Submarine Volcano Characteristics in Sabang Waters

Karakteristik Gunung Api Bawah Laut di Perairan Sabang

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(Received 27 April 2015; in revised form 16 November 2015; accepted 26 November 2015)

ABSTRACT: The aim of the study is to understand the characteristics of a volcano occurred in marine environment, as Weh Island where Sabang City located is still demonstrated its volcanic cone morphology either through satellite imagery or bathymetric map. Methods used were marine geology, marine geophysics and oceanography. Results show that surface volcanism (sea depth less than 50 m) take place as fumaroles, solfataras, hot ground, hot spring, hot mud pool and alteration in the vicinities of seafloor and coastal area vents. Seismic records also showed acoustic turbidity in the sea water column due to gas bubblings produced by seafloor fumaroles. Geochemical analyses show that seafloor samples in the vicinities of active and non-active fumarole vent are abundances with rare earth elements (REE). These were interpreted that the fumarole bring along REE through its gases and deposited on the surrounding seafloor surface. Co-existence between active fault of Sumatra and current volcanism produce hydrothermal mineralization in fault zone as observed in Serui and Pria Laot – middle of Weh Island which both are controlled by normal faults and graben.

Key words: submarine volcano, hydrothermal mineralization, Sabang-Weh-Aceh.

ABSTRAK: *Tujuan kajian adalah memahami karakteristik suatu gunungapi yang berada dalam lingkungan marin, sebagaimana Pulau Weh dimana Kota Sabang terletak masih menunjukkan morfologi kerucut volkaniknya baik melalui citra satelit maupun batimetri. Metoda yang digunakan adalah geologi kelautan, geofisika kelautan dan oseanografi. Hasil menunjukkan bahwa volkanisma permukaan (kedalaman laut kurang dari 50 m) terdapat dalam bentuk fumarola, solfatara, lahan panas, mata air panas, kolam lumpur panas dan alterasi sekitar lobang kepundan dasar laut dan pantai. Rekaman seismik juga menunjukkan turbiditas akustik dalam kolom air laut akibat gelembung gas yang dihasilkan oleh fumarola dasar laut. Analisis geokimia menunjukkan bahwa contoh-contoh dasar laut sekitar lobang kepundan fumarola yang aktif maupun tidak aktif kaya akan logam tanah jarang. Ini ditafsirkan bahwa proses fumarola tersebut membawa REE melalui gas-gasnya dan mengendapkannya pada permukaan dasar laut di sekitar. Ko-eksistensi antara Sesar Sumatera aktif dan volkanisma Resen menghasilkan mineralisasi hidrotermal dalam zona sesar seperti teramati di Serui dan Pria Laot – bagian tengah Pulau Weh yang keduanya dikontrol oleh sesar normal dan graben.*

Kata kunci: *gunungapi bawah laut, mineralisasi hidrotermal, Sabang-Weh-Aceh.*

*) Paper presented at IOPAC (Indian Ocean and Pacific Conference) 2013, Nusa Dua, Bali – Indonesia, June 18^{th}-20^{th}, 2013.

INTRODUCTION

According to Carey and Sigurdsson (2007) approximately three quarters of earth volcanism take place at seafloor, generally at Mid-Oceanic Ridge (MOR) of the world main oceans. Erubsion style along these MOR has been much studied and well characterized by many researchers. Main products of this eruption type are dominated by effusive production of pillow lava and sheet-flow lava of sea depth many thousand meters (Macdonald, 2001). On the other hand, another main erubsion style occurs along islands arc, where subduction of oceanic below continental plates triggers melting of mantle rocks through release of volatile components of water and carbon dyoxide. Seafloor volcanism is an important factor in an active island arc system (Carey and Sigurdsson, 2007).

As located in an island arc system of Sunda-Banda, Sabang is situated north of Weh Island – Aceh Province (Figure 1). Other islands surround Weh are Klah, Rubiah, Seulako and Rondo. Weh Island is popular for its diving spots which is consisted of well developed coral reefs and submarine fumaroles

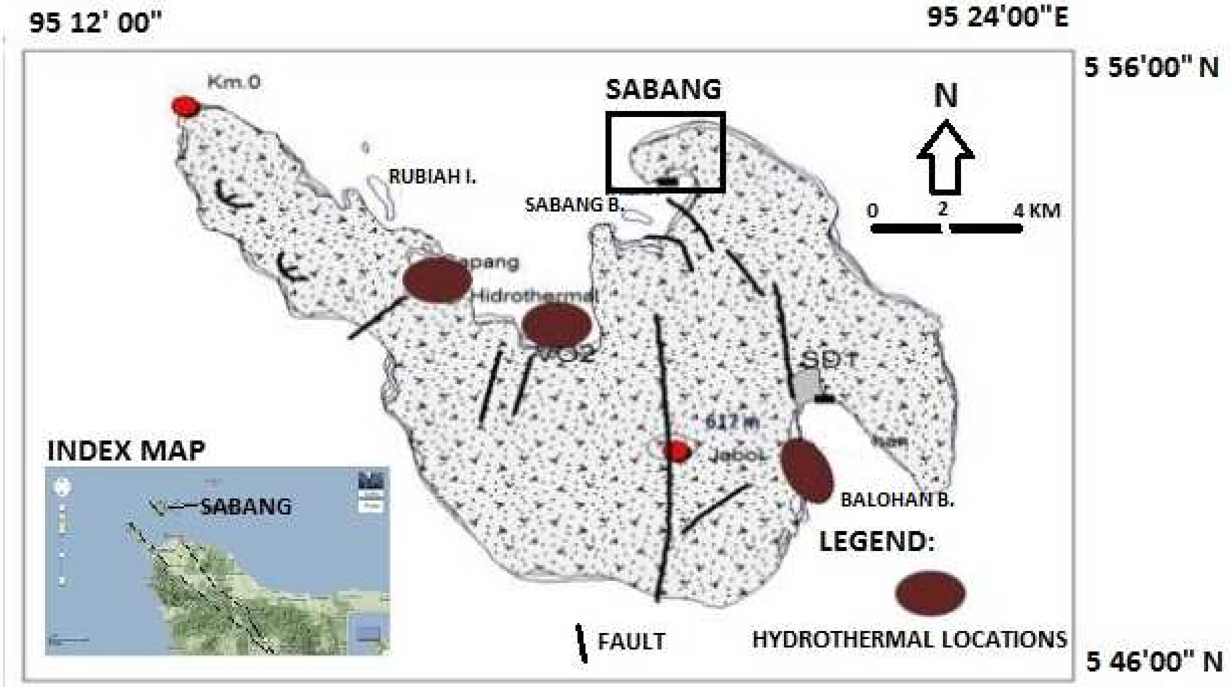

Figure 1. Weh Island. Sabang City is located at north part of the island. The index map explain regional terrain setting of North Sumatra which include Sumatran fault passing through the island (Source: terrain earthgoogle).

activities. The submarine fumaroles are accessible either to divers or to tourists using boats.

The island itself is about 15 km length and 10 km width, and this small island has area of 156.3 square kilometers which consisted of many mountains, with the highest peak 617 m or 2,024 feet located at Jaboi (Figure 1 left). Some submarine fumaroles are observed in this island.

The marine hot spots are accessible and become tourism destination, especially divers. Local government of Sabang has developed infrastructures which accommodate tourism stake holders to construct facilities for either national or international visitors. Many international standard resorts and dive spots could be found here.

The submarine volcano activities were already surveyed by MGI in the middle of 2012. The activities occur at coastal waters of sea depth less than 50 m. The volcanism stage takes place as fumaroles and mud volcanoes at several hot spots either at sea bottom or coastal zone. The activities were and are causing mineralization evidence by occurrences of hydrothermal minerals at the surveyed area.

Sabang – Weh Island is located at the northwestern most of Sumatra Island. It is in a volcanic belt which runs through the whole length of Sumatra. The belt has direction northwest – southeast which is almost at the same location of Great Sumatran Fault or GSF at western coastal zone of this island (Sieh and Natawidjaja, 2000). In Sumatra, volcanic belt seems terminated at Weh Island. It continues approximately 1000 km further northwestward at Andaman Sea. Weh Island had been the part of Sumatra, catastrophic volcano eruption at Pleistocene or lower Quaternary has separated these two islands. Dirasutisna and Hasan (2007) stated Weh Island is a stratovolcano composed of volcanic rocks with the last eruption took place at Pleistocene (Figure 2).

Tectonic setting of plate convergence between oceanic and continental plates of Indo-Australia and Eurasia takes place in this area. This setting is consisted of trench, outer non-volcanic arc, fore arc basin, inner volcanic arc and back arc or foreland basin, Sabang is positioned in inner volcanic arc.

Commercial gold deposits are already mined along this Sumatran volcanic belt. The area is also characterized by shallow earthquake (less than 100 km) along GSF which indicates neo-tectonics.

Local geological condition based on field observation: andesitic and basaltic lava occupies approximately 58 percent of the research area, volcanoclastic rocks consisted of sandy tuff and laharic breccias approximately 30 percent, and others such as coral reef, hydrothermally influenced rocks and alluvium approximately 12 percent.

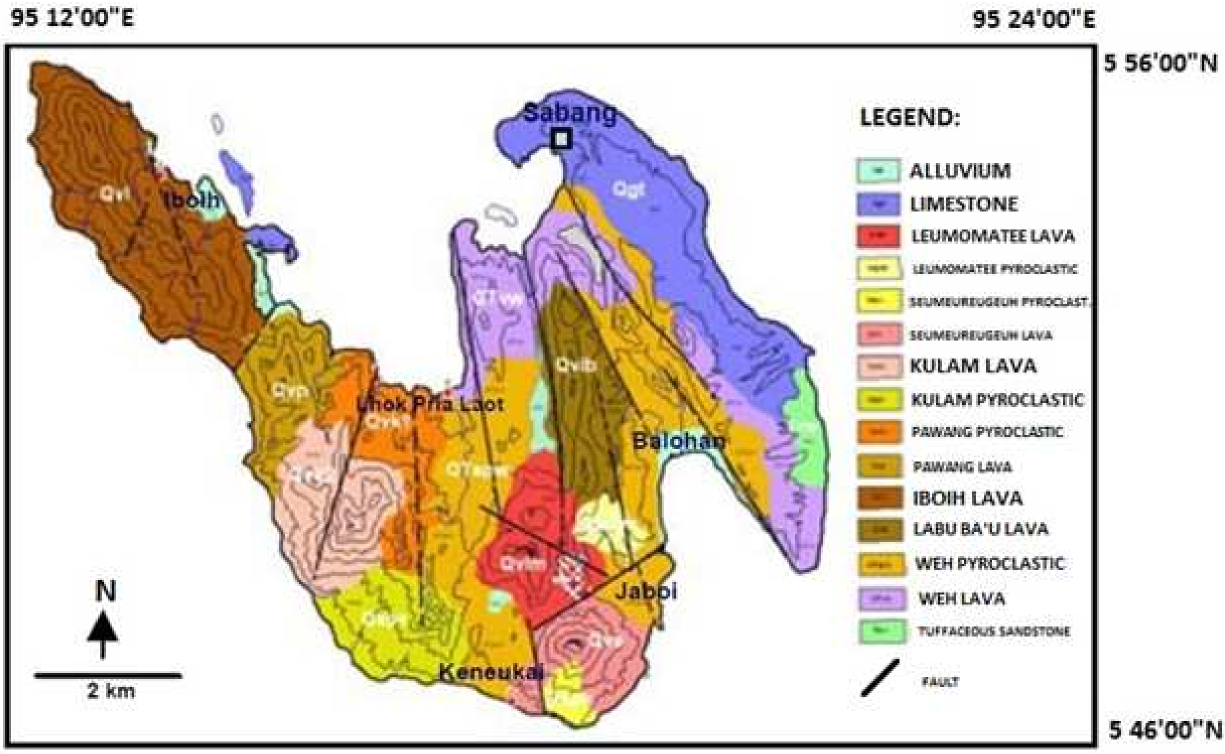

Figure 2. Geological map of Weh Island (Source: Suhanto et al, 2005)

According to Carey and Sigurdsson (2007) submarine volcano eruptions in an island arc system contribute to the formation of thick sedimentary sequences, provide sites for hydrothermal mineralization, and introduction of biogeochemically significant component Fe into upper water column.

Suhanto et al (2005) based on geophysics and geochemical anomalies at Jaboi – south of Weh Island stated that area of influence of geothermal is approximately 6 square kilometers; which could be possibly the magma chamber area beneath. Suhanto et al also measure geothermal reservoir through geo-electricity survey at 600 m under Jaboi fumaroles manifestation at ground surface. The reservoir is predicted at Weh old lava unit, and it is capped by clay cap of about 500 m thickness.

Resistivity survey at Jaboi by Suhanto et al shows low resistivity value (< 10 Ohm-m) which indicates subsurface lithology dominated by clay resulted from hydrothermal alteration at acid environment. This clay dominated rock is assumed as cap rock with thickness 400 – 500 m. Just below cap rock at depth about 600 m is found reservoir rock at the top of old lava of Weh. Reservoir temperature based on measurement by geothermometer is about 250 C.

Morphology of low relief is spread at limited coastal areas, such as surround Sabang Harbor at the north, Gapang northwest and Balohan Port at the south. Lithology of this coastal area is alluvial deposits. In general, the area is characterized by high reliefs of wavy mountain and steep hills formed by faults and erosion. The rocks compose the high reliefs are andesitic lava, laharic breccias and sandy tuff.

At south side of Weh Island, it could be observed morphology of two volcanic cones. The north cone is a geothermal field Jaboi, while the south cone its remnant could be observed from the sea (Figure 3). The cones seem at a north – south trending fault, which could be interpreted as a normal fault. Immediately north of Jaboi is developed a lake in a structural geology of graben.

East side of the island is observed an elongated mountain of southeast – northwest direction. It is a morphology reflection of strike-slip fault of the same orientation with Great Sumatran Fault (GSF). Other morphologies of relatively north – south directions are manifestations of normal faults developed in the research area. The southeast – northwest fault is the first order, while the north – south is the second order.

The aim of study

Characteristics of a submarine volcano where nowadays has become an island is tried to be studied here. Weh Island is a submarine volcano revealed by its cone volcanic morphology, as observed in satellite imagery and bathymetry map.

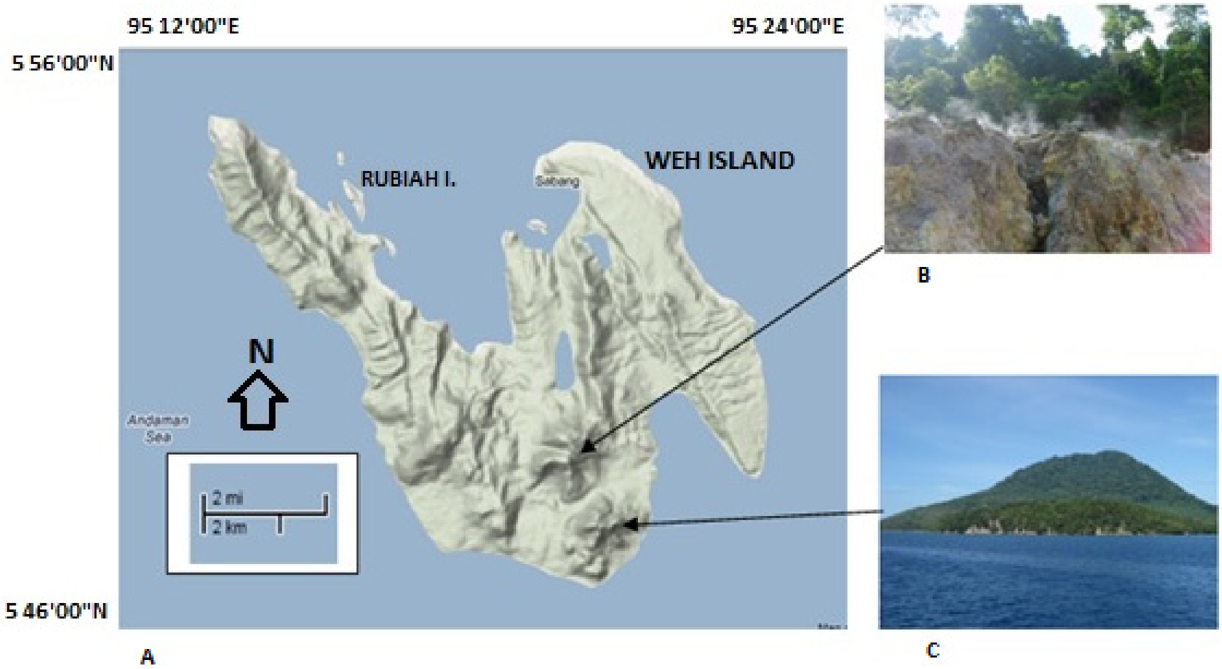

Figure 3. A. Weh Island morphology from terrain earthgoogle. B. Geothermal field of Jaboi. C. View of volcanic cone from the sea - south of the island (Photo source: paranamio earthgoogle).

The existence of NW –SE fault at eastern Weh Island is a continuation of Great Sumatran Fault that extends more than 2000 km until Sunda Strait. The existence is also supported by gamma ray dose values that increased from the middle of the island to the east closed to NW –SE fault (Masaaki et al, 2013). Gamma ray average values of Weh Island is 50.8 ± 4.8 nGy/h; which is less than global average value of andesitic rocks 64 ± 21.

Carey and Sigurdsson (2007) notice that the presence of pumice rafts, gas bubblings on the sea surface, local seawater color changes, and seismic activity are all direct indicators of submarine volcanic eruptions.

Carey and Sigurdsson also stated that nature of submarine eruptions depends upon the water depth or hydro-static pressure, composition and volatile content of ascending magma, and rate of magma discharge. Carey and Sigurdsson proposed that potential submarine explosive eruption styles include plinian (sustained discharge of volatile-rich magma), vulcanian (short-lived explosion resulting from failure of a solid plug in the vent), strombolian (bursting of large bubbles in low-viscosity magma), and fire fountaining (eruption of low-viscosity magma in the form a spray). Island arc systems seem the sites of abundant submarine explosive eruptions due to the volatile-rich nature of the magmas; and it is also more energetic than those at mid-ocean ridges and oceanic islands because of the higher magmatic volatile content, more viscous nature of the magmas, and larger individual volumes of magma chambers involved in island-arc eruptions.

Iizasa et al (1999) mentioned that the subduction-related island arc Kuroko-type deposits are richer in Au, Ag, Zn and Pb, but poorer in Fe and Cu; compared to the polymetallic sulfide deposits of mid-ocean ridge systems. Tikoff (1998) study the magmatic arc processes of Sunda volcanic belt and its tectonics. The belt is associated with many gold deposits through out Sumatra.

In shallow water, hydrothermal venting can include discharge of gases in addition to metal-rich fluids. The gases may be derived directly by exsolution from subsurface magmas or boiling seawater (Carey and Sigurdsson, 2007). High volatile content, such as H_2O and CO_2, contribute to the unique characteristics of the hydrothermal fluids and mineral deposits.

METHOD

The survey was carried out using marine geological, geophysical and oceanographical methods. The methods include coastal geological mapping, seafloor sediment sampling, shallow high resolution seismic, and measurements of oceanographical paramaters such as temperature and salinity.

RESULTS

Coastal geological mapping found out alteration and mineralization of rocks, especially closed to points of volcano activities (Figure 4). Alteration minerals are belonged to argillaceous minerals such as kaolinite, monmorillonite and illite; while mineralization is evidence by occurrence of calcite and chlorite.

Sediment types based on Folk classification (1980) could be recognized muddy silt, sand and gravel (Figure 5). The gravel mostly composed of corals, while sand is consisted of andesitic and basaltic rock fragments, corals and tuffaceous fragments. The sand is also could be differentiated into coarse and fine to medium sizes. Microscopic examination the sand is dark grey color with sandy size component (50-300 μm) about 70% and clay size matrix (1-50 μm) about 10%. The sand is loose, weathered, weak to high alteration, grain shapes angular to sub-rounded, the grains consisted of quartz, feldspar, and rock fragments; pyrite, chalcopyrite, magnetic, hematite, malachite, galena, barite were also found.

Shallow seismic data analyses and interpretation was obtained that seafloor volcano activities were identified through acoustic turbidity at sea water column. The seismic data also show geological structures interpreted as normal faults immediately below the turbidity. It seems that these structures control the submarine volcanic activities as shown in Figure 6.

The intensity of hydrothermal activities in Sabang's Waters is reflected in 32 discoveries of fumaroles points from shallow seismic data. Seismic characteristics obviously observed for submarine fumaroles are acoustic turbidity in sea water column and pulling-down effect (Figure 6).

Observations at sea floor found out that fumaroles occurred at an opening of north – south orientation (Figure 7 C). This north – south opening is actually a normal fault based on the ellipsoid analyses (Figure 7 A); and the seabed faults were interpreted based on seismic analyses (Figure 7 B). On land fault pattern is made based on lineations in terrain earthgoogle (Figure 7 D) which interpreted continue to the sea.

Sea water salinity measurement using portable valeport 108 resulted in range between 25.9 – 33.9 ‰. Threshold value stated by Environmental Ministry of Republic of Indonesia is 34 ‰. Thus, salinity value in the research area is secure still for marine biota.

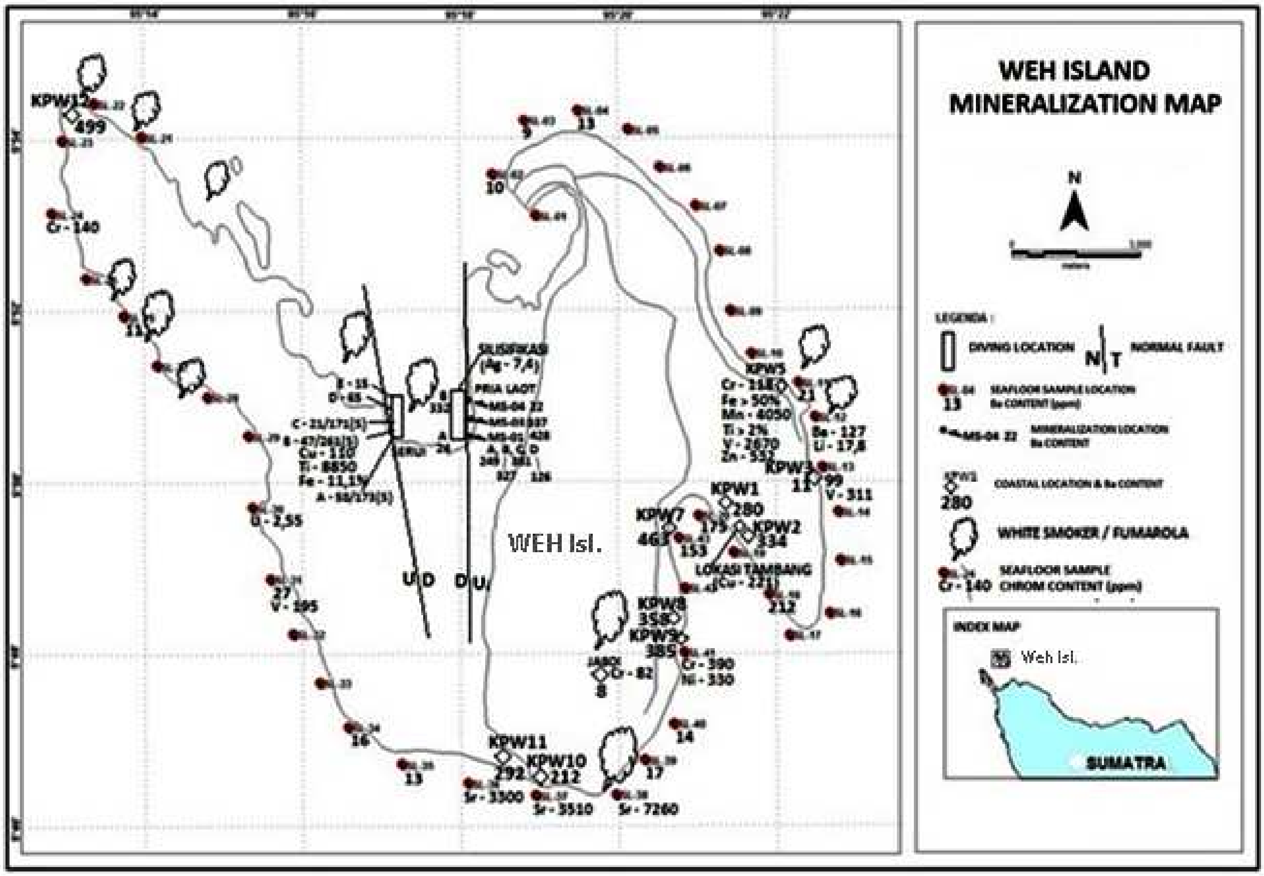

Figure 4. Mineralization map resulted from coastal geological mapping and geochemical analyses of selected samples. Seafloor geochemical data is also presented.

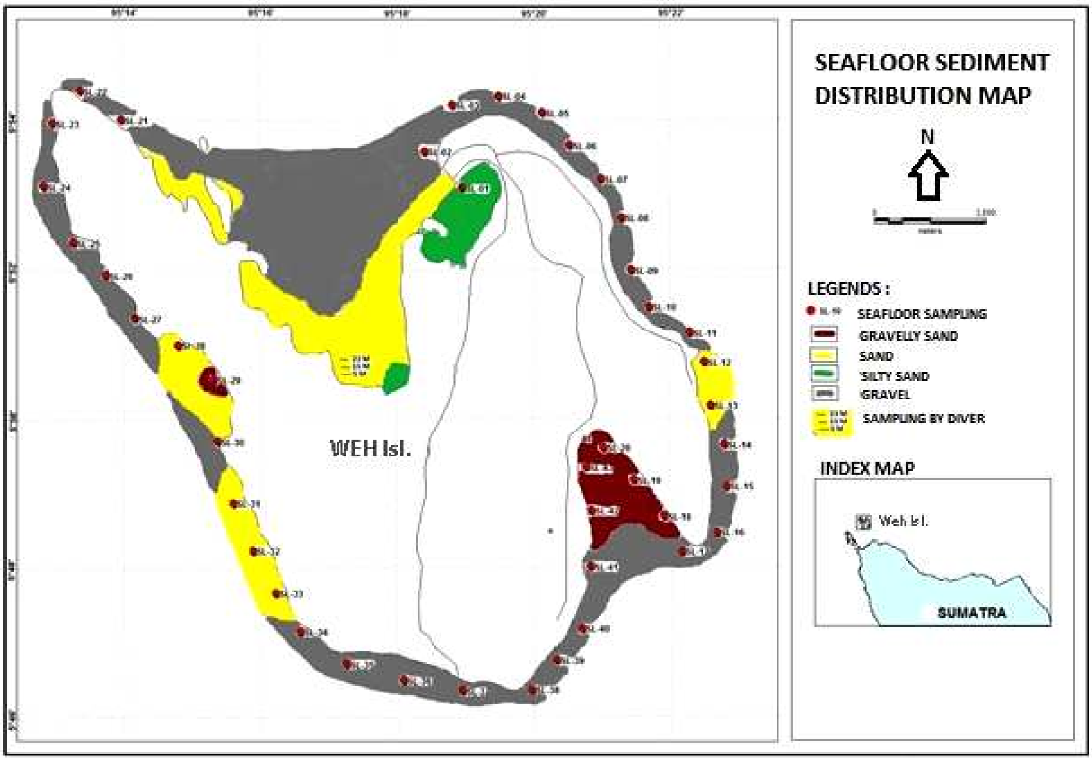

Figure 5. Seafloor sediment distribution map.

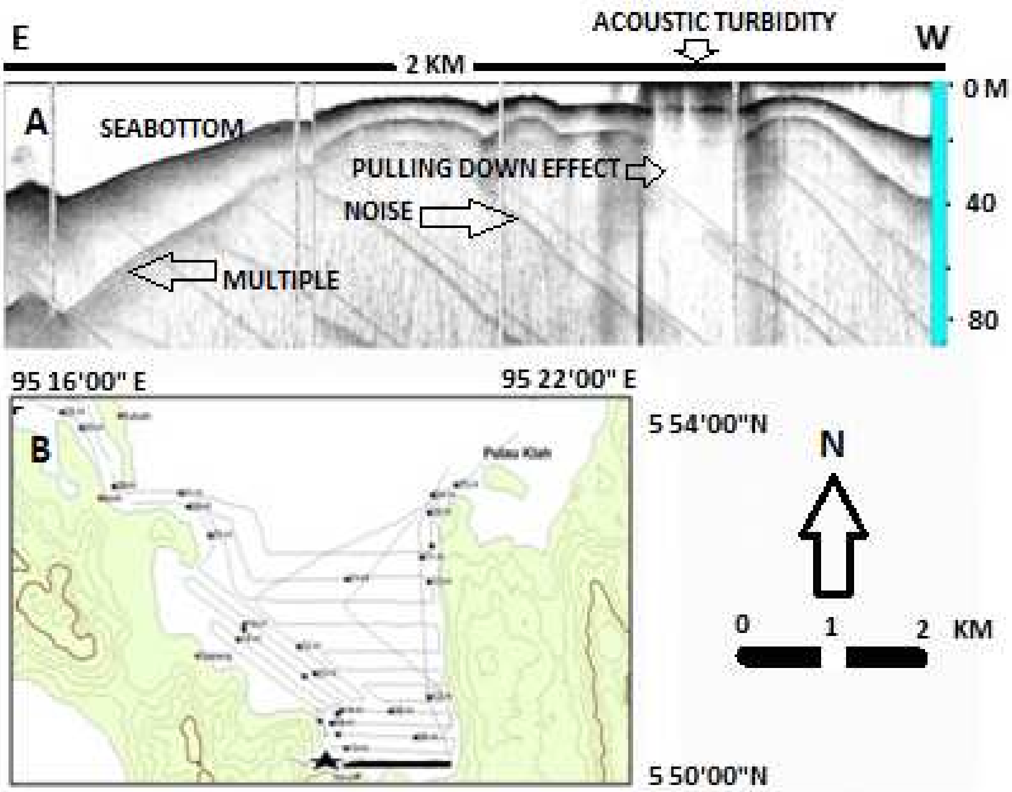

Figure 6. Seismic record show acoustic turbidity of water column (A). The acoustic turbidity also produces pulling-down effect immediately below, which blurred the seismic record. Record location is shown in B.

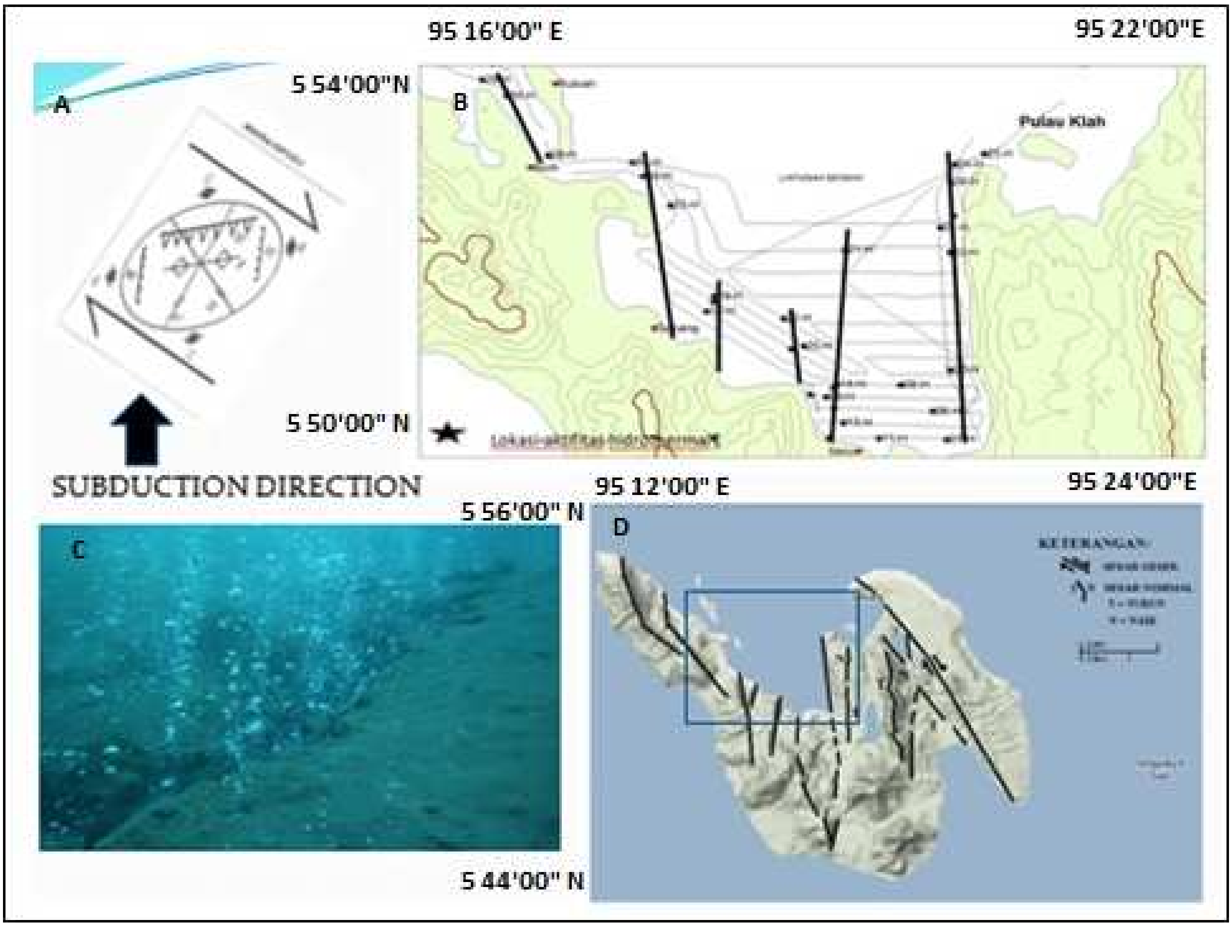

Figure 7. Fault analyses of the research area. Fault ellipsoid analyses (A. Source: Law et al., 2000). Seafloor fumarole points (B) assumed controlled by seafloor fault (C) which its orientation drived by terrestrial faults (D).

Distribution pattern of salinity, closer to fumaroles spot is the lowest value (Figure 8).

Temperature measurements at sea surface range between 28.075 and 29.694 C, where the highest value is distributed closed to spots of submarine and coastal fumaroles; while further away the temperatures decreased (Figure 9). At sea bottom, the temperature range between 27.228 and 29.020 C. Suitable sea water temperature for living organism is between 27 - 32 C (Mayunar, 1995). Thus, field temperature range above is still in tolerance.

DISCUSSIONS

Figure 10 demonstrates mechanism of shallow volcanism (magma less than 5 km depth), with its associations of ore-forming processes, meteoric water interactions, ore deposit types and a general differentiation between geothermal and volcanic-hydrothermal systems.

Visual observations during field work (Figure 11), in the research area could be found mud volcano phenomenon in a small crater (diameter ± 5 m, 11a), influence of acidic fluid on surface rocks (11b), fumaroles and solfatara points (11c), seafloor rock sampling by diver (11d), sea water vaporization in the fumaroles hole during high tide (11e), and hydrothermal minerals (11f).

Figure 12 A demonstrates that Sabang Island was possibly in the past becoming part of a Paleo-volcanic cone belt, as shown by seabottom morphology. Bathymetry map surrounding the island shows closure pattern resembles a submarine volcanic cone (B). Depth contour between Weh Island and Aceh mainland shows the least value (300 m), compared to the east of the island (1200 m), the north (700 m) and the west (500 m). the shallowest part in the south is possibly part of the collapse caldera during Pleistocene catastrophic eruption that separate Sabang Island with Sumatra mainland. Dating data shows catastrophic eruption occurred 1.5 Ma (million year ago).

Secondary data examination, especially from earthgoogle, found out that northwestrward of Weh Island was observed remnants of possibly volcanic necks (Figure 13). This phenomenon also explains that

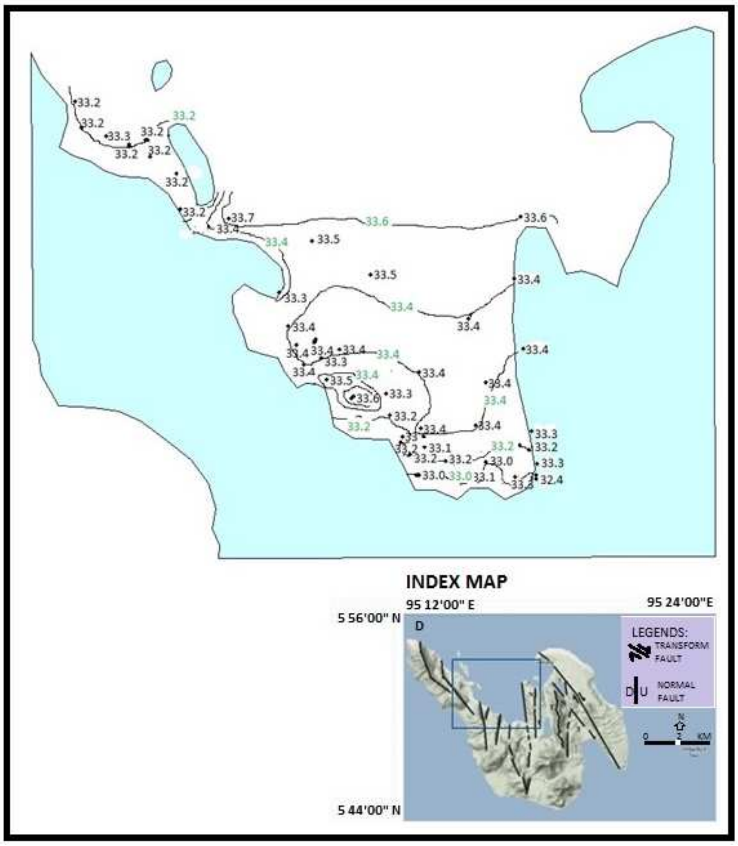

Figure 8. Plotting of salinity found out reduced values closed to seafloor fumaroles.

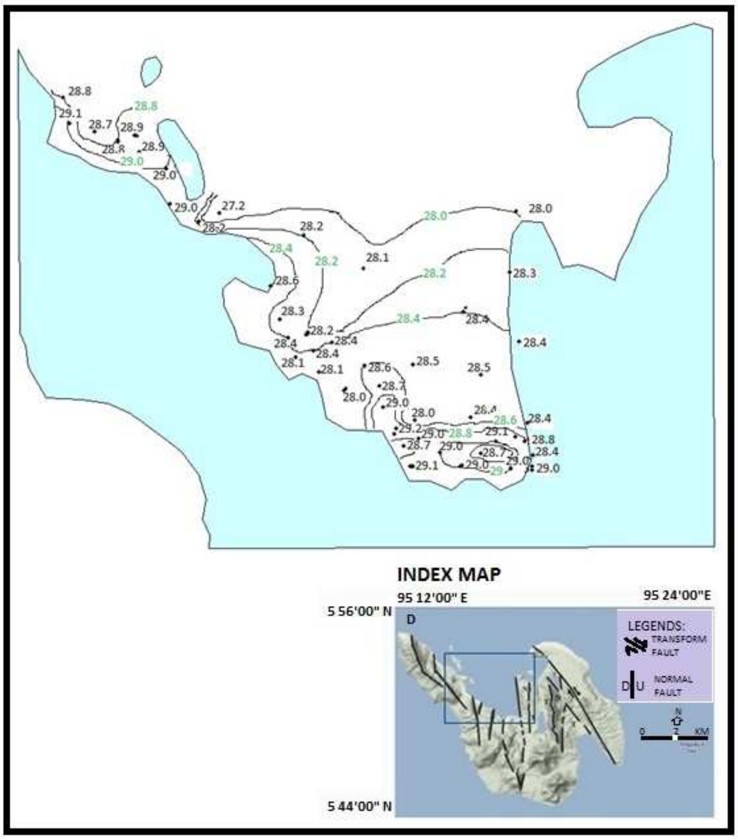

Figure 9. Seafloor temperatur distribution, closed to fumarole vent the values increased.

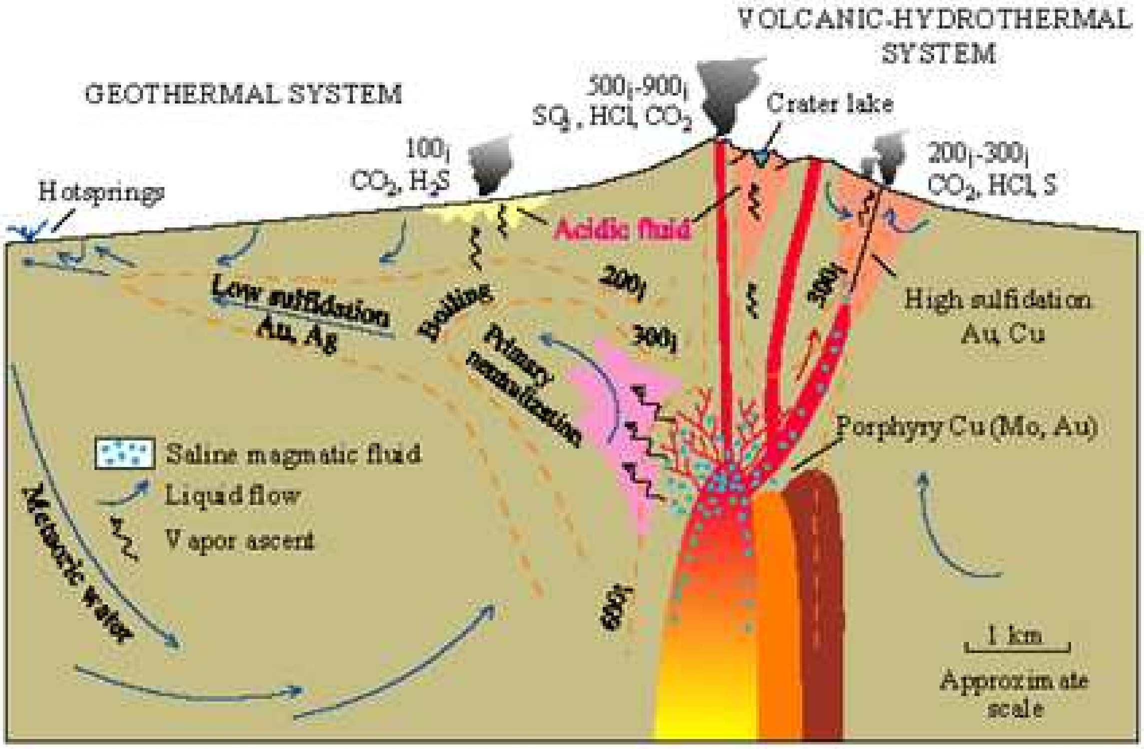

Figure 10. Model of geothermal and volcanic-hydrothermal system (Source: www.earthsci.org).

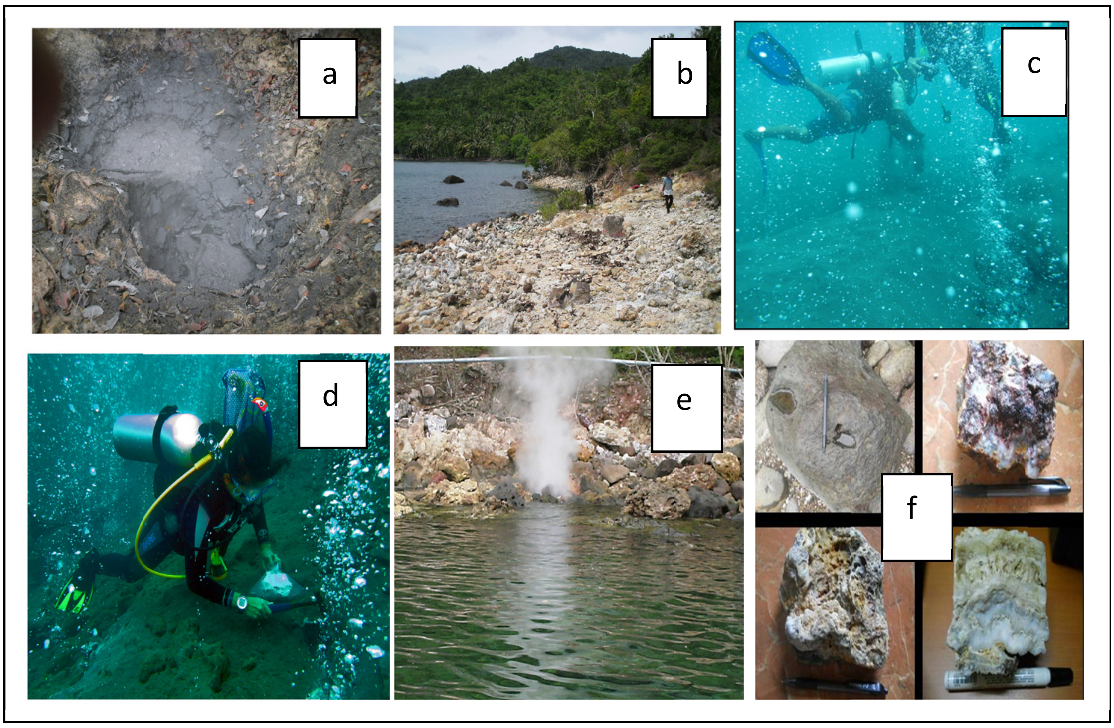

Figure 11. Indications of submarine volcano in Sabang's Waters.

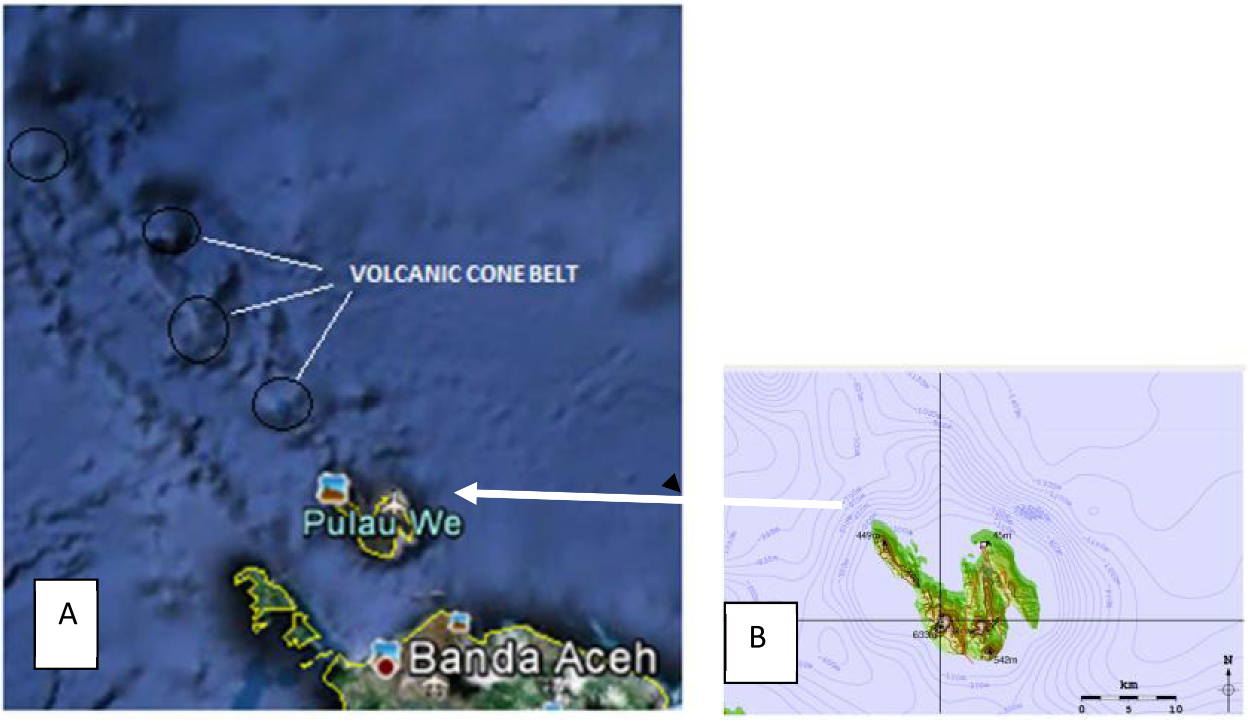

Figure 12. A possibly succession of volcanoes northwestward of Weh Volcano demonstrates by some cone-shape morphology (A). Bathymetry surrounding Weh Island shows closure pattern which resemble a submarine volcanic cone. (B).

to the mentioned direction, the volcano activities was terminated.

Space observationrevealed that south part of Weh Island still demonstrate series of cone shape morphologies (Figure 13). This volcano series is oriented north - south. Clear observation of cone shape morphology from the sea could also be seen in Figure 3.

Fumarole activities in the investigation area are controlled by geological structures, especially normal faults (Figure 14). Such faults have different orientation with main fault. It oriented north - south, and had been analyzed take place in tensional tectonic setting; while main fault - located at eastern of Weh Island, which is part of Great Sumatran Fault, directed northwest - southeast.

The changing orientation of Sunda trench was also influenced orientation of volcanic belt in Sumatra, especially at Aceh Province. Begin from southwest - northeast almost along the length of Sumatra Island, it suddenly changed to east west orientation (Figure 16), before continuing again to NW-SE direction which passing through Weh Island. It seems that coastline north of Aceh is following this east - west volcanic orientation.

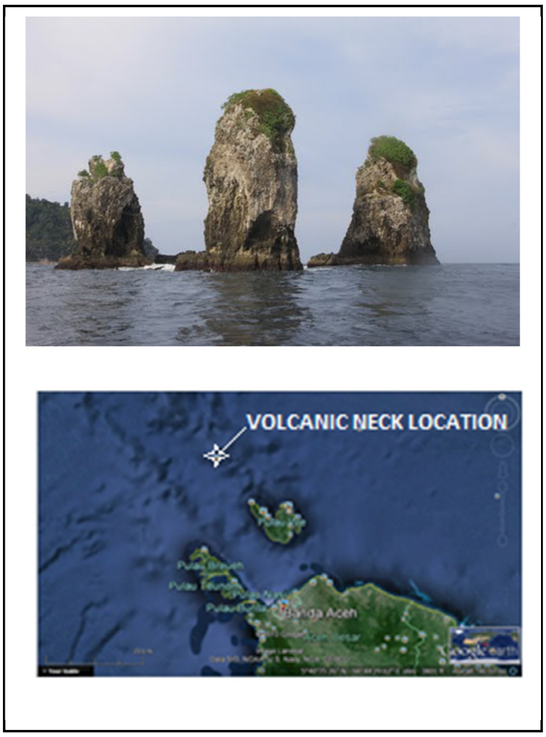

Figure 13. remnants of possibly volcanic necks northwest of Sabang Island (Source: paranamio and earthgoogle).

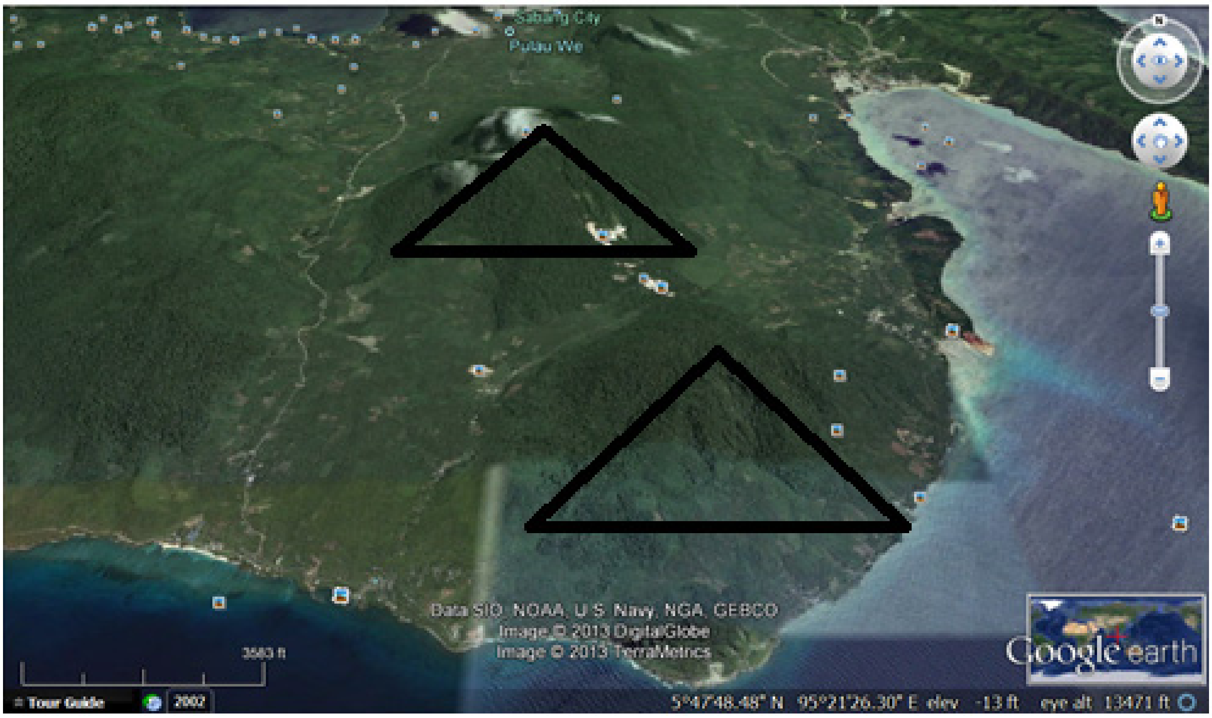

Figure 14. Three dimensions image of volcanic cones at the south of Sabang Island

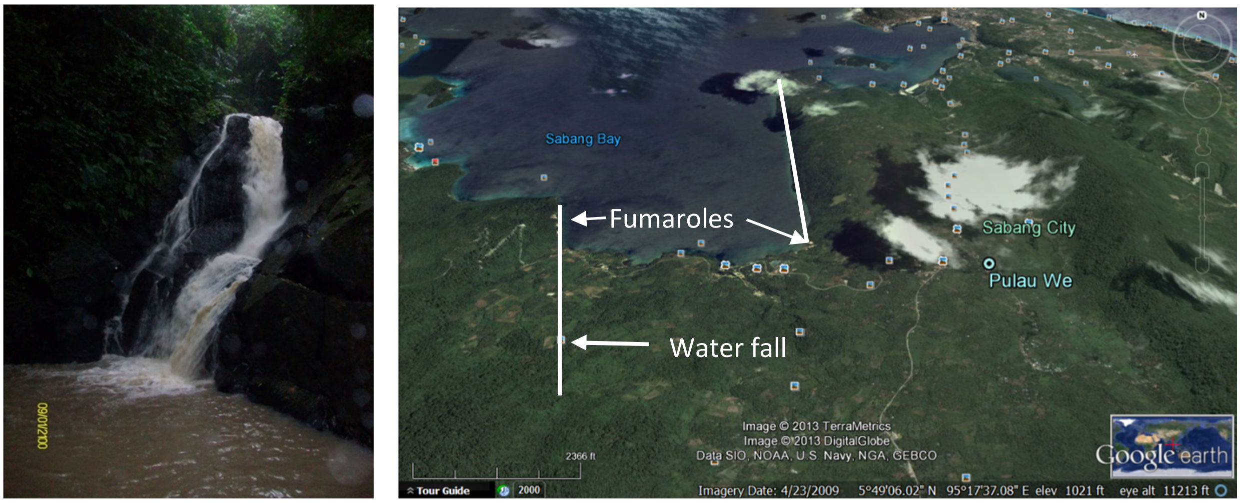

Figure 15. Waterfall as indication of a normal fault. The fault is oriented north-south. The fault is also the place for fumaroles. (Source: earthgoogle).

CONCLUSIONS

It could be concluded that the submarine volcano characteristics of Weh Island still show cone shape morphology as revealed from bathymetric data. Field work observations found out mud volcano phenomenon in a small crater, influence of acidic fluid on surface rocks, fumaroles and solfatara points, sea water vaporization in the fumaroles hole during high tide, and hydrothermal minerals.

Submarine volcano activities take place at seafloor and coastal area. The activity stage occurs as fumaroles and solfatara. The activity is also causing formation of hydrothermal minerals, anomalous temperature and salinity. It seems that normal faults control fumaroles activities in Sabang's Waters. Quite well preserved of coral reef and submarine volcanoes have become interesting dive spots.

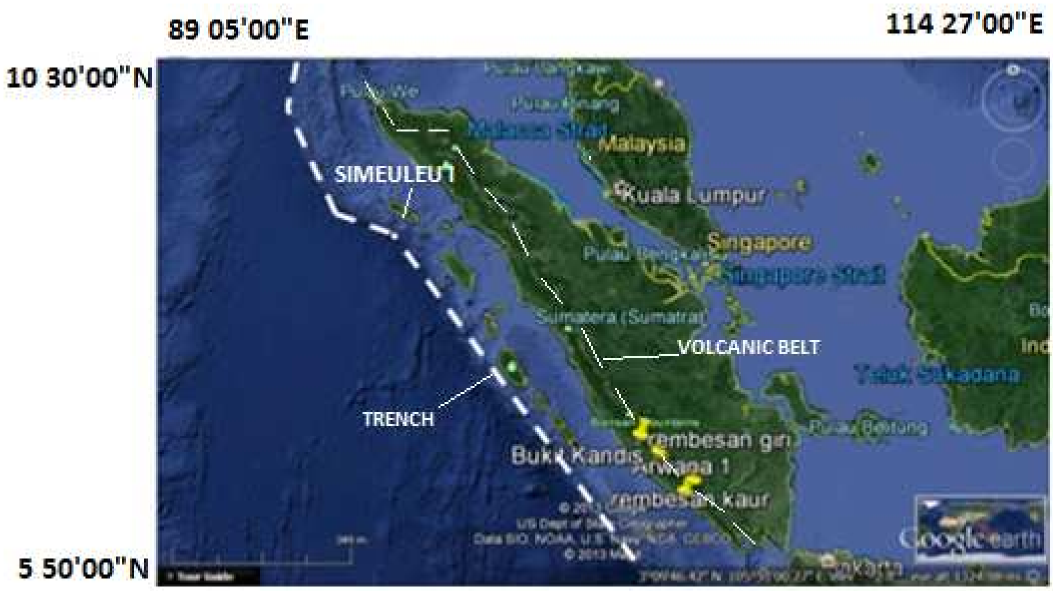

Figure 16. The bending of Sunda trench south of Simeuleu is also influence volcanic belt orientation of Sumatra from SE – NW along the south until E – W in Aceh-North Sumatra. (Source: earthgoogle).

REFERENCES

[1] Carey, S. and Sigurdsson, H., 2007, Submarine Arc Volcanoes. Oceanography, Vol. 20, No. 4, pp. 80-89.

[2] Dirasutisna, S. and Hasan, A.R., 2007, Geology of Jaboi Geothermal Area. Unpublished Report of Center for Geological Resources, Geological Agency of Indonesia, Bandung (In Indonesian)

[3] Iizasa, K., R. Fiske, O. Ishizuka, M. Yuasa, J. Hashimoto, J. Ishibashi, J. Naka, Y. Horii, Y. Fujuwara, A. Imai, and S. Koyama, 1999. A Kuroko-type polymetallic sulfide deposit in a submarine silicic caldera. Science 283: 975-977.

[4] Law, R.D., Eriksson, K. & Davisson, 2000. Formation, evolution, and inversion of the middle Tertiary Diligencia basin, Orocopia Mountains, southern California. The Geological Society of America, vol. 113 no.2 p. 196-221.

[5] Macdonald, K.C., 2001. Mid-ocean ridge tectonics, volcanism and geomorphology. Copyright © 2001 Academic Press. Doi: 10.1006/rwos.2001.0094.

[6] Masaaki, U., Muslim, D., and Motohiko, S., 2013, Gamma Ray Dose Rates in the Weh Island, Indonesia. Memoirs of Osaka Kyoiku University, Ser.III, Vol.61, No.2, pp.17-22 (February, 2013).

[7] Mayunar, 1995. Budidaya Ikan Laut dalam Karamba Jaring Apung. Pdf. www.sidik.litbang.kkp.go.id (In Indonesian)

[8] Robb, L., 2005, Introduction to Ore-Forming Processes. Blackwell Publishing, 373 p.

[9] Sieh, K., and Natawidjaja, D., 2000. Neotectonics of the Sumatran fault, Indonesia. Journal of Geophysical Research, Vol. 105, No. B12, pages 28,295 – 28,326, December 10, 2000.

[10] Suhanto, E., Sriwidodo, Munandar, A., Kusnadi, D., and Kusuma, D.S., 2005, Geological, geochemical, and geophysics integrated investigation on hydrothermal at Jaboi, Sabang – Nanggroe Aceh Darussalam. Geothermal Survey Presentations, Center for Georesources – Geological Agency – Bandung (In Indonesian).

[11] Tikoff, B., 1998. Sunda-style tectonics and magmatic arc processes, Eos Trans. AGU, 79(45), Fall Meet. Suppl., F222, 1998.

[12] www.earthsci.org