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

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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

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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 Permain 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 throughout 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 (Argakoe-soemah, 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
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; Herianto, 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; Febradi, 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 (Febradi, 2010), it is in fact fairly well delineated from drill holes and outcrop mapping from coal mine exploration. Moreover, a blue-green volcanioclastic unit often described as ‘tuffaceous’ is commonly identified in drill cores and mine faces in the same area. Both basalt and the blue-green volcanioclastic 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 volcanioclastics. In most cases, directly overlying the volcanioclastics 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 underlyng and cross cutting the main Senakin coal seam. The thickness between the top of the basement 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 volcanioclastic layer occurs overlying the predominantly ankeritic/sideritic
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 throughout 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 10° to greater than 35° 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 (2.83146°S/116.28221°E) (Figures 3 and 4). At this location the blue-green volcaniclastic was described and sampled. The second location (-2.93699°/116.26169°) 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
collection, samples were triple sealed in thick plastic bags and initially shipped to Universitas Gadjah Mada in Yogyakarta, 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).
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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.

**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                             | 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 volcanics | 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 volcanics | 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 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.
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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.

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
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.

![Figure 10. Pengapitan coal seam and underlying organic-rich mudstone at Location 1.](Image)

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 noticeable, 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                |
| Coal                            | 0.3           | 23.9                             | 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                                                                      | Figure 12                |
| Mudstone, dark grey, organic rich| 1.1           | 21.4                             | Laminated                                                                            |                          |
| Coal                            | 0.9           | 23.0                             | Possible lateral equivalent to the Pengapitan coal seam [could be thicker, could not see base of seam] | Figure 12                |

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

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).
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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, vesicles of varying sizes. |
| Location 1 | TJF-17-19  | volcaniclastics   | mafic clasts with pyroxene 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 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.

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