Bulletin of the Marine Geology, Vol. 35, No. 2, December 2020, pp. 91 to 102

Tectonics of Volcanogenic Massive Sulphide (VMS) Deposits at Flores Back Arc Basin: *A Review*

Kondisi Tektonik Deposit Sulfida Masif Volkanogenik pada Cekungan Busur Belakang Flores: Suatu Tinjauan

Noor Cahyo Dwi Aryanto* and Hananto Kurnio

Marine Geological Institute of Indonesia (MGI), Jalan Dr. Djundjunan No. 236, Bandung.

Corresponding author: *noor_aryanto@yahoo.com; noor.aryanto@esdm.go.id

(Received 14 September 2020; in revised form 18 September 2020; accepted 26 November 2020)

ABSTRACT: The bathymetry, petrology, marine magnetic, and seismic-SBP data have identified the northwest-southeast direction submarine ridge that shows hydrothermal activity. This activity occurred through Mount Baruna Komba, Abang Komba, and Ibu Komba. The volcanic rocks are andesite basaltic lava flows, tuff, and pumice. The andesite basaltic lava shows porphyritic, intergranular, intersertal to glomeroporphyritic textures. The rock composes anhedral minerals of k-feldspar, plagioclase, and pyroxene. These minerals present in small-sized, short prismatic dispersed in very fine groundmass minerals or glasses. Most of the volcanic rocks have experienced various degrees of alteration. The k-feldspar and plagioclase are most dominantly transformed into sericite, clay mineral, carbonate, epidote and oxide mineral, opaque mineral, and secondary plagioclase through the albitization process, while pyroxene replaced by chlorite. Other minerals are biotite and quartz, and base metals are present Cu, Zn, Ag, As, Pb, and gold. Mineralization categorizes as the phyllic zone, sub-prophylithic zone, and phyllic-potassic zone that formed at a temperature range of 250-400^{o}C. The submarine hydrothermal alteration in the Komba Ridge is associated with a volcanogenic sulphide deposit controlled by crust thinning due to the crust rifts in the back-arc tectonic setting.

Keywords: volcanic rocks, submarine hydrothermal alterations, Komba ridge, volcanogenic massif sulphide (VMS), back-arc

ABSTRAK: Data batimetri, petrologi, magnetic laut dan seismic-SBP telah memetakan dan mengidentifikasi suatu punggungan bawahlaut berarah baratlaut-tenggara yang memperlihatkan aktifitas hidrotermal bawah laut. Aktifitas tersebut muncul melalui Gunung Baruna Komba, Abang Komba dan Ibu Komba. Batuan gunungapi penyusun adalah aliran lava andesit basaltic, tuf dan pumis. Lava andesit basaltik memperlihatkan tekstur porfiritik, intergranular, intersertal to glomeroporfiritik. Mineral penyusun berupa k-felspar, plagioklas, dan piroksen dalam bentuk mineral anhedral, prismatik pendek berukuran kecil yang berada dalam masa dasar mineral sangat halus atau gelas. Batuan vulkanik telah mengalami ubahan dalam berbagai tingkat, dimana k-flespar dan plagioklas paling dominan terubah menjadi serisit, lempung, karbonat, epidot dan mineral oksida, opak atau plagioklas sekunder melalui proses albitisasi sedangkan piroksen mengalami proses ubahan digantikan oleh klorit. Mineral ubahan lainnya adalah biotit dan kuarsa dan logam dasar seperti Cu, Zn, Ag, As, Pb, dan emas. Mineralisasi dikategorikan sebagai zona filik, zona sub-profillitik, dan zona filik-potasik yang terbentuk pada kisaran suhu 250-400^{o}C. Alterasi hidrotermal bawah laut di Punggungan Komba berasosiasi dengan suatu endapan sulfida volkanogenik yang dikontrol oleh penipisan kerak akibat peregangan kerak dalam tatan tektonik busur belakang.

Keywords: *batuan gunungapi, alterasi hidrotermal bawah laut, punggungan Komba, sulfida massif vulkanogenik, busur belakang*

Contributorship:
The main contributors: Noor Cahyo Dwi Aryanto and Hananto Kurnio.

INTRODUCTION

The study area is located in the Flores back-arc basin (Karig, 1983; McCaffrey and Nabelek, 1984; Tikku, 2011; Gorsel, 2018 and Magni, 2019), northeast of Flores Island, East Nusa Tenggara Province (Figure 1). The area is divided into three different submarine ridges, the first ridge is the Komba active volcano island (Batutara island) on the most northern part, 400 meters above sea level (Sarmili, and Suryoko, 2012). Next, the second, to southeastward, those are Baruna, and Abang Komba and third, is Ibu Komba ridge (Sarmili *et al.*, 2003 and 2004). These ridges immediately place in the north of the Flores back-thrust and at the southwest margin of South Banda Basin (Hamilton, 1979). The purpose of this paper is to assess and review the previous result regarding the VMS deposition process in the Flores Sea, Indonesia, especially those related to tectonic setting, and of mineral deposits results.

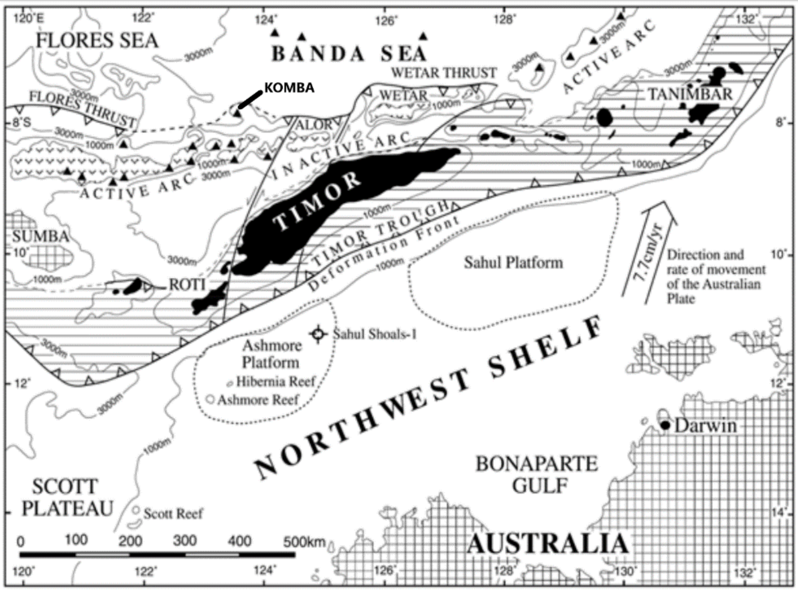

Figure 1. Regional map of the Flores back-arc basin showing active and inactive segments of the Banda volcanic arc. The Alor-Wetar sector has been inactive for about 3Ma after the subduction zone locking the Timor Trough. The northward active back-arc thrusting accommodates partially the northward movement of the Australian Plate (Gorsel, 2018).

Volcanogenic Massive Sulphide (VMS) deposits

Volcanogenic massive sulphide ore deposits, VMS, are a type of metal sulphide ore deposit composed mainly by copper and zinc. The VMS associated with and created by volcanic hydrothermal events in submarine environments (Colin-Garcia *et al.*, 2016; Galley *et al.*, 2007 and Mercier-Langevin *et al.*, 2014). It occurs along mid-oceanic ridges, within back-arc basins and forearc rifts. It also termed as volcanic hosted massive sulphide (VHMS) deposits. Specific density deposit is 4.5 and mostly occurs as stratiform accumulations of sulphide minerals from hydrothermal fluids. It happens either above or below seafloor in many ancient and actual geological conditions. The last is synonymous with sulfurous black smokers. The ideal profile of VMS shows in Figure 2. There are 300 sites of hydrothermal activity in modern submarine hydrothermal systems, and mineral deposits have been recognized worldwide. The 100 sites are a high-temperature type of submarine hydrothermal systems known as black smokers, 65% of those have spread over 55,000 Km of mid-ocean ridges, 22% in the back-arc environment, while 12% appear in submarine volcanic arcs activity and less than 1% present as intraplate volcanoes (Hannington *et al.*, 2005).

The metals source of VMS deposit is a combination of leached incompatible elements from sub-seafloor hydrothermal alteration zone and driven by deep-seated heat related to rock especially gabbro intrusions. The hydrothermal fluids convection is responsible for metal transport where the heat supplied by magma chamber below volcanic edifice. Mixing with cool water, the hydrothermal fluids expelled into the ocean enriched in sulfur and metal ions, and then precipitate as stratiform sulphide ore (Hannington, 2014).

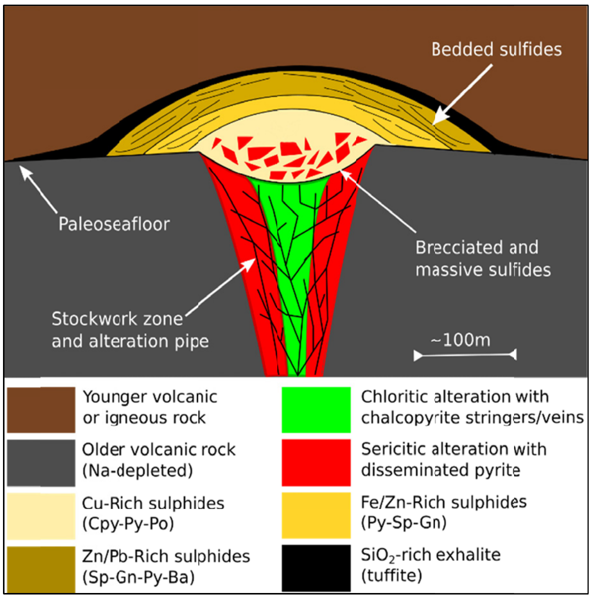

Figure 2. A profile of a VMS ore deposit (Hannington, 2014).

The caldera related VMS deposit formation can be recognized through its multiphase sill-like sub-volcanic intrusion. An abrupt change in thickness, orientation, and extensive-thick-pyroclastic/volcaniclastic deposits are characters of caldera related VMS deposit formation. The other characters are thick-ponded flow succession, internal angular, erosional unconformities, megabreccias as a product of collapse, and numerous dikes and sills. The orthogonal, radial, or concentric syn-volcanic faults and intense semi-conformable alteration controlled caldera related VMS deposit (Gibson, 2007).

Gibson (2007) pointed out that VMS deposits are located within and adjacent to a caldera where they occur within volcanic vents localized along syn-volcanic faults and fissures. VMS deposit and caldera formations occur in the late evolution of volcanoes, while caldera formation itself is associated with high heat flow and cross-stratal structures. Permeability focused on time explains the time-stratigraphic control of VMS deposit formation, while its focus on space explains the clustering of deposits (Gibson, 2007). On the other hand, shallow magmatism offers potential for a magmatic-hydrothermal contribution of metal preservation (Gibson, 2007).

Hydrothermal Fluid Mechanism in Producing VMS

Massive sulphide deposits formed at or near the sea floor where non-boiling fluids are cooled by steep thermal gradients or by quenching in cold seawater. Metal precipitation is rapid if boiling occurs (Drummond and Ohmoto, 1985). The main controls on the vigour and pattern of convection are intrusion geometry and depth, and the permeability of the intruded environment. These factors are broadly related to geologic setting and host-rock composition and thus to conventional classification of VMS deposits (Barrie, C., *et al.*, 1999).

Furthermore, Barrie. *et al.* (1999) mentioned that the stability of alteration mineral assemblages in vent areas can provide a reliable estimate of the average vent temperatures (Figure 3). The ability of a hydrothermal fluid to transport and form metal deposit is related to venting temperatures, and to intrinsic parameters including the pH, salinity, H2S, and fO_2 of the fluid, which themselves are dependent on interaction with host rocks and sulphide.

Upwelling mantle causes heat flux increase and upward bending of isotherms (thermal fronts). On the contrary, the heat flux drives volcanism as well as circulation of evolved seawater at higher crustal levels. High heat flow, plutonism, high-temperature volcanism, sedimentation, and subsidence focused on time and space are essential to the formation of high temperature hydrothermal systems responsible for the formation of VMS deposits (Gibson, 2007).

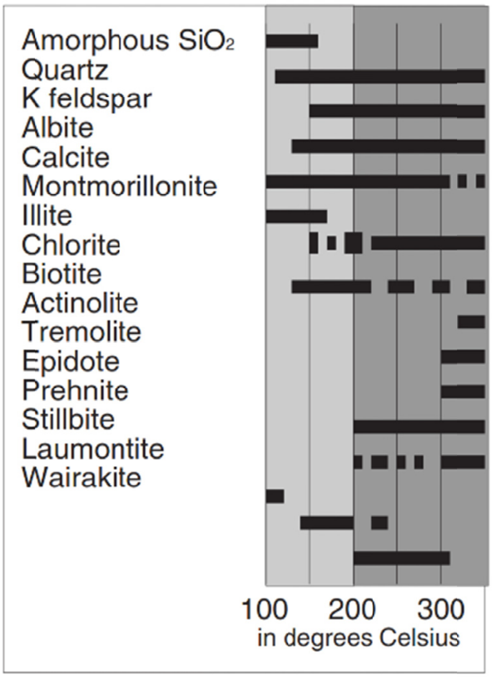

Figure 3. Temperature ranges summary for the mineral stability of common alteration minerals in geothermal areas (Modified after Henley and Ellis, 1982)

Black smokers as direct magmatic contributions in the seafloor may be leading to Cu and Au rich systems (Hedenquist *et al.*, 1993), for an example in the White Island New Zealand: Cu – 110,000 kg/year and Au – 36 kg/year. The results of the Bandamin-1 cruise in the Northern Flores Waters, Indonesia, are the gold concentrations up to 300 ppb, 4 ppm Ag, 80 ppm As, 106 ppm Zn were found, Cu concentrations up to 100 ppm and Pb reached 80 ppm (Aryanto, 2011). These black smokers usually occur in seafloor calderas but they are not the usual setting for large VMS deposits due to smaller magma chambers beneath. Nevertheless, these VMS are potentially having higher grade deposits (Hedenquist *et al.*, 1993).

Tectonics of Back Arc Basin

Tectonic setting of VMS deposits influences the nature of the igneous basement, the physical and chemical characteristics of the hydrothermal fluids especially its temperature, salinity and oxygen fugacity (Hannington *et al.*, 1999). Hannington *et al* further pointed out that VMS deposits are known in 12 different tectonic settings: fast, intermediate, slow and ultraslow spreading centers of mid-ocean ridges; ridge-hotspot intersections; ridge-transform intersections; off-axis volcanoes; intraplate volcanoes; sediment-covered ridges; intracontinental rifts; intra-oceanic arcs; transitional or island arcs; continental margin arcs; intra-oceanic back-arc basins and intracontinental back-arc basins. While on modern geodynamic, VMS could be found in intra-continental rifts, intra-oceanic arcs, transitional or island arcs, continental margin arcs, intra-oceanic back-arc basins and intra-continental back-arc basins (Hannington *et al.*, 2005). Gibson (2007) noticed that back Arc VMS occur at a rift, that are fault-bounded basins produced by extension of the crust.

Geological Setting of Flores back-arc Basin

Geologically, the Flores-Wetar Basin is part of the back-arc basin which is still young (Silver, *et al.*, 1983). In this area, the island arc of active volcanoes have been cut and shifted by a large shear fracture system which regionally includes the islands of the Lesser Sunda Islands (LSI) which are volcanic arc islands (Bali, Lombok, Sumbawa, Flores, Sumba, Timor, Alor, Wetar, Romang, Damar, and Tanimbar Island), which mainly have been built by volcanic activity resulted from partial melting of the subducted plate. The LSI mainly has two-phases of tectonic settings (Purwandono, *et al.*, 2019). An extensional phase of LSI was started from ~20 – 4 Ma, which resulted in the south-migrating of Sumba Microcontinent and also the opening of basins i.e. Banda, Flores, Savu, and Weber Basin (Wensink, 1994; Hinschberger, *et al*, 2005; Hall, 2012) (Figure 4). After the extensional phase, the incoming Australian continental crust induced a collisional phase from ~8 Ma onwards which is started at the south of Wetar island and spreading to its surrounding at the east and west side (Hall, 2012; Tate, *et al.*, 2015). This present day configuration coupled with the kinematic framework (Koulali, *et al.*, 2016) shows the eastern of Indonesia has undergone an anticlockwise rotation. There are two subduction types south of volcanic islands of eastern Sunda Arc: thrusting of Australia beneath deformed outer arc Timor in the east and consumption of oceanic Indian plate at Java Trench in the west (McCaffrey and Nabelek, 1984). The eastern part of the Sunda-Banda edge collision is in the transition region starts from the Indian oceanic crust subduction system in Java trench up to the area of the collision between the thick Australian continental crust with southern Banda arc. Among these subduction and collision zones there is a transition zone whereas the Scott platform is a thin continental crust (McCaffrey, 1988). This transition zone is allegedly dominant with collisions compared to subduction system. Sunda-Banda island arc generated by the tectonic process also forms part of the southern and eastern edge of the Flores-Banda basin (Silver, *et al*; 1983).

The crust in the Flores back-arc basin is experiencing isostatic in-equilibrium as evidence by a large negative free-air gravity anomaly (-110 mGal) over the accreted wedge. This suggests that the Flores Basin crust is underthrusting beneath the island arc (McCaffrey and Nabelek, 1984). The east-west back-arc thrust, which extends from the north of the Lombok

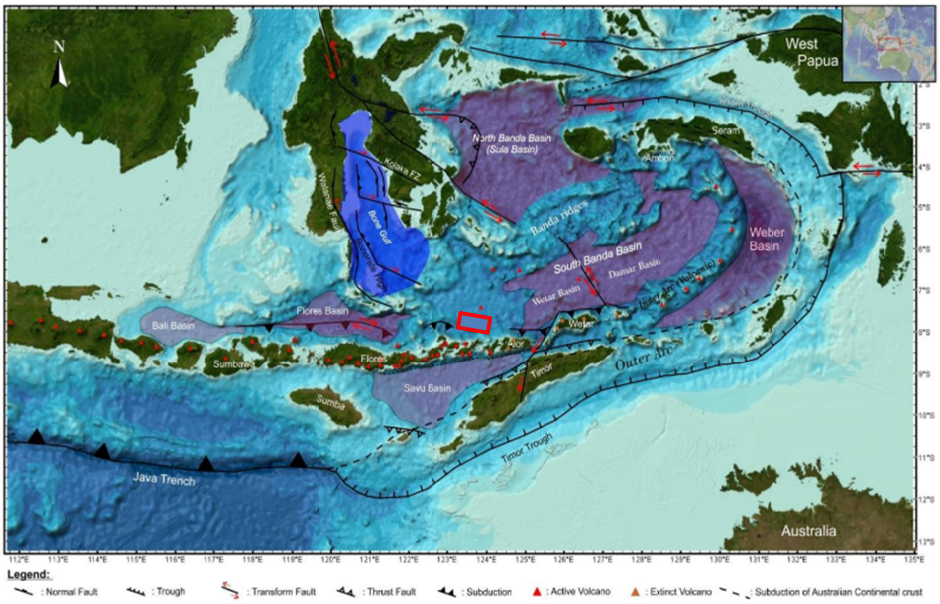

Figure 4. Tectonic setting of Lesser Sunda Island (LSI; simplified), and its volcanism occurrences (compiled from Hinschberger, *et al.*, 2005; Hall, 2012; Camplin and Hall, 2014); □: Komba ridges

island to the Flores island, disappears around the study area. Furthermore, after being cut off by the Wetar fault which traverses northeast-southwest or parallel to the Pantar fault, this upward fault appears again in the north of Wetar Island which extends to the east (Silver, et. al., 1983).

METHODOLOGY

This study is based on the review of various published or unpublish data on a tectonic and a VMS formation topic. The principal data are published and unpublished data and marine expedition report on the existence of submarine hydrothermal activities at the northeast of the Flores Sea or Batutara (Komba) area in the Flores back-arc environment. The marine expeditions had carried out by MGI, namely Bandamin-1 Cruise in 2002, Bandamin-2 Cruise in 2003 (Halbach, et. al., 2003a) and Sangeang Cruise in 2013 (Sarmili, L., et. al., *Internal report,* 2013). The marine expeditions have produced very high-value data. These data is presented in various related publications, such as bathymetry, processed seabed magnetic, rock type and mineralization, and single channel seismic or sub-bottom profiles.

RESULTS

The Bandamin expedition in the northeastern Flores Sea has mapped a northwest-southeast direction submarine ridge. The ridge depth is less than 3000 m occupied by mountain peaks at 700-300 m below sea level (Sarmili, and Suryoko, 2012). The mountain peaks show submarine hydrothermal activities known as Baruna Komba, located at the northwest end, Abang Komba in the middle, and Ibu Komba at the southeastern end of the ridge (Sarmili, 2003 and 2004). The cone shape peak of the Baruna Komba volcano is suggesting still active (Halbach, *et al.*, 2003a). The isolated hill forms around the foothills of Baruna Komba at depths of 800-1000 m are likely eruption product of Baruna Komba mountain in 2007 or earlier (Sarmili and Suryoko, 2012) which until now still active to forms volcano cones with an altitude 300m below sea level (Sarmili and Troa, 2014). In contrast, the peaks of the Ibu and Abang Komba mountains are relatively elongated and flat at a depth of 300 m (Abang Komba) and 800-900 m peaks of Ibu Komba. This morphology is interpreted that both mountains have erupted and then experienced erosion or because it is dominated by lava flows ((Sarmili and Troa, 2014). Three pairs of southwestern-northeastern valleys cut off the Komba Ridge. The valley on the northwest side of Mount Baruna Komba, about 200 m wide and depth 1100-1200 m. The narrow valley on the southeast side of Mount Baruna Komba is about 100 m wide at a depth of 800-1100 m. According to Sarmili and Troa (2014), to the southeast of the Komba ridge, a valley 800-1000 m wide at a depth of 2500-2700 m separates Mount Baruna Komba and Abang Komba. At the south of Mount Baruna Komba and Mount Abang and Ibu Komba observe two near west-east-directed lineaments (Figure 5). The southwest-northeast direction valleys are interpreted as a graben while a shear fault is the almost west-east trend lineament. The lineament of the Komba Ridge itself is suppose controlled by deep fault. This fault extends from the research area to the direction southwest through Pantar Island to the southern part of Timor Island and is known as the Pantar Fault (Darman, 2012).

Komba

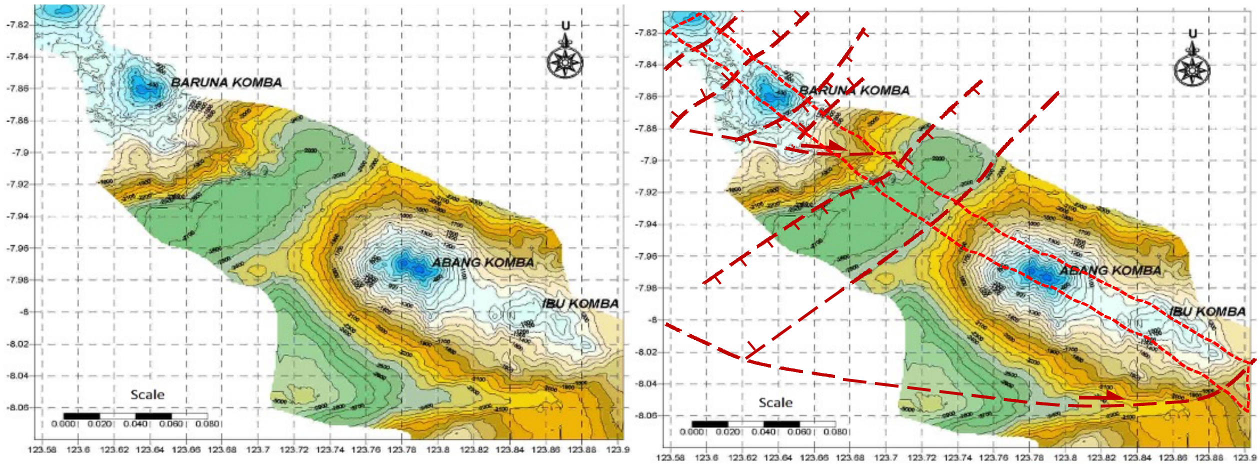

Figure 5. Bathymetric map of Baruna, Abang and Ibu Komba submarine ridges (Sarmili and Suryoko, 2012) and structural lineament interpretation. The Komba ridge cut by three pairs of normal faults, strike slip fault and interpretation of deep fault.

The marine magnetometer data shows the presence of two ridges showing differences magnetic anomaly value (Figure 6). High anomaly magnetic value indicates the presence of metal elements rich rocks (Sarmili, L., and Suryoko, M.A., 2012). These rocks are related to the presence of magma source beneath the volcano. This magnetic data supposed that Abang and Ibu Komba's ridge is strongly related to the volcanic magma source. It is different from the appearance of Baruna Komba (which morphologically shows the appearance of an active volcano, characterized by a cone-shaped peak), but in terms of magnetic anomaly values, it shows different results. In contrast, the Baruna Komba ridge shows a low magnetic anomaly value (Figure 6). This fact interpreted that Mount Baruna Komba is composed of volcanic deposits resulting from Komba volcano eruption. Therefore, measurable magnetic anomaly value is not directly related to the activity or magmatism process (Sarmili and Suryoko, 2012). Another opinion is the volcanic material deposits as a result of the Komba caldera collapse triggered by frequent eruptions.

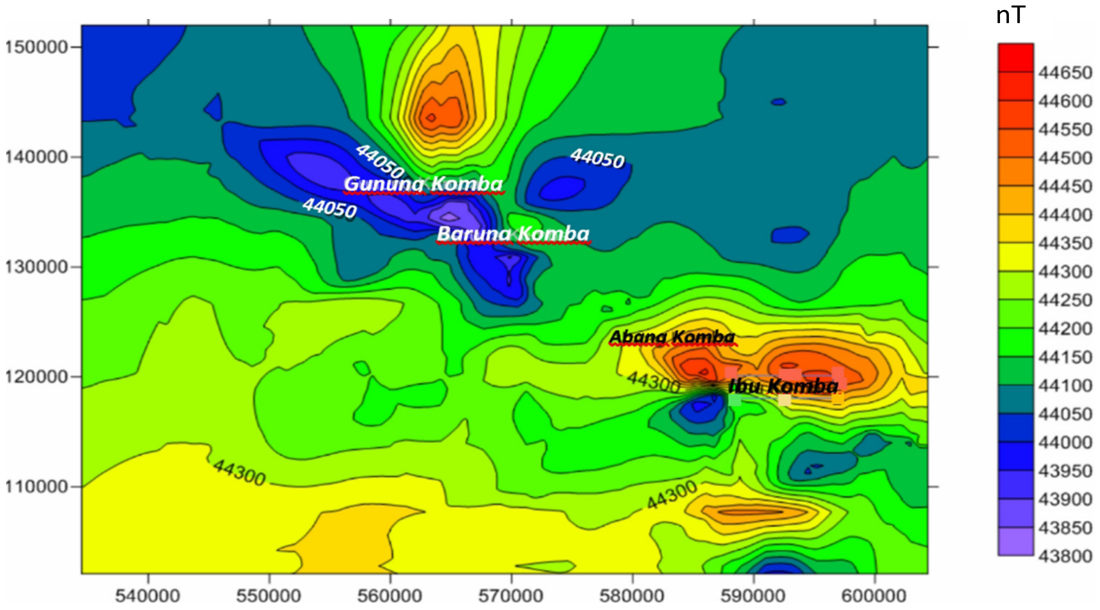

Figure 6. Marine magnetics anomaly map of Study area (Sarmili and Suryoko, 2012)

Figure 6 shows Baruna Komba a negative anomaly submarine ridge which is interpreted does not have the elements associated with iron metal element of magnetization (Sarmili and Suryoko, 2012).

Based on Figure 6, the anomaly which declined sharply, especially at Baruna Komba has anomaly about 43,820 nT. It can be interpreted that the rock has a very low intensity magnetic likely are not related to volcanic magma or assumed as a collapse caldera material resulting from Komba volcanic eruption and deposited on Baruna Komba and its surrounding.

The collapsed caldera was caused by an inner steep reverse fault or triggered by an outer normal fault associated with the extension of the caldera rim (Cole *et al.*, 2005; Acocella, 2007, in Kim, *et al.*, 2013). Intra-caldera fill is a caldera formation process. Many large calderas collapse during an eruption that produces a volcanic ash flow followed by a subsidence process and then caldera wall sliding (Lipman, 1997). This evidence

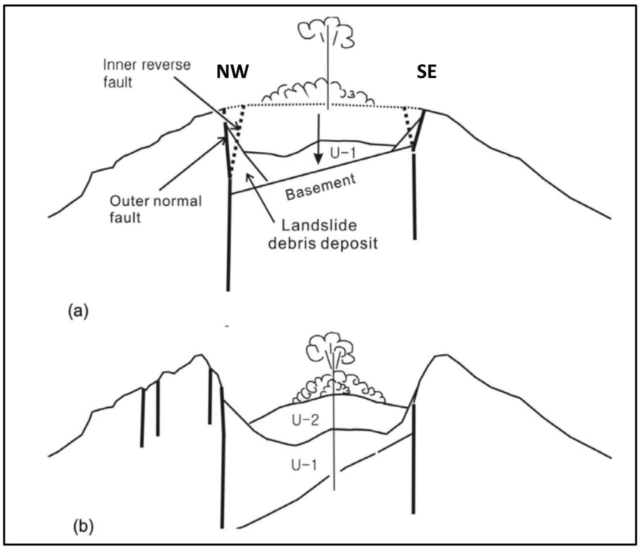

Figure 7. Schematic diagram showing a possible sequence of events associated with the formation of the caldera (modified from Kim *et al.*, 2013)

of caldera collapses happened in the submarine volcano at Tonga, South Pacific (Kim *et al.*, 2013).

The rock of mount Komba composed of basaltic andesite lava flow, pumice and dacite. The pumice rocks are also observed around Baruna Komba Ridge. The rock show porphyritic, intergranular, intersertal to glomeroporphyritic textures. The rock comprises K-feldspar, plagioclase, pyroxene, biotite, hornblende, and opaque oxide minerals that spread out in a very fine grain groundmass. The volcanic rock generally experienced a different degree of rock alterations, while those containing sulphide minerals found in the north and south sides of Mount Abang Komba (Halbach *et al.*, 2003a).

The mineral alteration of Mount Abang Komba rocks is the same with minerals hydrothermal alteration from other regions (Evans, 1987). The volcanic rocks have experienced alteration processes of chloritization, carbonation, sericitization, pyritization, and propylitization. Plagioclase is a highly intensive hydrothermal alteration mineral replaced by sericite, clay minerals, carbonates, epidotes, and opaque minerals. The mineral alteration belongs to propylitic zones characterized by chlorite, especially on the north side of Abang Komba which shows the surface alteration process (Sarmili and Hutabarat, 2014). Chlorite and carbonate alteration are the dominant minerals in andesite and dacite in addition to other secondary minerals such as clay minerals, sericite, and secondary quartz. Carbonate is the result of plagioclase alteration, biotite, pyroxene, and K-feldspar; and in some samples show complete replacement textures (pseudomorph) and as groundmass.

Sometimes, it occurs as vein associated with sericite and secondary quartz. Alteration of Abang Komba rocks can be grouped into two zones: chlorite-carbonate zone and carbonate-sericite-clay minerals group (Sarmili and Hutabarat, 2014) or classifies as the phyllic zone up to the sub-prophylithic zone, formed at a temperature of 250-300^{o}C. The presence of quartz and biotite can be classified as phyllic-potassic zone that form in 250-400^{o}C (Corbett and Leach, 1997).

The hydrothermal activity occurred at seafloor ridges of Abang, and Ibu Komba in the Flores back-arc basin, which is located about 200 – 300 km above the subduction slab (Halbach, *et al.*, 2003b in Sarmili and Troa, 2014). Referring to Sarmili and Troa (2014) as seen in the seismic recordings in the southwest of the Abang Komba ridge submarine, showing a reflector pattern that is parallel to almost parallel (parallel to oblique); (Figure 6). Based on the seismic record, it means that the area is represented by sedimentary rocks that have fine fractions and based on the grain size analysis results that the sediment at this location is quite soft pelagic clay. According to the interpretation of reflected seismic, it can be seen that the faults in the study area have the same directional pattern as the presence of submarine ridges as mentioned above.

This northwest-southeast trending fault is crossed perpendicularly by a fault that runs southwest-northeast. These faults influence east-west direction back-arc thrust. Thrust imbrications were also observed from the seismic, while parallel reflector patterns are interpreted as fine pelagic sediments as revealed from the core obtained on the seafloor (Figure 8), (Sarmili and Troa, 2014). According to Sarmili and Troa (2014) Abang Komba and Ibu Komba submarine ridges formation are closely related to a deep fault system, whereas magma reaches out near the surface and formed a submarines volcano. The deep fault is

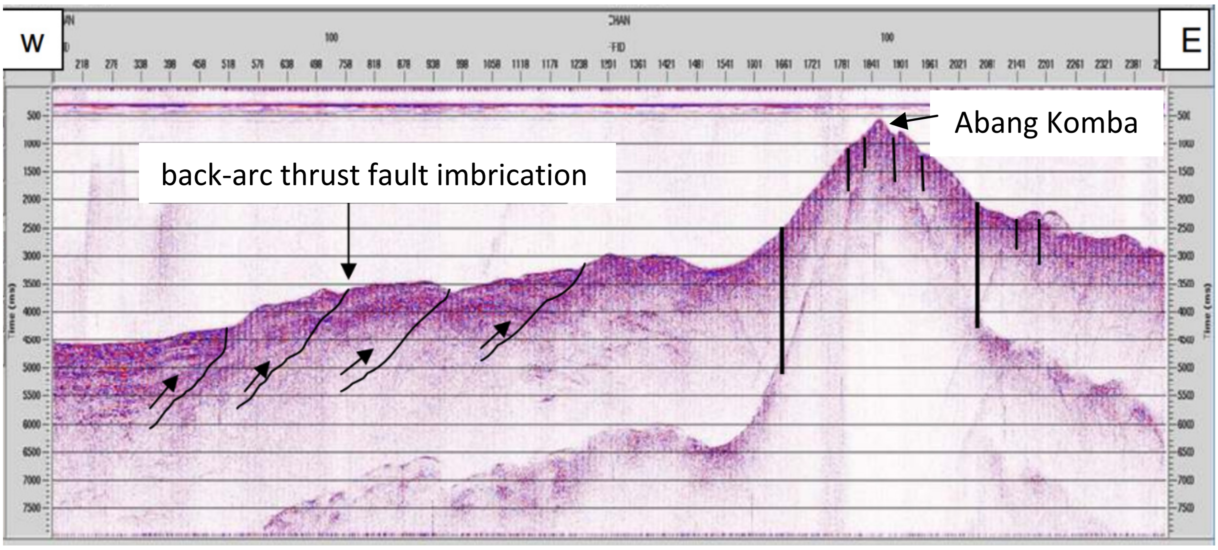

Figure 8. Seismic line record which intersects Abang Komba (Sarmili and Troa, 2014)

hypothetically interpreted as NW-SE trending shear fault, or along the Komba ridge whereas the magma reaches out. The seismic section interpretation showing that deep fault is a normal fault.

DISCUSSION

Baruna Komba, as one of three submarine ridges, morphologically shows the appearance of an active volcano, characterized by a cone-shaped peak, but in terms of magnetic anomaly values, it shows a low value. This fact interpreted that Baruna Komba is composed of volcanic deposits resulting from Komba volcano eruption or assumed as a collapse caldera material.

Tectonic processes that influence the VMS systems formation are still a debate among scientists. The opening of the back-arc as one of the tectonic settings of VMS formation is associated with the faults formed closely related to the basin (fault-bounded basins), triggered by the crust extension process (Gibson, 2007). The west-east regional dextral strike-slip fault located at the east of the Flores Basin forms the boundary between the Savu and Wetar Basins (pull-apart??). This fault system is probably the model referred to by Gibson (2007) which forms the northwest-southeast direction of the Komba Ridge lineament (McCaffery, 1988). The northeast-southwest Pantar fault zone crosses the northwest-southeast volcanic arc in the submarine Komba Ridge (Darman, 2012). The north-east lineament is the submarine volcanic ridge Komba or Batutara Island to Ibu Komba (Sarmili, *et al.*, 2003). NW-SE lineament is considered older than any other lineament in this area.

The VMS deposit formation usually starts at the early arc rifting or proto back-arc basin (Gibson, 2007). At the early arc-rifting is characterized by a narrow depression cut off or formed behind arc front, commonly in the form of a short trough-like graben (< 100km long and 30-40km wide), and possibly similar to a caldera-like depression in the arc rift crust. The arc rifting is commonly associated with voluminous felsic volcanism, such as pumice. The pumice materials, usually in hot condition, are deposited in the rift grabens. This hot material provides heat to the melting process on the deep crust. Arc rifting process causes extensional faulting that accommodates the large-scale hydrothermal solution convection. The VMS formed on the back-arc basin that is in the rifting stage. This tectonic setting is characterized by normal faults of the fragile continental crust and frequent magma intrusion. This tectonic setting is a favorable environment for hydrothermal systems development (Ishibashi *et al.*, 2014).

CONCLUSION

In the study area, the ridge depth is up to 3000 m occupied by mountain peaks at 700-300 m depth. The mountain peaks show submarine hydrothermal activities known as Baruna Komba, located at the northwest end, Abang Komba in the middle, and Ibu Komba at the southeastern end of the ridge.

Tectonically it is a back-arc basin, characterized by the presence of back-arc thrust faults whose direction is no longer west-east, but trending almost northwest-southeast, this may be due to faults that cut and are older, so that the direction changed to NW-SE. These facts, could be seen of the reflected seismic interpretation, and also have same directional pattern with the appearance of the submarine ridges. This northwest-southeast trending fault is crossed perpendicularly by a fault that runs southwest-northeast. These faults were influencing the east-west direction of the back-arc thrust. Three ridges, Abang and Ibu Komba are volcanic ridges as shown by marine data magnetism which reveals high and positive anomalies. On the other hand, Baruna Komba which lies closed to active volcano Komba/Batutara is not a submarine volcanic as shown by its low or negative magnetic anomalies. It is only a submarine volcanic material deposit formed by a volcanic detritus or non-magnetized deposits and presumed as caldera-collapse material deposits from Mount Komba.

The phenocrysts on some rock samples, and supported also by the variation of unhomogeneous grain sizes and the presence of volcanic glass in groundmass, then it indicates that the possibility of contamination of the magma during its path to surounding crust.

Crystallization stages from plagioclase and pyroxene to biotite and ore minerals are characteristics of volcanic calk-alkaline. Resorption and reaction texture as observed at pyroxene margins showing corrosion by fine aggregates are indications of fractional crystallization and magma mixing. Existence of hornblende shows that hydrothermal fluids crystallized at water saturated condition. Xenocryst at some rock samples show magmatic contamination by the intruded crust.

The interaction between hydrothermal fluid and cold sea water occurs at high temperatures, at normal pH conditions, this is known by the presence of chlorite. With carbonate varies from the type of siderite to dolomite presence, relating to VMS type, which reflects its alteration in host-rock, usually filled / associated with Fe-rich zone and interaction with sea water.

ACKNOWLEDGEMENT

Acknowledgements to Head of Marine Geological Institute for his support and opportunity for authors to write this paper. Thanks to all colleagues who had been helped by the completion of this paper. Also addressed to all editors of Bulletin Marine Geological who were helping during preparing the manuscript.

REFERENCES

Abadi PS., 1996. Mine planning at Kali Kuning pit, PT Prima Lirang Mining, Indonesia, *Unpublished Company Report,* p 8.

Acocella, V., 2007. Understanding caldera structure and development: An overview of analogue models compared to natural calderas, *Earth Sci. Rev.*, **85**, 125–160.

Aryanto, Noor C.D., 2011. Eksplorasi Mineral Laut Dalam di Perairan Indonesia Sebagai Upaya Inventarisasi Mineral Dasar Laut, *Buletin Pusdiklat Geologi*, ISSN: 0216-1494.

Barker, P.F. and Hill, I.A., 1980, *"Asymmetric spreading in back-arc basins".*Nature. 285 (5767): 652–654. Bibcode:1980 Natur.285.652B. doi:10.1038/285652a0

Barrie, C.T., Cathles L. M., Erendi, A., Schwaiger, H., and Murray, C., 1999. Heat and Fluid Flow in *Volcanic-Associated Massive Sulphide-Forming Hydrothermal Systems In book: Volcanic-associated massive sulphide deposits: Processes and examples in modern and ancient settings.* Ed.8, Ch. 9. 201-220, Publisher: Society of Economic Geologists.

Cole, J. W., D. M. Milner, and K. D. Spinks, 2005. Caldera and caldera structures: A review, *Earth Sci. Rev.*, **69**, 1–26.

Colin-García, M., A. Heredia,G. Cordero, A. Camprubí, A. Negrón-Mendoza, F. Ortega-Gutiérrez, H. Beraldi, S. Ramos-Bernal, 2016. "Hydrothermal vents and prebiotic chemistry: a review". *Boletín de la Sociedad Geológica Mexicana.* 68 (3): 599?620. doi:10.18268/BSGM2016v68n3a13.

Darman., 2012. Tectonic map of the Lesser 64 Sundalands, Berita Sedimentologi, the *Indonesian Journal of Sedimentary Geology* No. 25.

Drummond, S.E., and Ohmoto, H., 1985. Chemical evolution and mineral deposition in boiling hydrothermal systems: *Economic Geology*, v. **80**, p. 126–147.

Evans, Anthony M., 1987. An Introduction to Ore Geology, *Second Edition Geoscience Text*; V.2. Blackwell Scientific Publications, London.

Galley, Alan G., M. D. Hannington, and I. R. Jonasson, 2007. Volcanogenic massive sulphide deposits". *Geological Association of Canada, Mineral Deposits Division,* Special Publication. 5: 141–161.

Gibson, H.L., 2007. The Role of Extension and Rifting in the Formation and Location of Volcanogenic Massive Sulphide Deposits. Criteria for Recognition. VMS Short Course "Exploration for Volcanic Massive Sulphide Deposits", *Manitoba Mining and Minerals Convention. Laurentian University* MERC.

Gorsel, J.T. van, 2018. Banda Sea, Lesser Sunda Islands (incl. Timor). *Bibliography of the Geology of Indonesia and Surrounding Areas.* Edition 7.0.

Halbach, P., Sarmili, L., Karg, N., Pracejus, B., Melkert, B., Post, J., Rahdens, E., and Haryadi, Y., 2003a. The Break-up of a Submarine Volcano in the Flores-Wetar Basin (Indonesia): Implication for Hydrothermal Mineral Deposition. *International Ridge News*, **121**/1:18-22.

Halbach, P., Sarmili, L., Pracejus, B., Karg, M., Melchert, B., Post, J., Rahders, E., Haryadi, Y., Supangat, A., 2003b. Tectonics of the "Komba-ridge" area in the Flores-Wetar Basin (Indonesia) and associated hydrothermal mineralisation of volcanic rocks, *Bulletin of Marine Geology, Marine Geological Institute,* vol. 18, No. 3.

Hall, R., 2012. Late Jurassic–Cenozoic reconstructions of the Indonesian region and the Indian Ocean. Tectonophysics 570-571, 1-41.

Hannington MD, Poulsen KH, Thompson JFH, Sillitoe RH, 1999. Volcanogenic gold in the massive sulphide environment. Volcanic-associated massive sulphide deposits, processes and examples in modern and ancient settings. *Rev Econ Geol 8*:325–356.

Hannington, M.D., de Ronde, C.E.J., and Petersen, S., 2005. Sea-floor tectonicsand submarine hydrothermal systems, *in* Hedenquist, J.W., *et al.*, eds., EconomicGeology 100th Anniversary Volume, Society of Economic Geologists,p. 111–141.

Hannington, M.D., 2014. "Volcanogenic massive sulphide deposits". *Treatise on Geochemistry (Second Edition).* 13: 463–488. doi:10.1016/

B978-0-08-095975-7.01120-7. ISBN 9780080983004

Hedenquist, J.W., Matsuhisa, Y., Izawa, E., White, N.C., Giggenbach, W.F.,and Aoki, M., 1993. Geology, geochemistry, and origin of high sulfida-tion Cu-Au mineralization in the Nansatsu district, Japan: EconomicGeology, v. 89, p. 1–30.

Hinschberger, F., Malod, J.A., Réhault, J.P., Villeneuve, M., Royer, J.Y. and Burhanuddin, S., 2005. Late Cenozoic geodynamic evolution of eastern Indonesia. Tectonophysics, 404(1-2), pp.91-118.

Ishibashi, J., Ikegami, F., Tsuji, T. and Urabe, T., 2014. Hydrothermal Activity in the Okinawa Trough Back-Arc Basin: Geological Background and Hydrothermal Mineralization. *Subseafloor Biosphere Linked to Hydrothermal Systems*, pp 337-359.

Karig, D.E., 1983. Temporal relationships between back arc basin formation and arc volcanism with special reference to the Philippine Sea. The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands: Part 2*., Geophys. Monogr. Ser.,* vol. 27, edited by D. E. Hayes, pp. 318-325, AGU, Washington, D. C.

Kim, H.J., Hyeong-Tae Jou, Gwang Lee, Ji-Hoon Na, Han-Joon Kim, Bong-Cool Suk. 2013. Caldera structure of submarine Volcano #1 on the Tonga Arc at 21^{0}09 S, southwestern Pacific: Analysis of multichannel seismic profiling. 2013. *Earth Planets and Space* 65(8):893-900. DOI: 10.5047/eps.2013.01.002

Koulali, A., Susilo, S., McClusky, S., Meilano, I., Cummins, P., Tregoning, P., Lister, G., Efendi, J. and Syafi'i, M.A., 2016. Crustal strain partitioning and the associated earthquake hazard in the eastern Sunda-Banda arc. *Geophysical Research Letters*, 43(5), pp.1943-1949.

Lipman, P. W., 1997. Subsidence of ash-?ow calderas: relation to caldera size and magma-chamber geometry, *Bull. Volcanol.*, 59, 198–218.

Magni, V., 2019. The effects of back-arc spreading on arc magmatism. *Earth and Planetary Science Letters* 519 (2019) 141-151.

McCaffrey, R. and Nabelek, J., 1984. The Geometry of Back Arc thrusting along the Eastern Sunda Arc, Indonesia; Constraints from Earthquake and Gravity Data. *Journal of Geophysical Research, Vol. 89, No. B7, pages 6171-6179*, July 10.

McCaffrey R, 1988. Active tectonics of the eastern Sunda and Banda arcs. J Geophys Res 93:15163–15182.

Mercier-Langevin, Patrick., Gibson, Harold L., Hannington, Mark D., Goutier, Jean., Monecke, Thomas., Dubé, Benoît., Houlé, Michel G, 2014. "A Special Issue on Archean Magmatism, Volcanism, and Ore Deposits: Part 2. Volcanogenic Massive Sulphide Deposits Preface". *Economic Geology.* 109 (1): 1–9. doi:10.2113/econgeo.109.1.1

Purwandono, A.F., Bonte, D., Utami, P. and Pramuwijoyo, S., 2019. Tectonic and compositional variation in Flores Island, Indonesia: implication for volcanic structure and geothermal occurrences. *European Geothermal Congress 2019. Den Haag, The Netherlands, 11-14.*

Sarmili, L., Aryanto, Noor C.D., Halbach, P., Pracejus, B., Rahders, E., Susilo, J., Hutabarat, J. Djohor, S. D., Makarim, S., Purbani, D., Kusumah, G., and Mubandi, A., 2003. Low Temperature Hydrothermal Komba Mountain Complex Waters, Flores Sea, Indonesia. In: *Proceedings of the Forum for Research and Development of Energy and Mineral Resources, Jakarta.*

Sarmili, L., Halbach, P., Pracejus, B., Rahders, E., Burhanuddin, S., Makarim, S., Purbani, D., Kusumah, G., Soesilo, J., dan Hutabarat, J., 2004. A New Prospect in Hydrothermal Mineralization of the Baruna Komba Submarine Volcano in Flores-Wetar Sea, East Indonesia. In: *Bulletin of Marine Geology*, 19 (1): p. 19-26.

Sarmili, L. and Suryoko, M.A., 2012. The Formation of Submarine Baruna Komba Ridge on Northwest Flores Waters in relation to low anomaly of marine magnetism. *Bulletin of Marine Geology, Vol. 27, No. 1,* December 2012, pp. 67-75.

Sarmili, L., Widiatmoko, H.C., Mustafa, M.A., Kamiludin, U., Aryanto, N.C.D., 2013. Laporan Penelitian Sumberdaya Mineral Kelautan Perairan Sangeang, Sumbawa Nusa Tenggara Timur, Puslitbang Geologi Kelautan Bandung, *Unpublish Report.*

Sarmili, L., and Troa, R.A., 2014. The occurrence of faults and their relationship to the formation of submarine volcanoes on Komba Waters, East Nusa Tenggara, *Jurnal Geologi Kelautan, vol. 12, no. 1, 55-64* (in Bahasa).

Sarmili, L., and Hutabarat., J., 2014. Indication of Hydrothermal Alteration Activities Based on Petrography of Volcanic Rocks in Abang Komba Submarine Volcano, East Flores Sea. *Bulletin of the Marine Geology*, 28 (2): 51-60.

Silver, E.A., Reed D., McCaffrey R., Joyodiwiryo, Y., 1983. Back-arc thrusting in the eastern Sunda arc, Indonesia, a consequence of arc-continent collision. *J. Geophys Res* 88:7429–7448.

Tate, G.W., McQuarrie, N., van Hinsbergen, D.J., Bakker, R.R., Harris, R. and Jiang, H., 2015. Australia going down under: Quantifying continental subduction during arc-continent accretion in Timor-Leste. *Geosphere*, 11(6), pp.1860-1883

Tikku, A.A., 2011. A Revision to the Tectonics of the Flores Back-Arc Thrust Zone, Indonesia. *American Geophysical Union, Fall Meeting 2011*, abstract id. T51A-2304.

Wensink, H., 1994. Paleomagnetism of rocks from Sumba: tectonic implications since the late Cretaceous. Journal of Southeast Asian Earth Sciences, 9(1-2), pp.51-65.