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EXPLORATION RESULTS IN THE SARULLA BLOCK, NORTH SUMATRA, INDONESIA

Richard Gunderson[1], Novi Ganefianto[2], Ken Riedel[2], Lutfhie Sirad-Azwar[2] and Syafei Suleiman[3]
[1]Unocal Geothermal Technology & Services, 1300 N. Dutton Ave., Santa Rosa, CA, USA 95401
[2]Unocal North Sumatra Geothermal, Senayan Office Tower, P.O. Box 1264, Jakarta 10012, Indonesia
[3]Pertamina Geothermal, Gedung Kwarnas Lt. 6, Jl. Merdeka Timur 6, Jakarta 10110, Indonesia

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ABSTRACT

From mid-1993 through early 1998 Unocal, under a Joint Operation Contract with Pertamina, conducted an extensive exploration program designed to locate and evaluate commercial geothermal systems within the Sarulla Block of North Sumatra, Indonesia. The exploration program included geological, geochemical, and geophysical surveys, the results of which were used to target 13 deep wells. This exploration program resulted in the discovery and appraisal of three new geothermal systems: Eastern Sibualbuali, Silangkitang, and Namora-I-Langit, with combined proven reserves of 330 MW for 30 years.

Four wells were drilled in the Eastern Sibualbuali geothermal field, which is located on the extinct Sibualbuali andesitic stratovolcano and is cut by several major strands of the Great Sumatra Fault. The wells were all productive, finding a geothermal system with a maximum temperature of 267°C and with production zone temperatures of 218-248°C. Strong lateral and vertical temperature gradients found in the system are attributed to channeling of fluids along strands of the Great Sumatra Fault.

Five wells were drilled in the Silangkitang field, located in the Sarulla graben along the main trace of the Great Sumatra Fault. Two of the wells found a strong upflow zone with fluid temperatures in excess of 310°C. A large-diameter well drilled in this zone is capable of producing fluid sufficient for 50 MW equivalent of generation, and has a maximum flowing wellhead pressure of more than 60 bar. As at Sibualbuali, the permeability of the Silangkitang system is also strongly controlled by the Great Sumatra Fault.

Four wells were drilled in the Namora-I-Langit field, which is located several kilometers west of the main trace of the Great Sumatra Fault in an area of extensive thermal activity. These wells were all highly productive, encountering a large, high permeability geothermal system. The wells all produced fluids with temperatures in excess of 260°C, with a maximum measured temperature of 276°C. Three of the wells produced neutral Na-Cl brine, but the fourth produced a low-pH Na-Cl-SO_4 fluid. The permeability of the Namora-I-Langit system, in contrast to Sibualbuali and Silangkitang, appears to be widely distributed and is not directly controlled by the Great Sumatra Fault.

1. INTRODUCTION

In February of 1993 Unocal, Pertamina and PLN signed joint operations and energy sales contracts, permitting Unocal to explore for and develop geothermal energy in the Sarulla Contract Area, North Sumatra, Indonesia. The contract enables Unocal to develop and produce up to 1000 MW, with an initial phase of 330 MW.

From May 1993 through March 1998 Unocal conducted an extensive exploratory program designed to locate and evaluate commercial geothermal systems within the contract area. The initial phase of the exploration program involved geological and geochemical methods. This included mapping of lithologies, alteration, and geologic structure as well as locating, sampling, and analyzing fluid from all surface thermal features within the block (Gunderson et al., 1995). The second phase consisted of a geophysical program utilizing gravity, time-domain electromagnetic (TDEM) and magnetotelluric (MT) surveys. The latter two of these methods are used to define the electrical resistivity structure of the subsurface over the area of the survey. These two exploration programs identified four main prospects within the contract area. The third exploratory phase involved the drilling of 13 deep wells in the three highest priority prospects. This paper describes the results of that exploration drilling program.

2. EXPLORATION PROGRAM OBJECTIVE

The objective of the Sarulla exploration program was to prove the existence of 330 MW (30 years) commercial geothermal reserves at minimum unit cost. The strategy adopted to accomplish this objective was to minimize the number of wells used to prove reserves. This required careful planning of the drilling program to accurately target the exploration wells and to acquire the needed type and quantity of information from each well. Careful exploratory work was also necessary to achieve sufficient well spacing to prove sizable reserves while maintaining relatively low exploration well risk.

Most of the exploration wells were designed as hybrid wells: to be drilled using standard rotary drilling technology down into the geothermal reservoir, and then continuously cored below that (if necessary) using diamond coring technology (Furry et al, 1996). These wells were designed to be capable of production and yet to also be capable of reliably attaining targeted depths to prove sufficient reservoir thickness. Information regarding reservoir porosity, permeability, and structure could also be retrieved through analysis of the deep continuous cores (Moore et al., 1998). In addition to the hybrid wells, two large diameter holes were drilled during the program in order to prove production hole deliverabilities. Initially the exploration wells were designed and drilled as vertical holes, but later as the nature of the permeability came to be understood, many of the wells were drilled directionally.

All of the Sarulla wells penetrated a thick sequence of volcanic rocks and were capable of production. The wells discovered and appraised three new geothermal systems with more than 330 MW of geothermal reserves (30 years).

3. EASTERN SIBUALBUALI

The Sibualbuali volcano is an extinct, deeply dissected andesitic stratovolcano located at the southeast end of the Sarulla contract block (Figure 1). The volcano is bounded on its western and eastern flanks by the two major strands of the Great Sumatra Fault, a large right-lateral strike-slip fault system extending along the length of the island of Sumatra. At Sibualbuali these two main strands are approximately 7 kilometers apart (Figure 2). The eastern strand is manifested in several fault splays that define a fault width of about of 1 kilometer. Nineteen areas of fumaroles, mud pots, and other acid sulfate thermal features are distributed around the Sibualbuali volcano primarily along small fault traces parallel to the Great Sumatra Fault over an area of about 45 km^2. The NCG contents of the fumaroles, several of which are superheated by as much as 30°C, are quite variable, ranging from 0.2 to 14 wt %, and gas geothermometry suggests subsurface temperature range of 250-310^{o}C.

A regional gravity survey found a large area of low gravity surrounding the volcano, suggesting an underlying thick sediment-or tuff-filled basin. Drilling results have shown this to be a sequence of silicic tuffs more than one kilometer thick. The resistivity surveys found a central core of high resistivity beneath the central core of the volcano ringed by several distinct areas of low resistivity. These areas of low resistivity are closely linked in most cases with the acid sulfate thermal features and their associated alteration. Drilling results have shown that the more distal parts of these low resistivity areas are related to accumulations of clay-rich volcaniclastic sediments, whereas on the higher flanks of the volcano, as expected, they result from clay-rich hydrothermal alteration of the volcanic rocks. Some of this clay represents relict alteration, as mineralogic and fluid inclusion evidence for retrograde temperatures was found both at the surface and in one of the Eastern Sibualbuali wells.

Four wells (1266-2439 meters) were drilled into geophysical and structural targets on the eastern flank of Sibualbuali in 1994-1996. The wells, three of which were drilled directionally through strands of the Great Sumatra Fault, all found a thick sequence of rhyolitic tuffs underlying the altered surficial andesitic rocks of the Sibualbuali volcano. The wells were all productive, finding a geothermal system whose temperature and permeability structure is strongly controlled by the Great Sumatra Fault (Figure 3). The maximum temperature measured in the Eastern Sibualbuali wells is 267°C, but production zone temperatures are in the 218-248°C range. Alteration mineralogy in three of the wells reflects the thermal and chemical properties measured in the geothermal system. However, in the fourth well the observed mineralogy gives indications of considerably higher temperatures at shallow depths during an earlier phase of the system's history. Mineralogical and fluid inclusion evidence for an earlier, hotter and shallower phase of hydrothermal activity was also found both above and within the Sibualbuali reservoir. The system was found to have strong lateral and vertical temperature gradients, which are attributed to the channeling of fluids along strands of the Great Sumatra Fault. Volumetric and reservoir modeling evaluation of the drilled portion of the Eastern Sibualbuali geothermal system suggests reserves of sufficient energy to generate 40 MW of electricity for 30 years. It is expected that further drilling on the north, western, and southern flanks of Sibualbuali will lead to the discovery of significantly more reserves.

4. SILANGKITANG

A series of hot springs and fumaroles is located within the Sarulla graben near the village of Silangkitang in the central part of the Sarulla contract block (Figure 1). These thermal features are primarily concentrated in a 1 x 3 kilometer strip on and west of the principal (eastern) strand of the Great Sumatra Fault, and are about one kilometer north of the 0.12 million year old Sarulla rhyolite dome (Figure 4). The chemistry of the springs falls into two distinct groups. The springs concentrated near the Great Sumatra Fault have low-Mg, neutral chloride waters that yield geothermometry values of roughly 270°C. Those few springs scattered to the north more than about one kilometer from the Great Sumatra Fault have neutral to slightly alkaline chloride-sulfate-bicarbonate waters that yield geothermometry values around 200°C. The fumaroles, which are found at slightly higher elevations only on the fault trace itself, have NCG concentrations of 3-6% and yield gas geothermometry values of about 275-300°C.

Gravity values within the Sarulla graben are low relative to the surrounding areas. As at Sibualbuali, drilling results confirm that this reflects a thick section of silicic tuffs, which at Silangkitang appear to fill the Sarulla graben. A closed gravity low within the graben that is coincident with the thermal area indicates locally thicker graben-fill, suggesting a local area of increased extensional faulting and downdrop. Subsurface resistivity as measured by MT and TDEM are also lower at Silangkitang than in the already low resistivities characteristic of the Sarulla graben. This local low resistivity fingerprints the shallow, clay-rich alteration and elevated temperatures associated with the geothermal system at shallow depths.

Five wells (2031-2330 meters) were drilled at Silangkitang in the period 1994-1998, again encountering a geothermal system whose permeability is strongly controlled by the Great Sumatra Fault. The wells all drilled through a thin section of shallow sediments beneath the Sarulla graben valley floor, followed by more than 1500 meters of silicic tuffs from which the wells produce. One well drilled vertically through these tuffs into the underlying coarse-grained sedimentary rocks, and one drilled northeast across the Great Sumatra Fault into the adjacent Paleozoic meta-argillites. The subvolcanic rock units were not productive. Two of the Silangkitang wells that were targeted directionally into the Great Sumatra Fault zone found a very strong upflow in the vicinity of the fault that is significantly overpressured with respect to a normal hydrostatic gradient. In this upflow zone, fluid temperatures exceed 310°C (Figure 5). A large diameter well drilled in this zone is capable of producing more than 50 MW of fluid, and has a maximum flowing wellhead pressure of more than 60 bar. Alteration mineralogy within the reservoir rocks closely reflects the current thermal and chemical state of the reservoir (Moore et al., 2000), although fluid inclusion data suggest that the system had a more extensive upflow zone in an earlier stage. Following extensive testing of the wells, volumetric evaluation and reservoir modeling of the geothermal system have confirmed reserves for generating 80 MW for 30 years at Silangkitang.

5. NAMORA-I-LANGIT

The Namora-I-Langit volcanic complex is located at the northwest end of the Sarulla contract block (Figure 1). Namora-I-Langit, like Sibualbuali is situated between the major eastern and western strands of the Great Sumatra Fault. The complex consists of two broad coalescent volcanoes made up of andesitic to rhyolitic lavas and tuffs dated at 0.75 to 0.16 million years old. Associated with this volcanic complex is an extensive array of surface thermal features, comprising primarily fumaroles and acid sulfate springs, but also including neutral Cl-sulfate-bicarbonate hot springs, gas seeps, and numerous warm bicarbonate springs covering an area of about 30 km^2 (Figure 6). The fumaroles are found in two groups, a northern group covering several hectares, and a southern group that covers more than four square kilometers. The Namora-I-Langit fumaroles, unlike those at Sibualbuali and Silangkitang, are not concentrated along NW-oriented fault traces, but instead are widely distributed away from obvious structures. Fumarole temperatures range as high as 117°C. The NCG in steam from Namora-I-Langit fumaroles is generally >15%, but ranges from as low as 1% to as high as 44%. The high gas flux from the system is manifested by the extensive acid sulfate alteration and acid surface water runoff as well as historically-mined sulfur deposits.

The Namora-I-Langit volcanic complex, like Sibualbuali and Silangkitang, lies within a gravity low between the two principal strands of the Great Sumatra Fault. Once again drilling results have shown that this gravity signature reflects a thick sequence of graben-filling tuffs and sediments found underlying the lavas of the Namora-I-Langit volcanic complex. There is also a distinctive layer of low resistivity at Namora-I-Langit measured by TDEM and MT. This layer is found at the surface in the vicinity of the large southern thermal area and extends at depth over an area of almost 30 square kilometers. This layer is interpreted as clay alteration overlying the widespread geothermal system.

Four wells (1333-1722 meters) were drilled at Namora-I-Langit in 1997-1998, following the construction of extensive new access roads into the area. All of these wells were drilled through the lavas of the Namora-I-Langit volcanic complex and were completed in the thick tuff section. These wells found a large geothermal system whose temperature and permeability distribution, in contrast to those of Sibualbuali and Silangkitang, appear **not** to be tightly controlled by the Great Sumatra Fault. Instead, permeability is widely distributed, and vertical and lateral temperature gradients are very low within the reservoir (Figure 7) . The wells all found high permeability and produced fluids with temperatures in excess of 260°C. Three of the wells produced neutral, dilute Na-Cl brine, but the fourth produced a low-pH Na-Cl-SO_4 fluid. The alteration mineralogy encountered in these wells, excepting a single zone in this fourth well, is indicative of a neutral pH, high temperature geothermal system.

Based on the results of the wells and their extensive flow testing, the drilled portion of the Namora-I-Langit reservoir has been evaluated as capable of sustaining 210 MW of electrical generating capacity for 30 years. Additional drilling throughout the remainder of the geophysical target has the potential of increasing this capacity significantly.

6. CONCLUSIONS

The Sarulla exploration program has proved the existence of commercial geothermal reserves capable of supplying 330 MW of electrical generating capacity for 30 years. The program, which included geologic, geochemical, geophysical, and drilling phases, was designed to minimize the per-unit cost of proving the reserves by minimizing the number of wells required. The geology, geochemistry, and geophysics programs were used to define the drilling targets, which were then drilled using hybrid rotary-coring technology. The data collection program for the wells was optimized to provide all data required for complete resource evaluation. This exploration program discovered and appraised three new geothermal systems with widely varying thermal and permeability characteristics.

The two smaller of the geothermal systems discovered in Sarulla have permeability and temperature distributions that are strongly controlled by the Great Sumatra Fault, whereas the largest one does not. The hottest, most permeable parts of the Eastern Sibualbuali and Silangkitang geothermal fields are found within the fault zone itself. Directional drilling is a crucial method needed to explore such a reservoir. This structural control strongly limits the areal extent of the reservoir. In contrast, high temperature and high permeability in the much larger Namora-I-Langit field are widely distributed and are not found strictly associated with the fault.

The Sarulla exploration program has shown that the integrated interpretation of surface geology and geochemistry results along with resistivity data from combined TDEM and MT surveys can be very successful in identifying the extent of the alteration halo overlying active geothermal systems, although alternative sources of electrically conductive clay (primarily sedimentary clay) can complicate the interpretation in some instances. The use of combined rotary-core technology in drilling the Sarulla exploration wells has proven to be a cost-effective way to reliably reach targets deep within underpressured reservoirs and to retrieve reservoir rock samples for use in resource evaluation studies.

Over the period 1994-1998 the thirteen wells drilled at Sarulla found three new geothermal fields with reserves of at least 330 MW. These reserves are now proven and await development when the economic climate in Indonesia improves. Significant additional potential remains in the Sarulla block in the undrilled portions of the Sibualbuali and Namora-I-Langit fields as well as in the undrilled Donotasik prospect.

7. REFERENCES

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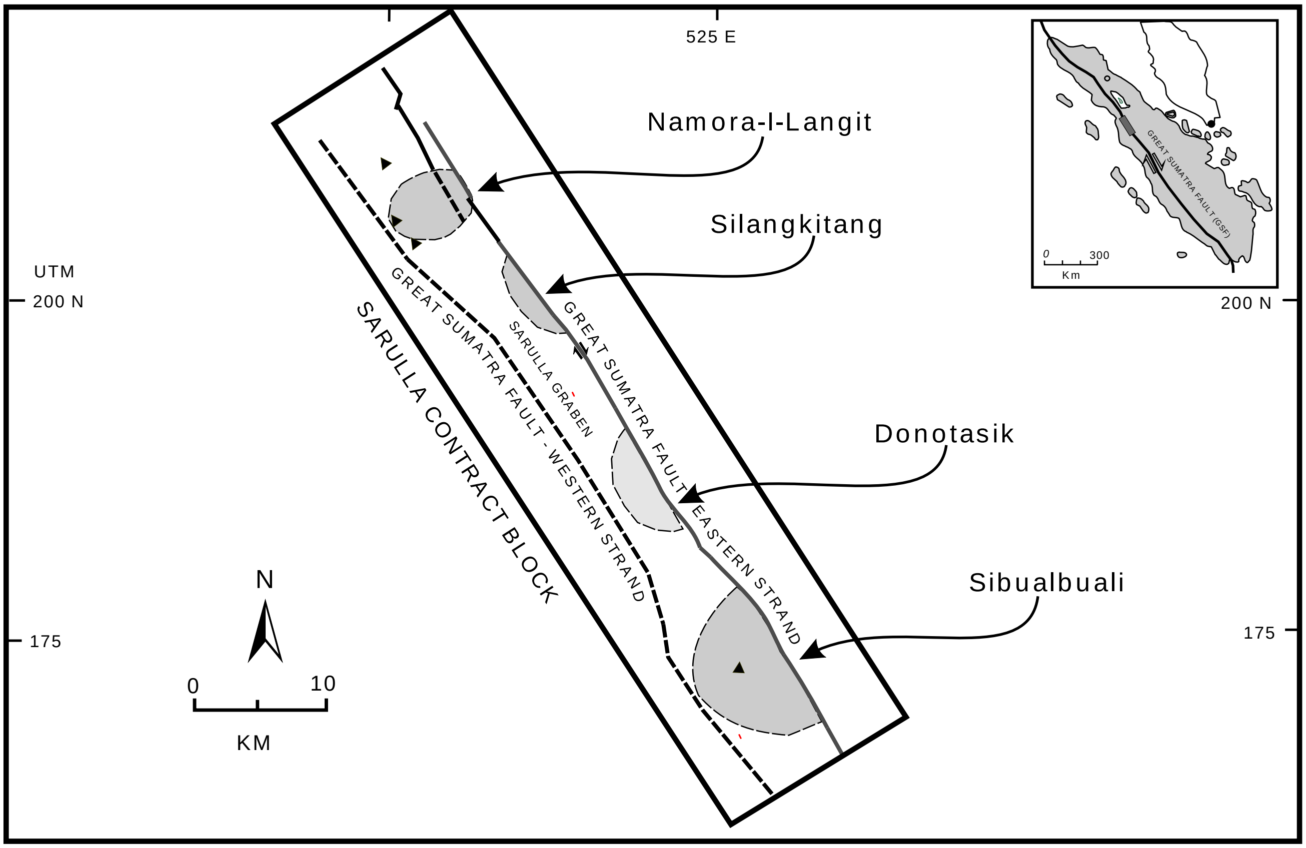

Figure 1: Map showing four large geothermal prospects in the Sarulla contract block North Sumatra, Indonesia. The Namora-I-Langit, Silangkitang, and eastern portion of the Sibualbuali prospects have now been drilled.

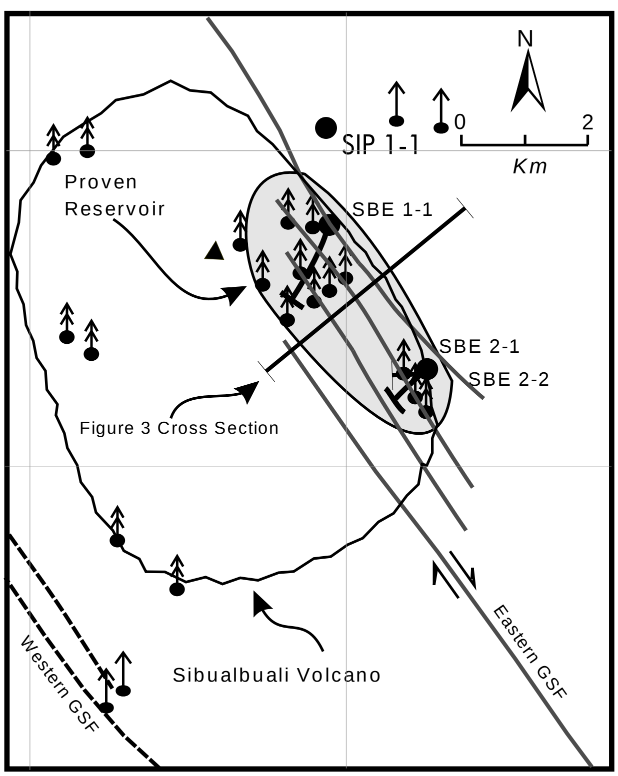

Figure 2: Sketch map showing elements of the Sibualbuali geothermal field

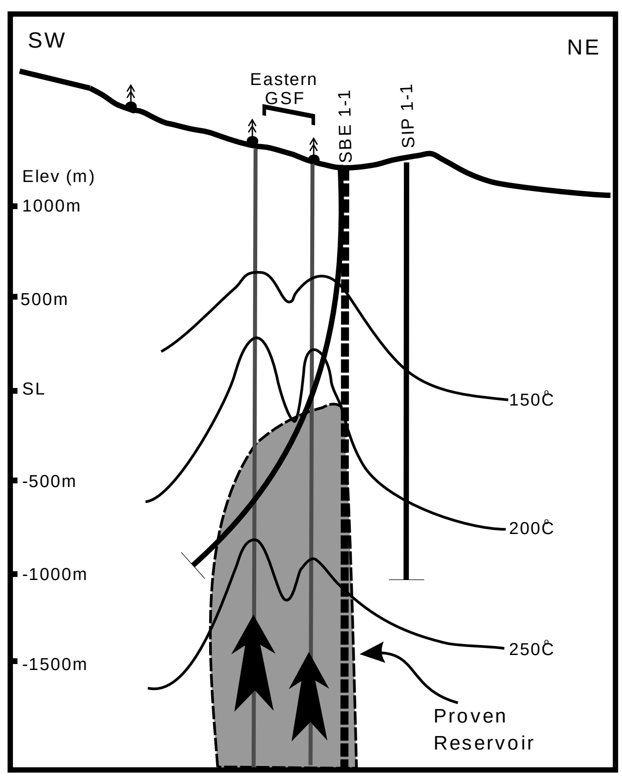

Figure 3: Schematic cross section through the eastern Sibualbuali geothermal field.

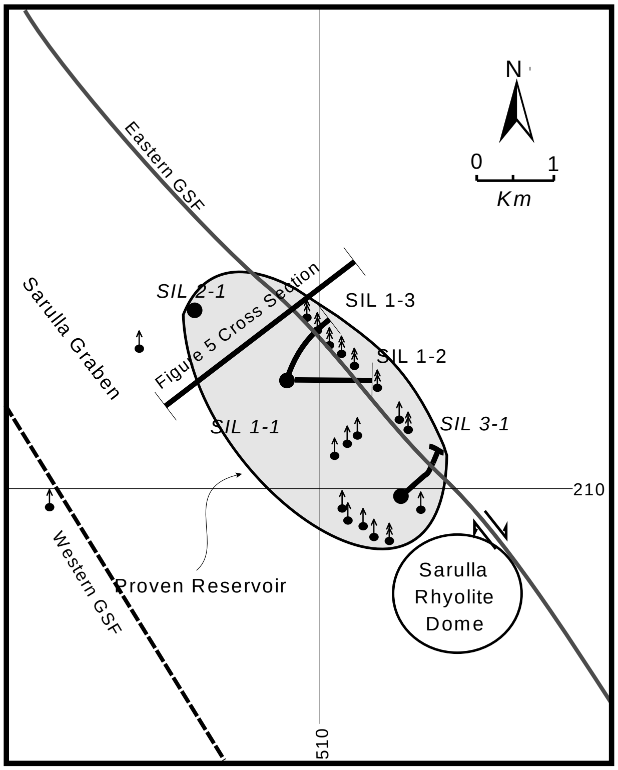

Figure 4: Map showing the main elements of the Silangkitang geothermal field

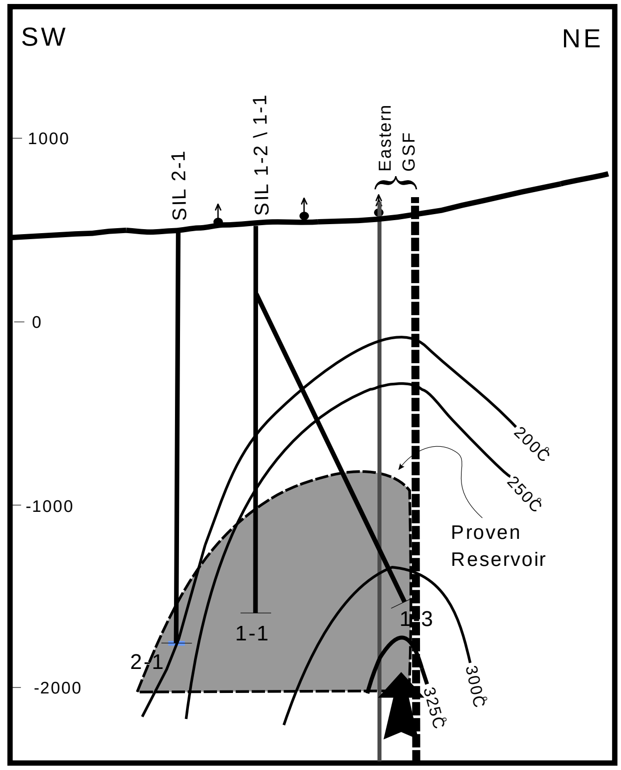

Figure 5: Schematic cross section through the Silangkitang geothermal field.

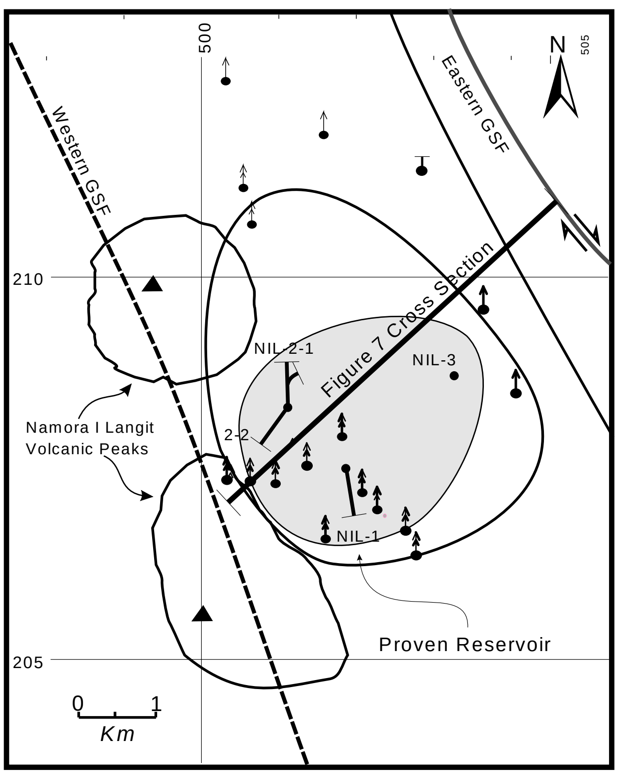

Figure 6: Map showing the main elements of the Namora-I-Langit geothermal field

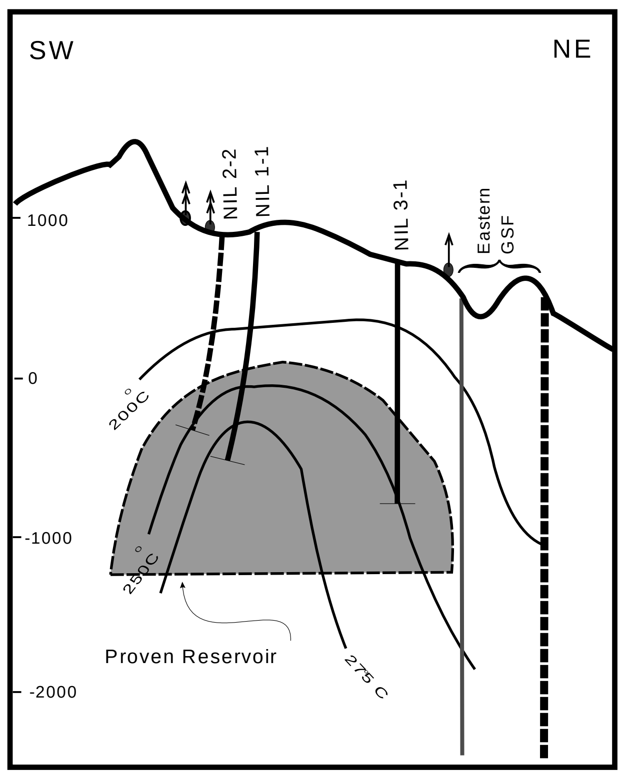

Figure 7: Schematic cross section through the Namora-I-Langit geothermal field.