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Deep to shallow-marine sedimentology and impact of volcanism within the Middle Triassic Palaeo-Tethyan Semantan Basin, Singapore

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A R T I C L E I N F O

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A B S T R A C T

The Middle Triassic Pulau Ayer Chawan Formation is a predominantly deep-marine, occasionally shallow-marine sedimentary succession, deposited in the Singapore sector of the Palaeo-Tethyan Semantan Basin. The formation provides an important record of the dynamic interplay between a siliciclastic sedimentary system and the products of an adjacent active volcanic arc. It is characterised by six sub-environments, including: deep-marine turbidite fan, deep-marine background sedimentation, subaqueous debris cone, shallow-marine, volcanically-sourced turbidite fan, and hyaloclastite mound or ridge. Turbidite fan deposits preserve the input of both siliciclastic and volcaniclastic sediments from the shelf, transported into the deep-marine environment by a suite of subaqueous sediment gravity flow processes, including: turbidity currents; mixed flow types (hybrid event beds); concentrated and hyper concentrated sediment gravity flows, and debris flows. Thick heterolithic successions of debrites were likely sourced through regular collapse of an unstable shelf. The presence of hybrid event beds, encountered within the deep-marine turbidite fans, supports a slope that was out-of-grade, and may have been actively retreating towards the hinterland. Together, these factors suggest regional-scale uplift of the eastern margins of the Semantan Basin during Triassic times, most likely facilitated through volcanic activity in the adjacent Palaeo-Tethys Sukhothai Arc. Evidence for contemporaneous, arc-related magmatism includes ubiquitous volcaniclastic sedimentary rocks within formation, including pyroclastic density current deposits and perhaps more-strikingly through the hyaloclastites of the Nanyang Member. The hyaloclastites formed through quenching of magmas delivered into the deep-marine setting from a series of sub-sea vents or mounds.

1. Introduction

Globally, deep-water environments (and turbidite fan settings in particular) form heterolithic sedimentary successions (*cf.* Richards and Bowman, 1998), which display complex vertical and lateral geometries internally (Zhang et al., 2017 and references therein; Bell et al., 2018; Dodd et al., 2019b), and record a large range of sedimentary flow processes (Lowe, 1979; Shanmugam et al., 2009; Haughton et al., 2009; Kane and Pontén, 2012; Talling, 2013 and references therein). Deep-water (and nearshore) settings provide a record of activity in the adjacent hinterland, particularly in island-arc and fore-arc settings where the deposits can form useful tools, or sedimentary 'tape recorders', relating to the associated volcanism. Excellent examples of such systems include: the Upper Cretaceous Rosario Formation in the Peninsular Ranges forearc basin, Baja California del Notre, USA (Morris and Busby-Spera, 1990; Busby et al., 1998; Kimbrough et al., 2001); the Miocene Caleta Herradura Formation, Mejillones Peninsular Chile (Di Clema and Cantalamessa, 2007); the Mesozoic Fossil Bluff and LeMay groups, Alexander Island, Antarctica (Doubleday et al., 1993); the Oligocene Izu-Bonin Basin, Japan (Hiscott et al., 1992, 1993); the Upper Cretaceous–lower Eocene Xigaze Basin, Tibet (Orme et al., 2015); and the Val d'Aveto Formation and Taveyanne Sandstones of the Alps and the Apennines of central Europe (Di Capua and Groppelli, 2018).

Characterising such systems is important as they preserve a relatively continuous account of deposition throughout time (compared with generally higher energy shallow-marine or even terrestrial settings), and can therefore be used to more accurately reconstruct both palaeoslope processes and associated activity (e.g. volcanism or

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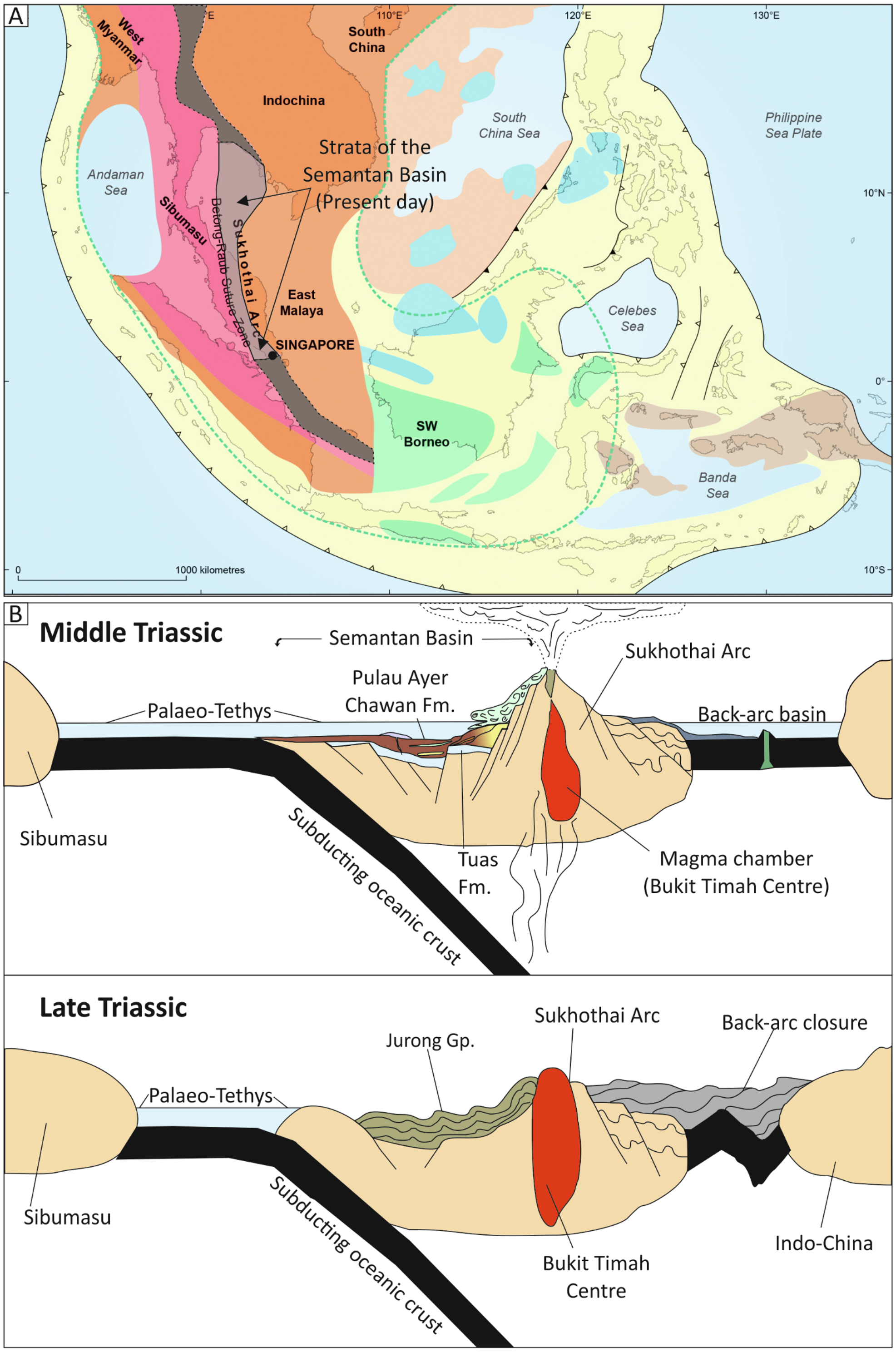

Fig. 1. Present day and Triassic tectonic settings of Southeast Asia and Singapore. (A) Present day tectonic setting of Southeast Asia, detailing the wide variety of terranes or blocks that comprise the region. The location of Singapore, at the southerly end of Peninsular Malaysia is marked. Peninsular Malaysia comprises three belts: the western belt, along with the central and eastern belts, the latter two representing the geology in Singapore. The distribution of the Sukhothai Arc, and by association the volcani-sedimentary rocks of the Semantan Basin, are marked, following the strike of Peninsular Malaysia, and lying east of the trace of the Bentong-Raub Suture Zone, modified after Metcalfe (2011; *cf.* Hall 2009). (B) Schematic sections depicting the Middle and Upper Triassic elements and overall tectonic setting recorded in the bedrock of Singapore. The position of the Pulau Ayer Chawan Formation, Semantan Basin, and their relationship with the active Sukhothai Arc during the Middle Triassic are indicated. The formation, along with the rest of the Jurong Group strata, later became folded during the final closure of Palaeo-Tethys. *(BGS © UKRI 2020).*

seismicity) in the hinterland (Orme et al., 2015). As these rock types often form bedrock components under major cities, including those of Southeast Asia (e.g. Singapore and Kuala Lumpur), and are used for many purposes, including: underground storage projects (i.e. the Jurong Caverns in Singapore; Winn et al., 2018, 2019); geotechnical engineering in general (Mohamed et al., 2007; Ismail et al., 2011); and groundwater aquifers (Hamzah et al., 2006; Manap et al., 2013), understanding their distribution and character is of great importance.

Southeast Asia has a complex geological history, with a number of key publications that summarise the regional geological knowledge (Hutchison and Tan, 2009 and references therein; Hall, 2009, 2012; Metcalfe, 2013; Searle et al., 2012; Sevastjanova et al., 2016; Metcalfe, 2017a, 2017b). A number of studies focus in particular on the diverse geology of Peninsular Malaysia (Burton, 1973; Lee et al., 2004; Metcalfe, 2000, 2011; Sone and Metcalfe, 2008; Hutchison and Tan, 2009). Located at the southern end of Peninsular Malaysia (Fig. 1A), Singapore shares much of its geological history with the Central and Eastern belts of Peninsular Malaysia. Together these two belts comprise what was the Palaeo-Tethyan Sukhothai Arc, constructed on the oceanward margin of the Indochina-East Malaya block (*cf.* Metcalfe, 2017a), along with surrounding or adjacent depocenters (e.g. the Semantan Basin; Fig. 1B). Previous studies, published as a wide variety of

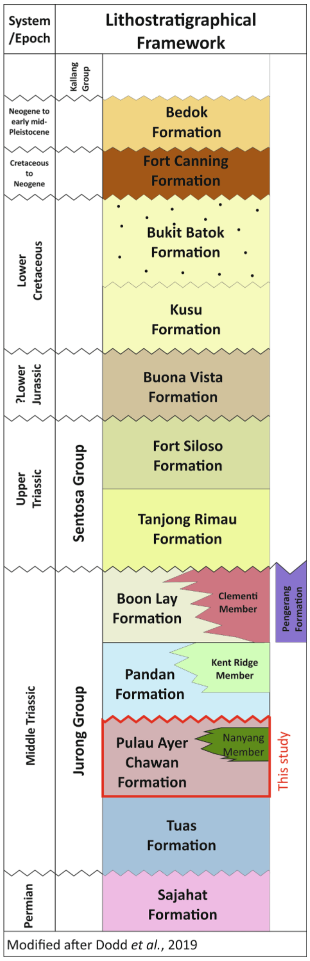

Fig. 2. The lithostratigraphical framework of Singapore comprising 13 newly-defined formations, three members and three groups. Triassic sedimentation in Singapore is represented by the Jurong Group, and overlying Sentosa Group, the former containing the focus of this study; the Pulau Ayer Chawan Formation. The Pulau Ayer Chawan Formation is considered to be Middle Triassic in age, and contains a single member: the Nanyang Member (modified after Dodd et al., 2019a). *(BGS © UKRI 2020).*

article types, have discussed the geology of Singapore (see Logan, 1851; Scrivenor, 1924; Alexander, 1950, Burton, 1964; Chin, 1965; Kobayashi and Tamura, 1968; PWD, 1976; DSTA, 2009; Hutchison and Tan, 2009; Lat et al., 2016; Oliver and Prave, 2013; Oliver et al., 2014; Oliver and Gupta, 2017). In general, these studies were based on very limited outcrop data, much of which has now been urbanised and no longer exists.

A new set of studies, based on *c.* 20,000 m of borehole core samples collected in 2016, augmented with outcrop analysis and published in 2019, provided a significant update to the understanding of the geology of Singapore (Dodd et al., 2019a; Gillespie et al., 2019; Leslie et al., 2019). The revised lithostratigraphical framework (see Dodd et al., 2019a) is divided into 13 newly-defined formations, (with three member-level sub-divisions), and three new groups (Fig. 2). The Pulau Ayer Chawan Formation forms part of the newly defined 'Jurong Group'. The group includes three other new formations: the Tuas Formation lies beneath the Pulau Ayer Chawan Formation, the Pandan and Boon Lay formations overly it. Strata, previously assigned to the 'Ayer Chawan Facies' in Singapore (PWD, 1976; DSTA, 2009; Winn et al., 2018, 2019; Oliver and Gupta, 2017, 2019), are thought to be broadly correlative (or equivalent) to the strata of the newly defined Pulau Ayer Chawan Formation. In some instances however, a one-to-one correlation between the facies scheme of DSTA (2009) and the newly-defined lithostratigraphical units is not possible (as discussed in Dodd et al., 2019a).

The Pulau Ayer Chawan Formation comprises interbedded sandstone and mudstone with subsidiary, but upwards increasing occurrences of volcanogenic/volcanigenic rock (tuff, lapilli-tuff, and tuffite) and conglomerate; the formation reflects deposition in a deep-marine sedimentary environment that occasionally grades into a shallow-water setting (Fig. 3; Dodd et al., 2019a). The formation contains the Nanyang Member, which is characterised by occurrences of pyroclastic rocks, specifically hydroclastic (quenched) lapilli-tuff, and lapillistone. These strata were deposited as a result of a series of subaqueous eruptions from a sub-sea vent (Dodd et al., 2019a) into a deep-marine environment. These volcanogenic rocks are associated with contemporaneous arc-related magmatism, which provided volcaniclastic input along with the siliciclastic sediments filling the forearc Semantan Basin (Gillespie et al., 2019).

The Pulau Ayer Chawan Formation is thought to be Middle Triassic (Anisian) in age based upon a sample of tuff from BH1A9, which gives a U-Pb zircon age of 245 ± 1 Ma (Gillespie et al., 2019). The Middle Triassic age determination is corroborated by a U-Pb zircon date of 240.6 ± 1.2 Ma obtained from pyroclastic 'peperite' deposits from the 'Ayer Chawan Facies' of the Jurong Caverns in Singapore (Winn et al., 2018). The Pulau Ayer Chawan Formation, and more widely the Jurong Group, has been correlated with the Middle to Upper Triassic Semantan Formation (or the Gemas Formation) of the Semantan Basin in Peninsular Malaysia (Fig. 1B; Jaafar Ahmad, 1976; Metcalfe et al., 1982; Peng, 1983; Metcalfe and Chakraborty, 1994; Ismail et al., 2007; Madon, 2006, 2010; Mohamed, 2016; Dodd et al., 2019a).

Of the *c.* 20,000 m of borehole core data collected across south-western Singapore (see Dodd et al., 2019a), *c.* 2,600 m represents strata of the Pulau Ayer Chawan Formation and a further *c.* 192 m from the Nanyang Member (Figs. 4 and 5). Through a detailed sedimentological analysis of this dataset, this study addresses the following questions:

i. What are the dominant set of processes that transported and deposited the sedimentary successions of the Pulau Ayer Chawan Formation and Nanyang Member?
ii. What are the key depositional systems and sub-environments within the deep-marine to shallow-marine environment of the Pulau Ayer Chawan Formation?
iii. What are the main controls on siliciclastic and volcaniclastic input from the hinterland into the Semantan Basin during Middle Triassic times?
iv. How does contemporaneous volcanism within the adjacent Sukhothai Arc impact on the sedimentology in the Semantan Basin?
v. What are the implications for regional geology and palaeogeographical models of this part of Southeast Asia during the Middle Triassic?

Through answering these questions, this study provides a detailed characterisation and comprehensive understanding of the sedimentary and volcano-sedimentary processes that formed the Pulau Ayer Chawan Formation and Nanyang Member of Singapore. This is important as the formation represents an important rock record for deposition within the wider-scale Semantan Basin that sat outboard from Sukhothai Arc throughout Middle Triassic times, and, in general, preserves geological processes occurring during the amalgamation of Sibumasu, and final closure of Palaeo-Tethys.

2. Geological setting

Southeast Asia is composed of a number of continental blocks and volcanic arc terranes welded together along suture zones marking the sites of destroyed Tethyan Ocean basins (e.g. Sone and Metcalfe, 2008; Searle et al., 2012; Metcalfe, 2016, 2017a, 2017b). The new continental block that forms the 'core' of present day Southeast Asia (referred to as

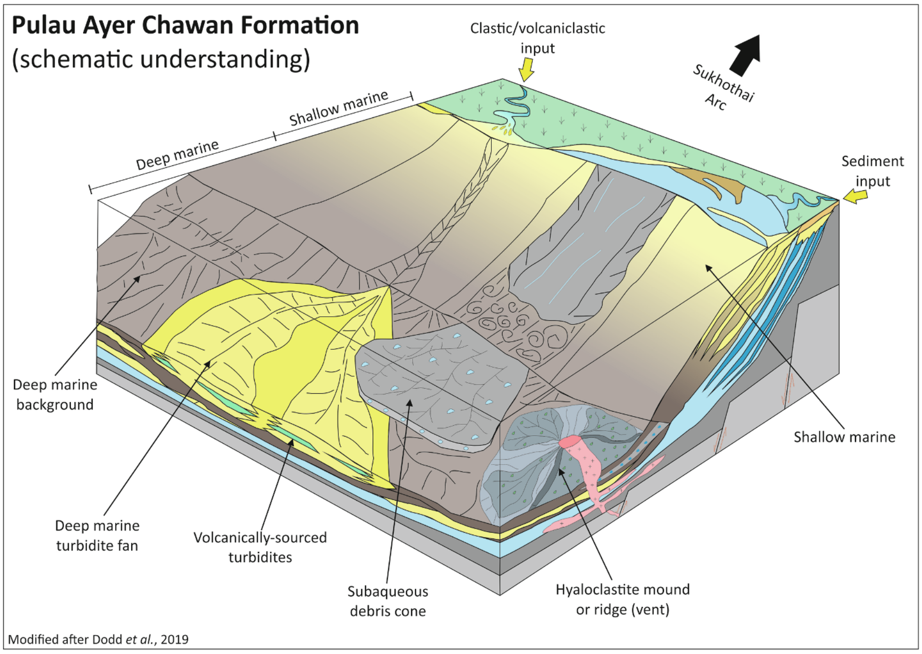

Fig. 3. A 3D block diagram summarising the current understanding of the deep, but occasionally shallow-marine environment of the Pulau Ayer Chawan Formation (*sensu* Dodd et al., 2019a). The formation comprises a highly heterogeneous succession of sedimentary deposits, which include deep-water hemi-pelagic mudstones, turbidite fans, subaqueous debris cones, volcanic eruptive deposits from sub-sea vents (hyaloclastite mound or ridge) and shallow-marine deposits. The formation is thought to be deposited in the Semantan Basin; a Triassic-aged depocenter that occupied areas surrounding the Sukhothai Arc (modified after Dodd et al., 2019a). *(BGS © UKRI 2020).*

Sundaland) formed through the initial rifting, transportation, and subsequent re-accretion of these various terranes during the later parts of the Palaeozoic and into the early Mesozoic (Hutchison, 1989; Hall, 2009; Metcalfe, 2011). Peninsular Malaysia (and the along-strike geology of Singapore) is composed of two continental fragments referred to as Sibumasu and Indochina-East Malaya, both of which separated from the Northwest Indian-Australian margin of the Gondwanan supercontinent at different times during the Palaeozoic (Hall, 2012, and references therein; Metcalfe, 2011, 2013, 2017a, 2017b, and references therein; Sevastjanova et al., 2016). These fragments are now joined together, along with rocks assigned to the Sukhothai Arc 'terrane', across the trace of the Bentong-Raub Suture Zone. The rocks of

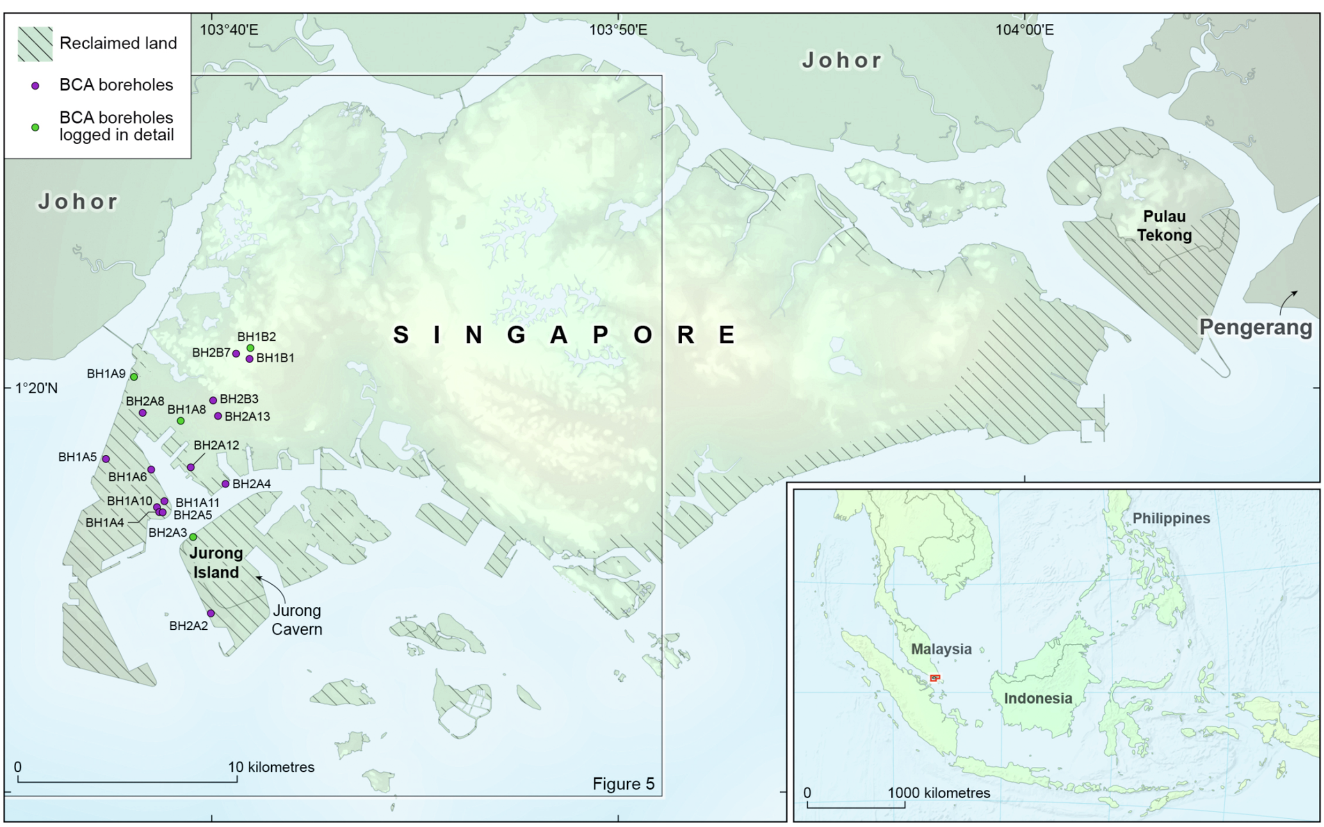

Fig. 4. Modern-day shaded-relief map of Singapore, along with Johore and neighbouring islands. See inset map for the location of Peninsular Malaysia, and Singapore, in respect to the rest of Southeast Asia. The 'top-hole' locations for all boreholes that intersect the Pulau Ayer Chawan Formations are marked in black, with the sections logged in detail in this study marked in green. The Pulau Ayer Chawan Formation has been intersected in boreholes largely in the western and south-western parts of Singapore. The area shown in Fig. 5 is marked on the map. *(Contains borehole location data © BCA 2020).*

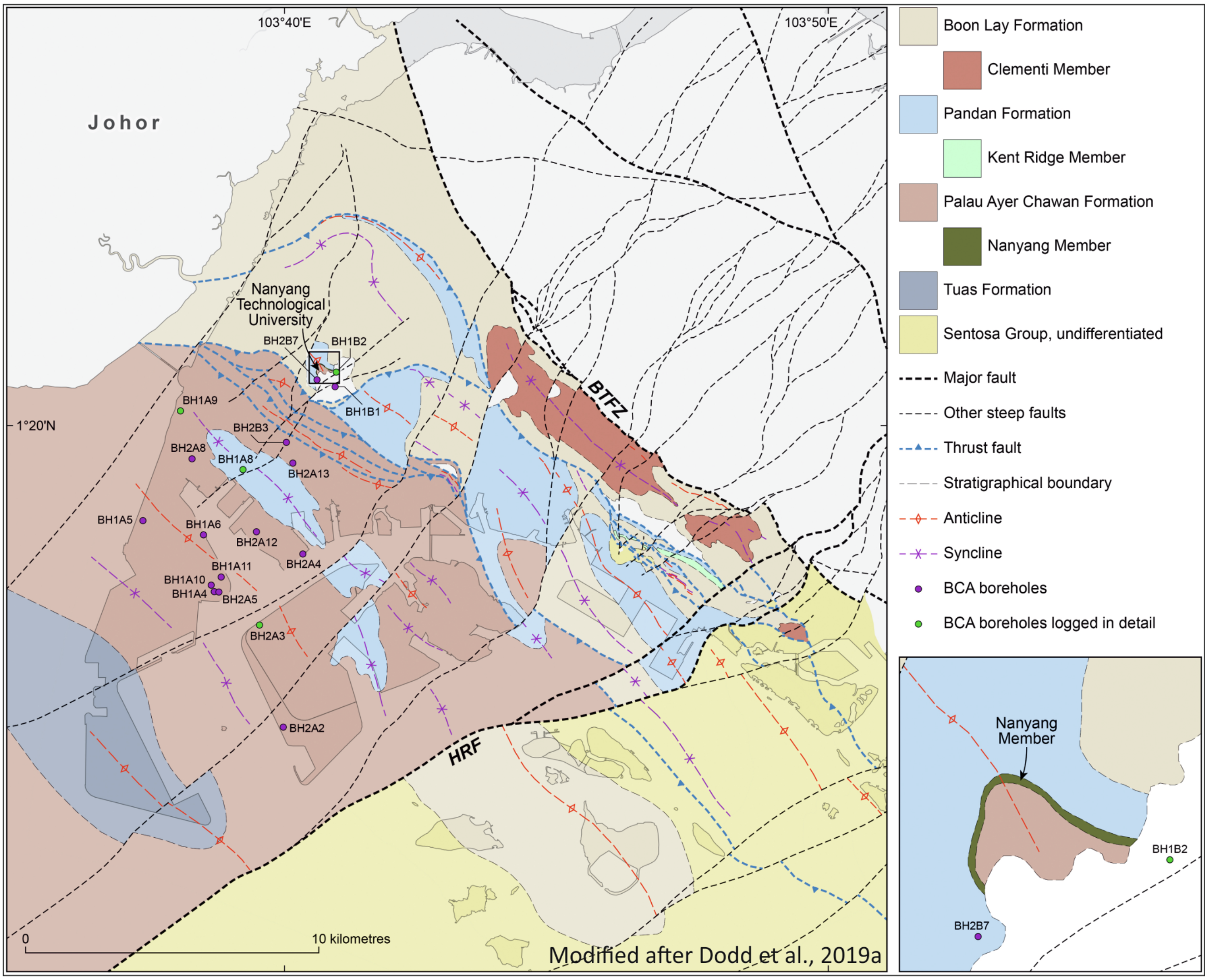

Fig. 5. The distribution of the Jurong Group strata in Singapore, with specific focus on the areas where the Pulau Ayer Chawan Formation represents the surface bedrock (modified after Dodd et al., 2019a). The location of the Nanyang Member, as mapped around the Nanyang Technological University campus, has been marked (see inset map). The top-hole location of boreholes that intersect the Pulau Chawan Formation are shown. Structural linework, including faults (HRF: Henderson Road Fault; BTFZ: Bukit Timah Fault Zone), overall structures and stratigraphic boundaries have been marked, and are derived from Leslie et al. (2019). *(Contains borehole location data © BCA 2020).*

the Sukhothai Arc now lie immediately to the east of that generally north-south oriented structure (Fig. 1A).

Initial rifting from the Northwest Indian-Australian margin of Gondwana involved the separation of the Indochina-East Malaya block from the supercontinent in the Devonian, resulting in the opening of the Palaeo-Tethys Ocean through the late Devonian into the early Carboniferous (Hall, 2009; Metcalfe, 2002, 2011, 2013, 2017a). This block then moved northwards, eventually becoming attached to Asia. The next stage of development involved rifting of the Sibumasu block away from Gondwana during the early to middle Permian, resulting in the opening of the more southerly located Meso-Tethys seaway by the end of the Permian (Metcalfe, 2011). As the Sibumasu block moved northwards, Palaeo-Tethys began to close, with Palaeo-Tethyan oceanic crust subducted beneath Indochina-East Malaya, and the associated development of the Sukhothai Arc (Fig. 1B; Hall, 2009, 2012; Metcalfe, 2011, 2013, 2017a). The arc system initially began to form on the continental margin of the Indochina-East Malaya block, but then became separated from the margin by the developing ‘Jinghong Nan-Sra Kaeo’ back-arc basin system (Sone and Metcalfe, 2008; Metcalfe, 2011; Oliver et al., 2014). Subsequent back-arc collapse led to the Sukhothai Arc being accreted back onto the continental margin (Sone and Metcalfe, 2008; Metcalfe, 2011, 2013). Consequently, the Sukhothai Arc is characterised as a highly folded and faulted pile of: Devonian to Carboniferous ‘basement rocks’; deep-marine to terrestrial Permo-Triassic volcani-sedimentary successions; and I-type granitoid plutons of Permian and Triassic age. Singapore and the adjacent areas represent the southernmost exposure of the Sukhothai Arc in Southeast Asia. The Triassic-aged Jurong Group strata, including the Pulau Ayer Chawan Formation of Singapore, record the products of the adjacent basins surrounding the Sukhothai Arc (Fig. 1B), and consequently are characterised by a diverse assemblage of rock types. They are also spatially and geologically associated with the Triassic-aged I-type and subduction-related mafic and felsic plutonic rocks of Central and Eastern Singapore (Gillespie et al., 2019).

The Semantan Basin is interpreted as a Palaeo-Tethyan depocenter formed along a convergent margin, as a forearc basin associated with the continued northward subduction of West Malaya beneath East Malaya (Fig. 1B; although referred to as a ‘foreland basin’ in Ismail et al., 2007). The sedimentary fill of the Semantan Basin is represented by the Raub Group in Peninsular Malaysia (Lee et al., 2004) and the Jurong Group in Singapore is most likely a correlative. Deposits of the Semantan Formation, one of the formations of the Raub Group, have previously been correlated to part of the 'Jurong formation' (Mohamed, 1989; Ismail et al., 2007); a stratigraphical attribution that predates the new lithostratigraphical framework for Singapore (Dodd et al., 2019a). The age, sedimentary character and volcanically-derived components of the Jurong Group in Singapore, and by association the Pulau Ayer Chawan Formation, suggest these sedimentary successions are most likely correlatives (Dodd et al., 2019a).

The Semantan Formation comprises: deep-marine sediments, transported into the basin through turbidity currents, high energy mass flows, and debris flows (Metcalfe et al., 1982; Metcalfe and Chakraborty, 1994; Madon, 2010); mass transport processes and slumping (Madon, 2006; Ismail et al., 2007; Madon, 2010); with instances of shallow-marine sedimentation (Mohamed and Abdullah, 1993; Khoo, 1998). Palaeocurrent data record sediment transportation in a west to southwest (Metcalfe et al., 1982; Madon, 2010), or an easterly to south-easterly direction (Madon, 2010), even within a single exposure (Metcalfe and Chakraborty, 1994), leaving some uncertainty regarding this. However, sedimentary facies distributions suggest proximal settings in the east (present day) and distal settings further west, indicating a (now) west-facing continental slope (*cf.* Madon, 2010), indicating that a west or south-westward sedimentary transport direction may be more likely. Crucially, for correlation of the Semantan Formation with the Pulau Ayer Chawan Formation, widespread occurrences of volcanically-derived products have been recognised within the Semantan Formation (Metcalfe et al., 1982; Azhar, 1992; Metcalfe and Chakraborty, 1994; Ismail et al., 2007). The Semantan Formation is also correlative with the Gemas Formation (Peng, 1983) that outcrops in Johore, with the Semantan Basin (in which they were both deposited) sometimes referred to as the Semantan-Gemas basin (Mohamed, 2016).

Following the Triassic, Upper Jurassic–Lower Cretaceous major basin reconfiguration occurred, with a number of continental blocks rifting from the north-west Australian margin and moving northwards to be accreted onto the now-combined Indochina-East Malaya and Sibumasu terranes during the Cretaceous (Hall, 2009, 2011, 2012; Metcalfe, 2011, 2013, 2017a). This period is characterised by strike-slip tectonics associated with uplift, extension, and the development of intracontinental basins within which red-bed sandstone and conglomerate were deposited (Abdullah, 2009).

3. Methodology

This study makes use of high-quality geological specimens and data collected between 2012 and 2017 by the Building and Construction Authority of Singapore (BCA). The physical and digital records collected include over 20,000 m of 61 mm diameter core samples (continuous) recovered from 121 separate boreholes across Singapore (see Dodd et al., 2019a for locations; borehole samples were retained by BCA and are accessible upon request). Of this dataset, 2599.70 m represent sedimentary rocks of the Pulau Ayer Chawan Formation and 192.47 m represents the Nanyang Member (Table 1), across 18 separate boreholes (Fig. 4). In addition, high resolution photographs were taken of all borehole core samples and form an important dataset.

High-resolution borehole core photographs from the Pulau Ayer Chawan Formation have been visually inspected; 10 cm vertical resolution sedimentary logging of a sub-set of borehole core samples (Table 1) has captured information on lithology, grain size and sedimentary structures. Facies analysis of the detailed sedimentary logs provides an interpretation of the environment of deposition (Figs. 6 and 7; *cf.* Walker, 1992). This technique involves the detailing of sedimentary facies, grouping into facies associations, in order to eventually interpret the overall environment of deposition. Example images from the borehole core samples through the formation have been provided (Figs. 8–13) in order to characterise the range of sedimentary structures (and inferred flow processes), textures and lithological variability within the formation. 3D schematic block diagrams were constructed from this analysis, in order to depict the range of interpreted sedimentary systems through time, and show their probable relationships in 3D space (Fig. 14).

The remaining borehole core photographs have been examined in lesser detail, with broad lithological and sedimentary information recorded in order to support the depositional model for the formation, displayed as simplified summary logs. A first attempt has been made to geographically place these sedimentary systems relative to the modern day landscape of Singapore (Fig. 15). This final step comes with many issues, most notably surrounding the limited nature of core data (one dimensional) and its use in the construction of much larger scale palaeogeographical maps, along with the post-depositional deformation that has pervasively faulted and altered the sedimentary successions into their now complicated present-day configurations (see Leslie et al., 2019).

In order to provide some context for the wider Semantan Basin, these interpretations have been integrated and correlated at the regional scale in order to demonstrate the significance of the geology of Singapore to the wider Southeast Asia area. Finally, to help better understand the sedimentology of the Pulau Ayer Chawan Formation, analogous systems have been identified in literature.

Table 1
A list of borehole cores that contain intervals of Pulau Ayer Chawan Formation, along with the Nanyang Member drilled in Singapore between 2012 and 2017. The boreholes numbers highlighted in bold were logged in detail (10 cm scale resolution) and are key to this study. Total thickness are provided, with *c.* 2600 m of core from the Pulau Ayer Chawan Formation, and an additional *c.* 193 m that represent strata of the Nanyang Member.

Borehole Number (L = logged)	Pulau Ayer Chawan Formation (thickness and interval depths)	Nanyang Member (thickness and interval depths)
BH1A4	172.03 m (33.00–205.03 m)	None
BH1A5	170.00 m (30.00–200.00 m)	None
BH1A6	170.48 m (34.52–205.00 m)	None
BH1A8 (L)	66.84 m (138.16–205.00 m)	None
BH1A9 (L)	156.90 m (48.10–205.00 m)	None
BH1A10	176.50 m (28.50–205.00 m)	None
BH1A11	139.00 m (66.00–205.00 m)	None
BH2A2	176.30 m (28.70–205.00 m)	None
BH2A3 (L)	166.00 m (39.00–205.00 m)	None
BH2A4	183.00 m (22.00–205.00 m)	None
BH2A5	165.00 m (36.00–201.00 m)	None
BH2A8	188.50 m (16.50–205.00 m)	None
BH2A12	167.50 m (11.50–179.00 m)	None
BH2A13	131.20 m (51.00–147.50 m and 170.30–205.00 m)	22.80 m (147.50–170.30 m)
BH1B1	37.30 m (167.70–205.00 m)	53.30 m (114.40–167.70 m)
BH1B2 (L)	86.05 m (118.95–205.00 m)	55.91 m (62.99–118.90 m)
BH2B3	150.65 m (38.00–171.85 m and 188.20–205.00 m)	16.35 m (171.85–188.20 m)
BH2B7	96.45 m (104.55–201.00 m)	44.11 m (60.44–104.55 m)
Total Thickness	**2599.70 m**	**192.47 m**

4. Facies analysis

The sedimentary rocks of the Pulau Ayer Chawan Formation have been subdivided into 21 sedimentary or volcani-sedimentary facies (Table 2), on the basis of the lithology and dominant sedimentary structure. The facies have been grouped into nine separate facies associations (Fig. 6). The nine facies associations are further grouped into six sub-environments, which together reflect the components of the heterolithic Pulau Ayer Chawan Formation sedimentary system, and hydroclastic Nanyang Member.

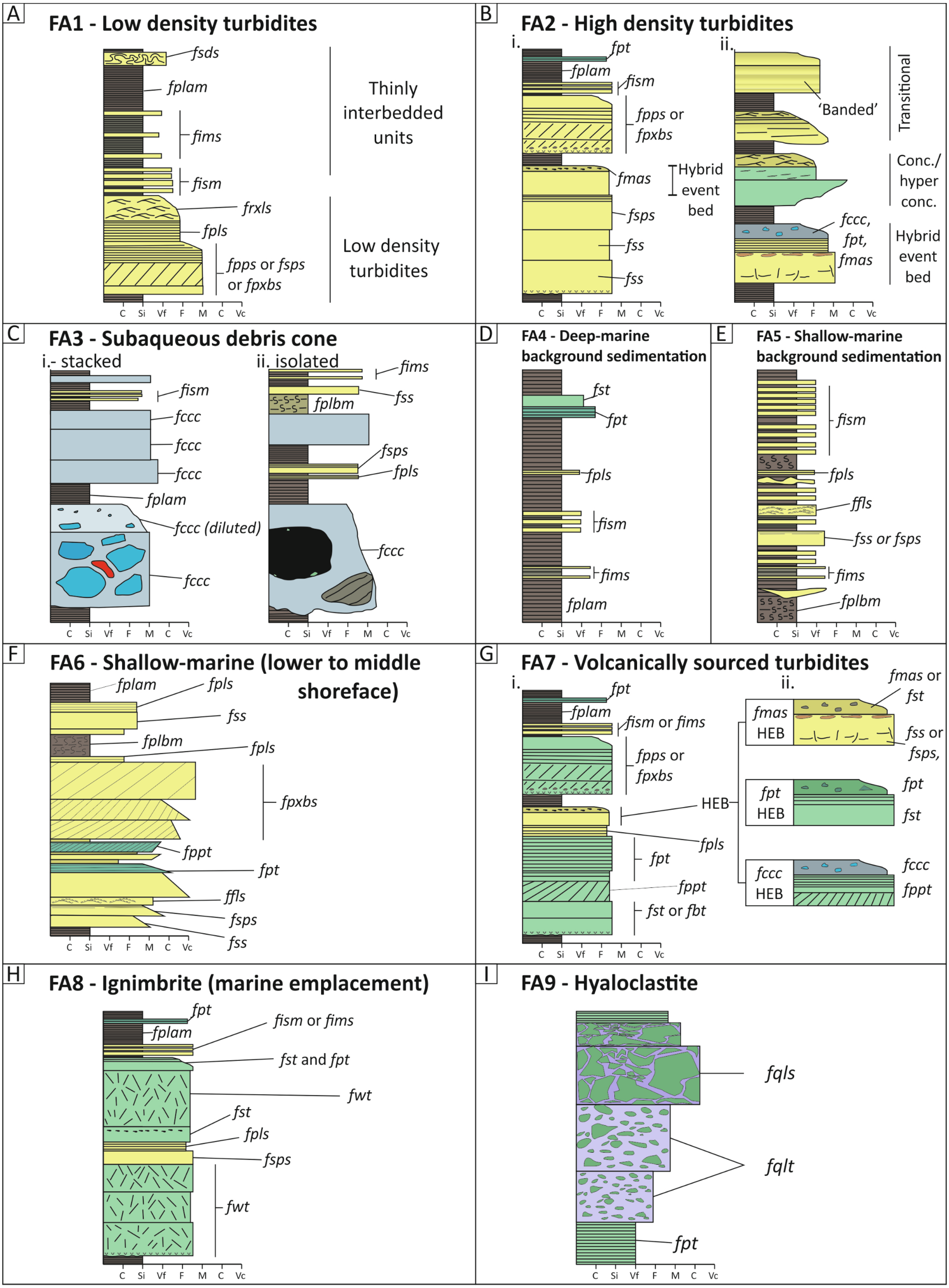

Fig. 6. Nine idealised facies associations that comprise the depositional model for the Pulau Ayer Chawan Formation. A combination of these facies associations are used to describe and characterise the range of sedimentary processes within parts of the formations, and ultimately aid in the interpretation of sub-environments, and overall depositional setting of the formation. (A) FA1 – Low density turbidites. (B) FA2 – High density turbidites. (C) FA3 – Subaqueous debris cone. (D) FA4 – Deep-marine background sedimentation. E) FA5 – Shallow-marine background sedimentation. (F) FA6 – Shallow-marine (lower to middle shoreface). G) FA7 – Volcanically sourced turbidites. (H) FA8 – Ignimbrite. (I) FA9 – Hyaloclastite. *(BGS © UKRI 2020).*

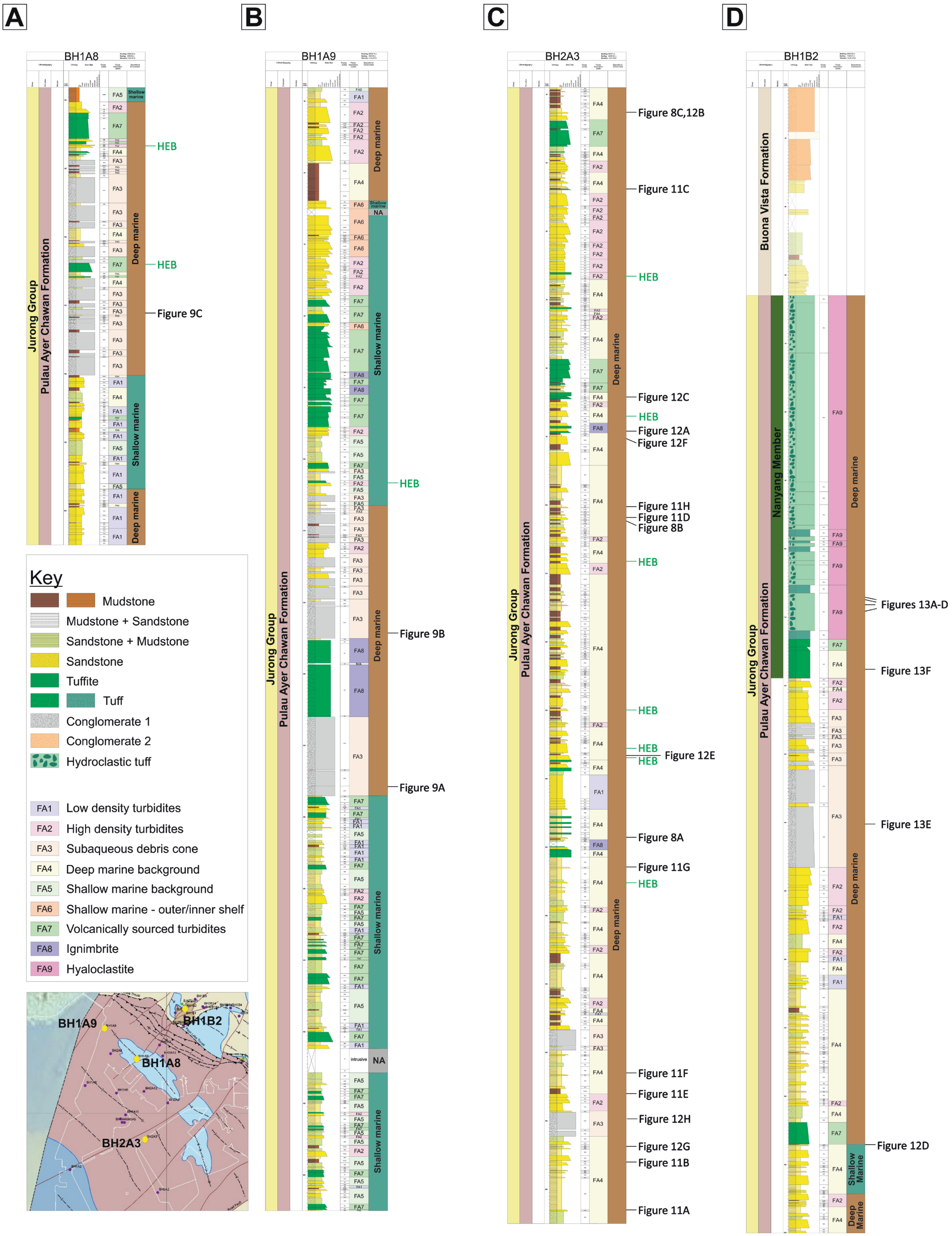

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Fig. 7. Detailed sedimentary logs through four boreholes core samples from the Pulau Ayer Chawan Formation. The sedimentary logs show lithology, bed thickness and grain size, with the sedimentary facies (containing the sedimentary structure information), facies associations and overall interpreted depositional environment displayed to the right. The location of hybrid event beds (HEB) has been marked on three of the four sedimentary logs where they are observed. (A) Sedimentary log through the lowermost part of BH1A8 (*c.* 138–205 m). (B) Sedimentary log of BH1A9 (*c.* 48–205 m). (C) Sedimentary log of BH2A3 (*c.* 39–205 m). (D) Sedimentary log of BH1B2, with Pulau Ayer Chawan Formation and/or Nanyang Member sediments from *c.* 200–63 m, and deposits of the younger Buona Vista Formation (*c.* 63–32.5 m). *(BGS © UKRI 2020)*.

4.1. Facies association 1 (FA1) – Low density turbidites

4.1.1. Description

FA1 is composed of a lowermost unit of thinly-developed planar cross-bedded to parallel-laminated sandstone (*fpps*), or structureless to parallel-laminated sandstone (*fsps*), or planar cross-bedded sandstone (*fpxbs*), typically followed by more thickly-bedded parallel-laminated sandstone (*fpls*) and/or ripple cross-laminated sandstone (*frxls*), which can form as amalgamated beds and often display normal grading (Table 2; Figs. 6–8). The upper part of the facies association is marked by gradation into interbedded sandstone and mudstone (*fism*), interbedded mudstone and sandstone (*fims*) or parallel-laminated mudstones (*fplam*). Occasionally, isolated units of soft sediment deformed sandstones (*fsds*) are interspersed within FA1.

4.1.2. Interpretation

FA1 (Fig. 6A) represents deposition by low density (dilute) turbidity currents, likely within a distal and/or fan fringe location, within a deep-marine turbidite fan setting. The interbedded, amalgamated, normally-graded units of *fpls* and *frxls* (e.g. Fig. 8B) indicate the presence of decelerating turbidite flows (Allen, 1984). The examples of *fpps* or *fpxbs* that display dune-scale cross-bedding and have erosional bases indicate an element of slope bypass at these locations (*sensu* Stephenson et al., 2015). The isolated units of *fsds* represent the products of slumps, probably associated with soft sediment deformation and/or de-watering of the substrate or levees by ensuing sediment gravity flow events. The transition into *fism* and/or *fims* marks the reduction in coarser grained siliciclastic supply into the basin and return to background, hemi-pelagic processes (see FA4 below).

4.2. Facies association 2 (FA2) – High density turbidites

4.2.1. Description

FA2 comprises either isolated or amalgamated units of structureless sandstone *(fss) or fsps* (T1-T27 in Fig. 10), which are often thickly-bedded (*c.* 0.1–10 m); or planar cross-bedded to parallel-laminated sandstone (*fpps*) and typically display loaded bases (Figs. 6 and 8). Units of *fss* are also observed to be overlain by *fpps* or *fpxbs (*Table 2*)*. The units of *fsps* or *fss* are typically capped by *fpls*, which displays well-pronounced normal grading. In some examples, this is capped by a discrete bed top composed of carbonate clast-rich conglomerate (*fccc*), or mud-clast-rich argillaceous sandstone (*fmas;* FA2ii in Fig. 6). The very top of this facies association is often marked by: a gradation into *fplam,* not exceeding more than 1 m in thickness (at which point it becomes FA4); *fism;* or very rarely parallel-laminated tuffite (*fpt*).

4.2.2. Interpretation

This facies association represents deposition by high density turbidity currents, with *fss,* and to some extent *fsps,* representing initial rapid suspension fall-out and loading of structureless sandstones (*sensu* Lowe, 1982). When units of *fss* and *fsps* are observed in amalgamated packages, these types of deposits are indicative of a channel or more axial position within a turbidite fan or lobe setting, respectively. Examples of FA2 that display *fpps* and/or *fpxbs* indicate an element of slope bypass, signified by the planar cross-bedding structures, and by the presence of mud-clast horizons that sometimes form as basal lags (*sensu* Stephenson et al., 2015). The presence of *fpls* and normal grading indicates a deceleration of the flow, and the gradation into *fism or fplam* at the top of FA2 marks the return to hemi-pelagic, background deposition. The occurrences of interbedded units of *fpt* highlights a continued and protracted influence of volcanism and/or the presence of a volcanoclastic hinterland from which these sediments were being derived.

Examples of FA2 that display bed tops composed of *fccc, fpt* or *fmas* (Fig. 6) are interpreted as the product of events that displayed mixed flow behaviour, and are termed hybrid event beds (HEBs; *sensu* Haughton et al., 2003, 2009). Other deposits that also show evidence for mixed flow behaviour in the dataset are represented by transitional flow deposits (TFDs) that include 'banded' units (*sensu* Kane and Pontén, 2012; Figs. 8 and 11), along with concentrated and hyper concentrated sediment gravity flow deposits (*sensu* Haughton et al., 2009). When present, these deposits generally suggest a more distal or lobe fringe setting within the turbidite fan or lobe setting (Haughton et al., 2009; Talling, 2013; Kane et al., 2017).

4.3. Facies association 3 (FA3) – Subaqueous debris cone

4.3.1. Description

FA3 comprises poorly-sorted matrix-supported conglomerates of *fccc* (Table 2), which typically display sharp, sometimes erosional contacts with the underlying sediments, and form as either stacked successions or isolated units (Fig. 6C). The upper parts of *fccc* sometimes show enhanced sorting of the matrices, with a generally lower mud-content (comparatively dilute), along with fewer and smaller suspended clasts. A major component of the clast assemblage of *fccc* is represented by 1–10 cm long, angular to rounded carbonate clasts that are interspersed with more minor volumes of volcaniclastic fragments, armoured mudstone clasts, granitic clasts and shelly debris, including crinoid vesicles (Fig. 9). The intervals of stacked *fccc* (Fig. 6Ci) are, in most cases, repeatedly capped by up to one meter thick units of *fplam* (more than one meter thick units of *fplam* are classed as FA4) and can be followed by a combination of units of *fpls*, *fsps*, *fss*, *fism* and *fims*. On rare occasions, the upper parts of FA3 comprise a unit of parallel-laminated bioturbated mudstone (*fplbm*).

4.3.2. Interpretation

FA3 is interpreted as the deposits of debris flows, likely deposited within a subaqueous debris cone setting (Figs. 3 and 14B). Vertical stacking or amalgamation of *fccc* indicates a depositionally active, potentially proximal or apex locality within the debris cone. In contrast, the interbedded and repeated relationship between *fccc* and *fplam* that is also observed (Fig. 6ii) indicates intermittent delivery of debris flows into the low oxygen or anoxic environment (Table 2), forming repeated packages of discrete debrite-forming 'event beds' and thinly-bedded hemi-pelagic mudstones.

Where *fpls*, *fsps* or *fss* cap units of *fccc* (Fig. 6ii)*,* these intervals represent the deposits of comparatively lower density flows (i.e. turbidites) within the debris cone environment. These more dilute flows may have entered the basin as originally lower concentration sediment-water mixes (than compared with the debris flows), perhaps immediately following the initial collapse of the shelf, and would have been relatively restricted to more proximal locations along the palaeoslope. Alternatively, they may represent the distal expression of originally more concentrated flows (such as debris flows), which underwent down-flow dilution as more water became incorporated and/or expansion occurred. The latter interpretation would further support

Table 2
Facies table, containing the 21 separate sedimentary, volcano-sedimentary, and volcani-sedimentary facies identified within the Pulau Ayer Chawan Formation in this study.

Facies code	Facies Title	Description	Processes and Interpretation
fism	Interbedded Sandstone and Mudstone	Interbedded sandstone and mudstone with common parallel laminations and weak to intense bioturbation. Thinly-bedded sandstones are vf to medium grained, often contain both symmetrical and asymmetrical ripple cross lamination, sometimes rafted clasts or rip-up clasts near to bed bases, sometimes structureless and common soft-sediment deformation.	Sub-aqueous deposition, mixing of "background" sedimentation and clastic input, forming thinly interbedded facies. Dominance of coarse grained material over mudstone suggests more proximal locations to sediment input and close to processes of re-working i.e. shallow water.
fsps	Structureless to Parallel-laminated Sandstone	Very fine to medium grained, structureless (massively bedded) sandstone, with 1–2 cm thick bed tops that display parallel lamination and isolated asymmetrical ripples, normal grading and argillaceous material along the laminae (some of which might be volcanogenic). Occasional banding. Weak to moderate bioturbation, rare dish structures at the base of the facies. Rafted and rip-up mud-clasts are common.	Rapid deposition, supressing the development of internal structuring. Deposition of a traction carpet, followed by the onset of parallel lamination developed from lower flow velocities, indicating a decelerating flow. Normal grading and asymmetrical ripples also support rapid deceleration. Where argillaceous lamination forms bands, particularly near to the top of the beds, these likely represent the products of transitional flows (Kane and Pontén, 2012)
fims	Interbedded Mudstone and Sandstone	Interbedded mudstones and sandstones, with parallel lamination, common asymmetrical ripples, weak to intense bioturbation, occasional dish structures, rare thinly interbedded tuffites, rip-up clasts and soft sediment deformation.	Sub-aqueous deposition, mixing of "background" sedimentation and clastic input, forming thinly interbedded facies. Dominance of mudstones material over sandstone suggests more distally locations, away from sediment input or processes of reworking. Asymmetrical ripples only suggest different environment to FISM
fpls	parallel-laminated Sandstone	Very fine to medium grained, moderate to well-sorted, parallel-laminated sandstone with occasional normal or reverse grading. The bed tops can contain isolated occurrences of asymmetrical ripples, weak to intense bioturbation, also at the top of the bed. Can display and erosive base, often with rip-up mud-clasts. Often show upwards increasing mud-content, particularly when normally graded.	Deposition during waning flow condition forming upper flow tractional structures.
fccc	Carbonate Clast-rich Conglomerate	Typically fine to medium grained, dark-grey, matrix or clast supported, massively bedded conglomerate, composed of a wide range of 1–10 cm, angular and rounded carbonate clasts of various carbonate types, 1–10 cm wide mud-clasts, occasional angular volcanogenic clasts, with rare rounded granitic and lithic clasts. Clasts rarely are sorted and tend to float within the unit, fully supported by the finer grained matrix. This facies is rarely clast-supported. Some of the units shown better sorted (moderate) matrices, with poorly developed parallel lamination and clast imbrication near to the top of the bed.	**Re-deposition of older carbonate – slope failure products** - The product of cohesive debris flows, with some evidence for flow dilution, particular near to the top of the deposit (sorting, parallel lamination and clast-imbrication), indicating that the cohesive flow contains slightly more water in the upper part. Clasts floating in the finer grained matrix provide evidence for a relatively cohesive flow, which instantaneously froze when movement ceased. Limited transport distance for flow which resulted in these deposits
fss	Structureless Sandstone	Very fine to very coarse grained, poor to well sorted, structureless, occasionally normal or reversely sandstone. This facies can exhibit both loaded and erosional bases; in some cases both bed-base types can co-exist. The facies can exhibit de-watering dish structures. Common development of asymmetrical ripples, with rafted mud-clasts at the top and rip-up mud-clasts at the base. Common dish structures.	For structureless sandstones = rapid deposition from fluidal flow, supressing the development of internal structuring. High sedimentation rates, "dumping of sand". Interpretation - laminar behaviour within the traction carpet of a high density turbidite flow as opposed to bed aggradation. Rafted mudclasts buoyantly rafted to the top of the bed, indicated inter-granular support, or significant dispersive pressure. Units with rip-up clasts are more erosional up-stream/up-dip.
fplam	parallel-laminated Mudstone	parallel-laminated mudstones, with thin siltstone and rare very fine grained sandstone and tuffite laminae. These can be organic rich, can contain weak bioturbation, are rarely soft sediment deformed, contains rare asymmetrical ripples and can contains thin laminae of tuffite/bentonite	Hemi-pelagic or hemi-limnic fall-out from the water column. Suspension fall-out, considered as background sedimentation, with intermittent ash-input. This very fine grained sandstone laminae and colour variability may reflect seasonal productivity and low quantities of clastic input. Lack of bioturbation indicated either anoxic conditions in either a deep-water setting or a restricted shelf. Lack of coarse-grained clastic input may interbedded with the mudstones may suggest deeper, more basinal locations
fplbm	parallel-laminated Bioturbated Mudstone	parallel-laminated, moderate to intensely bioturbated mudstones and thin very fine to fine grained sandstone laminae, which are rare completely bioturbated forming massive (structureless) mudstones. Can have thin intervals of flasar lamination and lenticular bedding (sub 10 cm thick). Speckled texturing in the most intensely bioturbated examples.	Hemi-pelagic fallout/suspension products from the water column – regarded as background sedimentation (*sensu* Stow and Tabrez, 1998). Higher degree of insitu bio-activity and lenticular bedding may suggest a shallow water environment, but at the least oxygen rich, optimum environment for life to thrive (i.e. not deep-water and not anoxic/restricted). Presence of lenticular bedding of coarse grained sandstones may suggest shallow water, oscillatory working of sediment and therefore not deep water.
fpps	Planar cross-bedded to parallel-laminated Sandstone	Well sorted, medium to coarse-grained, planar cross bedded, becoming parallel-laminated sandstone with abundant rip-up clasts near to the base, and rafted mud-clasts at the very top. Common occurrence of mud-drapes lining the foresets on the cross-bedding structures.	Duneform migration forming large-scale cross-stratification through sustained bedload transport of coarse-grained sediment below flows with low aggradation rates (Allen, 1982). Representative of flows that by-passed this part of the slope (*sensu* Stephenson et al., 2015). The upper part of the facies, displaying parallel lamination, represent the decrease in flow velocity, and ultimately the termination of flow at that particular locality.
frxls	Ripple Cross Laminated Sandstone	Well sorted, very fine to fine grained, occasionally medium grained, asymmetrically ripple laminated sandstone. This facies is typically well sorted, clast poor and texturally mature.	Migration of less than 1 cm scale bedforms (ripples) forming at lower flow energies with a single, dominant flow direction. This encompasses all forms of asymmetrical ripples i.e. sinuous vs lingoid vs in phase vs out of phase ripples (subdivision is beyond the scope of what BGS recorded for the project)

(*continued on next page*)

Table 2 (*continued*)

Facies code	Facies Title	Description	Processes and Interpretation
fsds	Soft-sediment Deformed Sandstone	Well sorted, fine to medium grained sandstones and thinly interbedded mudstones, with strong post-depositional soft-sediment deformation and weak to moderate bioturbation in places. Upwards increasing mud content within some examples.	This is a highly deformed facies – Always should be applied if soft sediment deformation has been recorded as the first structure. Soft sediment deformation may have occurred through a number of different processes, including: slumping of wet sediment; seismicity; or disturbance of the bottom mud-to water interface by flow events, resulting in substrate delamination (Fonnesu et al., 2016)
fmas	Mud-clast-rich Argillaceous Sandstone	Mud-clast rich, (rafted or concentrated) medium to very fine grained, typically normally-graded, moderate, becoming poorly sorted, argillaceous-rich, structureless sandstone, displaying a gradual upwards increase in dark-coloured, argillaceous material within the matrix and a concentration of mud clasts near to the top of the bed. Occaional rip-up mud-clasts. The increase in mud-matrix contenct will typically be either very abrupt (across a discrete internal boundary in the deposit), or be very gradual, often mimicing the grain size reduction.	Hybrid event bed/Transitional flow (Haughton et al., 2009; Kane and Pontén, 2012) deposits - * a different style of transitional flow bed type to the example of FPS. One model is of flow segregation and the other is of flow transformation.
fpt	parallel-laminated Tuffite	Volcanogenic material, re-worked into parallel-laminated tuffite (+25% volcanic grains), typically with upwards increasing fines and occasional dish structures and rare interbedded sandstones and mudstones. Floated clasts and rafted mud-clasts (rare). Rare developement of very thin (sub 1 cm thick) sectionf of ripple lamination at the bed tops.	Reworking of volcanic material by fluidal flows, forming upper bed tractions structures in decelerating flow. Typically interbedded or interlaminated with hemi-pelagic deposition, represented by mudstones (mudstone and tuffite).
fst	Structureless Tuffite	Massively bedded, commonly normally graded, occasionally parallel-laminated in the upper 1/3 tuffite. Upwards increasing fines within the bed is a common occurrence along with rafted mudclasts, and rare soft sediment deformation, and very thin (sub 1 cm thick) sections of parallel laminations developing at the top of the beds.	Rapid deposition of volcanic material, in a fluidised, high density flow (turbidite) which is undergoing turbulence suppression, forming structureless tuffite. Re-working of material formed win a volcaniclastic source area. Could be re-working or could be primary volcanic flow.
fpxbs	Planar Cross-bedded Sandstone	Fine to coarse grained planar cross bedded sandstone with occasional lithic clasts, with rare, poorly-formed dish structures that disrupt cross bed sets, occasionally normally graded and rarely mottled. Occassionally, fine to medium grained, reversely graded, with rafted mudclasts, roots and rare mottling. The facies can display well-developed mud-drapes on the cross-bed foresets. Poorly-developed parallel lamintion at the very top of the bed (sub 1 cm thick)	Duneform migration forming large-scale cross-stratification through sustained bedload transport of coarse-grained sediment below flows with low aggradation rates (Allen, 1982). Representative of flows that by-passed this part of the slope (*sensu* Stephenson et al., 2015).
fppt	Planar cross-bedded to parallel-laminated Tuffite	Planar cross bedded tuffite with common parallel lamination at the bed tops, occasional rip-up clasts near to the base and common structureless near to the base. Can exhibit either normal or reverse grading. Rip-up clasts near to bed bases and mud-clast floating within the matrix. Upwards increasing fines.	Re-working of volcaniclastic material in the migration of dune-scale bedforms in high energy and deceleration of flow forming tractional structures later on during the event. Quite likely deposits of turbidite flows, which show evidence for by-pass (pxb in a turbidite) that have been sourced from a volcanic hinterland.
fqlt	Quenched Lapilli-tuff	Quenched texture – Dominant finer grained, ash grade ground mass and minor interstitial pillows, composed of igneous rock with a glassy ground-mass.	Hyaloclastite formed from quenching of lavas through sub-aqueous eruption into water from sub-sea vent, or lava delta progradation into the marine realm. Deposition/formation away from the subaqueous volcanic vent (a more distal hyaloclastic facies), or through the start-up phase of an eruption.
fqls	Quenched Lapillistone	Quenched texture – Minor fine grained ground mass and dominant interstitial pillows, composed of igneous rock with a glassy ground-mass.	Hyaloclastite formed from quenching of lavas through sub-aqueous eruption into water from sub-sea vent, or lava delta progradation into the marine realm. Deposition/formation in close proximity to the volcanic vent (a more proximal hyaloclastic facies).
ffls	Flasar Laminated Sandstone	Very fine to medium grained, moderate to well sorted, flasar laminated sandstone, with common asymmetrical ripples and rare symmetrical ripples. Key characteristic is common mud drapes, which form on the ripple clinoforms and occur in slightly thicker laminae across ripple-sets and re-activation surfaces. Typically well sorted sediment and clast-poor.	Deposition of coarse(r) grained units by one current/energy and the finer grained, mud laminae by a second current of lower energy, perhaps in a varying direction – diagnostic of low energy tidal process. However, it can also be encountered in specific fluvial settings, in ponds/outer-channel/point bars, where flow can pulse, creating the same effect.
fwt	Welded Tuff	Welded lapilli within a finer grained, volcanic matrix of ash, occasionally containing block sized fragments and rarely displaying planar cross-bedding, parallel lamination and flattening textures. Commonly found to be reddened/altered.	This facies could be sub-divided in the future. Tuff “proper” – include all variations of primary tuff, i.e. lapilli tuff etc. This encompasses all primary volcanic deposits erupted above land and therefore could be subdivided.
fbt	Bioturbated Tuffite	Weak to moderately bioturbated tuffite, with common massive bedding (structureless) and occasional soft sediment deformation	Re-worked volcanic material, re-deposited in fluidal flows, most likely by turbidity currents, which may have then deformed after deposition (soft sediment) – Once deposited, these units have been mixed/churned by bioturbation

these deposits as being representative of a more distal position within the debris flow cone along the palaeoslope.

In the few examples where *fccc* is capped by *fplbm* (Fig. 6Cii), these may represent deposition of debrites into an environment with more-oxygenated bottom waters (compared with the relatively undisturbed *fplam*). In these cases, these deposits may be relatable to temporary shallowing of the basin associated with uplift, seismicity and slope collapse. Although, they could simply be related to temporary oxygenation of the water column following the introduction of the underlying debrites.

4.4. Facies association 4 (FA4) – Deep-marine background sedimentation

4.4.1. Description

FA4 is predominantly composed of *fplam* typically more than one meter in thickness (Fig. 6; Table 2). Units can (but do not necessarily

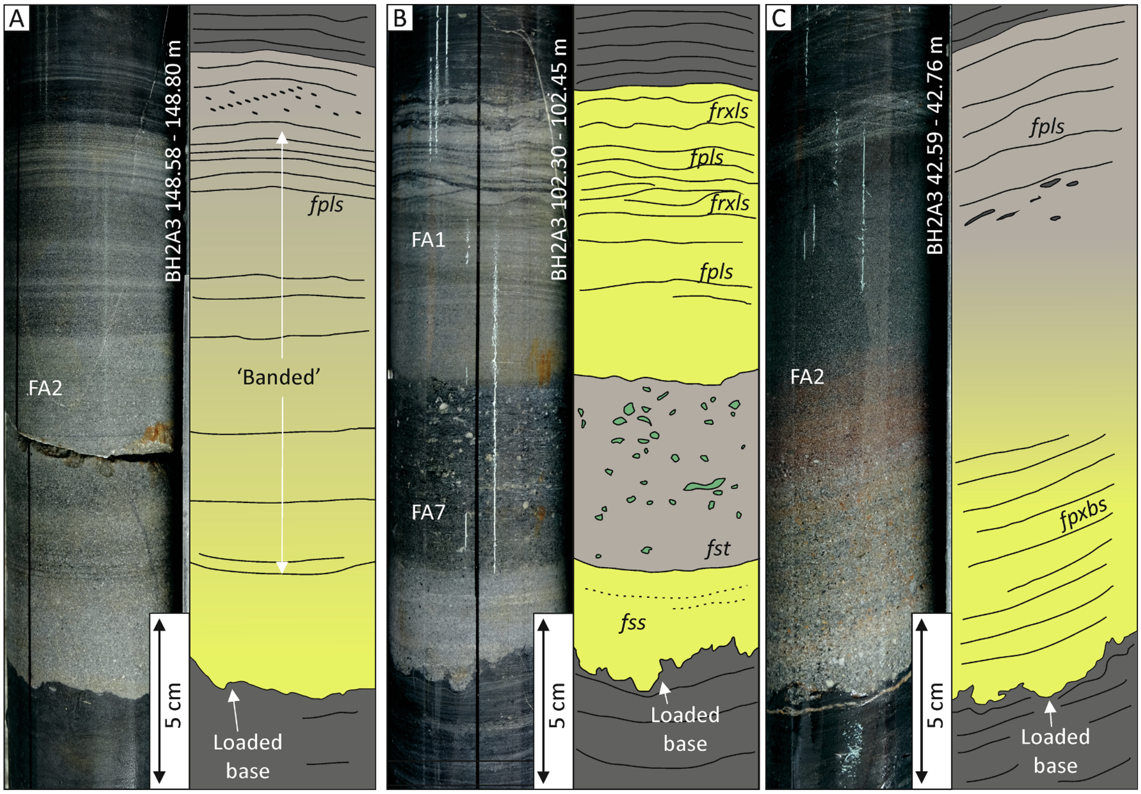

Fig. 8. Examples images of borehole core samples from the Pulau Ayer Chawan Formation. (A) A normally-graded event bed, with a loaded base, 'banded' texture of FA2. (B) A unit of FA7, with a basal unit of *fss* that loads into the background hemi-pelagic mudstones below. This is overlain by an upper unit of *fst* that displays an upwards increasing clast component, comprising volcanic fragments that increase in size towards the top of FA7. The unit is overlain by a normally-graded unit of FA1, with well-developed *frxls* and an overall cleaning upwards trend. (C) An example of FA2, displaying a heavily loaded base, planar cross-bedding structures (*pxbs*), normal grading, an upwards increase in mud content, and parallel laminations developing near to the top (*fpls*). *(BGS © UKRI 2020).*

have to) contain thinly-developed *fism, fims, fpls.* In places, FA4 contains thin beds of *fpt* and/or structureless tuffite (*fst*). The absence of *fplbm* is a key (negative) diagnostic criterion for FA4.

4.4.2. Interpretation

FA4 represents deposition through hemi-pelagic background sedimentation, probably in a deep-water setting and/or restricted areas of a shelf. An absence of bioturbation within the mudstones of FA4 (presence of *fplam* rather than *fplbm*), and resulting preservation of parallel laminations (hemi-pelagic/compositional), suggests a low-oxygen, or anoxic environment, and therefore most-likely a deep-water setting. Such hemi-pelagic sedimentation involves deposition of biogenic and terrigenous material through suspension fall-out within the water column, and slow lateral advection processes, resulting in clay and silt grade, often organic-rich material in deep-water settings (Stow and Tabrez, 1998). Interbedded units of *fism*, *fims* or *fpls* within FA4 signify periodic siliciclastic input, most likely transported into the basin by low density turbidity currents and subsequent re-working by bottom water circulation. The units of *fst* or *fpt* are interpreted as ash fall deposits into water (bentonites), and record the impact of far-field volcanism on sedimentation accumulating in the distally-located basinal areas.

4.5. Facies association 5 (FA5) – Shallow-marine background sedimentation

4.5.1. Description

FA5 is composed of units of *fplbm*, typically over one-meter in thickness (Fig. 6; Table 2). The observed bioturbation ranges from weak to intense, with a range of well-defined burrow geometries. Units of *fplbm* are generally interbedded with *fism*, *fims* and can also exhibit thin, isolated units of *fpls*, *fss, fsps* or flaser laminated sandstone (*ffls*). Successive beds typically coarsen and thicken upwards. Bedding geometries comprise tabular, lenticular and wavy sub-types.

4.5.2. Interpretation

FA5 represents background sedimentary processes occurring within a shallow-marine environment. The thickly developed intervals of pervasively bioturbated mudstones of *fplbm* suggest a well-oxygenated bottom water, in which the sediments could be sufficiently homogenised through infaunal activity. The observation of *ffls*, along with lenticular and wavy bedding types, suggests working of waters through oscillatory currents, therefore indicating the influence of wave energy on sedimentation.

The common occurrence of interbedded, coarser grained facies (*fism*, *fims*, *fpls* and *fss*) indicate consistent, low-volume sediment input (dilute flows) into the depositional environment. These observations suggest a setting in close proximity to the basin margin, in a well-oxygenated, shallow-water, likely marine environment.

4.6. Facies association 6 (FA6) – Shallow-marine (lower to middle shoreface)

4.6.1. Description

This facies association is represented by a basal unit of *fss* or *fsps* or *ffls*, transitioning upwards into more thickly-bedded, generally comparably coarser grained *fpxbs* (Fig. 6F). Units of *fpxbs* typically form as multiple vertically stacked packages, which sometimes display irregular set boundaries, with the cross-bedding often highlighted by grey argillaceous material, potentially representing mud drapes on foresets. The succession is typically capped by a unit of *fpls*, which is often inclined relative to the underlying bed bounding surface; the coarser grained component of FA6 is typically followed by, or interbedded

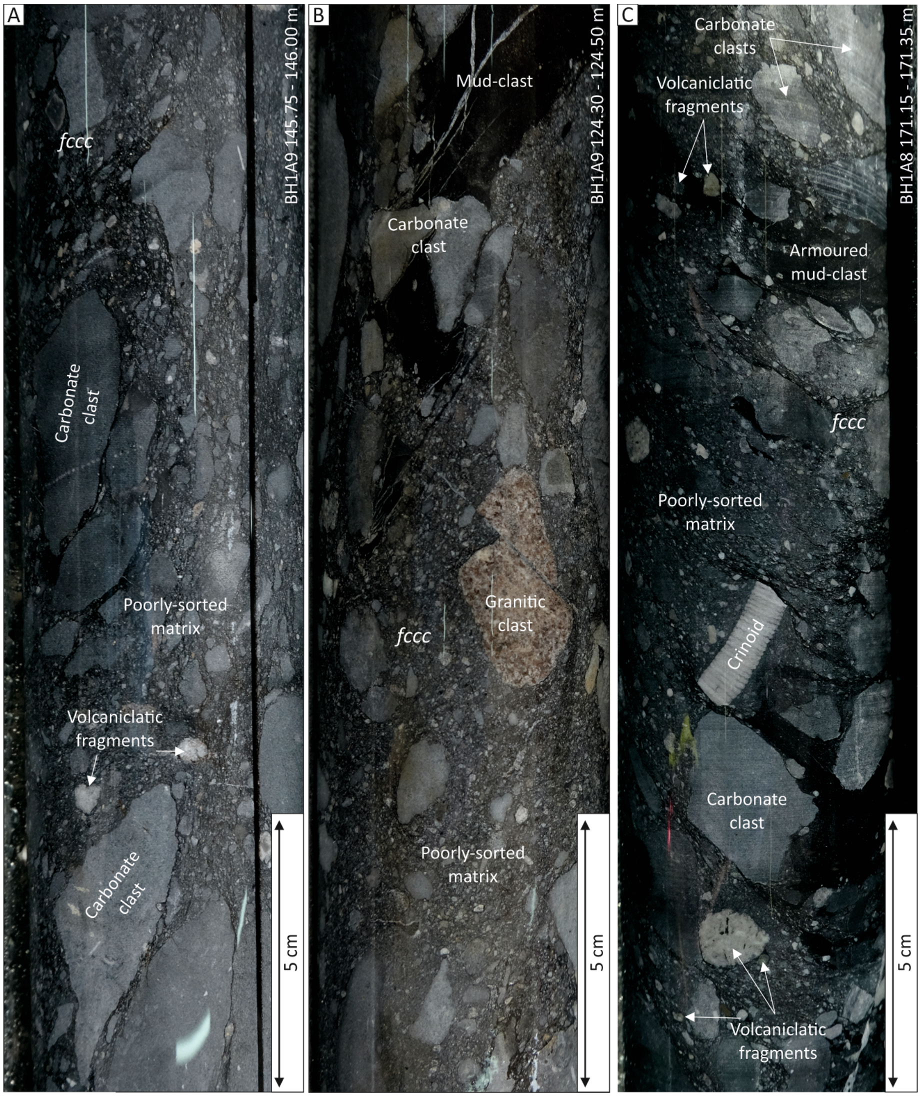

Fig. 9. Example borehole core images of carbonate clast-rich conglomerate (*fccc*), showing the range of clast types. (A) 1–5 cm long carbonate clasts within a poorly-sorted, matrix-supported conglomerate, and minor amounts of 0.1–0.5 cm wide, round volcaniclastic fragments. (B) 1–3 cm long carbonate clasts, 5 cm long mudstone clasts and a single 3 cm long granitic clasts, within a poorly-sorted matrix-supported conglomerate, along with more minor quantities of 0.1–0.5 cm long volcaniclastic fragments. The granitic clast has been post-depositionally fractured, and offset along with the rest of the conglomerates. (C) 1–3 cm carbonate clasts, 0.1–1 cm wide rounded volcaniclastic fragments, and armoured mud-clasts within a poorly-sorted matrix-supported conglomerate. A single 2 cm long crinoid vesicle is present in the centre of the image. *(BGS © UKRI 2020).*

with, thin units of either *fplbm* or *fplam*. FA6 often forms an overall thickening upwards, and generally coarsening upward succession, and beds can display reverse grading. Rare beds of *fpt* and *fppt* appear within FA6, and typically display reverse grading.

4.6.2. Interpretation

The lowermost part of FA6 (*fss*, *fsps* and *fpls*) represents the delivery of fluidised sediment-laden flows, likely sourced from an in-draining fluvial system (generally dilute flows), which fed directly into the shallow-water parts of the basin. The overlying transition into a coarsening upwards, thickening upwards succession of stacked units of *fpxbs* represent an upward increase in the energy regime, reflecting a shallowing-upwards pattern. The units of *fpls* that cap FA6 that are often slightly inclined relative to the underlying surface may represent low-angle inclined parallel lamination. The interbedding with *fplbm* indicates a well-oxygenated, probably shallow-water environment. The rare occurrences of *fpt* and *fppt* reflect the continued input of volcaniclastic sediment, which appears to be re-worked by the same sedimentary processes as the siliciclastic material above and below these units (e.g. *fpxbs* and *fpls* vs. *fppt*).

FA6 is interpreted as representing a shallow-water, lower to middle shoreface setting. In this environment, oscillatory waves worked the sediments in shallow-waters, with FA6 recording an overall shallowing upwards succession. The presence of argillaceous material along bed sets may suggest an environment with varying wave energies, or a tidal influence on deposition. This facies association is exclusively observed in BH1A9 (Fig. 7B), where the shallowest water sediments are observed within the dataset (Fig. 15).

4.7. Facies association 7 (FA7) – Volcanically sourced turbidites

4.7.1. Description

FA7 comprises a lowermost interval of thickly-bedded, amalgamated *fst*, *fpt* or planar cross-bedded to parallel-laminated tuffite (*fppt*), which often display erosional and/or loaded bed bases and normally graded bed tops (Fig. 6G; Table 2). These deposits are often followed by thinly-bedded units of *fpls*, *fism*, *fims*, or on some occasions, thin *fsps*, *fss* or *fst*. FA7 contains a high proportion of volcaniclastic material, with 1–5 cm wide, often sub-rounded to rounded pumice fragments, and elongate glass shards (fiamme) typically appearing within the matrices (Fig. 11C and D).

In some examples, FA7 displays a unit of either *fppt*, *fst*, and *fss* or *fsps,* directly overlain by a capping unit of either *fmas*, *fccc* or *fpt*, respectively (Fig. 6Gii), with the two sets of facies exhibiting a clear relationship between increasing matrix fines (clay content) and upwards developing sedimentary structures. These 'linked' units form discrete packages of sediment that range between 10 and 150 cm in thickness, and display a diverse range of sedimentary textures.

The facies association sometimes records instances of bioturbated tuffite (*fbt*) *or* isolated beds of *fpt*. The upper boundary of FA7 is

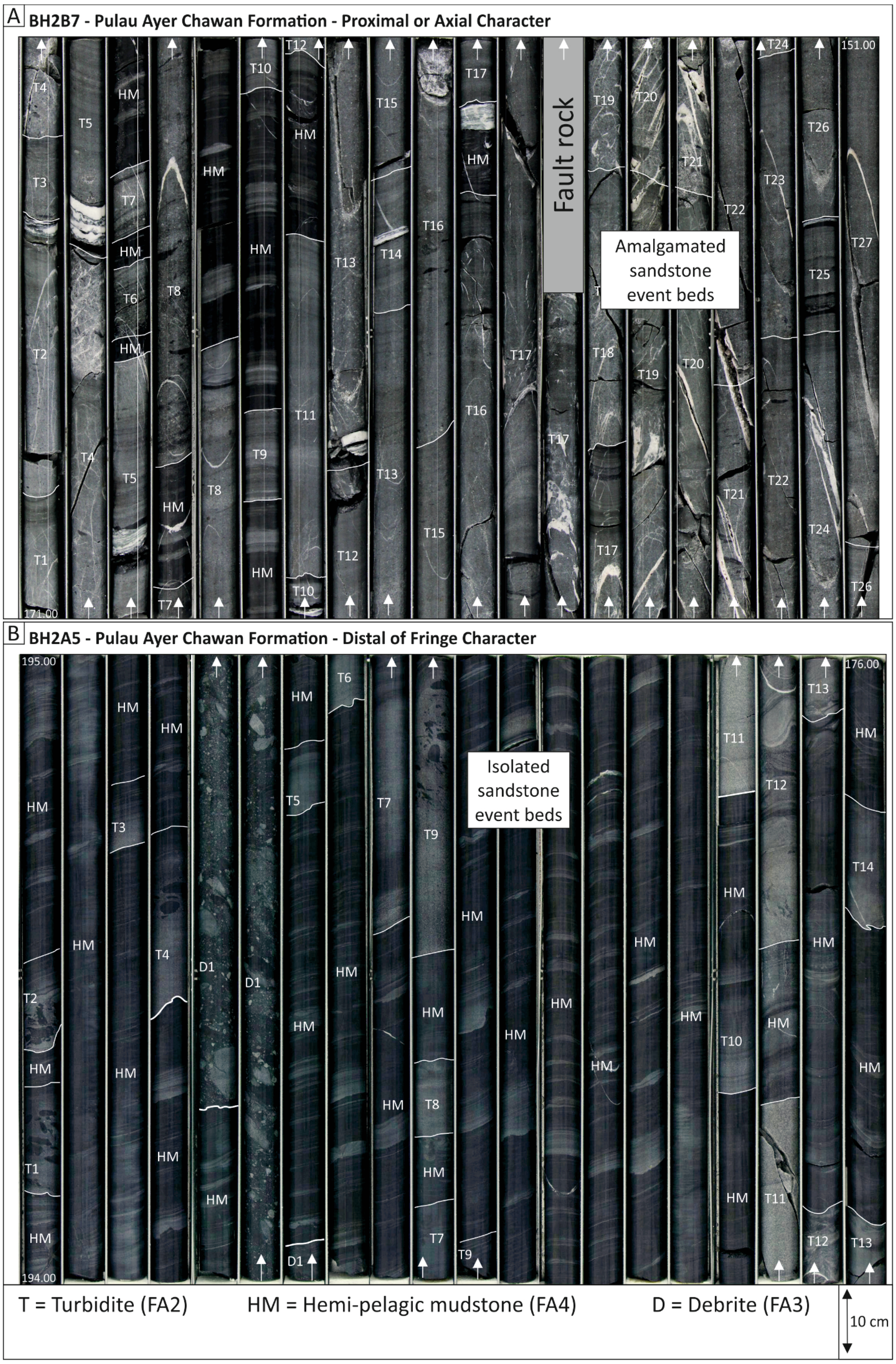

Fig. 10. The end-member character of the deep-marine turbidite fan deposits within the Pulau Ayer Chawan Formation, in borehole core samples. (A) Example images of borehole core samples from BH2B7 (171–151 m), representing proximal or axial character of the turbidite fan systems in the formation (see Fig. 15 for borehole location relative to interpreted palaeogeography). These kinds of deposits are dominated by amalgamated turbidites (FA2), along with occasional intervals of background hemi-pelagic mudstones (FA4). (B) Example image of borehole core samples from BH2A5 (194–176 m), highlighting the distal or fringing character of the turbidite fan systems in the formation (see Fig. 15 for borehole location relative to palaeogeography). In comparison to the proximal or axial turbidite deposits, these types of sediments are more dominated by background hemi-pelagic mudstones (FA4), with occasional, isolated turbidites (FA2), and rare debrites (FA3). *(BGS © UKRI 2020).*

typically marked by a unit of *fplam* that does not exceed one meter in thickness (otherwise FA4). Overall, FA7 is dominated by volcaniclastic material, over that of siliciclastic sediment.

4.7.2. Interpretation

The units of amalgamated *fpt*, *fppt*, *fst*, which are capped by *fpls*, *fpt*, *fmas* or *fccc* represent a mixture of high density turbidites and hybrid event beds, most likely formed within a turbidite fan setting. The regularity in volcaniclastic material being delivered into the deep-marine setting by these processes indicates a volcanically-active hinterland; a genetic link between the volcanically active hinterland and deposition in the turbidite fan setting is highly possible. The quantity (estimated from preserved thickness) and regularity of volcaniclastic sediment delivered into this setting is the key observation that defines FA7, and separates it from FA2.

The units of *fppt*, *fst*, and *fss*, or *fsps*, capped by *fccc*, *fpt* or *fmas* respectively are interpreted as the product of flows that displayed mixed flow behaviour, resulting in the deposition of hybrid event beds (*sensu* Haughton et al., 2009). These units show intriguing variation in style and origin, most likely controlled by the nature and composition of the original flow, incorporation of material into the flows through erosion of the substrate, and deposition of material in the basin. The *fpt* HEBs (Fig. 6ii) are influenced by volcaniclastic input, with the volcanic material potentially degrading to clays during the flow event, leading to enhanced segregation into separate flows. This observation is intriguing, as it may have implications for down-flow partitioning and flow transformation models in volcanically-influenced settings, where fine-grained, clay-prone upper parts of the flow may enhance mixed

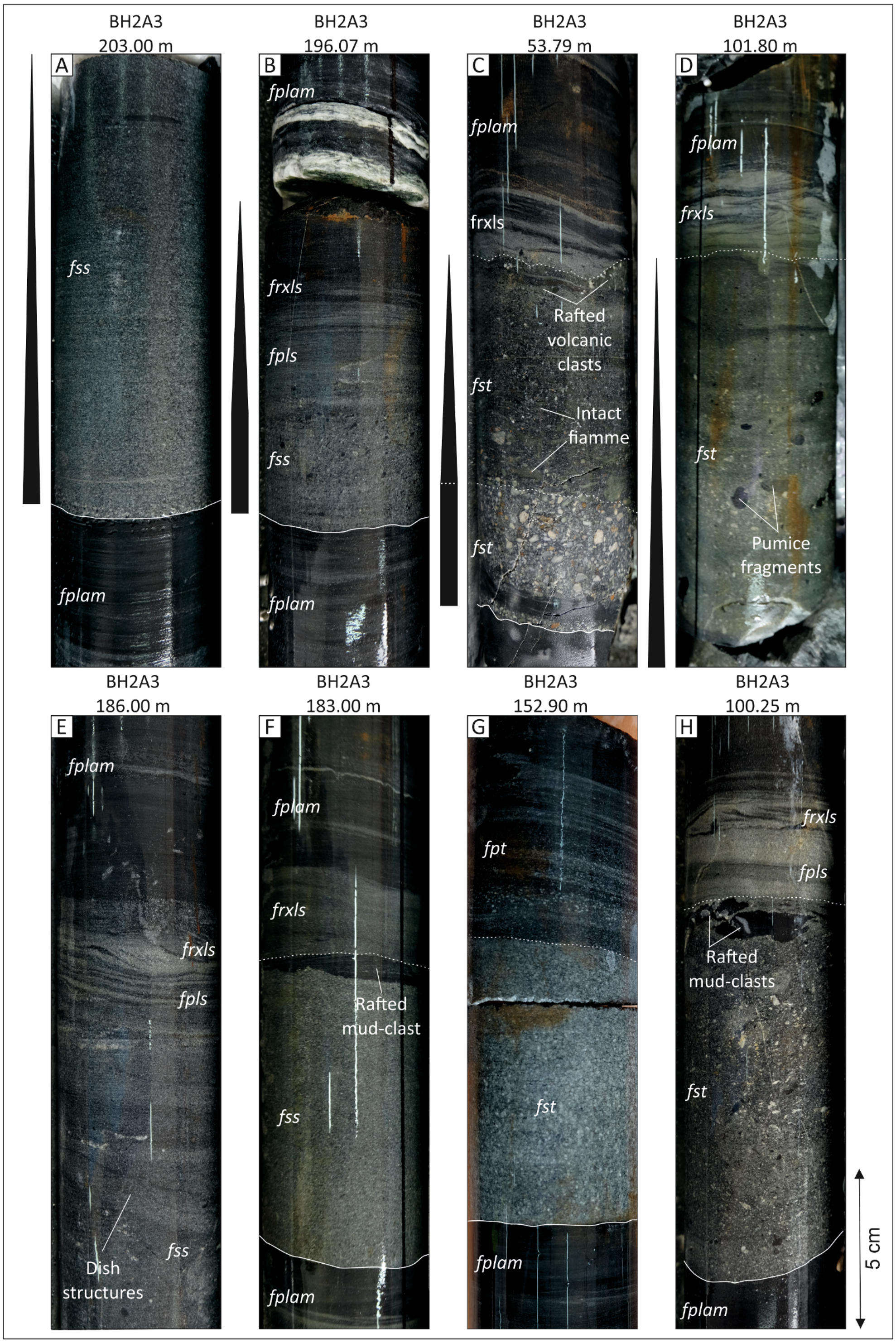

Fig. 11. Examples of borehole core sample images from BH2A3 through the Pulau Ayer Chawan Formation, showing mainly transitional flow deposits (TFDs; *sensu* Kane and Pontén 2012). These examples are representative of event beds in FA2 or FA7. (A) Normally-graded *fss* on top of *fplam*, showing an upwards increase in mud/fine-grained sediments towards the top. (B) A relatively thin, normally graded unit showing high density structures near the base, transitioning into lower density structuring towards the top. (C) Stacked, erosively based units of *fst*, with 0.1–0.5 cm wide volcaniclastic fragments and intact fiamme. (D) A normally-graded unit of *fst*, overlain by *frxls*, grading back out into *fplam*. (E) A normally-graded unit of *fss*, with well-developed dish structures, a feint 'banded' texture, and a low density bed-top (*fpls* and *frxls*). (F) A discrete unit of relatively well-sorted, erosively-based *fss*, with rafted-mud-clasts at the top. There is an abrupt contact between the *fss*, and the overlying *frxls*, possibly signifying a flow boundary (traction carpet). (G) A unit of normally-graded *fst*, overlain by *fpt*. (H) A unit of *fst* with normal grading near to the top, where mud-clasts are also rafted and concentrated. A sharp boundary exists between the lowermost interval of *fst*, and the overlying lower-density structuring of *fpls* and *frxls*, potentially representing a flow boundary (traction carpet deposition vs. dilute top and deceleration of flow). (*BGS © UKRI 2020).*

behaviour flow processes (*sensu* Haughton et al., 2003, 2009; Kane et al., 2017).

The *fccc* HEBs (Fig. 6ii) that contain carbonate clasts at the top of the event bed (*fccc*) are required to be derived from collapse of the palaeo-shelf, and therefore formed through down-flow segregation of a single flow into multiple flow types. It is entirely possible that *fccc* HEBs represent the more proximal versions of *fpt* HEBs, as limited amounts of firstly the carbonate, then the volcaniclastic material are deposited, leaving just a siliciclastic sediment-water mix in the more distal parts of the flow.

The *fmas* HEBs (Fig. 6ii), which are encountered interspersed within FA7, represent the 'normal' siliciclastic turbidite system of the deep-marine environment, and are directly comparable to the HEB deposits observed and described in FA2. However, these deposits potentially have an interesting relationship with the *fpt* HEBs; with a limited total volume of volcaniclastic delivered into the basin, it is quite possible that as *fpt* HEBs deposit-out their volcaniclastic material, they transition into *fmas* HEBs in the more distal parts of the system. In these areas, the flows would still be able to incorporate siliciclastic material into the flows through substrate de-lamination (*sensu* Fonnesu et al., 2016), but unable to 'bulk-up' in carbonate or volcaniclastic material, resulting in a siliciclastic HEB in amongst a largely volcaniclastic turbidite system.

4.8. Facies association 8 (FA8) – Ignimbrite (marine emplacement)

4.8.1. Description

FA8 comprises either isolated or stacked units of *welded tuffite (fwt)* or *fst,* (Fig. 6; Table 2), which form meter to decimeter thick, isolated or amalgamated units. Units of *fwt* are characterised as welded lapilli-sized fiamme, within a finer grained, volcanic ash matrix, displaying a 'flattening texture' (Table 2). Units of *fst* typically occur at either the base, or at the top of FA8, and are often normally graded. Facies *fst* often grades into a unit of *fplam* not exceeding one meter in thickness (otherwise FA4), whereas *fwt* is usually overlain by *fsps*, *fpls*, *fism* or *fpt*.

4.8.2. Interpretation

The deposits of FA8, specifically the isolated or stacked units of *fwt,* are interpreted as ignimbrites, deposited by pyroclastic flows that entered a marine environment. Ignimbrites are high-temperature eruptive deposits, more typically formed by pyroclastic flows on land, but can be encountered (somewhat controversially) in the subaqueous, marine setting (*sensu* Kokelaar and Busby, 1992; Kokelaar and Königer, 2000). These flows are also referred to as 'pyroclastic density currents' or 'PDCs' (*sensu* Di Capua and Gropelli, 2016b); a preferred genetic term in this study. The welding of fiamme observed in *fwt* permits the inference of high-temperature emplacement, and therefore represents a key criterion for such deposits. Units of *fwt* are inferred to have been emplaced through continued and progressive aggradation of hot ignimbrite, and not through conventional 'plug' or laminar flow (*cf.* Kokelaar and Königer, 2000).

The units of *fst* reflect the upper (and potentially lower), or tailing parts of the PDCs, which have cooled sufficiently in order for mixing and interaction with ambient seawater to occur (*cf.* Kokelaar and Königer, 2000). In this scenario, the upper part of the PDC began to fragment and disaggregate during the mixing and cooling process. As this was occurring, the resulting volcaniclastic sediment-water mix was potentially quite variable in terms of density, leading to the advent of laminar or turbulent flow conditions near to the top of the depositing unit. When considered together, this set of coeval processes explain the resultant structureless, sometimes normally graded tuffite units of *fst*, as deposition would be rapid not permitting structuring, with the normal grading simply reflecting a flow that was gradually decelerating. The occasional units of *fpt* likely represent the waning stages of the flow, during which time lower flow regime tractional structures (parallel lamination) are developed as the flow decelerated.

The overlying units of *fss*, *fpls*, *fism* represent deposition by intervening subaqueous sediment gravity flows that transported a mixture of siliciclastic and volcaniclastic material into the deep-water setting. These units typically follow intervals of *fwt* and *fst* (that represent the deposits of the initial PDC) and were either sourced through the collapse of destabilised sediment on the shelf by volcanic-related seismicity, or from sediment on the margin that became physically displaced by the PDC.

4.9. Facies association 9 (FA9) – Hyaloclastite

4.9.1. Description

FA9 is characterized by interbedded quenched lapilli-tuff (*fqlt*) and quenched lapillistone (*fqls*), with both facies comprising polygonal, volcanic breccia, set in a finer grained, typically ash-grade matrix or groundmass (*fqls*; Table 2; Figs. 6 and 13), interbedded with *fpt*. The polygonal volcanic breccia of *fqls* typically has a 'jigsaw-like' appearance. In general, bed thicknesses range between 0.5 and 3 m, with some units being much thicker, reaching 48 m in one example (Fig. 7). Individual units of either *fqlt* or *fqls* can form amalgamated packages or present as isolated occurrences within the interbedded succession. Up to 8 cm long, dark grey sub-rounded mudstone clasts, with irregular, sometimes cuspate margins are commonly observed within *fqls* (Fig. 13A and 13B). Finally, thin (1–20 cm thick) units of *fplam* are also observed interbedded within intervals of equally thinly-bedded *fpt* (Fig. 13F).

4.9.2. Interpretation

FA9 records a complex interplay between hydroclastic and siliciclastic sediments, facies that record the introduction of magmas/lavas into a subaqueous setting, resulting in the instantaneous quenching, solidification and hydrofracturing of rocks (Wohletz, 1983). The facies variation in these deposits can be used to reconstruct the specific eruptive and depositional mechanisms at the time (Bergh and Sigvaldason, 1991). In a very general sense, facies that displays larger blocks of quenched magma (*fqls* and *fqlt* of Fig. 13A–C) represent more proximal deposition relative to the source/vent, whereas the finer grained facies (*fqlt*, *fpt* and *fplam* of Fig. 13D–F) represent more distal locations. The range of facies in the Nanyang Member is comparable to that of parts of the facies model described in Bergh and Sigvaldason (1991), namely: 'bedded hyaloclastite' (equivalent to *fpt*); 'sideromelane shard hyaloclastite' (equivalent to *fqlt*); and 'isolated and broken pillow hyaloclastite breccia' (equivalent to *fqls*). Together, these facies represent the upper or outer (or distal) parts of the 'hyaloclastite flows' as described in Bergh and Sigvaldason (1991).

The complete lack of any coarser grained siliciclastic facies with FA9 suggests an extremely active, and likely rapid period of formation. It also may indicate relative uplift of these areas, with any coarser grained siliciclastic sediment that would otherwise be derived from the shelf, being diverted away from the eruptive sites. It is possible that local-scale uplift of the vent areas occurred as a consequence of magma entering the underground chamber below the vents, leading to upwards heave of the palaeo-seafloor during this time.

Similar rocks have been reported from the 'Ayer Chawan Facies' exposed in underground caverns in the Jurong Island area (Fig. 4); an area now mapped as part of the Pulau Ayer Chawan Formation (see Dodd et al., 2019a). These rocks were described as an 'interbedded sequence of mudstone and pyroclastic rock layers', interpreted as 'peperite' deposits (Winn et al., 2018; Fig. 15). Peperite deposits are typically formed through the intrusion of magmas into wet sediments (*cf.* Goto and McPhie, 1996), or 'along the contacts of lava flows or hot volcaniclastic deposits with unconsolidated wet sediments' (Skilling et al., 2002). However, these deposits of the Pulau Ayer Chawan Formation or 'Ayer Chawan formation' (as described in Winn et al., 2018), are more representative of the products of subaqueous eruptions from volcanic edifices located on the seafloor (*sensu* Bergh and Sigvaldason, 1991; Yamagishi, 1991) as opposed to being 'peperite' deposits, *sensu stricto*.

5. A depositional model for the Pulau Ayer Chawan Formation

The nine facies associations can be assigned to six separate sub-environments, including: deep-marine turbidite fan; deep-marine background sedimentation; subaqueous debris cone; shallow-marine; volcanically-sourced turbidite fan; and hyaloclastite mound or ridge.

5.1. Deep-marine turbidite fan

The Pulau Ayer Chawan Formation contains numerous examples of turbidite fans systems, deposited in the deep-marine setting (Fig. 15). In general, deep-water turbidite fans typically form lithologically heterogeneous, spatially-complex successions of strata that are often challenging to map and model in the subsurface (e.g. Walker, 1978; Richards et al., 1998; Richards and Bowman, 1998).

This deep-marine turbidite fan sub-environment comprises high density turbidites (FA2) and more thinly-bedded low density turbidites (FA1), which pass-out distally or laterally into deep-marine background sediments (FA4; Fig. 14A). In the examples where FA2 occurs as stacked or amalgamated packages (Fig. 10A), this type of arrangement is typical of proximal or axial channel settings within a turbidite fan, where high

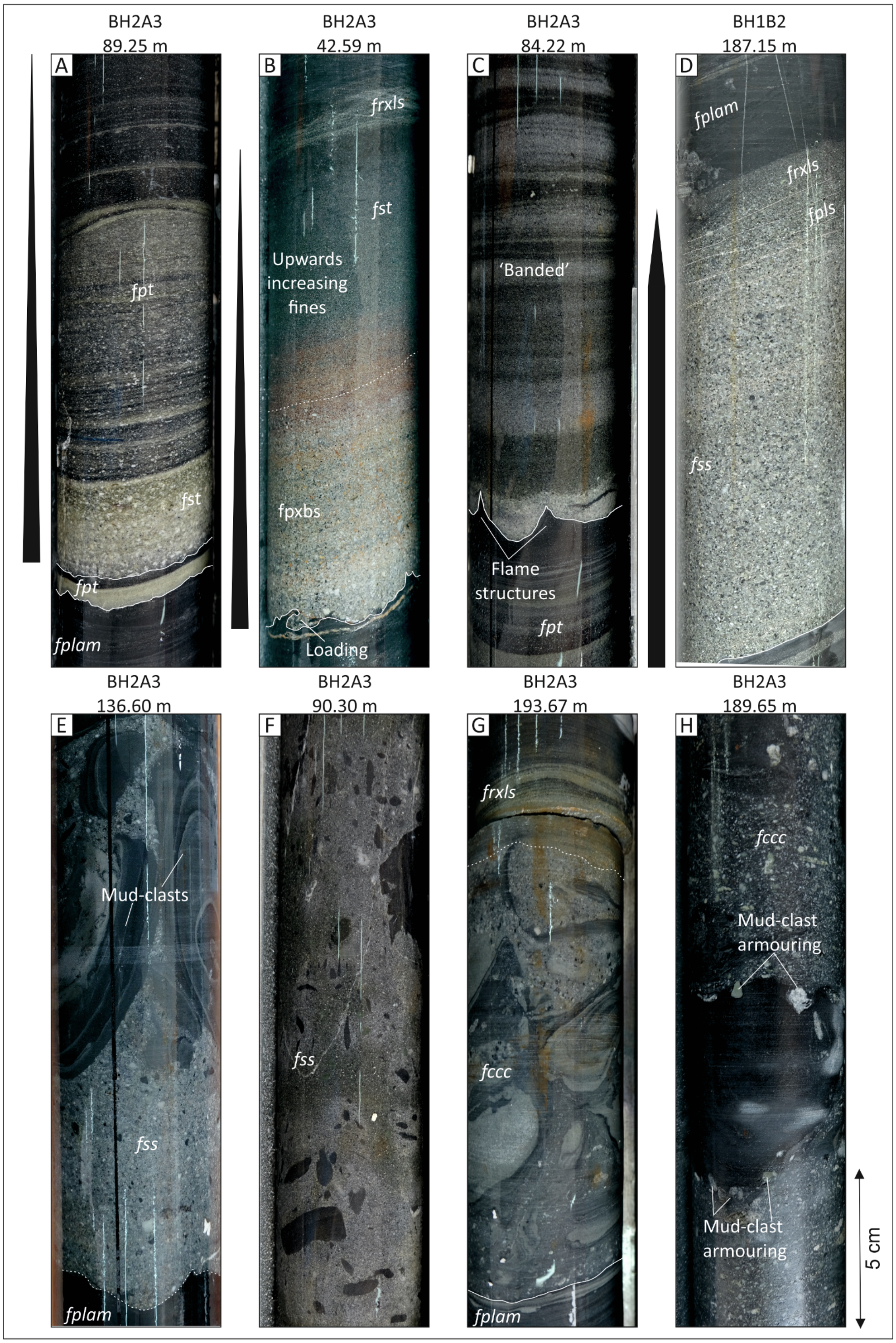

Fig. 12. Examples of borehole core sample images from BH2A3. (A) Volcanically-sourced, low density turbidite showing normal grading, comprising a lowermost thin unit of *fst* transitioning into a much thinker units of *fpt*. (B) A volcanically-sourced high density turbidite, displaying well-developed normal grading, upwards-increasing fine-grained component within the matrix and a loaded base. The unit comprises a lowermost interval of *fpxbs*, grading upwards into *fpt*, with the fine-grained component comprising green-coloured volcaniclastic material (clays derived from down-flow disaggregation). (C) Banded sandstone, with loading evident by well-developed flame structures at the base. (D) An event bed, with a lowermost interval of *fss*, and a bet top that shows normal grading, transitioning into *fpls*, *frxls* and eventually into *fplam* at the top. (E) A unit of *fss* with a loaded basal contact and of 3–6 cm long, elongate to ovoid-shaped mud-clasts that have been rafted towards the top of the bed. (F) A unit of *fss* with a high proportion of entrained mud-clasts (that comprise less than 25% of the matrix), that are randomly organised, floating within the moderately-sorted matrix. (G) A unit of *fccc*, with an erosive base, showing a poorly-sorted, mud-rich matrix suspending a mixture of clast lithologies, including mud-clasts, volcaniclastic fragments and rare carbonate clasts. (H) A unit of *fccc*, showing a poorly-sorted matrix composed of volcaniclastic fragments and containing a 7 cm wide armoured mud-clast, which displays embedded out-sized volcanic fragments compared with the surrounding matrix. *(BGS © UKRI 2020)*.

energy flows operate (Walker, 1967, 1978; Lien et al., 2003; Dodd et al., 2019b). In comparison, the more distal or fringing areas of the turbidite fans are typified by more thinly-bedded intervals of FA1 (Fig. 10B), interbedded with progressively fewer occurrences of FA2, and increasing thicknesses of FA4 (Fig. 14A).

Hybrid event beds (HEBs; and other products of flows that show mixed flow behaviour; Fig. 6Bi), are present mostly within the deep-marine parts of the Pulau Ayer Chawan Formation, typically within FA2 or FA4 (Fig. 7), and therefore are associated with lobe fringes or more distal settings (Haughton et al., 2003, 2009; Talling, 2013; Kane et al., 2017). The presence of hybrid event beds within this sub-environment (Figs. 11 and 12) is significant as it indicates that the up-dip slope was in disequilibrium, over-steep or 'out-of-grade' (*sensu* Haughton et al., 2003, 2009).

This is particularly interesting when also considering the presence of debrites sourced from an unstable shelf (FA3), alongside the products of adjacent contemporaneous volcanism (FA7, FA8 and FA9; Fig. 14A and B). These factors suggest a palaeo-shelf along the eastern edge of Semantan Basin that had significant tectonic, volcanic, and sedimentary instability during Middle Triassic times, now preserved in the bedrock geology of south-western Singapore (and most likely more widely across the relict Semantan Basin and adjacent Sukhothai Arc that

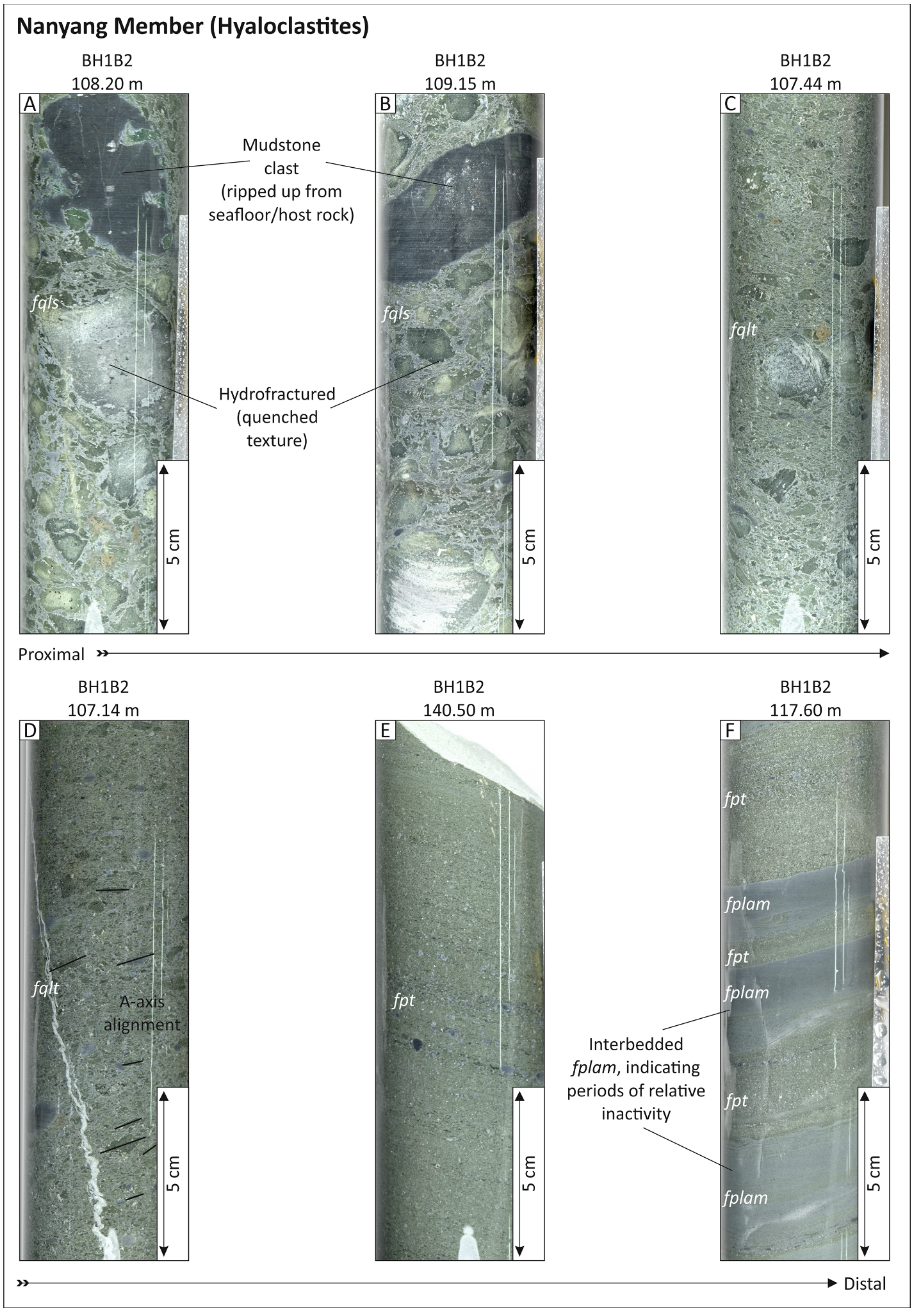

Fig. 13. Borehole core sample images from the hyaloclastites (FA9) of the Nanyang Member, observed in BH1B2. The six examples represent an overall proximal to distal transition in hydroclastic facies away from the sub-sea vent. (A) An example of quenched lapillistone (*fqls*) with a 5 cm wide mudstone clast that was likely ripped up from the host rock, or the seafloor through which the eruptions occurred. (B) An example of quenched lapillistone from BHAB2, with a comparably smaller and more widely spaced clasts, demonstrating the hydrofractured or quenched texture that forms a series of fragmental, angular clasts of volcanic glass within a finer grained matrix. (C) An example of quenched lapilli tuff (*fqlt*) with a number of 0.1–1 cm wide angular clasts suspended in a finer grained, ash-grade matrix. (D) An example of *fqlt* that has comparably less and smaller angular fragments, along with a very crude A-axis alignment of elongate fragments that produces a crude texture. (E) Parallel-laminated tuffite (*fpt*), showing sorting of volcanic clast sizes along laminations. (F) Interbedded parallel-laminated background mudstones (*fplam*) and parallel-laminated tuffite (*fpt*), forming a repeated succession. *(BGS © UKRI 2020).*

underlies much of Peninsular Malaysia).

5.2. Deep-marine background sedimentation

This sub-environment comprises mainly FA4, representing the deposits of 'normal' background sedimentation in the deep-marine environment (hemi-pelagites; Fig. 14A). These deposits are occasionally interbedded with thin occurrences of FA1, reflecting the lateral transition from the background sedimentary processes of FA4 into adjacent turbidite fan systems represented by FA1 (Fig. 14A). In these settings, background sedimentation is often and periodically punctuated by low density (dilute) turbidites (FA1) that represent distal expressions of adjacent turbidite fan systems (Fig. 15). In general, this sub-environment represents a low oxygen, or anoxic setting, as evidenced by the lack of bioturbation and thick intervals of *fplam* that characterise the setting.

5.3. Subaqueous debris cone

This subaqueous debris cone sub-environment comprises debrites (FA3; Fig. 14B), interbedded with deep-marine background sediments (FA4) in more distal locations, and shallow-marine deposits (FA5) in more proximal parts of the basin. The diverse assemblage of clast lithologies, comprising carbonate clasts, volcaniclastic fragments, mudstone clasts (Fig. 9; Table 2), and in particular the presence of large granitic clasts, reduces the likelihood of a possible interpretation of FA3 representing carbonate tallus, deposited immediately down-dip from a shallow-marine reef system (e.g. Grasso and Pedley, 1998).

Instead, it is likely the debrites were sourced from an actively destabilising, failing margin composed of mixed carbonate and siliciclastic rock types, from which the debris flows transported sediment into the basin (Fig. 14B). Some debrites show signs of having prolonged transportation distances, with a poorly-sorted, yet well-homogenised matrix, along with examples of 'dilute tops' (diluted *fccc*; Fig. 6Ci), indicating

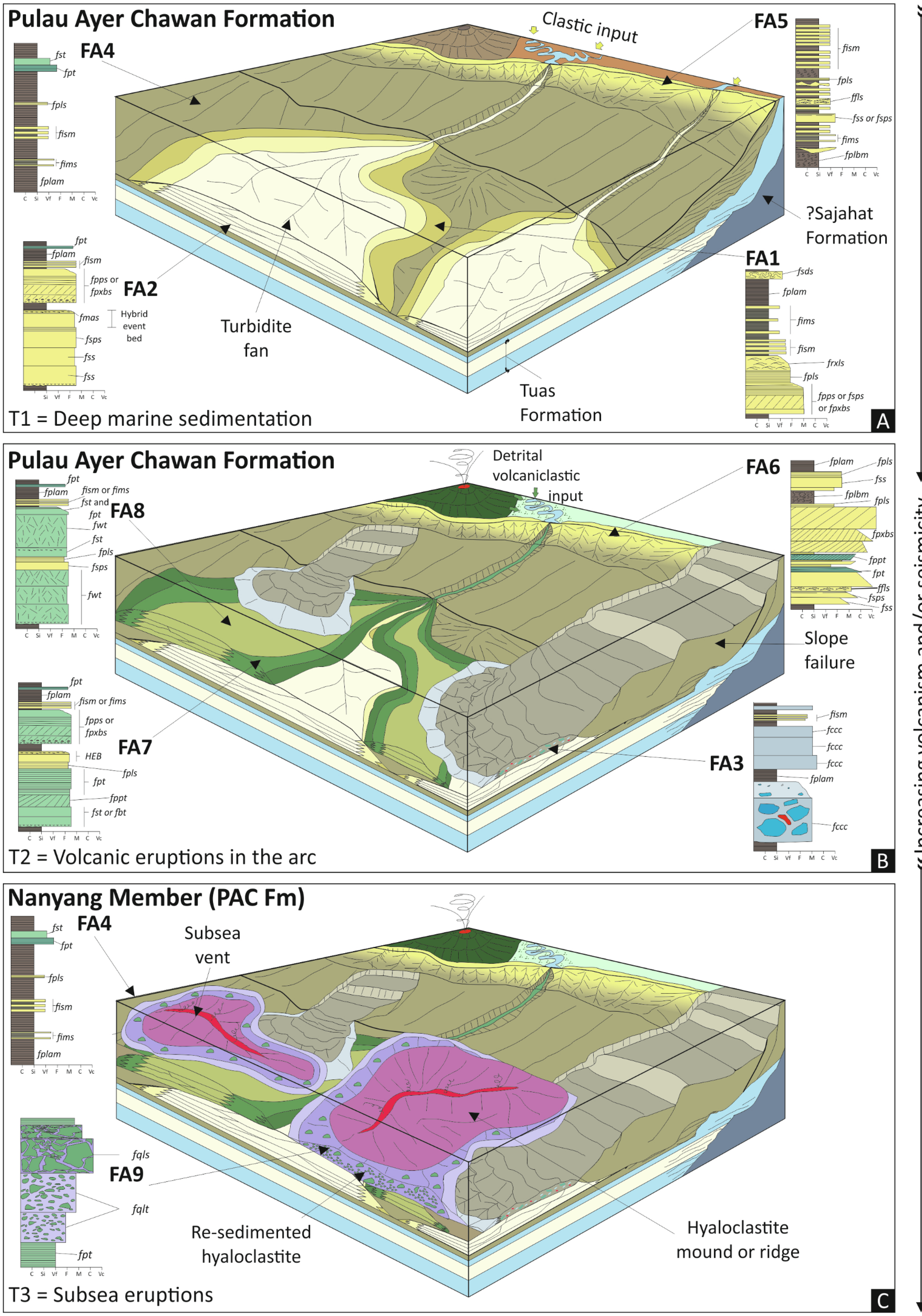

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Fig. 14. 3D schematic block diagrams of deposition throughout Pulau Ayer Chawan Formation times in Singapore. The three examples depict the increasing volcanism and/or seismicity that typifies the formation. Facies associations 1–9 are related to the facies associations outlined in Fig. 6, and discussed within the text. (A) The deep-marine to shallow-marine setting of the Pulau Ayer Chawan Formation. Deep-marine background sedimentation (FA4) was periodically punctuated by both low density (FA1) and high density (FA2) turbidity currents that formed turbidite fans. The deep-water environment transitions into shallow-marine sedimentation (FA5) towards the hinterland. (B) Volcanic eruptions and related seismicity were common occurrences during Pulau Ayer Chawan Formation times, leading to the input of vast amounts of volcaniclastic material into the region, which was transported offshore by turbidity currents, forming volcanically-sourced turbidite fans (FA7) or by marine ignimbrites forming welded aggradational units (FA8). The associated seismicity caused uplift of the region, resulting in a destabilised shelf that commonly experienced failure, and thereby sourcing subaqueous debris cone deposits (FA3) within the basin. (C) During this volcanically disturbed period, a number of sub-sea vents within the deep-marine areas (FA4) erupted lavas into the cold waters. This caused rapid quenching and (hydro) fracturing of the volcanic rocks on the seafloor, which depending on the vent morphology, likely formed mound or ridge systems (FA9). *(BGS © UKRI 2020).*

efficient mixing of the sediments following the initial failure and delivery into the basin from the shelf areas. The presence of multiple occurrences of either amalgamated or isolated debrite event beds, interbedded with turbidites (Fig. 6C), indicates a relatively long-lived subaqueous debris cone setting, and precludes an alternative model whereby thick intervals of FA3/*fccc* may otherwise be interpreted as a single, thick mass transport deposit (or MTD).

The ideal candidate formation for the sourcing of the material preserved by FA3 is present directly below the Pulau Ayer Chawan Formation; the Tuas Formation (Figs. 2 and 14) comprises interbedded successions of limestone and siliciclastic sedimentary rocks (Dodd et al., 2019a). However, volcaniclastic sediments within FA3 are not easily attributable to being sourced from the underlying Tuas Formation as there is a general absence of volcaniclastic material in that formation (Dodd et al., 2019a). Instead, they are more likely derivatives of the volcanic arc during Pulau Ayer Chawan Formation times, likely aggrading on and along the shelf, and subsequently becoming included within the debris flow during the shelf failures.

5.4. Shallow-marine

This sub-environment comprises shallow-marine background sedimentation (FA5; Fig. 14A), which passes into a shallow-marine, lower to middle shoreface setting (FA6; Fig. 14B). The sub-environment also preserves common instances of low density turbidites (FA2), along with less common FA7 and FA8, and rarely FA2.

The common occurrence of *fism* and *fims* in FA5, along with the presence of FA2, reflects constant delivery of very fine- to fine-grained sands into the basin, signifying relative proximity to the shelf. Additionally, the more regular occurrence of *fplbm* in FA5 suggests a more oxygenated water column and therefore likely shallower waters. The coarsening-upwards, thickening-upwards planar cross-bedded lower to middle shoreface of FA6 represent wave-worked deposits within a shallow-water setting. Additionally, mud drapes observed on the sedimentary structures in both FA5 and FA6 (within *ffls* and *fpxbs*) indicate varying wave energies, and potentially even suggest the influence of tidal processes.

The transition from deep-marine sediments into shallow-marine deposition may simply be related to palaeogeographical variations in the shelf, with northerly deposits representing more proximal depositional environments compared with their south-westerly counterparts (Fig. 15). Alternatively, the shallow-marine sediments may be relatable to periodic relative sea level falls, potentially linked to tectonic uplift associated with the active volcanic arc setting, and/or further complicated by climatically-driven variability (eustatic). Further work, including more detailed, higher resolution geochronological evidence, combined with analysis of global sea level curves would be required in order to further investigate this.

5.5. Volcanically-sourced turbidite fan

This environment comprises volcanically-sourced turbidite fans (FA7) and rare occurrences of PDCs or ignimbrites (FA8; Fig. 14B). During this time, the hinterland, from which the turbidite fans were sourced, comprised a volcanically-active fore-arc setting, in which vast quantities of volcanoclastic material were being erupted and subsequently re-incorporated into the adjacent sedimentary environments. The shear availability in volcanoclastic material resulted in its erosion and transportation by proximally-located fluvial systems on land that drained into the shallow-marine settings, ultimately feeding into the deep-marine turbidite fan systems. The principal transportation method was through a variety of subaqueous sediment gravity flow processes described within FA7 (Fig. 6G).

Occasionally, PDCs sourced directly from a nearby volcanic edifice, flowed across the coastline and entered the marine setting of the Pulau Ayer Chawan Formation. These currents emplaced marine ignimbrites (FA8), formed as high temperature deposits through rapid aggradation of tuff in the deep-marine setting. The palaeo-direction of PDC input remains uncertain, although it is envisaged that they may have followed the valley lows on land, entering the marine setting at similar points along the margin as the fluvial systems that fed the volcanically-sourced turbidite fans. For this reason, the ignimbrites have been deposited along with the volcanically sourced turbidite fan systems (Fig. 14B). It is equally possible that the PDCs entered the basin from a completely different point (volcanic edifice) along the basin margin, and they have no spatial or genetic link with the volcanically-sourced turbidite fan systems, other than under and overlying them in the basin setting. The possibility for FA8 being erupted from a sub-sea vent (e.g. Group I of White, 2000), as opposed to originating from an edifice from land, cannot be ruled-out. Future work would be required to determine the exact relationship between these two types of deposits.

5.6. Hyaloclastite mound or ridge

This sub-environment comprises amalgamated intervals of hyaloclastite deposits (FA9), which show considerable textural variability, represented by 'finer grained' *fqlt*, 'coarser grained' *fqls* (Fig. 13), and grade laterally out into deep-marine background sediments (FA4). These deposits are formed as the product of hydrofracturing or brecciation of magmas through rapid quenching in (sea)water (*sensu* Yamagishi, 1991). It is possible for these magmatic products to be introduced into the deep-water basins through either lava deltas (*cf.* Watton et al., 2013), or perhaps more likely the case for the Pulau Ayer Chawan Formation, through sub-sea vents linked to sill and dyke systems in the subsurface (Fig. 3; *cf.* Yamagishi, 1991). Depending on the nature of the sub-sea vent and feeder dyke (e.g. circular vs. elongate), they could present as a range of geomorphological features on the palaeo-seafloor that include mounds (circular forms), or ridges (elongate features).

When amalgamation of *fqlt* with *fqls* is observed (Figs. 6 and 7), and taking into consideration the large size, and 'jigsaw-like' nature (comparable to pseudo-pillows of Yamagishi, 1991) of the fractured pillows of *fqls* (Fig. 13), these deposits indicate areas in close proximity to the eruptive vents (Figs. 14C and 15). In theory, hyaloclastite mounds or ridges should also include interbedded units of hemi-pelagic mudstones (FA4), particularly at distal locations relative to sub-sea vents. In the distal areas, the delivery of hydroclastic sediments will be less frequent than compared with the more-proximal localities, permitting the preservation of FA4 through normal suspension fall-out processes. Following the same logic, the absence of FA4 within BH1B2 (Fig. 5)

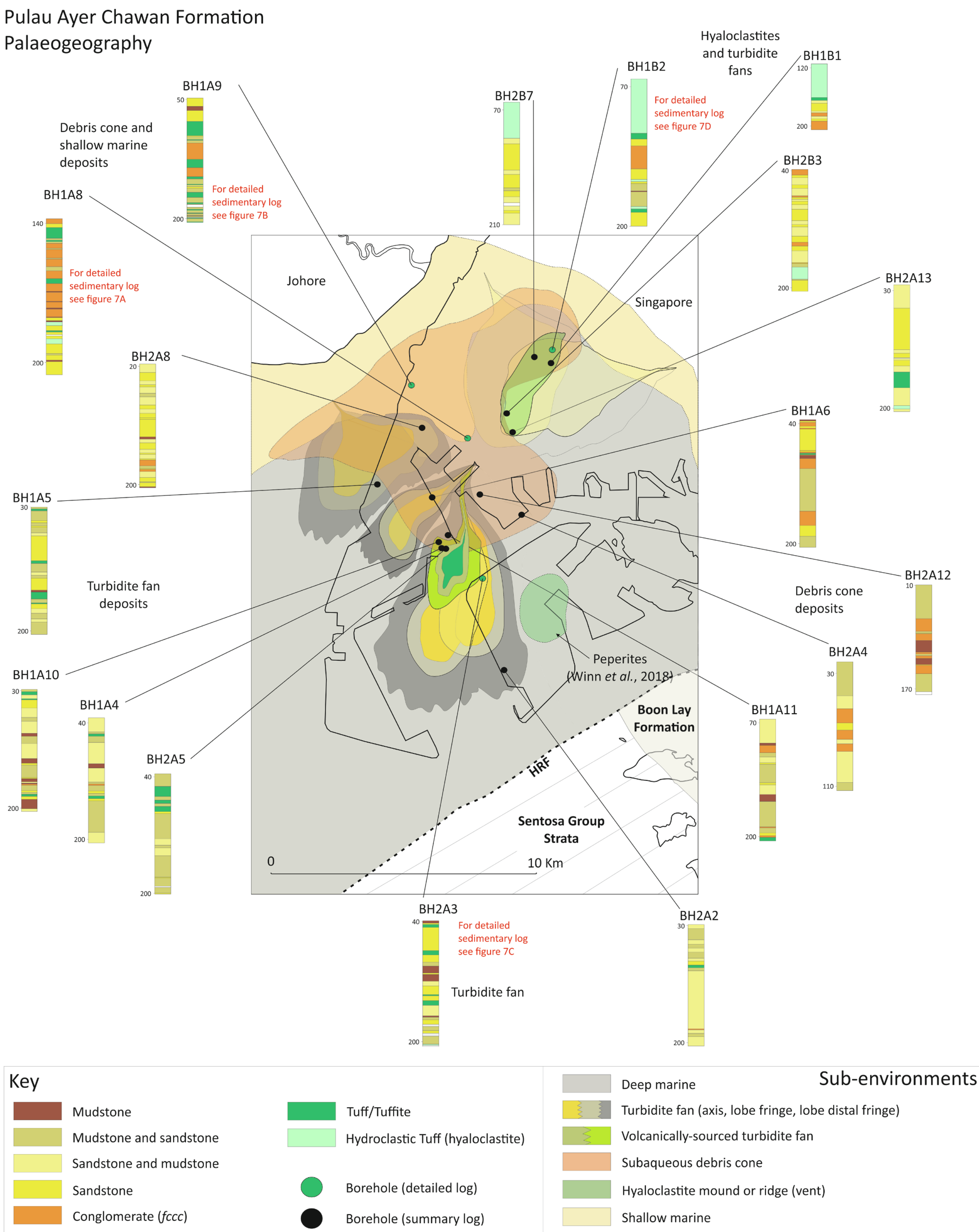

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Fig. 15. An attempt to place the deposits of the Pulau Ayer Chawan Formation within a palaeogeographical context, relative to the present day outline of Singapore (see black outline). Summary logs produced from visual inspection of high-resolution core photography are provided for all boreholes in the dataset that intersect the formation, with detailed logs for BH1A8, BH1A9, BH1B2 and BH2A3 in Fig. 7. Overall, the pattern and distribution of sediments in the boreholes suggest a geometrically complex shelf edge, with an overall NW-SE striking trend. The more basinal areas are interpreted in the south-western parts of Singapore, moving more proximal in a northwards direction. The shallowest sediments within the dataset are observed in BH1A9, suggesting a possible 'jutting-outwards' of the coastline that may be related to a deltaic systems potentially located to the north. Hyaloclastite deposits are clustered in the north, potentially representing a sub-sea vent in this area, with a second potential vent located in the more basinal areas, as evidenced by the presence of 'peperite deposits' in the Jurong Caverns on Jurong Islands (see Winn et al., 2018; BGS © UKRI 2020).

provides additional support of relative proximity to vents.

In the new lithostratigraphical framework for Singapore (Dodd et al., 2019a), hyaloclastite mound or ridge deposits have been grouped into the Nanyang Member of the Pulau Ayer Chawan Formation. The textural variability and volcano-sedimentary rocks exposed in BH1B2 (Fig. 7), along with other boreholes that intersect the Pulau Ayer Chawan Formation (Fig. 15), require additional analysis in order to determine the distribution and character of the Nanyang Member. In particular, the volcani-sedimentary facies should be further studied in order to map and model the distribution and potential palaeogeographical sources for the magmas/lavas introduced into the deep-marine environment during Triassic times.

6. Discussion

6.1. Analogue volcano-sedimentary systems to the Pulau Ayer Chawan Formation

There are only few studies that deal with deep-water sedimentary systems where volcanically-influenced sedimentation is superimposed on the 'normal' siliciclastic supply (Di Capua and Groppelli, 2018 and references therein). One particular example — that analyses sediment of the Val d'Aveto Formation in the Northern Apennines of Italy — documents a succession of PDC, debris avalanche, and lahar-related subaqueous flow deposits, formed in a deep-water siliciclastic fan environment (Di Capua et al., 2016; Di Capua and Groppelli, 2018). The Val d'Aveto Formation occupied an Eocene to Oligocene foreland and foredeep basin related to the beginning of subduction of the Adriatic Plate beneath the European Plate (Di Capua and Groppelli, 2018). In this setting, volcanic particles were encountered, in varying quantities, within the depositional sandstones, which were probably introduced into the deep-water environment through erosion and transportation of volcaniclastic detritus by rivers (Di Capua and Groppelli, 2018). Similarities, in terms of overall depositional environment, can be drawn between the Val d'Aveto Formation and the Pulau Ayer Chawan Formation.

A second possible analogue for the Pulau Ayer Chawan Formation in Singapore are the Taveyanne Sandstones that outcrop in France and Switzerland (Ruffini et al., 1997; Di Capua and Gropelli, 2016a; Lu et al., 2018), and which are also referred to as the Taveyannaz Formation (Lu et al., 2018). This unit is interpreted to represent a thick submarine volcaniclastic fan and hemi-pelagite succession, deposited in the Oligocene Northalpine Foreland basin (Ruffini et al., 1997).

The turbidite fans, volcanic arc products and other associated deep-water sediments of the Pulau Ayer Chawan Formation reported here, and illustrated in Fig. 14, represent an interesting addition to the case examples of these seemingly under-reported sedimentary systems, and one that still has much to offer in terms of scientific research topics for the future.

6.2. Controls of sediment input into the Semantan Basin

Both the Pulau Ayer Chawan Formation of Singapore, and its correlative unit the Semantan Formation of Peninsular Malaysia, record the along-strike variability in processes and events that occurred along the eastern margin of the Semantan Basin (Fig. 1). Consequently, the Pulau Ayer Chawan Formation has much to offer in terms of additional insights into sedimentary processes within the wider Semantan Basin, and more generally during the final closure of Palaeo-Tethys.

The source of the siliciclastic sediments being transported into the basin was likely from a hinterland composed the Indochina-East Malaya block, and possibly the Sukhothai Arc, the former comprising parts of the pre-Devonian rocks of Gondwana from where the amalgamated terranes were derived. Some of the siliciclastic material may have been supplied directly from the hinterland, delivered to the margin by fluvial systems (Fig. 14A), and then transported offshore by a series of sub-aqueous sediment gravity flow processes, in a broadly (then) east-west transport direction (Fig. 15). In comparison, the source of volcaniclastic material within the formation was likely from onshore eruptions in the Sukhothai Arc (*sensu* Metcalfe et al., 1982), with some components being delivered by sub-sea eruptions in the deep-water setting. The volcanoclastic products on land were likely re-worked into detrital volcaniclastic material by fluvial systems that drained into the basin (Fig. 14A). Much like with the 'normal' siliciclastic systems, the fluvial systems may have fed volcaniclastic material into the basin by directly entering the sea at the coastline at deltas and estuaries, transitioning into turbidity currents that fed the offshore-located turbidite fan systems.

Regional, and potentially periodical uplift of the Singapore area of the Semantan Basin, related to volcanic activity in the Sukhothai Arc, likely occurred throughout this time, with a number of lines of evidence that support this. Firstly, dyke and sill emplacement under the region needed to have occurred in order to form a network of magma conduits that fed the volcanic vents forming the FA9 hyaloclastite deposits, along with the edifices on land that erupted volcanoclastic material, which eventually sourced the turbidite fans (FA7 and FA8) in the deep-water areas. In general, the Sukhothai Arc was a site of heightened volcanic activity related to the melting of the down-going Palaeo-Tethys oceanic crust under the Indochina-East Malaya block, resulting in the contemporaneous emplacement of voluminous granitic bodies of the Bukit Timah Centre in Singapore throughout Triassic times (Gillespie et al., 2019). It is therefore extremely unlikely that the Singapore area of the Semantan Basin, or the Sukhothai Arc in general, did not experience uplift during this time. Secondly, evidence for slope instability, potentially associated with volcanic-related seismicity, exists documented by FA3 of the Pulau Ayer Chawan Formation. These types of deposits are also observed in correlative rock units in Peninsular Malaysia; deep-water mass transport deposits, made up of sandstone blocks and boulders comprising shallow-water gastropods and bivalves derived from a shelfal source, are commonly observed within the Semantan Formation (Madon, 2010). Finally, hybrid event beds that are observed in the Pulau Ayer Chawan Formation, indicate a shelf or slope that was in disequilibrium, was over-steep or 'out-of-grade' (Haughton et al., 2003, 2009), further supporting a destabilised shelf. All of these lines of evidence are relatable to periods of uplift of the eastern margin of the Semantan Basin during the Middle Triassic, which contributed to, and possibly fundamentally controlled, the input of sedimentary material into the basin.

6.3. Syn-depositional volcanism

In Singapore, it is clear that during deposition of the Pulau Ayer

Chawan Formation, sedimentation in the Semantan Basin was strongly influenced by activity in the nearby Sukhothai Arc (Fig. 1B), which provided vast quantities of volcanogenic material and volcaniclastic sediment into the region.

The volcani-sedimentary deposits within the Semantan Basin forearc include: FA3 that was likely derived from basin margin collapse and probably associated with volcanic-related seismicity (Fig. 14B); FA7 that transported and re-worked both siliciclastic and volcaniclastic sediments into the deep-water setting (Fig. 14B); FA8 formed by eruptions entering the water body (Fig. 14B); and FA9 of the Nanyang Member, deposited by sub-sea eruptions within this deep-marine environment (Figs. 14C and 15). These volcanically-influenced strata interdigitate with those of the rest of the siliciclastic Pulau Ayer Chawan Formation (Fig. 14A), testifying to the dynamic link between volcanism and sedimentary process of the Semantan Basin in Middle Triassic times.

Overall, the upwards increase in FA7, FA8 and FA9 signifies elevating tectonic, seismic, and volcanic instability during the Middle Triassic in the Singapore part of the Semantan Basin (Fig. 14), probably associated with parallel increases in activity in the Sukhothai Arc. Gillespie et al. (2019) argue that large-scale eruptions must have taken place at this time in association with the emplacement of the plutons making up the Bukit Timah Centre in Singapore. The hyaloclastites of the Nanyang Member provide perhaps the most striking evidence for syn-depositional volcanism during Pulau Ayer Chawan times. Other authors have identified 'peperite' deposits within the previously defined, broadly equivalent 'Ayer Chawan Facies' (Winn et al., 2018); the evidence for syn-depositional volcanism in the Semantan Basin during Pulau Ayer Chawan Formation times is unequivocal.

6.3.1. The influence of volcaniclastic material on HEB development

The presence of hybrid event beds associated with the turbidite fan deposits in the formation represents an intriguing topic, with a large proportion of the upper parts of these deposits containing (sorting and preserving) high volumes of volcaniclastic products (Figs. 11 and 12). In general, the role of finer grained sediments (clay and silt-grade material) in controlling flow rheology is an important topic concerning research into flows that display evidence for mixed flow behaviour (see Haughton et al., 2009; Talling, 2013; Kane et al., 2017). Volcaniclastic influenced sediments, which are often composed of fine-grained ash, volcanic glass shards (fiamme), and larger volcanic clasts (pumice), present an excellent source of fine-grained material. They also have the potential to further contribute finer grained material to the flows through down-slope disaggregation of immature volcanic glass particles into clays during a single flow event. The examples of hybrid flow types in the Pulau Ayer Chawan Formation document a potential relationship that requires future work in order to better assess.

6.4. Basin-scale implications for the Semantan Basin during the Middle Triassic

The Pulau Ayer Chawan Formation records deposition in a predominantly deep, but occasionally shallow marine environment (Figs. 14 and 15), representing the most distal (deepest water) deposits observed within the Singapore sector of the Semantan Basin. Following deposition of the Pulau Ayer Chawan Formation there is a general shallowing-upwards of facies types moving upwards through the Singapore stratigraphy (see Dodd et al., 2019a). It therefore records the latest stages of deposition within the Palaeo-Tethys seaway, immediately prior and/or during the progressive closure of Palaeo-Tethys during Triassic times (Fig. 1B; Metcalfe, 2011).

The transition from a shallow-marine carbonate environment of the underlying Tuas Formation, into the deep-marine setting, signifies a deepening event within the Semantan Basin that marks the base of the Pulau Ayer Chawan Formation. The boundary between the Pulau Ayer Chawan Formation and the underlying Tuas Formation is conformable but quite abrupt, indicating a sudden change in water depth and/or sedimentation. This may be related to rapid generation of accommodation space through tectonic subsidence (e.g. see normal faults offsetting the Tuas Formation in Fig. 1B) and/or through a eustatically-influenced rise in relative sea level, both of which may have contributed to the transgression of the shallow-marine shelf of the Tuas Formation. However, tectonism associated with the adjacent Sukhothai Arc likely played a key role in relative sea level variability during this time.

The volcanic (tectonic) perturbations of the region throughout Pulau Ayer Chawan Formation times likely impacted upon relative sea level in the Semantan Basin (at the local and semi-regional level), which led to intermittent shallowing or deepening events, that are typically best observed at basin margins. This tectonically-influenced relative sea level fluctuation was likely associated with the filling and emptying of the magma chambers in the subsurface, leading to semi-localised uplift or development of accommodation space within the basin. Indeed, relative sea level fluctuation during this time are supported by sedimentological evidence, with deep-marine sediments transitioning into shallow-marine deposits, and then back to deep-marine deposits in BH1A8, BH1A9, and BH1B2 (Fig. 7). Furthermore, in BH1A8 and BH1A9 (Fig. 7) the relative deepening, from shallow-marine to deep-marine deposition, appears to be associated with the coeval input of debris cone deposits (FA3) into the basin, related to collapse of the palaeo-shelf, likely as a consequence of volcanic-related seismicity. Together, these factors point towards heightened, possibly increasing volcanically-driven tectonic activity during Pulau Ayer Chawan Formation times (Fig. 14), and which imposed considerable control on relative sea level in the region.

A concluding uplift phase may have led to the subsequent shallower water conditions and effective shut-off of siliciclastic supply into this part of the basin, resulting in the termination of the Pulau Ayer Chawan Formation deposition. The formation was then followed by the ensuing succession of thickly-bedded shallow-marine carbonates of the overlying Pandan Formation (for details see Dodd et al., 2019a), from which point the Semantan Basin shallowed as Palaeo-Tethys finally closed in this part of the world.

7. Conclusions

- The Pulau Ayer Chawan Formation comprises a suite of 21 facies that reflect the diverse range of sedimentary processes recorded in the heterogeneous sedimentary rocks of the formation. These facies have been grouped into 9 facies associations that include: low density turbidites (FA1), high density turbidites (FA2), subaqueous debris cone (FA3), deep-marine background sedimentation (FA4), shallow-marine background sedimentation (FA5), shallow-marine (lower to middle shoreface; FA6), volcanically sourced turbidites (FA7), ignimbrite (marine emplacement, FA8), and hyaloclastite (FA9).
- Combinations of these facies associations reflect six different sub-environments, including: deep-marine turbidite fan, deep-marine background sedimentation, subaqueous debris cone, shallow-marine, volcanically-sourced turbidite fan, and hyaloclastite mound or ridge. Collectively, these sub-environments characterise the variability within the overall deep to shallow-marine Pulau Ayer Chawan Formation; a volcanically-influenced sedimentary rock unit that underlies much of the south and south-western parts of Singapore.
- The formation records a period of time when volcanic eruptions resulted in substantial and periodical uplift of the region. This is recorded by the products of slope instability in the basin, including debris flow cone deposits sourced from the actively destabilising shelf, volcaniclastic hybrid event bed deposition within turbidite fans and by correlative mass transport deposit observed in the Semantan Formation of the Semantan Basin in Malaysia.
- The Pulau Ayer Chawan Formation, along with the Semantan

Formation, record the range of sedimentary processes along the eastern margin of the Semantan Basin, throughout the Middle Triassic, and possibly into the Upper Triassic. Both these formations are typified by not only siliciclastic sedimentation, but also considerable volumes of both volcanoclastic and volcaniclastic material.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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