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Configuration of the Geothermal Prospects in the Leyte Geothermal Reservation (Philippines) and Implications of a Volcano-Tectonic Framework in Exploration

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ABSTRACT

The island of Leyte in The Philippines hosts the largest developed liquid-dominated geothermal system in the world. The Leyte geothermal production field is located within the Leyte geothermal reservation along with several other geothermal prospects that are adjacent to areas with Neogene to Pleistocene period of volcanism (Bayrante & Palma, 1987). This field is located in the northern flank of the eroded Ancestral Mount Bao (AMB) volcano (Lagmay et al., 2003). The other prospects southeast of LGPF are Alto Peak, Lobi, Mahagnao and Bato Lunas, all located within the traverse of the Philippine Fault System.

Several exploration well drilling in Alto Peak, Lobi, and Mahagnao have proven the existence of high temperature volcanic systems with different physical and chemical reservoir characteristics. Alto Peak hosts an immature geothermal system related to a young volcanic center. Lobi and Mahagnao, on the other hand, have encountered high temperature systems but the reservoir is within the basement ultramafic complex that is inherently impermeable. These geothermal prospects have yet to fully develop for power generation.

Recent analysis of volcano-tectonic structures and analog sand cone experiments indicate that the existing producing wells in LGPF straddle the crypto-Philippine fault, a master fault that induced fracture-controlled permeability within the geothermal field. The structural model suggests that the southern flank of the AMB directly above the southern extension of the master Philippine Fault is an ideal geothermal target (Lagmay et al., 2003). The drilling of a deep well in Lobi in 2003 did not reach this postulated extensional area so the above structural model has not been confirmed. However, considering these latest structural analyses, the area south of LGPF within the concave side of the identified sigmoid structure may warrant further detailed geoscientific studies for geothermal exploration.

1. INTRODUCTION

Leyte Island in Central Philippines is considered a geothermal province owing to the numerous geothermal prospects that exist parallel to the main trace of the Philippine Fault System. In fact, the worlds' largest liquid-dominated geothermal field – the Leyte Geothermal Production Field (LGPF), which comprises the Tongonan and Mahanagdong reservoirs, lies in the northern part of the island right along the Philippine Fault (PF). Other geothermal prospects in the area are Alto Peak, Lobi, Mahagnao and Bato Lunas, which are all located within the Leyte geothermal reservation area (Figure 1).

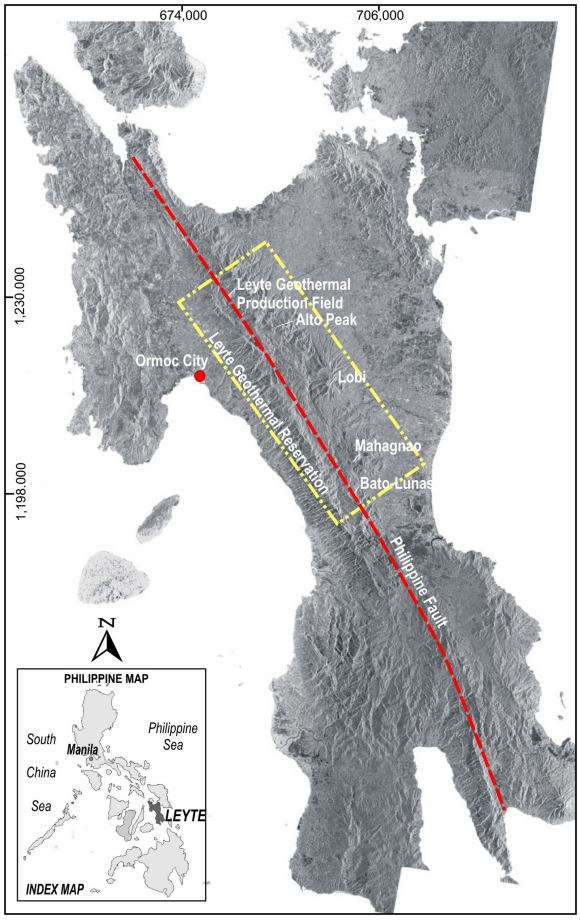

Figure 1: Location map of Leyte Geothermal Reservation showing the different geothermal prospects

This paper focuses on the distinct characteristics of each geothermal prospect based on recent data and their exploration and development potentials with the use of new and emerging technologies.

2. GEOLOGY AND STRUCTURAL SETTING

The volcanoes in Leyte are confined within a volcanic zone about 200 km long and 15 km wide (Bayrante and Palma, 1987). The occurrence of thermal manifestations such as solfataras, extensive acid alteration, acid sulphate springs, chloride springs and cold altered grounds (or Kaipohans) are associated with these volcanic centers (Figure 2).

There are about 18 Tertiary to Recent volcanic units that are recognized in the Leyte geothermal reservation that may be grouped into four volcanic formations or series (Bayrante and Palma, 1987). The volcanics are intercalated with

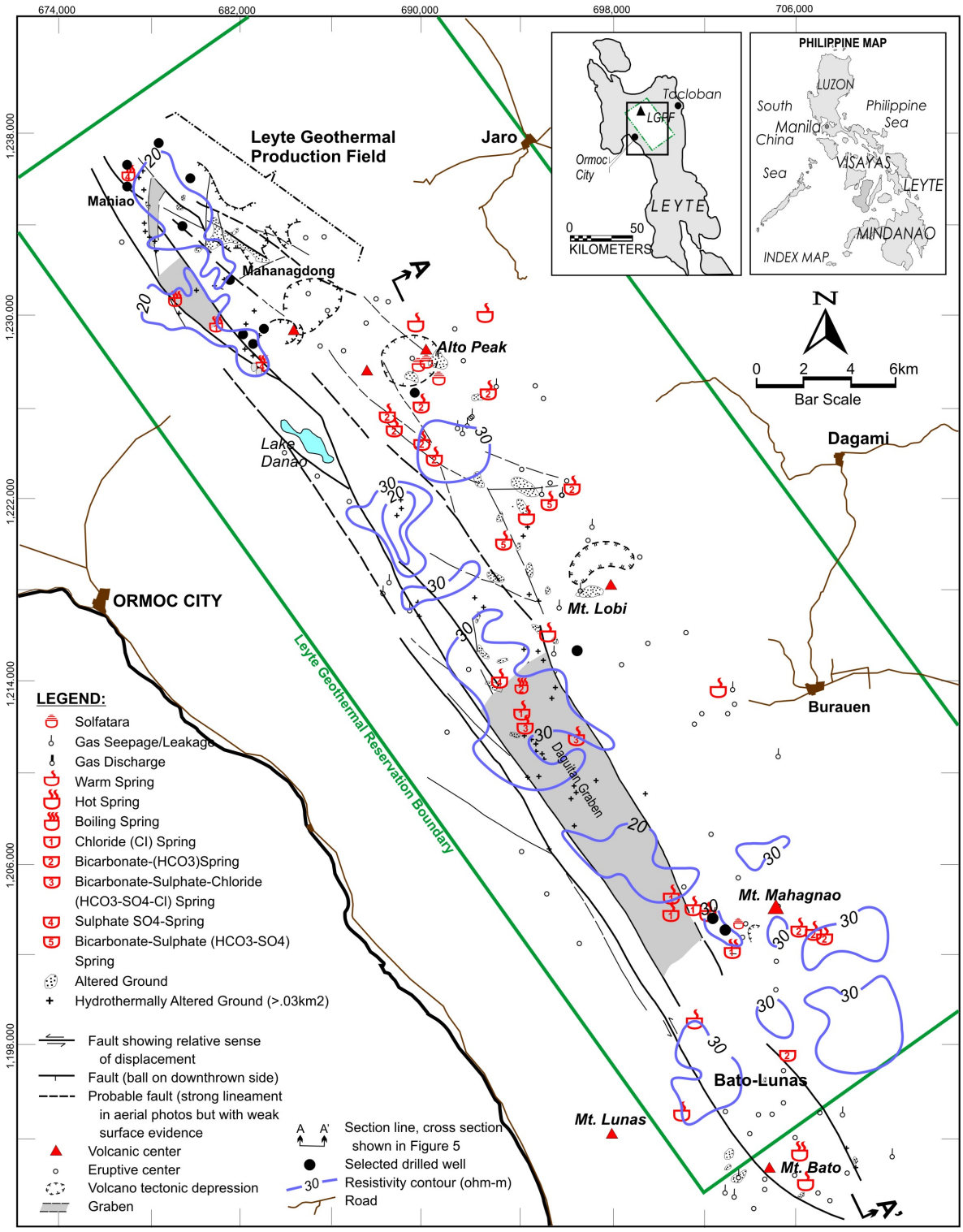

Figure 2: The Leyte geothermal reservation showing geothermal prospects, major fault traces, surface thermal manifestations, apparent resistivity anomalies and selected wells drilled

Miocene to Recent sedimentary units that are intruded by pre-Tertiary to Tertiary intrusives consisting of mafic, ultramafic and felsic bodies. The highly jointed and faulted Neogene volcanics and part of the ultramafic complex were perceived to be the most favorable reservoir rocks (Bayrante and Palma, 1987), but deep drilling in Tongonan and Mahanagdong proved that the permeable reservoir rocks are Miocene sediments that are intruded by dikes, while deep wells in Lobi and Mahagnao were drilled through serpentinized ultramafic rocks. This lithology proved to be inherently impermeable owing to its plastic to pseudo-plastic behavior to deformation. This impermeability within the ultramafic rocks is consistent with selected wells in LGPF that penetrated this formation. It is evident based on drilling that slivers of the basement complex are present in some areas on the western side of the field. The presence or absence of the ultramafic basement complex, metamorphic schists and claystone play a major role in the occurrence of a permeable and exploitable geothermal reservoir in Leyte.

3. VOLCANO-TECTONIC SETTING

Recent structural studies by Lagmay et al. (2003), which focused on the anatomy of volcanic cones in the Ancestral Mt. Bao (AMB) within LGPF, established the deformation characteristics of a volcano traversed by a strike-slip fault. Deformational features that were recognized include: a summit graben, sigmoidal surface feature, cone elongation, normal faults and reverse faults. All these deformational features as observed in the sand cone models are present in the field (Figure 3).

In the same study, it was presented that the sigmoidal feature has a significant role on secondary permeability. The producing wells at LGPF are all located on the concave side of the sigmoid, while wells drilled on the convex side encountered metamorphic schists, slivers of serpentinite bodies, and claystone deposit that contributed to poor permeability. Considering that the observed deformation structures are symmetrical, there is a possibility that a similar permeable zone on the southern segment of the sigmoid within the concave side may be present. The occurrence of a similar high temperature and productive geothermal resource, however, is yet to be established since deep drilling in Lobi was only able to probe the convex side of the southern segment of the sigmoid (Figure 4).

4. CHARACTERISTICS OF GEOTHERMAL AREAS

4.1 Leyte Geothermal Production Field

The Tongonan and Mahanagdong geothermal systems in LGPF are related to Quaternary volcanoes and domes in Mahiao-Sambaloran and Paril-Mahanagdong, respectively (PNOC-EDC, 1990). The reservoir lithology is composed of Miocene to Pliocene volcanic sequence and sedimentary breccias, which are intruded by micro-diorite dikes. Resource temperature is 300-320^{o}C, while permeability is largely derived from faults. The entire LGPF has a combined installed capacity of more than 700MWe which supplies power to the central Philippine Islands and Luzon.

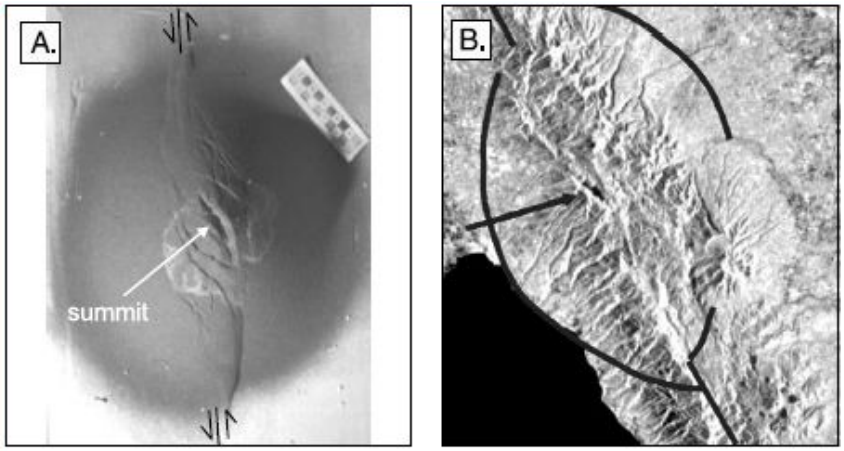

Figure 3: Comparison of sand cone model of a volcanic cone traversed by a strike slip fault (A) and the Ancestral Mt. Bao (B). Adopted from Lagmay et al., 2003

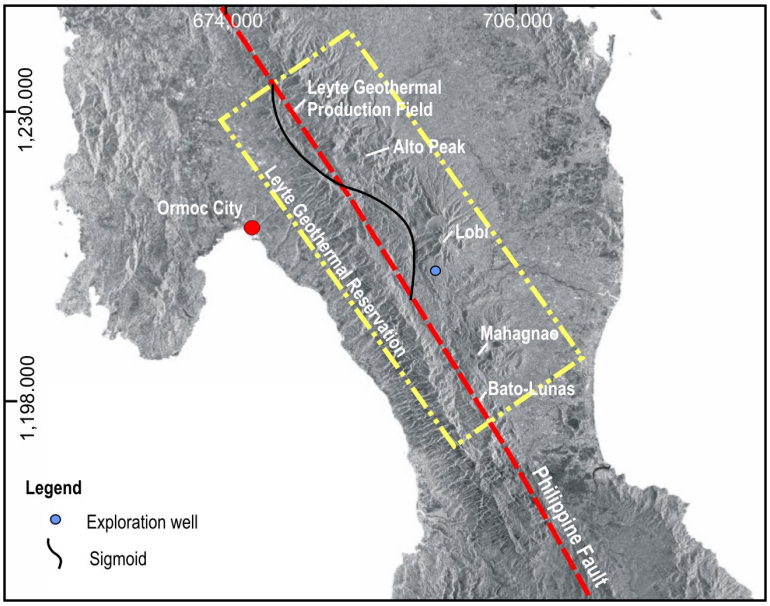

Figure 4: Map showing the sigmoid deformational feature. LGPF is located on the concave side of the northern flank while a structurally symmetrical area is identified on the southern segment, located directly west of Mt. Lobi. Modified from Lagmay et al., 2003

4.2 Alto Peak

The Alto Peak geothermal system is related to a young eruption center and an ancestral caldera (PNOC EDC, 1990). Surface lithologies are composed of andesite-dacite lava flows, breccias and pyroclastics, while the reservoir rock is composed of sequence of interlayered sedimentary breccia, carbonaceous siltstone, tuff and sandstone. The most evident surface thermal manifestation in Alto Peak are the solfataras, extensive altered grounds and gas seepages or kaipohans, with a number of bicarbonate hot springs. A low resistivity anomaly was also delineated southwest of the Mt. Alto Peak.

Out of the 9 production wells and 1 injection well drilled in Alto Peak, some wells discharged acidic fluids while others yielded neutral geothermal brine but with non-commercial well head pressure. EDC is in the process of re-evaluating the commercial viability of the project in the light of new technologies being developed by EDC such as the Acid Inhibition System (AIS) technology.

4.3 Lobi

The Mt. Lobi geothermal prospect includes the Mt. Lobi volcanic complex and the Burauen graben that is located southwest of Mt. Lobi peak. Surface thermal manifestations are extensive in this prospect which comprise of numerous hydrothermally-altered grounds, gas seepage and discharges, warm springs, and bicarbonate-chloride-sulphate hot springs with some that are close to boiling. Most of these surface thermal manifestations are located within the Daguitan graben located west-southwest of Mt. Lobi. An extensive resistivity anomaly is also present that defines the thermal areas within the graben.

Surface deposits in the area are composed of basaltic to andesitic lava flows, while the only well drilled in the prospect penetrated through a thick volcanic deposit from the surface before hitting the serpentinized ultramafic complex. Apparently, the prognosticated reservoir rock in this prospect which is composed of sedimentary deposits similar to those found at LGPF does not exist. With regard permeability, the exploration well was drilled in the convex side of the sigmoid that was described by Lagmay et al. (2003) that may have relatively poor permeability. However, it was not ascertained whether the lack of permeability in the well was attributed to the nature of the subsurface lithology or to the fact that the well was drilled in the convex side of the sigmoidal structure.

4.4 Mahagnao

The Mahagnao geothermal prospect was postulated to be associated to volcanism related to the Mahagnao dome. A number of chloride and bicarbonate springs, solfatara and hydrothermally altered ground comprise the surface thermal manifestations in the area, while a number of low resistivity anomalies were identified that represent clay mineralization assemblages.

Drilling of two wells in 1990-1991 by PNOC EDC penetrated a high-temperature (290-340^{o}C) geothermal system with one of the wells discharging superheated steam and reservoir chloride of more than 20,000 ppm (PNOC EDC, 1991). However, the wells drilled through serpentinite deposits which comprise most of the rocks below the production casing, resulting to very low permeability. No further geothermal exploration activities were done in the prospect since.

4.5 Bato-Lunas

The Bato-Lunas geothermal prospect is at the southeastern end of the Leyte Geothermal Reservation. It is defined by the presence of several dacite porphyry domes east-northeast of Mt. Bato and Mt. Lunas, with surface thermal manifestations comprising of solfataras, hydrothermally-altered grounds, chloride and bicarbonate hot springs and gas seepages. It is characterized by dissected collapse features with pre-, syn-, and post-collapse dacite-andesite dome complexes overlying sedimentary sequences with limestone and ultramafic breccias or conglomerates. An extensive resistivity anomaly clearly defines the hydrothermal clay alteration in the prospect, which is distinctly different from the Mahagnao geothermal prospect. The area is yet to be explored by deep drilling.

5. OPPORTUNITIES AND CHALLENGES

The Leyte geothermal reservation hosts six (6) distinct geothermal resources, two (2) have been fully developed which are the Tongonan and Mahanagdong geothermal fields, while Alto Peak, Lobi and Mahagnao have been explored through deep well drilling. Detailed surface studies were already done in Bato-Lunas but is yet to be drilled.

All these geothermal resources follow the trend of volcanic complexes in the northern and central part of Leyte Island, which are associated to the movement of the PF. The left lateral movement of the PF created extensional and compressional regimes that were formed in different episodes. Extensional-related deformations are typically manifested as syn-sedimentary structures such as growth faults, pre-tilting normal faults and slump structures. Compressional-related deformations, on the other hand, are usually expressed as conjugate pre-tilting inverse faults, syn-folding thrusts, strike-slip sets and combination of several of these structures (Aurelio et al, 1993). It is in the area of extensional structural deformations where commercially viable geothermal resources may exist. As for the case of the highly developed LGPF, the entire geothermal field is located in the permeable concave side of the sigmoidal feature (Lagmay et al, 2003) where grabens and normal faults dominate. This sigmoidal structure also provides a symmetrical concave side located south of LGPF which is directly west of Mt. Lobi. Based on structural analysis, the concave side is along the surface projection of the crypto-Philippine Fault, which is the buried master fault of the Philippine Fault system. Structurally, there is evidence that a permeable area may be present west of Mt. Lobi. However, the presence of a geothermal resource, either commercially viable or constrained by the ultramafic complexes or other factors, cannot be ascertained due to lack of exploration drilling data. This area remains a challenge as well as an opportunity for further geothermal exploration and development.
Defining the boundaries of this ultramafic complex is therefore one of the important parameters to further refine the exploration strategy in Lobi and Mahagnao.

Another equally important factor that defines the geothermal resource viability in Leyte is the relative age of volcanism which determines the maturity of the reservoir.

As in the case of Alto Peak, the relatively young volcanic complex resulted to an immature geothermal system. Although this system has a high temperature source with superheated fluids, it also produces acidic fluids with magmatic component that provide development constraints. One big challenge for this project is in defining the extent of the exploitable neutral-pH resource and how to address fluid acidity.

No well is yet to be drilled in Bato-Lunas prospect but further exploration work is warranted to define the boundaries of the possible geothermal resource and map out the probable extent of the ultramafic basement complex.

Overall, the undeveloped geothermal prospects within the Leyte geothermal reservation - Alto Peak, Lobi, Mahagnao and Bato Lunas, have high potential for further exploration and possible development. However, the constraints on fluid acidity and reservoir permeability must be properly taken into consideration in future exploration works as this may define the technical viability of the prospects. On the other hand, the presence of distinct heat source for the geothermal prospects provides an opportunity to address the development risks separately (Figure 5). Identifying the specific risks and addressing these risks, therefore, is the challenge. The presence of a highly developed large geothermal resource within the same region also provides a good reference in further exploration work in these prospects. Research advances in the utilization of acid wells can be applied in young geothermal systems, while more detailed study must be conducted on fracture deformation in serpentinized ultramafic complexes to address the permeability constraints.

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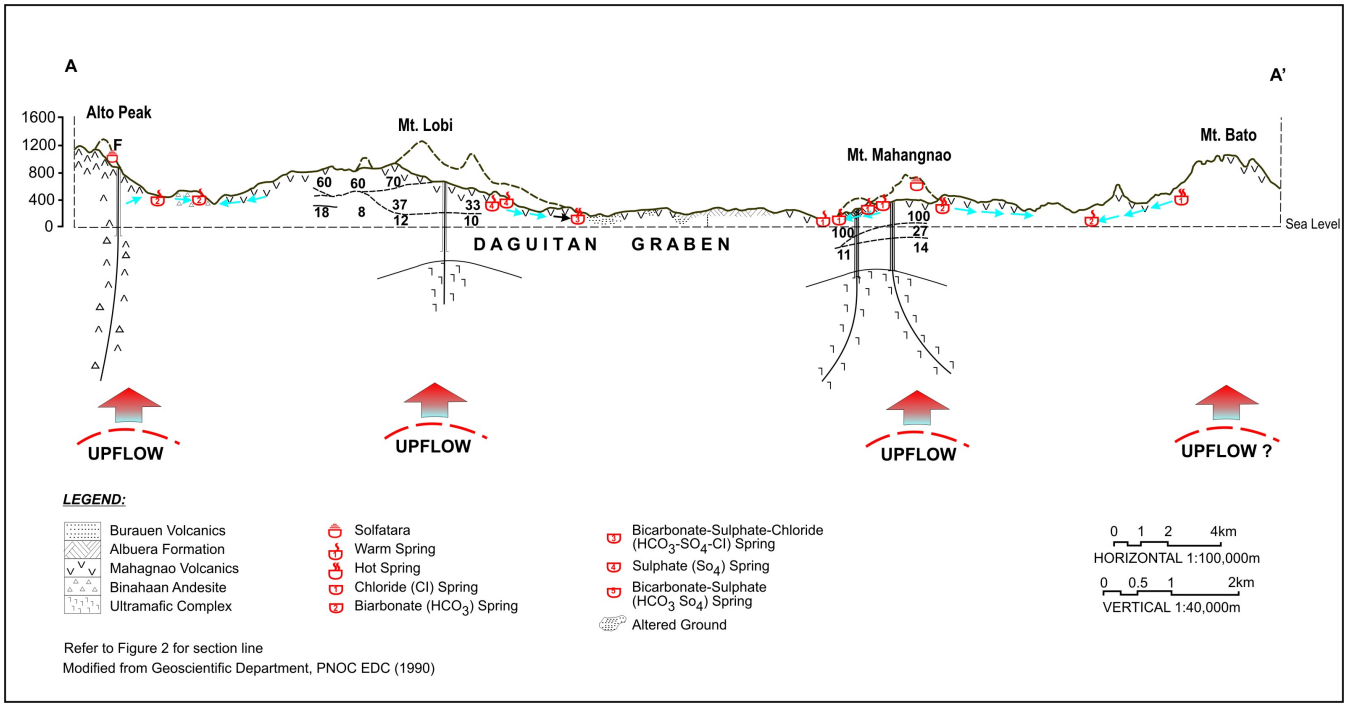

Figure 5: Cross section across the geothermal prospects Alto Peak, Lobi, Mahagnao and Bato-Lunas showing lithologies, associated surface thermal manifestations and possible location of distinct heat source