are illustrated in horizontal sections from the 3D model in the Fig. 7. According to the interpretation by Alfaro et al. (2017), the high resistivity zone corresponds to the crystaline basement which is shallow towards the Eastern limit of the geothermal area and there corresponds to the core of Tibasosa-Toledo anticline. Igneous solid and degassed intrusions, as those posed underlying the Alto Los Volcanes dome complex are also resistive with similar resistivity to that of the basement rocks (Fig, 10). The very low resistivity zone possibly corresponds to the circulation circuit of sodium sulfate saline water which is near to the surface extends in a NE direction around the strip between El Hornito and Canocas faults. The intermediate resistivity would be related to the sedimentary sequence. Note that, as expected, in a sedimentary geological environment, the possible sedimentary shallow reservoir and the cap rock, assumed in clayish level of the sedimentary sequence, do not produce a resistivity contrast as it is normally observed in geological environments dominated by igneous rocks.

2.5 Shallow temperature soundings

Temperature measurements at 150 cm deep, excluding hot springs emergency zones, allowed to determine an average soil temperature of 4.9° C above the environmental average temperature. Two (2) main positive anomalies about 8.5 °C above the same reference temperature (Fig. 8), were observed. The first anomaly is located in the zone where NE faults of El Bizcocho and El Batán cross Santa Rita, El Tuno and Paipa-Iza faults, NW of Alto Los Volcanes dome complex. The second anomaly is located in the strip between El Hornito and Canocas faults NE from El Durazno igneous body (Rodríguez & Vallejo, 2013). A third anomaly of lower magnitude and defined just for fewer data is located between Buenavista and Agua Tibia faults, N from the Alto Los Godos dome complex. According to Alfaro et al. (2017), the first mentioned anomaly could be related to warm (34°C) low salinity circulation water that is discharging from a 97 m deep well (ITA Well) located at about 3 km NE from El Durazno. Negative shallow temperature anomalies are observed between the dome complexes zone which was attributed to the thermal isolation produced by altered pyroclastic deposits.

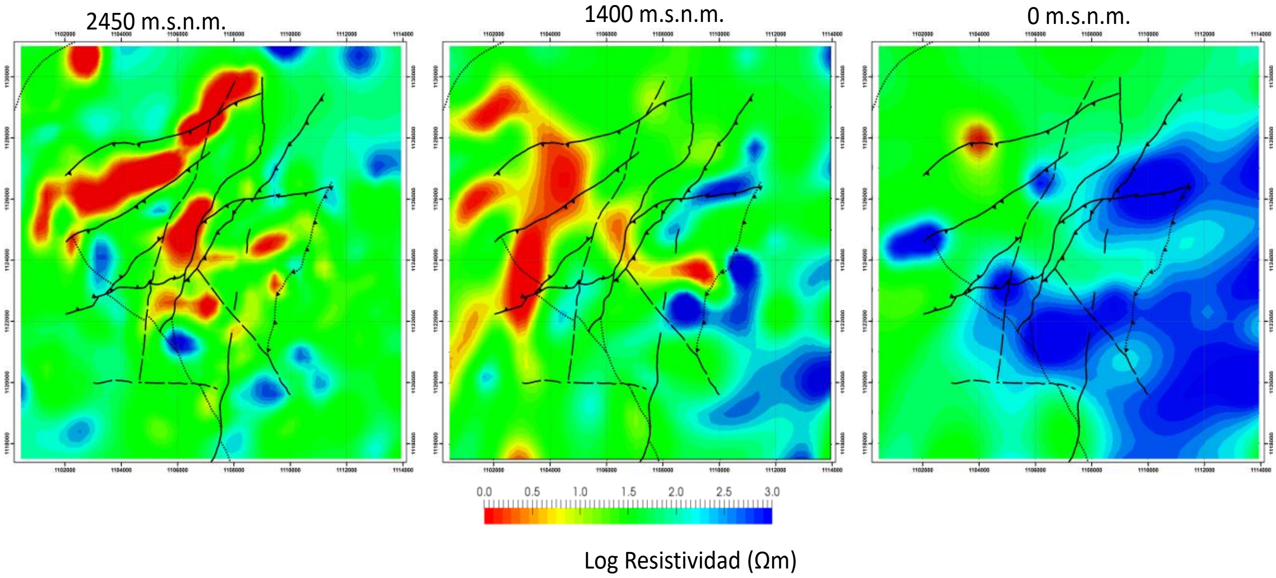

Figure 7: Horizontal sections from the 3D magnetotelluric model (Siripunvaraporn, 2016; In González – Idárraga and Rodríguez-Rodríguez, 2017): 2450, 1440 y 0 m.a.s.l., a partir del modelo 3D. Taken from Alfaro et al. (2017).

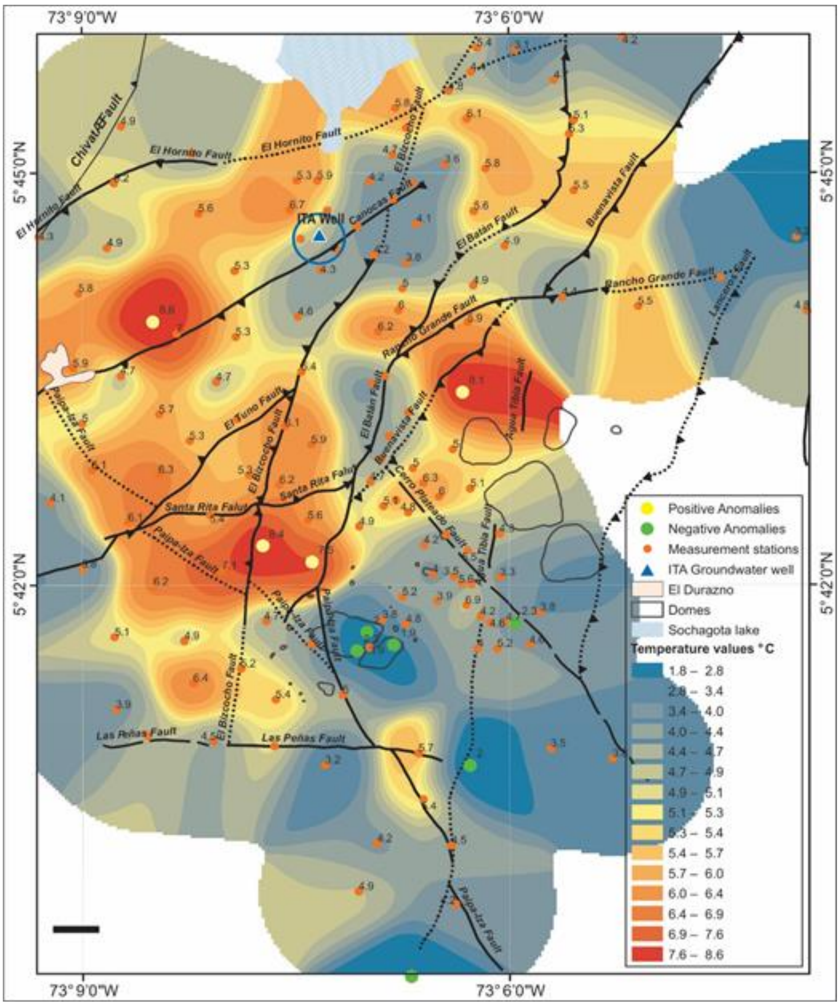

Figure 8: Shallow temperature soundings. Temperature anomalies at 150 cm depth. Taken from Rodríguez & Vallejo (2013).

2.6 Geoelectrical study update

The geoelectrical study based on vertical electrical soundings whose investigation depth was about 300 m, allowed to determine that near the surface Paipa geothermal area is dominated by relatively low resistivities (< 400 Ω.m), with extensive conductive anomalies, observed in Figure 9 (Franco, 2016). According to the author, the conductive anomalies would be related to the rock's saturation with hydrothermal and saline water. Alfaro et al. (2017) related the highest conductive anomaly (around 1 Ω.m) to the Chicamocha river topographic low to the east of Sochagota Lake, where the sodium sulfate water gets its highest concentration. Other conductive anomalies (between 5 and 10 Ω.m) could be related to the water circulation of a lower salt concentration, hydrothermal fluid circulation and clayish levels inside the sedimentary sequence.

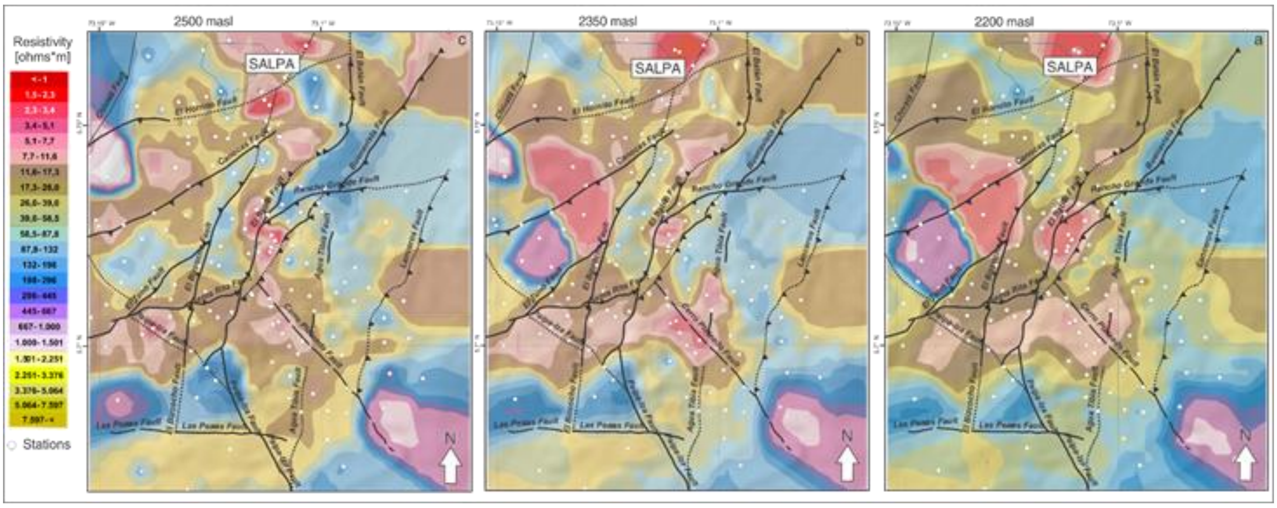

Figure 9: Isoresistivity maps from SEVs. Left: 2500 m.a.s.l. Center: 2350 m.a.s.l. Right: 2200 m.a.s.l. Taken from Franco (2016)

3. UPDATED DESCRIPTIVE CONCEPTUAL MODEL

From the joint interpretation of the 3D geological model, and particularly from the 3D density model, with the results of previous and new studies, in addition to general hydrogeological considerations regarding mainly the permeability and dip of the stratification planes of sedimentary rocks, Alfaro et al. (2017) posed an updated descriptive model presented in the Figure 10 and described below.

Paipa geothermal system is located in terrain tilted to the north, limited to the east and southeast by a topographical elevation that corresponds to the Tibasosa-Toledo Anticline, whose western flank presents extensive outcrops from Une Formation, formed by sedimentary high permeability rocks which act as a regional recharge zone. In the valley, a deep infiltration occurs through normal estructure such as Paipa-Iza and Las Peñas faults and crosses between faults (Paipa-Iza and Agua Tibia). The groundwater is heated by interaction with the magmatic crystallized intrusion underlying the igneous dome complexes (Alto Los Volcanes and Alto Los Godos. This heat source could come from the residual heat of magmatic events. It could be complemented by the radiogenic heat derived from the concentration of radiogenic elements in those igneous intrusions. Los Godos. This heat source could come from the residual heat of magmatic events. It could be complemented by the radiogenic heat derived from the concentration of radiogenic elements in those igneous intrusions.

The upflow of the geothermal fluid would occur from the contact planes between igneous intrusions and basement rocks at depth and with the sedimentary sequence at shallower depths. In the mentioned sequence, Une formation would act as a sedimentary reservoir in Quebra Honda valley, between the two dome complexes, south from Cerro Plateado fault.

In the valley, the intersection of the geothermal fluid is prevented by impermeable layers which possibly correspond to clayish layers from the sedimentary sequence and/or altered pyroclastic deposits. The outflow towards the north, presumably through the same Une formation, is favoured by the NW Cerro Plateado fault up to the western limit of Une formation which roughly corresponds to El Bizcocho fault trace on surface. From there, the flow direction turns to the northeast until it finds enough permeability to give rise to the main discharge zone (ITP-Lanceros Sector). It happens to the right of the cross between El Bizcocho and El Hornito faults, in an area influenced by Labor y Tierna, a high permeability formation. At about 1 km to the north of Cerro Plateado, below the cross between El Batán and Rancho Grande faults, exists a small and scanty discharge zone called La Playa, which is made of one steam vent and a few hot springs; one of them, El Batán, is the hottest hot spring of the system (76°C) which salinity reflects the smaller contribution of the saline sodium sulfate source.

Along the outflow, possibly throughout the Cerro Plateado fault, the geothermal fluid mixes with the lower temperature saline water and gets the contribution of organic gases. Due to the mixing processes the geothermal fluid loses its chemical and isotopic signature which prevents a reliable estimation of the reservoir temperature. However, this could be or could have been a high temperature system (>230°C), from the non-pervasive hydrothermal alteration identified in xenolyths.

On the other hand, a shallower circulation network of lower temperature, but still thermal, is posed in the strip defined between the NE faults El Hornito y Canocas. Its heat source could be related to radiogenic heat from El Durazno (?). This circulation flow would be isolated from the sodium sulfate saline water which would follow the same NE strip but to a greater depth.

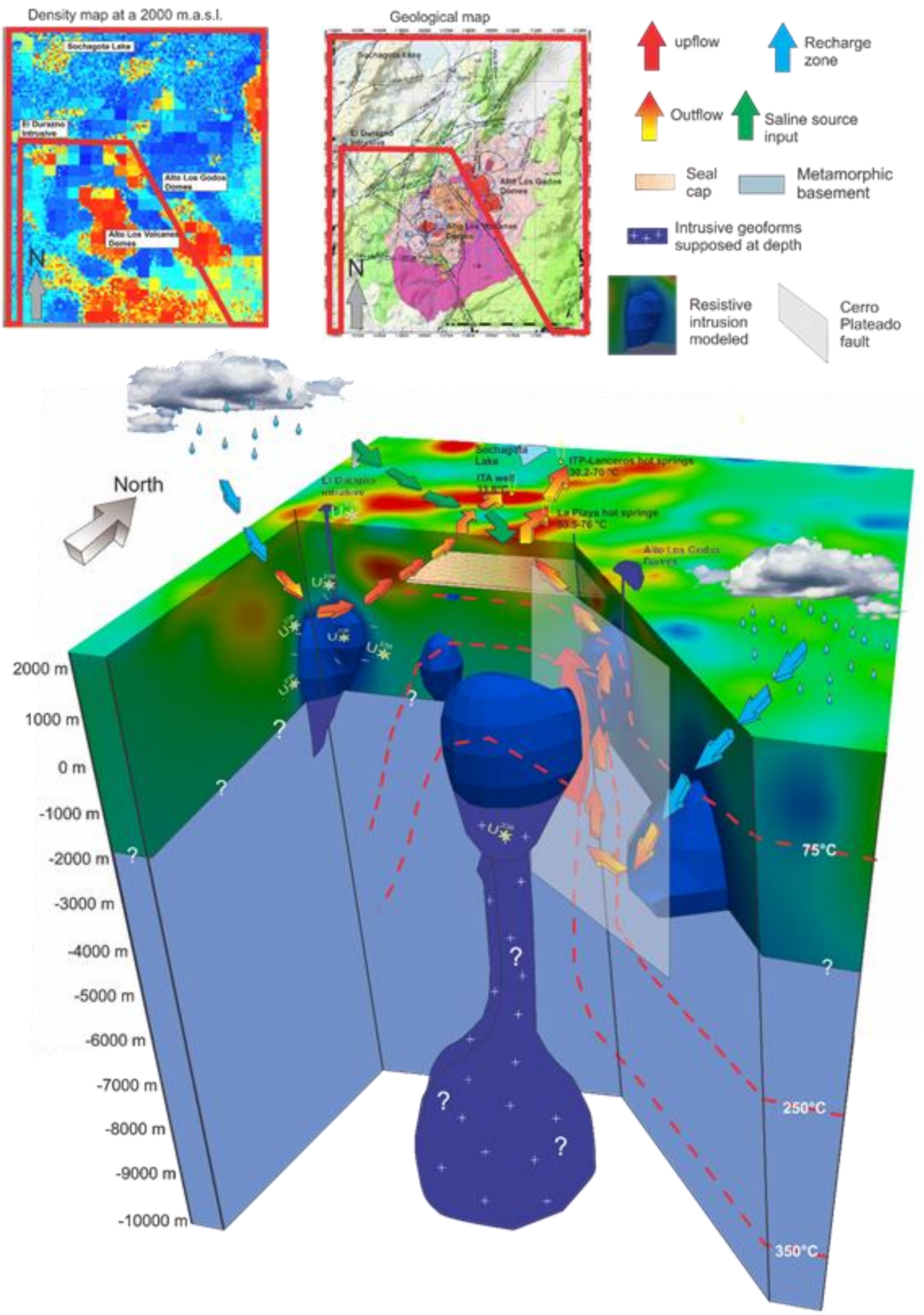

Figure 10. Schematic diagram of the updated descriptive conceptual model of Paipa's geothermal system. Horizontal plane: resistive (magnetotelluric) model (in red, conductive zones related to circulation of brackish water which mixes with geothermal fluid). Taken from Alfaro et al. (2017).

5. RESOURCE ESTIMATES AND FUTURE STUDIES

From the current model (a rough preliminary estimation of the resource) by applying the heat in place method (USGS) with Montecarlo simulation, indicating power of 18 MW, on the basis of a reservoir of 3.5 km^3 (extension of 5 km^2 and thickness of 0.7 km), 230 °C, rock's thermal capacity of 0.8 kJ/kg °C, rock density of 2500 kg/m3, a project life of 30 years, thermal recovery factor of 10%, utilization factor of 12% and plant load factor of 80%. Although the estimated power generation is not on a large scale, it could benefit the air quality as its production could substitute the power produced from a local active coal fired power station. On the other, the geothermal resource could be utilized in multiple direct uses. Considering the basis of Paipa's economy, the best options for utilization could be grass drying, milk pasteurization,d and space heating.

Based on the current scope of the prefeasibility studies, a new stage of studies is being developed. This includes drilling of geothermal gradients holes and gas chemical and isotopic study. With these studies, the target of the prefeasibility studies assumed by the Colombian government will be achieved. Future prefeasibility and feasibility stages should be carried out by companies from the energy sector. The geothermal gradient holes drilling plan includes two (2) holes of about 500 m depth with total core recovery and to complete well logging and temperature measurements for a period of twice the drilling time. Besides the vertical gradient estimation, the purpose of the holes is the direct observation and confirmation of the modelled geological structure, measurements of geophysical parameters and sampling intercepted aquifers.

The gas geochemistry study intends to complete and update previous efforts to characterize the abundant gas discharges of the surface hydrothermal manifestations of Paipa's geothermal system, and to establish the possible current influence of the magmatic source.

6. CONCLUSIONS

Paipa's geothermal system has singular features derived from 1) the sedimentary environment where is located, 2) the evidence of persistent magmatic activity for about 9 Ma in the last 10 Ma, 3) the presence of igneous rocks with relatively high concentration of radioactive elements, 4) the coexistence of the geothermal fluid circuit with a saline sodium sulfate circuit and, 5) the presence of hydrocarbons (coal mantles and oil seeps) in the sedimentary sequence.

The main regional recharge zone would be the western flank of the Titasosa-Toledo Anticline on high extension outcrops of the Une sedimentary formation.

The crystalline basement possibly hosts a deep reservoir's lateral extension which is limited to fractured rocks in the vicinity of the heat source (igneous intrusions) with temperature above 230°C.

The heat source is magmatic and is related to the residual heat of the intrusions, which could be younger than those dated on surface (as inferred from the helium isotopes ratio in hot springs, from which, its results are not presented in this paper) and possibly, to radiogenic heat, as it is suggested from the relatively high radioactive elements concentrations around the dome complexes and El Durazno igneous body.

The geothermal fluid upflow is conducted through contact between the magmatic intrusions and the rocks located in the basement or the sedimentary sequence. It gets accumulated at shallow depth in Une formation, between the two volcanic dome complexes forming a sedimentary reservoir.

The cap rocks of the shallow sedimentary reservoir would correspond to claystone levels from the sedimentary sequence, particularly from Une and Churuvita formations, and the altered volcano-sedimentary deposits. This structure in sedimentary environment, does not show resistivity contrast in magnetotellurics.

This system has two main discharge zones shaped by hot springs and one steam vent in the sector known as ITP-Lanceros and La Playa. The chemical and isotopic composition of the fluid discharged by the hot springs reflects mixing processes with a saline sodium sulfate source and with organic gases, which prevents a reliable estimation of the current temperature at the reservoir. However, the mineralogy of the low intensity hydrothermal alteration poses that Paipa be a high temperature system.

Paipa's geothermal system has potentiality for power generation (18 MWe) and for direct uses.

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