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Lobi and Mahagnao: Geothermal Prospects in an Ultramafic Setting Central Leyte, Philippines

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ABSTRACT

The Lobi and Mahagnao Geothermal Prospects are located in the center of Leyte Island, Philippines. Starting in 1980-1982, geological, geochemical, and geophysical surveys were conducted in central Leyte to evaluate viability of prospect areas found southeast of the successful Tongonan Geothermal Field.

Results of surface exploration studies indicated hotter reservoir temperatures in Mahagnao prospect in comparison to Lobi. Hence, in 1990-1991, two exploration wells (MH-1D and MH-2D) were drilled in Mahagnao to confirm the postulated upflow beneath Mahagnao solfatara and domes. Well MH-1D, targeted towards the center of the resource was non-commercial despite high temperatures of ~280ºC because of poor permeability of the Leyte Ultramafics. Well MH-2D was drilled westward but intersected low temperatures of ~165ºC. Drilling results showed that the only exploitable block in Mahagnao lies beneath the volcanic domes covering an area of ~5 km^2.

In 2001-2002, the Lobi prospect was re-evaluated by conducting a magnetotelluric (MT) survey and structural geologic studies. Based on MT results, an exploration well (CL-1D) was drilled in 2003 to probe the MT anomaly southwest of Mt. Lobi. Located ~15 km north of well MH-1D, well CL-1D was likewise non-productive because it intersected the Leyte Ultramafics below –300 m MSL resulting in poor permeability and absence of circulating hydrothermal fluids.

Exploration drilling in both Mahagnao and Lobi areas proved that commercial geothermal production is not viable in ultramafic-hosted reservoirs. Recent magnetotelluric survey mapped out extent of the impermeable Leyte Ultramafics as well as the distribution of sediments that can serve as possible permeable reservoir for a low-temperature geothermal resource.

1. INTRODUCTION

The Lobi and Mahagnao geothermal prospects, located in Central Leyte, lie ~25 km southeast of the Leyte Geothermal Production field, the largest steam field in the country with a current installed capacity of 723 MWe. These areas are part of the northwest-southeast-trending volcanic centers aligned along the Philippine Fault in Leyte starting from Biliran Island to Mt. Cabalian (Fig. 1) which are likewise the interests for exploration and development. Numerous impressive surface manifestations such as solfataras, steam heated grounds, and hot springs with temperatures reaching 97ºC characterize the two prospect areas (PNOC EDC, 1982).

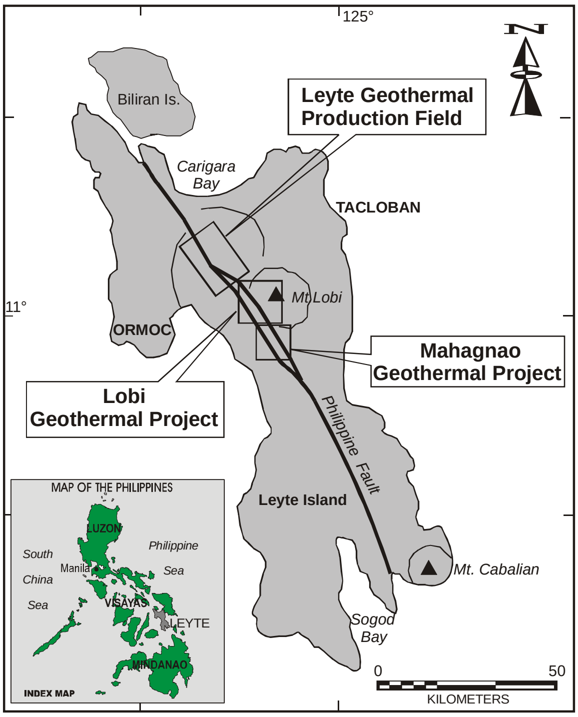

Figure 1: Location Map of Central Leyte

This paper presents the results of 23 years of exploration in Central Leyte starting in 1980 including the drilling of two wells in Mahagnao in 1990-1991 and the recent one in Lobi in 2003. The Central Leyte project gives an insight on the prospects of a geothermal system in an ultramafic terrain that contrasts with the andesitic volcano-sedimentary hosted fields in all the other Philippine geothermal production areas.

2. EXPLORATION HISTORY

Geoscientific investigations conducted by PNOC-EDC in Central Leyte were done in three major time frames: 1980-1982, 1990-1991, and 2001-2004.

2.1 1980-1982

Preliminary surface exploration work consisting of geological, geochemical and shallow resistivity sounding surveys started in Central Leyte from early 1980-mid 1982 to be able to identify well locations for the next exploration phase (Obusan *et al.*, 1982).

Field investigations showed Mt. Lobi and Mt. Mahagnao as prospective areas for exploratory drilling. Between the two areas, Mt. Mahagnao proved to be the more attractive sector based on more impressive thermal activities, higher temperatures based on silica geothermometry (180°C vs. 160°C) and mixing model (260°C vs. 220°C), and lesser high-temperature relict alteration minerals. The DC Schlumberger Resistivity traverse method mapped two anomalies in the Lobi-Mahagnao areas: the Mahagnao Anomaly, an ill-defined zone characterized by 20 and 50 ohm-m resistivity contours enclosing the Mahagnao altered ground and chloride springs; and the Anonang Anomaly, a well defined low-resistivity zone west of Mt. Lobi which is enclosed by a 50 ohm-m iso-contour. Geoelectric data interpretations suggest that the two major upflow zones are associated with the young Mahagnao volcanic edifice and Mt. Lobi volcanic center.

2.2 1990-1991

In 1990-1991, PNOC-EDC undertook another evaluation study of the Leyte island including geology, geochemistry, and Schlumberger resistivity measurements. Hydrothermal fluids were postulated to be upflowing beneath the Mahagnao domes where solfataric emanations are found. These fluids then flow laterally mainly to the northwest as manifested by Color, Soongon, and Lugsungan springs with minor outflows to the east (Humiranat springs) and to the southwest (Mahagnao springs) (PNOC-EDC, 1991) (Fig. 2). The anomaly defined by the <10 ohm -m resistivity low is ~10 km^2 with a maximum reservoir temperature of 282º C based on gas geothermometry. It also enclosed two significant arcuate features called the “Inner” and “Outer Calderas. ” This anomaly, the Mahagnao Anomaly, became the basis for drilling the two exploration wells MH-1D and MH-2D (Fig. 3).

2.3 2001-2003

After a decade, PNOC-EDC undertook an integrated re-assessment of the Mt. Lobi area in 2002 (PNOC-EDC, 2002). It included recent geologic structural interpretations on the Ancestral Mt. Bao, a concept, which evolved since 1994 on a large volcanic cone encompassing both LGPF and Mt. Lobi. Traversed by the Philippine Fault with a sigmoidal trace, it postulates that since the LGPF is within the northern concave half of the Philippine Fault, Mt. Lobi may duplicate LGPF’s productive capability as it is located in the southern concave half of the sigmoid.

The review further showed that the hot springs in Lobi indicate a single source of fluids with a minimum temperature of 145º C (Fig. 2). Magnetotelluric (MT) survey in August 2001 to March 2002 delineated a shallow third resistive layer proximal to Mt. Lobi which was interpreted as the geothermal resource. The MT anomaly was the target of drilling of well CL-1D in the first quarter of 2003 (Fig. 3).

MT survey was subsequently done in Mahagnao in the last quarter of 2003 to early 2004.

3. DRILLING RESULTS

Two exploration wells MH-1D and MH-2D were drilled in 1990-1991 to confirm the postulated upflow beneath the Mahagnao solfatara and domes. In 2003, well CL-1D was drilled ~15 km north of well MH-1D to probe the MT anomaly southwest of Mt. Lobi.

3.1 Well MH-1D

Well MH-1D was sited within the Mahagnao anomaly and the ”Inner Caldera” and drilled towards the southeast in October 1990 to February 1991. It encountered the Plio-Pleistocene biotite to pyroxene-bearing hornblende andesite lava flows and tuff breccia (260 m thick), top Late Miocene-Pliocene (planktonic foraminiferal zone N18-N21) sedimentary breccia, silty claystone and limestone deposited in an inner neritic environment (550 m thick); and the serpentinized websterite and lherzolites of the Leyte Ultramafic Basement from 790 mVD till the well bottom at 1870 mVD (Pagado and Herras, 1991) (Table 1, Fig. 4). Dikes ranging in composition from andesite, microdiorite and quartz micromonzodiorite intrude the ultramafics sporadically between 1560-1670 mVD (Reyes, 1991) (Table 1).

Fluid inclusion homogenization data, mineral alteration and vein mineralogy of biotite, actinolite, clinopyroxene, clinozoisite, and epidote starting at 1585 mVD suggest temperatures of ≥ 280ºC (Reyes, 1991) (Table 2, Fig. 4).

The well was tested in May to June 1991. A maximum temperature of 286°C was measured during the vertical discharge (Fig. 5). The Na-K-Mg geothermometry of the discharged fluids of 280°C-320°C was consistent with measured temperatures, while Cl_{res} was 20,000-29,000 ppm. Gas geothermometry T_{H2Ar} gave comparable results of 260°C-318°C. The gases also indicated absence of any magmatic contribution. Intermittent discharge showed the reservoir to be >98% highly liquid-dominated (PNOC-EDC, 1991).

Two permeable zones at 1133 mVD and 1326 mVD were detected during the waterloss surveys. The well had an injectivity index of 10.2 l/s-MPag at 1326 mVD or 3.31 l/s-MPag (WHP).

The well dried up after three days of discharge with non-commercial wellhead pressure at full-bore condition. A power output of 1.5 MWe was calculated at BBP-B2 and at 100 mm-diameter orifice plate but the well pressure still declined within a one week period. Gas-rich fluids with a total NCG 0f 10% characterize the well fluids and had a potential for calcite deposition. Carbonate blockages developed at 1125 mVD and 613 mVD after the well was shut. Re-testing for four hours in July 1991 showed an increase in well output up to 1.5 MWe but the well head pressure dropped from 1.5 to 0.85 Mpag suggesting that a prolonged well discharge cannot be sustained due to its poor permeability. The well was eventually plugged at shallow level.

3.2 Well MH-2D

The well was drilled in February-April 1991 towards the southwest to test the northwest elongation of the 12- km^2 anomaly interpreted as the outflow path of geothermal fluids (PNOC-EDC, 1991). It was located 625 m, N55ºW of MH-1D at an elevation of 432 mAMSL, 32 m lower than MH-1D. It was targeted towards the west outside of the “Outer Caldera” to intersect permeabilities related to Color Fault and Central Fault Splay B which control the alignment of Color and Lugsungan springs, respectively.

Drilled to a total depth of 2180 mVD, it encountered the same rock units as in MH-1D. However, the top Late Miocene-Pliocene sedimentary sequence (N19-N21) deposited in an outer neritic environment is thicker (~1.3 km) in this well compared to MH-1D (Pagado and Herras, 1991) (Fig. 4). Dikes are notably absent. The low temperature of the well is indicated by the Static Formation Temperature Tests (SFTT) (88ºC at 799 mVD and 118ºC at 1172 mVD), fluid inclusion homogenization temperature analysis (133ºC at 1142 mVD), and measured temperatures of 165ºC at the well bottom (Fig. 5) The increase in pump pressure even with reduced flowrate during hydrofracturing manifest the tightness of the well. The low injectivity index of 3.44-3.60 l/s-MPag likewise suggests low permeability similar to MH-1D (PNOC-EDC, 1991).

3.3 Well CL-1D

The well intersected a comparable stratigraphic sequence as MH-1D and MH-2D, varying only in formation thicknesses: Plio-Pleistocene hornblende pyroxene andesite (565 m thick), Early Pliocene (N19) sandstone-siltstone-fossiliferous limestone- andesitic tuff sequence (380 m thick) and the serpentinized garnet-bearing pyroxene peridotite of the Leyte Ultramafics starting at 1075 mVD (Fig. 4). Schistose to semi-schistose texture were observed below 1498 mVD while rare fragments of possible andesite porphyry dike occur at 1518m VD and 1550 mVD. Tectonic breccia at 1547-1586 mVD consists of fragmental serpentinized peridotite in a pseudo-sedimentary matrix of brown siltstone and claystone. The Leyte Ultramafics occurs at comparable depths in MH-1D (~ -340 m MSL).

The persistence of cristobalite and tridymite at ~949 mVD suggests estimated temperatures of ~100-120ºC and was confirmed by the SFTT not exceeding 151ºC (Fig. 5). Both low temperatures and inherent impermeability of the ultramafics led to the premature termination of drilling at 1598 mVD without setting the production casing shoe and reaching the programmed total depth of 2434 mVD.

4. 2004 MAGNETOTELLURIC SURVEY RESULTS

An MT survey consisting of thirty seven (37) stations was conducted in Mahagnao in October 2003 to January 2004 to map out the extent of the Leyte Ultramafics and delineate the lateral and vertical distribution of the overlying sediments. The data was tied up with the earlier MT survey in Lobi. The results showed that the ≤ 20 ohm-m resistivity values coincide with the Late Miocene-Early Pliocene sediments. The bottom of this low resistivity layer defines the top of Leyte Ultramafics which is also the top of the electrical basement in the area and is characterized by ≥ 30 ohm-m resistive layer (Fig. 6).

The survey further delineated a 3 km^2 anomaly beneath Lake Mahagnao as defined by a 30 ohm-m resistivity contour at –1500 m elevation (Fig. 7). This area, south of the bottom of well MH-1D may represent a possible low-temperature geothermal resource within the Late Miocene-Late Pliocene sediments.

5. DISCUSSIONS

Drilling results of MH-1D and MH-2D confirmed the preliminary exploration model in Mahagnao. Neutral-pH, liquid-dominated fluids with temperatures of 280-320ºC upflow beneath the Mahagnao domes. This high temperature regime is related to dikes intruding the ultramafics in the MH-1D sector. However, discharge was not sustained despite the elevated temperatures because of the inherent impermeability of ultramafic reservoir.

The absence of alteration in the ultramafics indicates poor circulation of hydrothermal fluids within this formation. The secondary minerals observed in the ultramafics such as antigorite, actinolite, talc, chlorite, and garnet are attributed to the serpentization process resulting from deuteric or metamorphic hydration of primary olivine and pyroxenes in the presence of water at temperatures as high as 500ºC. It probably occurred prior to the Late Pliocene emplacement of the Leyte Ultramafics as serpentinite sheets along the Philippine Fault mobile belt. This timing is consistent with the regional tectonic framework of Leyte.

The quasi-plastic to ductile reaction of the serpentinized peridotites to internal stress or deformation renders the Leyte Ultramafics impermeable despite the several geologic structures intersected by the wells. Thus, fluid flow is restricted within the ultramafics and only localized along the dikes as manifested by the high temperature alteration mineralogy in the intrusives. At shallower levels, the fluids take a more permeable path along the ultramafic-sediment stratigraphic boundary, and along the bedding planes of these sediments.

The low temperatures encountered in MH-2D showed that the resource is confined in the upflow region within the “Outer Caldera. ” This arcuate feature probably serves as the structural boundary between the hot block of the MH-1D sector and the cold block beneath MH-2D (Fig. 8). The prospective viable area in Mahagnao was therefore reduced from 12 km^2 to 5 km^2. The northwest anomaly initially interpreted as the outflow tongue of hydrothermal fluids is now attributed to the thick Miocene-Pliocene sedimentary pile intersected by MH-2D.

In Lobi, low temperatures not exceeding 151°C, manifested in both the SFTT’s and alteration mineralogy of well CL-1D, coupled with the presence of the impermeable Leyte Ultramafics significantly downgrade the exploration value of the area. The shallow resistive MT anomaly, believed to represent the geothermal resource and the drilling target of CL-1D, proved to be the ultramafic basement.

Correlation of recent MT results with stratigraphy in Mahagnao and Lobi revealed that MT interpretations in an ultramafic setting deviate from that of an andesitic-hosted geothermal field. In Central Leyte, the electrical basement defined by ≥ 30 ohm-m resistivity layers coincides with the Ultramafic basement in contrast to its correlation with the upflow region of the geothermal resource in an andesitic setting. It further showed a 3 km^2 anomaly south of well MH-1D bottom which may represent a possible low temperature geothermal resource within the Late Miocene-Late Pliocene sediments.

6. CONCLUSIONS

Exploration drilling in both Mahagnao and Lobi areas proved that commercial geothermal production is not viable in ultramafic-hosted reservoirs mainly because of the inherent impermeability of the rocks. It has also shown Mahagnao as the more prospective sector where there is favorable temperature. However, the geothermal resource is confined in the vicinity of volcanic domes, and within thin layers of the Late Miocene-Pliocene sediments found at shallow depths above -500 m MSL. This low- temperature geothermal resource may be tapped for possible binary system development.

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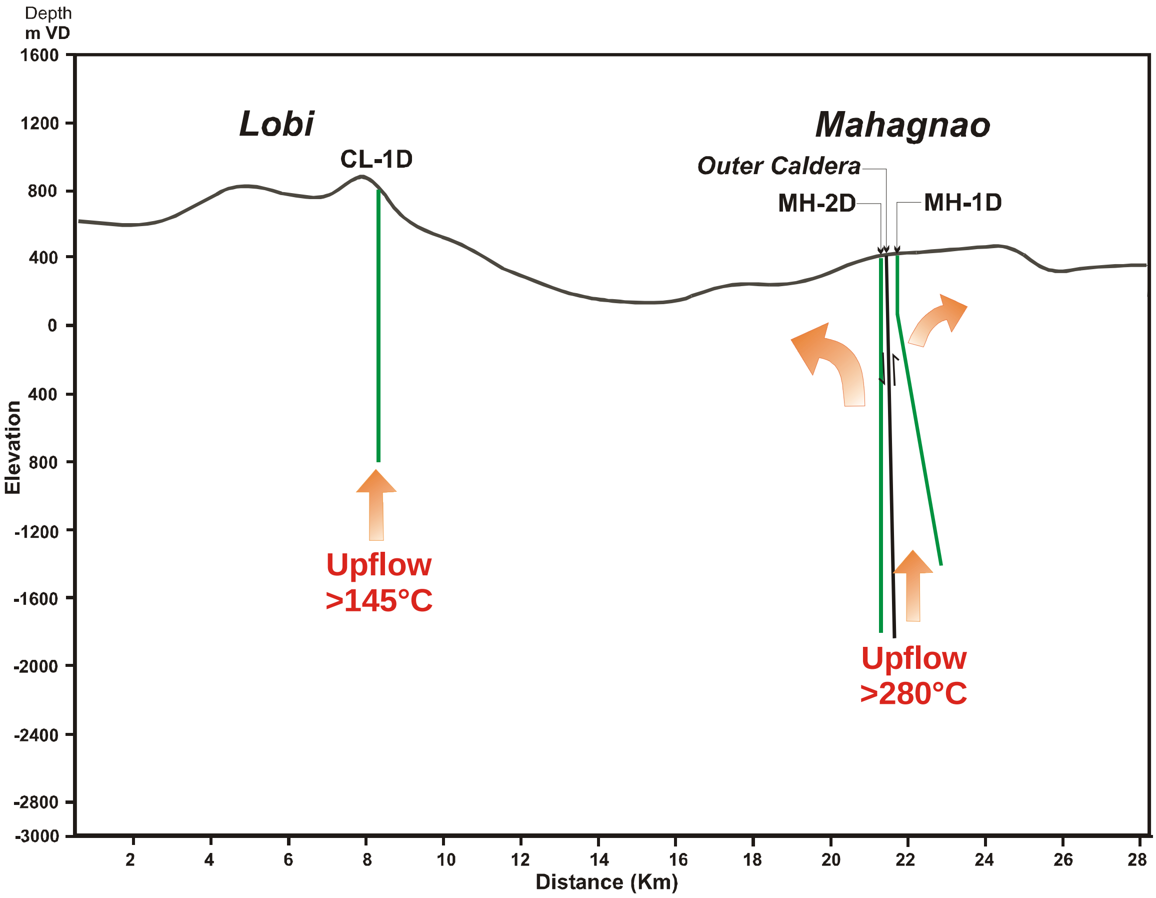

Figure 2: Pre-Drilling Geohydrological Model in Central Leyte

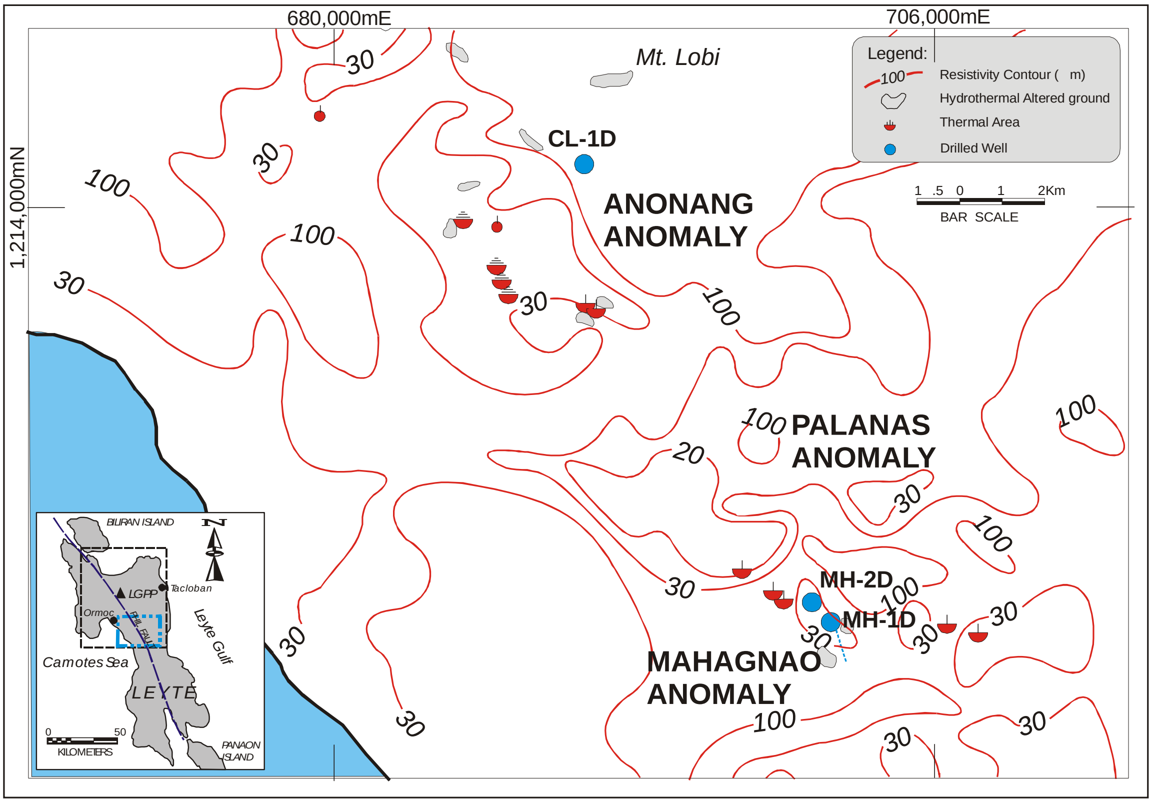

Figure 3: Geophysical Anomalies and Well Tracks in Central Leyte

Table 1. Surbsurface Stratigraphy of Central Leyte

Rock Unit	Age	Description	Thickness (m)
Mahagnao/Burauen Volcanics	Plio-Pleistocene	Biotite- to pyroxene-bearing hornblende andesite; tuff, tuff breccia	126 – 565
Dikes	Late Pliocene?	Porphyritic andesite, microdiorite, quartz monzodiorite	12 – 28
Sedimentary Formation	Top Late Miocene-Early Pliocene (N18-N21)	Siltstone; fossiliferous, calcareous, carbonaceous sandstone; bioclastic limestone; sedimentary breccia	380 – 1,300
Leyte Ultramafic Basement	Pre-Cenozoic	Serpentinized peridiotite, websterite, lherzolite, rare dunite	Minimum 1070

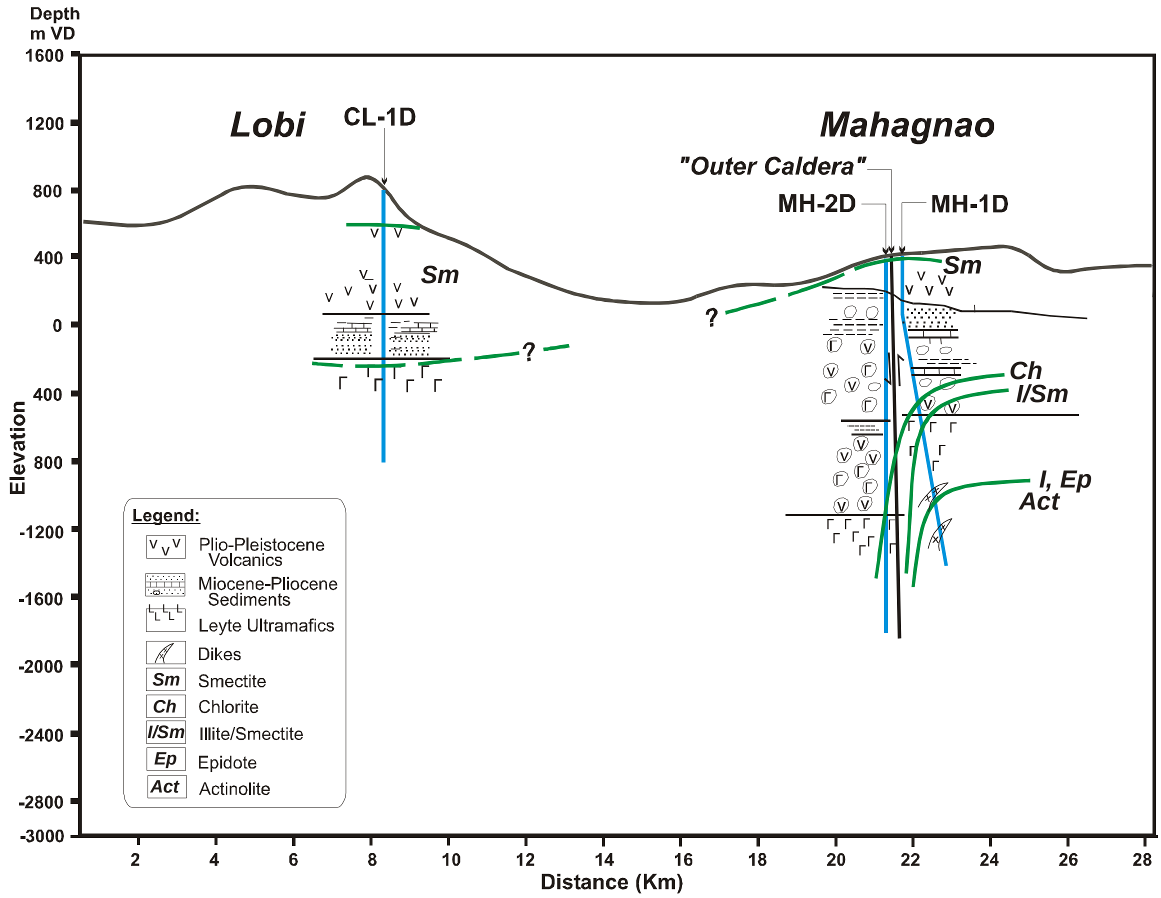

Figure 4: Stratigraphic and Alteration Correlation in Central Leyte Wells

Table 2. Alteration Mineralogy in Central Leyte Wells

Well	Alteration Mineralogy	Bottom Temperature (°C)	
		Predicted	Measured
MH-1D	Biotite, actinolite, clinopyroxene, clinozoisite, epidote	>280 (F.I. 277)	286
MH-2D	Mg-rich expandable clays: vermiculite, corrensite, saponite	≤ 165	165
CL-1D	Cristobalite, tridymite, smectite	≤ 150	151

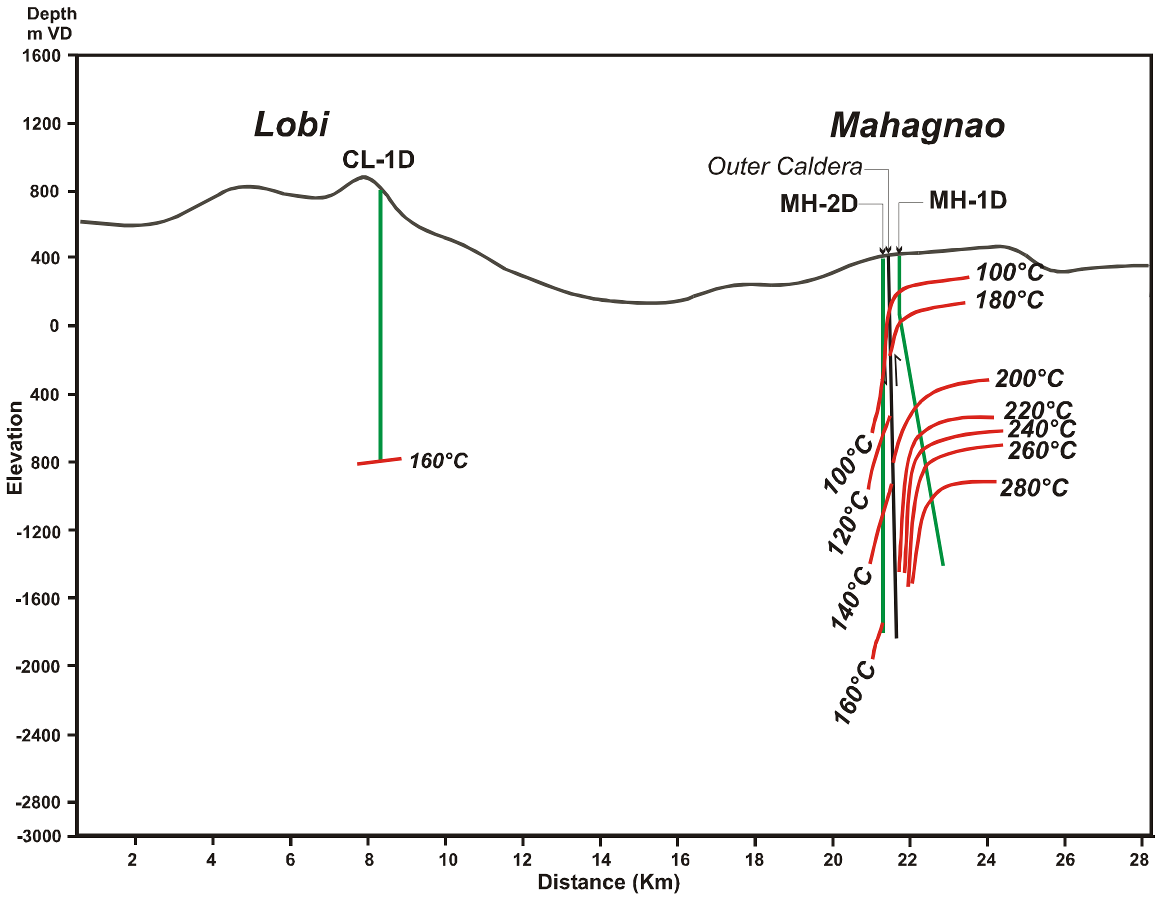

Figure 5: Isotherms in Central Leyte Wells

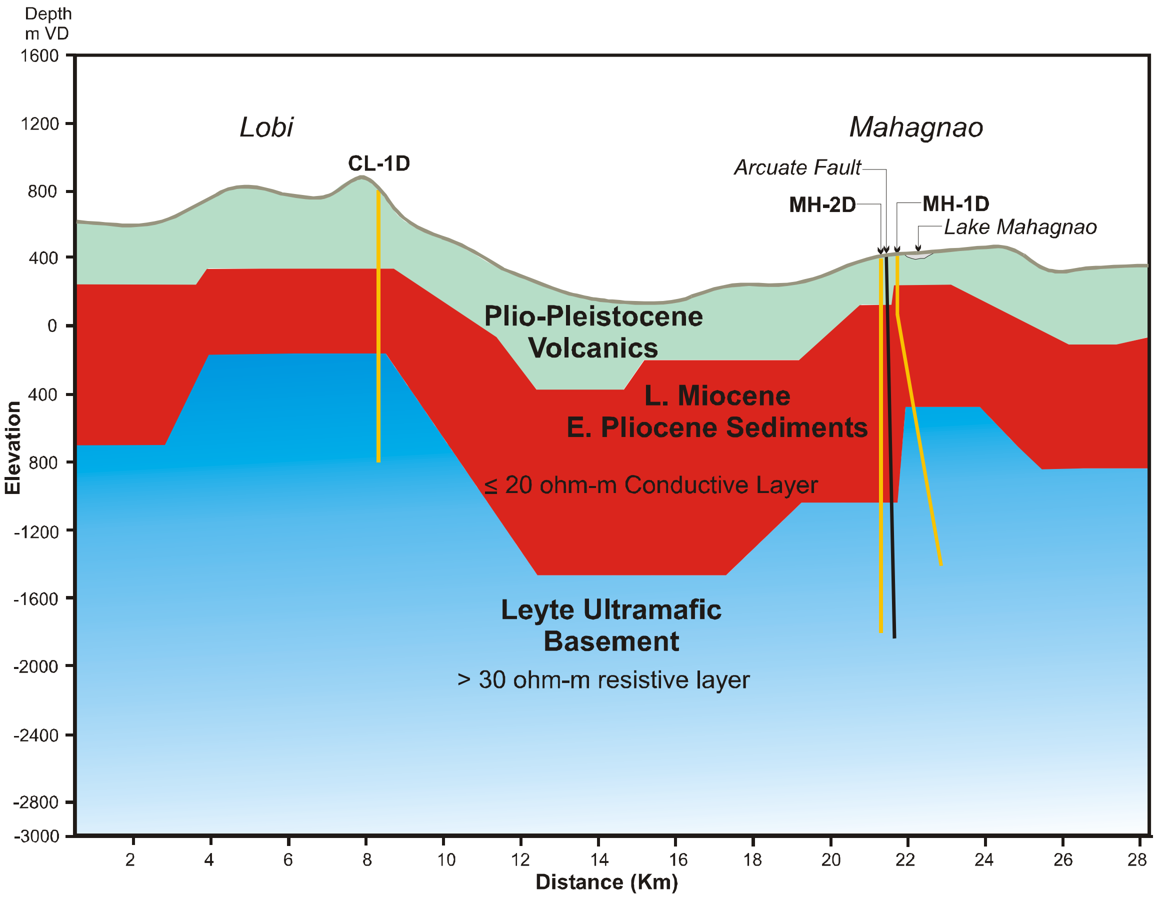

Figure 6: Correlation of MT Resistivity Layers and Stratigraphy of Central Leyte

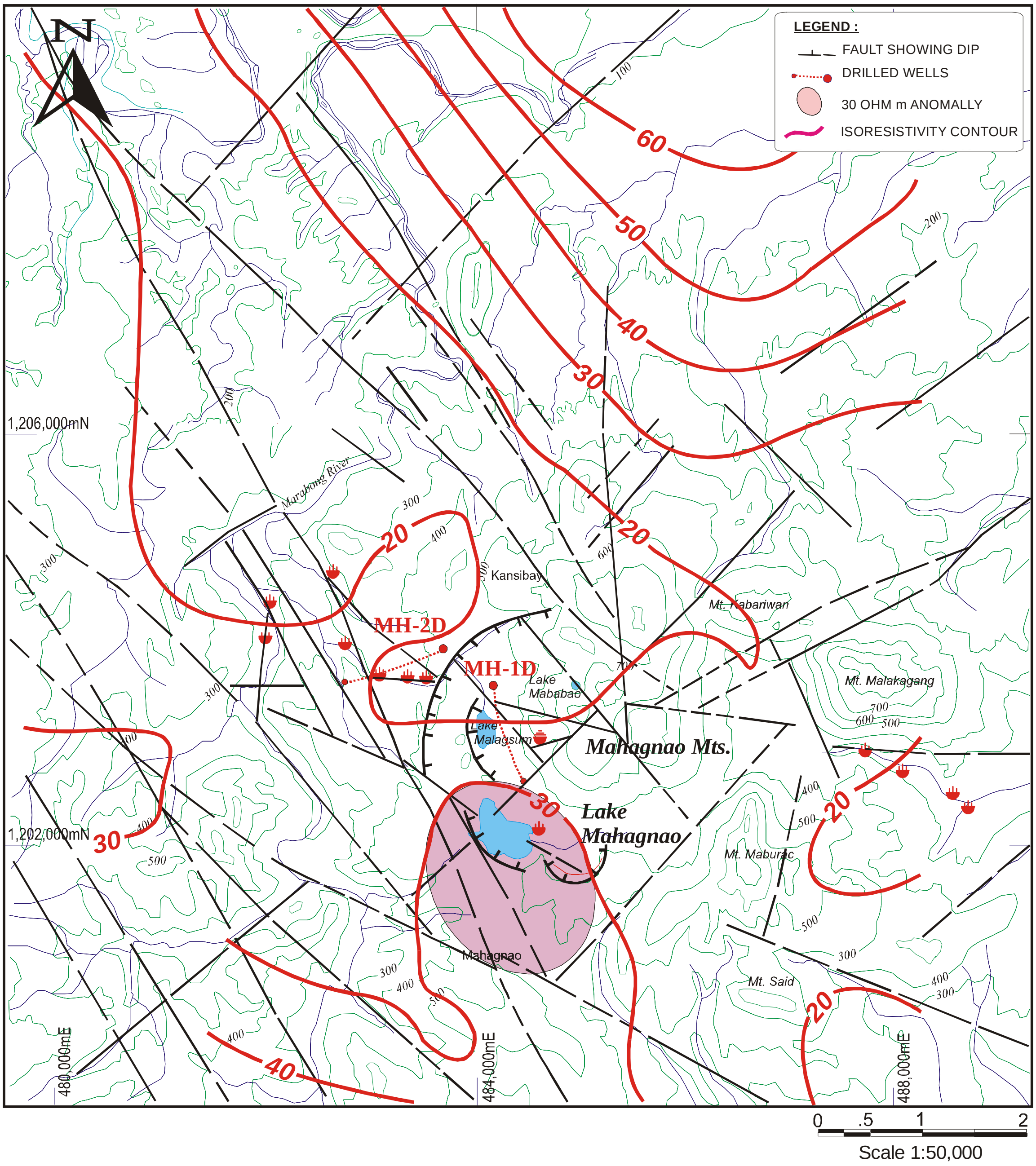

Figure 7: Isoresistivity Map at –1500 m Elevation

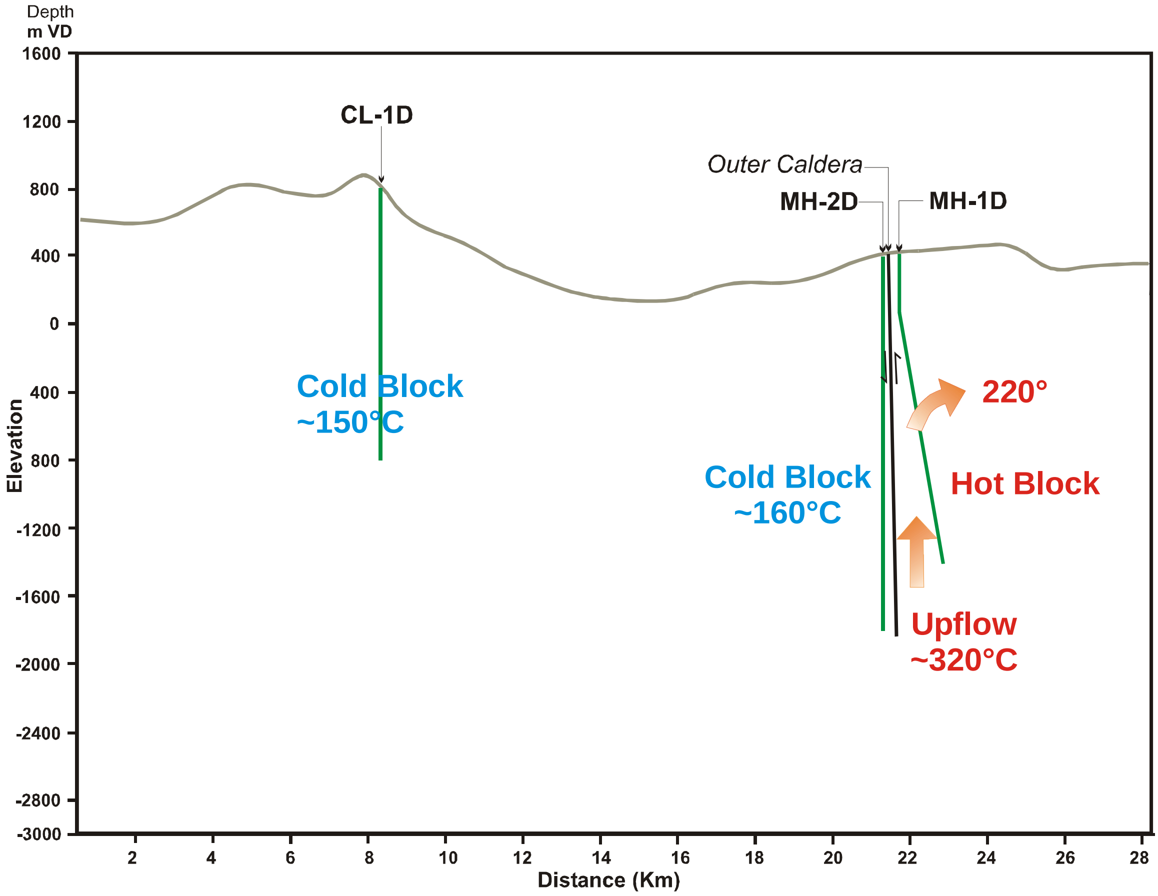

Figure 8: Post-Drilling Model of Central Leyte