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Exploration and Delineation Drilling in a High-Temperature Geothermal Reservoir: Northern Negros Geothermal Field, Central Philippines

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ABSTRACT

The Northern Negros geothermal field is located in Negros island, Central Philippines, and lies on the northwestern flank of Mt. Canlaon. It is underlain by two stratigraphic units – Pleistocene-Recent Canlaon Volcanics and Late Miocene-Pliocene Talave Formation.

Results of exploration and delineation drilling show that the center of the geothermal system lies in Pataan sector where hot neutral brine is presently upflowing along permeable faults. Mineralogic data and borehole surveys indicate that hot fluids with temperature of ~280-290°C are flowing at –1500 m MSL beneath wells PT-5D, PT-7D and possibly, PT-8D. The hot geothermal resource is bounded in the southwest by Asia Splay Extension based on declining temperature trends towards well PT-3D. The northwestern margin, on the other hand, is likely defined by Dinagaan Fault as suggested by cooling temperatures going to well PT-6D. This reservoir model agrees with geophysical surveys which also identified the upflow region in Pataan sector, possibly extending further southeast towards Sumaguan area. The heat source of the present geothermal system is likely related to the oldest eruption vent of Mt. Canlaon, the Hardin Sang Balo volcanic center which lies southeast of Pataan.

To complete steam requirement for the 40 MWe Northern Negros geothermal power plant, at least one more production well needs to be drilled in Pataan sector. On the other hand, three injection wells drilled in the northwestern sector of Pataan are already sufficient for disposal of spent brine from production wells. Expected commissioning of the Northern Negros power plant in 2006 will help meet growing electricity demand in Central Philippines.

1. INTRODUCTION

The Northern Negros geothermal field (NNGF) is located in the northern portion of the central Philippine island of Negros, and lies on the northwestern flank of Canlaon Volcano (Fig. 1). PNOC-EDC conducted exploration activities in NNGF from 1978 up to 1997 with a total of eight exploration wells drilled. Results of exploration drilling proved the existence of a hot geothermal resource in Northern Negros centered in Pataan sector where ~260-270°C neutral-pH brine is upflowing to –1100 m MSL along permeable faults (Zaide-Delfin *et al.*, 1998). A total reserve of ~40 MWe was estimated for NNGF which PNOC-EDC plans to develop to meet growing electricity demands in Central Philippines.

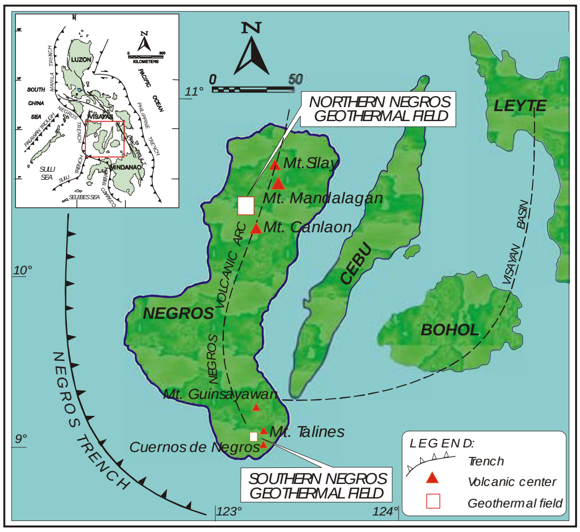

Figure 1: Location map of Northern Negros geothermal field

To further delineate extent of the geothermal resource, six more wells were drilled in Pataan sector from 2000 till 2003. Because of the national park boundary, these delineation wells cannot be drilled further east to reach the postulated center of the geothermal resource. Hence, they were drilled from existing pads outside of the park boundary with one well spudded from Pad A (PT-6D), and five from Pad B (PT-5D, 7D, 8D, 9D and 10D) (Fig. 2). For wastewater injection, three wells were drilled in Pad RI northwest of Pataan sector (Fig. 2). A magnetotelluric (MT) survey was conducted in 2000-2001 to define subsurface configuration of the geothermal resource.

This paper uses geologic and petrologic data derived from subsequent delineation and injection wells in NNGF to refine the current reservoir model of the Northern Negros geothermal system.

2. STRATIGRAPHY

Two stratigraphic formations underlie the NNGF - the Pleistocene-Recent Canlaon Volcanics (CnV) and the Late Miocene-Pliocene Talave Formation (TF) (Table 1). The term Talave Formation is now used in place of Caliling Formation (Zaide-Delfin *et al.*, 1998) to refer to the sedimentary sequence underlying the CnV. Based on microfossil dating in subsequent Pataan wells, the age of this sedimentary unit has been established as Late Miocene to Pliocene; thus it should be called Talave Formation based on regional stratigraphic nomenclature (BMG, 1982). The term Caliling Formation refers exclusively to Plio-Pleistocene carbonates exposed in the southwestern sector of Negros Occidental (PNOC-EDC, 2001).

Table 1: Stratigraphic column of NNGF wells

Formation	Lithology	Age
Canlaon Volcanics (CnV)	Dacite and andesite lavas and tuff breccias	Early Pleistocene to Recent
Talave Formation (TF)	Bioclastic limestone interlayered with breccias, conglomerates, and finer clastics	Late Miocene (N17) to Pliocene

2.1 Canlaon Volcanics

The Canlaon Volcanics is composed mainly of andesitic and dacitic effusives from various vents of Mt. Canlaon. Its oldest deposits were erupted during Early Pleistocene or 1.62-1.81 Ma based on fission-track dating (Hayashi, 1996), while its youngest units are Recent eruptives derived from the active Canlaon crater (Pamatian *et al.*, 1992).

The CnV consists of a thin (<100-250 m) layer of fresh two-pyroxene andesite lavas overlying a thicker sequence of altered andesite and dacite lavas and tuff breccias. The fresh andesite layer exhibits a pilotaxitic to hyalopilitic texture. Medium-grained plagioclase, hypersthene and augite phenocrysts are set in a groundmass which grades in composition from glassy to plagioclase-rich. On the other hand, the underlying altered sequence is made up of porphyritic lavas ranging from dacitic to andesitic composition. Phenocrysts consist of hornblende, biotite, and augite; while accessory minerals include zircon and magnetite. The breccias are composed of subangular clasts of dacite and andesite with minor amounts of olivine pyroxene basalt, microdiorite and limestone. Lithic fragments in breccias are held together by a matrix of tuffaceous materials, occasionally calcareous or hematized.

The Canlaon Volcanics is relatively thick in comparison with Pleistocene deposits in other Philippine geothermal fields that have an average thickness of only ~250-300 meters. The thickness of CnV in Pataan sector is ~1800 m reaching a maximum of ~2350 meters in well PT-1D (Fig. 3).

2.2 Talave Formation

The Talave Formation is separated from the overlying Canlaon Volcanics by a paleosol layer. It is generally made up of fossiliferous limestones interlayered with breccias, conglomerates and finer clastics. Paleobathymetry data indicate an environment of deposition ranging from inner-middle neritic extending down to outer bathyal (Lubas, 2001).

Sparitic to micritic limestone beds contain abundant planktonic and benthonic foraminifera, and minor amounts of mollusks, echinoid spines and red algae. Rare amounts of very fine crystals of plagioclase, quartz, ferromagnesian minerals, and altered rock fragments are also present in the carbonate rocks. Recrystallization is common in bioclasts and in interstitial cement.

Variable amounts and thicknesses of sandstone, siltstone, claystone, volcanic breccia and conglomerate characterize the clastic package of the TF. The epiclastic fragments in breccias and conglomerates are andesite, dacite, microdiorite with rare chert and quartzite. These clastic rocks may be tuffaceous, calcareous, carbonaceous, or rarely hematized.

The TF is thickest in Catugasan sector (well CT-1D) where it reached ~1280 meters (Zaide-Delfin *et al*., 1998). Its top occurs at various levels due to fault displacements. It is shallowest in Mambucal (well MC-1) at -170 m MSL, and deepest in Pataan (well PT-1D) where it lies below -1430 m MSL (Fig. 3).

3. PERMEABILITY

Good productivity is exhibited by most wells in Pataan sector that intersected highly permeable faults cutting mainly the Talave Formation or occasionally, the Canlaon Volcanics (Table 2). The major aquifers of these productive wells are correlated with significant amounts of drusy veins, sheared rocks and drilling losses. Among the permeable structures intersected by Pataan wells are Mambucal A (PT-1D, 2D, 6D), Kinabkaban B (PT-4D, 7D), Kinabkaban C (PT-5D), Catugasan C (PT-8D) and Pataan C (PT-3D, 7D, 9D, 10D) (Fig. 2). Except for PT-3D and PT-6D which encountered low temperatures, most Pataan wells yield good productivity based on discharge tests.

The three injection wells drilled in northwest Pataan sector also encountered permeable faults including Mambucal A (PT-1RD) and Napatagan A (PT-2RD, 3RD). However, Mambucal A was cased off in PT-1RD to prevent possible communication with the production sector during exploitation.

Outside of Pataan sector, faults are generally impermeable as observed in CT-1D (Catugasan), HG-1D (Hagdan) and MC-2 (Mambucal) which yielded low permeability due to tightness of faults they encountered. In Mambucal area, however, good lithologic permeability exists at shallow depths as seen in MC-1 where massive losses at –400 m MSL coincide with lithologic contacts within the TF (Reyes, 1979).

4. HYDROTHERMAL ALTERATION

The reservoir rocks in Northern Negros have been altered by deeply circulating, neutral-pH hydrothermal fluids. The common alteration suite includes quartz, epidote, illitic clays, anhydrite, pyrite, calcite and zeolites that occur as replacement of primary minerals and matrices, and as veins and vug fills.

Results of exploration drilling have established that in Pataan sector, hot, neutral-pH fluids are presently upflowing beneath wells PT-1D, PT-2D and PT-4D with temperatures of ~260-270°C at –1100 m MSL (Zaide-Delfin *et al*., 1998). These hot fluids outflow northwards between –100 and –600 m MSL through lithologic contacts emerging 4 kilometers away as neutral-chloride springs in Mambucal thermal area. No outflow of fluids occurs southwest towards Hagdan where poor structural and lithologic permeability exist.

Using additional alteration data from six delineation wells and three injection wells in Pataan, the distribution of alteration mineral geothermometers can now be determined in more detail. Table 3 lists alteration minerals that are used for predicting reservoir temperatures in NNGF. Figure 4 shows first occurrences of some of these mineral geothermometers including quartz and epidote.

Table 3. Alteration minerals used as geothermometers in NNGF

Alteration Mineral/s	Predicted Temperature (°C)
Chlorite	~120
Quartz (abundant)	~150
Laumontite	~150-230
Illite-smectite	~150-220
Illite	$\geq$220
Incipient Epidote	~180-200
Anhedral Epidote	~200-220
Subhedral Epidote	~220-230
Euhedral Epidote	$\geq$240-250
Wairakite	$\geq$240
Garnet	$\geq$260

In NNGF, the highest temperature predicted by mineralogy is ≥260°C using veins of garnet and euhedral epidote. Higher-temperature alteration geothermometers such as actinolite (~260-280°C) and biotite (~280-300°C) are not observed in NNGF wells; thus, fluid inclusion homogenization temperatures are used to predict reservoir temperatures at deeper levels.

Figure 5 shows predicted reservoir temperatures using alteration data from all wells drilled in NNGF. Though not shown in the figure, petrologic data from wells PT-4D, 9D, 10D, 2RD and 3RD were included in constructing the predicted isotherms. Data from subsequent delineation wells confirm the high-temperature region in Pataan sector. Based on fluid inclusions, and veins of garnet and euhedral epidote, the temperature of hot fluids in Pataan is ~280-290°C at -1500 m MSL as seen in wells PT-5D and PT-7D (Fig. 5). Due to blind drilling, no petrologic data exists at deeper levels in PT-8D. However, based on its similar alteration trend with adjacent well PT-5D, the maximum temperature in PT-8D is also predicted to be ~280-290°C. Downhole surveys recorded a maximum temperature of 280°C in PT-5D and PT-7D at –1500 m MSL (Fig. 6). On the other hand, the highest temperature measured in PT-8D (~250°C) is not yet stable (Yglopaz, pers. comm., 2003).

The absence of high-temperature minerals can be used to delineate the boundaries of the hot region in Pataan. The lack of euhedral epidote in wells PT-6D and PT-3D that caused the drastic plunge of the 240°C contour (Fig. 5) signifies that these two wells already exist at the margins of the high-temperature region in Pataan. Persistence of anhedral epidote, laumontite and illite-smectite down to bottom of PT-6D and PT-3D indicates low temperatures of ~220-230°C at –1100 m MSL. This predicted temperature is confirmed by fluid inclusion studies as well as downhole surveys.

The northern outflow of fluids at shallow reservoir levels was encountered by wells PT-1RD, 2RD and 3RD (Fig. 5). These fluids with temperatures of ~150-180°C are flowing along the permeable boundary of CnV and TF between –500 and –600 m MSL in PT-1RD and 2RD; and at –800 m MSL in PT-3RD.

5. GEOLOGIC MODEL OF THE GEOTHERMAL SYSTEM

Based on all mineralogic data and downhole surveys, the center of the geothermal system in Northern Negros is truly located in Pataan sector. The hottest region lies nearest to the bottom of wells PT-5D, PT-7D and possibly, PT-8D where hot, neutral-pH fluids with temperature of ~280-290°C are rising up to –1500 m MSL (Fig. 7). Permeable faults such as Mambucal A and Kinabkaban C transport the brine across the geothermal reservoir.

In comparison to other Philippine geothermal fields where the hot region (≥280°C) usually occurs shallower than –1000 m MSL, the geothermal resource of Northern Negros lies at much deeper levels (-1500 m MSL). This deeper occurrence of the NNGF resource can be attributed to the relatively thick (~1800 m) Pleistocene deposits of Canlaon Volcanics that probably served as an impermeable cap overlying the geothermal reservoir.

Well PT-3D was drilled in the southwestern resource margin where temperatures abruptly declined across Pataan C fault from ~270-290°C in PT-7D to ~230°C in PT-3D (Fig. 8). The northwest-trending Asia Splay Extension possibly marks the southwestern margin of the hot geothermal resource in Pataan.

In the north, fluid temperatures rapidly decrease along Mambucal A fault from ~270°C in PT-2D to only ~220-230°C in PT-6D (Fig. 8). This rapid temperature decline towards PT-6D signals the northwestern margin of the geothermal resource that may likely be bounded by Dinagaan fault.

From the upflow region in Pataan, reservoir fluids migrate to the north-northwest at shallow reservoir levels as confirmed by the 3 injection wells (Fig. 7). These shallow outflowing fluids with temperatures of ~150-180°C are moving along permeable horizontal structures such as stratigraphic and intraformational boundaries, finally emerging on the surface as neutral-chloride springs in Mambucal thermal area (Fig. 7). No shallow outflow of reservoir fluids occurs southwest towards Hagdan sector based on poor lithologic and structural permeability in this area.

The geologic model correlates well with results of magnetotelluric (MT) surveys which also delineated the location of the geothermal resource within Pataan sector, possibly further extending southeast towards Sumaguan area (Fig. 9) (Maneja *et al.*, 2001). Based on MT results, all productive wells in Pataan were drilled within the geothermal resource defined by the MT anomaly; while wells PT-3D and PT-6D lie along the margins (Fig. 9). On the other hand, wells CT-1D, HG-1D, MC-1, MC-2 and the 3 injection wells all occur outside of the geothermal resource.

No direct input of magmatic gases is found in fluids discharged by NNGF wells based on geochemistry (PNOC-EDC, 2001). Hence, the possible heat source in Northern Negros is not correlated with active magmatism in Canlaon. Instead, the present geothermal system is linked to Hardin Sang Balo volcanic center (PNOC-EDC, 2001), the oldest eruption vent of Canlaon which lies ~3 kilometers southeast of PT-7D (Fig. 8). In the vicinity of Hardin Sang Balo crater, presence of sub-volcanic stocks and intrusives is suggested by a positive gravity anomaly (Maneja *et al.*, 2001). Residual heat from these intrusive bodies associated with Hardin crater is likely driving the present geothermal system in Northern Negros.

6. DEVELOPMENT STATUS

At present, the available power in the NNGF is ~25 MWe from PT-2D, PT-4D, PT-5D, PT-7D and PT-8D (Yglopaz, D., pers. comm., 2003). The last two wells drilled, PT-9D and PT-10D, remain to be tested; but assuming an average of 5 MWe per well, at least one more production well needs to be drilled in Pataan sector to complete steam requirement for the 40 MWe Northern Negros geothermal power plant. This additional production well should target permeable faults known to channel hot fluids of ~280-290°C at –1500 m MSL. On the other hand, three injection wells, PT-1RD, PT-2RD and PT-3RD, drilled northwest of Pataan are already sufficient for disposal of spent brine from production wells. This year, PNOC-EDC will start to build the 40 MWe Northern Negros geothermal power plant, fluid collection and recycling system and its associated switchyard and cross-country transmission lines (PNOC-EDC, 2001). With its expected commissioning in January 2006, this power plant will help meet the growing demand for electric power in Central Philippines.

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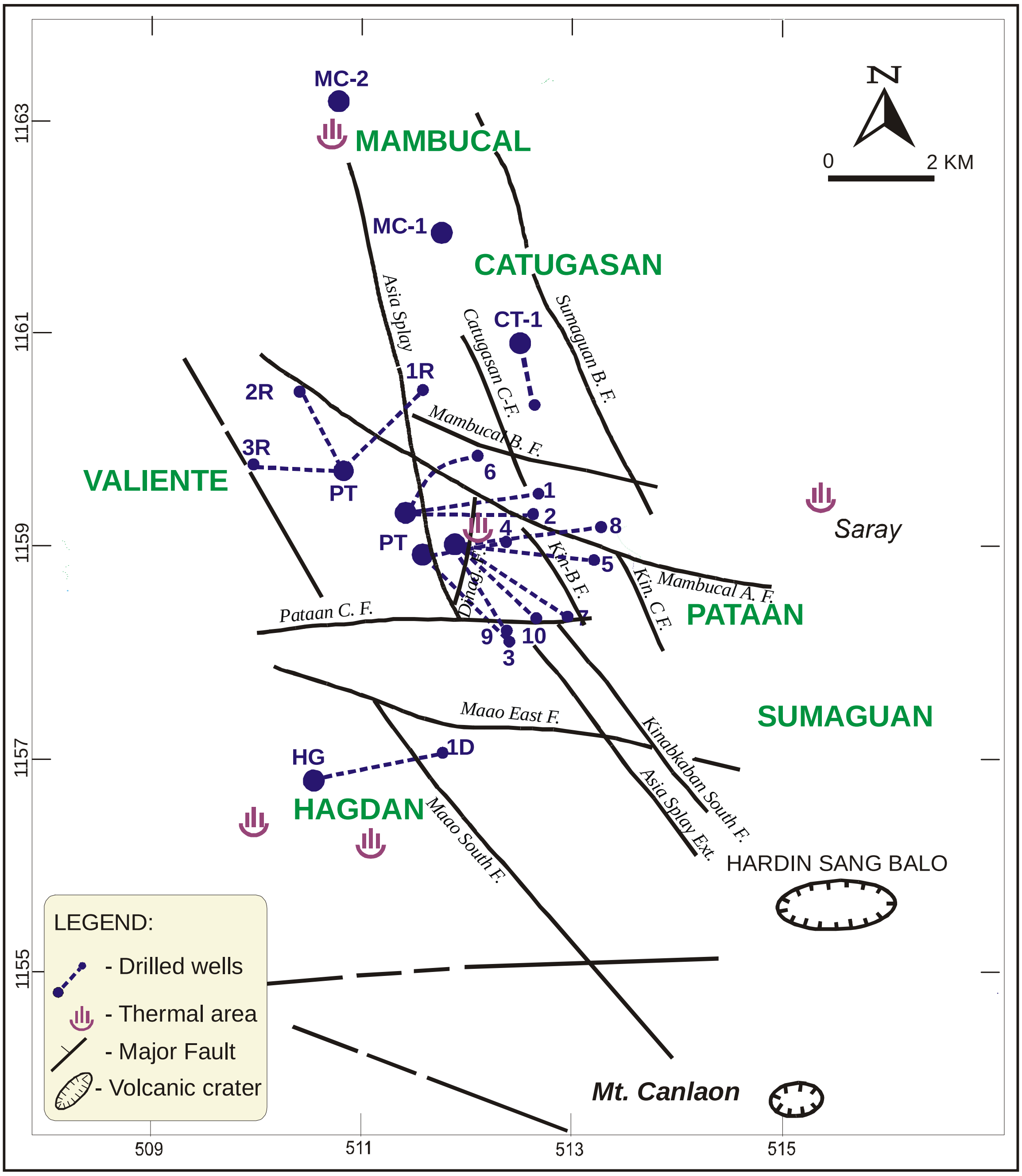

Figure 2: Structural map and location of wells in Northern Negros

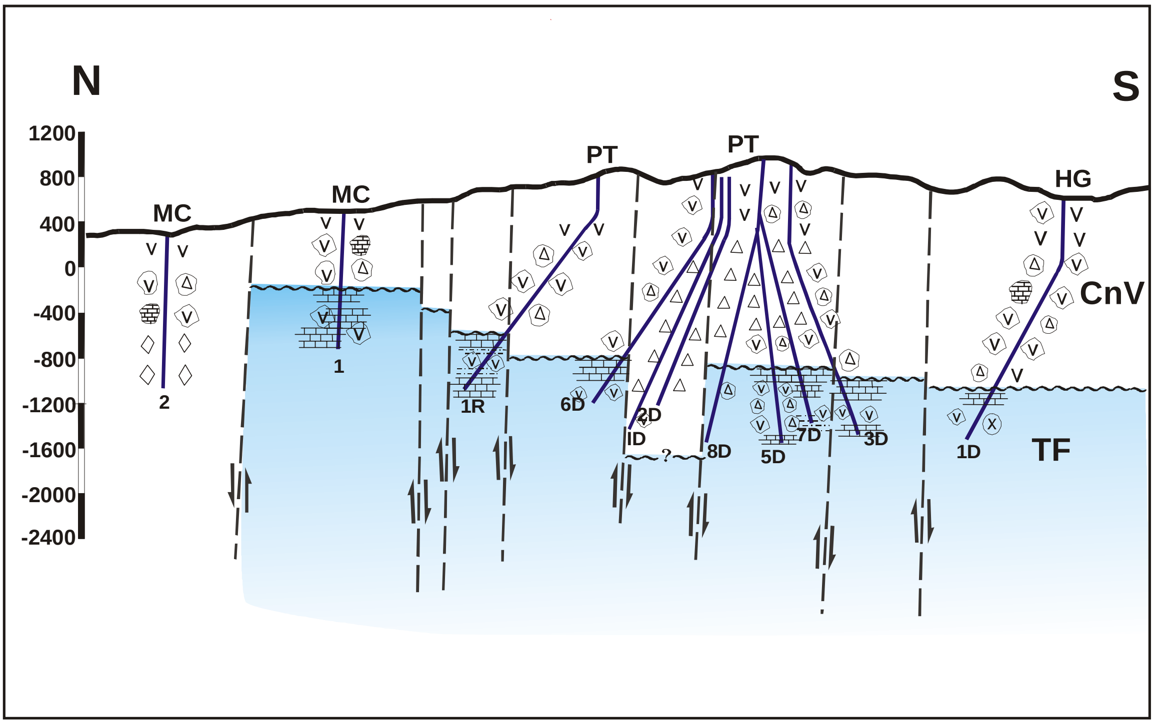

Figure 3: Subsurface stratigraphy of Northern Negros

Table 2: Permeability in NNGF wells

Well	Main Permeable Zone (m MSL)*	Structure/s	Stratigraphic Unit
PT-1D	-650 to –810	Mambucal A	Canlaon Volcanics
PT-2D	-1125 to –1165	Mambucal A	Canlaon Volcanics
PT-3D	-740 to –820	Pataan C	Canlaon Volcanics
PT-4D	-1000 to –1070	Kinabkaban B	Talave Formation
PT-5D	-1440 to –1520	Kinabkaban C	Talave Formation
PT-6D	-1180 to –1250	Mambucal A	Talave Formation
PT-7D	-1204 to –1280	Kinabkaban B/Pataan C	Talave Formation
PT-8D	-810 to –895	Catugasan C	CnV/TF contact
PT-9D	-1210 to –1220	Pataan C	Talave Formation
PT-10D	-1322 to –1451	Pataan C	Talave Formation
CT-1D	-1780 to –1860	Sumaguan D	Talave Formation
HG-1D	-1085	Maao South	Canlaon Volcanics
MC-1	-370 to –410	Lithologic contacts within TF	Talave Formation
MC-2	-615 to –685	Asia A	Canlaon Volcanics
PT-1RD	-890 to –1030	Asia Splay A & B	Talave Formation
PT-2RD	-985 to –1085	Napatagan A	Talave Formation
PT-3RD	-970 to –990	Napatagan A	Talave Formation

**Based on completion tests results*

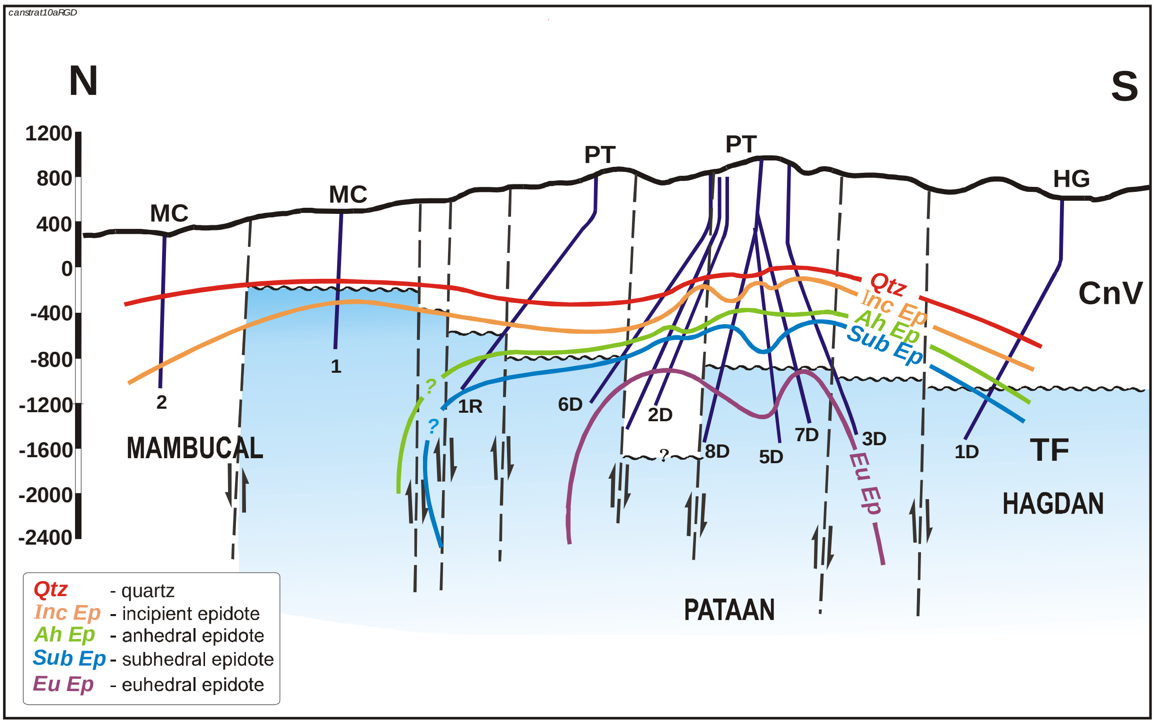

Figure 4: First occurrence of epidote and quartz in Northern Negros wells

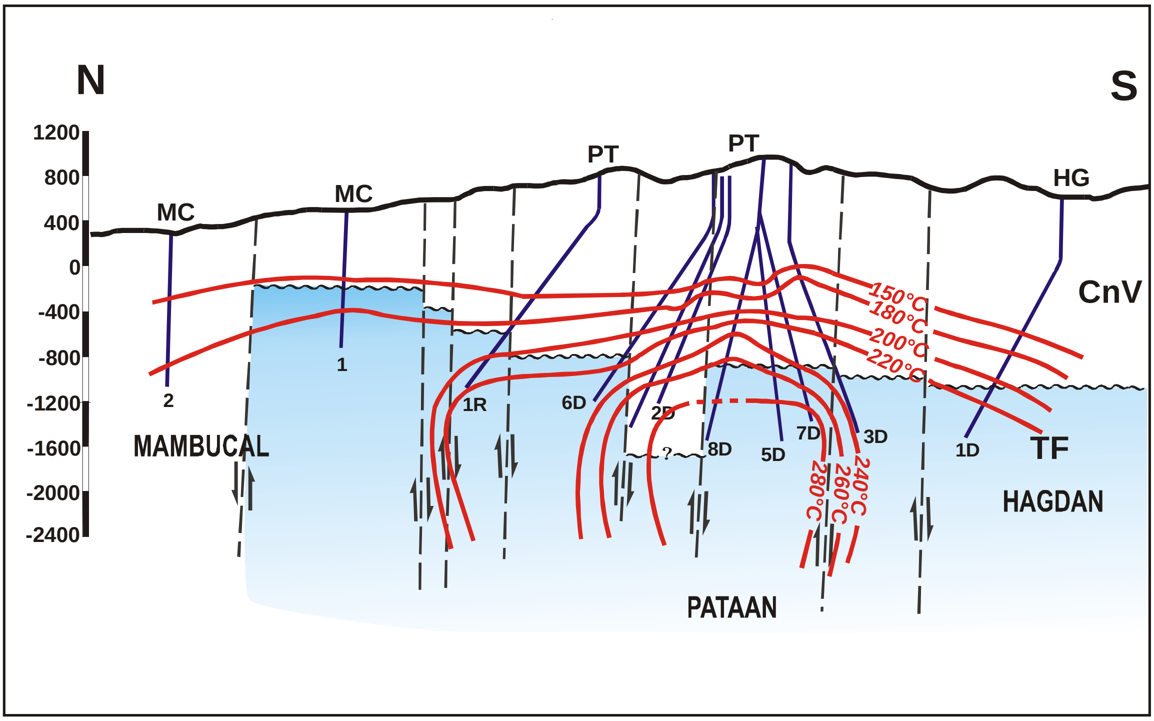

Figure 5: Predicted reservoir temperatures based on alteration mineralogy and fluid inclusion data in Northern Negros wells

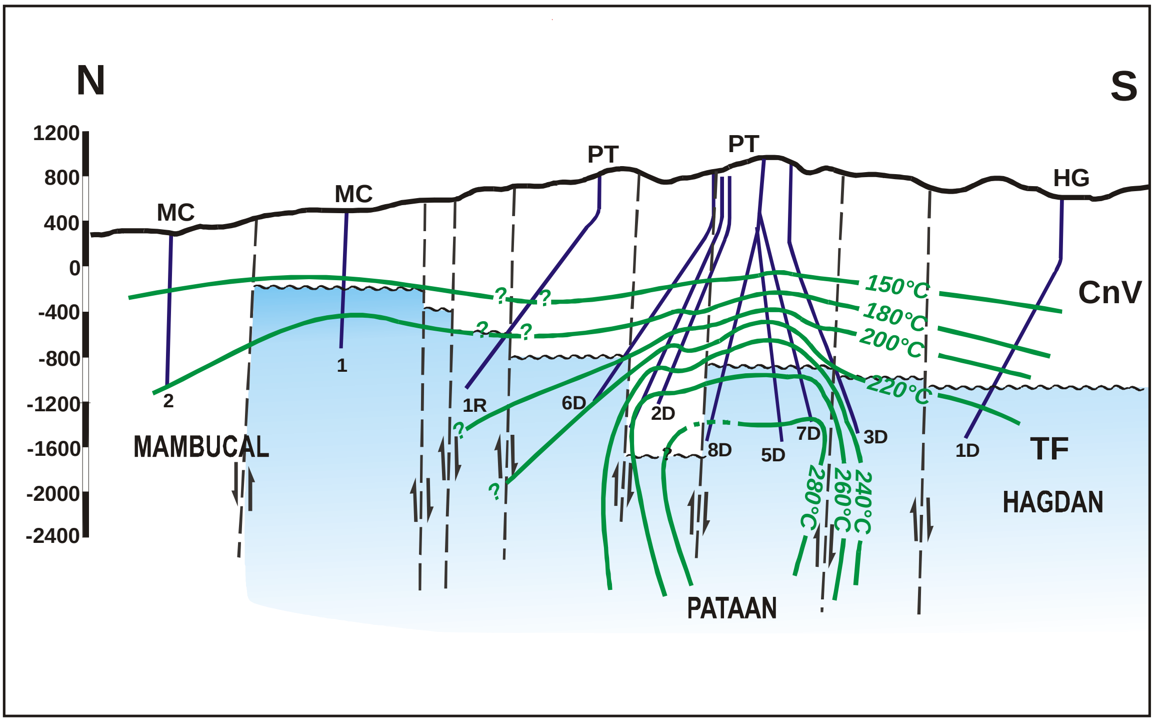

Figure 6: Stable measured isotherms in Northern Negros

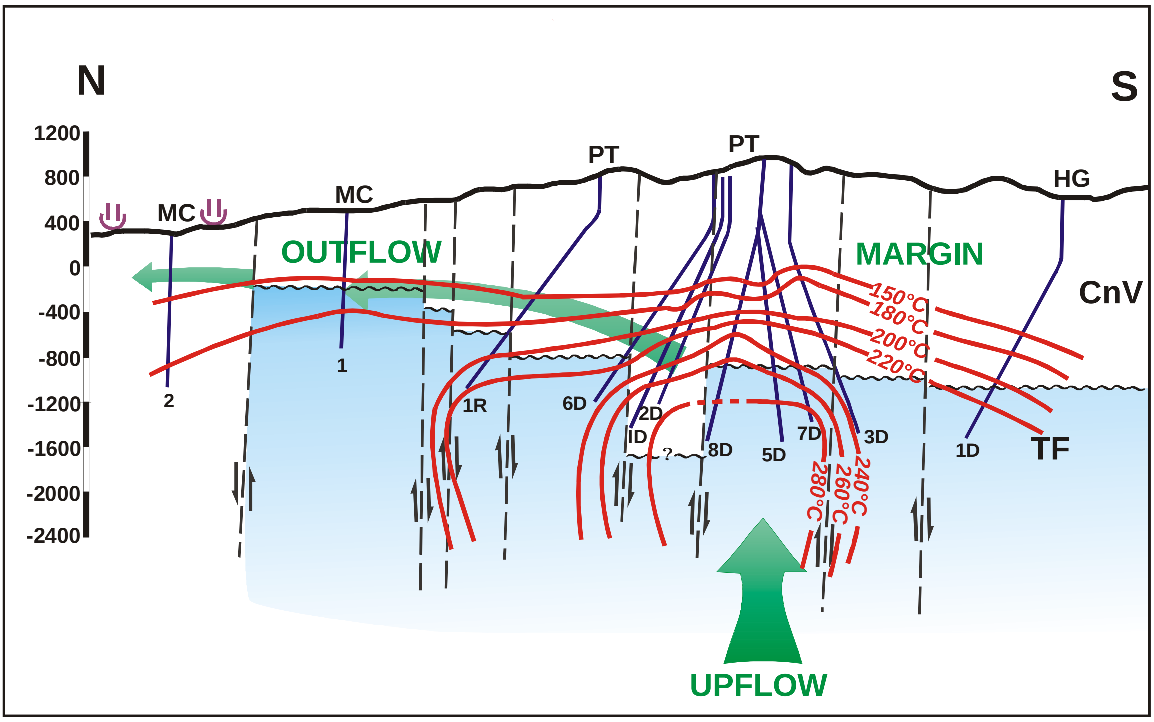

Figure 7: Geologic model of the Northern Negros geothermal system

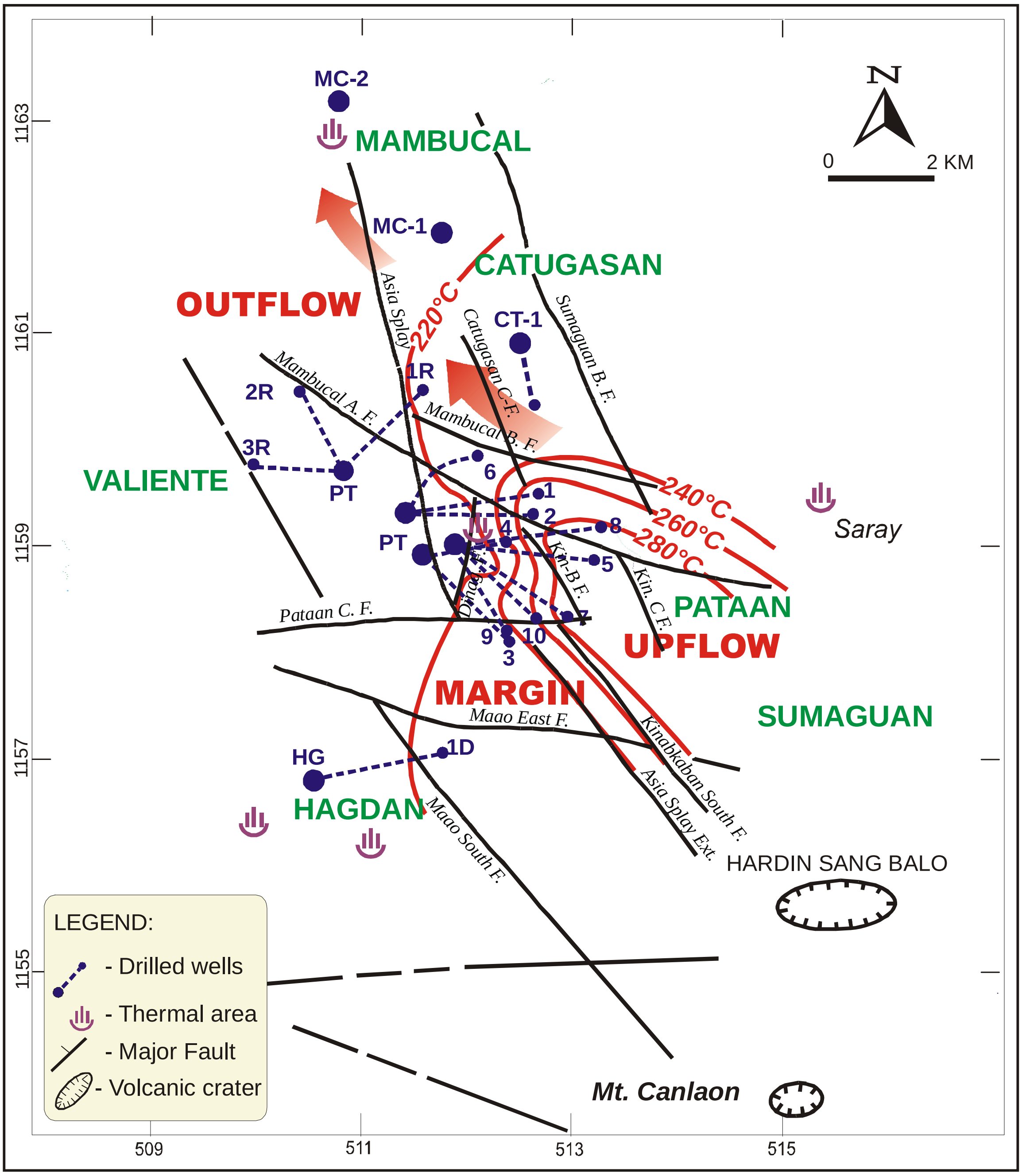

Figure 8: Geologic model of the Northern Negros geothermal system

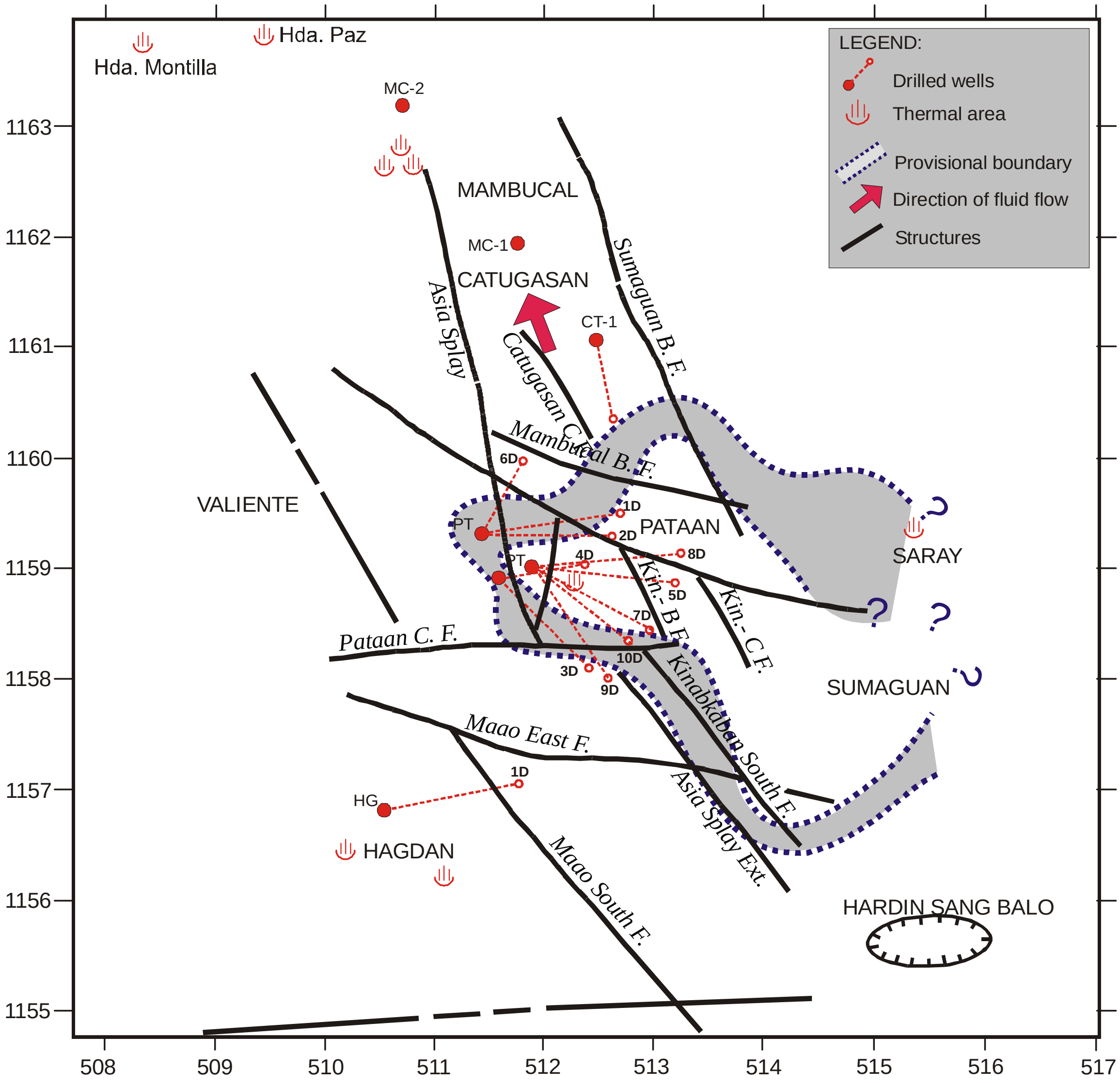

Figure 9: Geophysical model of Northern Negros geothermal field showing resource boundary (Maneja *et al.*, 2001)