Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

The Impact of Understanding an Arcuate Feature to the Upper Mahiao Expansion Sector, Tongonan, Leyte Island Philippines

John Michael V. Austria

Energy Development Corporation, One Corporate Center, Julia Vargas cor. MERALCO Ave., Ortigas, Pasig City, Philippines

austria.jv@energy.com.ph

Keywords: Upper Mahiao, Tongonan, Caldera, Crater, Flank Collapse, Arcuate Structures

ABSTRACT

Identification of arcuate structures such as craters, calderas and flank collapse is important in geothermal exploration especially in inferring the location of the heat sources of a geothermal system and in mapping possible volcano-related geohazards. This study suggests criteria for the recognition and classification of different arcuate structures especially in highly-eroded volcanic terrains such as that of the Tongonan Geothermal Project (TGP), Leyte and in the understanding of their roles in the development of a geothermal system. This paper also presents the results of a recently conducted geologic mapping and remote sensing analysis in TGP which was used to refine the understanding of a known arcuate structure called the Cabungangan Crater and its impact to the further development of the geothermal resource. This volcanic feature has been previously considered to be breached crater of the Cabungangan Volcano and has been targeted for permeability and temperature in six geothermal wells. However, the types of rocks observed within the vicinity of the area are not typical deposits associated to the formation of any of the aforementioned arcuate structures. The integrated results of remote sensing, field mapping and assessment of drilled wells indicate that the Cabungangan Crater is merely an erosional feature rather than a volcanic crater.

1. INTRODUCTION

Cabungangan Crater is a circular, arcuate feature approximately 2km in diameter that straddles the southwestern flank of Mt. Cabungangan. This feature, as seen in Figure 1, was delineated in the remote sensing studies conducted using the TerraSAR and Light Detection and Ranging (LiDAR) imageries in 2016. It is initially interpreted as a breached crater, which sparked the potential of having a separate heat source or an upflow zone within this area. However, this theory was also immediately debunked because of the relatively lower pressure and temperature data observed in the wells drilled inside the Cabungangan Crater.

Because of the discordance in the geologic interpretation and actual well data, the evolution and identity of Cabungangan Crater has been put into question. This study aims to understand the formation of this feature, relate it to known arcuate features in volcanic terrains such as caldera collapse, crater and flank collapse and identify its implication to the development of an expansion sector in Upper Mahiao.

Arcuate features (e.g. calderas, flank collapse and crater) represent a significant episode in the life of the volcano and can be recognized through various geologic criteria. A caldera is a sub-circular depression in volcanic areas that straddles several kilometers in diameter (Williams, 1941 in Acocella, 2007). It is formed by the emptying of the magma chamber as a result if explosive eruptions and consequent massive magma withdraw (Cashman and Giordano, 2014).The typical configuration of a caldera includes a topographic rim, inner topographic wall, bounding faults, structural caldera floor, intra-caldera fill and the underlying solidified pluton (Lipman 1997). Because they are often associated with very large eruptions and collapse, calderas are easily recognized by multi-kilometer thick ash flow tuffs (ignimbrites) and slide breccias that often fill the circular depression (Lipman, 1976). Additionally, these deposits are often blanketed by resurgent younger lavas and tuffs which were emplaced by post-collapse vents.

In contrast to calderas, craters are much smaller features and are typically defined as being less than 1 km in diameter. Although both craters and calderas are most often associated with explosive eruptions, craters are typically formed by the ejection of material in and surrounding the upper part of the conduit rather than by collapse and are thus commonly recognized by the presence of thick deposits of lavas intercalated with thin layers of monomictic poorly sorted volcanic breccias.

Flank collapse is usually a product of over steepening of flanks caused by intrusions (Tibaldi, 2001; Gorshkov, 1962), weakening of the core of the volcano by hydrothermal alteration (Reid et al., 2001; Komorowski et al., 2005), deposition of voluminous pyroclastic deposits on steep slopes (McGuire, 1996), phreatomagmatic activity (Moriya, 1980) and faulting (McGuire, 1996). One of the known examples of a flank collapse is that of Mt. St. Helens in Washington, USA which was triggered by the ascent of magma and emplacement of a cryptodome (Hunt et al., 2018).

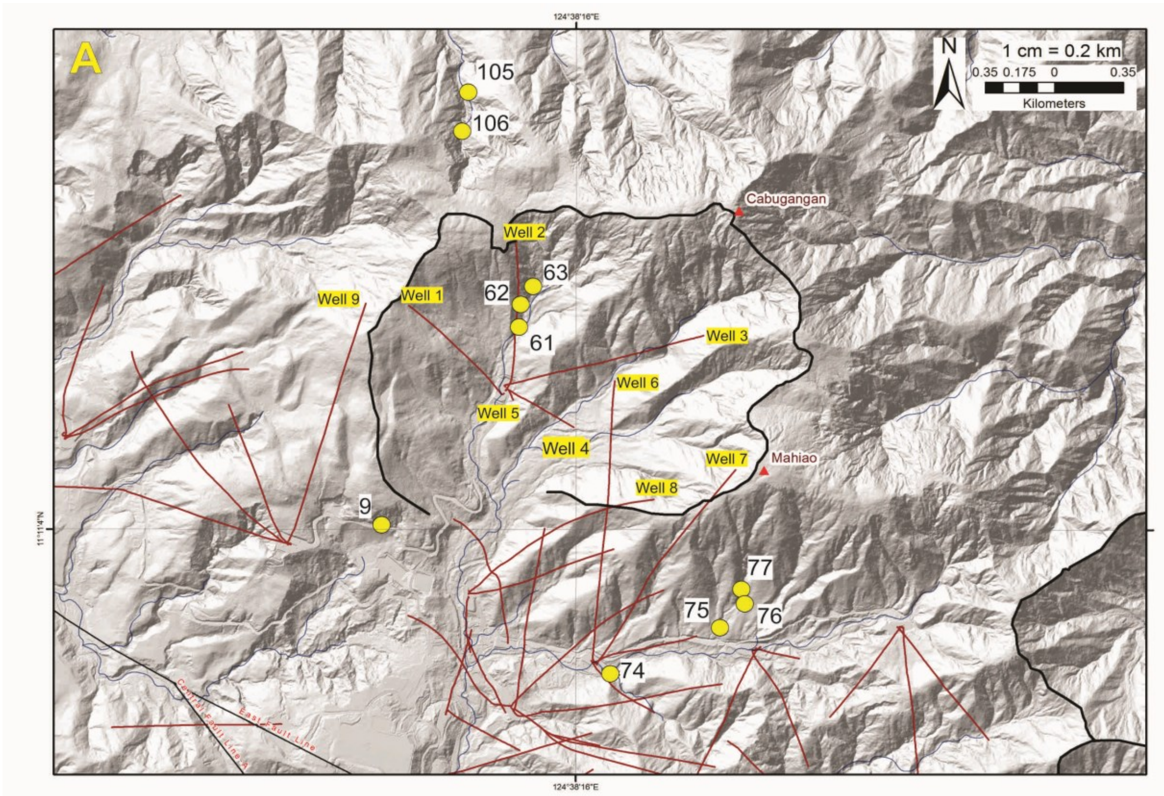

Figure 1 Shaded relief image of the study area showing the location of the Cabungangan Crater (bold black line) and the wells (maroon lines) that intersected it. The yellow dots represent the observation points (OP) wherein rock samples were collected

Collapse are best recognized by the presence of a horseshoe-shaped structure associated with an extensive exposure of debris avalanche deposits (DADs) which can flow down slope several tens of kilometers (Brunet et al., 2015). Another characteristic feature of a flank collapse is the mounds and ridges morphology of the DADs which are referred as hummocky topography (Paguican, 2012). Some of the typical exposures of DADs are classified into two facies such as in Mt. Iriga namely a block and a matrix facies (Aguila et al., 1986). The former is characterized by large brecciated blocks from the volcano such as well-stratified pumiceous tephra, basalt and pyroclastic deposits whereas the latter is distinguished by a chaotic mixture of material from the volcanic edifice with additional sediments picked up during transport. In some cases, DADs exhibit internal structures such as jigsaw cracks, injections and wide-spread shear-zone features (Bernard et al., 2008; Paguican, 2012).

2. METHODOLOGY

Remote sensing analyses of the area were initiated by generating topographic models particularly hillshade, slope gradient and slope aspect maps which are illustrated in Figure 3. These were all derived by processing the Digital Elevation model from the LiDAR image using ArcGIS, thus providing a graphical visualization of the subject's topography. Also presented in the same figure are two topographic profiles of Cabungangan Crater running NW-SE and NE-SW which were overlain with typical profiles of a caldera, crater and a flank collapse for comparison.

A subsequent fieldwork which covers the area within and outside crater was also conducted to complement the initial results of the remote sensing analyses. Furthermore, geologic data from drilled wells inside Cabungangan Crater were revisited to provide a more complete understanding of Cabungangan Crater. All these geologic data were then compared with the geologic signatures of the formations of a caldera, crater and flank collapse.

3. RESULTS AND DISCUSSION

3.1 Geomorphologic analyses

In Figure 2, the A-A' profile resembles that of a caldera except for the two prominent topographic highs in the middle. The depressed region is very wide to be categorized as a crater and does not resemble the ideal profile of a flank collapse as well. On the other hand, the B-B' cross section is closer to the typical profile of a flank collapse. The distinct circular depression typical for both craters and calderas is no longer evident in this section. However, due to the disparity between the interpretations for both sections, the data from the topographic profile is deemed inconclusive.

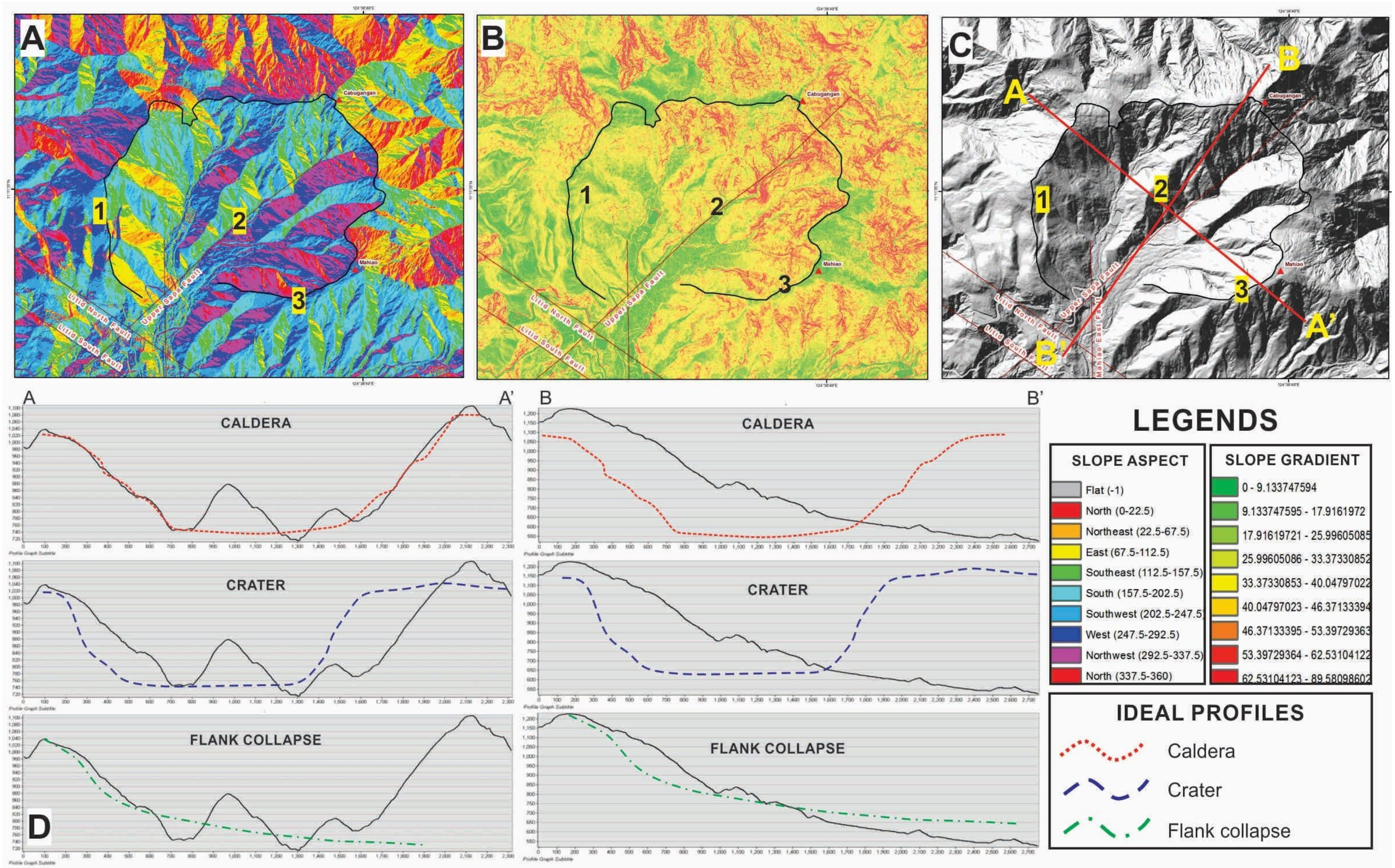

Figure 2 **Geomorphic analyses conducted in the area include the generation of (A) slope aspect map, (B) slope gradient map and (C) hillshade map. (D) Two topographic profiles of the study area, A-A' and B-B', are overlain with the ideal profiles of a caldera (red line), crater (blue line) and flank collapse (green line). The transect lines of these profiles are shown in the hillshade map.**

There are no published standard slope values for collapse walls. However, qualitative analyses of points 1, 2, and 3 show discordance against the alleged presence of a collapse feature in the area. As seen in the slope gradient map (Figure 2), the slope values at point 1 are distinctly different from any other parts of the collapse walls. At this point, slope values are generally gentle and range from 0-40° (green to yellow) compared to the northern and eastern side with slope values >40° (orange to red). This difference in slope values can either be interpreted as Slope 1 not being part of the collapse or the collapse may not be existent at all. Furthermore, it must be noted that escarpments due to collapse are usually steep which are apparently not exhibited in point 1.

Points 2 and 3 are separate ridges bounded by steep slopes on both sides and extend inwards of the arcuate feature. Instead of collapse walls, these two ridges can arguably be re-interpreted as distinct lava units that flow into the center of the arcuate feature. Although steep slopes define Points 2 and 3, these may not be configured to represent a flank collapse, caldera or a crater.

3.2 Surface geology inside Cabungangan feature

Three observation points were established inside the crater and they are all characterized by monomictic well sorted matrix-supported andesitic volcanic breccias which are composed of angular andesitic clasts set in a matrix of the same composition. Photos of these rock exposures and their respective locations are shown in Figure 3. Under the microscope, the clasts were identified to be andesite porphyry and are characterized by the abundance of hornblende and plagioclase phenocrysts set in a vitric groundmass. These types of deposit are common in the proximal facies of a volcano which contradicts the theory that the arcuate structure is a crater. Craters are formed in the central facies of a volcano wherein it is covered by thick layers of lava units intercalated with monomictic poorly-sorted breccias with clasts of varying sizes.

The absence of intrusive outcrops and extensive altered grounds may suggest that the arcuate structure was not formed due to lateral collapse of one of the flanks of volcano. Flank collapse structures are usually triggered by repeated dike intrusions or dome growth (Tibaldi, 2001) and the weakening of volcano core due to hydrothermal alteration (Reid et al., 2001) which should have been exposed when a certain part of the volcano collapses.

Basing on the geology inside the said collapse alone, caldera formation is being downplayed because of the absence of extensive highly silicic calderagenic deposits such as ignimbrites or welded tuff. These deposits are usually emplaced inside and outside of the depression after the explosive eruptions that results to the formation of a caldera.

Figure 3 (A & B) Exposures of monomictic andesitic volcanic breccias encountered inside the Cabungang Crater as observed in OP No 61 and 63, respectively. (C) Photomicrographs of the andesitic clasts collected in the volcanic breccia outcrops in plane polarized light (PPL).

3.3 Surface geology outside Cabungangan feature

Deposits outside of the crater (Figure 4) are generally composed of andesitic lavas with hornblende and orthopyroxene as major phenocryst composition. Quick assessment may imply that these deposits are representative of a crater formation; however, the identification of a possible dome called the Mahiao Dome complicates or downplays the crater formation inference. The extent of the said dome occupies the eastern wall of the arcuate structure (Figure 5) and is compositionally different from the other lava units observed around the crater. In contrast to the hornblende-pyroxene lava units encountered north and southwest of the Cabungangan Crater, the rocks collected from Mahiao Dome do not contain pyroxene phenocrysts. It is instead distinctly characterized by the presence of very large (>1cm) hornblende crystals set in a groundmass composed of finer plagioclase and hornblende grains. Figure 4 shows the andesitic lavas encountered southwest and north of Cabungangan Crater whereas Figure 5 shows the characteristic outcrops of Mahiao Dome.

Flank collapse structures, as in Mt. Iriga, Mt. Isarog and Mt. St. Helens, are easily recognized by the presence of DADs which represent the volume of materials transported during the evolution of the collapse. These are characterized as poorly sorted polymictic breccias containing a chaotic mixture of clasts and matrix composition and are located outside of the structure but in the direction of the collapse's opening. In the field, DADs were not observed within the vicinity of Cabungangan suggesting that the arcuate structure is also not a flank collapse. Similarly, the extensive ignimbrite deposits were not observed in the observation points established outside the crater; further signifying that the arcuate structure is neither a flank collapse nor a caldera.

Figure 4 (A, B and C) Exposures of porphyrytic hornblende-andesitic lavas located outside of the delineated Cabungangan Crater as seen in OP Nos 9, 74 and 106, respectively. Locations of these outcrops are shown in the topographic map.

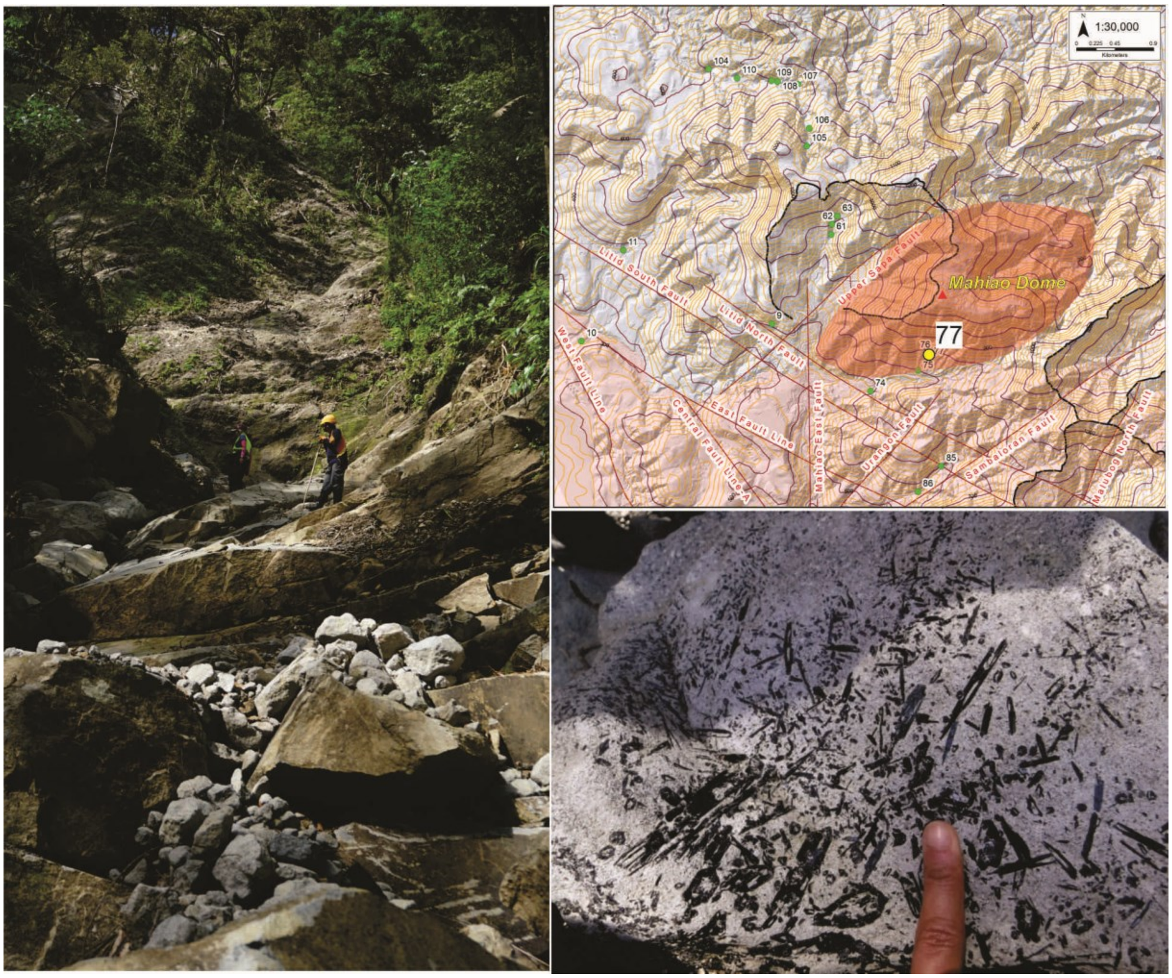

Figure 5 Andesite lava exposures along the southern flank of the Mahiao Dome (OP No 77) which is distinctly characterized by large hornblende phenocrysts. The extent of the Mahiao Dome is represented by the red-colored area.

3.4 Subsurface geology

As shown in Figure 1, six wells have already been drilled inside Cabungangan Crater. In general, these wells encountered a thick sequence of pyroclastic rocks intercalated with hornblende-andesite lavas and occasional tuff. At greater depths in Well 2 and Well 5, fresh diorite chips were reported whereas in Well 4 and Well 5, thick sequences of completely altered rocks were also noted. Figure 6 shows the stratigraphy of the different wells that were drilled inside the arcuate structure. With the identified alternating and intercalating layers of pyroclastic and lava, these deposits may be more closely interpreted as crater deposits.

If these wells are indeed drilled within a caldera collapse, it would have encountered a thick layer of ignimbrite or welded tuff deposits to represent the large collapse-inducing eruption. Lava/ dike complexes may also be intersected at greater depths as this represent the original solidified part of the magma chamber. However, similar to the observations during the fieldwork, there are no ignimbrites reported in the megascopic logs.

Instead of ignimbrites, well geology reports noted the intersection of thick layers of andesitic/ dacitic tuff breccias. Revisiting the cuttings in the aforementioned wells may be value-adding to be able to confirm that the andesitic/dacitic tuff breccias encountered in the wells are not associated to the formation of a caldera. Furthermore, it is also good to note if these pyroclastic rocks encountered in the entire wells exhibit the same petrological characteristic to affirm that they have been deposited by a single large eruption event that resulted to the formation of a caldera.

Moreover, it is difficult to ascertain from megascopic cuttings whether the feature is a flank collapse because DADs are better appreciated at outcrop and macroscopic scale. However, it may be inferred that wells drilled within a flank collapse should encounter breccias with chaotic mixture of altered and unaltered clasts of different compositions. Flank collapses can also be recognized by the shallow intersection of the argillic zone. Both are arguably not intersected in the reviewed wells.

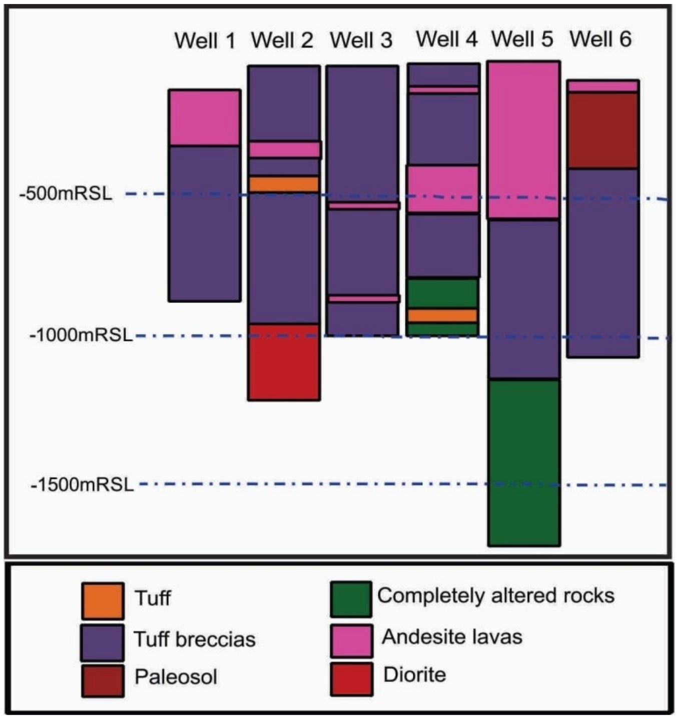

Figure 6 Simplified representation of the rocks encountered in the six wells drilled within the Cabugangan Crater

4. CONCLUSIONS AND IMPLICATIONS TO GEOTHERMAL DEVELOPMENT

Based on the incoherent and inconsistent evidence from field and desktop study, the arcuate feature in Cabungangan can neither be classified as a crater, a caldera nor a flank collapse.

Although, a 2km- depression-like morphology may be observed in LiDAR imageries, the widespread ignimbrite deposit that characterizes a caldera-inducing eruption was not observed. While it can be argued that the absence of the welded tuff deposits resulted from pronounced erosion or superposition of younger volcanic deposits, these types of deposits are typically very thick and extensive and therefore cannot be eroded easily without the arcuate feature being eroded as well.

The crater formation theory is also being downplayed primarily because of the size of the structure. In contrast to calderas, craters are much smaller features with a diameter of approximately one kilometer. Additionally, the identification of the Mahiao Dome which occupies the eastern segment of the alleged crater further complicates the possibility that Cabungangan is indeed a crater.

Lastly, the feature is not considered as a flank collapse because of the absence of hummocky topography in its distal end, debris avalanche deposits, and the exposure of extensive altered grounds and intrusive bodies within the escarpment.

With these considerations, the Cabungangan Crater is herein interpreted as a mere erosional feature rather than a distinct volcanic structure. In fact, the presence of a lava ridge at the center of the delineated circular feature and the identification of Mahiao Dome support this proposition as these features break the original delineation of the structure. Hence, it is proposed that this feature be erased from the structural map.

This new understanding of the feature further supports that no separate heat source or upflow zone is present in the expansion sector. Alternatively, more detailed study may be conducted to identify the role and implication of the Mahiao Dome to the geothermal development. Radiometric dating of rock samples from this eruptive center may be pursued to ascertain its potential to generate heat for the development of a geothermal system underneath the study area.

During the drilling of wells in Upper Mahiao, some structural indicators were interpreted to be attributed to the Cabungangan Crater. A review of the fault assessments show that these fault manifestations can still be attributed to other faults whose intersection overlaps with that of Cabungangan Crater. In example, fault indicators attributed to Cabungangan Crater that were observed during the drilling of Well 6, Well 7 and Well 8, can also be associated to Balabag Fault (Well 7), NE Balabag Splay (Well 7), Balabag-B Fault (Well 8) and Kapanyahan West-B (Well 6). Therefore, the Cabungangan Crater may not also exist even at subsurface.

Austria

REFERENCES

Acocella, V.: Understanding caldera structure and development: An overview of analogue models compared to natural calderas. Elsevier, (2007).

Aguila, L.C., Newhall, C. G., Miller, C.D., Listanco E.L.: (Reconnaissance geology of a large debris avalanche from Iriga Volcano, Philippines. Philippine Journal of Volcanology, (1986), 3:54-72

Bernard, B., van Wyk de Vries, B., Barba, D., Leyrit, H., Robin, C., Alcaraz, S., Samaniego, P.: The Chimborazo sector collapse and debris avalanche: Deposit characteristics as evidence of emplacement mechanisms. Journal of Volcanology and Geothermal Research, 176 (2008), 36-43.

Brunet, M., A. Le Friant, G. Boudon, S. Lafuerza, P. Talling, M. Hornbach, O. Ishizuka, E. Lebas, H. Guyard, and IODP Expedition 340 Science Party: Composition, geometry, and emplacement dynamics of a large volcanic island landslide offshore Martinique: From volcano flank-collapse to seafloor sediment failure?, Geochem. Geophys. Geosyst.,17 (2015), 699–724.

Cashman, K.V. and Giordano, G.: Calderas and magma reservoir. Journal of Volcanology and Geothermal Research, (2014).

Gorshkov, G.S.: On the classification and terminology of Pelee and Katmai type eruption. Bulletin of Volcanology, 24 (1962), 155-165.

Hunt, J.E. et al.: Multi-stage volcanic island flank collapses with coeval explosive caldera-forming eruptions. Scientific Reports, (2018).

Komorowski, J.-C., Boudon, G., Semet, M.P., Beauducel, F., Anténor-Habazac, C., Bazin, S., Hammouya, G.: Guadeloupe. In: Lindsay, J.M., Robertson, R.E.A., Shepherd, J.B., Ali, S. (Eds.), Volcanic Atlas of the Lesser Antilles. Seismic Research Unit, The University of the West Indies, Trinidad and Tobago, (2005), 65–102.

Lipman, P.W.: Caldera-collapse breccias in the western San Juan Mountains. Geological Society of America Bulletin, (1976).

Lipman, P.W.: Subsidence of ash-flow calderas: relation to caldera size and magma chamber geometry. Springer-Verlag, (1997).

Mc Guire, W.J.: Volcano instabilities: a review of contemporary theme. In: McGuire, W.J., Jones, A.P., Neuberg, J. (Eds.), Volcano Instability on the Earth and Other Planets: Geological Society. Special Publication, 110, (1996), 1–23.

Moriya, I.: Bandaian eruption and landforms associated with it. Collection of Articles in Memory of Retirement of Prof K Nishimura from Tohoku University, (1980), 214– 219.

Paguican, E.M.: The structure, morphology, and surface texture of debris avalanche deposits: field and remote sensing

Reid, M.E. et al.: Gravity, deformation and the earth’s crust. London Academic Press, London, (1981).

Tibaldi, A.: Multiple sector collapses at Stromboli Volcano, Italy: how they work. Bulletin of Volcanology, (2001).