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The characteristics and morphology of columnar dacite in Tawau, Sabah

Elvaene James[1,2,*], Hennie Fitria W. Soehady Erfen[3], Azman A. Ghani[2], Angela Vidda Chuwat[4], Gerald Eko Ejiga[2]

[1] Dept. of Geoscience, Faculty of Earth Science, University Malaysia Kelantan, 17600 Jeli, Kelantan, Malaysia
[2] Department of Geology, Faculty of Science, University of Malaya, 50603 Kuala Lumpur, Malaysia
[3] Faculty of Science & Natural Resources, University Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia
[4] School of Physics, University Sains Malaysia, 11800 Penang, Malaysia
* Corresponding author, e-mail: Elvaene_anne@yahoo.com

Abstract: The occurrence of columnar jointing is commonly associated with volcanic rocks and a rapid cooling environment. We recently discovered well-preserved columnar dacite on the road cutting slope in the eastern part of Tawau town, Sabah. This paper briefly describes the occurrences and morphology of columnar dacite in the study area. Columnar dacite exhibits entablature feature since it has thinner and chaotic columns. The hexagon side dominates the columnar joints with minor pentagons to heptagon sides. Columns for dacite are much smaller compared with columnar basalt Tawau. The formation of columnar joints was influenced mainly by external fluid where the water flow on top of the cooling lavas makes it cool rapidly.

Keywords: columnar dacite, entablature, Tawau, rapid cooling

Abstrak: Kejadian kekar turus biasanya berasosiasi dengan batuan volkanik dan persekitaran yang cepat menyejuk. Penemuan terbaru dasit turus yang terpelihara secara baik telah dijumpai pada cerun pemotongan jalan raya yang terletak di bahagian timur bandar Tawau, Sabah. Kajian ini menjelaskan serba sedikit berkaitan dengan kejadian dan morfologi dasit turus di kawasan kajian. Dasit turus menunjukkan ciri-ciri '*entablature*' memandangkan ianya mempunyai turus yang lebih nipis dan tidak teratur. Kekar turus lebih didominasi oleh sisi hexagon selain turut menunjukkan sisi pentagon ke heptagon. Turus untuk dasit adalah lebih kecil jika dibandingkan dengan turus basalt di kawasan Tawau. Formasi kekar turus lebih banyak dipengaruhi oleh cecair luaran memandangkan air yang mengalir pada bahagian atas lava yang sedang menyejuk boleh mengakibatkan penyejukkan cepat.

Kata kunci: dasit turus, entablature, Tawau, penyejukan cepat

INTRODUCTION

The occurrences of columnar basalt in Tawau, Sabah is considered as a fascinating and spectacular scenery that attracted many tourists to visit this area. Columnar jointing is not usual; however, it does occur around the world with different rock types. In East Malaysia, columnar basalt are exposed in few locations such as Tawau, Tatau and Kapit (Lim, 1988; Nur Iskandar, 2006; Sanudin *et al*., 2010; Moul & Noweg, 2018). Unlike columnar basalt in Tawau, the exposure of columnar jointing in Sarawak is not vast. Around the world, only a few places report the exposures of columnar jointing that consists of felsic volcanic rocks such as St. Mary's Island, India (columnar rhyolite; Melluso *et al*., 2009), Atsumi Japan (columnar dacite; Goto & Tsuchiya, 2004) and Papuk Geopark, Croatia (columnar rhyolite; Balen & Petrinec, 2014). Usually, columnar jointing is associated with igneous bodies, which can be divided into columns and a network of polygonal fractures (Hetényi *et al*., 2012). The fractures are formed during the cooling-induced contraction of lava which leads to hydrothermal fluid circulation (Lamur *et al*., 2018). Recently we discovered an outcrop of columnar dacite on the road cutting near the Tawau town area. The columnar dacite has different morphology compared to columnar basalt in Tawau. This paper will briefly describe the occurrences and morphology of columnar dacite.

GEOLOGICAL SETTING

Sabah is located in the northern part of Borneo and is considered part of the Eurasian Plate or Sundaland Block (McCaffrey, 1996; Simon *et al*., 1999; Hall, 2012). Sabah basement rocks consists of the Mesozoic crystalline basement (Hutchison, 1988) and overlain by a Cenozoic sedimentary rock (Hall, 2013). In the Early Miocene, a collision between northern Borneo and the South China continental margin led to Sabah orogeny and ceased the subduction of the Proto-South China Sea (Rangin *et al.*, 1990; Hall, 1996; Hutchison, 1996; Hall & Wilson, 2000; Hutchison *et al*., 2000). During the Late Miocene, plutonic magmatism started to intrude into the Crocker Formation to form Mount Kinabalu (Cottam *et al*., 2010; Hall, 2012) due to extensional thinning of the crust during the Early Neogene (Hall, 2013). Cottam *et al*. (2010) suggested that the forming of plutonic intrusion during the Late Miocene is not related to subduction.

The occurrences of volcanic rocks are mainly focusing on the eastern part of Sabah. Semporna Peninsula is divided into Mesozoic oceanic crust, the Middle Miocene volcanic arc, and Plio-Pleistocene volcanic arc (Sanudin *et al*., 1995; Hutchison, 2007). Volcanic rocks in Semporna and Dent Peninsulas are related to the northward subduction of the Celebes Sea (Hall & Breitfeld, 2017). The formation of the Sulu Arc was related to the subduction of the Proto-South China Sea (Rangin & Silver, 1990). The Sulu Arc can be traced onshore on Semporna and Dent Peninsula (Chiang, 2002) and extended westward of the Semporna Peninsula towards the Zamboanga Peninsula (Garwin *et al*., 2005). Southeast Sulu Sea volcanic rocks characterized by N-MORB/island arc tholeiite (IAT) transitional features, and island arc tholeiitic (Spadea *et al*., 1991, 1996). However, calc-alkaline lavas features are dominant in the north Sulu Sea (Spadea *et al*., 1991, 1996). Neogene volcanism occurs across Tawau, Kunak, and Semporna on the Semporna Peninsula (James *et al*., 2019). Macpherson *et al*. (2010) explained mantle resembling Ocean Island Basalt (OIB) might occur in the Semporna Peninsula, throughout the Sulu Arc and the South China Sea. However, the subduction-related signature is more dominant in Semporna Peninsula volcanic rocks (James *et al*., 2019). Volcanic rock at other places such as Kunak shows features of MORB (James *et al*., 2019). Trace elements geochemical on subduction related volcanic rocks from Semporna shows mixture tectonic significance of island arc and plate margin basalt, while OIB-like and MORB volcanic rocks fall under continental setting (James *et al*., 2019). The study area is located in Tawau, southeast of northern Borneo (Figure 1A). In the Tawau area, most eruptions occurred through cinder cones (Macpherson *et al*., 2010). Olivine basalt at Taman Bukit Tawau, Tawau, is considered the youngest phase of magmatism, which shows the age of Pleistocene based on Thermoluminescence age dating (Takashima *et al*., 2005) and zircon U-Pb dating (Yi-Ju, 2018). The occurrence of olivine basalt may be formed as a monogenetic volcano as it came up from a deep-seated magma reservoir (Takashima *et al*., 2005). Zircon U-Pb

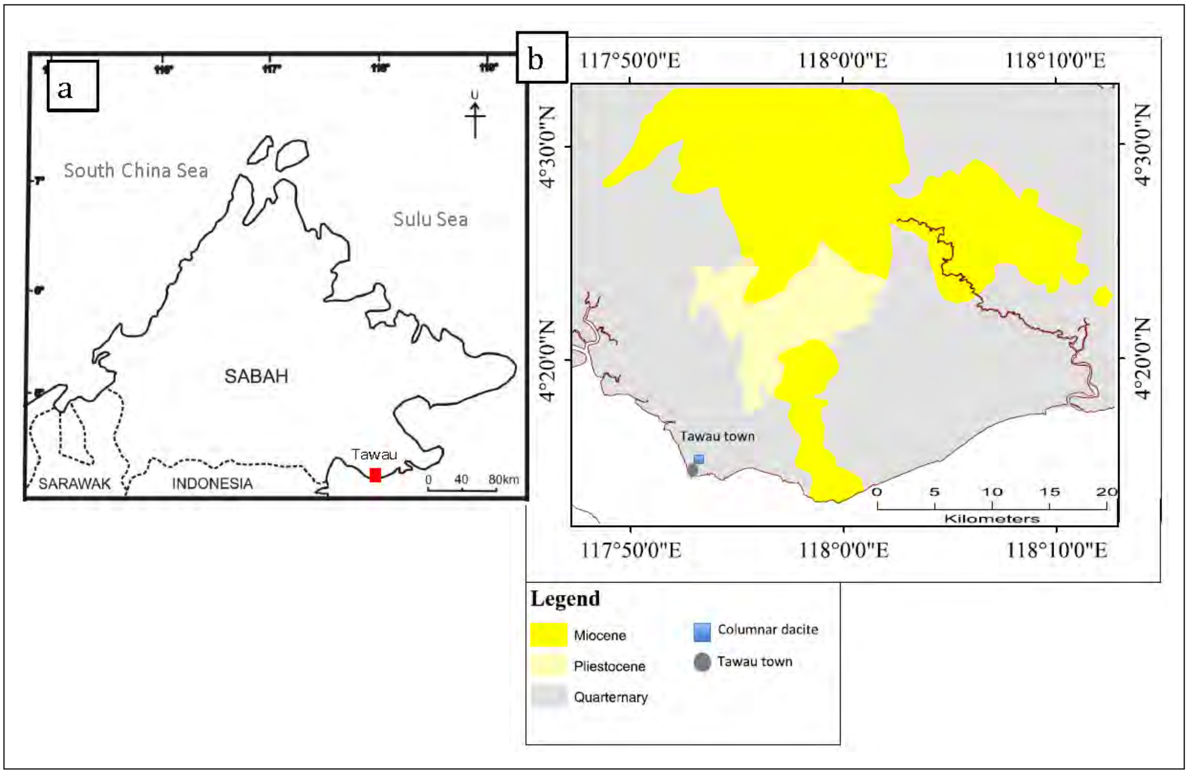

Figure 1: (A) Satellite image of Tawau located in southeastern of Sabah, East Malaysia. Figure taken from Google map. (B) Locations of columnar joints in Tawau, Northern Borneo.

dating shows that the age of columnar dacite is around 9.26 ± 0.26 Ma and indicates magmatic origin (James & Ghani, 2019).

OCCURRENCES, MORPHOLOGY, FORMATION AND FACIES OF COLUMNAR JOINTS

The outcrop of columnar dacite is exposed at the roadside near the Tawau town area (coordinate: 4°17.873' N, 117°56.727' E) (Figure 1B). The outcrop is covered with vegetation and palm plantation (Figure 2a and overlain by dacitic lavas flow (Figure 2b). The height of the outcrop is around 6 meters, and the width is not more than 20 meters. Columnar joints have two jointing facies which consist of a colonnade with regular columns and near-planar sides and entablature, which have more thinner, less regular columns with a curving side (Spry, 1962; Daniels *et al.*, 2013) and chaotic columns to flow top (Figure 2c). Columnar dacite in the study area shows entablature signatures with thinner and curving columns (James & Ghani, 2018). Columnar jointing dacite is dominated by hexagon shape, with minor occurrences of pentagons to heptagon shape, which also similar to columnar basalt Tawau (Sanudin *et al.*, 2010). The formation of columnar joints is mainly influenced by external fluid which results in highly rapid cooling due to the water flow on top of the lava. Lamur *et al.* (2018) demonstrate that columnar jointing forms well in a solid-state volcanic rocks and further promotes advective cooling in magmatic-hydrothermal environments. Furthermore, a combination of large-scale constitutional supercooling and thermal contraction processes may play essential roles in developing the columnar jointing (Balen & Petrinec, 2014).

PETROGRAPHY

The colour of the dacite is light greyish and slightly weathered on the outer layer surface (Figure 3). Dacite shows fine-grained, aphanitic, and porphyritic textures (Figure 4a). The phenocrysts consist of plagioclase,

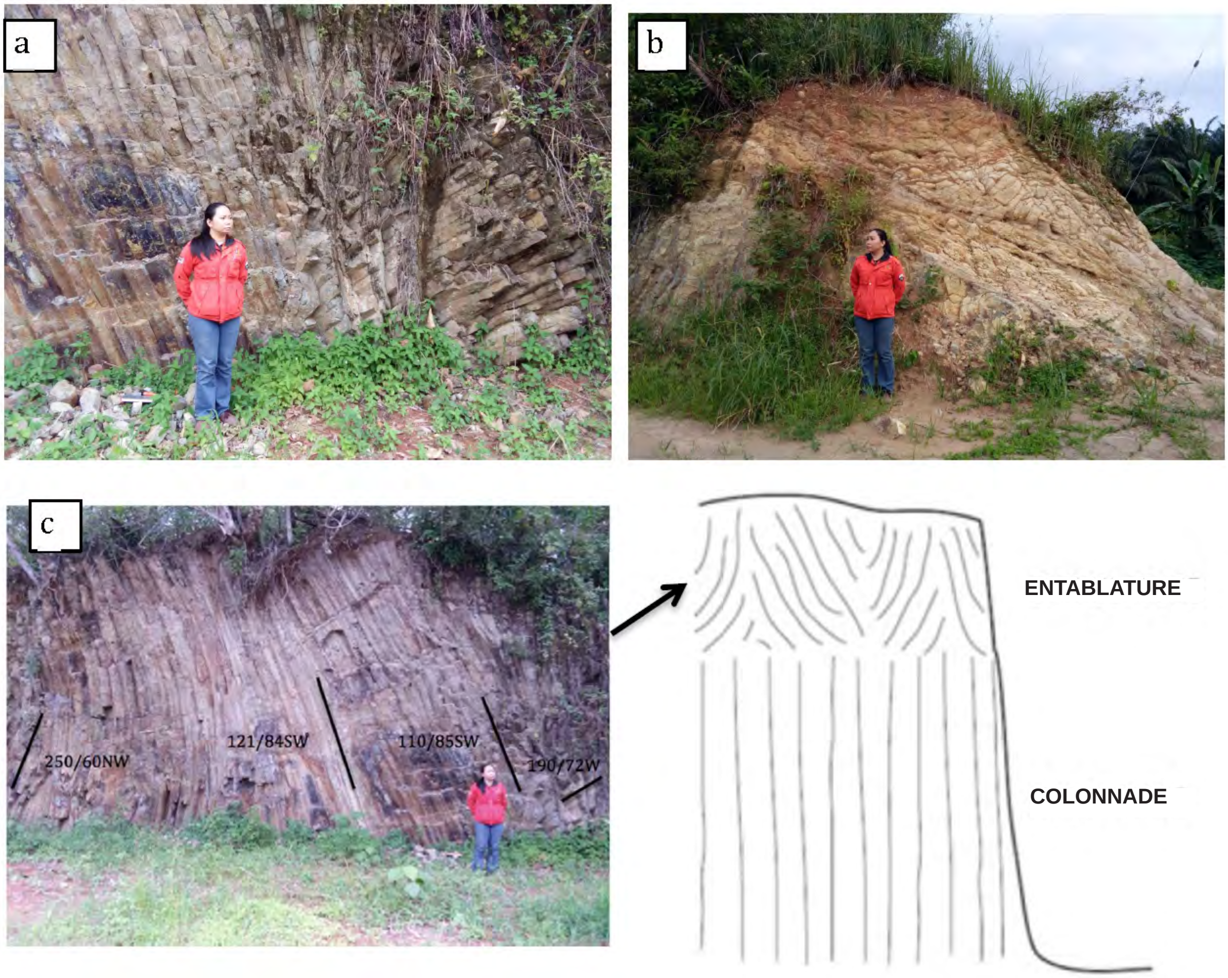

Figure 2: (A) Columnar dacite has characteristic of entablature. (B) Columnar dacite is overlain by dacitic lavas. (C) Top columnar joint (entablature) which similar with columnar dacite. (Illustration after Daniels *et al.*, 2013).

Figure 3: Dacite shows light greyish and slightly weathered.

quartz, hornblende, alkali feldspar, Ti-magnetite, and minor orthopyroxene, enclosed by quartzo-feldspathic groundmass or matrix. Plagioclase is subhedral with sizes ranging from 0.1 – 0.4 mm, and albite twinning is common. Some of the plagioclase showing weak foliation (Figure 4c), zoning (Figure 4d) and alteration to sericite (Figure 4e). Hornblende phenocrysts shows subhedral to euhedral in shape and ranging from 0.2 – 0.6 mm, brown (plane-polarize light), and strongly pleochroic (Figure 4b). Hornblende also shows perfect cleavage exhibits two sets of cleavage with the intersection of approximately 124/56 and has an inclusion of quartz (Figure 4d and 4F). The margin of most hornblende phenocrysts is altered to a secondary mineral such as biotite. Quartz phenocrysts are subhedral to anhedral ranging from 0.1 – 0.15 mm, and some appear to fill up the crack or spaces in plagioclase and hornblende phenocrysts. The groundmass for dacites comprises quartz, alkali feldspar, plagioclase, sericite, and minor iron oxides.

MODE OF FORMATION AND MORPHOLOGY OF COLUMNAR JOINTS

Columnar joints in volcanic rocks were formed during the cooling process of hot lava. The resulting structures usually cut the rock into either quadrangular, pentagonal, or hexagonal prisms (Xia *et al*., 2020). The columnar joints could vary from a few millimeters in diameters to a few meters, while the length could extend up to dozens of meters (Weinberger & Burg, 2019). The formation of these columnar joints could be related to differences in the contraction of the composite rock-forming materials relative to the adjoining parts. The differences in contraction develop as a result of the rapid cooling of the lava, initiating tensile stress, which becomes higher than the maximum stress that the material can withstand before failure, which eventually starts the joints (Pollard & Aydin, 1988). The joint formation occurred from thermal stress resulting from the contraction during the lava's cooling and solidification processes (Pollard & Aydin, 1988). The formation is such that the joints' tip usually follows the solidifying front as the lava cools. As the surface joints form, it propagates inward towards the center of the material in a cyclic manner and leaves behind a trace of the ordering process in a prismatic column formation (Aydin & DeGraff, 1988). Budkewitsch & Robin (1994) and Goehring & Morris (2008) inferred that the columnar joint scaling is such that the column width is inversely proportional to the cooling rate.

COMPARISON BETWEEN COLUMNAR DACITE AND COLUMNAR BASALT IN TAWAU

Columnar basalt is discovered along the Balong River in Tawau. The exposure of columnar basalt does not associate with any types of volcanic rocks in the Semporna Peninsula. The length column for basalt is relatively more significant from half a meter to almost 1 meter (Sanudin *et al*., 2010) (Table 1). On the contrary, the length of the columnar dacite is less than 25 cm. It appears that the diameter for columnar basalt is more than twice bigger compared to columnar dacite. Based on the observation in the field, columnar basalt shows a colonnade feature with regular columns and near-planar sides, while columnar dacites exhibit entablature features. Both columns are showing pentagon to hexagon sides.

CONCLUSION

The columnar dacite occurrences in Tawau, Semporna, shed some light on the columnar jointing associated with supercooling magmatic-hydrothermal environments. Even though the vicinity of the study area is surrounded by felsic volcanic rocks, the columnar jointing is only exposed in these small scales. The possibility of finding another columnar jointing of different types of rocks might be possible since columnar basalt occurs in the Tawau area. Based on the characteristics of columnar dacite, it has an entablature signature with thinner and curving columns. Columnar jointing dominated by hexagon sided with minor pentagons to heptagon sides. The columns are much smaller compared with columnar basalt Tawau. The general mineralogy of columnar dacite is consists of fine-grained, porphyritic, and aphanitic textures.

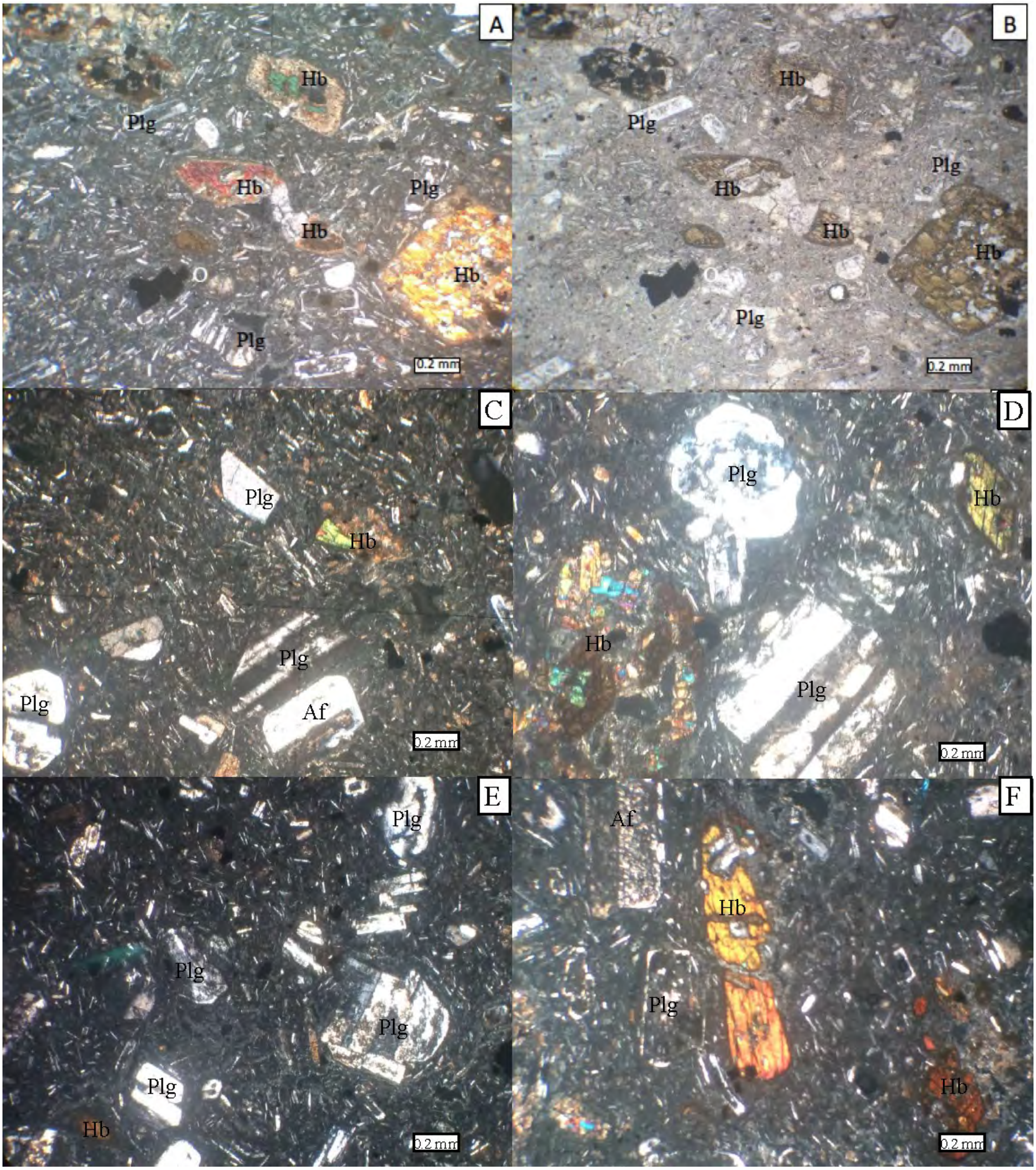

Figure 4: (A) Dacite shows fine-grained, aphanitic, and porphyritic textures. (B) Hornblende phenocrysts showing brown in colour, and strongly pleochroic under the plane polarize microscope. (C) The weak foliation of plagioclase can be seen in dacite. (D) Plagioclase showing zoning in dacite. (E) Some of the plagioclase phenocrysts showing alteration of sericite. (F) Hornblende phenocryst has the inclusion of quartz.

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REFERENCES

Aydin, A. & DeGraff, J. M., 1988. Evolution of polygonal fracture patterns in lava flows. Science, 239, 471–476.

Balen, D. & Petrinec, Z., 2014. Development of columnar jointing in albite rhyolite in a rapidly cooling volcanic environment (Rupnica, Papuk Geopark, Croatia). Terra Nova, 26, 102-110.

Budkewitsch, P. & Robin, P.-Y., 1994. Modelling the evolution of columnar joints. Journal of Volcanology and Geothermal Research, 59(3), 219-239.

Chiang, K. K., 2002. Geochemistry of the Cenozoic igneous rocks of Borneo and tectonic implications. (Unpublished doctoral dissertation). University of London, England.

Cottam, M., Hall, R., Sperber, C. & Armstrong, R., 2010. Pulsed emplacement of the Mount Kinabalu granite, northern Borneo. Journal of the Geological Society of London, 167, 49-60.

Daniels, K. A., Brown, R. J. & Witham, F., 2013. The Formation of Columnar Joints Produce by Cooling in Basalt at Staffa, Scotland. Bulletin of Volcanology, 75, 715.

DeGraff, J. M. & Aydin, A., 1987. Surface morphology of columnar joints and its significance to mechanics and direction of joint growth. Geological Society of America Bulletin, 99, 605–617.

Garwin, S., Hall, R. & Watanabe, Y., 2005. Tectonic setting, geology, and gold and copper mineralization in Cenozoic magmatic arcs of Southeast Asia and the West Pacific. Economic Geology 100th Anniversary Volume, 891-900.

Goehring, L. & Morris, S.W., 2008. Scaling of columnar joints in basalt. Journal of Geophysical Research, 113(B10).

Goto, Y. & Tsuchiya, N., 2004. Morphology and growth style of a Miocene submarine dacite lava dome at Atsumi, northern Japan. Journal of Volcanology and Geothermal Research, 134, 255-275.

Hall, R., 1996. Reconstructing Cenozoic SE Asia. In: Hall, R. & Blundell, D. J. (Eds.), Tectonic Evolution of SE Asia. Geological Society London Special Publication, 106, 153-184.

Hall, R., 2012. Sundaland and Wallacea: geology, plate tectonics and palaeogeography. In: D.J. Gower, J.E. Richardson, B.R. Rosen, L. Rüber & S.T. Williams (Eds.), Biotic Evolution and Environmental Change in Southeast Asia. Cambridge University Press, United Kingdom, 32-78.

Hall, R., 2013. Contraction and extension in northern Borneo driven by subduction rollback. Journal of Asian Earth Sciences, 76, 399-411.

Hall, R. & Wilson, M. E. J., 2000. Neogene sutures in eastern Indonesia. Journal of Asian Earth Sciences, 18(6), 781-808.

Hall, R. & Breitfeld, H. T., 2017. Nature and demise of the Proto-South China Sea. Bulletin of the Geological Society of Malaysia, 63, 61-76.

Hetényi, G., Taisne, B., Garel, F., Médard, E., Bosshard, S. & Mattsson, H. B., 2012. Scales of columnar jointing in igneous rocks: field measurements and controlling factors. Bulletin of Volcanology, 74(2), 457-482.

Hutchison, C. S., 1988. Stratigraphic-tectonic model for Eastern Borneo. Bulletin of the Geological Society of Malaysia, 22, 135-152.

Hutchison, C. S., 1996. Geological Evolution of Southeast Asia. Geological Society of Malaysia, Kuala Lumpur.

Hutchison, C. S., 2007. Geological Evolution of South-East Asia (2nd ed.). Geological Society of Malaysia, Kuala Lumpur.

Hutchison, C.S., Bergman S.C., Swauger, D.A. & Graves, J.E., 2000. A Miocene collisional belt in north Borneo: uplift mechanism and isostatic adjustment quantified by thermochronology. Journal of the Geological Society of London, 157, 783-793.

James, E. & Ghani, A. A., 2018. Golumnar basalt and columnar dacite: A significant geosite in Tawau, northern Borneo. In: Proceedings of Regional Geoheritage Conference (pp. 49). Khon Kaen.

James, E. & Ghani, A. A., 2019. Zircon U-Pb and Hf isotope constraints on the Neogene Semporna Peninsula volcanic rocks and its tectonic implications. Warta Geologi, 45(3), 256-257.

James, E., Ghani, A. A., Asis, J. & Simon, N., 2019. Peranan subduksi tehadap batuan volkanik berusia Neogen di Semenanjung Semporna: Perspektif petrologi dan geokimia. Sains Malaysiana, 48(11), 2473-2481.

Lamur, A., Lavalee, Y., Iddon, F. E., Hornby, A., Kendrick, J. E., von Aulock, F. W. & Wadsworth, F. B., 2018. Disclosing the temperature of columnar jointing in lavas. Nature Communications, 9, 1432.

Lim, P.S., 1988. Geology and Geothermal potential of the Tawau area, Sabah. Geological Survey of Malaysia Annual Report, Malaysia.

Macpherson, C.G., Chiang, K.K., Hall, R., Nowell, G.M., Castillo, P.R. & Thirlwall, M.F., 2010. Plio-Pleistocene intra-plate magmatism from the southern Sulu Arc, Semporna peninsula, Sabah, Borneo: Implications for high-Nb basalt in subduction zones. Journal of Volcanology and Geothermal Research, 190, 25-38.

McCaffrey, R., 1996. Slip partitioning at convergent plate boundaries of SE Asia. In: R. Hall & D.J. Blundell (Eds.), Tectonic evolution of SE Asia. London: The Geological Society of London, Special Publications 106, 3-18.

Melluso, L., Sheth, H. C., Mahoney, J. J., Morra, V., Petrone, C. M. & Storey, M., 2009. Correlations between silicic volcanic rocks of the St Mary's Island (southwestern India) and eastern Madagascar: implication for Late Cretaceous India – Madagascar reconstructions. Journal of the Geological Society London, 166, 283-294.

Moul, E. & Noweg, G. T., 2018. The geology of Upper Baleh River, Kapit, Sarawak. Borneo Journal of Resource Science and Technology, 8(2), 109-116.

Nur Iskandar Taib, 2006. K-rich basalt in the Bukit Mersing area, Third Division, Sarawak. Bulletin of the Geological Society of Malaysia, 56, 79-85.

Pollard, D. D. & Aydin, A., 1988. Progress in understanding jointing over the past century. Geological Society of America Bulletin, 100, 1181-1204.

Rangin, C. & Silver, E., 1990. Geological Setting of the Celebes and Sulu Seas. In: C. Rangin, E.A. Silver & M.T. von Breyman (Eds.), Proceeding of Ocean Drilling Program 124 (pp. 35-42). Texas: Initial Reports.

Rangin, C., Bellon, H., Benerd, F., Letouzey, J., Muller, C. & Sanudin, T., 1990. Neogene arc-continent collision in Sabah, Northern Borneo (Malaysia). Tectonophysics, 183, 305-319.

Sanudin, T., Shariff, A.K.O. & Majeed, M.F., 1995. Middle Miocene volcanic sequence in Eastern Sabah. Borneo Science, 1(1), 9-27.

Sanudin, T., Baba, M. & Ismail, A. R., 2010. Geological heritage features of Tawau volcanic sequence, Sabah. Bulletin of the Geological Society of Malaysia, 52, 67-73.

Simons, W. J. F., Ambrosius, B. A. C., Noomen, R., Angermann, D., Wilson, P., Becker, M., Reinhart, E., Walpersdorf, A. & Vigny, C., 1999. Observing plate motions in SE Asia: Geodetic results of the GEODYSSEA project. Geophysical Research Letters, 26, 2081-2084.

Spadea, P., D'Antonio, M. & Thirlwall, M.F., 1996. Source characteristics of the basement rocks from the Sulu and Celebes Basins (Western Pacific): Chemical and isotopic evidence. Contributions to Mineralogy and Petrology, 123(2), 159-176.

Spadea, P., Beccaluva, L., Civetta, L., Coltorti, M., Dostal, J., Sajona, F., Serri, G., Vaccaro, C. & Zeda, O., 1991. Petrology of basic igneous rocks from the floor of the Sulu Sea. In: E.A. Silver, C. Rangin & M.T. von Breyman (Eds.), Proceeding of Ocean Drilling Program 124 (pp 251-269). Texas: Scientific Results.

Spry, A., 1962. The origin of columnar jointing, particularly in basalt flows. Australian Journal of Earth Sciences, 8, 191-216.

Takashima, I., Nazri, A. A., Siong, L. P., Koseki, T., Mouri, Y., Nasution, A. & Sucipta, I. G. B. E., 2005. Precise Thermoluminescence Dating for heat source volcanic rocks and alteration products at the Tawau Geothermal area, Sabah. Malaysia. Turkey: Proceedings World Geothermal Congress.

Weinberger, R. & Burg, A., 2019. Reappraising columnar joints in different rock types and settings. Journal of Structural Geology, 125, 185-194.

Xia, Y., Zhang, C., Zhou, H., Chen, J., Gao, Y., Liu, N. & Chen, P., 2020. Structural characteristics of columnar jointed basalt in drainage tunnel of Baihetan hydropower station and its influence on the behavior of P-wave anisotropy. Engineering Geology, 264, 105304.

Yi-Ju, H., 2018. Age and geochemical characteristics of Neogene volcanic rocks from SE Sabah, Borneo. (Unpublished Master dissertation). National Taiwan University, Taiwan.

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