A tuffaceous volcaniclastic turbidite bed of Early Miocene age in the Temburong Formation of Labuan, North-West Borneo and its implications for the Proto-South China Sea subduction in the Burdigalian

Stuart D. Burley1,2 | H. Tim Breitfeld3,4 | David ‘Stan’ Stanbrook5 | Robert J. Morley3,6 | Jochen Kassan7 | Mohamad Sukarno8 | D. Wantoro Wantoro9

1Basin Dynamics Research Group, University of Keele, Staffordshire, UK
2Discovery Geoscience, Lapworth, UK
3Southeast Asia Research Group, Royal Holloway University of London, Egham, UK
4Chemostrat Ltd, Welshpool, UK
5Murphy Exploration & Production Company, Houston, TX, USA
6Palynova, Littleport, UK
7Whistler Research, Noosa, Qld, Australia
8CoreLabs, Bekasi West Java, Indonesia
9CoreLabs, Jagakarsa, Indonesia

Correspondence
Stuart D. Burley, Basin Dynamics Research Group, University of Keele, Staffordshire, UK.
Email: stuart.burley@hotmail.co.uk

Abstract
A 2 m thick bed of smectite-rich clay within a sequence of distal deep water turbidites and marine mudstones of the Temburong Formation on the island of Labuan, Sabah, North-West Borneo, is an altered, re-sedimented pyroclastic tuff which is geochemically of rhyolite-dacite composition. The tuff bed was deposited in deep water, although probably <1,000 m, by traction currents and retains relic siliceous shards, feldspar phenocrysts and biotite crystals but was dominated by ash-grade material. The tuff is interpreted as a turbidite deposit and most probably records long distance sub-marine transport down the depositional slope from an active volcanic system in the hinterland. It has a zircon U–Pb weighted mean age of 19.6 ± 0.1 Ma whilst combined foraminiferal and nannofossil ages from the enclosing marine mudstones range from 21.5 to 19.4 Ma; together these indicate an early Miocene age for the Temburong Formation. The tuff is the result of a very short-lived volcanic arc magmatic episode and was either related to similar aged volcanics of the Sintang Suite in central Borneo or a product of the Proto-South China Sea subduction beneath the Cagayan arc north-east of Borneo. The age indicates that deep water sedimentation in North-West Borneo continued into the Burdigalian suggesting the subduction trench of the Proto-South China Sea was active into the early Miocene, beneath the depocentre of the Temburong turbidite fan. By contrast, sandstones representative of the typical marine Temburong Formation yield abundant zircons which are dominately Cretaceous in age indicating an important switch in source provenance during the Early Miocene from the Crocker Formation that is dominated by Permian-Triassic zircons. This difference in zircon populations likely reflects an important tectonic event in the early Miocene that resulted in uplift of central Borneo to supply sediment to the Sabah Trough whilst the input of material derived from the western terrains diminished. The Temburong Formation was sourced by reworking of uplifted Rajang Group, Sapulut or Trusmadi formations.

KEYWORDS
deep water Temburong Formation, volcaniclastic tuff, zircon dating
1 | INTRODUCTION

Subaqueous tuffs are unusual in that diagnostic evidence confirming their presence is often lacking because of post-depositional alteration (Thurow & von Rad, 1992; White & Busby-Spera, 1987). They are commonly identified on the basis of an abundance of smectitic minerals, although this is dependent on the mineralogy of the original deposit. The significance of subaqueous tuffs is that they are contiguous with the enclosing sediments and their alteration is essentially syn-depositional so they are therefore ideally suited for dating the enclosing sedimentary sequences.

A smectite-rich tuff bed is described from the Temburong Formation on the southern part of the island of Labuan, off the Malaysian coast of Sabah in Borneo (Figure 1). The Temburong Formation is a deep water turbidite deposit which is the time equivalent of the better known West Crocker Formation (WCF), one of the largest Palaeogene to Neogene sedimentary deposits of South-East Asia (Crevello, 2006; Hattum et al., 2013; William et al., 2003; Zakaria et al., 2013). The smectite-rich bed is interpreted as an altered volcaniclastic turbidite deposited in deep water. It is dated in this study by zircon U–Pb geochronology as early Miocene, between ca 19 and 21 Ma, which is consistent with new biostratigraphic data presented herein from the same sequence.

Although the WCF and the Temburong Formation are commonly interpreted as being deposited contemporaneously with active subduction of the Proto-South China Sea (PSCS) (Hall, 2013a; Hall & Breitfeld, 2017; Hattum et al., 2013; Hutchison, 2005), no evidence of volcaniclastic intervals or volcanic detritus has been recorded from these sequences thus far. The presence of extrusive volcanic activity at this time has significant implications for the tectonic evolution of the western margin of Borneo.

This paper focusses on the geological setting of the smectite-rich bed and considers the provenance of sandstones associated with it to demonstrate that the smectite-rich bed has a short lived, local magmatic provenance. This volcanism is a result of either a large eruptive event at the end of the PSCS subduction or a very short-lived magmatic event related to deep-seated faults, extension and denudation processes, most probably in the Sintang Suite of central Borneo or in the East Kalimantan gold belt.

2 | GEOLOGICAL CONTEXT AND SIGNIFICANCE OF THIS WORK

The stratigraphy of Labuan Island documents the first period of northerly progradation of the North-West Borneo margin during the Palaeogene into the Neogene (Hutchison, 2005; Jackson et al., 2009; Lee, 1977; Levell, 1987; Madon, 1994; 1997; Rice-Oxley, 1991; Zakaria et al., 2013). The geology of the island is dominated by the NNE-SSW trending Labuan Anticline (Figure 1), initiated in the Late Oligocene but continuously active through to the Middle Miocene in response to collision between the Reed Bank-Dangerous Grounds continental fragment and North-West Borneo (Hutchison, 2005; Madon et al., 1999). Indeed, the very presence of the island is a consequence of the steep, narrow Labuan Anticline that strikes along the centre of the island, typical of other similar anticlines separated by broad synclines in the offshore Sabah Basin. The adjacent Labuan-Paisley Syncline contains in excess of 8 km of gently folded Miocene and Pliocene sediments (Vliet et al., 1987; Wong, 1997).

The lower-most stratigraphic unit in Labuan is the Temburong Formation, which is the focus of this study. The Temburong Formation is considered to consist of deep water deposits of mostly Oligocene to early Miocene age, well known from onshore Brunei (Tjia, 2016), western Sabah (Burgan & Ali, 2009; Wilson & Wong, 1964; Zakaria et al., 2013), Labuan Island (Madon, 1997; Simmons et al., 1999;
Wilson & Wong, 1964) and the adjoining islands of Rusukan and Kumaran where turbidite sandstone sequences are described (Crevello et al., 2005).

The Temburong Formation was first introduced as a stratigraphic term by Brondijk (1962) and revised by Wilson and Wong (1964). The formation as originally described is dominantly argillaceous, characterised by a rhythmic repetition of siltstones and mudstones, and is remarkably uniform in these lithologies (Hutchison, 2005). Wilson and Wong (1964) recognised sedimentary structures indicative of deposition from turbidity currents, including erosive bases, graded bedding and flute and groove casts in the siltstones. The Temburong Formation is widely interpreted to have been deposited in bathyal conditions in several hundreds of metres to kilometres of water depth (Johnson & Huong, 1988; Madon, 1997; Tate, 1994; Wilson & Wong, 1964). In addition, the occurrence of debris flow deposits within the unit and widespread soft sediment deformation provide evidence for active slope failure and contemporary periodic growth of the Labuan Anticline during deposition of the Temburong Formation (Jackson & Johnson, 2009; Madon, 1994). In the south-western part of Sabah, the Temburong Formation contains slumped olistoliths and stratigraphically reworked microfossils and lithic-clastics (Lunt & Madon, 2017).

The Temburong Formation is unconformably overlain by the fluviol-deltaic to shallow marine Belait Formation and the enigmatic Layang-Layangan Beds (Abdullah et al., 2013; Lukie & Balaguru, 2012; Madon, 1994; Wilson & Wong, 1964). Hutchison (2005) divided the Temburong Formation into four separate units, an older Kiamsam series at the core of the anticline, followed by progressively younger Limbayong, Sabong and the Layang-Layangan Beds. In the Temburong River valley area of eastern Brunei the Temburong Formation occurs directly below the early Miocene shallow water Meligan Formation (Hutchison, 1996; Wilson & Wong, 1964). The Layang-Layangan Beds that underlie the basal conglomerates of the Belait Formation in the northern part of Labuan Island were first ascribed to the Temburong Formation (see Brondijk, 1962; Hutchison, 2005; Lee, 1977; Madon, 1994) largely based on their position beneath the conglomerate interval. However, Wilson and Wong (1964) considered them part of the Belait Formation, a view supported by limited geochemical data (Albaghdady et al., 2003; Gou & Abdullah, 2010) which indicates that the Layang-Layangan Beds have some geochemical similarities to the Belait Formation. Hennig-Breitfeld et al. (2019) followed this interpretation and informally renamed the Layang-Layangan Beds the Lower Belait Formation. The end of deep water sedimentation in North-West Sabah, which coincides with the top of the Temburong Formation, is generally considered to be demarked by the Top Crocker Unconformity (TCU) shown as 25 Ma in Hattum et al. (2013) and described as 19–20 Ma by Hall (2013a). The change from the Layang-Layangan Beds to the Belait Formation is generally interpreted to represent the Deep Regional Unconformity (DRU), an unconformity well known from seismic sections offshore Sabah (Abdullah et al., 2013; Lukie & Balaguru, 2012; Madon, 1994).

The Late Oligocene and Early Miocene was a period of micro-continental fragment collision with the western edge of Borneo (Hall, 2013a; Hattum et al., 2013; Pubellier & Morley, 2014). Subsequently, vast amounts of siliciclastic sediments, estimated to be 12 km in thickness, were rapidly deposited in the marginal basins in and around Borneo throughout the Neogene (Hall et al., 2002; Hamilton, 1979).

Dating the altered, syn-deposition subaqueous tuff within the Temburong Formation by zircon U–Pb geochronology as between 19 and 21 Ma not only establishes the youngest age for the Temburong Formation, but moreover confidently pushes the age of deep water sedimentation in Sabah well into the Early Miocene, thus indicating subduction of the PSCS was on-going into the Burdigalian.

3 | SAMPLES AND METHODS

Outcrops of the Temburong Formation on the western coast of Labuan and on the nearby islands of Kumaran, Rusukan Besar and Rusukan Kecil (Figure 1) were logged to produce lithological and grain-size sedimentary logs of the exposed Temburong Formation in the vicinity of Labuan (Figure 2). Additionally, a sandstone sample was taken from the Layang-Layangan Beds on the western coast of Labuan to represent the youngest potential Temburong Formation sequence. The smectite-rich bed within the Temburong Formation occurs on the south-western coast of Labuan at Kiamsam shore (Figure 1; grid reference 5°14′57.74″N 115°9′44.75″E) and is approximately 2 m thick in the exposed section. This section was logged at high resolution, photographed and 12 representative samples were taken from the smectite-rich bed and enclosing shales (Figure 3, Table 1). To provide a broader stratigraphic context, samples from the Temburong Formation on Rusukan Besar Island and at Beboluh quarry in the south-west part of Labuan were also taken. A simple stratigraphic correlation between these sections was created based on measured and projected strike directions observed from Google Earth images of the foreshore and shallow offshore assuming that there are no unrecognised folds in the section (Figure 2). Although this is only an approximation, it places the samples in a stratigraphic order over about 1.4 km of vertical section so that the biostratigraphic data can be plotted as a sequence (Table 1).

Representative material was collected from the smectite-rich bed as well as the overlying and underlying Temburong Formation shales for petrographic, mineralogical and biostratigraphical studies. The samples of the tuff bed
FIGURE 2  Measured sections in the Temburong Formation from Kiamsam shore, Bebuloh quarry, Rusukan Kecil and Ruskan Besar arranged in approximate depth order, assuming the sections are along strike. Note the tuff bed logged some 220 m from the base of the Kiamsam shore section.
**FIGURE 3** Detailed measured section of the tuff bed from Kiamsam shore. The tuff bed (between 160 and 330 cm) is enclosed in marine mudstones with a distinctive *Nereites* ichnofacies recognised by the presence of meandering and spiral grazing burrows and *Tubotomaculum* dwelling burrows. The tuff bed is 1.7 m in thickness and capped with an associated sandstone that erodes into the uppermost part of the tuff. Study samples are shown on the left side of the measured log, cf Tables 1 and 2

| cm  | Lith       | Grain size               | Description                                                                                                                                                                                                 |
|-----|------------|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 0   |            |                          | Grey to dark grey, laminated, silty mudstones with patchy carbonate cements and thin, fine grained, rippled sandstones characterised by sharp bases and tops.                                                     |
| 50  |            |                          | Fine to medium grained, cross-bedded dark grey coloured sandstone with a sharp erosive base (down cutting by up to 20cm) and containing pebble-sized rip-up mud clasts. Small sub-vertical burrows common. |
| 100 |            |                          | Generally pale green to cream coloured, alternating soft and indurated siliceous clay-rich beds (on a 3-5cm spacing) containing angular floating grains of very fine to fine grain size. The more indurated beds have undulatory tops and sharp bases. |
| 150 |            |                          | Upper section includes a highly indurated, brown coloured, fractured mudstone bed (5cm in thickness) with a sharp top and base. The topmost 20cm comprise dark bluish-grey to reddish brown mottled silty mudstones with lenses of carbonaceous material and *Ophiomorpha nodosa* burrows. The basal 10cm section is cut by numerous fibrous calcite veins ('beef') oriented more-or-less parallel to the bed base. |
| 200 |            |                          | Predominantly dark grey non-calcareous mudstones, generally poorly laminated, but with infrequent carbonaceous lenses and laminae, interbedded with thin silty to very fine grained sandstone lenses and beds. Section is largely devoid of bioturbation except for occasional grazing trails and possible bioglyphs, and distinct siderite cemented *Tubotomaculum* burrows with pellet coatings. Rare *Palaeodictyon* present on weathered slabs. Stratabound siderite concretions common, invariably cementing *Tubotomaculum* burrows. |
| 250 |            |                          | Fine grained, pale cream to buff coloured, laminated and rippled sandstone with calcareous cement concentrated in bed centre. Sharp top and base, no obvious grain size variation, bioturbation absent. |
| 300 |            |                          | Dark grey, laminated mudstone.                                                                                                                                                                                   |
| 350 |            |                          |                                                                                                                                                                                                              |
| Sample reference | Nominal position (m) | Description | Analysis |
|------------------|----------------------|-------------|----------|
| LL1              | 1,400                | Fine to medium-grained laminated and rippled sandstone in thickest package of thin beds, | Petrography, XRD, ZU-Pb |
| BB2              | 1,204                | Fine to medium-grained laminated and rippled sandstone in thickest package of thin beds, upper quarry face | Petrography, XRD |
| BB1              | 1,200                | Dark grey, laminated pelagic shale above last thin-bedded lobe sandstone package, upper quarry face | Biostrat, including palynology |
| RB8              | 1,067                | Carbonate-cemented, fine-grained sandstone from centre of channel sand | Petrography, XRD, ZU-Pb |
| RB7              | 1,062                | Dark grey, laminated, pelagic shale 70 m above the top of the main channel sand | Biostrat, including palynology |
| RB6              | 1,042                | Dark grey, laminated, pelagic shale 50 m above the top of the main channel sand | Biostrat, including palynology |
| RB5              | 992                  | Dark grey, laminated, pelagic shale 10 m above the top of the main channel sand | Biostrat, including palynology |
| RB4              | 883                  | Dark grey, laminated, pelagic shale 1 m above the top of the main channel sand | Biostrat, including palynology |
| RB3              | 983                  | Carbonate-cemented, fine-grained sandstone from centre of main channel sand | Petrography, XRD, ZU-Pb |
| RB2              | 982                  | Laminated, erosive base of fine-grained sandstone eroding into the underlying shale | Petrography, XRD, ZU-Pb |
| RB1              | 973                  | Organic matter-rich, dark grey laminated shale 1 m below base of basal sandstone | Biostrat, including palynology |
| RK2              | 855                  | Medium-grained sandstone from centre of channel at western end of island | Petrography, XRD, ZU-Pb |
| RK1              | 840                  | Medium-grained sandstone from centre of channel at western end of island | Petrography, XRD, ZU-Pb |
| KSF14             | 340                  | Fine-grained, massive, porous sandstone at top end of section | Petrography, XRD, ZU-Pb |
| KSF13             | 310                  | Dark grey, deformed pelagic shale from MTD above the massive sandstone | Biostrat, including palynology |
| KSF12             | 290                  | Fine to medium-grained, massive sandstone at younger end of section | Petrography, XRD, ZU-Pb |
| KSF11             | 252                  | Dark grey, laminated pelagic shale 24 m above the tuff horizon | Biostrat, including palynology |
| KSF10             | 228                  | Dark grey, laminated pelagic shale immediately above the tuff horizon | Petrography, XRD, XRF |
| KSF9              | 228                  | Laminated, erosive base of coarse to medium-grained sandstone eroding into the upper part of the tuff | Petrography, XRD, ZU-Pb |
| KSFT6             | 228                  | Red-brown, massive tuff horizon | Petrography, XRD |
| KSFT5             | 227                  | Fine-grained, prominent hard tuff bed | Petrography, XRD, XRF |
| KSFT4             | 226                  | Fine-grained, soft tuff bed | Petrography, XRD, XRF |
| KSFT3             | 226                  | Fine-grained, prominent hard tuff bed | Petrography, XRD, XRF |
| KSFT2             | 226                  | Fine-grained, whitish-green, laminated tuff bed | Petrography, XRD, XRF |
| KSFT1             | 226                  | Calite veins at base of tuff bed | Petrography, XRD |
| KSF8              | 226                  | Red-brown, indurated shale, immediately below the tuff bed | Biostrat, including palynology |
| KSF7              | 226                  | Dark grey, laminated, pelagic shale 1.2 m below the tuff bed | Biostrat, petrography, XRD, XRF |
| KSF6              | 218                  | Siderite concretion in dark grey pelagic shale with siderite concretion 1.48 m below the tuff bed | Petrography, XRD |

(Continues)
were impregnated with blue-dyed epoxy and thin sectioned for optical petrography. Photomicrographs were taken of all lithologies and supplemented with scanning electron microscope (SEM) images to characterise the fabric and mineralogy of the tuff. The SEM micrographs were taken with a digital imaging system attached to a FEI Quanta FEG250 SEM operating at an accelerating voltage of 15 kV. Qualitative elemental compositional analysis using an interfaced Thermo Fisher Noran System 7 Energy Dispersive Spectroscopy (EDS) unit was used to identify minerals present based on the concentration of their major elements.

The grain size of the Temburong Formation sandstone samples was determined using a Malvern Mastersizer® laser diffraction system. Samples for laser particle size analysis (LPSA) were cleaned with toluene solvent and disaggregated using a rubber pestle and mortar. From the disaggregated sand a 2 g sub-sample was dispersed in 75 ml of 1,000 ppm concentration sodium hexametaphosphate dispersant solution. Particle size distributions across the size range of 0.02–2,000 µm are measurable with this instrument.

The enclosing shales and tuff bed were analysed by x-ray diffraction (XRD) and x-ray fluorescence (XRF) to determine their mineralogy and geochemistry, respectively. The XRD analyses of the samples were performed using a powder diffractometer equipped with a Cu radiation source (40 kV, 40 mA). Whole rock samples were analysed over an angular range of 2–60 degrees 2-theta at a scan rate of one degree/minute. Air-dried and glycol-solvated clay fraction mounts were analysed over an angular range of 2–50 degrees 2-theta at a rate of 1.5 degrees per min.

The XRF analyses were performed on a 2010 PANalytical Axios sequential XRF spectrometer with 4 kW Rh-anode X-ray tube. The tuff and associated mudstone samples were processed and homogenised with a tungsten-carbide mill. Major elements were analysed on fusion discs using the La₂O₃-bearing Spectroflux 105, and trace elements on pressed pellets with matrix corrections calculated from the major elements. Multiple heating steps of fusion discs were performed to determine and account for loss on ignition. The XRF data tables for analysed samples are presented in Table 2. An artificial glass bead was analysed every third sample to correct for instrumental drift, which was at the <1% level. Thirty to 40 international rock standards were used for calibration. Calibration graphs are publicly available at https://www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/earth-sciences/research-laboratories/x-ray-fluorescence-laboratory/. The quality of the straight line fit of these graphs is the best indicator of accuracy over a wide range of concentrations. Where there is more scatter, this can reflect poor precision of the XRF analyses relative to the calibrated concentration range (e.g. Sn, where precision is ca ± 2 ppm, and the calibrated range only 15 ppm); inaccuracies in the published standard data (e.g. S, Cl), or inaccuracies in the XRF data (e.g. at < 100 ppm F).

The biostratigraphy of the enclosing shales above and beneath the smectite-rich bed was also studied to provide an independent assessment of the age range of the Temburong Formation in the outcrop sections. Four samples were taken below the tuff (KSF2 to KSF7), whilst the remainder were sampled above the tuff bed and are considered to be stratigraphically younger (Table 1). For each sample, the total number of foraminifera recovered from 30 g of sediment, and the total number of nannofossils on six traverses of a prepared nannofossil analysis slide, were recorded.

Five sandstone samples were analysed to determine detrital zircon U-Pb ages of the Temburong Formation and test for any contemporaneous magmatism. Friable samples were crushed using a pestle and mortar, while indurated samples were ground with a carbide-tungsten disk mill. A 63–250 µm fraction was separated by washing and sieving. Standard heavy liquids lithium heteropolytungstate at a density of 2.89 g/cm³ and di-iodomethane at 3.3 g/cm³ were used for heavy mineral separation. A FRANTZ magnetic barrier separator was also used to maximise the purity of the zircon separates.

Zircons were dated with U-Th-Pb LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) at Birkbeck College, University of London with a NWR 193 laser ablation system coupled to an Agilent 7700 quadrupole-based plasma mass spectrometer (ICP–MS) with a
|    | KSF7 Mudstone | KSF2 Tuff | KSF3 Tuff | KSF4 Tuff | KSF5 Tuff | KSF10 Mudstone |
|----|---------------|-----------|-----------|-----------|-----------|----------------|
| SiO₂ | 65.13         | 73.60     | 78.41     | 68.52     | 79.64     | 78.75          |
| Al₂O₃ | 18.75         | 16.73     | 13.00     | 14.34     | 14.30     | 10.81          |
| Fe₂O₃ | 6.33          | 2.39      | 2.25      | 6.42      | 1.53      | 4.42           |
| MgO  | 2.44          | 1.88      | 1.54      | 2.18      | 1.55      | 1.33           |
| CaO  | 0.50          | 2.71      | 2.32      | 5.48      | 0.25      | 0.13           |
| Na₂O | 1.11          | 1.59      | 0.96      | 1.02      | 1.14      | 1.08           |
| K₂O  | 3.75          | 0.34      | 0.41      | 0.27      | 0.37      | 2.00           |
| TiO₂ | 0.778         | 0.270     | 0.210     | 0.194     | 0.176     | 0.523          |
| MnO  | 0.072         | 0.049     | 0.036     | 0.204     | 0.008     | 0.016          |
| P₂O₅ | 0.113         | 0.046     | 0.043     | 0.036     | 0.036     | 0.067          |
| SO₃  | 0.054         | 0.056     | 0.007     | 0.091     | 0.029     | 0.119          |
| Total| 99.02         | 99.65     | 99.24     | 98.76     | 99.02     | 99.25          |
| LOI  | 6.32          | 6.90      | 6.21      | 10.91     | 4.26      | 6.23           |
| Ni   | 44.3          | 4.1       | 4.8       | 3.6       | 65.4      |                |
| Co   | 14.0          | <1.3      | <1.3      | <1.3      | 21.3      |                |
| Cr   | 103           | 4         | 5         | 5         | 58        |                |
| V    | 159           | 13        | 12        | 13        | 89        |                |
| Sc   | 19.2          | 3.1       | 2.9       | 4.1       | 10.3      |                |
| Cu   | 31            | 5         | 6         | 5         | 28        |                |
| Zn   | 113           | 54        | 43        | 46        | 70        |                |
| As   | 10.4          | <1.0      | 1.0       | 1.0       | 39.3      |                |
| S    | 6,006         | 492       | 458       | 473       | 16,336    |                |
| F    | 673           | 582       | 526       | 532       | 584       |                |
| Cl   | 2,682         | 2,195     | 1,431     | 1,386     | 494       |                |
| Br   | 6.9           | 7.4       | 5.8       | 5.7       | 2.5       |                |
| Ga   | 22.4          | 18.3      | 17.5      | 16.6      | 11.6      |                |
| Pb   | 22.1          | 30.2      | 23.2      | 25.0      | 54.3      |                |
| Sr   | 106.6         | 69.5      | 69.2      | 42.0      | 58.1      |                |
| Rb   | 184           | 5         | 5         | 9         | 92        |                |
| Ba   | 268           | 84        | 140       | 142       | 260       |                |
| Zr   | 231.2         | 211.2     | 159.8     | 141.3     | 190.9     |                |
| Nb   | 13.5          | 9.6       | 7.2       | 7.2       | 9.4       |                |
| Ta   | 2.0           | 3.5       | 3.5       | 3.6       | 2.6       |                |
| Mo   | <1.5          | <1.5      | <1.5      | <1.5      | 2.6       |                |
| Th   | 14.6          | 25.9      | 26.3      | 26.0      | 11.7      |                |
| U    | 3.4           | 5.5       | 3.6       | 5.9       | 3.1       |                |
| Y    | 26.0          | 36.8      | 49.7      | 37.2      | 20.9      |                |
| La   | 34.2          | 26.2      | 26.8      | 27.3      | 21.2      |                |
| Ce   | 70            | 60        | 59        | 58        | 48        |                |
| Nd   | 30.6          | 25.7      | 26.0      | 25.0      | 22.2      |                |
| Sm   | 6             | 6         | 7         | 6         | 4         |                |
| Yb   | 3.7           | 4.0       | 4.1       | 4.1       | 3.9       |                |
| Hf   | 6.9           | 8.1       | 6.9       | 6.5       | 5.9       |                |
| Cs   | 15            | <1.5      | <1.5      | 2         | 7         |                |
| Sn   | 2             | 6         | 7         | 4         | 3         |                |

**TABLE 2** XRF data from the tuff bed on Kiamsam shore and enclosing marine Temburong Formation shales, see Figure 3 for stratigraphic position.
two-cell sample chamber. Zircons were imaged in transmitted light and with secondary electron microscopy cathodoluminescence (SEM-CL) to avoid inclusions or cracks for the analysis spot selection, and to identify internal zonation of zircons. Laser spot size was 25 μm. The Plešovice zircon standard (337.13 ± 0.37 Ma; Sláma et al., 2008) and a NIST 612 silicate glass bead (Pearce et al., 1997) were used for calibration. GLITTER software (Griffin et al., 2008) was used for data reduction and the common lead correction method of Andersen (2002) for 204Pb common lead-independent analysis. The age obtained from the 207Pb/206Pb ratio is given for grains older than 1,000 Ma. For ages younger than 1,000 Ma, the age obtained from the 238U/206Pb ratio is given, because 207Pb cannot be measured with sufficient precision in these samples resulting in large analytical errors (Nemchin & Cawood, 2005). Concordance was tested by using a 10% threshold between the 207Pb/206Pb and 206Pb/238U ages for ages greater than 1 Ga and for ages below 1 Ga between the 207Pb/235U and 206Pb/238U ages. The data are displayed in age histograms with probability density plots created using an R script written by Inga Sevastjanova based on the approach of Sircombe (2004) for calculating probability density. The Tera-Wasserburg plot and the weighted mean age calculation were done in Isoplot 4.15 (Ludwig, 2008).

4 | RESULTS

4.1 | Facies of the Temburong Formation

Extensive sections through the Temburong Formation are exposed in the core of the Labuan Anticline (Figure 1) which extends broadly north-east to south-west through the centre of the island. As a result, much of the Temburong Formation sequence is exposed on the southern coast of the island of Labuan and southwards on strike to the small islands of Kuraman, Rusukan Besar and Rusukan Kecil, 6–8 km south-west of Labuan Island. An additional section in Kampung Bebuloh quarry on the south-west of Labuan exposes a slightly younger part of the sequence on the eastern limb of the anticline (Figure 1). As these sections are broadly on strike, together they expose a stratigraphic sequence of ca 1.4 km through the Temburong Formation.

All the exposed sections of the Temburong Formation are dominated by thin-bedded, fine-grained sandstone beds, sometimes attaining medium-grain size, dominantly in the range of ca 5–20 cm in thickness, interbedded with mudstones which contain continuous bands and nodules of siderite (Figure 4). At Kiamsam, these beds are near vertical to overturned on the eastern side of the anticline, providing ca 350 m of continuous exposed section at low tide (Figure 4A). Each thin-bedded sandstone is sharp-based, typically very fine to fine-grained, occasionally medium-grained, and characterised by planar laminations, ripple lamination and disturbed ripple lamination, representing the Tb-Tc part of the Bouma (1962) turbidite sequence in a waning order of sedimentary structures (sensu Kneller et al., 1995). Ripple laminations are usually lined with carbonaceous material. Climbing ripples and starved ripples are also common, occurring in approximately 10% of beds. Scour and flute marks on the base of individual beds are frequently observed. Palaeocurrent data measured on these current indicators are all broadly N–S (ripples range 332° through 070°; flutes 228° through 036°; grooves 348°-064°; primary current lineations 353°-022°). The thin-bedded sandstones are not uniformly distributed through the measured sections but clusters, often spatially associated with thicker sandstones beds up to 2 m in thickness, are present. Such clustering is well developed in Kampung Bebuloh quarry where bed thickness and concentration are distinctly organised into sandstone-rich and sandstone-poor sections.

Thicker sandstones, often with mud clast-rich basal lags, and more commonly reaching medium-grain size, are sporadically developed in the Temburong Formation sequence (Figure 5). Individual sandstones are 0.4 to ca 1 m in thickness, but commonly amalgamate into sandstone packages which attain 2–3 m in thickness. These thicker sandstones vary from massive to parallel laminated, passing into wavy-bedded hummocks and climbing ripples with dish structures. The 35 m thick sandstone package at the base of the Rusukan Kecil section comprises stacked and amalgamated, fine to medium-grained sandstone beds characterised by sharp, erosive bases and predominantly parallel laminations. Carbonaceous clasts are common throughout these sandstones but especially so near the top of the succession.

Within all outcrop sections there are mudstone-dominated sequences in which the occurrence of thin sandstone and siltstone beds is substantially reduced. The mudstones are generally poorly laminated, but contain frequent carbonaceous lenses, interbedded with thin silty to very fine-grained sandstone lenses. Most of the mudstones are medium to dark grey in colour, often containing high concentrations of organic matter. Large scale slumps and intraformational folds are developed in the mudstone-dominated sequences, spectacularly so in the upper part of the Kampung Bebuloh quarry, and in the south shore section on Rusukan Besar (Figure 5B).

The Rusukan Besar section is characterised by thin-bedded sandstones dominantly in the range of ca 5–20 cm in thickness interbedded with mudstones of comparable thickness which contain continuous bands and nodules of diagenetic siderite. The outcrop is less well exposed than the Kiamsam section making detailed observation of the section generally difficult, but the bedding style is clearly laterally continuous over the ca 650 m length of the shoreface. Where well exposed, the thin-bedded sandstone section is similar to that of the Kiamsam section, being sharp-based, fine to very fine-grained
FIGURE 4  Representative photographs of Temburong Formation thin-bed sedimentology and tuff bed. (A) Wide angle view of Kiamsam shore showing very steeply dipping thin-bedded distal turbidite sandstones in a mudstone-dominated sequence. Kuraman (right) and Rusukan Kecil (left) islands visible on the skyline. (B) Detail of an individual thin sandstone bed showing the sharp base, rippled fine-grained sandstone and laminated woody organic matter-rich top. (C) The tuff bed showing the green to orange-brown banding and sharp base. Note the contrast in colour with the enclosing normal marine mudstones.
(occasionally medium-grained) and characterised by planar and ripple lamination sedimentary structures in a waning sequence. Within the packages of thin beds glide surfaces, slumping, folds and fold noses are present (Figure 5B).

At the top of the thin-bedded sequence a small erosive-based channel storey (sensu Groenenberg et al., 2010; Prélat et al., 2009) is developed with an approximate width of 155 m and thickness of 1.5 m at the axis. The vertical profile of the channel includes amalgamation surfaces, dewatering structures (flames, pipes and dishes; see Figure 5C) and syn-depositional deformation of sedimentary structures, all of which point to rapid deposition of frequent turbidity current events, closely spaced in time, that passed through the channel. The presence of transported siderite clasts within the body of the channel sandstones indicates erosion up-dip from this location.

Above the channel interval is a 105 m thick shale-dominated section that contains thin, continuous silty bands. The top part of this section is remobilised as a mass transport deposit (MTD). The rugose upper surface of the MTD contains discrete and discontinuous bands of sandstones that heal the topography created by the MTD. The poorly exposed section above this MTD contains multiple highly deformed MTDs. At the top of this section there is a ca 14 m thick channel (at axis) that is approximately 600 m in lateral extent. On the present-day seabed, approximately 230 m offshore, the base of the channel can be seen on Google Earth images to erode into the underlying shale substrate.

Ichnological traces in the Temburong Formation comprise a low-diversity, low faunal size-range population and low ichnological trace population abundance (Figure 6), comparable to that described by Jasin and Firdaus (2019). The overall bioturbation index (sensu Taylor & Goldring, 1993) of the section is low, typically 0–1, but is locally very high, reaching 5–6. Where the bioturbation index is what enigmatic. The channel dimensions (14 m by 630 m) give an aspect ratio of 1:45 which is consistent with a mid-slope. The aspect ratio can therefore be used to infer degree of confinement which can be used as a proxy for position relative to the break of slope. The channel towards the top of the section is somewhat enigmatic. The channel dimensions (14 m by 630 m) give an aspect ratio of 1:45 which is consistent with a mid-lower slope channel, comparable to the interpretation for the western part of the section.

The overall arrangement of the sandstone architecture indicates low energy, waning flows deposited in a distal position with respect to channel axis. The disturbed and folded mudstone-dominated sections represent large slumps and MTDs, confirming deposition on a continental slope setting. The water depth for the Temburong Formation is very clear from foraminiferal analyses of the studied samples. It can be defined on the one hand by reference to published foraminiferal assemblages at measured water depths from the Snellius II expedition results (Marle, 1989), and on the other by comparison with foraminiferal analyses of ‘top’ seafloor samples from recent sea floor studies (Orange et al., 2010). The regular presence of the agglutinated foraminifera Glomospira gordialis and Rhabdammina spp., together with the calcareous benthonics Globocassidulina spp., Stilostomella spp., Cibicidioides bradyi and Planulina wuellestorfi, indicate water depths of at least 500 m, based on van Marle (1989). The presence of Spirolectammina spp.,
**Figure 5** Representative photographs of Temburong Formation sandstone sedimentology. (A) The amalgamated, stacked sandstone channels from Rusukan Kecil, up to 35 m in thickness. (B) Folded 1 m thick sandstone bed defining a north-westward dipping slump, Rusukan Besar. (C) Detail of an amalgamated channel sandstone body from the lower part of the Rusukan Besar section. (D) Sedimentary structures of two thin sandstone beds showing sharp bases, climbing ripples and asymmetrical rippled tops with Bouma (1962) Tc (lower bed) and Tb-Tc (upper bed) units.
**4.3 | The smectite-rich tuffaceous bed**

The smectite-rich bed occurs approximately mid-way in the Kiamsam shore section (Figures 1 and 2). The tuff is 1.7 m in thickness at the high water mark, but when exposed across the shoreface at low tide, varies in thickness up to 2 m along strike. In outcrop the smectite-rich bed displays centimetre-banded bedding, alternating between soft, pale green to cream coloured clay and a more indurated orange-brown clay, the latter weathering proud (on a 3–5 cm spacing), containing very fine to fine-grained, angular fragments of predominantly silica, and more rarely, K-feldspar, floating in the clay matrix (Figures 3 and 4C). The more indurated beds have undulatory tops and sharp bases and have the appearance of being a relict depositional feature (Figure 4C). The bedded section of the smectite-rich bed contains intra-bed open folds which do not extend to the top of the unit, and are not present in the basal part, indicating syn-depositional slumping or folding. The basal 10 cm section is cut by numerous fibrous calcite veins (‘beef’) oriented more-or-less parallel to the bed base. The base of the bed is planar and sharp but not obviously erosive and sits above 20 cm of reddened marine mudstone which is highly indurated and fractured. The topmost 20 cm of the smectite-rich unit comprises dark bluish-grey to reddish brown, mottled, silty mudstones with lenses of carbonaceous material and vertical Ophiomorpha nodosa burrows and drapes the banded part of the smectite-rich bed.

The smectite-rich bed is capped by a fine to medium-grained, cross-bedded, dark grey coloured sandstone with a sharp erosive base (down-cutting by up to 30 cm) and containing pebble-sized rip-up mud clasts (Figure 3). This sandstone erodes down into the uppermost few centimetres of the smectite-rich bed and incorporates fragments of it as granules. Small, centimetre-length, cylindrical sub-vertical burrows are common in this sandstone. The smectite-rich bed and this cross-bedded sandstone cap contrast with the enclosing marine mudstones and the typical Temburong Formation sandstones in terms of appearance, colour, sedimentology, mineralogy and geochemistry.

**4.4 | Mineralogy and geochemistry of the Temburong Formation**

**4.4.1 | Mineralogy of Temburong Formation marine mudstones**

Petrographically, the marine mudstones always contain a significant silt component and exhibit a microscale lamination which results from the abundant woody organic matter contained within the mudstone (Figure 7A), common in Miocene mudstones offshore Borneo (Saller et al., 2006), suggesting these mudstones include fine-grained material deposited from waning turbidite plumes. A SEM examination of these mudstones confirms the detrital nature of the clay, being dominated by irregular clay plates of 2–3 μm in diameter (Figure 7B), mixed with minor authigenic pyrite and siderite. Clay fraction XRD confirms the presence of quartz representing the silt-grade material, and indicates the <2 μm clay fraction is dominated by illite with subordinate kaolinite and chlorite (Figure 7C). The air-dried illite peak typically has a small high d spacing asymmetry which is removed on heating to 440°C, suggesting the presence of a small proportion of expandable material. Semi-quantitative
estimates of clay proportion indicate that illite comprises 60%–70% of the clay mineral assemblage, kaolinite 20%–30% and chlorite is ca 10%. There is no discernable change in mudstone mineralogy with changes in colour, with the indurated, reddish-coloured mudstones beneath the tuff bed being characterised by the same mineral assemblage.

**FIGURE 6** Details of the *Nereites* soft-ground ichnofacies typical of the Temburong Formation in Labuan. (A) Small horizontal *nereites* burrows on the base of a thin-bedded sandstone with current flutes. (B) Meandering *Cosmoraphe*-type burrows on the base of a sandstone bed. (C) *Palaeodictyon* colony on the top of a thin-bedded sandstone. (D) Branching *chondrites*-type burrow network. (E) Rare vertical burrow. (F) Pelleted, siderite-replaced *Tubotomaculum* burrow preserved with mudstone. Scale bar in cm (A through D), boot and lighter for scale in (E) and (F), respectively.
4.4.2 | Mineralogy of the Temburong Formation sandstones

Most of the sandstones from the Temburong Formation examined in thin section are moderately well sorted, very fine to fine-grained and variably argillaceous (Figure 8A). Laser grain-size analysis indicates that 50%–70% of the detrital components are fine to very fine-grained sand in most of the sandstones (Figure 8B). Thin sections from the base of the thicker sandstone beds document that they also contain mud clasts. Petrographically, all the sandstones are dominated by well rounded, monocrystalline detrital quartz grains, with a subordinate proportion of detrital feldspar (ca 5%) together with various altered and opaque grains (Figure 8A) and woody material. Many of the detrital feldspar grains exhibit partial alteration to kaolinite, and the presence of occasional oversized pores suggests that some detrital feldspar...
FIGURE 8  Representative petrography and mineralogy of the Temburong Formation sandstones (KSF12). (A) Plane polarised thin section micrograph showing the moderately well sorted grain size dominated by detrital quartz. Purple authigenic cement is alizarin red-S stained ferroan calcite cement which post-dates quartz overgrowth cementation. Blue is intergranular porosity revealed by coloured epoxy. (B) Laser particle cumulative grain-size plot for a typical sandstone showing the dominance of fine to very fine-grained detrital sand grade material. (C) Clay fraction XRD trace dominated by illite
grains have been dissolved during diagenesis. The angular appearance of some of the quartz grains is due to the presence of diagenetic quartz overgrowths.

The bulk XRD analysis of these sandstones confirms the quartz-dominated mineralogy, whilst the clay fraction XRD analysis indicates a dominance of illite with subordinate kaolinite and chlorite (Figure 8C), comparable to the marine mudstones.

4.4.3 | Mineralogy of the smectite-rich bed

In thin section the smectite-rich bed comprises a largely unstructured matrix of clay-grade smectite exhibiting a low refractive index and moderate birefringence, including up to second-order colours, containing abundant siliceous angular fragments which commonly have crescentic, sickle-shaped, or bi-concave outlines, typical of volcanic glass shards. Much of the matrix material exhibits a spurious buff colour in thin section with a well developed mottled appearance (Figure 9A), suggestive of a relic texture. A SEM examination of several samples of freshly broken tuff surfaces indicates the matrix clay is dominated by small (<5 µm) flake-like plates of irregular shape with common whispy projections. Although the matrix is the dominant constituent, many angular fragments are also present. Most of these are optically and compositionally silica, although a significant proportion are brown or green coloured and moderately birefringent; EDS analyses reveals these coloured fragments contain Na, Mg and Fe, whilst a few colourless fragments are compositionally consistent with K-feldspar. Some of the feldspars are partially dissolved, and contain secondary intragranular pores.

The XRD analysis of the clay fraction confirms that the smectite-rich bed is dominated by a 12.4 Å basal spacing smectite which expands on glycolation to a basal spacing of between 16 and 17 Å (Figure 9C). The absence of higher d spacing refractions supports an interpretation that the clay is predominantly smectite rather than a mixed-layer combination. Bulk XRD analysis of the smectite-rich bed indicates the presence of subordinate quartz, plagioclase, kaolinite, chlorite and the zeolite clinoptilolite, the latter two minerals most likely being responsible for the green colour of the bed in outcrop.

The smectite-rich bed is not uniform in texture or mineralogy on a millimetre-scale but includes laminae containing rounded grains and plant fragments (Figure 9). Detrital grains in these laminated beds are distinctly more rounded than in the structureless beds, and the former are usually cemented with non-ferroan calcite microspar, which contributes to the ‘banded’ appearance in outcrop (Figures 3 and 4). The banding comprises centimetre-scale pale green and orange-brown layers that are traceable across the extent of the outcrop.

The sandstone capping the smectite-rich bed is characterised by a smectite clay matrix and contains abundant clay clasts that attain 2 mm in diameter which are clearly derived from the underlying smectite-rich bed.

4.4.4 | Geochemistry of the sediments

Representative samples of the Temburong Formation marine mudstones and the smectite-rich bed were analysed by XRF for their major and trace elements. The data are shown in Table 2, and aspects of the composition of the shales and tuff are illustrated in Figures 10 and 11.

The smectite-rich bed samples have ca 68.5 to 80 wt% SiO₂ and are rhyolitic to dacitic in composition on the Le Bas et al. (1986) total alkali/silica plot (Figure 10A). Their trace element signature is indicative of an active continental margin provenance (Figure 10B, Schandl & Gorton, 2002). They plot into island arc to active continental margin fields in the Roser and Korsch (1986) discrimination diagram (Figure 10C).

The marine mudstones above and below the smectite-rich bed are relatively silica-rich, reflecting their silt content and the abundance of illitic clays. They plot into the passive-margin field of the Roser and Korsch (1986) SiO₂/K₂O-Na₂O diagram, indicating periods of no magmatism before and after the magmatic interval (Figure 10C).

The spider plots of trace element composition also support a volcanic arc source for the smectite-rich bed samples, with enrichment of large-ion lithophile elements over high-field-strength elements (HFSE; see Figure 11). Prominent elemental troughs occur in Rb, Nb, Sr, P and Ti, while Th, U and Pb are enriched. Some HFSE elements such as Zr and Y are enriched over NMORB, which are also indicative of an A-type magmatic source. The Temburong Formation marine mudstone samples have a typical upper continental crust signature with prominent troughs in Sr and Ba, probably related to feldspar diagenesis and dissolution. Compared to the smectite-rich bed samples, the mudstones are enriched in Cs, Rb and K, and troughs in Sr, P and Ti are less prominent.

4.5 | LA-ICP-MS geochronology: Dating the smectite-rich bed and detrital zircons

Results of the LA-ICP-MS U-Pb zircon age dating for the Temburong Formation smectite-rich bed are given in Figure 12, and for the detrital sandstones in Figure 13. The age data and characteristics of the zircons in each of the samples are summarised herewith. The location and stratigraphic position of the samples are shown in Figures 1 through 3.
4.5.1 KSF9—volcaniclastic sandstone at the top of the tuff bed at Kiamsam Shore

Zircons in this sample are predominantly colourless to pale orange in colour and are of a prismatic, euhedral grain shape, completely unrounded, indicating they have not undergone significant transport or reworking. All exhibit concentric magmatic zonation. A total of 102 concordant analyses were acquired from 122 zircons. Almost all analyses form an age cluster between ca 18 to 22 Ma. Two ages of 23 ± 1 and 24 ± 1 Ma fall outside this narrow range, and the sample inherits two Mesozoic zircons (111 ± 2 and 235 ± 3 Ma). Some discordant zircons indicate common Pb contamination. The sample is dated as 19.6 ± 0.1 Ma (early Burdigalian) based on the weighted mean age calculation of a cluster of 94 zircon ages (Figure 12).
4.5.2 | KSF12—fine to medium-grained sandstone at Kiamsam Shore, immediately above the tuff bed and the volcaniclastic sandstone

Zircons in this sandstone show a wide range of sub-rounded crystals and anhedral fragments which are colourless, orange or pink. A total of 117 concordant analyses were acquired from 124 zircons. The sample comprises 78 Phanerozoic and 39 Precambrian grains. The Phanerozoic ages have a bimodal distribution with a dominant Cretaceous age population that ranges from ca 66 to 140 Ma and a subordinate Permian-Triassic population from ca 215 to 260 Ma. Accompanying these two Phanerozoic main populations are a small number of Jurassic and Palaeozoic zircons. Precambrian ages are scattered and peak in the Proterozoic at ca 600 Ma, 0.75 to 1 Ga and 1.75 to 1.9 Ga, and 2.45–2.55 Ga at the Proterozoic-Archean boundary. The oldest age is 3,095 ± 16 Ma (Mesoarchean) and the youngest zircon is 99 ± 1 Ma (Cenomanian, Late Cretaceous). There are no zircons of similar age to KSF9.

4.5.3 | RB2—channel sandstone from Rusukan Besar Island

Similar to sample KFS12, the zircons in this sandstone exhibit a wide range of abraded shapes and colours. However, there is a greater number of sub-rounded pinkish zircons. A total of 129 concordant analyses were acquired from 132 zircons. The sample set consists of 71 Phanerozoic and 58 Precambrian grains. The Phanerozoic ages show a wide distribution in the Mesozoic that extend into the Permian. The most significant age population is in the Cretaceous at ca 110–120 Ma where it forms a narrow age peak. Additionally, there are some lower Palaeozoic ages. The Precambrian ages show four narrow main peaks, accompanied by scattered ages in between. The main peaks are at ca 800 Ma, 950 Ma, 1.85 Ga and 2.5 Ga. The oldest age is 3,095 ± 16 Ma (Mesoarchean) and the youngest zircon is 99 ± 1 Ma (Cenomanian, Late Cretaceous).

4.5.4 | RK1—channel sandstone from Rusukan Kecil Island

Zircons from RK1 are dominated by colourless abraded euhedral crystals and anhedral fragments. Subordinate orange and pinkish coloured zircons also occur. A total of 119 concordant
analyses were acquired from 129 zircons, consisting of 84 Phanerozoic and 35 Precambrian zircons. The age populations are similar to sample KSF12. The Phanerozoic zircons display a bimodal distribution, dominated by Cretaceous zircons and a narrow age peak in the Early Triassic. Additionally, there are Jurassic (peaking in the Late Jurassic), Permian, Carboniferous and Silurian ages in the dataset. The Precambrian population is dominated by a narrow age peak at ca 1.85 and 2.5 Ga, accompanied by a few scattered ages. The oldest age is 2,619 ± 11 Ma (Neoarchean) and the youngest zircon is 76.6 ± 0.7 Ma (Campanian, Late Cretaceous).

4.5.5 | LL1—sandstone from the Layangan beds

Similar to sample KFS12, the zircons in LL1 show a wide range of crystal shapes and colours, including euhedral crystals, anhedral fragments and sub-rounded crystals of colourless to pink or orange colour. A total of 107 concordant analyses were acquired from 115 zircons, of which 73 are Phanerozoic and 34 are Precambrian zircons. The Phanerozoic zircons are dominated by Cretaceous ages that peak at ca 90 and 110 Ma. In contrast to other samples the Cretaceous component is very dominant and covers a smaller time interval compared to samples KSF12 and RK1. Scattered ages range from the Jurassic to the Cambrian, and there are three Cenozoic zircons. The Precambrian population peaks at ca 1.8–1.9 Ga and at 800 Ma. The oldest age is 2,514 ± 13 Ma (Neoarchean) and the youngest zircon is 42.5 ± 0.7 Ma (Lutetian, Eocene).

4.6 | Biostratigraphy: further constraints on the age of the tuff

A total of 11 representative samples of the mudstones were taken above and below the smectite-rich bed for biostratigraphic study. Four samples were taken below the tuff (KSF2 to KSF7), whilst the remainder were sampled above the smectite-rich bed and are considered to be stratigraphically younger (Table 1). For each sample, the total number of foraminifera recovered from 30 g of sediment, and the total number of nannofossils on six traverses of a prepared nannofossil analysis slide were recorded (Figure 14).

The lower-most sample (KSF2), taken some 200 m below the base of the smectite-rich bed, is undated, due to the absence of age diagnostic microfossils. All the other samples yield microfossils indicating an age equivalent to the Lower N5 foraminiferal zone and the NN2 nannofossil zone and fall within the VIM36 to upper VIM34 depositional cycles of Morley et al. (2011; 2016; 2020). The Lower N5 attribution is based on the presence of Globigerioides primordius and Globorugadrina binaensis with rare Globigerina cf ciperoensis but without Globorotalia kugleri. The NN2 date is based on the presence of Triquetrohabdulus carinatus and Discoaster adamanteus without the presence of Discoaster belemnos or Sphenolithus heteromorphus. The presence of Discoaster druggii in KSF10 places most of the section into zone NN2. This assigns the section to the latest Aquitanian to early Burdigalian of the Early Miocene.
The biostratigraphic ages from the studied interval (KSF2 to BB2; Figure 2) thus range from ca 21 Ma at the base of the section to as young as 19.4 Ma at the top (based on the presence of *Globoquadrina biniaensis*, following Wade et al. (2011) which is consistent with the zircon U–Pb age of 19.6 ± 0.1 Ma, and confirms a Burdigalian age for the studied part of the Temburong Formation.

4.7 | Interpretation of the smectite-rich bed textures, mineralogy and terminology

The ca 2 m thick smectite-rich bed occurs approximately mid-way in the Kiamsam shore section within a Temburong Formation section that is clearly of deep water origin, most likely deposited in ca 1 km of water depth, on the basin
slope, winnowed by distal turbidity currents and occasional channelised flows. The sharp base of the smectite-rich bed, centimetre-banded bedding and reworked top are also all indicative of current flows. The presence of intra-bed folding within the smectite-rich bed suggests the presence of either slumping or dewatering, and is consistent with rapid deposition on a palaeo-slope. Petrographic textures and the overall mineralogy with angular floating fragments of very fine to fine-grain size which are predominantly composed of silica, but are more rarely K-feldspar, are consistent with the smectite bed being the alteration product of a fine-grained, matrix supported volcaniclastic rock which contained quartz and feldspar glass shards and was of overall rhyolitic, possible active continental margin affinity. The smectite-rich bed contrasts with the enclosing marine mudstones in terms of appearance, colour, sedimentology, mineralogy and geochemistry, indicating that the smectite-rich bed is a discrete event, most probably representing a highly altered volcaniclastic deposit.

Extensive post-depositional alteration of volcaniclastic material makes interpretation of their petrogenesis difficult and often ambiguous. The extent of alteration largely prohibits identification of the original depositional fabric and process, although the bedding and presence of angular floating grains and shards suggest deposition from a low energy turbidity flow, rather than marine settling of volcanic ash fall-out or a viscous sub-aqueous lava flow. The shards typically have crescentic, sickle-shaped, or bi-concave outlines suggesting that they were produced by the shattering of a vesicular glass. However, there is no evidence for in situ explosive interaction with sea water or non-explosive quenching and granulation, as would be expected from sub-marine lava flows (Carey & Schneider, 2011). The relatively consistent mineralogy of the shards and chemical composition of the smectite-rich bed is consistent with a syn-eruptive event, suggesting that the original pyroclasts were emitted during a single volcanic event or genetically linked, short-lived volcanic events.

Prior to alteration the smectite-rich bed is most probably to have originally been a vitric or lithic ash, and therefore can be considered a tuff deposit. Petrographic and geochemical data suggest that the tuff was crystal-poor. There is insufficient depositional fabric preserved to definitively ascertain if the bed is an ash-fall deposit, a primary turbidite linked to an eruptive event or a secondary turbidite resultant of reworking of a primary accumulation of volcaniclastic material (Schneider et al., 2000). It is possible that the main part of the smectite-rich bed represents an altered air-fall tuff which now has a current re-worked top. However, given that the tuffaceous material in the main body of the tuff bed is mixed with other minerals as well as transported organic matter it is likely that the main part of the tuff has at least been partially reworked by turbidity currents, rather than it being a direct ash-fall deposit. The transport distance is unknown but the
duration of transport is likely to have been short, given the preservation of acicular shards as seen in thin section. These depositional characteristics are in keeping with the tuff bed being deposited by a single, or low-number of, turbidity current events. Examples of the preservation of acicular volcanic material in short duration transport events can be found, also in the Miocene, in the Gulf of Mexico (Stanbrook et al., 2020). The Temburong Formation tuff bed, being contemporaneous with the enclosing/adjacent mudstones and siltstones, thus defines the age of deposition for the Temburong Formation. Based on the overall sedimentology, mineralogy and geochemistry of the smectite-rich bed the most appropriate terminology to describe the bed is a volcaniclastic turbidite of dacitic to rhyolitic composition.

5 | DISCUSSION

5.1 | The stratigraphy of the Temburong Formation and age of the TCU

The U-Pb dating of zircons in the volcaniclastic sandstone at the top of the tuff indicates an early Burdigalian age (weighted mean age of 19.6 ± 0.1 Ma) for the Temburong Formation in Labuan. This confirms that deep water sedimentation in North-West Sabah continued well into the Early Miocene and requires a revision to the age of the Crocker Formation and TCU which is generally considered to mark the end of deep marine sedimentation in the PSCS. The presence of a tuff within the Temburong Formation section also indicates magmatic activity at this time. Based on the biostratigraphy of the enclosing mudstones above and below the tuff bed, together with recent literature (Asis et al., 2015; Breitfeld et al., 2020b), the Temburong Formation on the island of Labuan is restricted in age from 21.5 to 19.4 Ma, with the base of the observed section extending down to the Aquitanian.

Some confusion has been associated with the exact stratigraphic position and status of the Temburong Formation. It was placed in the late Oligocene by Hattum et al. (2013) but considered to range from the Late Oligocene to Early Miocene by Sandal (1996) and Lambiase et al. (2003). The Temburong Formation is thus the deep water equivalent of the tidally-influenced, shallow marine Nyalau Formation in North Sarawak (Hassan et al., 2013). Recent consensus based on analysis of planktonic foraminifera confirms a Chattian (Late Oligocene) to Burdigalian (late Early Miocene) age for the Temburong Formation (Asis et al., 2015; Breitfeld et al., 2020b). It is unconformably overlain by the shallow marine clastic Layang-Layangan Beds (Madon, 1994). The unconformity directly above the Temburong Formation is considered to be the TCU and correlated with the slightly younger top Nyalau Unconformity of ca 17 Ma in Sarawak (Breitfeld et al., 2020a; Hennig-Breitfeld et al., 2019). This unconformity is not visible on the island of Labuan as either erosion or vegetation obscure exposures. Offshore Sarawak a similar age is interpreted for the Early Miocene Unconformity (EMU) by Madon et al. (2013) which may correlate to the top Nyalau Unconformity and the TCU. The Layang-Layangan Beds are in turn overlain by conglomerates of the Belait Formation. This boundary is interpreted by some authors as the DRU (Jackson & Johnson, 2009; Madon, 1994, 1997; Som et al., 2011); see Figure 2) and/or the Middle Miocene Unconformity (MMU; Balaguru & Lukie, 2012). Hennig-Breitfeld et al. (2019) doubted the interpretation as DRU and included the Layang-Layangan Beds as Lower Belait into the Belait Formation and emphasised the importance of the regional unconformity below the Layang-Layangan Beds.

The TCU likely represents the collision of South China-derived micro-continental fragments with North-West Borneo following the subduction of the PSCS (Hall, 2013a; Hall & Breitfeld, 2017; van Hattum et al., 2006; van Hattum et al., 2013). The Temburong Formation is thus the last record of deep water deposition onshore western Sabah and indicates that the PSCS subduction was on-going into the Burdigalian.

5.2 | Sedimentation rates in the Temburong Formation

A precise age provided by U–Pb dating of syn-depositional zircons coupled with biostratigraphic ages for the Temburong Formation enables simple calculations of the sedimentation rate to be undertaken, and compared with other basins in Borneo. The Temburong Formation succession on Labuan includes all or part of VIM36 and VIM34 (as in Morley et al., 2016) from a minimum of 19.4 Ma for the top of the section at Bebuloh quarry to 21.0 Ma at the base of the section at Kiamsam shore. Assuming constant deposition, for 1,000 m of section, this gives a sedimentation rate of 62 m per 100 kyr, indicating that the sedimentation rate of the Temburong Formation is high. The system that sourced these sediments had a discharge nearly double that of the modern Mahakam Delta (Morley et al., 2016; Prasetya et al., 2013). Such a high sedimentation rate suggests that the depositional process on the Temburong Formation slope in the Labuan area was dominated by distal turbidites rather than hemipelagic suspension fall-out, and that a major proximal delta system must have been developed in-board of the preserved deep water Temburong Formation deposits. This delta system comprised the tide-influenced shoreface of the Nyalau Formation (Collins et al., 2018; Hassan et al., 2013; Hassan et al., 2017) and most likely other deltas across the north-eastern Borneo coast active at that time. Tidal modelling (Collins et al., 2017) demonstrates that spring tides along these early Miocene coastlines of the South China...
Sea (SCS) were meso-tidal to macro-tidal and capable of transporting sand, reflecting high tidal inflows through wide ocean connections to the Pacific Ocean coupled with tidal amplification due to constriction of the tidal wave in the blind gulf morphology of the SCS. In this tidally-influenced coastal system, mangrove flats were extensive, resulting in high productivity and sediment trapping, available for tidal transport to the shelf edge (Collins et al., 2017, 2018).

At this time during the Early Miocene similar major prograding deltas with high sedimentation rates developed across Sundaland in Kutai (the ‘Proto-Mahakam’), Nam Con Son and Luconia (Hall & Nichols, 2002; Morley et al., 2016). These high sedimentation rates reflect not only the tidal currents of the SCS, but ultimately derive from the intense weathering and high erosion rates in the wet tropical hinterlands of central Borneo coupled with available accommodation space in the adjacent depocentres. The change in character of sedimentation in East Kalimantan has been ascribed by many authors to underthrusting of North Borneo by extended South China crust at the end of the Oligocene, causing uplift of the region in-board of the Temburong-Crocker accretionary prism (Hamilton, 1979; Hazebroek & Tan, 1993; Hutchison et al., 2000; Taylor & Hayes, 1983). Underthrusting and the resultant uplift likely continued throughout the early Miocene to generate the large sediment volumes that characterise the shelves and slopes offshore Borneo.

5.3 | Detrital sources for the Temburong Formation

Detrital zircon grains in the Temburong Formation sandstones are predominantly Mesozoic with two significant abundance peaks in the Cretaceous and Triassic (Figure 13). Precambrian zircons are also present in the Temburong Formation sandstones with populations at ca 600 Ma, 800 Ma, 950 Ma, 1.85 Ga and 2.5 Ga and indicate recycling of older sources. There are no contemporaneous zircons in the deep-marine turbidite channel sandstones on Rusukan Kecil Island. Comparable age populations in clastic sediments in northern and western Borneo have been reported for the Maastrichtian to Late Eocene Belaga Formation of the Rajang Group (Galin et al., 2017; Hennig-Breitfeld et al., 2019) and the Kayan and Ketungau Groups of the Kuching Supergroup (Breitfeld & Hall, 2018). Van Hattum et al. (2013) also reported similar populations from the Eocene part of the Crocker Formation, and from the Cretaceous to Eocene Sapulut and Trusmadi formations of Sabah. The overlying Belait Formation and younger sediments of the Miri Zone (e.g. Tukau Formation) also have similar detrital zircon age populations (Hennig-Breitfeld et al., 2019; Nagarajan et al., 2017).

The Cretaceous zircons in the Temburong Formation sandstones were most likely ultimately derived from the Schwaner Mountains of South-West Borneo where numerous Cretaceous plutonic, volcanic and metamorphic rocks are exposed (Breitfeld et al., 2020b; Davies et al., 2014; Hennig et al., 2017; Williams et al., 1988). Permian-Triassic zircons are reported from the Malay-Thai Tin belt (Dodd et al., 2019; Gillespie et al., 2019; Oliver et al., 2014; Searle et al., 2012; Sevastjanova et al., 2011) and Triassic zircons from the West Borneo province (Breitfeld et al., 2017; Hennig et al., 2017; Seiawan et al., 2013). Recently, Burton-Johnson et al. (2020) reported Triassic zircons from Triassic granitoids in eastern Sabah, which could also have provided a minor contribution. The Precambrian zircons are multi-cycled and show similarities with sediments in Sibumasu (Liebermann et al., 2017; Sevastjanova et al., 2011), East Malaya (Dodd et al., 2019; Sevastjanova et al., 2011), Indochina (Burrett et al., 2014; Carter & Moss, 1999; Hennig et al., 2018; Nguyen et al., 2018; Wang et al., 2016), West Borneo (Breitfeld et al., 2017) and basement rocks in South China (Chen et al., 2016; Li, 1997; Liu et al., 2009, 2014). These zircons are probably recycled in the tidal embayment of the SCS from older clastic successions in Borneo that were exposed along the northern margins of Sarawak and Sabah.

The sample from the Layang-Layangan Beds has a different detrital zircon age distribution (Figure 13). Besides the dominant Cretaceous age double peak in the LL1 sample, there are no other prominent populations in the Phanerozoic. In contrast to the other Temburong Formation samples which have 12%–20% Permian-Triassic zircons, the amount of Permian-Triassic zircons in LL1 forms only ca 10% of the zircon ages (Figure 13). However, the scattered ages from the Triassic to the Silurian are not present in the other samples. LL1 also yielded two Eocene zircons that pre-date the deposition of the formation and are also not observed in the other samples. Similar Eocene zircons occur in very low numbers throughout Cenozoic formations in Borneo (as reported in Breitfeld & Hall, 2018; Galin et al., 2017; van Hattum et al., 2013) and are potentially related to short-lived, restricted magmatism in the Eocene in Central Kalimantan (Bladon et al., 1989; Pieters et al., 1987). Hennig-Breitfeld et al. (2019) also dated the Bukit Piring and the Arip Volcanics of North Sarawak with U-Pb zircon geochronology as Middle Eocene (Lutetian to Bartonian) which is a geographically closer potential source. The slightly different zircon age population in the sample from the Layang-Layangan Beds (LL1), compared with the rest of the samples supports the interpretation that the succession may not be part of the Temburong Formation as suggested by Albaghdady et al. (2003), Gou and Abdullah (2010), Abdullah et al. (2013) and Hennig-Breitfeld et al. (2019).

By contrast, the volcanioclastic sandstone at the top of the tuff bed within the Temburong Formation is dominated by zircons with a contemporaneous, syn-depositional age (100 18–25 Ma zircons and only two older zircons), indicating
derivation from a separate short-lived magmatic event distinct from the majority of sediment in the Temburong Formation which was derived by recycling.

5.4 | Differentiating the Temburong Formation from the Crocker Formation

The Temburong Formation is generally regarded as a lateral equivalent of the WCF (Hutchison, 1996; Jackson et al., 2009; James, 1984; Lunt & Madon, 2017; Zakaria et al., 2013) and sometimes assigned to the youngest part of the WCF, forming the top of the Crocker sub-marine fan system (van Hattum et al., 2013; Madon, 2020). However, detrital zircon U-Pb data for the Oligocene part of the WCF are dominated by Permo-Triassic zircons (van Hattum et al., 2013) whilst the contribution of Cretaceous zircons is subordinate, clearly different from the Temburong Formation (Figure 15). Similar Permo-Triassic zircon age-dominant successions occur in the upper part of the Oligocene Tatau Formation and the Oligocene to early Miocene Nyulau Formation (Breitfeld et al., 2020a; Hennig-Breitfeld et al., 2019), which are also part of the westerly source system that deposited the Crocker Formation. A Cretaceous-dominated zircon age population was reported in the Eocene and older successions, e.g. Eocene part of the Crocker (Figure 15), Sapulut and Trusmadi formations in Sabah (van Hattum et al., 2013) and the Belaga Formation in Central and North Sarawak (Hennig-Breitfeld et al., 2019; Galin et al., 2017).

The dominance of Cretaceous zircons in the Temburong Formation indicates an important switch in source provenance during the early Miocene from the Crocker Formation to the Temburong Formation which is not apparent in the depositional environment of the Crocker and Temburong formations. Hennig-Breitfeld et al. (2019) and Breitfeld et al. (2020a) interpreted the Permian and Triassic-dominated successions to be derived mainly from East Malaya or Indochina via a ‘Sunda River’ with only minor input from central and southern Borneo whilst van Hattum et al. (2013) suggested a fluvial system from East Malaya passing through western Borneo. However, such direct derivations are unlikely in the Late Oligocene to Early Miocene since the inferred ‘Sunda River’ would have to flow across the rifts of the Malay Basin and the highlands of the Natuna Arch, probably an upland area at that time (Collins et al., 1996; Jong et al., 2017; Kessler & Jong, 2016; Murray & Dorobek, 2004; Shoup et al., 2013; Wirojudo & Wongsosntiko, 1985), and are more probably derived by re-cycling. This change in provenance from Permian-Triassic to Cretaceous zircons must reflect an important tectonic event in the early Miocene that results in uplift of northern and central Borneo to supply sediment to the Sabah trough whilst the input of material derived from the western terrains diminished. The Late Oligocene and Early Miocene was a period of collision and re-adjustment of micro-continental fragments along the western edge of Borneo (Hall, 2013a; van Hattum et al., 2013; Taylor & Hayes, 1983), probably responsible for the vast amounts of siliciclastic sediments, up to 12 km in thickness, that were deposited in marginal basins in and around Borneo throughout the Neogene (Hall & Nichols, 2002; Hamilton, 1979). These Neogene sediments in North Sarawak and in the Belait Formation on Labuan were derived by re-working of uplifted clastic successions of the Kuching Supergroup and the Rajang Group on Borneo (Hennig-Breitfeld et al., 2019). The reworking of fluvial sediments derived from uplifted terrains would have been enhanced by the meso-tidal to macro-tidal currents that affected the SCS during the Early Miocene. The Temburong Formation is herewith interpreted as being sourced by reworking of uplifted Rajang Group, Sapulut or Trusmadi formations, thus indicating the first phase of uplift in the Early Miocene before the onshore depositional system changed to the shallow marine-fluvial systems of the Miri Zone of Sarawak (including the Belait Formation and probably the enigmatic Layang-Layangan Beds). The zircon populations of the Temburong Formation are much more similar to the overlying Belait Formation than to the Oligocene part of the Crocker Formation.

5.5 | Volcanic activity within the early Miocene of Sabah and adjacent areas

The tuffaceous sandstone that sourced the Temburong Formation tuff bed has zircon ages that cluster around 19–20 Ma and zircon habits indicating that the zircons were contemporaneous with deposition, and the presence of angular shards in the tuff bed indicates it has not undergone significant abrasive transport. The evidence of extrusive volcanic activity at this time on Labuan has significant implications for the tectonic evolution of the western margin of Borneo. There are three possible origins for the tuff bed.

First, there are several small igneous bodies of Early Miocene age in Central Kalimantan and West Sarawak some 500 km to the south that are grouped under the term Sintang Suite (Moss et al., 1998; Soeria-Atmadja et al., 1999; Williams & Harahap, 1987). The Sintang Suite is interpreted as intraplate magmatism, a result of mantle upwelling into lithospheric thin-spots, rather than with subduction (Breitfeld et al., 2019). In Central and East Kalimantan Moss et al. (1998) suggested these igneous intrusions were associated with uplift and denudation. This uplift is contemporaneous with uplift in northern Borneo and the provenance change from the Crocker to Temburong deep-water system. Using apatite fission track annealing
FIGURE 15  FIGUComparison of Pb-U zircon ages in the Temburong Formation from the Crocker and Belait formations, showing the difference between the Oligocene part of the Crocker Formation and the Early Miocene Temburong Formation, and similarities of the Temburong Formation with the Eocene Crocker (a possible source) and younger successions (Belait Formation) that were all derived from uplifted central and/or northern Borneo. Data from the Crocker Formation by van Hattum et al. (2013). Data from the Belait Formation from Hennig-Breitfeld et al. (2019)
and K-Ar dating Moss et al. (1998) demonstrated that the north-western margin of the Kutai Basin in Central to East Kalimantan cooled rapidly on uplift at around 23 Ma, whilst volcanic and high-level intrusive activity was widespread within the Kutai Basin from 23 to 15 Ma. Uranium-Pb zircon ages of ca 19 Ma were reported by Settiabadi et al. (2007) and Davies et al. (2008) for igneous bodies in East Kalimantan similar to U-Pb ages reported by Breitfeld et al. (2019) for Sintang Suite rocks in West Sarawak. Rocks exhibiting within-plate type geochemistry characterise the Sintang Suite, while an adakitic character is reported from the slightly younger middle Miocene Bau Suite (Breitfeld et al., 2019). Such variations are not present in the Temburong Formation tuff. However, trace element spider plots are comparable to volcanic Sintang Suite rocks reported by Breitfeld et al. (2019; Figure 14). The Temburong Formation tuff could therefore be a part of this magmatic episode and result from long distance transport (e.g. air-fall) or it is possible that the Sintang Suite rocks extended much further to the north than the present-day exposures. However, the Sintang Suite rocks are bounded by the Lupar Fault system and its eastern continuation so a northern extension is unknown.

Second, the tuff could be related to the PSCS subduction beneath the Cagayan-Sabah Arc which was active in the Oligocene to early Miocene (Hall, 2013a; Hall & Breitfeld, 2017; Pubellier et al., 1991). The volcanic arc-related trace element character of the tuff could be derived from this subduction zone. This would extend the age of PSCS subduction from 25 Ma (Hall, 2013a) to ca 19 Ma. The tuff could represent a phase of late eruption before subduction ceased in the Burdigalian.

Third, volcanic activity is also known from the Southern Sulu Arc, comprising Early to Middle Miocene andesites, which record short-lived subduction of part of the Celebes Sea beneath the south-east part of Sabah (Cullen et al., 2013; Hutchison, 2005; Macpherson et al., 2010). In the Sulu Sea, sites drilled as part of Leg 124 of the Deep Sea Drilling Project encountered 220 m of basalt and diabase associated with 1 km of sediments and pyroclastics (Silver & Rangin, 1990). The bottom 40 m of Lower Miocene sediment comprises claystones interfingered with pyroclastic turbidites, whilst 200 m of dacitic pyroclastic flows and redeposited tuffs overlie the claystone. The ages are comparable to that of the Temburong Formation tuff and Pubellier et al. (1991) suggest the cessation of volcanism of the Cagayan Arc correlates closely with the opening of the Sulu Basin.

There is insufficient evidence preserved in the Temburong Formation tuff bed to indicate with certainty which of these three origins for the volcanicity activity are most probable. However, the absence of other contemporaneous zircons in the sandstones suggests volcanoes responsible for the tuff bed are far away, favouring the Sintang Suite of southern Sarawak. It is also noteworthy that volcanic lithics are common in Proto-Mahakam sediments during this same time period, equivalent to NN2 and NN3 in the early Miocene (Morley et al., 2016; Tanean et al., 1996), which reflects derivation from the Upper Sintang Volcanics. Volcaniclastics occurring in Kutei and Labuan at the same time suggest a common origin from the Sintang Volcanics, most probably in central Sabah. Regardless of the origin of the tuff, the very presence of deep-water sedimentation in North-West Borneo during the Early Miocene, directly comparable with the underlying Crocker Formation depositional system, implies the same tectonic environment of PSCS subduction with sedimentation in the fore-arc basin continued during deposition of the Temburong Formation.

5.6 Deposition of the tuff bed

There are several types of subaqueous pyroclastic flows which deposit volcaniclastic sediment in the deep sea (Carey & Schneider, 2011). The Temburong Formation tuff is a thin, single bed, suggesting it is either the distal portion of larger tuff unit, or that it is the product of a relatively small, locally sourced, single eruption. The absence of thick and widespread, tuff-dominated, volcaniclastic material argues strongly against the presence of major caldera-forming eruptions.

Eruption-fed sub-marine volcaniclastic deposits are very difficult to distinguish from later re-sedimentation processes other than by detailed mapping and facies analysis (Schneider et al., 2001). However, sub-aerial eruption, debris flows and lava-fed density currents can be reasonably excluded for the deposition of the Temburong Formation tuff bed because of the uniform fine-grain size of the deposit and presence of relict bedding. Rather, the Temburong Formation tuff bed is considered most likely to be a volcaniclastic turbidite based on the sedimentary features preserved in the tuff bed and the overall sedimentological setting.

The turbidite may have been initiated by a wide range of volcanic-related processes, including sub-aerial failure of a caldera or cone, a pyroclastic flow entering the marine environment, or by sub-marine slope failure. These source mechanisms are widely known to operate around South-East Asia and may extend over large lateral distances from the eruptive centre (Paris et al., 2014). Particle plumes and volcaniclastic turbidites associated with the Mariana Arc for example, spread over several kilometres from an active vent (Walker et al., 2008), whilst pyroclastic deposits from the 1883 Krakatoa eruption are up to 10 m thick some 20 km from the crater (Mandeville et al., 1996) and extend for a further >120 km into the Java Sea (Carey et al., 2000). Elsewhere, in the Miocene Obispo Formation for example, exposed along
the south-central coast of California, ca 450 km$^3$ of dacitic pyroclastic material erupted from a caldera and was deposited as an extensive sub-marine turbidite sheet (Schneider & Fisher, 1996). Similarly, ash-grade material from the Soufrière Hills 2003 eruption on Montserrat are deposited as turbidites that travel distances >40 km from the source (Trofimovs et al., 2008).

An alternative interpretation for the Temburong Formation tuff is that it represents sub-marine accumulation of an air-fall deposit. These are known to produce single event beds which cover vast lateral distances. For example, the June 1991 eruption of Mt. Pinatubo in the Philippines deposited an extensive, sub-marine ash layer covering an area of ca $4 \times 10^5$ km$^2$ that extends for up to 800 km across the central SCS, still 30 cm thick 300 km from the source (Wiesner et al., 2004). With increasing distance from Mt. Pinatubo, the coarse particle populations of two proximal beds merge to a fine-grain size-dominated, ungraded, single ash layer. Even more remarkable is the sub-marine accumulation of ash-fall from the 75 ka Toba eruption in northern Sumatra which extends for >2,000 km across the Bay of Bengal and Indian Ocean (Rose & Chesner, 1987).

The Temburong Formation tuff bed from the Kiamsam section lacks sufficient depositional fabric to definitively ascertain if the bed is an ash-fall deposit, a primary turbidite linked to an eruptive event or a secondary turbidite resultant of re-working of a primary accumulation of volcaniclastic material. However, given that tuffaceous material is mixed with other mineralogies as well as organic matter it is certain that the tuff has at least been partially re-worked and transported by turbidity currents. The transport distance by the turbidity current is unknown but the time in transport is likely of relatively short duration given the preservation of acicular shards as seen in the thin section petrography; this is in keeping with a single, or low-number of, turbidity current events being responsible for deposition of the Temburong Formation tuff bed. Examples of the preservation of acicular volcanic material in short duration transport events are present in the Gulf of Mexico, also in the Miocene (Stanbrook et al., 2020).

### 5.7 Implications for Borneo palaeogeography

Constraining the age of the Temburong Formation in Labuan to ca 19 Ma and the contrast in detrital modes between the Temburong and Crocker formations has significant implications for the palaeogeography of Borneo across the Oligocene–Miocene boundary and in the Early Miocene. In the Late Oligocene, the rift basins of the Gulf of Thailand were reactivated with sinistral displacement along major north-west/south-east faults resultant of collision between the Indian and Eurasian plates (Hall et al., 2002; Pubellier & Morley, 2014; Shoup et al., 2013; Taylor & Hayes, 1983). Widespread uplift associated with the beginning of closure of the PSCS and overall marine transgression formed a wide shelf area in Sundaland, with a large, partially enclosed East Natuna-Sarawak embayment, flanked by the Natuna Arch (Collins et al., 2018; Shoup et al., 2013; Wirojudo & Wongsonantiko, 1985). Extensive mangrove swamps flanked the eastern margin of the Natuna Arch and the western margin of the Nam Con Son Basin, where Chattian (ca 26 Ma) brackish water incursions extended into the Nam Con Son Basin of South Vietnam (Collins et al., 2018; Shoup et al., 2013). These coastal and shallow marine sediments pass into the deep water Crocker Formation and its lateral equivalents to the east, as seen in the Engkabang wells just south of the Baram Delta (Jong et al., 2016). Late Oligocene palaeoenvironments in the Engkabang region indicate that the Mulu Formation carbonate platform lay to the south, with outer shelf and slope facies to the north and east, suggesting that Oligocene sedimentation in this immediate area was derived from the west (Jong et al., 2017, their figure 18, map c). Flanking highlands as indicated by montane pollen taxa (Morley, 2018) were a local source of sediment supply, but most of the sediment delivered to the East Natuna-Sarawak embayment was provided by fluvial systems draining the Gulf of Thailand rift basins. Permo-Triassic zircons of the WCF from the Malay Tin Belt therefore have to be transported along the Gulf of Thailand rifts and recycled by tidal currents in the East Natuna-Sarawak embayment or were previously transported onto Borneo (Figure 16A).

The Early Miocene marks a major change in the basin development across eastern Sundaland (Hennig-Breitfeld et al., 2019; Morley, 2018; Morley et al., 2016; Moss & Wilson, 1998) coincident with rising sea level. By the Early Miocene, the PSCS was almost closed and extended continental crust from the rifted South China margin was being subducted under northern Borneo (Hall & Breitfeld, 2017; Hall et al., 2002; Taylor & Hayes, 1983). Regionally, rifting ceased across the eastern Gulf of Thailand (Khmer, Pattani, North Malay basins), Malay, Qiongdongnan, Song Hong/Yinggehai, Central Sumatra, South Sumatra and West Java basins, whilst central Borneo began to emerge (Morley et al., 2016; Shoup et al., 2013). Central Borneo uplift is reflected offshore in the development of northward-prograding deltas within Sarawak Cycle II/III in areas such as the offshore Balingian province (Hassan et al., 2017; Madon et al., 2013) and onshore in provenance changes from the Nyalau Formation to the overlying Kakus and Balingian formations attributed to the Nyalau Unconformity (Breitfeld et al., 2020a; Hennig-Breitfeld et al., 2019). Deltas also built out to the east in northern Luconia, epitomised by the Mulu Delta, and also in Vietnam, with the Dua Formation Delta in the Nam Con Son Basin (Lee et al., 2001).
The Nyalau Formation grades into the deeper water Setap Shale, Tangap and Sibuti formations to the north-east, which indicate open marine shelf deposition with shallow littoral to inner neritic conditions (Breitfeld et al., 2020a; Hennig-Breitfeld et al., 2019; Hutchison, 2005; Kho, 1968; Liechti et al., 1960; Wolfenden, 1960). Further to the north-east, the Nyalau-Setap succession grades into the Crocker Formation (Breitfeld et al., 2020a; Hennig-Breitfeld et al., 2019) and into the Temburong Formation, which extends to Labuan (Hassan et al., 2013). The Engkabang wells to the south of Baram Delta show this succession which is attributed to the Setap Shale by Jong et al. (2016), with deposition in an outer neritic to upper bathyal slope setting. This succession is also present in the Tarakan Basin of East Kalimantan, represented by deep marine facies (Scardina et al., 2018; Sudarmono et al., 2017).

In the Kutei Basin, the Mahakam Delta started prograding at this time (Morley et al., 2016). Volcanics are recorded in the Makakam Delta at the same time period, equivalent to nanofossil zones NN2 and NN3 as noted above (Morley et al., 2016; Tanean et al., 1996).

Zircon analyses from the Labuan Temburong Formation succession are dominated by Cretaceous zircons, which suggest ultimate derivation from the Cretaceous Schwaner Mountains in south-west central Borneo, most likely via recycling of the Rajang Group, Sapulut or Trusmadi formations to the south and east (Figure 16B). This interpretation is supported by palaeocurrents reported by Crevello et al. (2005) that show a western input for the Crocker Formation and a southern to south-east component for the Temburong Formation. The upper part of the Nyalau Formation also reveals a shift towards more Cretaceous-dominated zircon assemblages, although Permian-Triassic zircons still dominate (Breitfeld et al., 2020a), which indicates that the Temburong Formation must have received additional material from uplifted central and northern Borneo highlands compared to the upper Nyalau Formation.

Examination of sedimentation rates provides a surprising aspect of the Labuan Temburong Formation succession. Morley et al. (2016) mapped the Sunda region by comparing regional sedimentation rates for each delta system for different time slices. For the Burdigalian, moderately high sedimentation rates of between 40 and 80 m per 100 kyr were calculated for the Mahakam Delta and also for the Mulu region in Northern Luconia, whereas in comparison the deltas of Balingian would have been much smaller with values of less than 20 m per 100 kyr. For the basal early Miocene interval represented by planktonic zone N4 in the Engkabang-1, just prior to the deposition of the Labuan tuff, and in roughly similar facies to the Labuan succession (Jong et al., 2016), the sedimentation rate is about 11 m per 100 kyr. The
calculated sedimentation rate for the Labuan succession of 62 m per 100 kyr indicates a major sediment source to the east or south of the present-day Baram Delta, presumably in central Sabah. This infers the presence of a similarly large delta which sourced the turbidites. A potential candidate would be the poorly dated Meligan Formation, which formed a delta complex in the Late Oligocene to Early Miocene (Hutchison, 2005; Wilson & Wong, 1964). As the contemporaneous Nyalau Formation is mainly fed by sediment sources from the west (Breitfeld et al., 2020a), some material within the Temburong Formation may also have been derived from this sedimentary system and could reside in ‘storage’ on the Sabah Shelf. The source of the Temburong Formation turbidites thus need not be directly from a deltaic conduit, but a sediment-rich shelf.

6 | CONCLUSIONS

A 2 m thick bed of smectite-rich clay within a thick sequence of distal deep water marine mudstones and siltstone beds of the Temburong Formation of southern Labuan, Sabah, is interpreted as an altered re-sedimented pyroclastic tuff deposit which is geochemically of dacite-rhyolite composition. The tuff bed was deposited in deep water (probably <1,000 m) by traction currents and retains relict siliciclastic shards, feldspar phenocrysts and biotite crystals but was dominated by ash-grade material. The upper part of the tuff was winnowed by waning currents sufficiently strong to transport coarse-grained detritus. This suggests the altered tuff bed is a turbidite and may record long distance sub-marine transport down the depositional slope from an active volcanic system in the hinterland. There is, however, insufficient depositional fabric preserved to definitively ascertain if the tuff bed is a deep water ash-fall deposit, a turbidite linked to an eruptive event or a turbidite resulting from re-working of a primary accumulation of volcanioclastic material, although the latter is the preferred interpretation of the available data.

The age of the Temburong Formation ranges from ca 21.5–19.4 Ma, indicated by foraminifera, nannofossils and zircon dating. A volcanioclastic sandstone at the top of the tuff layer within the formation has a zircon U-Pb weighted mean age of 19.6 ± 0.1 Ma (early Burdigalian). This indicates that deep water sedimentation in nort-west Sabah continued well into the Early Miocene and requires a revision to the age of the Crocker Formation and TCU that marks the end of deep marine sedimentation in onshore and offshore North-West Borneo. The absence of other contemporaneous zircons in the sandstones suggests volcanoes responsible for the tuff bed were most likely the Sintang Suite magmatism in central and eastern Borneo, although a PSCS origin cannot be ruled out. Deep water sedimentation at 19 Ma suggests subduction of the PSCS beneath the Cagayan-Sabah arc extends into the Burdigalian.

Sandstones representative of the marine Temburong Formation in Labuan yield abundant zircons which are dominated by Cretaceous ages indicating a switch in source provenance during the Early Miocene since the Crocker Formation is mainly characterised by Permian-Triassic zircons. This is considered to reflect an important tectonic event in the early Miocene which involved the initial stage of the uplift of central Borneo to supply sediment to the Sabah Trough whilst the input of material derived from the Permo-Triassic terrains diminished. The Temburong Formation was sourced by reworking of the uplifted Rajang Group, Sapulut or Trusmadi formations, thus indicating the initial phase of uplift in the early Miocene before the onshore depositional system changed to shallow marine-fluvial deposition within the Belait Formation.

Simple calculations indicate that the sedimentation rate for the Temburong Formation at ca 62 m per 100 kyr is very high. The system that sourced these sediments had a discharge considerably higher than the modern Mahakam Delta, indicating that the depositional process on the Temburong Formation slope in the Labuan area was dominated by distal turbidites rather than suspension fall-out, and that the associated high erosion rates reflect intense tropical weathering in the source terrain hinterlands.

ACKNOWLEDGEMENTS

The authors thank Robert Hall for his support throughout this project as ideas developed and changed. Christina Manning kindly helped with the XRF sample preparation whilst Matthew Thirlwall (both Royal Holloway University of London) performed the XRF analysis. Martin Rittner and Andy Carter (Birkbeck University of London) helped with the U-Pb LA-ICP-MS geochronology. Alison Burley skillfully drafted the maps and Azad Bhatti drafted the section logs. The insight and constructive reviews of journal referees Mazlan Madon and Meor Hassan are appreciated, and a thoughtful review of an earlier version of the manuscript by Tom Dodd (BGS Edinburgh) helped clarify key points of the volcanioclastic turbidite deposition. All the authors confirm that they have no conflict of interest to declare in this work. Original data files are available on request.

ORCID
Stuart D. Burley https://orcid.org/0000-0002-7994-3065
H. Tim Breitfeld https://orcid.org/0000-0002-9563-1862
Robert J. Morley https://orcid.org/0000-0002-4053-2824

REFERENCES
Abdullah, W.H., Lee, C.P., Gou, P., Shuib, M.K., Ng, T.F., Albaghdady, A.A. et al. (2013) Coal-bearing strata of Labuan: Mode of
occurrences, organic petrographic characteristics and stratigraphic associations. *Journal of Asian Earth Sciences*, 76, 334–345.

Albaghdady, A., Abdullah, W.H. & Lee, C.P. (2003) An organic geochemical study of the Miocene sedimentary sequence of Labuan Island, offshore western Sabah, East Malaysia. *BULLETIN OF THE GEOLOGICAL SOCIETY MALAYSIA*, 46, 455–460.

Andersen, T. (2002) Correction of common lead in U-Pb analyses that do not report 204 Pb. *Chemical Geology*, 192, 59–79.

Anschutz, P., Jorissen, F.J., Chaillou, G., Abu-Zied, R. & Fontanier, C. (2007) Recent turbidite deposition in the eastern Atlantic: Early diagenesis and biotic recovery. *JOURNAL OF MARINE RESEARCH*, 60, 835–854.

Asis, J., Rahman, M.I.A., Jasin, B. & Tahir, S. (2015) Late Oligocene and early Miocene planktonic foraminifera from the Temburong Formation, Tenom, Sabah. *BULLETIN OF THE GEOLOGICAL SOCIETY OF MALAYSIA*, 61, 43–47.

Bakar, B., Tahir, S.H. & Asis, J. (2017) Deep marine benthic foraminifera from the Temburong Formation in Labuan Island. *Earth Science Malaysia*, 1, 17–22. https://doi.org/10.26480/esmy.02.2017.17.22

Balaguru, A. & Lukie, T. (2012) Tectono-Stratigraphy and Development of the Miocene Delta Systems on an Active Margin of Northwest Borneo, Malaysia. *Petroleum Geoscience Conference and Exhibition Extended Abstract volume*, April 2012. Conference Proceedings PGCE 2012European Association of Geoscientists & Engineers, https://www.earthdoc.org/content/proceedings/KualaLumpur2012

Bladon, G.M., Pieters, P.E. & Supriatna, S. (1989) Catalogue of isopic ages commissioned by the Indonesia-Australia Geological Mapping Project for igneous and metamorphic rocks in Kalimantan, Preliminary Report. Geological Research and Development Centre, Bandung.

Bouma, A.H. (1962) Sedimentology of some Flysch deposits: A graphic approach to facies interpretation. Elsevier, 168 p.

Breitfeld, H.T., Davies, L., Hall, R., Armstrong, R., Forster, M., Lister, G. et al. (2020b) Mesozoic Paleo-Pacific subduction beneath SW Borneo: U-Pb geochronology of the Schwaner granitoids and the Pinoh metamorphic Group. *Frontiers in Earth Science*, 8, 568715. https://doi.org/10.3389/feart.2020.568715

Breitfeld, H.T. & Hall, R. (2018) The eastern Sundaland margin in the latest Cretaceous to Late Eocene: Sediment provenance and depositional setting of the Kuching and Sibu Zones of Borneo. *Gondwana Research*, 63, 34–64.

Breitfeld, H.T., Hall, R., Galin, T., Forster, M.A. & BouDagher-Fadel, M.K. (2017) A Triassic to Cretaceous Sundaland-Pacific subduction margin in West Sarawak, Borneo. *Tectonophysics*, 694, 35–56.

Breitfeld, H.T., Hennig-Breitfeld, J., BouDagher-Fadel, M.K., Hall, R. & Galin, T. (2020a) Oligocene-Miocene drainage evolution of NW Borneo: Stratigraphy, sedimentology and provenance of Tataru-Nyalau province sediments. *Journal of Asian Earth Sciences*, 195, 104331.

Breitfeld, H.T., Macpherson, C., Hall, R., Thirlwall, M., Otley, C.J. & Hennig-Breitfeld, J. (2019) Adakites without a slab: Remelting of hydrous basalt in the crust and shallow mantle of Borneo to produce the Miocene Sintang Suite and Bau Suite magmatism of West Sarawak. *Lithos*, 344, 100–121.

Brondijk, J.E. (1962) Reclassification of part of the Setup Shale Formation as Temburung Formation. British Borneo Geological Survey Annual Report for 1962, pp. 56–60.

Burgan, A.M. & Ali, C.A. (2009) Characterisation of black shales of the Temburung Formation in West Sabah, east Malaysia. *European Journal of Scientific Research*, 30, 79–98.

Burrett, C., Zaw, K., Meffre, S., Lai, C.K., Khositanont, S., Chaodumrong, P. et al. (2014) The configuration of Greater Gondwana—Evidence from LA ICP-MS, U-Pb geochronology of detrital zircons from the Palaeozoic and Mesozoic of South East Asia and China. *Gondwana Research*, 20(1), 31–51.

Burton-Johnson, A., Macpherson, C.G., Millar, I.L., Whitehouse, M.J., Otley, C.J. & Nowell, G.M. (2020) A Triassic to Jurassic arc in north Borneo: Geochronology, geochemistry, and genesis of the Segama Valley Felsic Intrusions and the Sabah ophiolite. *Gondwana Research*, 84, 229–244.

Carey, S.N. & Schneider, J.L. (2011) Volcaniclastic processes and deposits in the Deep-sea. *Developments in Sedimentology*, 63, 45–515.

Carey, S., Sigurdsson, H., Mandeville, C. & Bronto, S. (2000) Volcanic hazards from pyro-clastic flow discharge into the sea: Examples from the 1883 eruption of Krakatau, Indonesia. *Geological Society of America Special Papers*, 345, 1–14.

Carter, A. & Moss, S.J. (1999) Combined detrital-zircon fission-track and U-Pb dating: A new approach to understanding hinterland evolution. *Geology*, 27, 235–238.

Chen, Z.H., Xing, G.F. & Zhao, X.L. (2016) Palaeoproterozoic A-type magmatism in northern Wuyishan terrane, Southeast China: Petrogenesis and tectonic implications. *International Geology Review*, 58, 773–786.

Clark, J.D. & Pickering, K.T. (1996) Architectural elements and growth patterns of submarine channels: Application to hydrocarbon prospectivity. *American Association of Petroleum Geologists Bulletin*, 80, 194–221.

Collins, D.S., Avdis, A., Allison, P.A., Johnson, H.D., Hill, J., Piggott, M.D. et al. (2017) Tidal dynamics and mangrove carbon sequestration during the Oligo-Miocene in the South China Sea. *Nature Communications*, 8, 15698. https://doi.org/10.1038/ncomms15698

Collins, D.S., Avdis, A., Allison, P.A., Johnson, H.D., Hill, J. & Piggott, M.D. (2018) Controls on tidal sedimentation and preservation: Insights from numerical tidal modelling in the Late Oligocene-Miocene South China Sea, Southeast Asia. *Sedimentology*, 65, 2468–2505.

Collins, J.F., Kristanto, A.S., Bon, J. & Caughey, C.A. (1996) Sequence stratigraphic framework of oligocene and miocene carbonates, North Sumatra Basin, Indonesia. Proceedings of the Indonesian Petroleum Association, 25th Convention & Exhibition, Jakarta, pp. 267–279.

Crevello, P.D. (2006) The great Crocker Submarine Fan: a world class foredeep turbidite system. Proceedings of the Indonesian Petroleum Association. 28th Annual Convention, 1, pp. 377–407.

Crevello, P.D., Johnson, H., Clayburn, J. & Rahman, R.A. 2005. Deltaic and turbidite reservoir systems of SE Asia: high resolution exploration and development models and applications, from outcrop to subsurface. AAPG Field Seminar Guide Book, July 15–23.

Cullen, A., Macpherson, C., Taib, N.I., Burton-Johnson, A., Geist, D., Spell, T. et al. (2013) Age and petrology of the Usun Apau and Linau Balui volcanics: Windows to central Borneo’s interior. *Journal of Asian Earth Sciences*, 76, 373–388.

Curtis, C.D. (1980) Diagenetic alteration in black shales. *Journal of Geological Society of London*, 137, 189–194.

Davies, A.G.S., Cooke, D.R., Gemmell, J.B., van Leeuwen, T., Cesare, P. & Hartshorn, G. (2008) Hydrothermal breccias and veins at the Kelian gold mine, Kalimantan, Indonesia: Genesis of a large epithermal gold deposit. *Economic Geology*, 103, 717–757.

Davies, L., Hall, R. & Armstrong, R. (2014) Cretaceous crust in SW Borneo: Petrological, geochemical and geochronological constraints
from the Schwaner Mountains. Proceedings Indonesian Petroleum Association, 38th Annual Convention and Exhibition, IPA14-G-025. Dodd, T.J., Gillespie, M.R., Leslie, A.G., Kearsley, T.I., Kendall, R.S., Bide, T.P. et al. (2019) Paleozoic to Cenozoic sedimentary bedrock geology and lithostratigraphy of Singapore. Journal of Asian Earth Sciences, 180, 103878.

Froelich, P.N., Klinkhammer, G.P., Bender, M.L., Luedtke, G.R., Heath, G.R., Cullen, D. et al. (1979) Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic: suboxic diagene-
sis. Geochimica et Cosmochimica Acta, 43, 1075–1090.

Galin, T., Breitfeld, H.T., Hall, R. & Sevastjanova, I. (2017) Provenance of the Cretaceous-Eocene Rajang Group submarine fan, Sarawak, Malaysia from light and heavy mineral assemblages and U-Pb zir-
con geochronology. Gondwana Research, 51, 209–233.

García-Ramos, J.C., Mangano, M.R., Pineula, L., Buatois, L.A. & Rodríguez-Tovar, F.J. (2014) The ichnogenus Tubotomaculum: an enigmatic pellet-filled structure from the Upper Cretaceous to Miocene deep marine deposits of southern Spain. Journal of Paleontology, 88, 1189–1198.

Gillespie, M.R., Kendall, R.S., Leslie, A.G., Millar, I.L., Dodd, T.J., Kearsley, T.I. et al. (2019) The igneous rocks of Singapore: new in-
sights to Palaeozoic and Mesozoic assembly of the Sukhothai Arc. Journal of Asian Earth Sciences, 183, 103940.

Gou, P., & Abdullah, W.H. (2010) The geochemical fingerprint of the Layang-Layangan Beds, Labuan Island, NW Sabah Basin: Belait or Temburong Formation? Warta Geologi, 36(2), 84.

Griffin, W.L., Powell, W.J., Pearson, N.J. & O’Reilly, S.Y. 2008. GLITTER: data reduction software for laser ablation ICP-MS. In: Sylvester, P.J. (Ed.) Laser ablation-ICP-MS in the earth sciences: current practices and outstanding issues. Mineralogical association of Canada, Short Course 40, 308–311.

Groenenberg, R.M., Hodgson, D.M., Prélat, A., Luthi, S.M. & Flint, S.S. (2010) Flow-deposit interaction in submarine lobes: Insights from outcrop observations and realizations of a process-based num-
merical model. Journal of Sedimentary Research, 80, 252–267. https://doi.org/10.2110/jsr.2010.028

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

Hall, R. (2013b) The palaeogeography of Sundaland and Wallacea since the Late Jurassic. Journal of Limnology, 72(s2), e1, 1–17.

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

Hall, R. & Nichols, G. 2002. Cenozoic sedimentation and tectonics in Borneo: climatic influences on orogenesis. In: Jones, S.J. & Frostrick, L.E. (Eds.) Sediment flux to basins: causes, controls and consequences. Geological Society of London Special Publications, 191, 5–22.

Hamilton, W. (1979) Tectonics of the Indonesian region. U.S.G.S. Prof. Paper 1078A, 345 pp.

Hassan, M.H.A., Johnson, H.D., Allison, P.A. & Abdullah, W.H. (2013) Sedimentology and stratigraphic development of the upper Nyalau Formation (Early Miocene), Sarawak, Malaysia: A mixed wave- and tide-influenced coastal system. Journal of Asian Earth Sciences, 76, 301–311.

Hassan, M.H.A., Johnson, H.D., Allison, P.A. & Abdullah, W.H. 2017. Sedimentology and stratigraphic architecture of a Miocene retro-
gradational, tide-dominated delta system: Balingian Province, offshore Sarawak, Malaysia. In: Hampson, G.J., Reynolds, A.D., Kostic, B. & Wells, M.R. (Eds.) Sedimentology of paralic reservoirs: recent advances. London, UK: The Geological Society of London, Special Publications, 444, pp. 215–250. https://doi.org/10.1144/SP444.12

Hazenbroek, H.P. & Tan, D.N.K. 1993. Tertiary tectonic evolution of the NW Sabah continental margin. In: Geh, G.H. (Ed.) Proceedings of the symposium on tectonic framework and energy resources of the western margin of Pacific Basin. Bulletin of the Geological Society of Malaysia, 35, 195–210.

Hennig, J., Breitfeld, H.T., Gough, A., Hall, R., Van Long, T., Kim, V.M. et al. (2018) U-Pb zircon ages and provenance of upper Cenozoic sediments from the Da Lat Zone, SE Vietnam: Implications for an intra-Miocene unconformity and paleo-drainage of the proto-Mekong River. Journal of Sedimentary Research, 88(4), 495–515.

Hennig, J., Breitfeld, H.T., Hall, R. & Nugraha, A.M.S. (2017) The Mesozoic tectono-magmatic evolution at the Paleo-Pacific subduction zone in West Borneo. Gondwana Research, 48, 292–310.

Hennig-Breitfeld, J., Breitfeld, H.T., Hall, R., BouDagher-Fadel, M. & Thirwall, M. (2019) A new upper Paleogene to Neogene stratigraphy for Sarawak and Labuan in northwestern Borneo: Paleogeography of the eastern Sundaland margin. Earth-Science Reviews, 190, 1–32.

Hutchison, C.S. (1996) Geologic evolution of South-East Asia, 2nd edition. Geological Society of Malaysia. Malaysia: Oxford University Press & Geological Society of Malaysia, 368 pp.

Hutchison, C.S. (2005) Geology of NW Borneo. Elsevier BV, Amsterdam, The Netherlands.: Elsevier Science, 444 pp.

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

Jackson, C.-A.-L. and Johnson, H.D. (2009) Sustained turbidity cur-
rents and their interaction with debris-related topography; Labuan Island, offshore NW Borneo, Malaysia. Sedimentary Geology, 219, 77–96.

Jackson, C.-A.-L., Zakaria, A.A., Johnson, H.D., Tongkul, F. & Crevello, P.D. (2009) Sedimentology, stratigraphic occurrence and origin of linked debrites in the West Crocker Formation (Olio-
Miocene), Sabah, NW Borneo. Marine and Petroleum Geology, 26, 1957–1973.

James, D.M.D. (1984) The geology and hydrocarbon resources of Negara Brunei Darussalam. Brunei Darussalam: Muzim Brunei and Brunei Shell Petroleum Co., 164 pp.

Jasin, B. & Firdaus, M.D. (2019) Some deep-marine ichnofossils from Labuan and Klias Peninsula, west of Sabah. Bulletin of Geological Society of Malaysia, 67, 47–51.

Johnson, H.D. & Huang, J. (1988) Geological field guide to Labuan Island. Sabah Shell Petroleum Company Ltd, Unpublished Shell field guide.

Jong, J., Idris, H.A., Barber, P., Kessler, F.L., Tan, T.Q. & Uchimura, R. (2017b) Exploration history and petroleum systems of the onshore Baram Delta, northern Sarawak, Malaysia. Bulletin of Geological Society of Malaysia, 63, 117–143.

Jong, J., Kessler, F., Noon, S. & Tan, T.T.Q. (2016) Structural develop-
ment, deposition model and petroleum system of paleogene carbonate of the Engkabang-Karap Anticline, Onshore Sarawak. Berita Sedimentologi, 34, 5–25.

Kessler, F.L. & Jong, J. (2016) The South China Sea: Sub-basins. Regional Unconformities and Uplift of the Peripheral Mountain Ranges since the Eocene. Berita Sedimentologi, 35, 5–54.
Kho, C.H. (1968) Bintulu Area, Central Sarawak, East Malaysia: Explanation of sheet 3/113/13, Report 5. Geological Survey, Borneo Region, Malaysia, 83 pp.

Kneller, B. (1995) Beyond the turbidite paradigm: physical models for deposition of turbidites and their implications for reservoir prediction. In: Hartley, A. and Prosser, D.J. (Eds.) Characterization of deep marine clastic systems. Geological Society Special Publication, pp. 31–49.

Lambiase, J.J., Abdul Razak, D., Simmonds, M.D., Abdoerrias, H.A. (2003) A depositional model and stratigraphic development of modern and ancient tide dominated deltas in NW Borneo. In: Sidi, F.H., Nummedal, D., Imbert, P., Darman, H. & Posamentier, H.W. (Eds.), Tropical deltas of Southeast Asia –sedimentology, stratigraphy and petroleum geology. SEPM Special Publication, 76, 109–124.

Le Le Bas, M.J., Maire, R.W., Streickeisen, A. & Zanettin, B. (1986) A chemical classification of volcanic rocks based on the Total Alkali-Silica diagram. Journal of Petrology, 27, 745–750.

Lee, C.P. (1977) The geology of Labuan Island, Sabah, East Malaysia. BSc. Hons Thesis, Jabatan Geologi, Universiti Malaya, 1976/77.

Lee, G.H., Lee, K. & Watkins, J.S. (2001) Geologic evolution of the Cuc Long and Nam Con Son Basins, offshore southern Vietnam, South China Sea. American Association of Petroleum Geologists Bulletin, 85, 1055–1082.

Levell, B.K. (1987) The nature and significance of regional unconformity in the hydrocarbon-bearing Neogene sequence offshore West Sabah. Bulletin of the Geological Society of Malaysia, 21, 55–90.

Li, X.H. (1997) Timing of the Cathaysia Block formation: constraints from SHRIMP U-Pb zircon geochronology. Episodes, 20, 188–192.

Liebermann, C., Hall, R. & Gough, A. (2017) Provenance of sediments from Sumatra, Indonesia-Insights from detrital U-Pb zircon geochronology, heavy mineral analyses and Raman spectroscopy, AGU Fall Meeting 2017, New Orleans, USA.

Liechti, P., Roe, F.W. & Haile, N.S. (1960) The geology of Sarawak, Brunei and the western part of North Borneo. British Territories of Borneo. Geological Survey Department, Bulletin (two, volumes) 3, 360 pp.

Liu, Q., Yu, J.H., O’Reilly, S.Y., Zhou, M.F., Griffin, W.L., Wang, L. et al. (2014) Origin and geological significance of Paleoproterozoic granites in the northeastern Cathaysia Block, South China. Precambrian Research, 248, 72–95.

Liu, R., Zhou, H., Zhang, L., Zhong, Z., Zeng, W., Xiang, H. et al. (2009) Paleoproterozoic reworking of ancient crust in the Cathaysia Block, South China: evidence from zircon trace elements, U-Pb and Lu-Hf isotopes. Chinese Science Bulletin, 54, 1543–1554.

Ludwig, K.R. (2008) User’s manual for isoplot 4.15. A geochronological toolkit for Microsoft Excel. Berkeley, CA: Berkeley Geochronology Center.

Lukie, T. & Balaguru, A. 2012. Sequence stratigraphic, sedimentologic and petrographic insights of the Miocene (stage IVA) outcrops of the Klias Peninsula and Labuan Island, Sabah, Malaysia, Borneo. American Association of Petroleum Geologists, Search and Discovery Article #10468.

Lunt, P. & Madon, M.B.H. (2017) Onshore to offshore correlation of northern Borneo: a regional perspective. Geological Society Malaysia Bulletin, 64, 101–122.

Macpherson, C.G., Chiang, K.K., Hall, R., Nowell, G.M., Castillo, P.R. & Thirlwall, M.F. (2010) Plio-Pleistocene intra-plate magmatism from the southern Sulu Arc, Semporna peninsula, Sabah, Borneo: implications for high-Nb basalt in subduction zones. Journal of Volcanology and Geothermal Research, 190(1–2), 25–38.

Madon, M. (1994) The stratigraphy of northern Labuan, NW Sabah Basin, east Malaysia. Geological Society of Malaysia Bulletin, 36, 19–30.

Madon, M. (1997) Sedimentological aspects of the Temburong and Belait Formations, Labuan (offshore west Sabah, Malaysia). Bulletin of the Geological Society of Malaysia, 41, 61–84.

Madon, M. (2020) Sand injections in the West Crocker Formation, Kota Kinabalu, Sabah. Bulletin of Geological Society of Malaysia, 69, 11–26.

Madon, M., Meng, K.L. & Anuar, A. (1999) Sabah basin. In: The petroleum geology and resources of Malaysia. Kuala Lumpur, Malaysia: Petromas, pp. 499–542.

Madon, M., Kim, C.L. & Wong, R. (2013) The structure and stratigraphy of deepwater Sarawak, Malaysia: implications for tectonic evolution. Journal of Asian Earth Sciences, 76, 312–333.

Mandeville, C.W., Carey, S. & Sigurdsson, H. (1996) Sedimentology of the Krakatau 1883 submarine pyroclastic deposits. Bulletin of Volcanology, 57, 512–529.

Morley, R.J. (2018) The complex history of mountain building and the establishment of mountain biota in Southeast Asia and Eastern Indonesia, Chapter 31. In: Hoorn, C., Perrigo, A. & Antonelli, A. (Eds), Mountains, climate and biodiversity. Oxford: John Wiley & Sons-Blackwell, pp. 475–493.

Morley, R.J., Hasan, S.S., Morley, H.P., Jasi, J.H.M., Mansor, A., Arhipin, M.R. et al. (2021) Sequence biostratigraphic framework for the oligocene to pliocene of Malaysia: high-frequency depositional cycles driven by glaciation. Palaeogeography, Palaeoclimatology, Palaeoecology, 561, https://doi.org/10.1016/j.palaeo.2020.110058

Morley, R.J. & Morley, H.P. (2013) Mid Cenozoic freshwater wetlands of the Sunda region. Journal of Limnology, 72, 18–35.

Morley, R.J., Morley, H.P. & Swiecicki, T. (2016) Mio-Pliocene palaeography, uplands and river systems of the Sunda region based on mapping within a framework of VIM cycles. Proceedings, Indonesian Petroleum Association 40th Annual Convention & Exhibition, May 2016. IPA16-506G, 26 pp.

Morley, R.J., Swiecicki, T. & Pham, D.T.T. (2011) A sequence stratigraphic framework for the Sunda Region, based on integration of biostratigraphic, lithological and seismic data from Nam Con Son Basin: Vietnam. Proceedings, Indonesian Petroleum Association 35th Annual Convention & Exhibition, May 2011, IPA11-G-002, 22 pp.

Moss, S.J., Carter, A., Baker, S. & Hurford, A.J. (1998) A Late Oligocene tectono-volcanic event in East Kalimantan and the implications for tectonics and sedimentation in Borneo. Journal of Geological Society of London, 155, 177–192.

Moss, S.J. & Wilson, M.E.J. (1998) Biogeographic implications of the Tertiary palaeogeographic evolution of Sulawesi and Borneo. In: Hall, R. & Holloway, J.D. (Eds.) Biogeography and geological evolution of SE Asia. Leiden, The Netherlands: Backhuys Publishers, pp. 133

Murray, M.R. & Dorobek, S.L. (2004) Sediment supply, tectonic subsidence and basin-filling patterns across the southwestern South China Sea during Pliocene to Recent time. In: Clift, P., Kuhnt, W., Wang, P. & Hayes, D (Eds.) Continental-ocean interactions within East Asian marginal seas. Geophysical Monograph Series, American Geophysical of Union Monograph Series. 149
Washington: American Geophysical Union, 235–254. https://doi.org/10.1029/149GM13

Nagarajan, R., Roy, P.D., Kessler, F.L., Jong, J., Dayong, V. & Jonathan, M.P. (2017) An integrated study of geochemistry and mineralogy of the Upper Tukau Formation, Borneo Island (East Malaysia): sediment provenance, depositional setting and tectonic implications. *Journal of Asian Earth Sciences*, 143, 77–94.

B. J., van der Zwan, C.J., Postma, G. et al. (2006) Benthic foraminifera from Pliocene sediments in offshore NW Sabah Area. *Proceedings of the Ocean Drilling Program, Scientific Results*, 28, 1585–1608.

Setiabudi, B.T., Campbell, I.H., Martin, C.E. & Allen, C.M. (2007) Platinum group element geochemistry of andesite intrusions of the Kelian region, East Kalimantan, Indonesia: Implications of gold depletion in the intrusions associated with the Kelian gold deposit. *Economic Geology*, 102, 95–108.

Plumhuis, B., Belousova, E., Reiners, P.W. & Simmons, M.D. (Eds.) (2012) Tectonic evolution of the Sibumasu-Indochina terrane collision zone in Thailand and Malaysia: constraints from new U-Pb zircon chronology of SE Asian tin granitoids. *Journal Geological Society of London*, 169, 489.

Seepage. Proceedings of the Annual Offshore Technology Conference, pp. 175–192.

E&P conference abstract volume. Olympia Exhibition Centre, London. https://www.pesgb.org.uk/wp-content/uploads/2018/06/PESGB-SEAPEX-2018-Session-4_3-Scardina-et-al_Abstract.pdf

Whelley, P.L. et al. (2014) Volcanic tsunami: A review of source activity. *Journal of Geology*, 124, 295–318.

Staiwana, N.I., Osanai, Y., Nakano, N., Adachi, T., Setiadi, L.D. & Wahyudiono, J. (2013) Late Triassic metatonalite from the Kelian region, East Kalimantan, Indonesia: Implications of gold depletion in the intrusions associated with the Kelian gold deposit. *Economic Geology*, 102, 95–108.

Setiawanna, N.I., Osanai, Y., Nakano, N., Adachi, T., Setiadi, L.D. & Wahyudiono, J. (2013) Late Triassic metatonalite from the Schwaner Mountains in West Kalimantan and its contribution to sedimentary provenance in the Sundaland. *Berita Sedimentologi*, 12(28), 4–12.

Sevastjanova, I., Clements, B., Hall, R., Belousova, E.A., Griffin, W.L. & Pearson, N. (2011) Granitic magmatism, basement ages, and provenance indicators in the Malay Peninsula: Insights from detrital zircon U-Pb and Hf-isotope data. *Gondwana Research*, 19, 1024–1039.

Shoup, R.C., Morley, R.J., Swieciecki, T. & Clark, S. (2013) Tectonostratigraphic framework and tertiary paleogeography of Southeast Asia: Gulf of Thailand to South Vietnam Shelf. *Houstin Geological Society of Bulletin*, 55, 27–39.

Silver, E.A. & Rangin, C. (1990) Leg 124 of the ocean drilling program. *Geophysical Research Letters*, 17(11), 2059–2060.

Simmons, M.D., Bidgood, M.D., Brenac, P., Crevello, P.D., Lambiase, J.J. & Morley, C.K. (1999) Microfossil assemblages as proxies for precise palaeoenvironmental determination – An example from Miocene sediments of northwest Borneo. In: Jones, R.W. & Simmons, M.D. (Eds.) *Biostratigraphy in production
and development geology. Geological Society of London Special Publications. Special Publications, 152 London: Geological Society of London, pp. 219–241.

Sircombe, K.N. (2004) AgeDisplay: an EXCEL workbook to evaluate and display univariate geochronological data using binned frequency histograms and probability density distributions. Computers & Geosciences, 30, 21–31.

Slama, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M. et al. (2008) Plesovice zircon — A new natural reference material for U-Pb and Hf isotopic microanalysis. Chemical Geology, 249, 1–35.

Sliter, W.V. (1975) Foraminiferal life and residue assemblages from oceanic basalts: implications for mantle composition and evolution of oceanic basalts: implications for mantle composition and development geology. Geological Society of London Special Publications, 152 London: Geological Society of London, pp. 219–241.

Soeria-Atmadja, R., Noeradi, D. & Priadi, B. (1999) Cenozoic magmatism in Kalimantan and its related geodynamic evolution. Journal of Asian Earth Sciences, 17, 25–45.

Som, M.R.B.M., Kadir, M.A., Ali, S.S., Jirin, S., Sulaiman, K.W., Mohsin, M. & Shah, S.S.M. (2011) Labuan outcrops revisited: new findings on Belait Formation facies evolution. Proceedings of Petroleum Geology Conference, March 2011. KLCC, Geology Paper 21.

Stanbrook, D.A., Capuzzo, N., LeCompte, B., Ducannin, M., Perez, G. & Seitchik, A. 2020. Onshore structural movement revealed through the presence of volcanlastic deposition offshore. Chohula-1EXP, Miocene Salinas del Istmo Basin, Mexico. AAPG Annual Convention and Exhibition Abstract volume, 3654, 17 pp. Houston, Texas, 29 September, 2020.

Suderamono, A., Direza, H.B. & Maulin, A.W. (2017) Some new insights to tectonics and stratigraphic evolution of the Tarakan Sub-Basin, North East Kalimantan, Indonesia. Proceedings Indonesian Petroleum Association 41st Annual Convention and Exhibition, IPA17-722-G, 22 pp.

Sun, S.S. & McDonough, W.F. (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D. & Norry, M. (Eds) Magmatism in oceanic basins. Geological Society of London Special Publications, 42, 313–345.

Tanean, H., Paterson, D.W. & Endharto, M. (1996) Source provenance interpretation of Kutei Basin sandstones and the implications for the tectono-stratigraphic evolution of Kalimantan. Proceedings of the Indonesian Petroleum Association, IPA-1.1-196, 333–345.

Tate, R.B. (1994) The sedimentology and tectonics of the Temburong Formation — deformation of early Cenozoic deltaic sequence in NW Borneo. Geological Society of Malaysia Bulletin, 35, 97–112.

Taylor, A.M. & Goldring, R. (1993) Description and analysis of bioturbation and ichnofabric. Journal of Geological Society of London, 150, 141–148.

Taylor, B. & Hayes, E. (1983) Origin and history of the South China Sea Basin. In: Hayes, D.E. (Ed.), The tectonic and geologic evolution of Southeast Asia seas and islands. Part 2, vol. 27, Geophysical Monograph, America Geophysical Union, Washington, pp. 23–56.

Thurov, J. & von Rad, U. (1992) Bentonites as tracers of earliest Cretaceous post-break-up volcanism off north-western Australia (legs 122 and 123). In: Gradstein, F.M., & Ludden, J.N. (Eds.), Proceedings of the Ocean Drilling Program. Scientific Results, Proceedings of the ODP Scientific Results, 123, Chapter 4, pp. College Station, TX, 123 89–110. https://doi.org/10.2973/odp.proc. sr.123.150.1992.

Tjia, H.D. (2016) Temburong and Setup in Northwestern Borneo: equivalent and different formations? Berta Sedimentologii, 35, 65–74.

Trofimovs, J., Sparks, R.S.J. & Talling, P.J. (2008) Anatomy of a submarine pyroclastic flow and associated turbidity current: July 2003 dome collapse, Soufrière Hills volcano, Montserrat, West Indies. Sedimentology, 55, 617–634.

van Hattum, M.W.A., Hall, R., Pickard, A.L. & Nichols, G.J. (2006) SE Asian sediments not from Asia: provenance and geochronology of North Borneo sandstones. Geology, 34, 589–592.

van Hattum, M.W.A., Hall, R., Pickard, A.L. & Nichols, G.J. (2013) Provenance and geochronology of Cenozoic sandstones of northern Borneo. Journal of Asian Earth Sciences, 76, 266–282.

van Marle, L.J. (1989) Recent and fossil benthic foraminifera and late Cenozoic palaeobathymetry of Seram, eastern Indonesia. Netherlands Journal of Sea Research, 24, 445–457.

Van Vliet, A. & Schwander, M.M. (1987) Stratigraphic interpretation of a regional seismic section across the Labuan syncline and its flank structures, Sabah, North Borneo. In: Bailey, A.W. (Ed.) Atlas of seismic stratigraphy. American Association of Petroleum Geologists, Studies in Geology, 27, 163–167.

Wade, B.S., Pearson, P.N., Berggren, W.A. & Palike, H. (2011) Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. Earth-Science Reviews, 104, 111–142.

Walker, S.L., Baker, E.T., Resing, J.A., Chadwick, W.W., Lebon, G.T., Lupton, J.E. et al. (2008) Eruption-fed particle plumes and volcanlastic deposits at a submarine volcano; NW Rota-1, Mariana Arc. Journal of Geophysical Research, 113, B08S11. https://doi.org/10.1029/2007JB005441.

Wang, C., Liang, X., Foster, D.A., Fu, J., Jiang, Y., Dong, C. et al. (2016) Provenance and geochronology of Cenozoic sandstones of northern Borneo. Geological Society of Malaysia, Borneo Region. Memoir, 17.

Tjia, H.D. (1998) Late Cenozoic palaeobathymetry of Seram, eastern Indonesia. Netherlands Journal of Sea Research, 24, 445–457.

Thurow, J. & von Rad, U. (1992) Bentonites as tracers of earliest Cretaceous post-break-up volcanism off north-western Australia (legs 122 and 123). In: Gradstein, F.M., & Ludden, J.N. (Eds.), Proceedings of the Ocean Drilling Program. Scientific Results, Proceedings of the ODP Scientific Results, 123, Chapter 4, pp. College Station, TX, 123 89–110. https://doi.org/10.2973/odp.proc. sr.123.150.1992.

Wiesner, M.G., Wetzel, A., Catane, S.G., Listanco, E.L. & Mirabueno, H.T. (2004) Grain size, areal thickness, distribution and controls on sedimentation of the 1991 Mount Pinatubo tephra layer in the South China Sea. Bulletin of Volcanology, 66, 226–242.

William, A.G., Lambiase, J.J., Back, S. & Kamiran, M.K. (2003) Sedimentology of the Jalan Salaiman and Bukit Meinsung outcrops, western Sabah: Is the West Crocker Formation an analogue for the Neogene turbidites offshore? Geological Society of Malaysia Bulletin, 47, 63–75.

Williams, P.R. & Harahap, B.H. (1987) Preliminary geochemical and age data from post-subduction intrusive rocks, northwest Borneo. Australian Journal of Earth Sciences, 34, 405–416.

Williams, P.R., Johnston, C.R., Almond, R.A. & Simamora, W.H. (1988) Late Cretaceous to early Tertiary structural elements of West Kalimantan. Tectonophysics, 148, 279–297.

Wilson, R.A.M. & Wong, N.P.Y. (1964) The geology and mineral resources of the Labuan and Padas Valley area, Sabah, Malaysia. Geological Survey of Malaysia, Borneo Region. Memoir, 17, 150.

Wirojudo, G.K. & Wongos制订, A. (1985) Tertiary tectonic evolution and related hydrocarbon potential in the Natuna area. Energy, 10, 433–455.
Wolfenden, E.B. (1960) The geology and mineral resources of the lower Rajang Valley and adjoining areas, Sarwak. Geological Survey of British Territories in Borneo, Memoir, 11, 167.

Wong, H.F. (1997) Sequence stratigraphy of the Upper Miocene Stage IVe in the Labuan-Paisley Syncline, northwest Sabah Basin. Geological Society of Malaysia Bulletin, 41, 53–60.

Zakaria, A.A., Johnson, H.D., Jackson, C.A. & Tongkul, F. (2013) Sedimentary facies analysis and depositional model of the Palaeogene West Crocker submarine fan system, NW Borneo. Journal of Asian Earth Sciences, 76, 283–300.

How to cite this article: Burley SD, Breitfeld HT, Stanbrook D’, et al. A tuffaceous volcanioclastic turbidite bed of Early Miocene age in the Temburong Formation of Labuan, North-West Borneo and its implications for the Proto-South China Sea subduction in the Burdigalian. Depositional Rec. 2021;7:111–146. https://doi.org/10.1002/dep2.132