Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

# Comparative Subsurface Geology and Hydrothermal Alteration of Pad A and Pad E Wells in Sorik Marapi, North Sumatra, Indonesia

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**Keywords:** Sorik Marapi, subsurface geology, hydrothermal alteration, permeable zones

## ABSTRACT

The Sorik Marapi Geothermal Project is a greenfield area located within the administrative region of Mandailing Natal in North Sumatra, Indonesia. Fast-tracked exploration and development drilling operation in Sorik Marapi geothermal field commenced in late 2016, successfully completing 18 deep wells in 2018. The first well drilled is Well A-101 in Pad A, situated close to the eastern flank of Mt Sorik Marapi and immediately west of the main Sumatran fault. The success of initial wells drilled on this pad encouraged exploration drilling in Pad E, about 4.5km NNE of the volcano.

To date, Pad A holds seven directional wells, drilled to a maximum depth of 2100mVD. The wells penetrated three volcanic units; Sibanggor Volcanics - the oldest composed mostly of altered undifferentiated volcanics; Roburan Volcanics - a relatively thin layer of predominantly Dacitic rocks and Sorik Volcanics - the youngest andesitic rocks overlying all other formations. Similarly, the two wells drilled in Pad E encountered these same formations, but Roburan Volcanics is notably extensive in this area of the field.

The dominant alteration mineral assemblage of A-series wells exemplified an alteration suite largely produced by neutral pH geothermal fluids. High-temperature alteration minerals are prevalent in the production zones of Pad A wells, where estimated formation temperature exceeds 250°C. On the other hand, Pad E wells showed low to medium ranked hydrothermal alteration mineralogy with subsurface temperature of less than 220°C.

The drilling results from Pad A confirmed the existence of a high temperature geothermal resource in Sorik Marapi's Resource Area 1. Contrarily, Pad E has now been found to have very low permeability and relatively cooler temperature, which revokes previous theory of a possible separate upflow in Area 2.

## 1. INTRODUCTION

Information on Sorik Marapi spans from the earliest reports on the thermal features, volcanic activity and hazards of the volcano as early as the 1920's. Characterization of its geothermal potential was initially undertaken by state-owned company – Pertamina in the 1990s. Under OTP Geothermal Pte. Ltd, more detailed geoscientific studies ensued between 2010 and 2016 which recognized and delineated the extent of the geothermal resource. At present, the geothermal project is owned and operated by KS Orka Renewables Pt. Ltd thru a local company known as Sorik Marapi Geothermal Power.

Previous geothermal investigations identified four (4) resource areas with possible separate upflows in Sorik Marapi – Areas 1, 2, 3, and 4 - based on the domal features obtained from the MT and gravity studies (SKM, 2011). Grounded on this interpretation, initial exploration drilling was prioritized in Areas 1 and 2, where Pad A and Pad E are constructed, respectively. Seven (7) wells were drilled from Pad A, while only two wells are completed in Pad E, after obtaining unfavorable results from this pad. Interpretations derived from early geoscientific studies has been redefined as more subsurface information becomes available. This paper provides an overview of the field's subsurface geologic conditions and sheds new understanding to the field's conceptual model, in light of new data from the recent drilling works in Sorik Marapi.

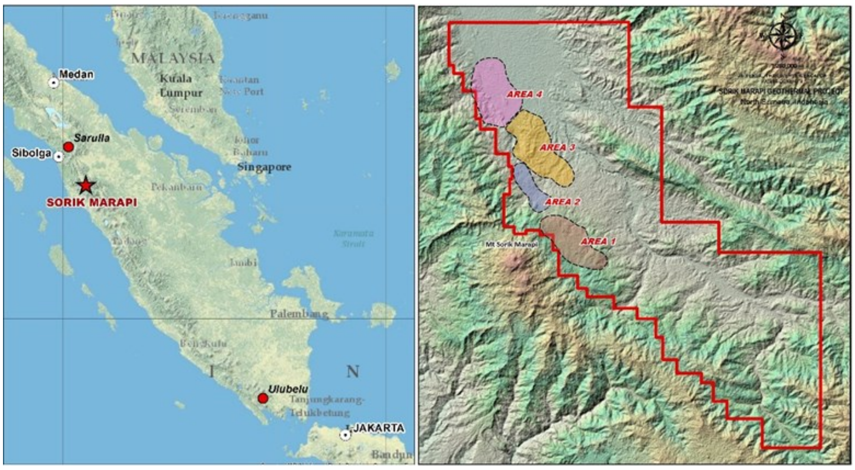


**Figure 1: Location map of the Sorik Marapi Geothermal Field showing the four resource areas recognized by SKM (2011)**

## 2. REGIONAL TECTONIC SETTING

Sumatra is the largest island in the Indonesian archipelago, located at the boundary between two colliding plates; the Indo-Australian and the Eurasian plates. On-going collision between these plates along the Sunda Trench generates NNE directed compressive forces acting upon the island (Barber 2000; Barber et al, 2003). The oblique compressional forces developed a trench-parallel shear component that resulted in a NW-SE right-lateral strike slip Sumatran Fault System (SFS).

The Sumatran Fault System (SFS) is a 1,900 km long right-lateral strike-slip fault which traverses the entire length of the Sumatra Island. It runs thru the length of the Barisan Mountains, the volcanic arc related to the Sunda trench. The Barisan Mountain is comprised of at least 35 volcanoes, one of which is an active strato-volcano – Sorik Marapi (2,145m). The geothermal sites in Sumatra are often associated with both the SFS and the young volcanic centers along the Barisan mountain range.

## 3. SUBSURFACE GEOLOGY

### 3.1 Stratigraphy

The stratigraphic units in Sorik Marapi as observed from the wells may be summarized into three (3) formations. From oldest to youngest, these are: (1) Sibanggor Volcanics, (2) Roburan Volcanics, and (3) Sorik Volcanics.

The Sibanggor Volcanics consists of thick, undifferentiated possibly Tertiary volcanic deposits with unidentified volcanic source. The rocks are frequently intensely altered with hardly discernible original fabric and composition and exhibiting high-temperature alteration minerals. Rock cuttings showed a general increase in well-formed secondary mineral crystals and abundant vein materials are observed specially within zones of fault intersections. The type of lithology, degree of alteration and existence of open fractures all indicate that this volcanic formation acts as the host for the geothermal reservoir.

The Roburan Volcanics is composed mainly of mesocratic to leucocratic dacite volcanics, dominantly lavas with well-preserved porphyritc texture and marked by the distinct presence of primary muscovite. This formation is relatively thin in Pad A wells (between 30m to 55m) and significantly thickens towards north in pad E, where more than 1000m thick of this formation was encountered.

The youngest Sorik Marapi Volcanics is comprised of unconsolidated, variably altered andesitic-dacitic lava and pyroclastics with minor occurrence of basaltic rocks. The young lava flow deposits radiate outwards from the active Sorik Marapi Volcano.

### 3.2 Structures and Permeability

Structural studies in Sorik Marapi have established the local structural pattern of the field. The dextral strike-slip Sumatran Fault System (SFS) which transects the Sorik Marapi geothermal field plays the pivot role in the formation of fault networks in the area. Continued movement along the Sumatran Fault generated synthetic and antithetic secondary fractures branching out from the main trace of the fault. These subsidiary structures are crucial in the development of the geothermal field as subsurface permeabilities are often associated with them. Based on drilling evidences (i.e., circulation losses) and completion test results, permeability of most wells are mainly controlled by faults targeted by the wells. Permeable zones identified during completion tests correspond to the depths of interpreted fault intersections. On the other hand, permeability associated with lithological contacts are quite limited.

There are at least three main fault trends associated with permeability in Sorik Marapi. These are faults oriented NNE, NE and roughly E-W. These set of structures are considered tensional, occuring in the same general direction as the subduction related main compressive force. These structures manifest permeability to the surface in form of vigorous fumaroles, thermal springs and altered grounds, particularly along major river systems (e.g. Sibanggor river, Maga river) which are coincident to the traces of these faults.

In the subsurface, apparent permeability along targeted structures are indicated by drilling breaks, massive circulation losses and eventual blind drilling of the wells. The permeable zones were later confirmed by completion test results, particularly among Pad A wells. In Pad E, however, permeability is considerably meager and fault targets appear to be tight and sealed.

## 4. HYDROTHERMAL ALTERATION

The dominant alteration mineral assemblage of A series wells exemplified an alteration suite largely produced by neutral pH geothermal fluids. Based on the distribution of secondary minerals and the amount and degree of epidote crystallinity in the cuttings, wells A-103 and A-107 appear to be drilled closest to the postulated upflow, while A-102 appears to have been drilled away from the main source as implied from the prevalence of medium ranked alteration throughout the bore.

At shallow levels (surface to 50masl), the alteration mineral assemblage of Pad A wells consists of silica + chlorite + smectite + calcite ± iron oxides ± pyrite, forming the argillic zone or clay cap of the reservoir. Smectite transitions to interlayered clays and completely dissipates at depth as high temperature illite + calcite + quartz become more prominent. The presence of common bladed calcite in Pad A wells at around +100 to +500masl insinuates boiling condition along these depths.

At deeper levels, neutral to alkaline environment remain evident with the noted presence of rare secondary amphiboles, temperature formation of which is at least 250°C. An assemblage of calcite + quartz + chlorite + illite + epidote ± pyrite ± wairakite are the most dominant alteration mineral towards bottom. This translates to an estimated temperature of ≥250°C at the bottom of A series wells. Abundant Epidote is observed in some intervals, but notably decreases as calcite becomes prevalent. The ubiquitous presence of calcite suggests neutral pH fluids with high $CO_2$ fugacity which hinders the growth of Epidote even at high temperatures.

On the other hand, Pad E wells in Area 2 typified low to medium ranked hydrothermal alteration mineral assemblage and normally devoid of crystallinity. Rare epidote was first noted in well E-201 at -810masl. Iron hydroxides are notably abundant throughout these wells suggesting that the volcanic formation may have been deposited in a water-lain environment and most likely formed syngenetic with volcanic rock deposition. The fact that these minerals survived along with rare epidote minerals at elevated temperatures, suggest an impervious barrier at this sector of the field, that prevents vertical or lateral migration of geothermal fluids.

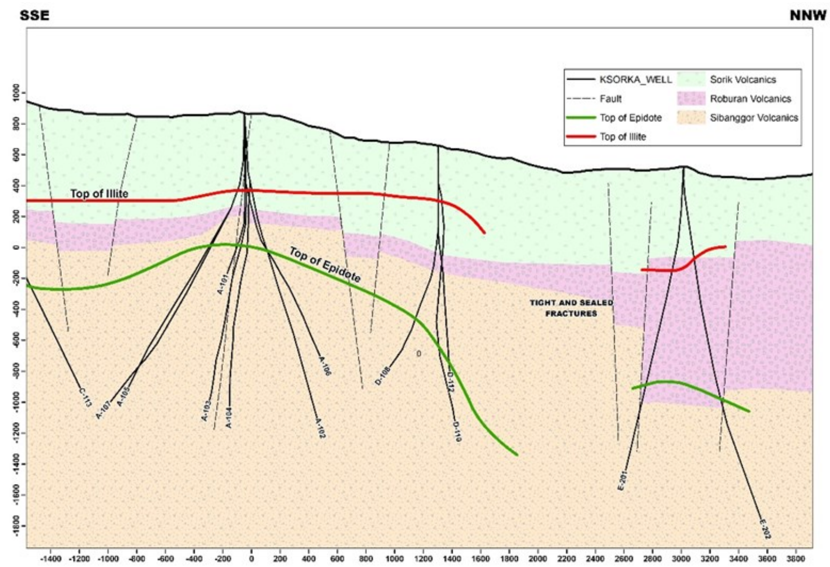


**Figure 2: Cross section across Resource Area 1 and Area 2 in SMGP showing stratigraphy and distribution of index hydrothermal alteration minerals.**

### 4.1 Temperature Distribution

Temperature and pressure surveys were routinely conducted in all wells to monitor the temperature recovery, distinguish the permeable zones identified during drilling and completion tests and characterize the reservoir conditions. The maximum temperature measured is 290°C in well A-103, at depth of -400m MSL, with a reversal down to hole bottom. A-107 has the highest temperature at the main feed zone at 282°C. Both A- 103 and A-107 were drilled towards west at the eastern fringes of Sorik Marapi volcano, which is considered to be the heat source of the geothermal system. Pad A wells that were directed away from the volcano (e.g., A-101, A-104, A-106) tapped a shallow two-phase zone at the top of the main liquid dominated reservoir. However, this two-phase zone is currently cased-off in most wells. The two-phase zone was projected during the drilling stage as evidenced by the presence of common bladed calcite in all the wells from +100 to +500m RSL. Temperature profiles falling within the boiling point for depth (BPD) curve from 100-200m MSL suggest boiling condition at depth. A-01 will develop wellhead pressure when shut, typical of a well with boiling condition, but its enthalpy remains single phase during discharge. Figure 3A shows the temperature profiles of wells in SMGP, while Figure 3B illustrates the stable temperature in all wells contoured at an elevation of -800mRSL. The isotherms suggest a gradual temperature decline from the west (A-103 and A-107) towards east (A-101, A-102 and A-104) and south (Pad C) which can be discerned as an outflow path. The steep thermal gradient towards north and farther east (the eastern block or foot wall of SFS) indicates little or no hydrological flow due to impermeable barrier.

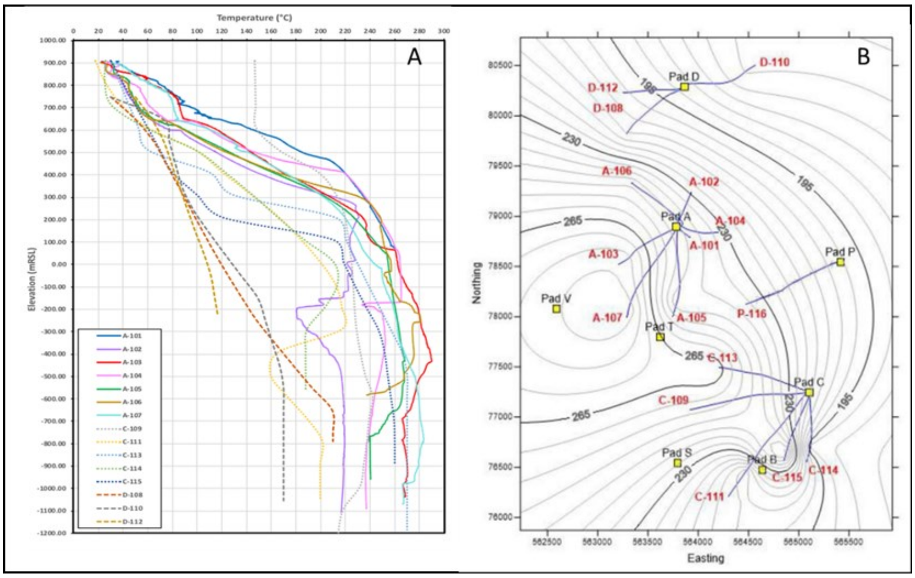


**Figure 3: Temperature profiles (A) and isothermal contour map at -800mRSL (B) of SMGP wells.**

## 5. CONCEPTUAL MODEL

The conceptual model of Sorik Marapi geothermal field has evolved over the years. Earlier model by SKM (2011) identified four resource areas with possible separate upflows based on MT and gravity data interpretation. However, at least one of the four areas (Area 2) has now been confirmed to have very low permeability and relatively cooler temperatures after the completion of two wells in Pad E.

Based on the initial drilling results, a revised hydrological model was conceptualized depicting a single main resource centered between Sorik Marapi and Sibanggor Tonga and possible outflow to the north (FEDCO, 2017; Licup et. al., 2017; Sarmiento et al, 2017) as shown in Figure 4. The model shows a single upwelling with mixtures of fluids and magmatic gases ascending vertically to the summit of Mt Sorik, discharging highly saline fluids with very low pH. Part of the mixtures finds its way laterally and percolate through fractures and faults leading to the Sibanggor thermal area where fumaroles occur. As the fluids migrate, the acidic fluids interact with the rocks and the overlying aquifer, forming a mature geothermal system with a neutral pH as manifested in the thermal springs. The benign nature of fluids tapped by Pad A wells has confirmed that the upflowing fluids have already undergone substantial neutralization.

The model also shows that geothermal fluids outflow to the lowlands and exits as chloride hot springs (96°C) at Sampuraga thermal area. However, current drilling results do not support this concept of hydrological connection to the north. Hydrothermal alteration, completion tests and heat-up surveys in Pad E wells indicated tight and low temperature formation. Additional drilling results from Pad D which is located in between Pads A and E, further confirmed this finding and suggests the existence of a cold, impervious block immediately north of Pad A.

Based on the new subsurface information, the conceptual model of the field may be revised and updated, as shown in Figure 5. Hydrothermal alteration and downhole temperature measurements reveal that the hottest part of the field is situated at the western section of the drilled area, or at the eastern flank of Sorik Marapi volcano. The ascending hot water flows eastward where it was tapped by A-103, A-107 and A-106. As the fluids maintains easterly flow and reached higher elevation, it started to boil, thus, forming a two-phase zone which fed the wells A-101 and A-104. Due to an impermeable barrier at the north, the hot fluids flowed laterally towards south where it was tapped by A-105.

## 6. CONCLUSIONS

The drilling results from Pad A confirmed the existence of a high temperature geothermal resource in SMGP. Downhole temperature data from Pad A wells showed increasing temperature trend generally towards southwest where Sorik Marapi volcano sits. Wells A-103 and A-107 gave the highest subsurface temperature (280°C-290°), insinuating that these wells were drilled closest to the probable upflow.

On the other hand, Pad E wells showed significantly cooler downhole temperatures (<220°) with tight and sealed fractures. This invalidates the previous notion of a possible separate upflow beneath Area 2, and its hydrological connection to Area 1. A cold block of low permeability is present outside the northern boundary of Resource Area 1, which may have hindered the fluid flow towards Pad E.

Hydrothermal alteration minerals identified in Pad A corroborates well with subsurface temperature distribution. The most dominant alteration mineral assemblage at the production zones of A series wells consist of calcite + quartz + chlorite + illite +epidote ± pyrite ± wairakite with rare occurrence of secondary amphiboles. These alteration minerals are largely produced by neutral PH geothermal fluids with estimated formation temperature >250°C. In the same way, alteration minerals from Pad E wells are formed in a neutral environment. However, low permeability is apparent from the persistence of iron hydroxides throughout the bore and scarcity of well-formed secondary minerals at depth.

Based on drilling evidences (i.e., circulation losses) and completion test results, subsurface permeability of most wells are mainly controlled by faults targeted by the wells. Permeable zones correlate well with depths of fault intersections, while permeability associated with lithological contacts are limited.

## ACKNOWLEDGMENT

The authors would like to thank the managements of KS Orka and PT SMGP for allowing us to present and publish this paper.

## REFERENCES

FEDCO (2016a). Due Diligence Study Report on Sorik Marapi Geothermal Field. Report Prepared for KS Orka Renewables PT. Ltd. March 2016.

FEDCO (2016b). Structural Geological Study of Sorik Marapi Geothermal Field. Report Prepared for KS Orka Renewable PT. Ltd. Manila, Philippines. November 2016.

FEDCO (2017). Sorik Marapi Geothermal Power Plant ("PLTP Sorik Marapi") 240 MW, Notice of Resources Confirmation, Unpublished Technical Report.

Licup, A.C., Baltasar, A.S.J., Juandi, D., Maneja, F.C., Jhonny, Esberto, M.B., Villareal, M.J.Z., Sari, P.P., Musa, R., Mulyani, S., Chandra, V.R., Omac, X.L. and Sarmiento, Z.F. (2017). Geothermal 3D Subsurface Modeling – A Case Study from Sorik Marapi Field, Indonesia. Proceedings: The 5th Indonesian International Geothermal Convention and Exhibition (IIGCE) 2017.

SKM, 2011. Preliminary Resource Assessment Report. Sorik Marapi Geothermal Project, Indonesia. Prepared for OTP Geothermal. Final Rev.1. 15 November 2011

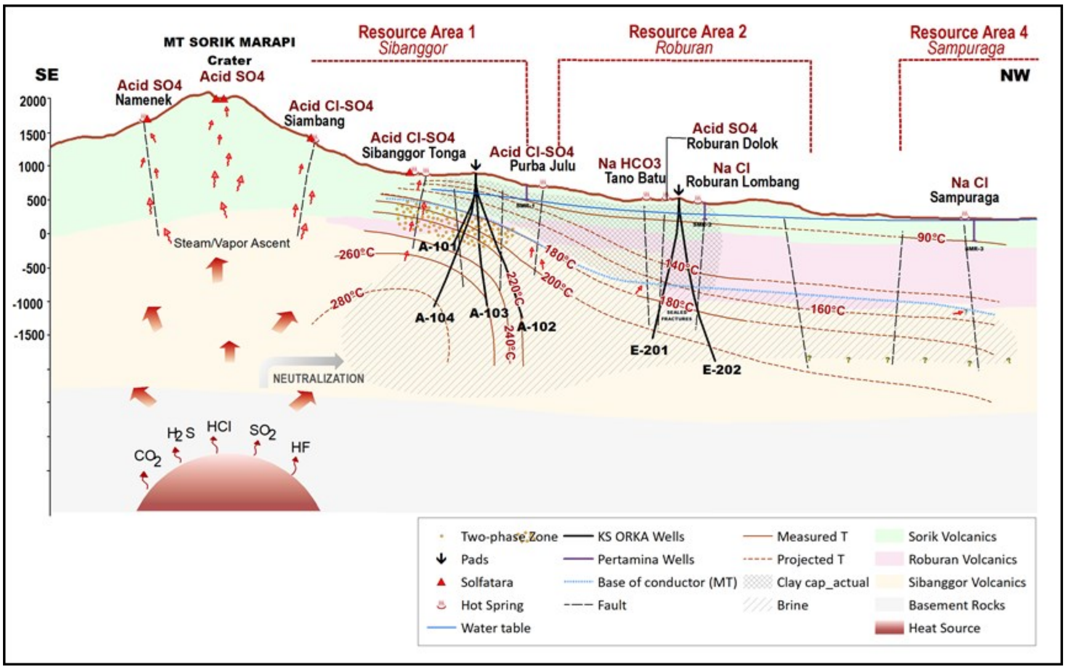


**Figure 4: Early conceptual reservoir model of Sorik Marapi (from FEDCO, 2017; see also Licup et al, 2017)**

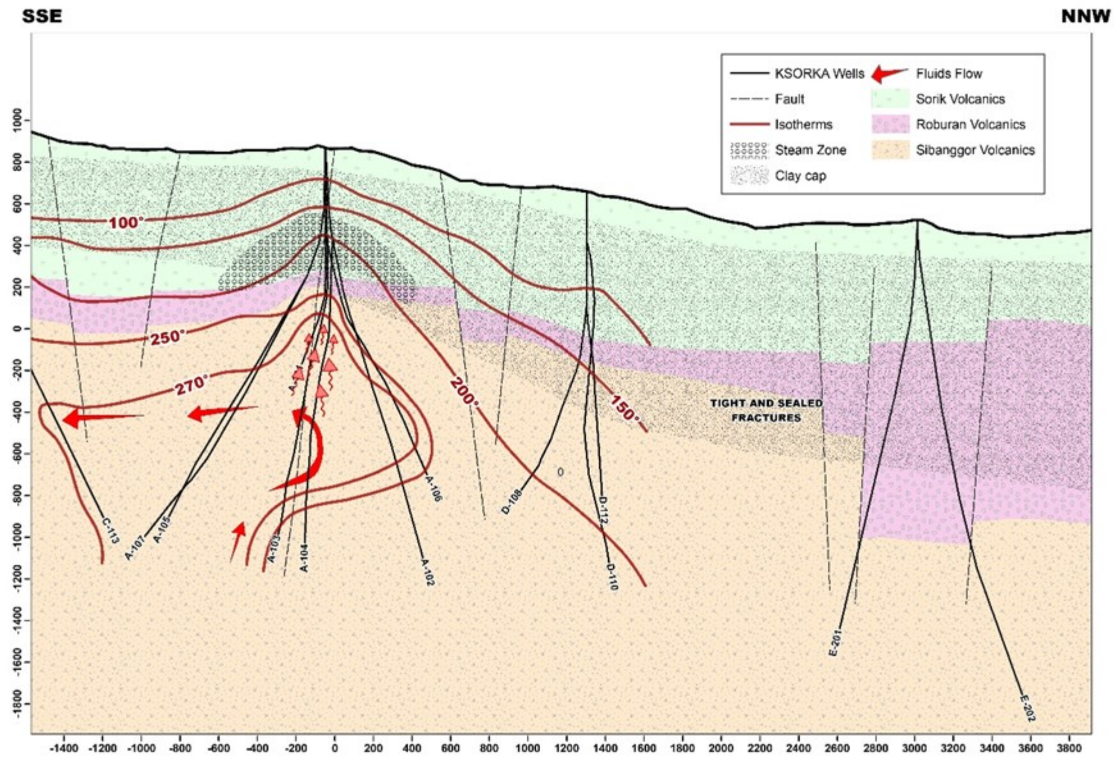


**Figure 5: Revised conceptual reservoir model of SMGP**