INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Syn-sedimentary Mafic Volcanics in the Eocene Coal-bearing Tanjung Formation, Senakin Peninsula, South Kalimantan (Borneo), Indonesia

Tim A. Moore[1,2,3], Mike C. Friederich[4], Jessica Trofimovs[2], Ferian Anggara[5,6], and D. Hendra Amijaya[5]

[1]International Research Centre for Coal Geology, School of Resources and Geoscience, China University of Mining and Technology, Xuzhou, China
[2] School of Earth and Atmospheric Sciences, Queensland University of Technology, Brisbane, QLD, Australia
[3]Cipher Consulting Pty. Ltd., 6 Stardust Street, Kenmore, QLD, Australia
[4]Independent Consultant, PO Box 636, Kenmore, QLD, Australia
[5]Department of Geological Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia
[6]Unconventional Geo-resources Research Group, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia

Corresponding author: tmoore@ciphercoal.com
Manuscript received: September, 03, 2019; revised: December, 27, 2019; approved: January, 23, 2020; available online: April, 23, 2020

Abstract - Syn-sedimentary mafic volcanism has been identified within a rift setting (Eocene Tanjung Formation) in the Senakin Peninsula, southeast Kalimantan. Fine-grained, dark-grey basalt lava occurs and has prominent vertically oriented columnar jointing. Petrographically, the basalt is composed of small euhedral pyroxene, olivine, and lath-shaped plagioclase phenocrysts within a very fine-grained dark coloured groundmass. A volcaniclastic unit also occurs and in outcrop has sharp contacts with underlying and overlying sedimentary mudstone. The unit is composed of cm-scale clasts of fine-grained to glassy textured basalt with vesicles of varying size and abundance. Euhedral pyroxene phenocrysts are observed within the clasts, although some with overprinting alteration. Palagonite alteration on the margins of some clasts is noted and is indicative of mafic composition volcanic material that has come into contact with sea water. Presence of bivalve and coral fragments in sandstone and mudstone underlying the volcaniclastic unit indicates emplacement into a marine environment. Core description from 33 locations over an 18 km transect length show that both the basalt and volcaniclastic sediments are extensive throughout the east Senakin area. Lithological relationships and compositional similarities between the basalt and volcaniclastic sediment suggest they are related and were contemporaneous with sedimentation within the Tanjung Formation. It is proposed that the basalt unit is designated the Tanah Rata Basalt Member of the Tanjung Formation. If a wider distribution occurs for the volcaniclastic unit it is proposed that it is termed the Gumbil Volcaniclastic Member of the Tanjung Formation.

Keywords: Tanjung Formation, Kalimantan, Eocene, Mafic volcanism, Volcaniclastic

© IJOG - 2020. All right reserved

How to cite this article:
Moore, T.A,. Friederich, M.C., Trofimovs, J., Anggara, F., and Amijaya, D.H., 2020. Syn-sedimentary Mafic Volcanics in the Eocene Coal-bearing Tanjung Formation, Senakin Peninsula, South Kalimantan (Borneo), Indonesia. *Indonesian Journal on Geoscience*, 7 (1), p.65-85. DOI: 10.17014/ijog.7.1.65-85

Introduction

The geology of Southeast Asia is nothing, if not complex. The pre-Cenozoic geology is a juxtaposition of Mesozoic and Palaeozoic volcanics and metasediments; understandably the origin and provenance of these sequences have been the focus of much study (Metcalfe, 1991, 2001, 2011; Hutchison, 2008, 2014; Hall, 2012). The tectonics, too, can only be described

as exciting. Subduction, obduction, rifting, and thrusting - the region often resembles a shattered plate more than solid, continuous rock. Volcanic/ magmatic activity has also played an important role throughout SE Asia's geological history, starting in the Permian and continuing until the present (Katili, 1968; Rock *et al.*, 1982; Carlile and Mitchell, 1994). Carlile and Mitchell (1994) identified 15 Cretaceous and Cenozoic magmatic arcs in the archipelago with a total land extent of 15,000 km. Not included in these belts are Eocene volcanic rocks found in scattered locations in SE Kalimantan, where they are spatially associated with Mesozoic accretionary terranes in the Meratus Range and Pulau Laut, and with Eocene sedimentary sequences in adjacent basins. However at that time, relatively little was known about these Eocene volcanic rocks in SE Kalimantan.

The Cenozoic geological history is no less thrilling and can arguably be termed the age of the organics for the region. Notably, Indonesia was one of the first places in the world where petroleum was exploited (Poley, 2010), all sourced from Cenozoic sediments. Although Indonesia ceased to be a net petroleum exporter in 2003, it is still the largest producer in Southeast Asia and a significant world player. Coal too is common through out Southeast Asia, but is most prevalent in Indonesia and thus it is not surprising that Indonesia is the largest thermal coal exporter in the world. Indonesia's coal resources are vast, though dominantly located in eastern Kalimantan and southern Sumatra (Lucarelli, 2015; Moore, 2015; Friederich *et al.*, 2016; Friederich and van Leeuwen, 2017).

Practically, all Cenozoic sedimentary basins in SE Asia initiated as rifts. Basins within Indonesia, in particular, are characterized by the initial deposition of rift sequences, from the Middle to Late Eocene (Cloke *et al.*, 1999; Doust and Noble, 2008; Pubellier and Morley, 2014). There is variation in the sedimentology between basins, but in almost all cases initial deposits are coarse- grained, often conglomeratic and grade conformably upwards into sandstones interbedded with siltstones and mudstones (Argakoesoemah, 2017). These sediments progressively become more interbedded with organic-rich intervals and then coal beds are often present that can be of considerable thickness (>3 m) and lateral extent (>20 km) (Moore and Ferm, 1988, 1992; Panggabean, 1991; Ruppert and Moore, 1993; Friederich *et al.*, 1999; Witts *et al.*, 2012; Moore, 2015; Friederich and van Leeuwen, 2017). These Eocene age coal beds are thought to mark the fresh water line where peat formed along a widespread coastal plain (Moore, 1990; Friederich *et al.*, 1999). Sediments overlying the main coal seams are mostly mudstones that eventually grade into marls and carbonates. The sequence is interpreted as transgressive, initially high energy freshwater fluvial at the base, to a broad coastal plain setting bordered by brackish water embayments, to shallow marine environments, then finally full open marine environments at the time of maximum subsidence (Doust and Noble, 2008; Friederich *et al.*, 1999, 2016).

The Tanjung Formation (and its lateral equivalent, the Kuaro Formation) is one such Eocene rift sequence, deposited within the Barito, Asem Asem, and Pasir Basins of southeast Kalimantan. Although the Tanjung Formation has been exploited for both petroleum and coal, there have only been relatively few studies of its sedimentary sequence (Tjia, 1970; Siregar and Sunaryo, 1980; Ruppert and Moore, 1993; Satyana *et al.*, 2001; Witts *et al.*, 2012). Although there have been no detailed published studies on the clastic sediments located in or around the Senakin Peninsula (Figure 1) there is nonetheless detailed proprietary data from coal exploration drilling (Anonymous, 1984). For this study, subsurface (from drill hole) and surface mine exposure data were collected. An immediate observation was that there appeared to be both volcanics and volcaniclastic sediments within the Tanjung Formation. Febriadi (2010) reported the presence of basalt within the lower part of the Tanjung Formation, but there were no other published reports or descriptions of

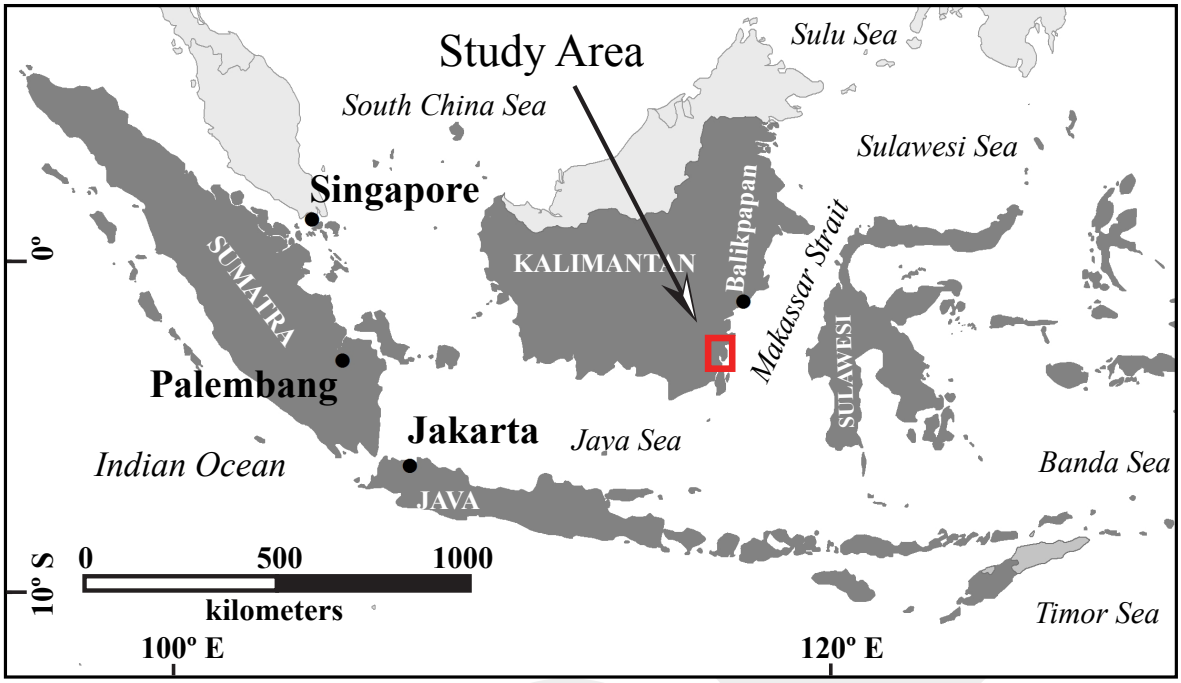

Figure 1. Indonesia index map showing study location.

the volcanics and volcaniclastic sediments at this location. Thus, it is the objectives of this paper to:

1. Describe and delineate the basalt and volcaniclastic deposits in the Senakin Peninsula,
2. Determine the timing of the volcanic sequences within the context of the deposition of the Tanjung Formation sediments,
3. Determine how the volcaniclastic units were emplaced, and
4. Determine if the volcaniclastic units and the coherent volcanic sequences are genetically related.

Previous Work and General Stratigraphy

It is beyond the objectives of this paper to review all studies that have been conducted on the Tanjung Formation. However, the most significant ones will be briefly covered in order to give context and scope to the present study. Most of the early works on the Tanjung Formation were through mapping (Sigit, 1959, 1963; Tjia, 1970; Baumann, 1972; Gerard and Oesterle, 1973; Hashimoto, 1973; Hashimoto and Koike, 1973) and regional studies (Van Bemmelen, 1949; Hamilton, 1979). A few of the later studies focused on aspects of the sedimentology (Tjia, 1970; Hashimoto, 1973; Moore and Ferm, 1988, 1992; Ruppert and Moore, 1993) or petroleum potential (Siregar and Sunaryo, 1980; Bon *et al.*, 1996). Most, though not all, were located in the Barito Basin, on the western side of the Meratus Mountains. More recent studies have also examined the Tanjung Formation from the perspective of petroleum, structure or coalbed methane potential (Satyana *et al.*, 2001; Heryanto, 2009; Simatupang and Amarullah, 2010; Won *et al.*, 2018).

Witts *et al.* (2011, 2012) presented by far the most detailed descriptions of the Tanjung Formation along exposed sections in the eastern side of the Barito Basin. Palynomorph and foraminifera indicates that the Tanjung Formation in the Barito Basin was deposited between the late Middle Eocene to late Early Oligocene. Sedimentologically, the base of the Tanjung Formation in the Barito is composed of coarse-grained sandstones and conglomerates, which are progressively interbedded with finer-grained mudstones and siltstones upwards along with occasional coal beds. Witts *et al.* (2011, 2012) interpreted the lower, coarse,

sediments as a fluvial/alluvial braided-plain, which is consistent with previous interpretations (Kusuma and Darin, 1989; Friederich *et al.*, 1995; Satyana *et al.*, 1999; Kupecz *et al.*, 2013). The overlying finer-grained sediments, including coal, are interpreted as a fluvial-tidal/coastal floodplain within an estuarine setting (Friederich *et al.*, 1999; Witts *et al.*, 2012); these in turn are overlain by marl and limestone, which are interpreted to be shallow marine (Witts *et al.*, 2012).

It is noteworthy, that only a few studies have noted volcanic-related units within the Tanjung Formation (Moore, 1990; Lumadyo *et al.*, 1993; Ruppert and Moore, 1993; Febriadi, 2010). These will be discussed later within the context of the results presented in this paper.

Although only one published paper notes the occurrence of basalt in the Tanjung Formation in the eastern area of the Senakin Peninsula (Febriandi, 2010), it is in fact fairly well delineated from drill holes and outcrop mapping from coal mine exploration. Moreover, a blue-green volcaniclastic unit often described as 'tuffaceous' is commonly identified in drill cores and mine faces in the same area. Both basalt and the blue-green volcaniclastic units have substantial lateral continuity.

The stratigraphy in east Senakin is shown in Figure 2. The basement is generally pre-Cenozoic altered or weathered igneous rock. Coarse to fine sandstone is in contact with the weathered basement and these grade upwards into mudstones. In some cases, the coal is in direct contact with the basement. Throughout much of the area covered by Figure 3, the mudstone or sandstone may be overlain by blue-green volcaniclastics. In most cases, directly overlying the volcaniclastics is more mudstone, which is then overlain by the thick (>5 m) Senakin coal seam. This is the main coal seam in the area and is the mining target. The seam has a high degree of lateral continuity (>20 km). In the southwest part of the section, there are basaltic units underlying and cross cutting the main Senakin coal seam. The thickness between the top of the basement

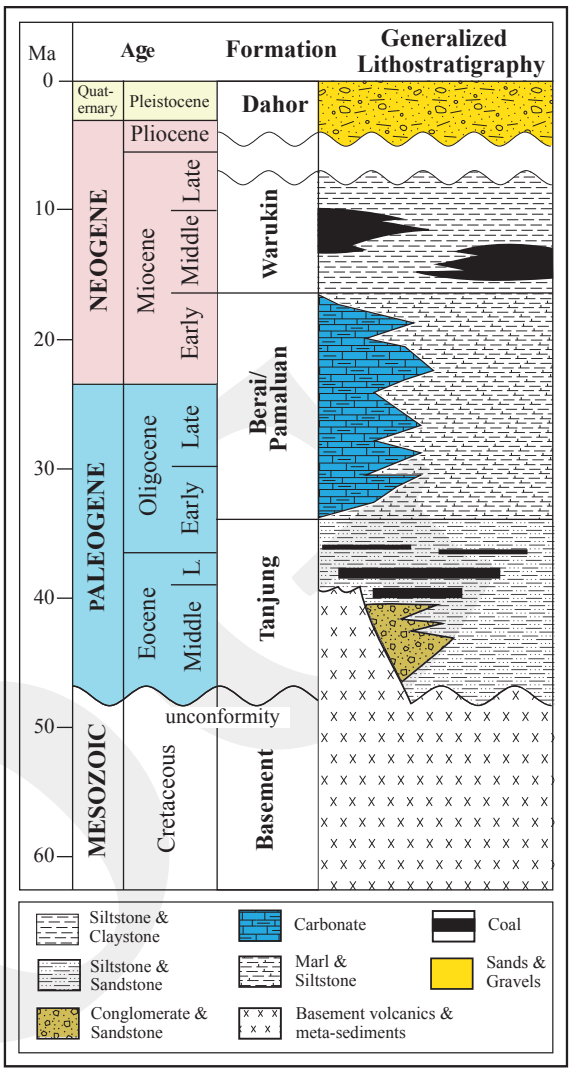

Figure 2. Generalized stratigraphic section of southeast Kalimantan (modified from Moore, 2015).

and bottom of the main Senakin coal seam varies from zero to at least 35 m. Overlying the main Senakin coal seam is mostly mudstone with common carbonate (ankerite/siderite) nodules and lenses, though some thin (<5 m) laterally discontinuous (<3 km) sandstones do occur. Also, in the southern part of the section, a rider coal seam of less than 2 m is present about 5 - 10 m above the main Senakin coal bed. A greenish, waxy layer containing marine fossils is also reported near the top of the mudstone unit. The mudstone unit above the main Senakin coal bed varies in thickness from 2 m to over 35 m. An extensive blue-green volcaniclastic layer occurs overlying the predominantly ankeritic/sideritic

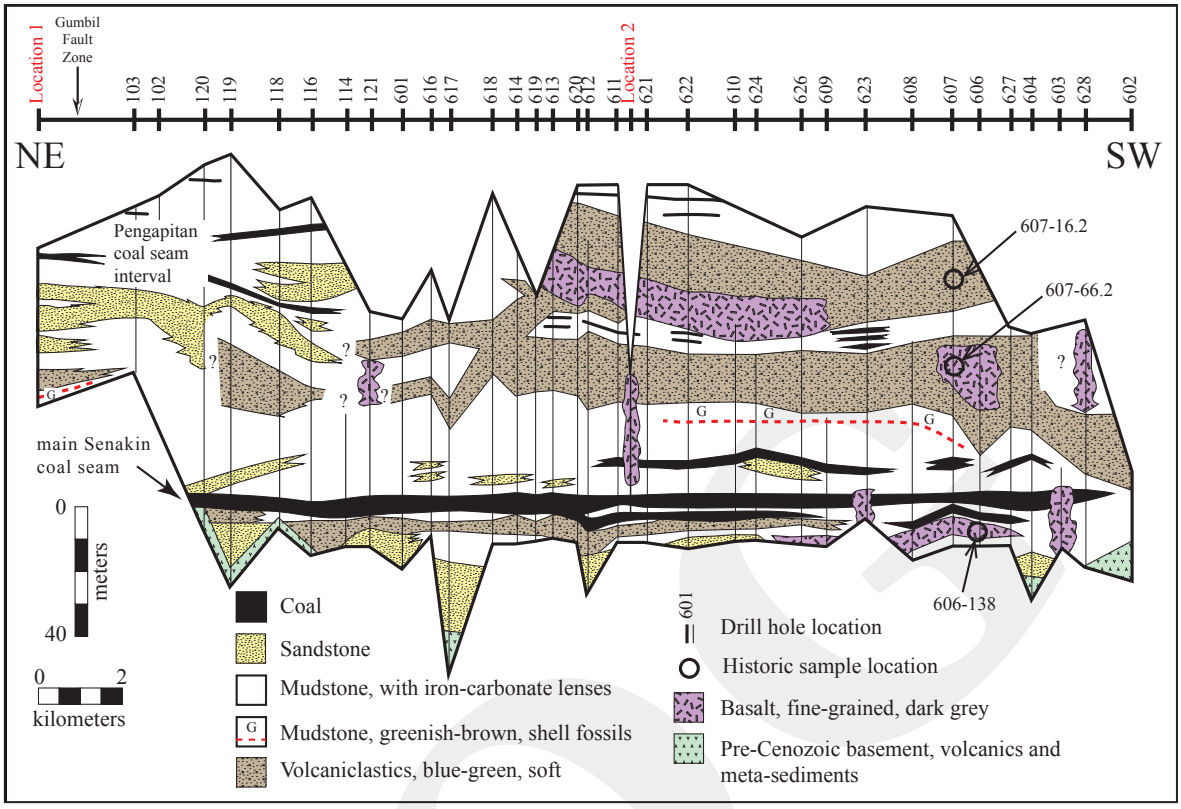

Figure 3. Cross section through east Senakin showing sampling Locations 1 and 2. Datum: Top of Senakin coal seam.

mudstone unit. This layer is almost 40 m thick in places, though it is much thinner in the northeast (2-3 m). The unit apparently occurs in two layers in the south west part of the area with coals, equivalent to the Pengapitan coal seam. The Pengapitan coal occurs between 40-65 m above the main Senakin coal bed. Dark grey basalts, with chlorite and calcite on joint surfaces also occur through out the volcaniclastic layer, though the basalt seems to be mostly in the south west area of the section. From mining data, the basalts have also been noted in close stratigraphic proximity (10 m) overlying the main Senakin coal seam.

Structurally, the Senakin Peninsula is an anticline with an axis oriented approximately north-south. Pre-Cenozoic basement is exposed along the anticline axis. The anticline plunges in both directions and the basement is thus surrounded by the unconformably overlying the Eocene Tanjung Formation and younger strata. Dips of the Tanjung Formation range from less than 10º to greater than 35º in some cases.

Sample Locations And Methods

Two sites were sampled in east Senakin; the first site is located north of the Gumbil Fault zone at the northeastern end of the cross section (2.83146ºS/116.28221ºE) (Figures 3 and 4). At this location the blue-green volcaniclastic was described and sampled. The second location (-2.93699º/116.26169º) is to the south of the Gumbil fault by about 13 km (Figures 3 and 4). At this location a thick section of dark grey, fine-grained basalt was described and sampled. In addition to these sample locations, 3 samples from 2 cores were previously collected and described (T.A. Moore, 1992, *unpublished data*). The locations of these samples are shown in Figure 3.

At both locations exposures were part of reasonably fresh faces as a result of mining. To ensure the best samples, the exposures were dug back to what appeared to be fresh rock. Nevertheless, weathering may have affected some samples. After

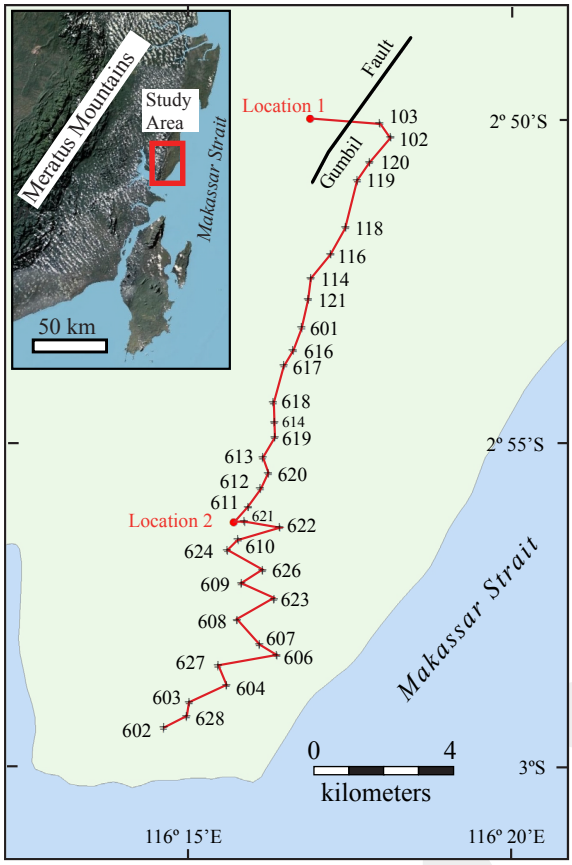

Figure 4. Position of cross section, drill holes, and sampling locations in the east Senakin Peninsula.

collection, samples were triple sealed in thick plastic bags and initially shipped to Universitas Gadjah Mada in Yogjakarta, Indonesia and then repacked and shipped to the laboratories at Queensland University of Technology, in Brisbane, Australia.

To assess textures and mineral content, thin sections were made from selected samples from both locations. Because of the friability, most samples were vacuum impregnated with epoxy resin before cutting and mounting on slides. Each slide was constructed and ground in the usual way for thin sections.

Results

Pit 14 - Location 1

The section for Pit 14, from here on referred to as Location 1, is an opencast mine high wall. The target for the mine is the main Senakin coal seam. Over 100 m of section, the coal was exposed in the mine high wall, starting at the top of the main Senakin coal seam but only 48.3 m of section was measured in detail (Figure 5). The blue-green volcaniclastic layer was identified about 40 m above the top of the main Senakin coal seam and the detailed measured section was initiated a few meters below that interval. Table 1 gives the lithological descriptions of the section and Figure 5 is a graphic log noting the location of the samples taken.

The distinguishing characteristic of the mudstone underlying the volcaniclastic unit is fossil bearing iron-carbonate (ankerite/siderite?) layers (Figure 6a). A fossiliferous zone has been identified elsewhere in multiple cores at about the same stratigraphic position; that is, about 1- 10 m below the volcaniclastic unit (Figure 3). The contact between the bottom of the blue-green volcaniclastic layer and the mudstone is sharp, but does not appear to be erosional (Figure 6b).

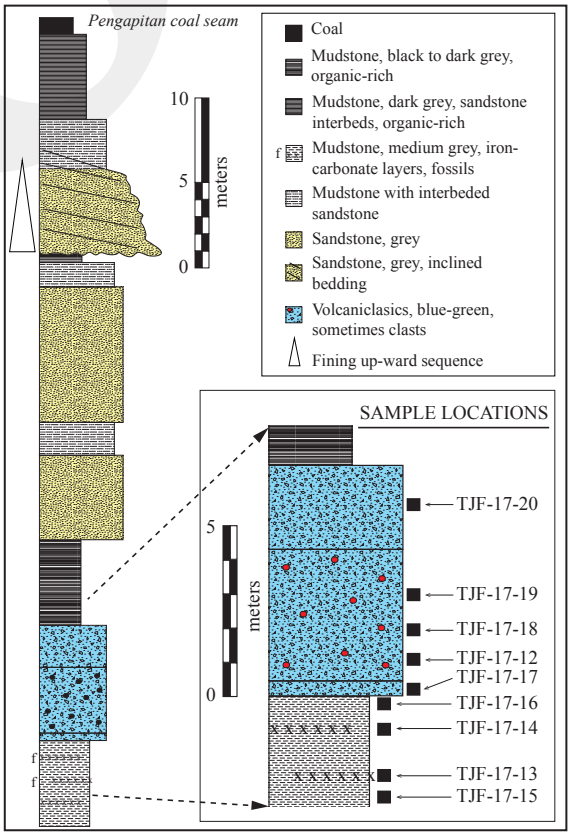

Figure 5. Graphic log of Location 1 showing lithology variation and sample locations.

Table 1. Lithological descriptions for Location 1 (-2.83146°/116.28221°; ±6m). Date of sample collection: 15 December 2017

Lithology	Thickness (m)	Elevation amsl (m), base of unit	Comments	Corresponding Photograph
Coal	1.0	79.3	Top of measured section; Pengapitan coal seam	
Mudstone with sandstone interbeds and organic material	5.0	74.3	Interbedded with sandstone	Figure 9b
Mudstone, dark grey with sandstone interbeds	3.0	71.3	Interbedded sandstone (5-15 cm) and mudstone, inclined and conformable with underlying sandstone, overall fining upwards	Figure 9
Sandstone, well bedded	5.0	66.3	Inclined bedding (5-20 cm thk), slightly erosional base, fining upwards	Figure 9
Mudstone, black, with organic material	0.5	65.8	Organic material parallel to subparallel to bedding	
Mudstone, dark grey with sandstone interbeds and organic material	1.5	64.3	Sandstone lenses with organic rich mudstone	
Sandstone, bedded	8.0	56.3	Fine- to medium-grained, coarsening upwards	Figure 8
Mudstone, dark grey with sandstone interbeds	2.0	54.3		Figure 8
Sandstone, bedded	5.0	49.3	Bedded sandstone, medium- to fine-grained	Figure 8
Mudstone, black	5.0	44.3	With siderite concretions	Figure 7
Volcaniclastics	2.5	41.8	Blue-green-grey, bedded, 5-10 cm thick; finer grain then unit below. Continuous contact. White mottles through out, soft. Significantly less round inclusions. Top of unit is sharp with the overlying mudstone.	Figures 6d; 7
Volcaniclastics	3.9	37.9	Blue-green-grey, massive (bedding not noted), soft; round inclusions of 1-2 cm, not well sorted and no preferred orientation; and white mottles throughout. Top is continuous with overlying volcaniclastics	Figure 7
Volcaniclastics	0.9	37.0	Base sharp, blue-green-grey, interbedded with some mudstone layers, blocky; white blebs throughout on fresh surface, soft but slightly stronger than overlying volcaniclastic unit	Figures 6b & c; 7
Mudstone, dark grey	5.0	32.0	Abundant siderite bands, some with fossil shells at the top of some siderite bands. Mudstone quite fissile and conchoidal fractures	Figure 6a

amsl = Average mean sea level, as determined from a hand held GPS

The volcaniclastic unit itself can be divided into two sections. The lower unit is more massive in appearance and contains rounded inclusions 1-2 cm in size (Figure 6c). The rounded inclusions are slightly more resistant to weathering and thus protrude from the blue-green soft matrix material.

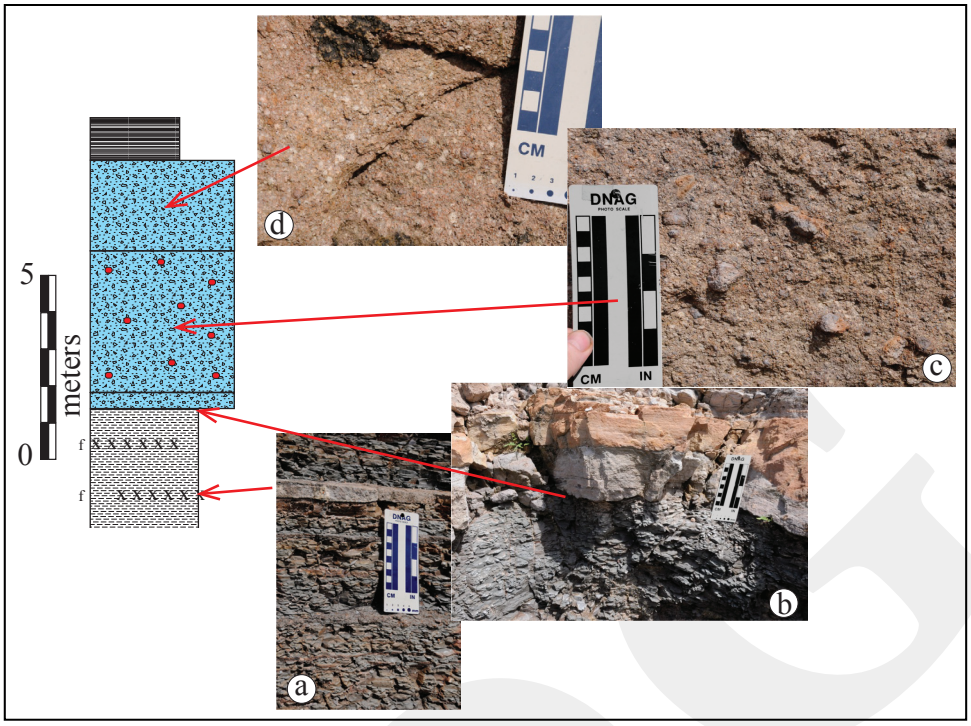

Figure 6. Photographs of (a) and (b) mudstone and (c) and (d) volcaniclastics at Location 1 illustrating field texture. Note a sharp contact between mudstone and volcaniclastic layer in (b).

The upper unit is bedded but has significantly less rounded inclusions (Figure 6d). Both units have abundant 1-3 mm white mottling. The top of the lower unit grades imperceptibly into the upper unit and the upper unit has a sharp contact with the overlying black mudstone (Figure 7). The total thickness of the volcaniclastic unit at Location 1 is 7.3 m.

Above the volcaniclastic unit is a succession of interbedded sandstone and mudstone units (Table 1; Figure 8). These units grade from one to the other without any major erosional surfaces noticeable. However, the upper sandstone unit (Figure 9) is distinctly different. The sandstone has an erosional base and inclined bedding, which can be traced into the overlying interbedded mudstone and sandstone unit. These beds gradually fine upward into dark grey mudstone with abundant organic material then into the Pengapitan coal bed, which here is less than a metre thick (Figure 10). The Pengapitan coal is a locally named bed that occurs between 60-80 m stratigraphically above the main Senakin coal bed.

Pit 20 - Location 2

The section at Pit 20, from here on referred to as Location 2 is a mine high wall within an abandoned and mostly flooded opencast pit (2.93699ºS/116.261691ºE). The mining target of this opencast pit was the main Senakin coal seam. A section was described from near water level to near the top of an overlying basalt layer (total section measured was 48.5 m). The section description is given in Table 2 and a graphic log with sample locations is given in Figure 11.

The stratigraphically lower-most unit exposed at Location 2 is a coal bed which is overlain by organic-rich mudstone (Figure 12). Two additional overlying layers of coal occur (Figure 13), which are locally mined. The total thickness of the three coal layers, plus the interbeds of mudstone is 4.1 m, although the net coal only accounts for about 2.2 m. The coal does not appear to be thermally altered.

The coal is overlain by a dark grey, organic-rich mudstone (Figure 14a), which is in near stratigraphic contact with the overlying basalt.

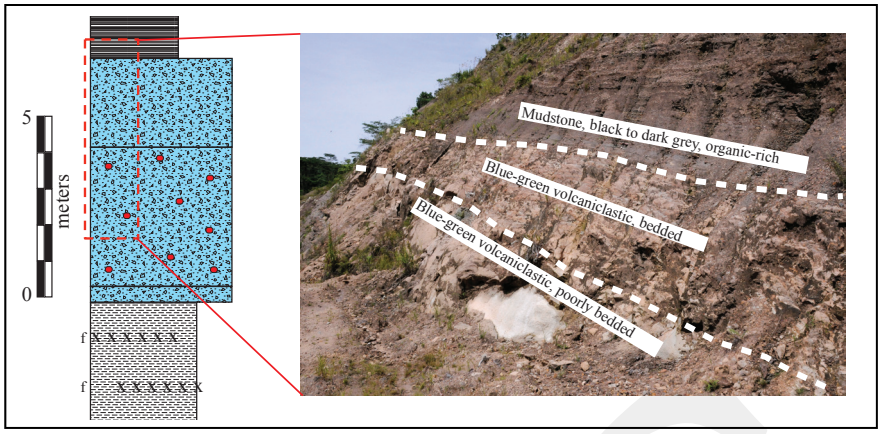

Figure 7. Oblique view of volcaniclastic unit and overlying organic-rich mudstone at Location 1. Note the sharp transition from the volcaniclastic layer into the mudstone.

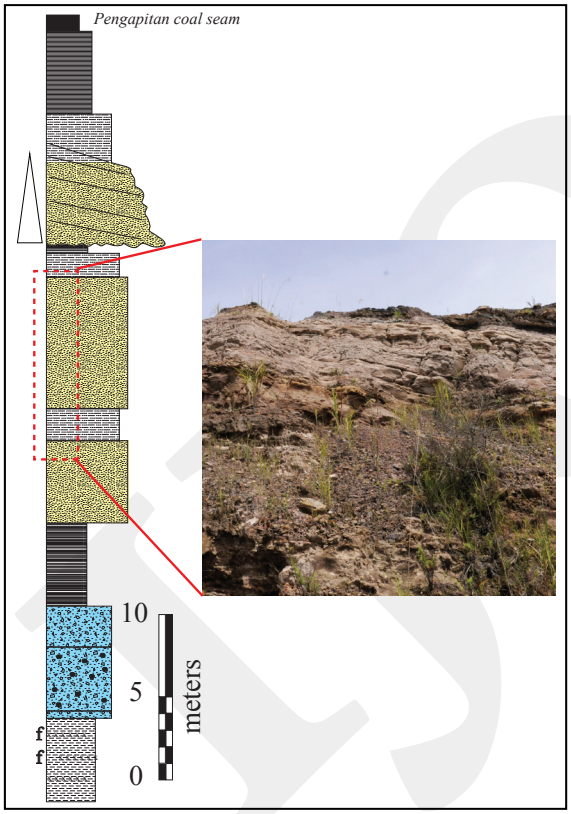

Figure 8. Sandstone and mudstone lithologies overlying the volcaniclastic layer at Location 1.

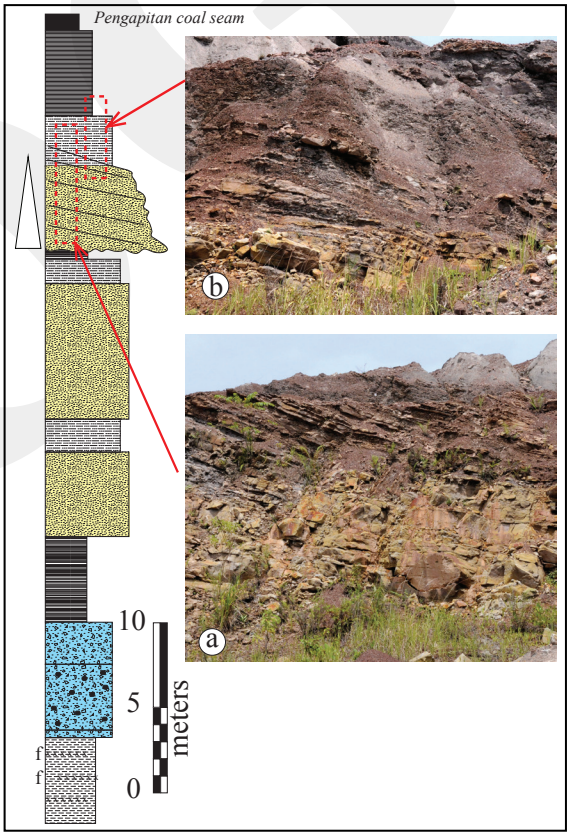

Figure 9. Sandstone, with an erosional base and inclined interbeds of mudstone at Location 1.

A white, waxy, claystone zone, however, occurs between the top of the mudstone and the bottom of the basalt (Figure 14b).

The basalt sequence is fine-grained (Figure 15) and in the lower part has prominent columnar joints (Figures 12 and 16). The upper sequence of basalt has less visible jointing but this is a result of the artificially graded slope angle. Also because of the slope angle, the top contact of the basalt was not identified as there was a gradual covering of soil.

The detailed stratigraphy of the coal and basalt from additional core data from the mining

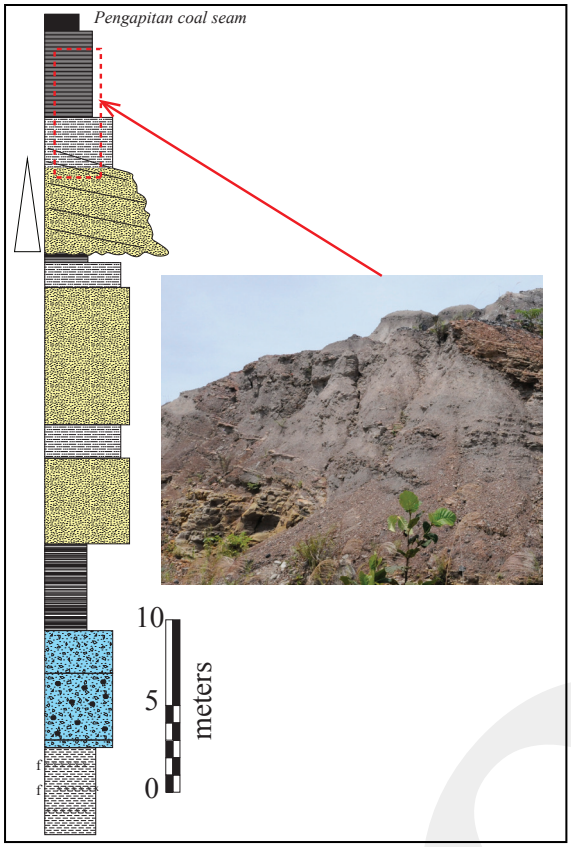

Figure 10. Pengapitan coal seam and underlying organic-rich mudstone at Location 1.

company (not shown) indicates that the coal is the main Senakin seam (see Figure 3).

Petrographic Analysis

Analysis of thin sections allows further documentation of the volcaniclastic, mudstone, and basalt units at Locations 1 and 2. Although a number of samples were taken at both locations (Figures 5 and 11), only the most relevant thin sections of samples are described herein (Table 3). At Location 1, thin sections of the volcaniclastic layer show distinct features of fragmented origins (Figure 17), such as clasts of different sizes (Figures 17a, b). The clasts are dark coloured and fine-grained with a crystalline to glassy texture. Some clasts contain vesicles, which are remnant gas bubbles from igneous melt, that vary in size, presence, and abundance within individual clasts (Figures 17c, d). Mineralogically, small pyroxene phenocrysts are common within the fine-grained groundmass (porphyritic texture) and are mostly euhedral in shape. Evidence of palagonite alteration of clast margins (Figure 17c) is also noted.

Table 2. Lithological descriptions for Location 2 (-2.93699°/116.261691°;±6m). Date of sample collection: 14 December 2017

Lithology	Thickness (m)	Elevation amsl (m), base of unit	Comments	Corresponding Photograph
Basalt	30.0	39.5	Fresh, columnar jointing noticiable, top not exposed	Figure 12
Basalt	10.0	29.5	Fresh, columnar jointing	Figures 12 & 14
Mudstone, whitish to grey	0.9	28.6	Waxy, looks altered	Figure 13
Mudstone, dark grey, organic rich	3.5	25.1	With sideritic layers	Figure 12, 13, 14
Coal	0.9	24.2	With inorganic layers	Figure 12
Mudstone, black, organic rich	0.3	23.9		Figure 12
Coal	0.9	23.0	Abundant inorganic layers, sulphur blooms more frequent towards the top; possible is the lateral equivalent to the Pengapitan coal seam	Figure 12
Mudstone, dark grey, organic rich	0.5	22.5	Root penetrated	
Mudstone, dark grey, organic rich	1.1	21.4	Laminated	
Coal	0.4	21.0	Possible lateral equivalent to the Pengapitan coal seam [could be thicker, could not see base of seam]	

amsl = Average mean sea level, as determined from a hand held GPS

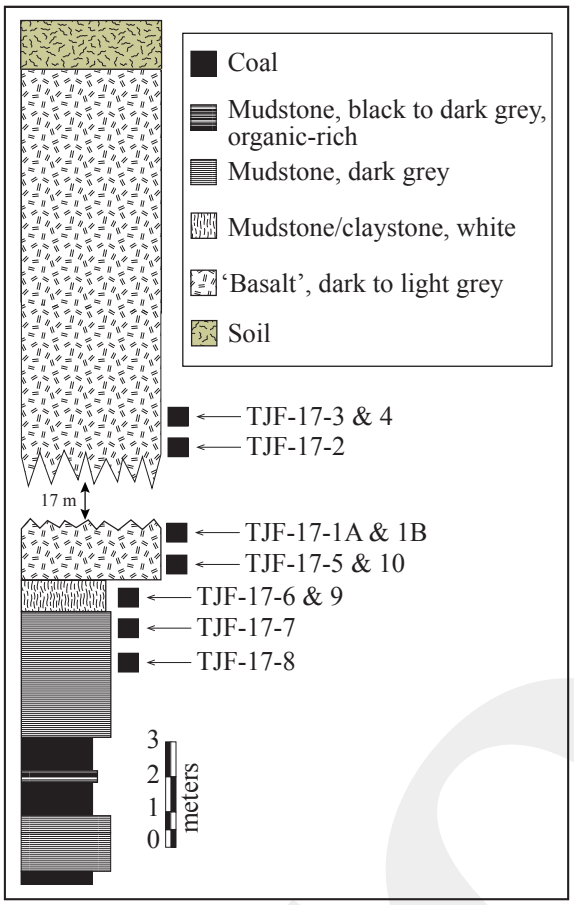

Figure 11. Graphic log of Location 2 showing basalt, the underlying sediments, and sampling locations.

Thin sections of the fossiliferous interval below the volcaniclastic layer clearly show bivalve fragments and coral, but also, interestingly, quartz of a probable volcanic origin (Figure 18). The quartz grains, most less than 0.25 mm in size, are sub-rounded to angular, suggesting brief to little transport. The clear, glassy nature of the quartz, together with euhedral habit, vacuoles and straight extinction character in cross-polarized light indicates that the quartz grains are likely have a volcanic provenance.

Thin sections of the basalt at Location 2 show an overall fine-grained texture (Figure 19). Olivine and euhedral pyroxene phenocrysts are common within the fine-grained groundmass, thus exhibiting a porphyritic texture. The fine-grained groundmass (Figures 19a, c) has abundant plagioclase microscale laths, which are easily identified in cross polarized light (Figures 19b, d). Previously analyzed thin sections from the basalt in different locations in east Senakin (Figure 3) are also fine grained with the presence of plagioclase and pyroxene with the occasional carbonate in-filling (Table 3). Thin section analysis clearly identifies these samples as originating from a mafic volcanism.

Discussion

The macro- and microscopic textural relationships for the volcaniclastic unit at Location 1 strongly supports a mafic volcanic origin, which was subsequently altered through contact with seawater. The clasts all comprise porphyritic textured mafic igneous rock with varied abundances of vesicles. Pyroxene phenocrysts are common and usually have a well-defined euhedral morphology. Thus, the mineralogy suggests it originated from mafic volcanism. The fragmental nature of the primary volcanic-derived material suggests that upon heated emplacement into a marine environment, the basalt quenched rapidly in the water. This rapid cooling results in non-explosive shattering of lava to produce glassy textured fragments, termed hyaloclastite (Watton *et al.*, 2013; Thien *et al.*, 2015). The presence of palagonite alteration overprinting the margins of some volcaniclastic clasts indicates that the mafic igneous material interacted with sea water (Stroncik and Schmincke, 2002). Mudstone stratigraphically underlies the volcaniclastic unit and contains fossils such as bivalves and coral, which indicate a marine depositional environment.

Volcanically derived quartz are present in the mudstone below the volcaniclastic unit. It is unclear whether these were transported by marine sedimentary currents, *e.g*. turbidity currents or contourites, or represent pyroclastic fallout from nearby explosive volcanoes. The angular morphologies of the quartz within the mudstone suggests that it was transported only a short distance. Thus, it is reasonable to suggest that quartz-rich, felsic volcanism was already present in the region, prior to the mafic volcaniclastic units being deposited.

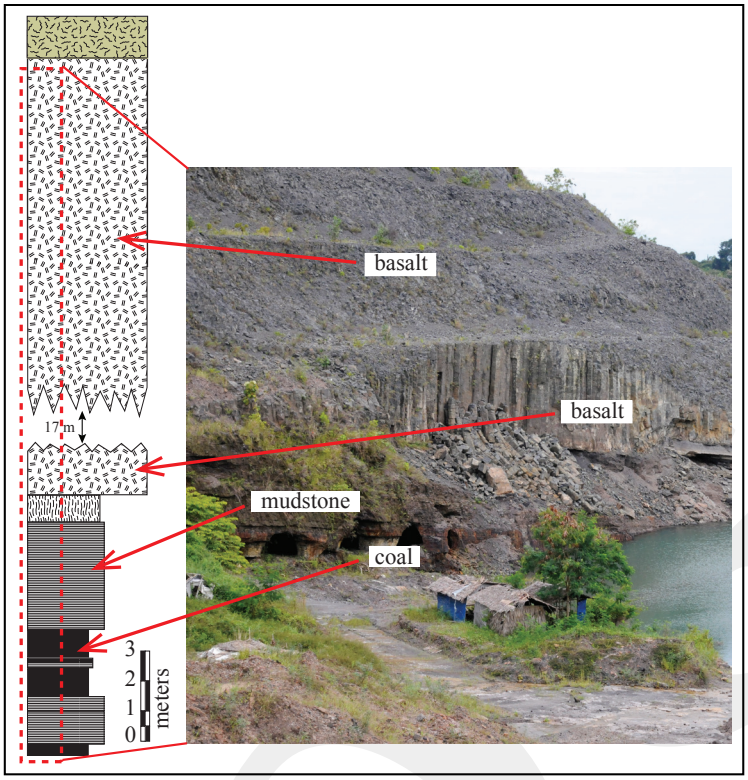

Figure 12. Overview of Location 2 from coal to near top of basalt.

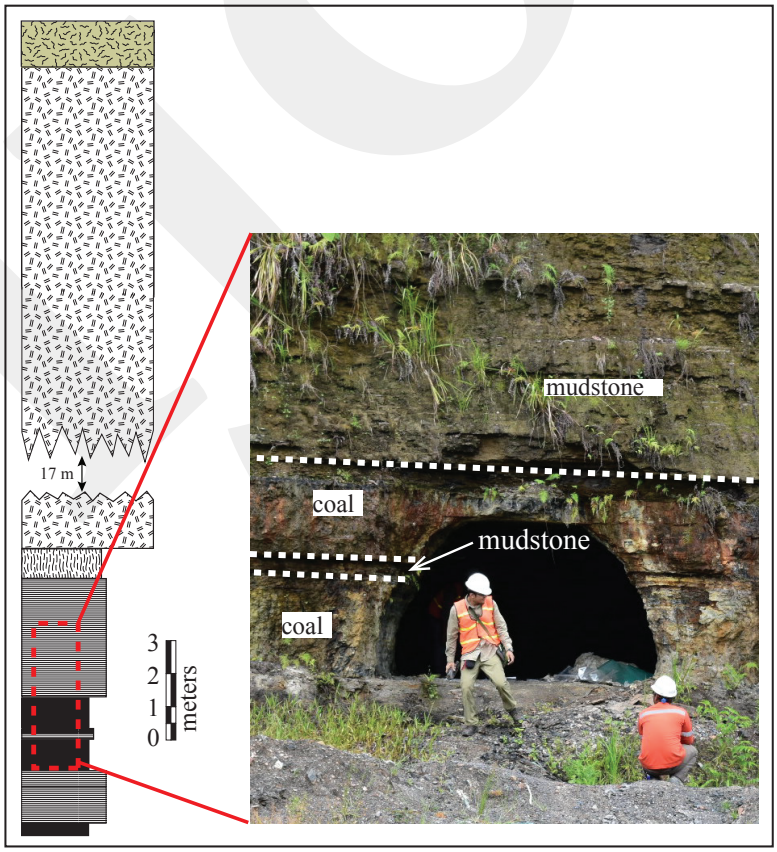

Figure 13. Close up of coal bed and overlying mudstone at Location 2.

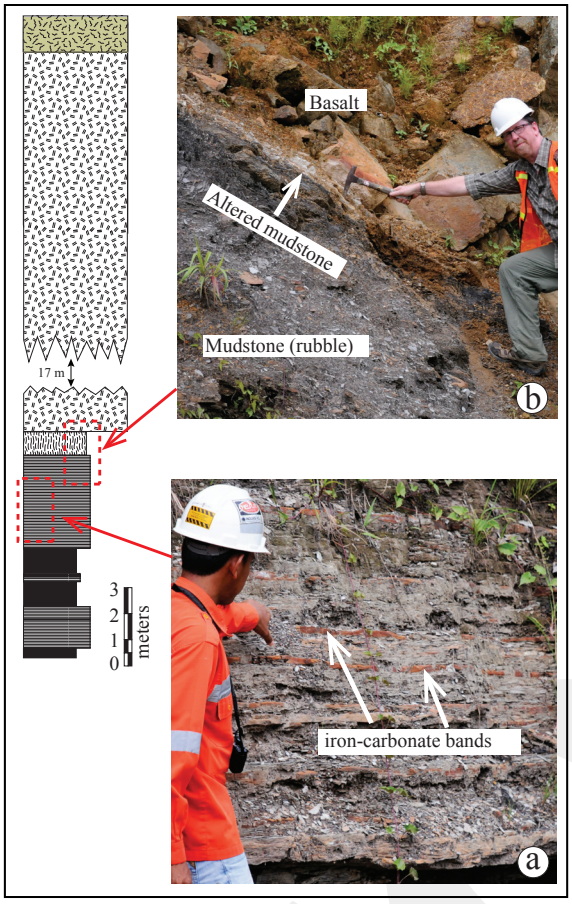

Figure 14. (a) The mudstone underlying the basalt at Location 2, and (b) the white, altered layer at the contact between the basalt and the mudstone at Location 2.

Figure 15. Hand specimen illustrating the fine-grained nature of the basalt at Location 2.

A previous mining report (Anonymous, 1984) has referred to the volcaniclastic unit as the 'Gumbil Volcanics' and it is proposed that this becomes the 'Gumbil Volcaniclastic Member' within the Tanjung Formation if it can be demonstrated to occur over a wider area than just the east Senakin Peninsula.

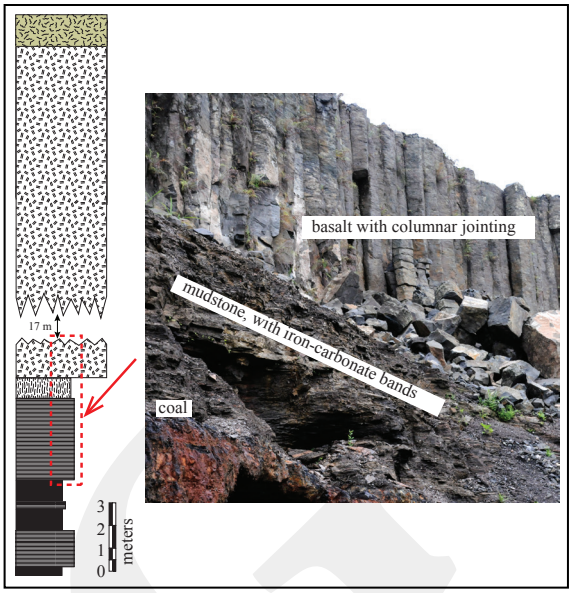

Figure 16. The interval from the top of the coal to the bottom of the basalt unit illustrating the well developed columnar joints at Location 2.

The thick, coherent basalt unit is texturally fine grained with prominent columnar cooling joints. The fine grain size indicates that the basalt was emplaced either at or near the earth's surface. Although the top of the basalt was not observed, a thin alteration zone appears to be present in the mudstone immediately underlying the unit. Lack of thermal alteration of the underlying coal (Febriadi, P.T. Arutmin, *personal communication*, 2017) also suggests that the basalt had a surface emplacement where heat could be dissipated quickly with little affect to underlying coal. A previous mining report (Anonymous, 1984) has referred to these units collectively as the 'Tanah Rata' basalt and it is proposed that this becomes the 'Tanah Rata Basalt Member' within the Tanjung Formation.

Plagioclase, pyroxene, and olivine are the dominant discrete minerals observed in thin sections and confirm the general mafic composition of the basalt. The mineralogical similarity between the basalt at Location 2 and the volcaniclastic unit

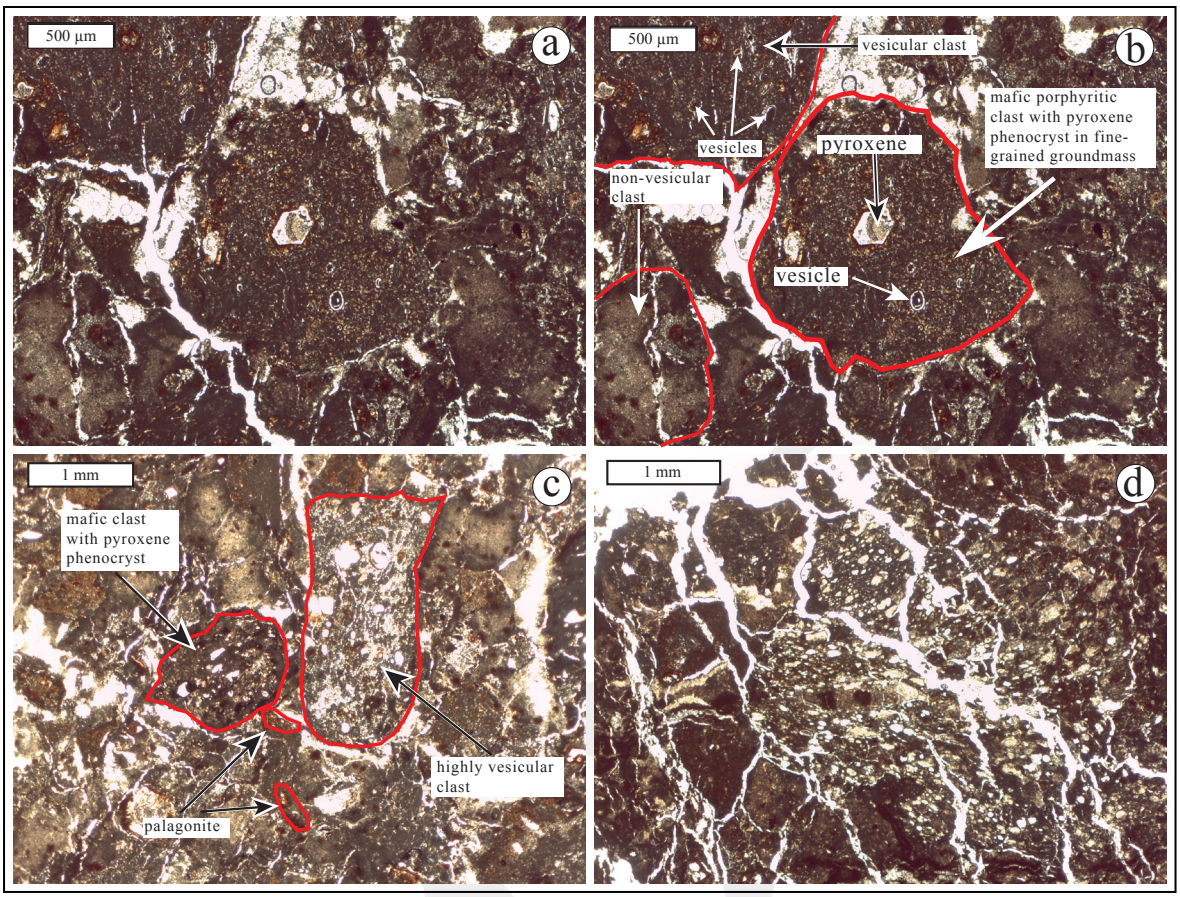

Figure 17. Photomicrographs from thin sections of the volcaniclastic unit from Location 1. (a) Clasts and vesicles of various sizes and phenocrysts are indicative of a volcaniclastic texture (plain polarised light; sample TJF-17-18). (b) At the centre, mafic porphyritic clast shows a euhedral pyroxene phenocryst within a fine-grained, dark coloured groundmass with 2-5% vesicles. (c) Fragmented textured sample with clasts exhibiting varied abundances of vesicles and phenocrysts within a fine-grained groundmass. Overprinting of palagonite mineral growth on edges of some clasts (plain polarized light; sample TJF-17-19). (d) Fragmented texture and varied vesicle abundance within a fine-grained groundmass (plain polarized light; sample TJF-17-20).

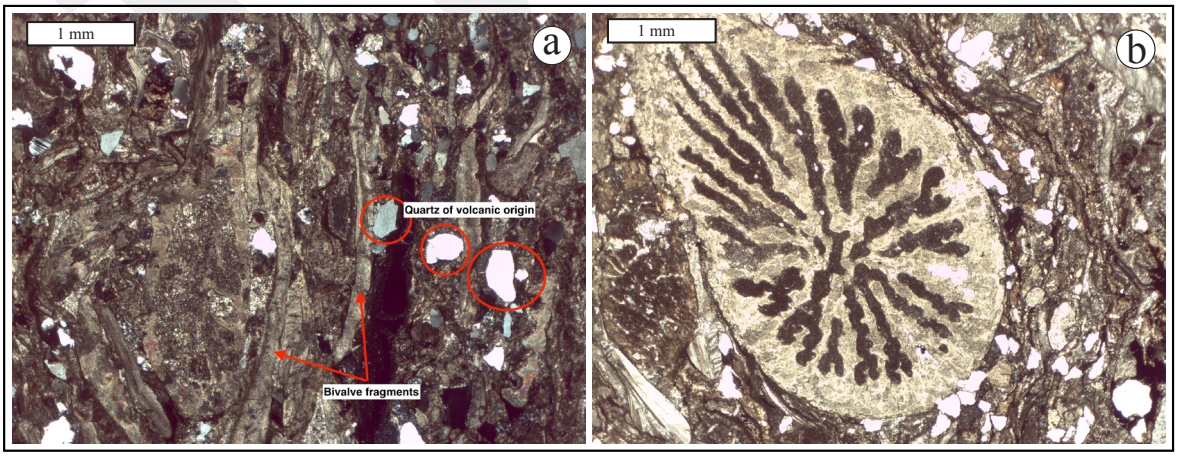

Figure 18. Photomicrographs from thin sections of mudstone from Location 1. (a) Abundant bivalve shell fragments in a matrix of clay; angular to sub-rounded quartz grains of volcanic origin (cross polarized light; sample TJF-17-14). (b) Cross section of coral (plain polarized light; sample TJF-17-14).

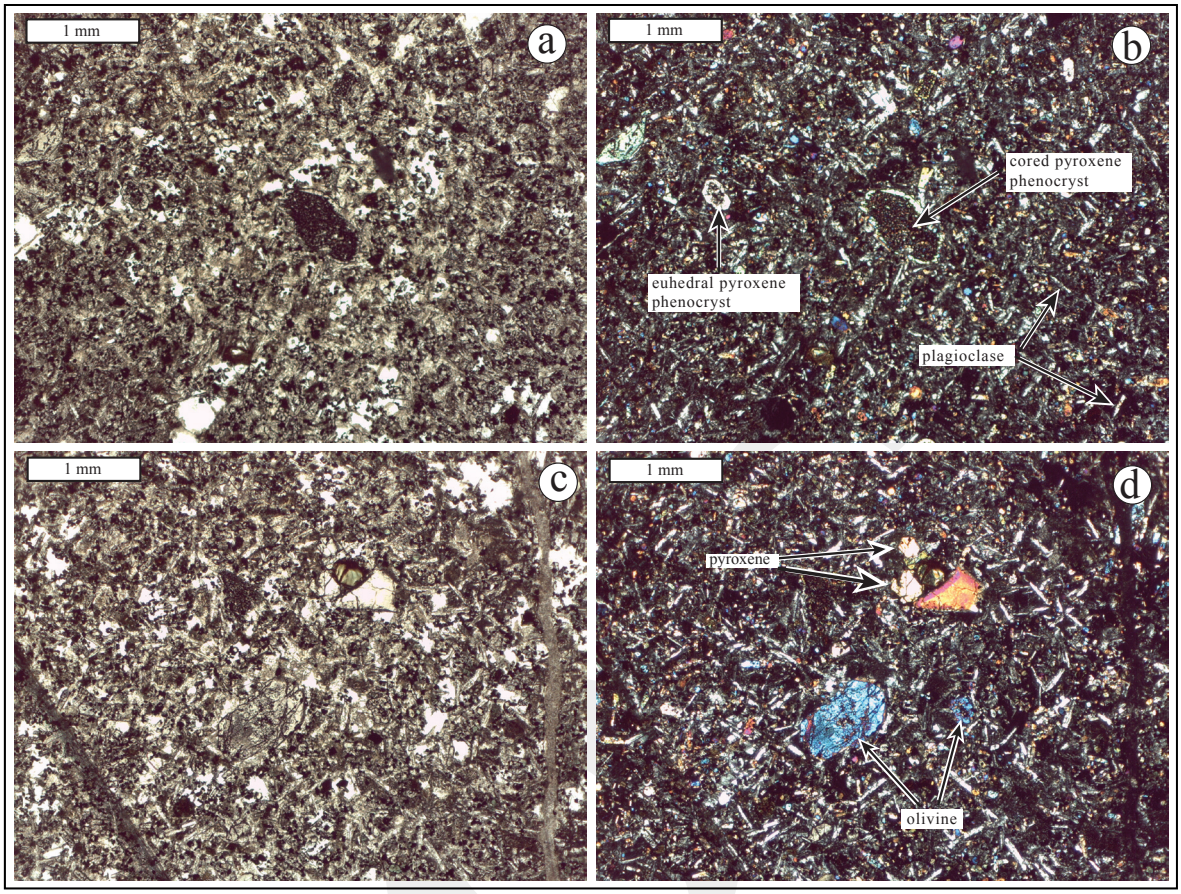

Figure 19. Photomicrographs from thin sections from Location 2. (a) Coherent mafic composition with pyroxene phenocryst in a fine-grained groundmass (plain polarized light; sample TJF-17-3). (b) Same view as previous but showing the cored nature of one pyroxene and the euhedral nature of another. Note the abundant rectangular plagioclase within the fine-grained groundmass (cross-polarised light). (c) Porphyritic textured basalt with olivine and pyroxene phenocrysts within a plagioclase-rich fine-grained groundmass (plain polarized light; sample TJF-17-3). (d) Same view as previous but showing olivine and pyroxene (cross-polarized light).

Table 3. Description of thin section discussed in the text

Location	Sample #	Field description	Thin Section Description
Location 1	TJF-17-18	volcaniclastics	clastic texture; mafic porphyritic clasts with pyroxene phenocryst; fine-grained, vescles of varying sizes.
Location 1	TJF-17-19	volcaniclastics	mafic clasts with pyroxine phenocrysts; highly vesicular texture; groundmass is fine-grained; presence of palagonite.
Location 1	TJF-17-20	volcaniclastics	mafic clasts; fine-grained; highly fragmented; vesicles of widely different sizes.
Location 1	TJF-17-14	mudstone	fine-grained groundmass of clay; abundant bivalve shell fragments; coral; quartz grains angular to subrounded; full extinction in cross polarized light.
Location 2	TJF-17-3	basalt	fine-grained groundmass with abundant plagioclase; euhedral pyroxene phenocrysts; olivine.
606 (core)	138	basalt	overall fine grain; presence of plagioclase.
607 (core)	16.2	volcaniclastics	overall fine grain; plagioclase; occasional carbonate in-filling.
607 (core)	66.2	basalt	overall fine grain; pyroxene, some alteration evidence; plagioclase.

at Location 1 suggests a linked source; that is, the proposed Tanah Rata Basalt and the Gumbil Volcaniclastic Members were derived from the same source in a series of magmatic pulses.

From the cross section (Figure 3), there appears to be several possible volcanic events, one pre-main Senakin coal seam deposition and two to three post-main Senakin seam deposition. Not much is known of the character and nature of the pre-main Senakin coal seam volcaniclastic and basalt units. The stratigraphically lower of the volcanic events post-main Senakin seam, appear to predate the Pengapitan coal seam in the south part of study area. Even before the deposition of the volcaniclastic unit, some volcanic activity must have occurred, as evidenced by the volcanic quartz mixed in with the underlying (marine) fossil-bearing mudstone. Thus, the pre-Pengapitan volcaniclastic unit was likely deposited within a shallow marine environment. The sediment above the main Senakin coal seam and its equivalents is often interpreted as a marine to brackish water environment (Friederich *et al.*, 1995, 1999, 2016; Witts *et al.*, 2012). The Gumbil Volcaniclastic Member sampled at Location 1 is correlative to the 'pre-Pengapitan' volcanic event.

The post-Pengapitan event seems only represented in the southern part of the study area, south of the Gumbil fault zone. The magnitude of this event seems similar to the previous event, based on the thickness of both the volcaniclastic sediments and the basalt.

Only three publications are known to cite basalt occurring within Eocene sediments of southeastern Kalimantan (Moore, 1990; Lumadyo *et al.*, 1993). Lumadyo *et al.* (1993) cites a basalt occurring at Muru and Tebruk, both about 120 km north of the Gumbil Fault in east Senakin (Figure 20), within the Kuaro Formation, which is a lateral equivalent of the Tanjung Formation. The study noted that the lower contact was altered and assumed it was deposited synchronously with the surrounding sediments. The occurrence of the basalt is also supported by numerous unpublished mining reports. Moore (1990) also reported basalt occurrences in the Tanjung Formation on the west side of the Senakin Peninsula (Figure 20). In the

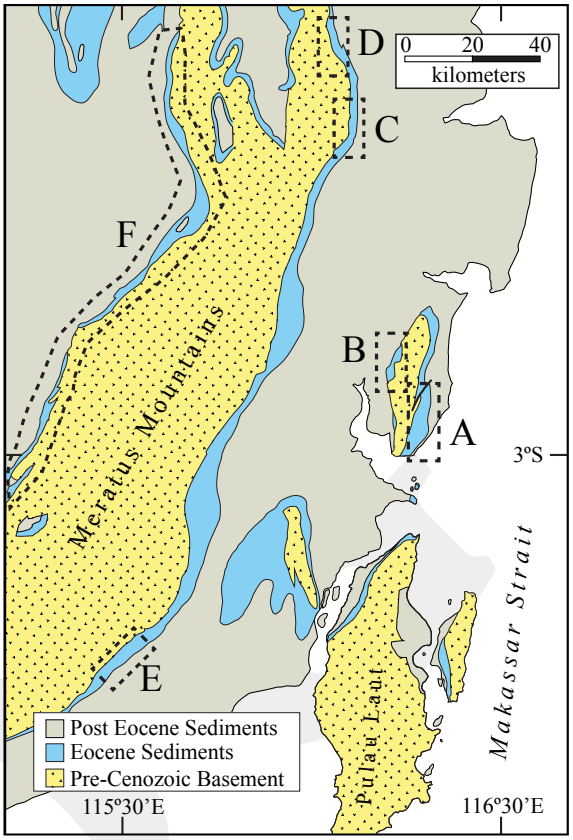

Figure 20. Status of the presence or absence of volcaniclastic sediments, basalt, and ash layers in coal in southeast Kalimantan. Areas not listed/demarcated have unknown status. (a) east Senakin peninsula - basalt, volcaniclastic sediments and ash layers in coal (this paper); (b) west Senakin peninsula - basalt, ash layers in coal (Moore, 1990; Ruppert and Moore, 1993); (c) Petangis - basalt, ash layers in coal (Moore, 1990; Lumadyo *et al.*, 1993); (d) Bindu and Betitit - ash layers in coal (Moore, 1990); (e) Satui - no basalt, volcaniclastic sediments or ash layers (Moore, 1990; Ruppert and Moore, 1993); (f) east Barito Basin - no basalt, volcaniclastic sediments or ash layers (Witts *et al.*, 2012).

west Senakin case, the basalt cross cuts the coal and raises the rank of unaltered coal from vitrinite reflectance of 0.50% to 2.20%. Febriadi (2010) also noted both basalts and volcaniclastic units in the east Senakin area. In addition to those studies, Hartono *et al.*, (1999) make reference to a basalt in Pulau Laut, associated with pre-Cenozoic basement, about 50 km to the south of east Senakin. The basalt was age dated from 62.5 to 19.5 Ma; with such a wide range in age it is not certain that this basalt is related to the Tanah Rata Basalt Member in east Senakin.

Other than the report by Febriadi (2010), Eocene age, volcaniclastic deposits, however, have

not been previously documented in southeast Kalimantan. The geographically closest are the Nyaan volcaniclastic sediments (Pieters *et al.*, 1987; Tate, 1991; Moss and Chambers, 1999; Bachtiar *et al.*, 2013) but these are many hundreds of kilometres from the Senakin Peninsula and it is hard to envision a connected origin.

As previously noted, volcanic ash layers were identified in the main coal seam in the Tanjung Formation by Ruppert and Moore (1993). These ash-fall layers, which have a distinctive 'pelitic' texture, are widely distributed throughout this seam in the Senakin Peninsula, and have been observed northward for at least 150 km (Moore, 1990).

The origin of the volcanic rocks is problematic. The Late Eocene timing is approximate for when western Sulawesi was drifting eastward, relative to Borneo (Fraser and Ichram, 1999; Hall, 2009; Witts *et al.*, 2012; Kupecz *et al.*, 2013) and may be related to crustal thinning and rifting in the Makassar Strait. Van Leeuwen (1981) and van Leeuwen and Muhardjo (2005) describe several Eocene volcaniclastic sediments and lava in the Eocene age Budungbudung Formation of western Sulawesi. It is conceivable that these units are related to the separation of Borneo and Sulawesi during that time and the units found in the Senakin Peninsula and northward are the western manifestation of the same event. However, these are speculations at best, for the moment, but may be possible to test through geochemical comparison of volcanics from the Budungbudung and Tanjung Formations.

Conclusions

Field and thin section analysis of the blue-green, soft mottled volcaniclastic and basaltic samples from the Senakin Peninsula has led to the following conclusions:

1. The Tanjung Formation hosts two syn-sedimentary volcanic units: a basaltic lava and a volcaniclastic unit. It is proposed these become respectively the 'Tanah Rata Basalt Member' and the 'Gumbil Volcaniclastic Member' (if the latter can be shown to occur outside the Senakin Peninsula).
2. Similarities in mineralogy and close temporal/spatial relationships suggest the two units had a common magma source and formed during the same event, which consisted of several magmatic pulses.
3. The basalt was emplaced at or near the surface, as indicated by the fine-grained nature of the lava, its distinctive columnar jointing, and field relationships.
4. The volcaniclastic unit was most likely deposited in a shallow marine environment as suggested by the fossil evidence from the underlying mudstone.
5. Quenching of the still hot igneous material through contact with sea water resulted in its fragmentation and the strongly developed porphyritic textures of the fragments. Rims of palagonite present on some clasts may have formed during this time.
6. There appears to have been multiple volcanic events in the east Senakin area resulting in both basalt and volcaniclastic units. One event is pre-main Senakin coal seam accumulation, another is pre-Pengapitan coal seam accumulation and the last, perhaps only confined to the southern part of the study area, is post-Pengapitan coal seam deposition.
7. The relationship of the basalt and volcaniclastic units with the volcanic ash layers that are widespread in the main coal seam of the Tanjung Formation is not known. However, together they show that considerable volcanic activity occurred during the deposition of this formation, something that has not been previously well recognized.
8. Eocene volcanics in southeast Kalimantan and southwest Sulawesi may be related as these two regions were more closely positioned at that time.

The recognition of syn-sedimentary mafic volcanism in a rift setting in southeast Kalimantan is intriguing. Additional fieldwork should be aimed at further defining the extent of the volcanic units and their relationship with the host sedimen-

tary rocks with the focus on boundary transitions and macroscopic textures. Major and minor geochemical analyses of the samples collected in this study are currently being conducted to help delineate the origin. Geochemical comparison with the Eocene volcanics in southwest Sulawesi would prove useful.

Acknowledgements

The authors wish to thank P.T. Arutmin Indonesia who kindly gave field support and advice during the 2017 field season. The authors particularly wish to thank Pak Elino Febriadi, Yogi Swara, and the rest of the personnel at P.T. Arutmin. Funds were made available for thin sections from QUT and TAM wishes to thank both Cipher Consulting Pty Ltd for funding of field activities and the International Research Centre for Coal Geology, China University of Mining and Technology for its support during the writing of this paper. The authors wish to thank the two anonymous reviewers who helped to greatly improve the manuscript.

References

Anonymous, 1984. Geology of the southern portion of East Senakin. P.T. Arutmin Indonesia, Jakarta, Indonesia, 6pp.

Argakoesoemah, R.M., 2017. Middle Eocene palaeogeography of the greater Makassar Strait region, Indonesia: A review of Eocene source rock distribution. *Proceedings, Indonesian Petroleum Association, 41st Annual Convention and Exhibition*, IPA17-247-G, Jakarta, Indonesia, 24pp. DOI: 10.29118/ipa.50.17.247.g

Bachtiar, A., Purnama, Y.S., Suandhi, P.A., Krisyunianto, A., Rozalli, M., Nugroho, D.H.H., and Suleiman, A., 2013. The Tertiary paleogeography of the Kutai Basin and its unexplored hydrocarbon plays. *Proceedings, Indonesian Petroleum Association, 37th Annual Convention & Exhibition*. Paper IPA13-G-126, Jakarta, Indonesia, 37pp. DOI: 10.29118/ipa.0.13.g.126

Baumann, P., 1972. Les faunes foraminiferes de L'Eocene superieur a la base du Miocene dans le Bassin de Pasir sud de Kalimantan. *Revue de L'Institut Francais du Petrole*, 27, p.817-829. DOI: 10.3406/bagf.1972.7877

Bon, J., Fraser, T.H., Amris, W., Steward, D.N., Abubakar, Z., and Sosromihardjo, S., 1996. A review of the exploration potential of the Paleocene Lower Tanjung Formation in the South Barito Basin. *Proceedings, Indonesian Petroleum Association, 25th Silver Anniversary Convention*. Indonesian Petroleum Association, IPA96-1.0-027, Jakarta, Indonesia, p.69-79. DOI: 10.29118/ ipa.2334.69.79

Carlile, J.C. and Mitchell, A.H.G., 1994. Magmatic arcs and associated gold and coppper mineralization in Indonesia. *Journal of Geochemical Exploration*, 50, p.91-142. DOI: 10.1016/0375-6742(94)90022-1

Cloke, I.R., Milsom, J.S., and Blundell, D.J.B., 1999. Implications of gravity data from East Kalimantan and the Makassar Straits: a solution to the origin of the Makassar Straits? *Journal of Asian Earth Sciences*, 17, p.61-78. DOI: 10.1016/s0743-9547(98)00056-7

Doust, H. and Noble, R.A., 2008. Petroleum systems of Indonesia. *Marine and Petroleum Geology*, 25, p.103-129. DOI: 10.1016/j.marpetgeo.2007.05.007

Febriadi, E., 2010. PT Arutmin Indonesia: Discovery of South Kalimantan coal. *In*: Basuki, N.I. and Prihatmoko, S. (Eds.), *Kalimantan Coal and Mineral Resources. MGEI-IAGI Seminar*, 29-30 March 2010, Balikpapan, Indonesia, p.27-48.

Fraser, T.H. and Ichram, L.O., 1999. Significance of the Celebes sea spreading centre to the Paleogene petroleum systems of the SE Sunda margin, central Indonesia. *Proceedings, Indonesian Petroleum Association, 27th Annual Convention & Exhibition*. Indonesian Petroleum Association, IPA99-G-166, Jakarta, Indonesia, 11pp. DOI: 10.29118/ipa.647.g.166

Friederich, M.C., Langford, R.P., and Moore, T.A., 1999. The geological setting of Indonesian coal deposits. *Pacrim* '99, Bali, Indonesia, p.625-631.

Friederich, M.C., Moore, T.A., and Flores, R.M., 2016. A regional review and new insights into SE Asian Cenozoic coal-bearing sediments: Why does Indonesia have such extensive coal deposits? *International Journal of Coal Geology*, 166, p.2-35.

Friederich, M.C., Moore, T.A., Lim, M.S.W., and Langford, R.P., 1995. Constraints on coal formation in southeast Kalimantan, Indonesia. *6th New Zealand Coal Conference*. CRANZ, Wellington, New Zealand, p.137-149.

Friederich, M.C. and van Leeuwen, T., 2017. A review of the history of coal exploration, discovery and production in Indonesia: The interplay of legal framework, coal geology and exploration strategy. *International Journal of Coal Geology*, 178, p.56-78. DOI: 10.1016/j.coal.2017.04.007

Gerard, J. and Oesterle, H., 1973. Facies study of the offshore Mahakam area. *Proceedings, Indonesian Petroleum Association, 2nd Annual Convention*. Indonesian Petroleum Association, p.187-194.

Hall, R., 2009. SE Asia's changing palaeogeography. *Blumea - Biodiversity, Evolution and Biogeography of Plants*, 54, p.148-161. DOI: 10.3767/000651909x475941

Hall, R., 2012. Late Jurassic - Cenozoic reconstructions of the Indonesian region and the Indian Ocean. *Tectonophysics*, 570-571, p.1-41. DOI: 10.1016/j.tecto.2012.04.021

Hamilton, H., 1979. *Tectonics of the Indonesia region*. U.S. Geological Survey Prof. Paper 1078, 345pp.

Hartono, U., Dirk, M.H.J., Sanyoto, P., and Permanadewi, S., 1999. Geochemistry and K/Ar results of the Mesozoic-Cenozoic plutonic and volcanic rocks from the Meratus Range, South Kalimantan. *Geological Society of Malaysia Bulletin*, 43, p.49-61. DOI: 10.7186/bgsm43199906

Hashimoto, W., 1973. An unconformity discovered on the Tanjung Anticline in the eastern rim of the Barito Basin, Kalimo Kalimantan Selatan (South Borneo), Indonesia. *Geology and Paleontology of Southeast Asia*, 12, p.179-188.

Hashimoto, W. and Koike, T., 1973. A Geological Reconnaissance of the Reservoir Area of the Riam Kanan Dam, East of Martapura, Kalimantan Selatan, Indonesia. *Geology and Paleontology of Southeast Asia*, 13, p.163-190.

Heryanto, R., 2009. Karakteristik dan Lingkungan Pengendapa Batubara Formasi Tanjung di daerah Binuang dan sekitarnya, Kalimantan Selatan. *Jurnal Geologi Indonesia*, 4, p.239-252. DOI: 10.17014/ijog.vol4no4.20092

Hutchison, C.S., 2008. The geological framework. *In*: Gupta, A. (Ed.), *The physical geography of Southeast Asia*. Oxford University Press, Oxford, p.4-23.

Hutchison, C.S., 2014. Tectonic evolution of Southeast Asia. *Geological Society of Malaysia Bulletin*, 60, p.1-18.

Katili, J.A., 1968. Permian volcanism and its relation to the tectonic development of Sumatra. *Bulletin of National Institute of Geology and Mining*, Bandung 1, p.3-13.

Kupecz, J., Sayers, I., Tognini, P., Hilman, A., Tanos, C., and Ariyono, D., 2013. New insights into the tectono-stratigraphic evolution of the South Makassar Basin. *Proceedings, Indonesian Petroleum Association, 37th Annual Convention & Exhibition*, May 2013. Indonesian Petroleum Association, IPA13- G-158, 41pp. DOI: 10.29118/ipa19.sg.214

Kusuma, I. and Darin, T., 1989. The hydrocarbon potential of the Lower Tanjung Formation, Barito Basin, S.E. Kalimantan. *Proceedings, Indonesian Petroleum Association, 8th Annual Convention*, October 1989. Indonesian Petroleum Association, Jakarta, Indonesia, p.107-138. DOI: 10.29118/ipa19.g.36

Lucarelli, B., 2015. Government as creator and destroyer. Indonesia's rapid rise and possible decline as steam coal supplier in Asia. *In*:

Thurber, M.C. and Morse, R.K. (Eds.), *The Global Coal Market*. Cambridge University Press, Cambridge, p.294-374. DOI: 10.1017/ cbo9781316136058.007

Lumadyo, E., McCabe, R., Harder, S., and Lee, T., 1993. Borneo: a stable portion of the Eurasian margin since the Eocene. *Journal of Asian Earth Sciences*, 8, p.225-231. DOI: 10.1016/0743-9547(93)90024-j

Metcalfe, I., 1991. Late Palaeozoic and Mesozoic palaeogeography of Southeast Asia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 87, p.211-221. DOI: 10.1016/0031-0182(91)90136-f

Metcalfe, I., 2001. Palaeozoic and Mesozoic tectonic evolution and biogeography of SE Asia-Australia. *In*: Metcalf, I., Smith, J.M.B., Morwood, M., and Davidson, I. (Eds.), *Faunal and floral migrations and evolution in SE AsiaAustralia*. A.A. Balkema Publishers, Lesse, p.15-34. DOI: 10.1086/345180

Metcalfe, I., 2011. Palaeozoic - Mesozoic history of SE Asia. *In*: Hall, R., Cottam, M.A., and Wilson, M.E.J. (Eds.), *The SE Asian gateway: History and tectonics of the Australia-Asia collision. Geological Society London*, London, p.7-35. DOI: 10.1144/sp355.2

Moore, T.A., 1990. *An alternative method for sampling and petrographically characterizing an Eocene coal bed, southeast Kalimantan, Indonesia. Ph. D dissertation*, University of Kentucky, Lexington, 240pp.

Moore, T.A., 2015. A field trip guide to ancient and modern organic-rich environments in Kalimantan Timur (Borneo), Indonesia. *The Society for Organic Petrology*, ISBN 978-0-646-93901-8, Reston, Va, 107pp.

Moore, T.A. and Ferm, J.C., 1988. A modification of procedures for petrographic analysis of Tertiary Indonesia coals. *Journal of Southeast Asian Earth Science*, 2, p.175-183. DOI: 10.1016/0743-9547(88)90028-1

Moore, T.A. and Ferm, J.C., 1992. Composition and grain-size of an Eocene coal bed in southeastern Kalimantan, Indonesia. *International Journal of Coal Geology*, 21, p.1-30. DOI: 10.1016/0166-5162(92)90033-s

Moss, S.J. and Chambers, J.L.C., 1999. Tertiary facies architecture in the Kutai Basin, Kalimantan, Indonesia. *Journal of Asian Earth Sciences*, 17, p.157-181. DOI: 10.1016/s0743-9547(98)00035-x

Panggabean, H., 1991. *Tertiary source rocks, coals and reservoir potential in the Asem Asem and Barito Basins, Southeastern Kalimantan, Indonesia*. University of Wollongong, Wollongong. 226pp., plus figures and appendices.

Pieters, P.E., Trail, D.S., and Supriatna, S., 1987. Correlation of early Tertiary rocks across Kalimantan, *Proceedings, Indonesian Petroleum Association*, *16th Annual Convention*, Jakarta, Indonesia, p.291-306. DOI: 10.29118/ ipa.84.291.306

Poley, J.P., 2010. *Eroïca, The quest for oil in Indonesia (1850-1898)*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Pubellier, M. and Morley, C.K., 2014. The basins of Sundaland (SE Asia): Evolution and boundary conditions. *Marine and Petroleum Geology*, 58, p.555-578. DOI: 10.1016/j. marpetgeo.2013.11.019

Rock, N.M.S., Syah, H.H., Davis, A.E., Hutchison, D., Styles, M.T., and Lena, R., 1982. Permian to recent volcanism in northern Sumatra, Indonesia: A preliminary study of its distribution, chemistry, and peculiarities. *Bulletin Volcanologique*, 45, p.127-152. DOI: 10.1007/ bf02600429

Ruppert, L.F. and Moore, T.A., 1993. Differentiation of volcanic ash-fall and waterborne detrital layers in the Senakin coal bed (Eocene), Tanjung Formation, Indonesia. *Organic Geochemistry*, 20, p.233-247. DOI: 10.1016/0146- 6380(93)90041-9

Satyana, A.H., Eka, M., and Imron, M., 2001. Coal seams within Eocene Tanjung Formation of the Barito Basin, Southeast Kalimantan: sequence stratigraphic framework and geochemical constraints for source potential. *Berita Sedimentology*, 15, p.14-26.

Satyana, A.H., Nugroho, D., and Surantoko, I., 1999. Tectonic controls on the hydrocarbon habitats of the Barito, Kutei, and Tarakan Basins, Eastern Kalimantan, Indonesia: major

dissimilarities in adjoining basins. *Journal of Asian Earth Sciences*, 17, p.99-122. DOI: 10.1016/ s0743-9547(98)00059-2

Sigit, S., 1959. Coal deposits from the southern Sungup and Selaro sector of Pulau Laut and Pulau Sebuku (T) - S. E. Kalimantan. *Perpustakaan Puslitbang Geologi*, Bandung, 27pp. DOI: 10.32693/jgk.11.3.2013.236

Sigit, S., 1963. Geological Investigations of the coal deposits of Pulau Sebuku (Southeast Kalimantan). *Publikasi Teknik - Seri Geologi Ekonomi*, 44pp.

Simatupang, D. and Amarullah, D., 2010. Coal bed methane potency of Tanjung Formation in Tanah Bumbu South Kalimantan. *Buletin Sumber Daya Geologi*, 5, p.1-8.

Siregar, M.S. and Sunaryo, R., 1980. Depositional environment and hydrocarbon prospects, Tanjung Formation, Barito Basin, Kalimantan. *Proceedings, Indonesian Petroleum Association, 9th Annual Convention*. Indonesian Petroleum Association, Jakarta, Indonesia, p.379-400. DOI: 10.29118/ipa.1950.379.400

Stroncik, N.A. and Schmincke, H.-U., 2002. Palagonite - a review. *International Journal of Earth Science*, 91, p.680-697.

Tate, R.B., 1991. Cross-border correlation of geological formations in Sarawak and Kalimantan. *Geological Society of Malaysia Bulletin*, 28, p.63-95. DOI: 10.7186/bgsm28199104

Thien, B.M.J., Kosalowski, G., and Kulk, D.A., 2015. Differential alteration of basaltic lava flows and hyaloclastites in Icelandic hydrothermal systems. *Geothermal Energy*, 3, 32 pp. DOI 10.1186/ s40517-015-0031-7

Tjia, H.D., 1970. Eocene directional indicators near Tanjung, southeast Kalimantan. *Bulletin of National Institute of Geology and Mining*, 3, p.29-32.

Van Bemmelen, R.W., 1949. *The geology of Indonesia*. The Hague, Government Printing Office, Volumes 1 and 2.

Van Leeuwen, T., 1981. The geology of southwest Sulawesi with special reference to the Biru area. *The Geology and Tectonics of Eastern Indonesia*, Geological Research and Development Centre, *Special Publication*, 2, p.277-304.

Van Leeuwen, T. and Muhardjo, 2005. Stratigraphy and tectonic setting of the Cretaceous and Paleogene volcanic-sedimentary successions in northwest Sulawesi, Indonesia: implications for the Cenozoic evolution of Western and Northern Sulawesi. *Journal of Asian Earth Sciences*, 25, p.481-511. DOI: 10.1016/j. jseaes.2004.05.004

Watton, T.J., Jerram, D.A., Thordarson, T., and Davies, R.J., 2013. Three-dimensional lithofacies variations in hyaloclastite deposites. *Journal of Volcanology and Geothermal Research*, 250, p.19-33. DOI: 10.1016/j. jvolgeores.2012.10.011

Witts, D., Hall, R., Morley, R., and BouDagher-Fadel, M.K., 2011. Stratigraphy and sediment provenance, Barito Basin, Southeast Kalimantan. *Proceedings, Indonesian Petroleum Association, 35th Annual Convention & Exhibition*. Indonesian Petroleum Association, Paper IPA11-G-054, Jakarta, Indonesia, 18pp. DOI: 10.29118/ipa.1894.11.g.054

Witts, D., Hall, R., Nichols, G., and Morley, R., 2012. A new depositional and provenance model for the Tanjung Formation, Barito Basin, SE Kalimantan, Indonesia. *Journal of Asian Earth Sciences*, 56, p.77-104. DOI: 10.1016/j. jseaes.2012.04.022

Won, S., Shinn, Y.J., Setiawan, H.L., Hadimuljono, J.S., and Son, M., 2018. A study on the petroleum exploration potential of Barito Basin in southeastern Kalimantan, Indonesia: comparison of petroleum system with adjacent Kutai Basin. *Journal of Petroleum and Sedimentary Geology*, 1, p.1-15. DOI: 10.31697/ jpsg.2018.1.1.1