USE OF AIRSAR / JERS-1 SAR DATASETS IN GEOLOGIC / STRUCTURAL MAPPING AT THE NORTHERN NEGROS GEOTHERMAL PROJECT (NNGP), NEGROS OCCIDENTAL, PHILIPPINES

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ABSTRACT:

A remote sensing study of the Northern Negros Geothermal Project (NNGP) was conducted using Airborne Synthetic Aperture Radar (AIRSAR) AND JERS-1 SAR images. A digital elevation model (DEM) was generated from the topographic SAR (TOPSAR) data sets where various hillshading maps were extracted to emphasize the general geology and the structural configuration of the study area. Due to the high resolution of the imagery, geologic mapping interpretations were done to refine the traditional and existing aerial photography interpretations including the volcanic history and its implication to the project.

The over-all result of this study have dealt with (1) the delineation of the semi-detailed geology at NNGP, thereby, giving way to the reinterpretation of the volcanic history of Canlaon volcano; (2) refinement of the structural map of Panem and Leynes (1996) with the establishment of chronological order of fault events where NW, WNW and ENE predominates the field; (3) delineation of new structural targets at Pataan area (e.g. Mambucal-B and -C, Asia-C, Asia Splay-A, -B, -C and -D, Catugasan-B Splay, Catugasan-C and -D, Kinabkaban-B, Kinabkaban-C and Pataan-C Splay); (4) confirmation of surface and subsurface interception of Talave Formation (rather than Caliling Formation) with findings of PNOC-EDC (2001); and (5) singling out of Hardin Sang Balo (rather than Tubidiao crater / collapse and Saray dome / collapse) as the probable heat source being tapped by the Pataan sector of NNGP.

1.0 INTRODUCTION

The study area is geographically bounded by Panay Island to the northwest, by Cebu Island to the west and structurally bounded by the Negros Trench to the southwest (Fig. 1). The PNOC Energy Development Corporation (PNOC-EDC) drilled 12 exploration and delineation wells (e.g. MC-1, MC-2, HG-1D, CT-1D, PT-1D, PT-2D, PT-3D, PT-4D, PT-5D, PT-6D, PT-7D and PT-1RD) within the study area (Fig. 2). Wells PT-7D and PT-1RD are yet fully tested while drilling of PT-8D is still ongoing as of this writing. The wells are distributed within the Mambucal, Hagdan, Catugasan and Pataan sectors, respectively, of the Northern Negros Geothermal Project (NNGP). PNOC-EDC intends to develop the Northern Negros Geothermal Project with an aggregate capacity of 40MWe.

This study is the result of integrating available remote sensing data (e.g. airborne synthetic aperture radar of NASA-JPL and JERS-1 synthetic aperture radar of ERSDAC) with the available geographic information system (GIS) database of NNGP.

The interpretation of AIRSAR imagery for geologic and structural mapping applications, however, was limited to the project site at the northwestern sector of Mt. Canlaon (Camit et al., 2000). Thus, to compensate for the lack of data in the other sectors, a three-strip mosaic of processed Topographic Synthetic Aperture (TOPSAR) data sets at 20-m contour interval were utilized to map geologic units. In addition, confirmation of said geologic units was likewise observed on JERS-1 SAR imagery from ERSDAC. The relative age of each unit was based on superposition relationships, flow morphology, degree of dissection, vent source, relief and textural differences. The paleontologic dates were derived from
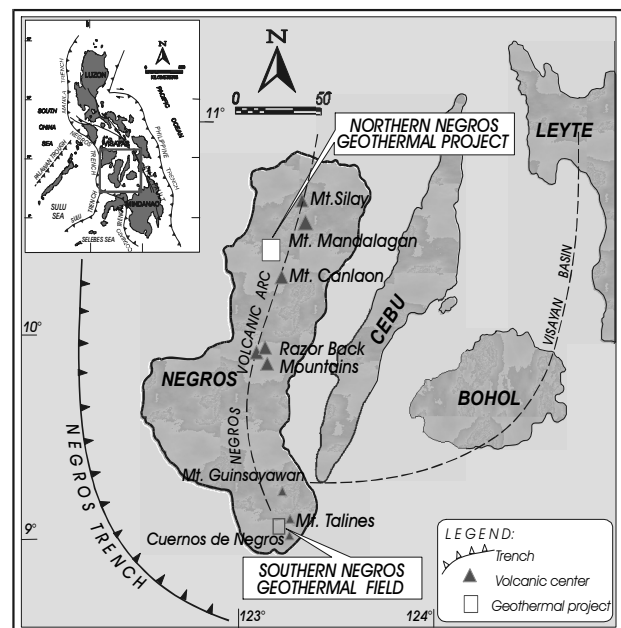

Figure 1. Location Map of the Northern Negros Geothermal Project and the Negros volcanic arc. The Southern Negros Geothermal Field is located at the southern side of the island.

four rock samples from wells and surface outcrops (Lubas, 2001).

The existing reports on the geology, volcanology and stratigraphy of the area have been freely consulted and used
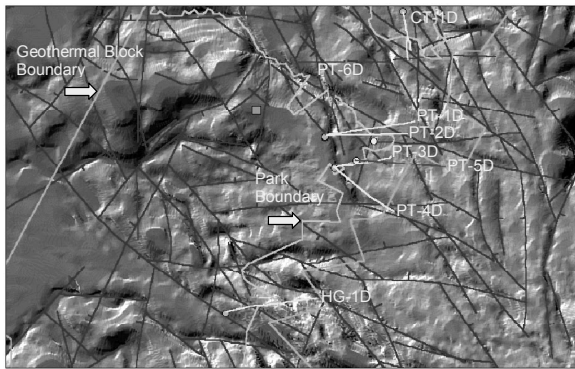
Figure 2. Location of NNGP wells at Mambucal, Hagdan, Catugasan and Pataan sectors showing geothermal block and Natural park boundaries. Mambucal wells MC-1 and MC-2 are located NW of Pataan (PT) wells.

Figure 3. Distribution of Active and Inactive Volcanoes and the Different Tectonic Features of the Philippines(Hamilton, 1979).

Table 1. Comparative analysis of Northern Negros stratigraphy illustrating the previous stratigraphy of the region and the result of this study.

when applicable to synthesize the geology and stratigraphy within the project (Melendres, 1975; Ferrer, 1979; BMGS, 1982; Umbal and Arboleda, 1987; Pornuevo, 1988; Umbal and Arboleda, 1988; Pamatian et al., 1992; Catane, 1994; von Biedersee and Pichler, 1995; PNOC-EDC, 1998; Martinez-Villegas, 1999).

This study presents: (1) the general geology, structural lineaments and proposed stratigraphy within the Northern Negros Geothermal Project (NNGP) and (2) a reinterpretation of the volcanic history of the Canlaon volcano. This study was based on interpretations made mainly from Topographic Synthetic Aperture Radar (TOPSAR) and JERS-1 SAR imageries and synthesis of earlier geological, petrological and paleontological studies.

2.0 METHODOLOGY

The C-DEM file was mainly used in this study where it was converted to physical parameters, generating the lambertian (shaded relief) surface and extraction of the polarimetric information such as the aspect and slope that was done using the topographic modeling option of ENVI 3.2. Final processing and interpretation of the topographic data are done through ILWIS 2.1. An attempt to delineate the general geology, stratigraphy and volcanic history of the study area was performed through the use of TOPSAR and JERS-1 SAR imageries.

Three imageries were used to extract the structural features at NNGP: (1) slant-to-ground range corrected radar imagery (TOPSAR and POLSAR imageries); (2) georeferenced JERS-1 SAR imagery; and (3) NW-directed / SE-directed hillshading maps (from NAMRIA 1:200,000 m scale map).

3.0 GEOLOGIC INPUTS

3.1 Tectonic Setting

Canlaon Volcano forms the mid-northern segment of the west-facing island arc system that is partly defined by the Negros volcanic arc in the western side of Central Philippines (Fig. 3). The volcanic belt consists of Cuernos de Negros, Razor Back Mountains, Mount Silay, Mount Mandalagan and two small island volcanoes east of Panay Island (30 km north of Negros Island) (Martinez-Villegas, 1999). The arc is the result of subduction of Sulu Sea Basin lithosphere along the Negros
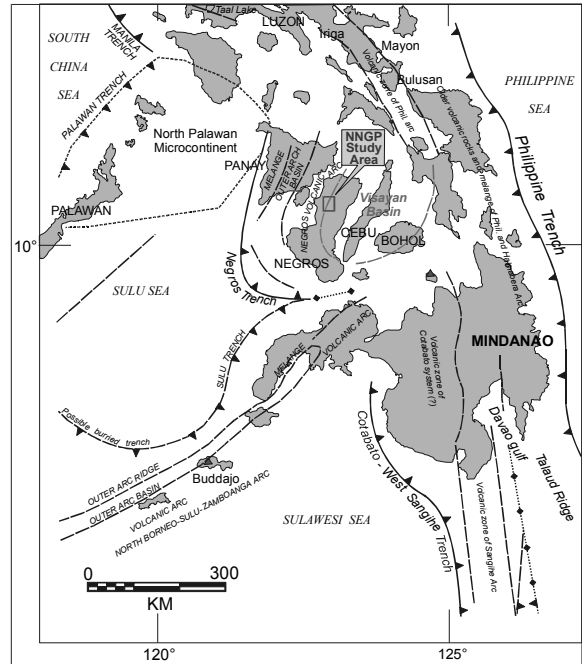
Trench (Acharya and Aggarwal, 1981) that has been an active subduction zone since the Miocene (Cardwell et al., 1980). This trench was eventually dammed when the North Palawan - SW Mindoro continental fragment collided with the Philippine Arc during the late Miocene. Geochemical evidence of high potassium content of Negros Volcanics have been similarly associated with source contamination by remnants of the continental crust of said collision (von Biedersee and Pichler, 1995). In addition, this 150 km deep Negros trench has no clearly developed Benioff-Wadati zone (Acharya and Aggarwal, 1980) but has a present day subduction rate of about 2 cm per year.

3.2 Geologic Mapping Results

Initially, the surface geology and inferred stratigraphy were mapped by this study using: (1) Topographic Synthetic

Aperture Radar (TOPSAR) and JERS-1 SAR imageries and (2) synthesis of surface and subsurface petrologic / paleontologic data from existing reports (i.e.; Reyes, 1979b; Wood, 1979a; Reyes, 1984b; De Guzman, 1995; De Guzman and Revilla, 1995; Lubas, 1997; Lubas, 2001; Dulce, 2001; Ramos, 2001).

Table 1 shows the comparison of the stratigraphy of Northern Negros and the results of this study. Figure 4 shows the modified geologic and structural map of Northern Negros based on the review of existing maps (Pamatian et al., 1992; Umbal and Arboleda, 1988; and Von Biedersee and Pichler, 1995), field survey of selected sites, aerial photo analysis and interpretation of remotely-sensed data (i.e. TOPSAR and JERS-1 SAR imageries).
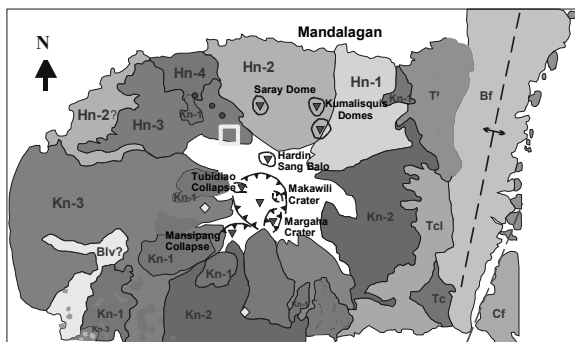

Figure 4. Modified Geologic Map of the Northern Negros Geothermal Project (NNGP) interpreted from Topographic Synthetic Aperture Radar (TOPSAR) and JERS-1 SAR Imagery.

There are five major stratigraphic units in the study area (from oldest to youngest): (1) Basak Formation (Bf); (2) Budlasan Volcanics (Blv); (3) Talave Formation (Tf); (4) Caliling Formation (Cf) and (5) Canlaon Volcanics (CnV). The formations are described below:

Basak Formation (Bf)

This consists of Cretaceous-Late Miocene marine sediments interbedded with pillow lavas (KRTA, 1980; BMGS, 1982). The formation trends N-S and is exposed to the east of the study area. The bathyal marine sediments are composed of mudstone, claystone and gravel conglomerates that dip 45° to the northwest while the lavas are mainly two-pyroxene basalt.

Well MC-1 was previously interpreted to have encountered Basak Formation from 610 mRSL to 718 mRSL where andesitic volcanics and calcareous sediments occur. However, re-evaluation of petrologic data (PNOC-EDC, 1998; Ramos, pers. comm., 2001; Lubas, 2001) indicated that the Basak Formation was never intercepted by Mambucal wells (i.e., MC-1 and MC-2) at depth.

Budlasan Volcanics (Blv)

This rock unit consists of thick columnar-jointed lava flows of hornblende andesite to two- pyroxene andesite. An inferred volcano root ("cinder cone" to Martinez-Villegas et al., 1999) exposed as a flat-topped plateau or dome-like structure is observed roughly 9 km SE of the active Canlaon crater (Pamatian et al., 1992). Well MC-1 was previously interpreted to have intercepted this unit between 406 mRSL to 610 mRSL (Pamatian et al., 1992). Based on the recent analysis of MC-1 rock cuttings by Ramos (pers. comm., 2001), the andesitic

volcanic breccias were considered part of the Talave Formation from said depths until TD of well at 718 mRSL.

An outcrop (located approximately 11.7 km SW of the active Canlaon crater) consisting of highly eroded terrane was interpreted from processed radar images as part of the real Budlasan Volcanics. The Budlasan Volcanics delineated by Pamatian et al. (1992) to the NW and south of the active Mt. Canlaon has distinct polarized signature similar to the younger Hardin and Canlaon Volcanics compared with the interpreted Budlasan Volcanics southwest of Canlaon volcano identified in this paper.

Talave Formation (Tf)

Based on the analysis of radar imagery, three distinct members of this formation are interpreted and correlated with the lower Talave limestone, middle Tigbao clastics and upper Bairan agglomerate mapped by BMGS (1982) at the eastern portion of the study area. The following lithologic descriptions of the Talave members are primarily obtained from Pamatian et al., (1992) and from observations in this study. The members are designated as Tc, Tcl, and Tl.

An upper member Tc (~Bairan agglomerate?) which appears straddling over deposits of a thicker member Tcl (~Tigbao clastics?) and the Basak Formation was observed from interpreted AIRSAR imagery at the southern section of the north-northeast trending Talave Formation (Fig. 4). In turn, the Tcl member underlies another member Tl (~Talave Limestone) at the northern section of the Talave Formation. The lower Tcl, middle Tl and/or an upper Tc comprise the Talave Formation in the study area. An aggregate thickness of 425 meters was estimated for Tcl and Tl (BMGS, 1982).

The Tcl member mapped by BMGS (1982) consists of laminated to thin-bedded, tuffaceous mudstone interbedded with conglomerate and thin-bedded, gray, sandy limestone. This unit exhibits low to moderate dipping "flat irons" feature at the southeast sector of Mt. Canlaon. This implies bedding structures within the Talave Formation. This formation is low- to moderately- folded beneath the younger Canlaon Volcanic Complex as seen and extrapolated from the processed SAR imagery. A north-northeast trending fold axis trace is inferred along the Basak Formation (Fig. 4). This interpretation is consistent with the inferrence made by Pamatian et al. (1992).

The Tl member is characterized by karst topography with low knobby hills. Within the study area Tl member is found as an isolated feature and onlaps the Tcl member. This unit consists of indurated well-bedded, fossiliferous calcisiltites and calcarenites with beds striking N20°E and dips 15°NW (Pamatian et al., 1992). This member is the equivalent of the Talave Formation of BMGS (1982) and Melendres (1975).

The Tc member at the southeast was also mapped by Pamatian et al. (1992) to have an angular unconformity with the older Basak Formation. This unit consists of sub-rounded to rounded clasts of pyroxene-bearing hornblende andesite to clinopyroxene andesite set in tuffaceous silty to sandy matrix. This deposit is only exposed to the southeast.

This formation was initially described as volcano-sedimentary complex in Pataan, Hagdan and Catugasan wells. However, to be consistent with known paleontologic dating of the sediments, a Late Miocene to Pliocene Talave Formation is

proposed for subsurface stratigraphy purposes (Ramos, pers. comm., 2001). This formation has a thickness of 1280 meters at well CT-1D (Ramos, pers. comm., 2001). It consists of fossiliferous limestone interlayered with calcareous to carbonaceous sandstone, siltstone, claystone, mudstone and volcaniclastics. Wells PT-1D and PT-2D did not encounter the Talave Formation. An estimated age range of Late Eocene to Pliocene was previously assigned to this unit (Pamatian *et al.,* 1992).

Caliling Formation (Cf)

This formation onlaps the older Basak and Talave Formations along the east coast of the study area as observed from the interpreted radar imageries of TOPSAR and JERS-1 SAR. This unit is characterized by karstic, friable, fossiliferous, calcisiltites, calcarenites and calcirudites. Its texture suggests massive bedding with dips of 20º-40º NE/SE (Pamatian *et al.,* 1992).

Canlaon Volcanics (CnV)

The term Canlaon Volcanic Complex was initially used by Pamatian et al. (1992) as a sack name for the deposits from vents of the ancestral Canlaon caldera (inferred), Makawili, Tubidiao, Hardin Sang Balo, Margaha, Mansipang and the active Canlaon (Fig. 4). Due to the presence of numerous, distinct vents within Canlaon, Pamatian et al. (1992) adopted the nomenclature Canlaon Volcanic Complex. In addition, Alincastre (1983) and Umbal and Arboleda (1987) also attest that Canlaon Volcano is not a single, vent-type of volcano.

For simplicity, the term Canlaon Volcanics that was used in PNOC (1998) is retained in this study to describe deposits of Canlaon Volcanic Complex (CnVC) at surface and subsurface levels (Table 1). Melendres (1975) and Ferrer (1979) called the same surface deposits as a Pleistocene to Recent "pyroclastic and volcanic flows" while BMGS (1982) called the same formation as Sagay Volcanics. The term Pleistocene to Recent Sagay Volcanics refers to the Quaternary volcanic deposits within Negros Island including the volcanic edifices of Cuernos de Negros, Silay, Mandalagan and Canlaon (BMGS, 1982).

This study confirmed the existence of different volcanic vents that deposited the various pyroclastic units and lava flows around the inferred ancestral Canlaon caldera (Pamatian *et al.,* 1992). Collapse structures (Umbal and Arboleda, 1987; PHIVOLCS, 1987; von Biedersee and Pichler, 1995; Martinez-Villegas, 1999) were mapped at the north, southwest and southeast rim of the inferred caldera of Pamatian et al. (1992). around the inferred ancestral Canlaon caldera (Pamatian *et al.,* 1992). Collapse structures (Umbal and Arboleda, 1987; PHIVOLCS, 1987; von Biedersee and Pichler, 1995; Martinez-Villegas, 1999) were mapped at the north, southwest and southeast rim of the inferred caldera of Pamatian et al. (1992). These structures were interpreted in this study as volcanic eruption-related craters and small-scale calderas such as the Mansipang Collapse, Tubidiao Collapse, Hardin Sang Balo crater, Margaha crater ("Lugad crater" of von Biedersee and Pichler, 1995), Makawili crater and the active Canlaon crater.

3.3 Canlaon Volcanic History

Spectral and morphologic evidences; such as polarized signatures, tone, texture and pattern (from the polarized synthetic aperture radar imagery) in combination with superposition sequences (using the digital elevation model of topographic SAR) of volcanic deposits were proven essential in interpreting a multiple vent source for the Canlaon Volcanic Complex. However, the lack of absolute dating of the various deposits is evident in the area. The available dates of surface deposit were from charcoal samples from two different pyroclastic flow units obtained a ^{14}C dating of 1920 ± 50 and 2570 ± 50 years BP (Fig. 4). These pyroclastic flow units could be associated with the active Canlaon crater and Tubidiao crater, respectively (Martinez-Villegas, 1999).

A modification of the volcanic history for the Canlaon Volcanics earlier proposed by Pamatian et al. (1992) is given below (from oldest to youngest) (Figs. 5I):

Canlaon Volcanics 1 (KN-1) - Initially, an ancestral Canlaon volcano is believed to be situated within the present location of inferred ancestral Canlaon. A single-vent series of eruption events led to the breaching of its western flanks. The volcanic events were thought to be confined within a single vent source that deposited Kn-1. At present the remnants of the past activities are still extant at the northeast, south, and southwest. The paroxysmal stage of the volcanic activity was presumably marked by an explosive event that led to the breached west flank. A resulting debris avalanche deposit occupies the southwest sector of the study area. This unit is characterized by its prominent hummocky topography with blocks and matrix facies. The present location of these deposits at La Castellana suggested that the deposits traveled a maximum distance of 33 km and has an estimated volume of 13 km^3 (Catane, 1994).

Canlaon Volcanics 2 (KN-2) - Contiguous (post, intra-caldera) volcanism ensued within the breached ancestral caldera producing Makawili and Mansipang volcanic centers. Lava and pyroclastic flows associated with Makawili occupy the eastern midslopes and lower slopes of the ancient caldera while Mansipang produced mainly airfall tephra and minor lava flows which are deposited to the southwest. A dome-like structure proximate to the resulting Mansipang collapse can be observed in the area.

Hardin Volcanics (HN-1) - After the eruptions (post, extra-caldera) of both Mansipang and Makawili, eruption at the northern flank of the breached Canlaon caldera ensued. This resulted to the Hardin Sang Balo crater with mainly ashfall and pyroclastic flow deposits distributed to the northeast of the study area.

Hardin Volcanics (HN-2) - A renewed eruption at the Hardin Sang Balo crater caused breaching of its northwest crater wall thereby depositing mainly distal pyroclastic deposits and near-vent lava flows to the north. Three prominent dissected dome-like structures are contained within these deposits (e.g. Saray and Kumalisquis domes?). These structures are inferred to be post-Hardin Sang Balo parasitic domes.

Hardin Volcanics (HN-3) - Thick, voluminous lava flows accompanied by minor airfall deposits predominate the volcanic terrain sourced from the same vent of Hardin Sang Balo crater. Two lava flow events are believed to represent these deposits to the northwest and north-northwest. The former probably has a basaltic andesite composition while the latter is of dacitic in composition. This is based on the observed low- to high-relief lava flow morphology of both deposits as seen on radar imagery. The intermediate lavas have traveled over a longer distance and exhibit a widened lobe structure (less viscous) while the silicic lavas formed short to near-vent deposits and show a constricted lobe features (viscous lavas).
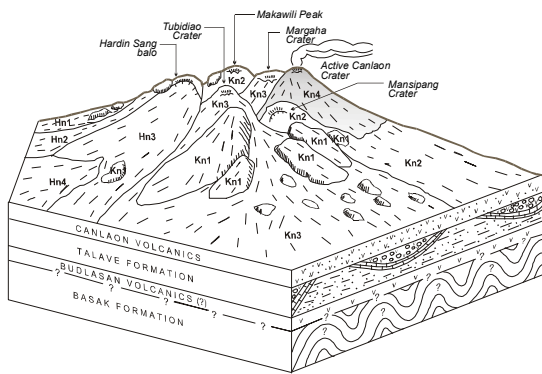
Figure 5. Three-dimensional Canlaon volcanic terrane showing Hn- and Kn- volcanic units. Subsurface geology of NNGP also shown (modified after Pamatian et al., 1992).

Hardin Volcanics (HN-4) - This volcanic sequence includes pyroclastic deposits believed to be transported along narrow valleys within Hn-3 units thereby emplacing its products along distal slopes northwest of the study area

Canlaon Volcanics 3 (KN-3) - Two volcanic sequences (e.g. Tubidiao and Margaha) correspond to this contiguous eruption event that produced KN-3. The distribution of the volcanic deposits in the area suggests that the Tubidiao collapse, an inferred volcanic center, deposited the pyroclastic flows as infills along valleys of previously breached western flanks of the ancient caldera. The Margaha crater (termed Lugad crater by Martinez-Villegas, 1999) influenced lava building (as near-vent deposits) that preceded the deposition of pyroclastic flows along narrow valleys of same Kn-3 lava banks mostly concentrated to the south - southeast slopes.

The Tubidiao pyroclastic deposits correspond to the andesite block-rich flows to the west at Guintubdan area as mapped by Martinez-Villegas et al. (1999) at its west slopes. A ^{14}C dating of charcoal sample obtained an age of 2570 ± 50 years BP. The Margaha volcanic center was the result of eruption at the southern slope of Makawili (Kn-2) thereby creating 1.5 to 2 km diameter crater (Pamatian *et al.,* 1992; von Biedersee and Pichler, 1995).

Canlaon Volcanics 4 (KN-4) - This volcanic event marks the most recent (historical) eruption deposits consisting of mainly pyroclastic flows and airfall tephra from the active Canlaon crater 100 meters to the south of the 1.5-2 km diameter Margaha crater (Fig. 5). However, it is observed that this airfall tephra thinly blankets the underlying lava flows to the south based on the analysis of radar imagery of the Canlaon study area. The pyroclastic flows initially described as valley in-fills correspond to the scoria-rich deposits identified by Martinez-Villegas et al. (1999) at Biak-na-Bato area to the south. A ^{14}C dating of charcoal sample gave a younger age of 1920 ± 50 years BP for this pyroclastic flow unit.

Two-isolated pyroclastic flow units (probably associated with Kn-4) have been similarly identified in this study along the general area of Talongo and Enyawan rivers. These deposits correspond to the pumice-rich pyroclastic flows overlain by andesite block-rich pyroclastic flow deposits mapped by Martinez-Villegas et al. (1999). These pumice-rich pyroclastic deposits could have been slightly older deposits of Kn-4.

Unfortunately, no data are available to absolutely constrain the age of the deposit.

4.0 STRUCTURAL CONFIGURATION VERSUS WELL DATA

The structural analysis done here supplements the structural map of Panem and Leynes (1996). Lineaments delineated from the radar imageries (e.g. TOPSAR: digital elevation model and JERS-1 SAR) and the NAMRIA-extracted digital topography map (DEM) was initially compared with the 1996 structural map. Commonly placed or redundant lineaments and spatially unique lineaments were filtered and retained from the resulting composite map. Since the study is based on remote sensing, the observed unique linear features (other than the ground-verified ones) were designated initially as lineaments. These new lineaments were given separate names while the existing names of structures defined by Panem and Leynes (1996) were retained. These new fault traces are Mambucal-B and -C, Asia-C, Asia Splay-A, -B, -C and -D, Catugasan-B Splay, Catugasan-C and -D, Kinabkaban-B, Kinabkaban-C and Pataan-C Splay. Most of these faults (e.g. Asia Splay -A, -B, -C and -D, Kinabkaban-B, Catugasan-C, Kinabkaban-C, Catugasan-B Splay and Mambucal-B) were intersected in the recently drilled wells PT-5D and PT-6D (Fig. 2 and 6).

The latest temperature well profile of well PT-5D further confirmed that the hottest region in the area of northern Negros lies east and beneath wells PT-2D, PT-4D and PT-5D. In the absence of actual tracer tests to approximate fluid flow paths, it is surmised that the channels are predominantly fault- related and to a minor extent interformational- to intraformational-related permeable zones (PNOC-EDC, 2001).

Assuming a N-S stress regime dominates the Negros Island, the E-W and N-S faults comprise the compression and eastern extensional faults, respectively. Due to the movements along the Mindoro–Panay collision zone, a postulated clockwise rotation of the stress regime from N-S to SE (~135°) at its
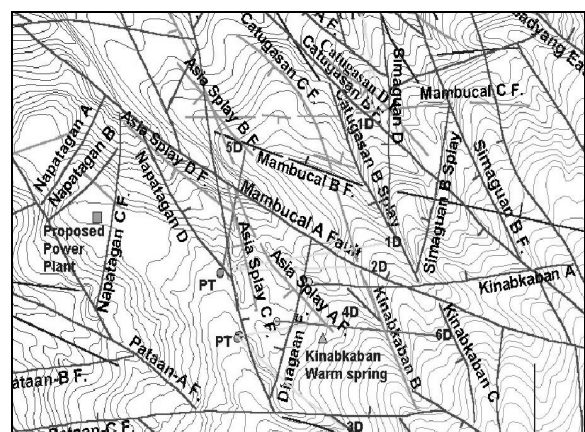

Figure 6. Composite structural map of the Northern Negros Geothermal project (NNGP) showing the structures.

southeastern fringes possibly caused the current structural configuration of the study area. This theory explains opening up of previous N-S fault networks previously correlated with the eastern - subducting Negros Trench where the volcanic

occurrences at Canlaon, Mandalagan and Silay are associated. With the postulated clockwise stress rotation, newly created NW structures might have hosted hydrothermal fluids associated with the volcanic episodes at Mount Canlaon. These hypotheses are supported by scientific findings of previous workers as shown below.

The subduction of the Sulu Sea Basin lithosphere along the Negros Trench was active since Miocene (Hamilton, 1979; Cardwell et al., 1980) and dip at a depth of 150 km beneath Negros (Acharya and Aggarwal, 1980) based on earthquake hypocenter data. The continuity of the Negros Trench (to the south) was consequently disrupted Late Miocene by the Mindoro-Panay and Sulu-Zamboanga collision zones (Barrier et al., 1991) which corresponds to the regional N-S compression phase. This phase is supported by clockwise rotation of paleomagnetic orientation, northeast fold axes and southeast-directed thrust axes observed in Panay, Negros and Cebu noted southeast of the Mindoro-Panay collision zone (McCabe et al., 1985). Consequently, a reported Plio-Pleistocene N-S directed extension might have accommodated volcanism at Negros where Canlaon, Mandalagan and Silay volcanic centers are associated with subduction processes at the Negros Trench (Aurelio et al., 1990) A localized rotation of stress fields are evident at the Northern Negros where NW structures was also observed to cut pre-existing NNW, WNW and NE structures.

Interpreted lineaments from the three imageries (e.g. TOPSAR / JERS-1 SAR, NW- and SE- directed hillshading maps) provide better control and information of the fault kinematics within the study area. It is observed that NW- and WNW-trending fault sets dominate and represent the active fault regime at NNGP (Fig. 6). The observed order of fault events is as follows (from young to old): NW, WNW / ENE, NNW and NE. The E-W and N-S structures are re-activated fault structures.

5.0   DISCUSSION

Previous works (Alincastre, 1983; PHIVOLCS, 1987; Umbal and Arboleda, 1987; Pamatian *et al.,* 1992; Von Biedersee and Pichler, 1995; Catane, 1994; Martinez-Villegas et al., 1999) and this study confirm a multiple vent source for the deposits of Canlaon and Hardin Volcanics. A possible shift in magma composition with time (e.g. from basaltic andesite to andesite to dacite and vice-versa) is also interpreted by Martinez-Villegas et al. (1999). Pamatian et al. (1992) and this study consistently subdivided the volcanic deposits according to their respective vent sources (e.g. from oldest to youngest; KN-1, KN-2, Hn-1, Hn-2, Hn-3, Hn-4, Kn-3 and Kn-4). The source vents are the Ancient Canlaon caldera (?), Hardin Sang Balo crater, Tubidiao crater collapse, Margaha crater and the active Canlaon crater, respectively. Based on the recorded but incomplete eruption history of Canlaon from 1866 to 1989 (COMVOL, 1981; Simkin, 1981), the generally phreatic type of eruption (some strombolian and phreato-magmatic) could only be associated with its latest stages Kn-3 and Kn-4 deposits. Charcoal dating (^{14}C) (Martinez-Villegas et al., 1999) on block-rich and scoria-rich pyroclastic flows of Tubidiao and the active Canlaon crater, indicate ages of 2570 ± 50 years BP and 1920 ± 50 years BP, respectively (Fig. 4).

With knowledge of the stratigraphy, volcanic history and structural networks within the study area, one can surmise a potential geothermal resource evident within the Northern Negros Geothermal Project (NNGP). It is believed that a nearby heat source to the southeast of the Pataan sector of NNGP could be associated with Hardin Sang Balo crater. The possible relationship of Saray dome / collapse to the ESE and Tubidiao crater / collapse to the south has been discounted as possible heat source for NNGP (PNOC-EDC, 2001). Hence, seepage of fluids are postulated to have been channeled to the northwest mainly along well - intercepted permeable major northwest-trending faults and splays with minor contribution of fluid flows along interformational- and intraformational-permeable zones within contacts of Canlaon Volcanics and Talave Formation. The location of the Mambucal thermal area, Hacienda Paz and Hacienda Montilla springs to the northwest are mapped surface manifestations of this brine leakage. Petrologic, geochemistry and geophysical data supports this postulation (PNOC-EDC, 2001).

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