



Facies, depositional environments, and anatomy of the Subis build-up in Sarawak, Malaysia: implications on other Miocene isolated carbonate build-ups

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Abstract

Isolated carbonate build-ups of Miocene age are important hydrocarbon reservoirs in SE Asia and globally. The architecture of the build-up rim and fore-reef talus is poorly understood. The Subis build-up is one of the cycle I–II carbonate outcrops exposed along the coastal Sarawak in an area of $5 \times 6 \text{ km}^2$, with an exposed thickness of 390 m. This provides an opportunity to document the composition and architecture of rim and talus deposits in an isolated build-up as an analogue for similar gas-bearing structures located offshore Central Luconia, in Malaysia, which were neither drilled nor cored so far. This paper documents sedimentological characteristics, lateral and vertical facies relationships, of the marginal sections of a build-up in a large quarry exposing the Subis Limestone. The Subis Limestone is composed of massive and branching corals, coralline red algae, benthic foraminifera, bivalves, gastropods, echinoids, and occasionally bryozoans and sponges. Eight microfacies types and four environments were defined to describe the Subis Limestone: outer talus, inner talus, reef rim, and lagoon. Nine genera of benthic foraminifera were interpreted, confirming an early Miocene age (cycle II) of the succession. Three major backstepping events were observed at the build-up, where they developed inward towards the center of the build-up.

Keywords Cycle II carbonate · Facies · Talus deposits · Backstepping · Central Luconia

Introduction

Miocene carbonate build-ups are economically important hydrocarbon reservoirs. They contain 43% of all reserves in carbonate build-ups globally (Greenlee and Lehmann 1993). Hydrocarbon production from such carbonates in Malaysia occurs in the Central Luconia province, an area extending for some 45,000 km² offshore Sarawak, northwest Borneo (Kosa 2015). About 200 carbonate build-ups of middle and late Miocene age (cycle IV and V) are mapped from seismic (Kosa 2015). Some 60 build-ups are hydrocarbon-bearing, contributing to about 40% of all gas reserves in Malaysia (Ho 1978; Doust 1981; Ali and Abolins 1999). These fields are mature, but gas production is predicted to decline (Wood Mackenzie 2015). However, additional hydrocarbon volumes are suspected in fore-reef talus deposits of these build-ups (Cheong et al. 2017). Reef-talus deposits are linked to reef erosion and formed adjacent to the reef under moderate-to high-energy conditions, preferentially on the windward side (Darwin 1842; Dana 1853; Braithwaite 2014). Talus deposits may have a lateral extent of several meters up to

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several tens of kilometers. Their dimensions and properties are documented for example from Cambrian build-ups in northern Greenland (Ineson and Surlyk 2000), Ordovician carbonates in Norway (Braithwaite and Heath 1992), Devonian carbonates in Australia (Playton et al. 2013), a Permian build-up in the USA (Longley 1999), or Permian-Triassic deposits of the Great Bank in Nanpanjiang Basin (Li et al. 2012). Despite their widespread occurrence, talus and other re-deposited fore-reef deposits are under-sampled in Malaysia. The environments are insufficiently investigated in the Miocene build-ups in Central Luconia, Malaysia. This paper characterizes this under-explored rim to talus section of the Miocene Subis Limestone (Fig. 1) exposed in quarries and compares it with adjacent lagoonal deposits.

Geological setting

Borneo Island, host to the Subis Limestone, formed out of a set of micro-continental fragments (Hall 1996, 2002, 2009a, b, 2011; Hutchison 1989, 2005; Mathew et al. 2014a, b; Mihaljevic et al. 2014; Wilson 2002). Although Borneo is a broad stable island today, it underwent an intense tectonic change in the past, which influenced the architecture of carbonate build-ups (Sorkhabi 2012). During the early Paleocene, rifting around the edges of the Sundaland initiated the formation of regional basins, which resulted in widespread marine deposits in eastern Borneo (Van de Weerd and Armin 1992; Wilson 2002). Carbonate sedimentation was common in the shallow waters bordering these Tertiary basins (Van de Weerd and Armin 1992; Wilson 2002).

The Sarawak Basin is a foredeep basin located at the eastern end of the Sundaland shelf (today's NW part of Borneo),

which is composed of more than 12-km-thick clastic and carbonate deposits, ranging from Late Cretaceous?-Eocene to Recent (Agostinelli et al. 1990; Hutchison 2005). These sediments were subdivided by Ho (1978) into eight cycles from the upper Eocene to Pliocene (Agostinelli et al. 1990). Each cycle is described with a basal transgression followed by a regressive sequence which is then interrupted by the basal transgression of the next cycle (Ho 1978).

Cycle I to cycle III are mainly formed by clastic sediments that filled synrift graben structures during Oligocene to early Miocene times (Agostinelli et al. 1990; Ali and Abolins 1999). Away from the clastic sources in the SW and SE, carbonates grew extensively on the horst structures during cycle I–II, which were covered by widespread argillaceous sediments that put the end of the first carbonate production (Agostinelli et al. 1990; Ali and Abolins 1999). The Subis build-up (Fig. 2) represents one of these carbonate build-ups. During cycles IV–V of middle to late Miocene age, continuous subsidence and the formation of half-graben structures resulted in a second episode of carbonate production at the northern part of the basin in today's Central Luconia province. These carbonates were covered by siliciclastic influx from the SW and SE by the end of the late Miocene to Pleistocene (cycle VI–VIII) (Agostinelli et al. 1990; Ali and Abolins 1999).

Stratigraphy of the Subis Limestone

The Subis build-up is also named “Gunung Subis” by the locals, as “Gunung” refers to a “hill” in the Malay word. It is a massive, cliff-forming limestone hill and hosts the famous Great Niah Caves at the northern flank of the build-up

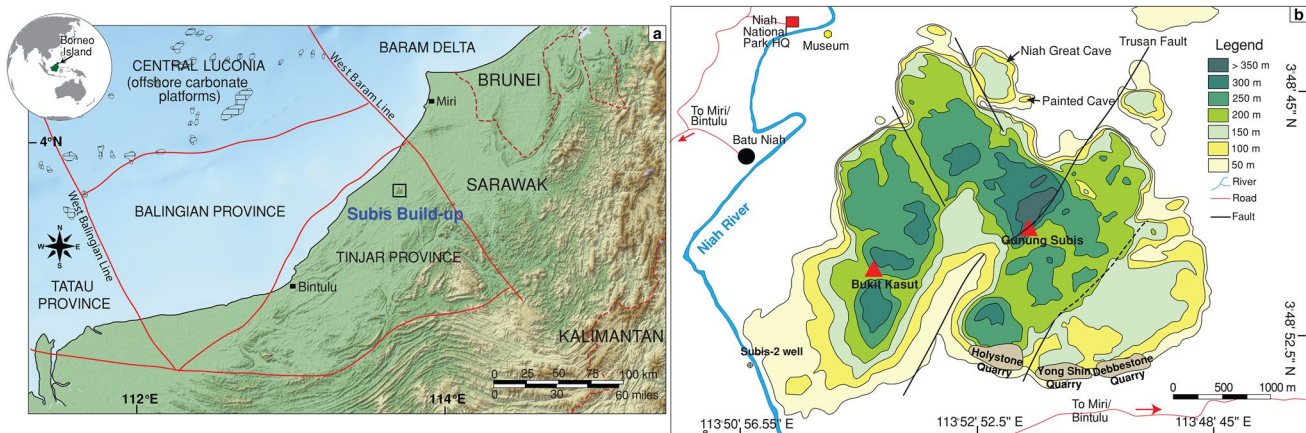


Fig. 1 **a** Location map of Sarawak, East Malaysia, Borneo Island. The Subis build-up is situated in the Tinjar Province. Central Luconia carbonates are located some 110 km northwest of the Subis build-up. **b** Topographic map of the Subis build-up. Two sets of faults cut through the build-up. The major Trusan Fault runs in a northeast–southwest direction and another fault strikes in northwest–southeast

direction. All three quarries, Debbestone, Yong Shin, and Holystone, are located at the edge of the southeastern block and the Subis-2 well located at the western flank of the build-up. The two red triangles show the location of two peaks of the Subis Limestone, Bukit Kasut, and Gunung Subis (adapted and modified from Google Terrain Map, 2016)

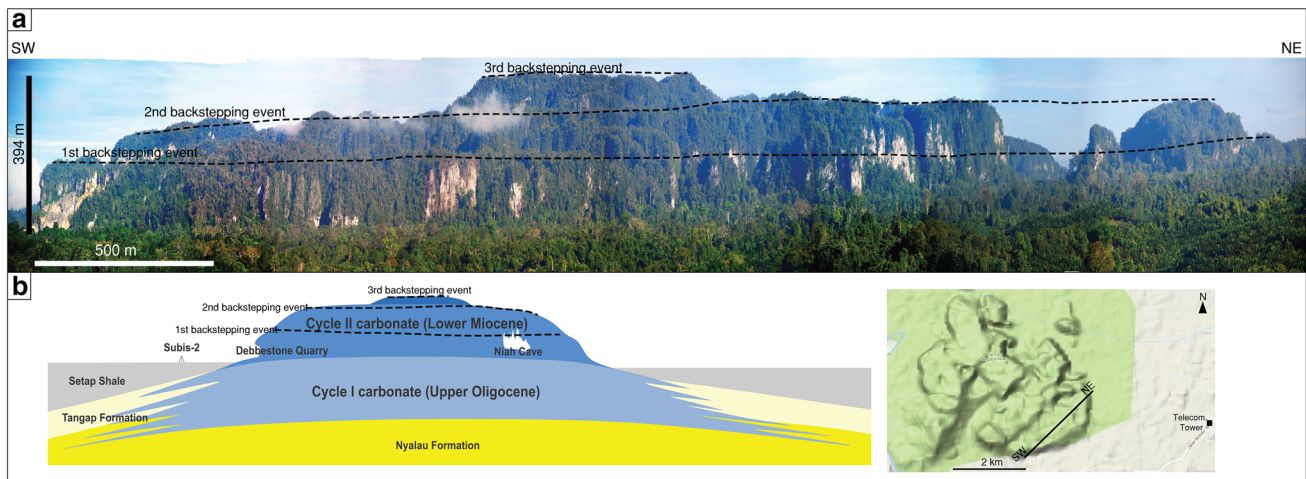


Fig. 2 The architecture of the Subis build-up. **a** View taken from the telecommunication tower at the eastern side, opposite to the Subis build-up. **b** The build-up is surrounded by Setap Shale, interfingering with the Tangap and Nyalau Formations, as shown in the schematic

(Fig. 1a). It extends approximately $5 \times 6 \text{ km}^2$, is 394 m high, and represents an isolated carbonate build-up that developed near the paleo-shelf margin (Wilson 2002).

The stratigraphic succession of the Subis build-up is named the Subis Limestone, which is composed of corals, red coralline algae, and benthic foraminifera, associated with echinoids, bryozoans, mollusks, and sponges (Liechti et al. 1960; Hazebroek et al. 2000; Dedeche 2012). It developed on paleo-high in clear, shallow seawater with normal salinity (Hazebroek et al. 2000; Hutchison 2005) and represents a carbonate build-up in a siliciclastic dominated section. The Subis Limestone is referred to as a member of Tangap Formation by Burr and Crews (1950) and Liechti et al. (1960), which is itself laterally equivalent to part of the wide-ranging but less calcareous Setap Shale. The Setap Shale is a thick clayey section that grades to the southwest into the sandy Nyalau Formation (Liechti et al. 1960; Haile 1962) (Fig. 2). In Brondijk (1962), was working in southernmost Sabah, where he split the Setap Shale into an older unit called the Temburong Formation and the Setap Shale, with a major unconformable boundary, dated as being in the basal part of the Letter Stage Te5 after Liechti et al. (1960), close to the Oligo-Miocene boundary. As noted by Lunt and Madon (2017) this Te4 to T5 boundary unconformity is almost certainly the cycle I to cycle II boundary as defined in unpublished Shell reports, based on biostratigraphy and evidence for dip contrast at the same time.

This widespread Te4 to Te5 unconformity (also noted by Liechti et al. 1960) is an important stratigraphic marker. Previous studies done in the Subis area (Haile 1962; Roohi 1994; Wilson et al. 2013; Lunt and Madon 2017) have found the main body of the Subis Limestone to contain Te5 (basal

cross-section diagram. Three main backstepping events are noticed as the build-up grew inward towards its top (modified from Dedeche 2012)

Miocene) foraminifera, but the mixed series of thin limestones and claystones in the nearby Subis-2 well (Fig. 1b) to be Te4 (Late Oligocene) in age. The Subis-2 well was drilled between 1951 and 1953 on the southwestern flank of the Subis Limestone. A core sample of 3077 m was taken. However, only about 195-m spot cores were retrieved and preserved.

Study area

The Subis build-up is located close to the village Batu Niah, Sarawak, approximately 20 km away from the shore of the South China Sea and about 90 km southwest of the city of Miri. The build-up is situated some 110 km southeast of the offshore gas carbonate fields of Central Luconia (Fig. 1a). Three active quarries are situated at the southern edge of the build-up, named: Debbestone Quarry ($N3^{\circ}46'21.49''$, $E113^{\circ}47'45.42''$), Yong Shin Quarry ($N3^{\circ}46'20.12''$, $E113^{\circ}47'27.14''$), and Holystone Quarry ($N3^{\circ}46'15.67''$, $E113^{\circ}47'12.27''$; Fig. 1b).

The northeast–southwest-trending Trusan Fault cut through the build-up and divided it into two major blocks. The southeastern block was thrust and uplifted, leading to exposure of upper Oligocene deposits adjacent to the Trusan Fault in the Holystone Quarry. A smaller fault lies in between the Holystone Quarry and Yong Shin Quarry separates the older carbonate deposits in Holystone Quarry with the younger carbonate deposits in Yong Shin Quarry and Debbestone Quarry (Fig. 1b). These two quarries (Debbestone Quarry and Yong Shin Quarry) share a continuous outcrop profile that is exposed over some 1000 m. However, this paper focuses on the Debbestone Quarry, located at the southeastern edge of the

Subis Limestone, as the Yong Shin Quarry is not permitted to enter Fig. 3.

Methodology

Fieldwork was carried out from April to May 2016. The outcrop investigated is about 560 m wide and 55–70 m in height, slightly slope at the easternmost area but cliff-surface at the rest of the outcrop. Modern karst-caves are present at the upper level of the quarry. Vertical stratigraphic sections were logged at representative locations across the outcrop to establish facies types and vertical and lateral facies relationships. Forty-five representative samples were obtained from the section exposed at the Debbestone Quarry (Fig. 4). These were used to document the composition of the carbonates in detail: lithology, Dunham texture, grain size (Wentworth 1922), components and their abundancy, and diagenetic features. Outcrop photographs were captured and stitched to give an overview of the Debbestone Quarry. Geometries, stratigraphic relationships, and boundaries were interpreted on these panels. Twenty-nine thin-sections were prepared and petrographically investigated with an Olympus BX51 microscope. J-MicroVision 1.2.7 software was used for point counting by describing 500–600 points in every thin-section to accurately capture the percentage of grains, matrix, cement, and porosity. Foraminifera were determined for a biostratigraphic age control of the layers investigated.

Results

Microfacies types

Eight microfacies types of the Subis build-up are described in Table 1. The outcrop and microfacies photos are shown in Figs. 5 and 6, respectively. The percentage of the grains, matrix, and cement of all the microfacies are shown in Fig. 7. Occurrence of nine benthic foraminifera genera, i.e., *Amphistegina* sp., *Austrotrilina* sp., *Lepidocyclina* sp., miliolid, *Miogypsina* sp., and *Operculina* sp., and occasionally *Discogypsina* sp., *Miogypsinoides* sp., and *Sorites* sp. (Fig. 8), which commonly occur throughout the Subis Limestone in the Debbestone Quarry, are documented by us in this study through the examination of thin-sections. The occurrence of the larger benthic foraminifera of each facies is shown in Fig. 8. The presence of *Miogypsina* sp. (Fig. 8) is the key marker for Letter Te5, basal Miocene age (Haak 1955; Adams 1965; Roohi 1994; Barbeito 2005; Ali 2013).

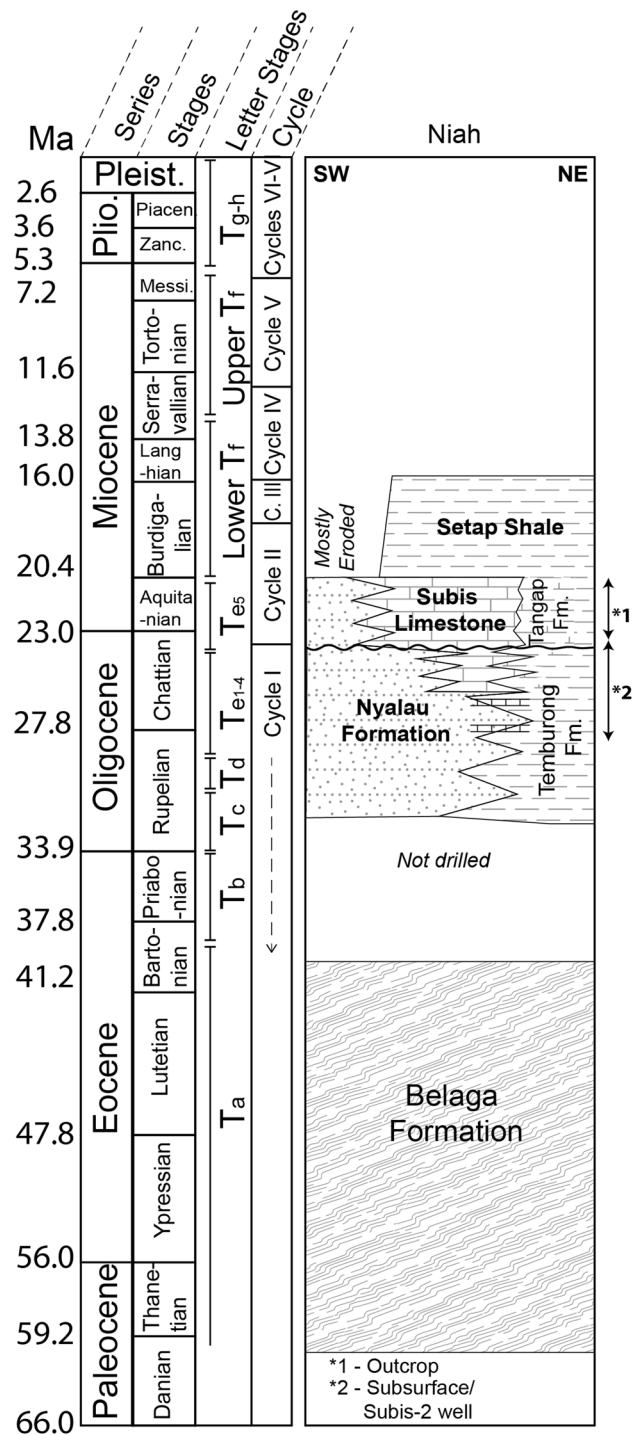


Fig. 3 Chronostratigraphic context of the Subis Limestone, Niah, Sarawak. The age of the Subis Limestone is late Oligocene to early Miocene, equivalent to cycle I–II carbonates in Central Luconia (after Liechi et al. 1960; Hutchison 2005; Wilson et al. 2013; Lunt and Madon 2017)

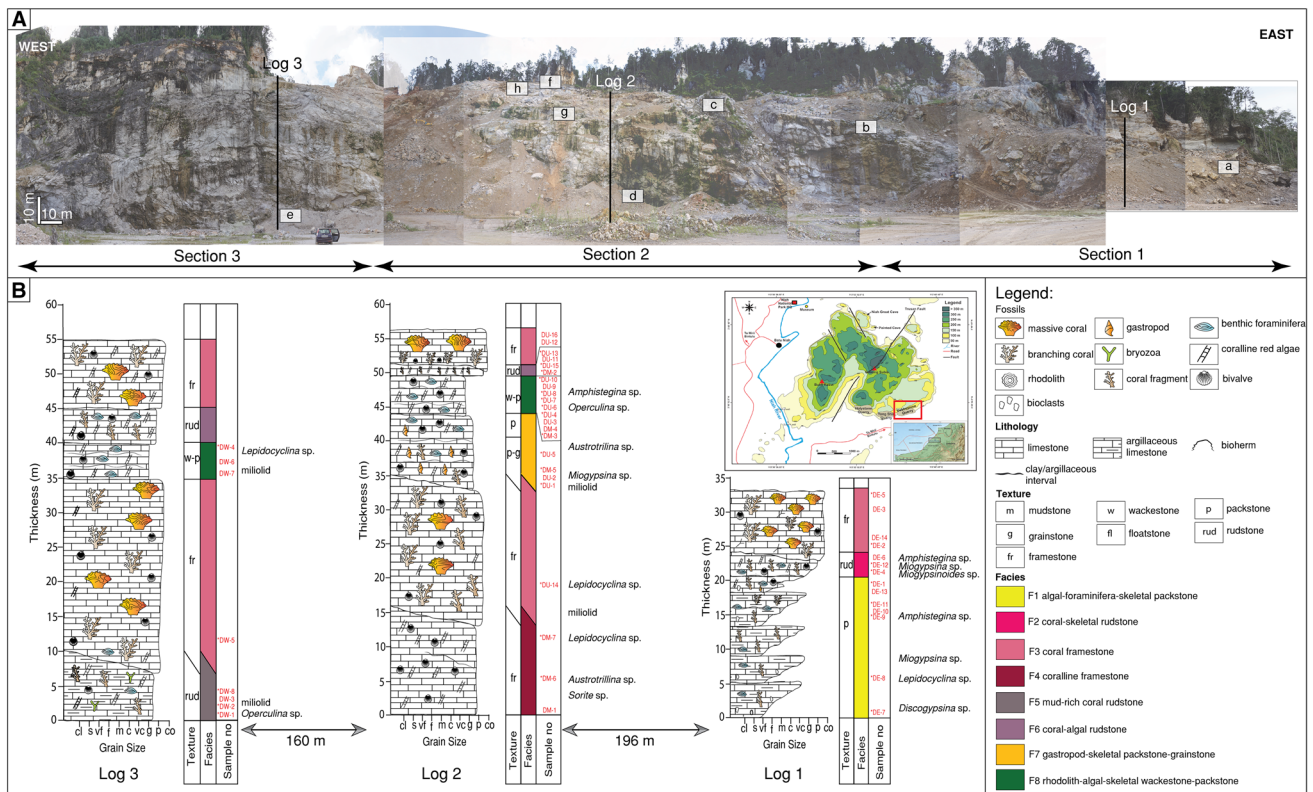


Fig. 4 Sedimentary sequence of the Subis Limestone in the Debbestone Quarry. (A) Three representative sections were described sedimentologically at the eastern, middle, and western parts of the quarry.

a–h in (A) represent the locations of samples. (B) The genera of benthic foraminifera, microfacies, and sampling point were shown in the logs

Discussion

Environment

Four depositional environments have been interpreted from the eight microfacies types of the Subis Limestone. The distribution of the eight microfacies and environments is shown in Fig. 9.

Outer talus

Geometry The microfacies of the outer talus environment consists of algal-foraminifera-skeletal packstone (F1) (Fig. 5a). It is a dark grey to medium-grey, well-cemented limestone with abundant stylolites and solution seams at the bottom. The geometry of the outer talus is characterized by inclined beds with an angle of 10°–15° dipping towards the southeast and can exclusively be observed at the southeasternmost flank of the Subis Limestone (Fig. 9). The overall thickness of this limestone facies is 15–35 m with a lateral extent of some 100 m, thinning out in a southeastward direction. Caves are formed in certain parts of the dipping beds, showing a bedding-independent dissolution of the limestone.

Interpretation This environment is located at a fore-reef environment. The respective deposits represent a mixture of reworked materials from the upper slope in a micritic matrix (Fig. 6a). The components are fragmented and less than 1 cm in size (Fig. 5a). For example, gastropods are less than 1 cm in size in the outer talus but more than 2 cm until 15 cm in the lagoonal environment; coral fragments are about 2 mm in size, but a boulder size of coral colony can be noticed at the reef rim in the outcrop. This environment has the most diverse fauna assemblages of the entire succession exposed in the Debbestone Quarry, indicating a low to moderate water energy in an open-marine condition. Furthermore, the beds show a dipping away from the build-up. The sediment volume as well as the lateral extent of the outer talus deposits seem to be rather small. With a lateral extent of 100 m, it probably does not exceed a few percent of the overall limestone volume. The high amount of micritic matrix (42%) and no porosity preservation in the outer talus deposits suggests poor reservoir properties.

Inner talus

Geometry The microfacies of the inner-talus environment is a coral-skeletal rudstone (F2) (Fig. 6b). It is a pale grey to

Table 1 Description of the eight microfacies types in the Debbestone Quarry

Facies abbrev.	F1	F2	F3	F4
Facies' name	Algal-foraminiferal-skeletal packstone	Coral-skeletal rudstone	Coral framestone	Coralline framestone
Lithology	Limestone	Limestone	Limestone	Limestone
Color	Dark grey to medium grey	Cream to pale grey	Pale grey to medium grey	Pale grey to pale brown
Thickness (m)	~15–35	25–30	~40–60	~15
Sedimentary structures	Inclined beds with an angle 10–15° towards the SE; hard; dense, well cemented and argillaceous	Massive beds; structureless; moderately hard; cemented	Massive beds; structureless; hard; dense; well cemented	Massive beds; structureless; hard; dense; well cemented
Grain size/sorting	Coarse arenite to granule; angular in shape; poorly sorted	Granule to cobble; angular in shape; poorly sorted	Cobble to boulder; angular in shape; poorly sorted	Granule to cobble; angular in shape; poorly sorted
Main components	Coral fragments, coralline algae, larger benthic foraminifera, gastropods, echinoid fragments, bivalves; fragmented	Coral debris, coralline algae, benthic foraminifera, bivalves, echinoid fragments; occasionally sponges (found in outcrop); components are fragmented	Branching and massive corals (in situ, colonial); coralline algae, benthic foraminifera, echinoid fragments, and bivalves	Coralline algae, sometimes benthic foraminifera, bivalves, echinoid fragments, and brachiopods
Texture	Packstone	Rudstone	Framestone	Framestone
Porosity	Poor	Poor	Poor, single vugs	Poor
Water energy	Low–moderate	Moderate–high	High	High
Depositional environment	Outer talus	Inner talus	Reef rim or reef front	Reef rim
Facies abbrev.	F5	F6	F7	F8
Facies' name	Mud-rich coral rudstone	Coral-algal rudstone	Gastropod-skeletal packstone	Algal-skeletal wackestone-packstone
Lithology	Limestone	Limestone	Limestone	Limestone
Color	Pale grey to medium grey	Pale grey to medium grey	Pale grey to cream	Pinkish to cream
Thickness (m)	5–8	5	5–8	5
Sedimentary structures	Massive beds; structureless; hard; dense; cemented	Massive beds; structureless; moderately hard; cemented	Massive beds; structureless; moderately hard to soft; sometimes cemented	Horizontal beds; structureless; soft and less dense; solution seams are common
Grain size/sorting	Granule to cobble; angular in shape; poorly sorted	Granule to cobble; angular in shape; poorly sorted	Granule to pebble; angular in shape; poorly sorted	Coarse arenite to granule; angular to subangular in shape; moderate to well sorted
Main components	Branching and massive coral debris, coralline algae, benthic foraminifera, bivalves; occasionally echinoid fragments, brachiopods, ostracods (in thin-section) and bryozoans (found in outcrop); components are fragmented	Branching and massive coral debris, coralline algae (articulate and non-articulate), benthic foraminifera, bivalves; occasionally gastropods and echinoid fragments	Gastropods, coralline algae, bivalves, benthic foraminifera, coral fragments, echinoid fragments, brachiopod fragments and ostracods (in thin-section); components are fragmented	Coralline red algae, echinoid fragments, benthic foraminifera, coral fragments, and bivalves
Texture	Rudstone	Rudstone	Packstone	Wackestone-packstone
Porosity	Poor	Poor	Poor	Poor
Water energy	Moderate	Moderate–high	Moderate	Low–moderate
Depositional environment	Protected reef rim, reef front?	Shallow lagoon	Shallow lagoon	Lagoon, probably deeper lagoonal environment

medium-grey, sometimes beige, well-cemented limestone. The geometry of this facies is characterized by a massive bed with no visible sedimentary structures within the beds, which show a slightly inclined bedding angle of less than 5°. The area of this environment is ~25–30 m thick and ~60 m laterally, located at the eastern part of the outcrop (Fig. 9).

Interpretation This environment is located at a shallow and proximal fore-reef/inner talus that formed seawards of the reef rim. The deposits are mainly composed of grainy sediments that accumulated under moderate- to high-energy conditions. Coral debris are large in size, up to 35 cm (Fig. 5b), transported not far from the reef rim. The pores within the skeletal components such as coral debris and bivalves are filled by carbonate mud, while the aragonitic wall of these components are replaced by calcite cement through neomorphism process. This leads to poor porosity preservation and thus poor reservoir quality.

Reef rim

Geometry The microfacies of the reef rim environment consists of coral framestone (F3) (Fig. 6c), coralline framestone (F4) (Fig. 6d), and mud-rich coral rudstone (F5) (Fig. 6e). These facies are pale to medium grey limestone with the thickness of a single bed of about 20 m or more. The beds are massive and structureless, but occasionally 5 mm to 1-cm-thick lamination is noticed. It covers the largest part of the outcrop with a lateral extent of 400 m and a vertical thickness of 40–70 m, is located at the middle to western part of the Debbestone Quarry, and extends to the next quarry in the west, the Yong Shin Quarry (Fig. 9). The border between the reef rim and lagoon is not clear in the outcrop. However, sharp changes of components and sedimentary structures are noticed, indicating the border is not in a straight line but rather an undulating boundary across the outcrop.

Interpretation Rock of this environment is composed of in situ grown branching (Fig. 5e) and massive corals (Fig. 5c) and coralline algae (Fig. 5d). The calcified red algae are common in shallow-water environments where they can build up small knolls (Bucur et al. 2008; Granier et al. 2008). The existence of miliolid foraminifera, *Sorites* sp., *Lepidocyclina* sp., *Amphitesgina* sp., and *Operculina* sp., indicate a protected area and a reef or near-reef environment (Adams 1965; Sleumer 1977; Ali and Abolins 1999; BouDagher-Fadel 2008). The in situ growth of branching and massive corals formed an approximately 60-m-thick biohermal structure with a lateral extent of several hundred meters. All the existing components are interpreted as pro-

tected reef setting with moderate water-energy conditions. Pores originally present within individual corals fragments are filled with carbonate mud. A high amount of micritic matrix (44–54%), especially at the bottom part of the outcrop, suggests a poor reservoir potential.

Lagoon

Geometry The microfacies of the lagoonal environment consists of coral-algal rudstone (F6), gastropod-skeletal packstone (F7) (Fig. 6g), and algal-skeletal wackestone-packstone (F8) (Fig. 6h). These rocks are pale grey to beige, horizontally bedded, and relatively soft limestone. This facies occurs predominantly in the upper middle part of the Debbestone Quarry. The thickness is about 10–15 m with a lateral extent of about 100 m (Fig. 9), sitting on top of reef rim deposits. Within the interval, a circa 1–3-m-thick horizontally bedded layer can be observed, which contains abundant gastropods. No porosity was observed in outcrops or in thin-sections.

Interpretation The abundance of large, well-preserved gastropods (Fig. 5g) with up to 15 cm in size, associated with other components such as bivalves, echinoderm plates and spine fragments and some reworked coral and coralline red algae fragments (Fig. 5h), indicates a lagoonal environment near the reef. A very thin layer of coral-algae facies was found at the top of the quarry, which probably shed off from the rim from the inner part of the build-up.

Implication of microfacies and reservoir potential

Eight microfacies were interpreted ranging from distal outer- to inner talus deposits to a proximal reef rim and lagoonal deposits. In general, the Subis Limestone is a grain-supported limestone, with about 45–70% of grains. The highest grain contents are developed in facies F2, which is mainly composed of coral debris, coralline algae, and benthic foraminifera. The amount of mud matrix is high in all facies (38–54%); except for facies F2 and F3, which show 25–26%. In contrast, the highest amount of sparitic cement can be observed in facies F3, with approximately 20%. Low percentages of sparite cement with less than 5% are present in facies F2 and F7. A comparison between the percentages of the components among all the facies is shown in Fig. 7.

The Subis Limestone is a tight limestone with rare or no observed pore spaces. All fractures that could be related to the uplift of the build-up are filled by calcite cement, probably due to the exposure to meteoric waters. However, enhanced dissolution is observed in the lower stratigraphic layers, resulting in the formation of caves. These caves are

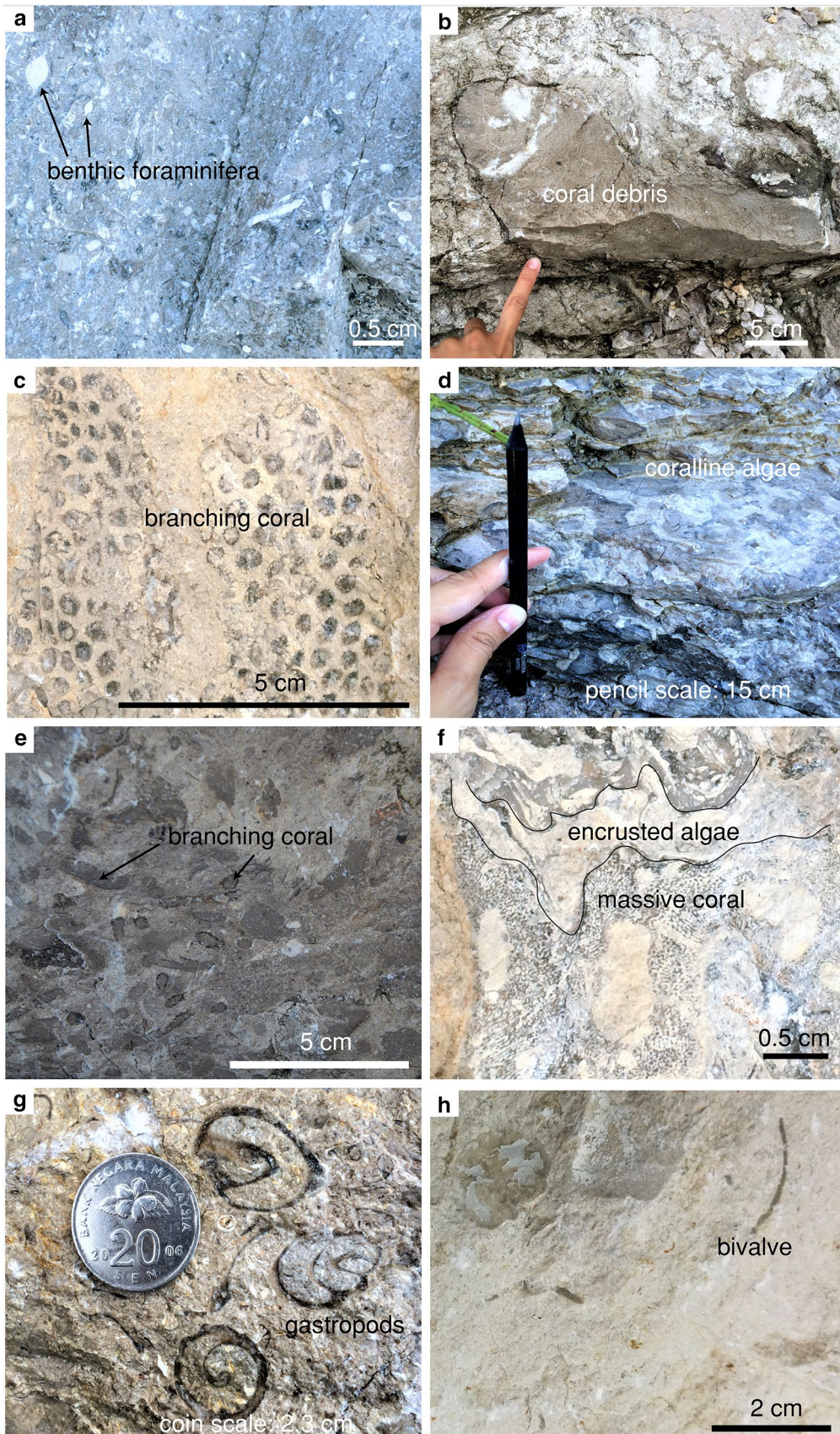


Fig. 5 The outcrop photos show the facies of the Subis Limestone. The locations of the photos are shown in Fig. 4. **a** (F1) Algal-foraminiferal-skeletal packstone, **b** (F2) coral-skeletal rudstone, **c** (F3) coral framestone, **d** (F4) coralline framestone, **e** (F5) mud-rich coral rudstone, **f** (F6) coral-algal rudstone, **g** (F7) gastropod-skeletal packstone and **h** (F8) algal-skeletal wackestone-packstone

subterranean sinkholes which cut across bedding planes and fractures, forming a deep-vertical karst system. No dolomite was observed in the outcrop, and only minor amounts in thin-section in outer talus deposits (F1).

Comparing the textures observed in the outcrops and thin-sections, a transition from more argillaceous outer-talus packstone dominated by benthic foraminifera and coralline algae (F1) to grainy, coral debris-rich inner talus rudstone (F2), and coral rud- and framestone (F3, F4, F5) representing reef rim deposits is observed. Lagoonal deposits show a grainy packstone-rudstone texture indicative of a shallow lagoonal facies, i.e., (F6) coral-algal rudstone and (F7) gastropod-skeletal packstone. Mud-dominated deeper lagoonal facies consists of algal-rich wacke- to packstone (F8).

The talus deposits are composed of inclined beds dipping away from the build-up in an angle of 10° – 15° . Close to the rim they are composed of rather coarse-grained coral debris that passes into muddier facies with smaller coral debris. Talus deposits at ~20–60 m from the reef rim are observed. The deposits consist of poorly sorted angular grains indicative of inadequate reservoir quality.

Deposits of the reef rim are influenced by the early sedimentation and later neomorphism that occurred in the corals. The original pore spaces from the coral cavities (intraparticle pores) are normally filled by carbonate mud. Rarely, the original framework porosity is preserved. Additionally, the aragonitic walls of corals have been dissolved and the moulds were filled by calcite cement. Consequently, a high permeability must be assumed for reef rim deposits. They could possibly act as a conduit for fluid-flow in the subsurface.

Lagoonal facies are basically characterized by horizontally bedded rocks. They mainly consist of gastropods, skeletal debris, and coralline algae. The original pore spaces within gastropods and bivalves are filled with carbonate mud; shells are dissolved and filled by calcite cements. This suggests poor reservoir quality despite having a grain-dominated packstone texture. If the deposits are high in grain content (e.g., rudstone, packstone) and considering the absence of the recrystallization of the secondary porosity, some reservoir potential can be assumed in inner talus and lagoonal deposits.

Depositional sequence

The Debbestone Quarry described in this work is the lowermost sequence of the early Miocene Subis build-up. The overall architecture of the Subis build-up shows three backstepping events (Fig. 2) as the carbonates retreat inwards towards the center of the build-up. The size of the build-up decreases from the first sequence with $5 \times 6 \text{ km}^2$ to $4 \times 3 \text{ km}^2$ in the second and about $1 \times 1 \text{ km}^2$ in the third sequence. This is probably related to a rapid flooding. The Subis build-up is ultimately covered by hemi-pelagic sediments, the Setap Shale.

In summary, the lowermost succession in the quarry is interpreted as representing a shift of the depositional environment from the outer reef to the reef core, followed by gastropod-rich lagoonal facies. The bottom part of the quarry is dominated by coralline algae, which passes rapidly into coral framestone (Fig. 9a). Changes in coral morphology can be observed: in the lower part of Sects. 2 and 3 (Fig. 9), mostly in situ small branching corals (~10–25 cm) are replaced upwards increasingly by massive corals (more than 80 cm), which are additionally and increasingly coated by coralline red algae, with changes of water depths from a deeper to shallower water level.

Laterally, from Sects. 1–2 (Fig. 9), a transition from argillaceous limestone, containing branching coral debris and larger benthic foraminifera, is followed by coralline algae-rich layers and massive beds of branching and massive corals. This massive coral framestone unit is overlain by horizontally bedded gastropod- and algal-rich layers (Fig. 9a). On top of the lagoonal deposits, a 10-cm-thick, brick-red layer is observed across the entire outcrop. It is interpreted as terra rossa, a product of carbonate weathering, and thus as a sequence boundary.

Above the terra rossa layer, inclined beds composed of massive coral rud- and framestone are observed (Fig. 9). The orientation of corals within the beds and the overall architecture suggests that these components are transported from the upper and inner part of Subis build-up. They can be found on top of all three sections and are likely related to the backstepping of the following sequence and thus derive from the inner part of the Subis Limestone, which cannot be reached in quarry outcrops.

Conclusions

1. The Subis Limestone consists of a fossiliferous, grain-supported limestone with an average of 45–70% grains in a micritic matrix of arenitic to boulder size.
2. The limestone is predominantly composed of massive and branching corals, coralline red algae, benthic

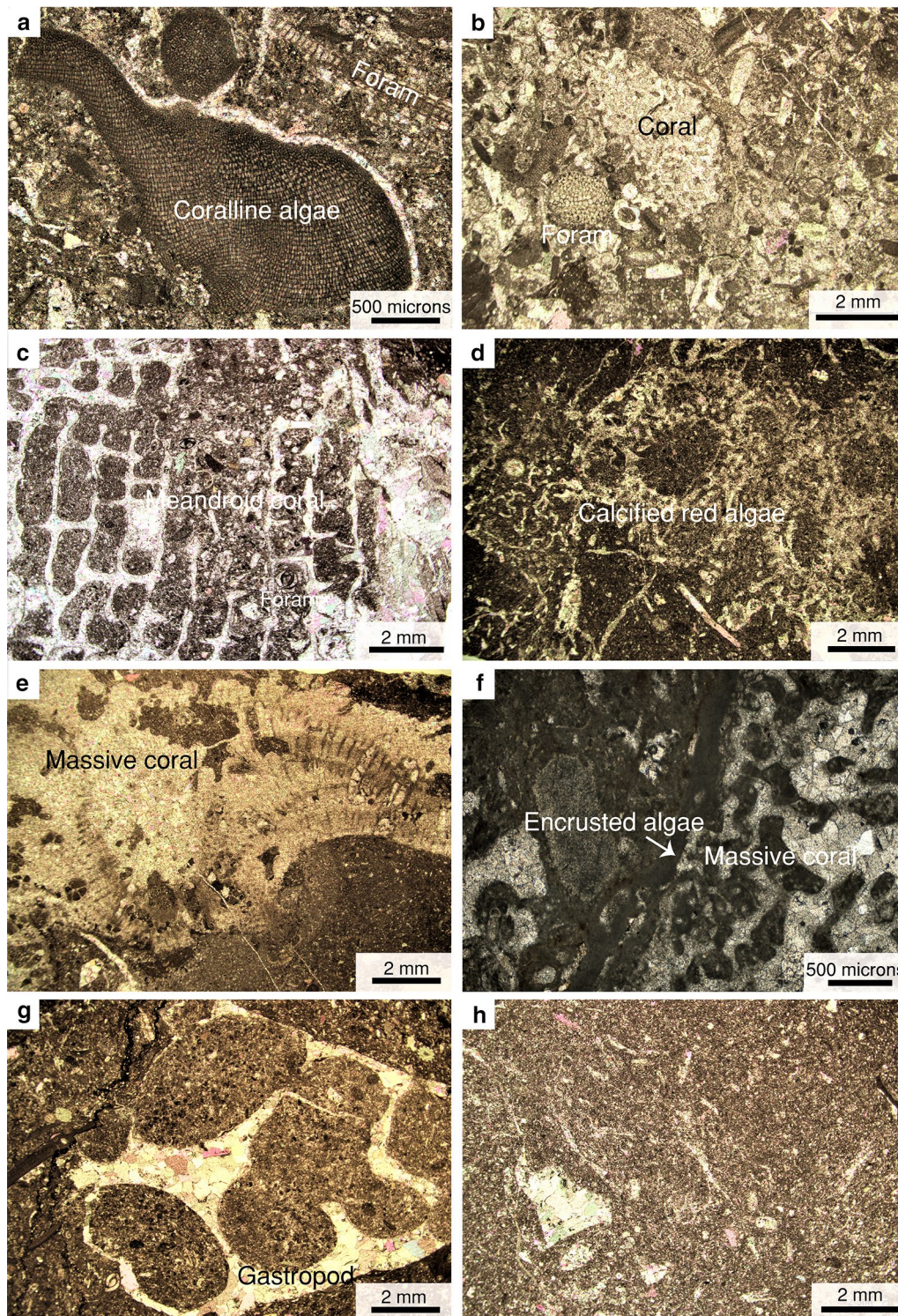


Fig. 6 Microphotographs of each of the facies. All the microphotographs were taken in cross-polarized light (XPL). **a** Sample DE-1: (F1) algal-foraminiferal-skeletal packstone. The components are generally fragmented in a micritic matrix. **b** Sample DE-4: (F2) coral-skeletal rudstone. This facies is grainy and slightly less in micritic contents compared to facies F1. **c** Sample DU-14: (F3) coral framestone. The walls of meandroid corals are filled with calcite cements. **d** Sample DM-6: calcified red algae in (F4) coralline framestone

facies. **e** Sample DW-8: (F5) mud-rich coral rudstone. Mud-supported limestone that contains massive coral debris. **f** Sample DU-13: (F6) coral-algal rudstone. Massive coral encrusted by red algae. **g** Sample: DM-5 (F7) gastropod-skeletal packstone. Abundant gastropods in a micritic matrix. **h** Sample DU-10: (F8) algal-skeletal wackestone-packstone. This facies is generally composed of bioclastic fragments in a micritic matrix

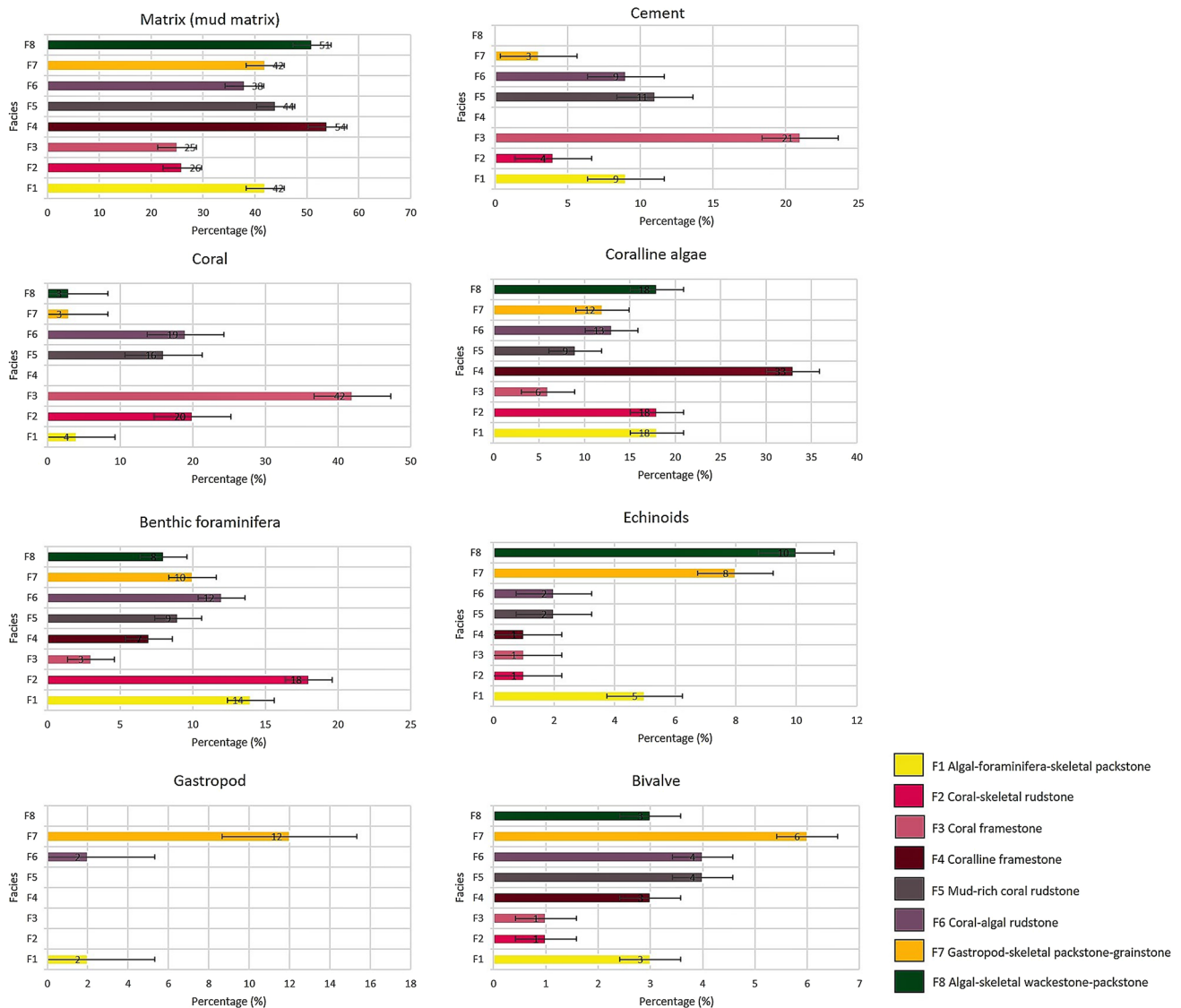


Fig. 7 Percentages of grains, matrix, and cement in all facies. The percentage of the mud matrix is high in all facies, except for F2 and F3. Coralline algae, benthic foraminifera, echinoids, and bivalves are found in all eight microfacies. Corals or coral debris/fragments occurred in all the facies except for F4. Gastropods are rare in F1 and

F6, abundance in F7, and no found in other microfacies. Note: The number shown in the bar chart is the percentage of each facies that total up to 100. (For the percentages of the components in each thin-section, see repository data)

foraminifera, bivalves, gastropods and occasional echinoids, bryozoans, ostracods, sponges, and brachiopods.

- The limestone is subdivided into eight microfacies types and four environments were interpreted: inner and outer talus, reef rim, and lagoon.
- The talus deposits are tens of meters thick, ~ 160 m wide; consist of inclined beds and are predominantly composed of fragmented, finer to coarser skeletal debris from outer to inner talus. Primarily aragonitic components were replaced by calcite, which suggests a poor reservoir quality.

- The reef rim is the only part of the build-up composed of in situ corals. The aragonitic walls of corals are replaced by calcite and the porosity is low.
- The lagoonal deposits consist of horizontally bedded rocks, grain-dominated packstone texture with abundant centimeter-scale gastropods, coralline red algae, and benthic foraminifera with a poor reservoir potential as most of the porosity has been filled either by micrite or calcite cement.

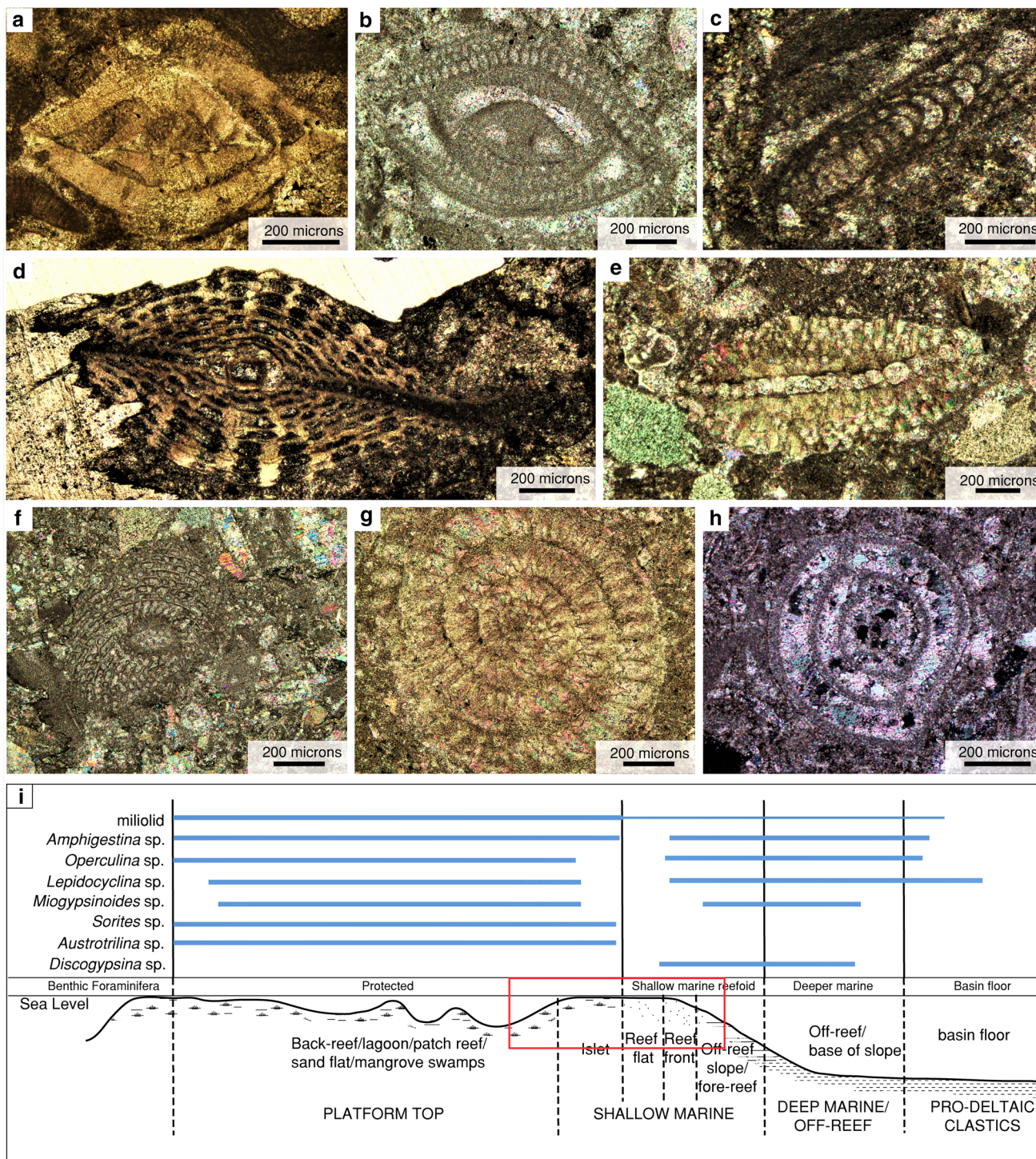


Fig. 8 The occurrence of benthic foraminifera documented in the Subis Limestone at Debbestone Quarry. **a** Sample DE-9: *Amphigestina* sp., **b** sample DU-1 *Austrorilina* sp., **c** sample DE-1: *Discogypsina* sp., **d** sample DM-7: *Lepidocyclina* sp., **e** Sample DE-4: *Miogypsina* sp. **f** sample DM-1: *Sorites* sp., **g** sample DW-2: *Operculina*

sp., **h** sample DU-1: miliolid, **i** the depositional environment of the benthic foraminifera (adapted from Ali and Abolins 1999). These benthic foraminifera indicate shallow-marine reefoid, from fore-reef to protected back-reef environments (red rectangle)

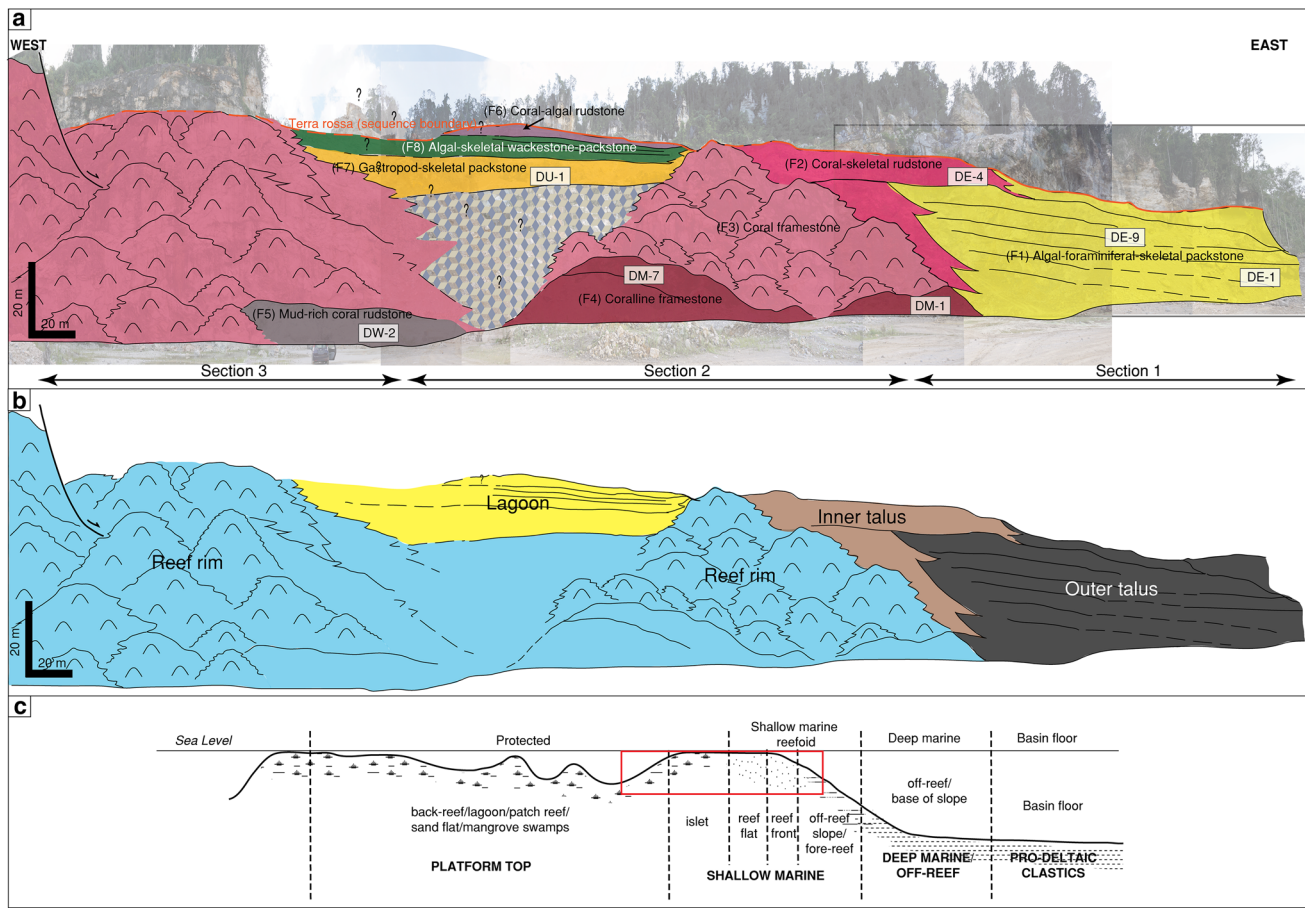


Fig. 9 a Distribution of the eight microfacies of the Subis Limestone in the Debbestone Quarry, Sarawak. The western and central parts of the outcrop are dominated by coral framestone. Towards the east, a transition to coral-skeletal rudstone and algal-foraminiferal-skeletal packstone can be observed. In the upper part of the outcrop, gastropod-skeletal packstone is followed by blocks of coral-algal rudstone.

A thin reddish layer (orange line) was interpreted as terra rossa. **b** The interpreted environments in the Debbestone Quarry outcrop: outer and inner talus, reef rim, and lagoon. **c** A schematic cross section of the Subis-build-up. The red rectangle shows the depositional environments observed in the Debbestone Quarry. The environment chart is adapted from Ali and Abolins (1999)

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