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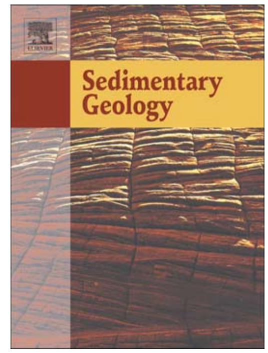

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Unravelling the depositional origins and diagenetic alteration of carbonate breccias

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Abstract

Carbonate breccias dissociated from their platform top counterparts are little studied despite their potential to reveal the nature of past shallow-water carbonate systems and the sequential alteration of such systems. A petrographic and stable isotopic study allowed evaluation of the sedimentological and diagenetic variability of the Cenozoic Batu Gading limestone breccia of Borneo. Sixteen lithofacies representing six facies groups have been identified mainly from the breccia clast on the basis of shared textural and compositional features. Clasts of the breccia are representative of shallow carbonate platform top and associated flank to basinal deposits. Dominant inputs are from rocky (karstic) shorelines or localised seagrass environments, coral patch reef and larger foraminiferal-rich deposits. Early, pre-brecciation alteration (including micritisation, rare dissolution of bioclasts, minor syntaxial overgrowth cementation, pervasive neomorphism and calcitisation of bioclasts and matrix) was mainly associated with marine fluids in a near surface to shallow burial environment. The final stages of pre-brecciation diagenesis include mechanical compaction and cementation of open porosity in a shallow to moderate depth burial environment. Post-brecciation diagenesis took place at increasingly moderate to deep burial depths under the influence of dominantly marine burial fluids. Extensive compaction, circum-clast dissolution seams and stylolites have resulted in a tightly fitted breccia fabric, with some development of fractures and calcite cements. A degree of facies-specific controls are evident for the pre-brecciation diagenesis. Pervasive mineralogical stabilisation and cementation have, however, led to a broad similarity of diagenetic features in the breccia clasts thereby effectively preserving depositional features of near-original platform top and margin environments. There is little intra-clast alteration overprint associated with subsequent clast reworking and post-brecciation diagenesis. The diagenetic-, and to an extent depositional- and clast-characteristics of the Batu Gading deposits are diagnostic of breccia origins. The predominance of: early and pervasive stabilisation of calcitic components, pervasive compaction resulting in a fitted texture, and paucity of meteoric dissolution or cementation effects are collectively all indicators of slope deposition and lithification. These features are comparable with other regional and global examples of submarine slope breccias, and consistent with the prior interpretation that the carbonate platform at Batu Gading developed in a rotating wedge-top basin (Wannier, 2009). The results of this study, along with regional analogues, suggest the potential for reworked carbonates debris in slope settings to be a viable way of investigating carbonate platform variability and their subsequent alteration in the absence of preserved platform top or margin deposits.

Key Words: Cenozoic carbonate platform, carbonate slope breccia, diagenesis, facies, SE Asia, Batu Gading Limestone

1. Introduction.

Carbonate breccias have multiple and highly varied origins, including: submarine slope deposits, subaerial talus deposits, karstic cavern collapse breccias, intra-formational breccias associated with accommodation generation in underlying units (e.g., evaporite dissolution) and fault breccias (e.g., Cook and Enos, 1977; Hopkins, 1977; Crevello and Schlager, 1980; James, 1981; Braithwaite and Heath, 1992; Friedman, 1997; Spence and Tucker, 1997; Blendinger, 2001; Sanders, 2010; Ferry et al., 2014; Udchachon et al., 2014; Quijada et al., 2014). Where carbonate breccias co-occur with their associated platform deposits the origins of the breccias are commonly evaluated (e.g., Crevello and Schlager, 1980; Wilson et al., 2012; Udchachon et al., 2014; Reijmer et al., 2015). Carbonate breccias that are, however, dissociated from platform deposits although common in the rock record have received little detailed study. The aim here is to evaluate what can be inferred about past carbonate platforms and their subsequent alteration from isolated breccia units that may be the only remaining or preserved record of coeval platform environments that are now hidden, metamorphosed, eroded or tectonised (McIlreath and James, 1978; Conglio and Dix, 1992).

Carbonate breccias have the potential to provide insights into the nature of past shallow water carbonate systems and their deposits, together with subsequent alteration both pre- and post-breccia forming processes (cf., McIlreath and James, 1978; Wilson and Bosence, 1996; Wilson et al., 2012; Madden and Wilson, 2013). In particular for carbonate breccias that lack their platform counterparts, such breccias offer the only opportunity to develop an understanding of the controlling influences affecting platform development of otherwise unavailable systems, as well as breccia origins and subsequent basin evolution. The question that is addressed here is “what can be learned and inferred from a carbonate breccia?” In this study a petrographic and geochemical investigation of carbonate breccia variability from the Batu Gading Limestone is presented. The Batu Gading limestone deposits are Late Eocene to Late Oligocene carbonates from the NW Borneo, SE Asia (Adams, 1965; Ngau, 1989; Wannier, 2009).

The hypotheses tested here are that: (1) in the absence of platform top or margin deposits inferences about both the facies variability and depositional conditions in these areas will be possible from the breccia clasts, (2) the early diagenetic signature of variable platform deposits can be preserved in reworked clasts and potentially vary from that subsequently affecting the breccia, and (3) the combined sedimentological and diagenetic characteristics of the breccia will allow the origins of the breccia to be evaluated. The results of this study offer insights into reconstructing: a "lost world" of shallow carbonate systems and their alteration, together with better understanding the origins and diagenesis of limestone breccias. The study also contributes to the understanding of diagenesis and development of carbonate systems in humid equatorial and tropical environments as well as the development of carbonates in tectonically complex settings of SE Asia. Insight from this work may contribute to the study of regional analogues elsewhere.

2. Geologic setting.

The northwest margin of Borneo has a complex Cenozoic tectonic history (Hall, 1996; 2002; Hutchinson, 2005; Hall et al., 2011; Wilson et al., 2013). During the Paleogene the area comprised a mosaic of thinned crust and/or microcontinental fragments originated from Indochina and South China and positioned to the north of the proto-South China Sea oceanic crust (Hall, 1996; Hall and Nichols, 2002; Wannier, 2009; Mihaljević et al., 2014). During the Eocene to Miocene the tectonically active NW Borneo margin included localised carbonate platforms developed along the clastic-dominated shelf (Adams, 1970; Hutchinson, 2005; Wannier, 2009; Wilson et al., 1999; 2013). The active margin was characterised by subduction of the proto-South China Sea oceanic plate under the northern margin of the Kalimantan Block producing the Rajang accretionary prism (Hall, 1996; Hutchinson, 1996; Wannier, 2009). In the Mid-Eocene, slab pull is inferred to have resulted in the southwards movement and subsequent docking of microcontinental blocks with the Rajang accretionary prism on the northwest Borneo margin (Hall, 1996; Hutchinson, 1996; 2005; Wannier, 2009). The Paleogene Batu Gading Limestone is interpreted as a partial time equivalent to the nearby Eocene to Early Miocene Melinau Limestone (Adams and Haak, 1962; Adams, 1970; Wilson et al., 1999; Wilson, 2002). These carbonate systems are thought to have formed in shallow marine wedge-top basins (DeCelles and Giles, 1996; Ingersoll, 2012) that began forming during the Eocene on submerged areas of the Rajang accretionary prism (Hutchinson, 2005; Wannier, 2009). The development of the wedge-top basins was likely structurally controlled over growing thrust faults in the accretionary prism and/or associated with the gravitational deformation of the prism and its sedimentary cover (Wannier, 2009). Continued stratal rotation in the wedge-topped basins from the Late Eocene to Early Miocene produced asymmetric accommodation space partially infilled by near-clean carbonates (Wannier, 2009).

The Batu Gading Limestone is an informal name given to several carbonate bodies outcropping along the Baram River approximately 80 km to the southeast of Miri, Sarawak, and has been included as part of the Melinau Limestone Formation (Fig. 1; Adams and Haak, 1962; Haile, 1962; Abdullah and Yaw, 1993; Wannier, 2009; Wilson et al., 2013). The Batu Gading Limestone has an angular unconformable contact with the underlying Cretaceous turbiditic Kelalan Formation (Adams and Haak, 1962; Haile, 1962; Ngau, 1989; Abdullah and Yaw, 1993). The Batu Gading Limestone dips northward at 12-15° (Hutchinson, 2005; Wannier, 2009) and consists of a transgressive sequence of sandy limestones to massive limestones: the latter 35-40 m thick with abundant larger benthic foraminifera (*Pellatispira, Discocyclina* and *Nummulites*) that are indicative of a Late Eocene age (East India Letter Classification: Tb; Adams and Haak, 1962; Adams, 1965; Abdullah and Yaw, 1993; Wannier, 2009). Unconformably overlying the Late Eocene Batu Gading massive limestone is a limestone breccia with a thickness of approximately 10 m and with an associated ~8 m of calcarenites and sandy limestone (Fig 2a; Wannier, 2009). The breccia deposits are recognised as Late Oligocene in age on the basis of the larger benthic foraminifera *Eulepidina spp.*, *Heterostegina borneensis* and *Miogypsinoides spp.* (the latter present in the upper calcarenites; Abdullah and Yaw, 1993; Wannier 2009). The Batu Gading Limestone is overlain by the deep marine Temburong Formation. The exact mechanism that led to formation of the Batu Gading limestone breccia is unknown. Most authors comment on the significant hiatus between the upper Late Oligocene brecciated part of the Batu Gading Limestone and the underlying Late Eocene limestones, with localised evidence of karstification associated with the hiatal surface, but do not comment on breccia origins (Adams and Haak, 1962; Adams, 1965; Leichti et al., 1960; Abdullah and Yaw, 1993). Wannier (2009) inferred for the Batu Gading breccia that, consistent with the Melinau basin, differential loading by fresh sediments maintained rotation of the thrusted part of the wedge-top basin leading to local reworking down-dip as well as incorporation into the wedge-top basin. While the structural development of the Batu Gading Limestone is postulated in Wannier (2009) and the foraminiferal stratigraphy of the deposits also outlined (Adams and Haak, 1962, Adams, 1965; Abdullah and Yaw, 1993), this is the first detailed account of the sedimentology and diagenesis of these deposits.

3. Methods.

Thirty-two samples, representing 27 breccia and five un-brecciated samples of the Batu Gading Limestone were collected and studied petrographically, the former including analysis of 134 individual breccia clasts. Lithological components, microfacies, diagenetic phases and the relative timing of diagenetic events were determined through thin-section petrography (Appendix 1). The relative abundance of components was determined quantitatively through point counting of ~30,000 points. Individual breccia clasts or the five unbrecciated samples were counted until percentages of components had reached an equilibrium (i.e., no more variance in relative component abundances with an increasing number of counted points was observed, and a minimum of 100 points had been reached). For most samples or clasts, reaching an equilibrium required counting 200-300 points, some clasts required up to 600 points (Appendix 1). The palaeoenvironmental context of these deposits was determined through assessment of: (1) diagnostic benthic foraminifera, their morphologies and/or their abundance with respect to planktonic foraminifera, (2) the presence and preservation of coralline algae, (3) the overall bioclastic assemblage, their degree of fragmentation and abrasion, and (4) lithological textures and degree of sorting (cf. van Gorsel, 1988; Beavington-Penney and Racey, 2004). Petrographic data together with field observations have been utilised to generate facies descriptions (Table 1) and a depositional model for the Batu Gading Limestone. Facies nomenclature follows the textural classification of Dunham (1962), modified by Embry and Klovan (1971), with components given in lithofacies names where they exceed 15% of the sample, or 5% for typically rare or minor, yet important, allochems (e.g., planktonic and smaller benthic foraminifera (such as miliolids), echinodermata and peloids). Age assignments following previous foraminiferal studies of the Batu Gading Limestone were through comparison with the modified East India Letter Classification for larger benthic foraminifera (van der Vlerk and Umbgrove, 1927; Adams, 1965; 1970; Abdullah and Yaw, 1993; Lunt and Allan, 2004), correlated against the 2004 geological timescale of Gradstein et al.. The relative abundance of diagenetic phases was recorded semi-quantitatively through visual estimates (Appendix 1; Mazzullo and Graham, 1988). Nomenclature for carbonate cement morphologies and other diagenetic features follows Flügel (2004).

Stable-isotope analysis ($\delta^{18}O$ and $\delta^{13}C$) was undertaken on twenty-six samples micro-drilled from the rock off-cut counterparts of the thin-sections. Drilling sites correspond to a range of depositional and diagenetic features identified in plane-light. Drilled samples include calcite crystals of potential neomorphic and/or pore filling cement origin, fracture filling cement, bioclasts and areas of matrix. Oxygen and carbon isotope analyses were run on a GasBench II system coupled online to a Delta XL stable-isotope-ratio mass spectrometer in continuous flow (Paul and Skrzypek, 2007). A three point normalisation was used to reduce raw values to the international scale (Skrzypek, 2013), with normalisation based on L-SVEC, NBS-18 and NBS-19 standards and reported relative to V-PDB (Coplen et al., 2006). External errors for $\delta^{18}O$ and $\delta^{13}C$ V-PDB were <0.15‰ and <0.1‰, respectively.

4. Facies classifications and depositional environments.

Sixteen lithofacies have been identified from combined petrographic analyses and field observations of samples from breccia clasts and unbrecciated sites (see also section 5). These lithofacies have been grouped into six facies groups on the basis of shared textural and compositional characteristics linked to environmental conditions (Table 1). The breccia samples contain clasts of various sizes, and facies groups (134 individual clasts; Appendix 1). Although depositional environments are inferred spatial relationships between original depositional environments are not suggested here due to an absence of spatial outcrop data. The clasts preserved in the Batu Gading limestone breccia dominantly represent a Late Oligocene platform margin setting, with few clasts representing the underlying Late Eocene massive limestone deposits. Facies classifications and interpretations of depositional environments are outlined below.

4.1 Planktonic Foraminifera Facies Group.

The Planktonic Foraminifera Facies Group contains common, well-preserved, planktonic foraminifera (8-14% of the total rock volume (T.R.V); on average (av.) 45% of all bioclasts present) in mud-wackestones, wacke-packstones and pack-grainstones. The micritic matrix component of this facies group ranges from 47 to 69% T.R.V. This facies group also contains common whole and fragmented shallow marine bioclasts, predominantly: coralline algae, perforate larger and smaller benthic foraminifera and less common corals. A Late Oligocene age (Te1-4) is interpreted for these deposits on the basis of common Lepidocyclinids including *Eulepidina spp.* (cf. Adams and Haak, 1962; Adams, 1965; Wannier, 2009). The abundance of micrite together with common planktonic foraminifera and small benthic foraminifera indicate a low energy, open oceanic, probably sub-photic depth depositional setting for the planktonic foraminifera facies group. The occurrence of abraded and fragmented shallow water bioclasts is suggestive of downslope reworking of marginal/upper slope or platform top grains. This facies group accounts for ~6% of facies observed in thin sections.

4.2 Bioclastic Facies Group.

The Bioclastic Facies Group contains abundant whole and fragmented, moderately-well preserved shallow marine bioclasts, including: branching and encrusting coralline algae and algal peloids, perforate larger benthic foraminifera, fragmented corals, molluscs, echinodermata and smaller benthic and planktonic foraminifera. The micritic matrix content of these deposits ranges from 47 to 59% T.R.V in dominantly wacke-packstone and grain-packstone textures, but also a few mud-wackestones. A Late Oligocene (Te1-4) age for the Bioclastic Facies Group is inferred for all but two clasts (BG121-005-3 and BG121-003-4; Appendix 1) on the basis of common Lepidocyclinids (including *Eulepidina spp.*), *Heterostegina* and *Cycloclypeus* (cf. Adams and Haak, 1962; Adams, 1965; Wannier, 2009). The biotic assemblage is stenohaline with good preservation of planktonic foraminifera indicative of an open oceanic influence. Uncommon, but well-preserved *Cycloclypeu*s tentatively suggest deposition under moderate- to deeper-photic depth slope or platform top settings (cf., Adams, 1965; Wilson and Vecsei, 2005). These low-moderate energy depositional environments (based on the abundance of micrite together with mud-wacke-packstones and pack-grainstones) received reworked diverse, abraded and fragmented shallow, higher-energy components. Although based on limited data points the preservation of abundant, robust, disarticulated echinoderm debris (6-11% T.R.V from three clasts) and limestone extraclasts (25% T.R.V within one breccia clast) in grain-packstone lithologies is consistent with shedding of shallow-water deposits into a slope environment. This facies group accounts for ~25% of facies observed in thin section. Two clasts containing common *Discocyclina* and *Asterocyclina* are indicative of a Late Eocene age (general Tb; Adams, 1965; Lunt and Allan, 2004), although age assignment for this lithology was not always possible.

4.3 Larger Benthic Foraminifera Facies Group.

The Larger Benthic Foraminifera Facies Group is dominated by moderately fragmented perforate larger benthic foraminifera within clasts of two dominant ages; Late Eocene and Late Oligocene, and accounts for 25% of clasts identified in thin section. Sixteen clasts of this Facies Group are assigned

Late Eocene ages on the basis of abundant robust *Discocyclina, Pellatispira, Asterocyclina,* and *Nummulites;* indicative of a general Tb age (Table 1, Appendix 1; Adams, 1965 Lunt and Allan, 2004). Nineteen clasts from Late Oligocene deposits are recognised on the basis of abundant thin flattened Lepidocyclinids including *Eulepidina*, with minor presence of *Heterostegina*, *Cycloclypeus*, *Amphistegina* and Alveolinids indicative of a general Te1-4 age (Adams, 1965 Lunt and Allan, 2004).

Late Eocene deposits with dominantly pack-grain-rudstone textures contain 9-52% T.R.V of moderately-fragmented perforate larger benthic foraminifera with 1-<10% T.R.V imperforate larger benthic foraminifera and common (<15% T.R.V) branching and encrusting coralline algae. Low abundances (typically <5% T.R.V) of corals, planktonic and smaller benthic foraminifera and algal peloids are also present. Deposition within the photic zone and under moderate to high energy conditions are inferred for these Late Eocene deposits on the basis of abundant fragmented photic zone biota and pack-grain-rudstone textures. Normal marine salinities are inferred due to the occurrence of stenohaline biota such as abundant perforate larger foraminifera. The high abundance of larger benthic foraminifera with width to height ratios of 1.5 to 5 (rotund to slightly elongate) may be representative of shallow foraminiferal shoal or bank deposits (Hallock, 1979; Hallock and Glenn, 1986; Beavington-Penney and Racey, 2004). *Discocyclina, Pellatispira* and *Biplanispira* are most consistent with seaward platform aspects and/or ramp-type margins (Beavington-Penney and Racey, 2004). The planktonic foraminifera indicate an open oceanic influence. This facies (and the bioclastic facies) as well as being present as breccia clasts are the only facies seen in the underlying *in situ* Eocene section.

Late Oligocene deposits with pack-grainstone textures contain 8-30% T.R.V moderately fragmented perforate larger benthic foraminifera with typically <5% T.R.V imperforate larger benthic foraminifera and common (4-19% T.R.V) branching and encrusting coralline algae. The larger foraminifera in these deposits are mostly thin-flattened forms with width to height ratios of >10. Planktonic and smaller benthic foraminifera and echinodermata are generally uncommon (<5%

T.R.V). Uncommon, but higher abundances of coral (1-9% T.R.V) than in the Eocene deposits are also present. A normal marine setting within the photic zone is inferred for these deposits on the basis of abundant and diverse larger benthic foraminifera co-occurring with other stenohaline light-dependant biota, such as corals. The depositional environments are interpreted as: (1) upper to mid-platform slope or, (2) platform-top settings. Thin-flattened forms of foraminifera are suggestive of deposition at moderate to deeper-photic depths (Hallock, 1979; Hallock and Glenn, 1986; Beavington-Penney and Racey, 2004; Wilson and Vecsei, 2005). The typically lower abundances (average 12% lower) of perforate larger foraminifera and higher abundances of fragmented bioclasts in the Late Oligocene compared to the Late Eocene deposits, might indicate higher degrees of reworking (consistent with a slope or bank/platform-top) and less of a strictly foraminiferal shoal-type setting. Nearby localised coral development, perhaps as coral carpets or patch reefs, is a possibility on the basis of the reworked corals present throughout Oligocene deposits of this facies group.

4.4 Algal Peloidal Facies Group.

The Algal Peloidal Facies Group is dominated by poorly preserved branching and encrusting coralline algae (8-46% T.R.V), as well as dasycladacean green algae with abundant algal peloids (5-<22% T.R.V), and grainstone textures. Coralline algal-rich breccia clasts are mainly comprised of: (1) rhodoids with encrusting growth and multi-layered internal structures, (2) disarticulated and highly abraded/rounded segments of geniculate branching forms, and less commonly (3) laminar crustose forms. Two distinctive lithofacies are identified within this facies group on the basis of additional miliolid content, in which miliolids are: (1) either common (>5-11% T.R.V, and up to 26% of all bioclasts), or (2) rare to present (typically <2-3% T.R.V.). Miliolid-rich lithofacies contain rare (1-3% T.R.V in some clasts) corals, molluscs and echinodermata with a low abundance (typically <5% T.R.V) of perforate larger benthic foraminifera. Few smaller benthic foraminifera are present (<1-3% T.R.V) and planktonic foraminifera were not observed. The miliolid poor lithofacies contains common whole and fragmented larger benthic foraminifera, corals and rare smaller benthic and planktonic foraminifera. Micritic matrix content of this facies group ranges from 5 to 51% T.R.V. Whole and fragmented larger benthic foraminifera are indicative of a general Te1-4 age (Appendix 1). Deposits of this facies group account for 24% of clasts observed in thin section.

Deposition of the miliolid rich lithofacies is inferred to have occurred in shallow-areas of the photic zone under moderate to high energy conditions on the basis of abundant highly abraded and fragmented light-dependant biota (including rhodoids) and original predominant grainstone textures. The co-occurrence of miliolids (20% of bioclasts on average), abundant dasycladacean green algae (up to 80% of the algal content in some cases), algal and miliolid peloids, encrusting coralline algae (including one example of a 'hooked' epiphytic form) and pervasive development of constructive micritic envelopes are suggestive of deposition either associated with: (1) seagrass development or (2) with a rocky shoreline (Davies, 1970; Perry, 1999; Benedetti-Cecchi, 2001; Shears and Babcock, 2002; Beavington-Penney and Racey, 2004; Beavington-Penney et al., 2004; Madden et al., 2013; Reich et al., 2015). The absence of planktonic foraminifera in these deposits suggests a setting distal to, or protected from an open oceanic influence, such as an embayment. Although, abundant dasycladaceans and miliolids may occur under raised salinities (locally restricted?; cf. Flügel, 2004), some stenohaline biota is still present.

The algae and peloid bioclastic grainstone (miliolid poor) deposits with well-developed encrusting coralline algae, geniculate branching coralline algae, few dasycladacean green algae, common fragmented corals and larger benthic foraminifera (common *Lepidocyclina, Heterostegina, Alveolina* and *Amphistegina*) and few planktonic foraminifera are interpreted to represent moderate-high energy deposition with an open oceanic influence either: (1) on a shallow platform slope or (2) at moderate-shallow photic depths on the platform top, perhaps again associated with rocky shorelines (Hallock, 1979; Hallock and Glenn, 1986; Beavington-Penney and Racey, 2004; Wilson and Vecsei, 2005).

4.5 Coralline Algae Bindstone Facies Group.

The Coralline Algae Bindstone Facies Group is rare, accounting for only 2% of clasts observed in thin-section. Encrusting coralline algae content varies from 56 to 74% T.R.V and produces laminar bindstone textures. Micritic matrix ranges from 11 to 25% T.R.V and is associated with minor occurrences (<2% T.R.V) of larger benthic and smaller benthic foraminifera and algal peloids. This laminar bindstone textures may represent parts of large (several cm) algal rhodoliths consistent with those seen in large clasts of the breccia in the field (see section 5) and the algal peloidal facies group. Alternatively, this facies group is inferred to have formed in a platform margin environment under moderate-high energies, and possibly spatially related to the Algae Peloidal Facies Group.

4.6 Coral Rich Facies Group.

The Coral Rich Facies Group accounts for 18% of clasts observed in thin-section, and consists of pack-floatstone textures with dominantly whole or fragmented coral clasts (16-94% T.R.V). Micrite is present as matrix (<1 to 67% T.R.V.) and infilling micro borings and coral chambers. Shallow marine bioclasts present include typically fragmented, encrusting and branching coralline algae, larger benthic foraminifera (*Lepidocyclina, Heterostegina, Cycloclypeus, Alveolina and Aphistegina)*, molluscs, smaller benthic and planktonic foraminifera and additional algal peloids. The abundance and diversity of light-dependant stenohaline bioclasts in this facies group is indicative of deposition in the photic zone under normal marine conditions. An open oceanic influence on deposition is inferred for this facies group, interpreted to represent deposition in either: (1) platform/bank margin to upper slope settings or (2) shallow areas of the platform top. The range and diversity of larger benthic foraminifera and abundance of corals many showing evidence of reworking could be consistent with either setting (Hallock, 1979; Hallock and Glenn, 1986; Beavington-Penney and Racey, 2004; Wilson and Vecsei, 2005). Pack-floatstone textures are indicative of moderate depositional energy. The abundance of reworked corals, but lack of evidence for coral frameworks is suggestive of nearby localised reefs or patch reef development on the platform top or its margin, yet with limited reworking of coral clasts into other shallow water platform-top environments (described above).

5. 'Outcrop' perspectives on facies variability and diagenetic features.

The Batu Gading Limestone is quarried from (low) outcrops and is used widely for construction of roads stone and sea defences, as at Miri. Due to the blasting and bulldozing extraction techniques the limestone in the quarry is now largely exposed as 2-10 m wide blocks, with little *in situ* material remaining (Fig. 2b). Large blocks of the Batu Gading Limestone seen along the Miri sea defences are composed of limestone breccia with a fitted fabric resulting from circum-clast dissolution seams and stylolites (Fig. 2c, d, e). Breccia clasts are up to 90 cm across but the majority of clasts are ≤30 cm. The breccia is composed entirely of limestone, with varied percentages of clasts from different facies groups. Ten to fifteen percent of clasts are recrystallised corals or coral rich lithologies of the Coral Rich Facies Group (Fig. 2c). These clasts are composed either wholly of massive coral heads or floatstone to pack-floatstone clasts; containing corals 4-30 cm across. Pale-grey carbonate mudstones to wackestones account for 5-10% of clasts with some representing the Planktonic Foraminifera Facies Group (Fig. 2d). Larger benthic foraminifera packstones to float-rudstones comprise 5-10% of clasts. These larger benthic foraminifera-rich facies can be divided into roughly equal proportions of: packstones with thin flattened forms (width to height ratio of >10; Fig. 2d), and those with robust forms (width to height ratio of between 3 and 5; Fig. 2e; i.e., as described in the Larger Benthic Foraminifera rich facies in section 4.3). The lithofacies containing robust larger benthic foraminifera may also include robust fragmented coralline algae (Fig. 2c). Clasts of coralline algal bindstones, or those containing branching coralline algal rhodoliths up to 5 cm across, account for approximately 5% of breccia clasts. The remaining 60-75% of clasts comprise medium to coarse grained bioclastic packstones to grainstones. Some of these pack-grainstones contain common coralline algal material, but in most cases it is difficult to distinguish bioclasts in the field.

Individual clasts are typically surrounded by a range of clasts of variable lithofacies. Between blocks there may be variability in clast size and clast content, however; the coral rich lithofacies are commonly found in blocks of larger clast size. Because of the rubbly nature of the quarried outcrop, and the loss of outcrop context in the Miri blocks, it is difficult to ascertain if the original succession within the quarry had any systematic up-sequence changes in clast types and/or sizes. The most prominent diagenetic feature noted from the blocks of breccia from the Batu Gading Limestone is the tightly fitted fabric that has resulted from post-brecciation, circum-clast stylolitisation (discussed below). In parts of the breccia some apparent preferential alignment or elongation of clasts is noted although it is unclear if this is a primary depositional fabric or one enhanced by, or imparted through, the stylolite development. Cement filled fractures up to 1 mm across are the other main post-depositional feature observed in the breccia (Fig. 2e). Ninety percent of these fractures cross-cut clast boundaries and there may be one or two main fracture orientations based on observed fracture intersection angles. Other observable diagenetic features within clasts are: the recrystallisation of corals (retaining up to eight percent intragranular porosity), and blocky calcite cements that typically infill shelter porosity or intergranular porosity in grainstone lithologies.

6. Diagenetic characteristics.

Although the Batu Gading limestone breccia displays high degrees of heterogeneity in terms of clast variability a broadly comparable set of diagenetic features is seen in many thin sections i.e., pre- and post-brecciation diagenesis is similar within and across individual facies and whole breccia samples (Appendix 1). The exact mechanism that led to breccia formation in the Batu Gading Limestone is unclear but may be related to slope depositional settings and is discussed in section 9. It should be noted that whilst the effects of post-brecciation diagenesis (compaction, stylolitisation and fracturing) have modified the depositional textures of the breccia, neither pre- or post-brecciation effects are responsible for the geometrical organisation of breccia clasts. Diagenetic features are described below in their relative order of occurrence as inferred from petrographic study.

6.1 Pre-brecciation diagenesis.

6.1.1 Micritisation.

Micritisation of bioclasts is prevalent in 129 of 139 breccia clasts. Micritic envelopes are visible in plane-polarised light (PL) as narrow (10-<100 µm), irregular dark brown rims to bioclasts (Fig. 3a). The near complete and partial micritisation of fragmented coralline algae and whole and fragmented miliolid foraminifera has resulted in the production of peloids, many retaining faint traces of the precursor allochem fabric (Fig. 3b). Coral clasts also show common and pervasive microborings infilled by micritic matrix (Fig. 3c). Micritisation of bioclasts is rare or absent in the Planktonic Foraminifera Facies Group and non-pervasive in mud-wackestone to wacke-packstone lithofacies, particularly of the Bioclastic, and Larger Benthic Foraminifera Facies Groups. Micritisation is a dominant diagenetic feature of the Algal Peloidal Facies Group.

6.1.2 Dissolution of selected bioclasts.

The highly selective dissolution of specific bioclasts is a relatively rare feature of pre-brecciation diagenesis (present in 25% of breccia clasts). The dissolution of thin-walled foraminifera is common in the Planktonic Foraminifera Facies Group, recognisable as small (<300 µm) regular cavities, infilled by later cementing phases. The uncommon and non-pervasive dissolution of thin-walled bioclasts is noted from all facies groups except for the Coralline Algae Bindstone Facies Group (although this may represent sampling bias as the facies group represents only 2% of clasts). The irregular dissolution (and later cementation) of coral chamber walls is an uncommon feature of the Coral Rich Facies Group (Fig. 3c).

6.1.3 Syntaxial overgrowths.

Syntaxial cements, present in 27% of breccia clasts, are common features overgrowing echinodermata fragments (Fig.3b, d) but are not a dominant or pervasive cementing phase (<1% of a sample). Syntaxial overgrowths typically exhibit well-formed crystal shapes, are commonly 500 µm to 1 mm in size and are cloudy and inclusion rich (Fig. 3b, d). Syntaxial cements post-date micritisation as they overgrow micritic boundaries but precipitated prior to later stage cementation or compaction; as they are commonly rimmed by cements or cross-cut by fractures. A greater abundance of syntaxial overgrowths is not coincident with higher volumes of echinodermata debris. Rather, overgrowths are most abundant from inferred shallow platform top deposits predominantly of the Coral Rich and Algae Peloidal Facies Groups and associated with pack-grainstone lithofacies. Overgrowths are rare or absent in the Bioclastic Facies Group and Planktonic Foraminifera Facies Group despite amounts of Echinodermata material (typically 1-3.5%) being comparable to other facies groups.

6.1.4 Granular mosaic calcite and contemporaneous calcitisation.

Granular mosaic calcite is a major diagenetic feature (up to >50% T.R.V of a clast), present in 55% of breccia clasts. Mosaic calcite consists of typically small, relatively equidimensional crystals with irregular to subhedral crystal margins (Flügel, 2004; Fig. 3e, f). This cement is colourless to pale-yellow in PPL and commonly has an inclusion rich "dusty" appearance. Mosaic calcites are confined to either: (1) (originally aragonitic) bioclastic components showing "ghost textures" of the original skeletal structure (Fig. 3e) or, (2) crystals showing aggradational growth from, and within, the micritic matrix of samples (Fig. 3g). Relicts of internal skeletal structures and coral walls are partially preserved as 'ghost' traces of their original fabric or through outlining by micritic envelopes (Figs. 3e, f). Granular mosaic cements affecting the micritic matrix are recognisable by their commonly cloudy, inclusion rich appearance, irregular sizes and "patchy" distributions (Fig. 3g). Contemporaneous with the granular mosaic calcites are blocky calcite cements that extend from areas of mosaic cements into chambers of bioclasts or areas of micritic matrix (Figs. 3f), this is present in 32% of breccia clasts. Granular crystals range in size from 50-200 µm, where they replace original coral skeletal structures, to 500 µm where perforate larger benthic foraminifera are replaced. Blocky cement (contemporaneous with the granular cement) crystal sizes that infill original bioclast chambers are consistently 500-750 µm. Concomitant blocky calcite cements from the granular mosaics is a rare to minor feature of all facies groups (where coral abundances are low), with the exception of the Coral Rich Facies Group where the cement is both an abundant and pervasive feature.

6.1.5 Mechanical compaction.

Mechanical breakage and compaction is present in 33% of the breccia clasts. The effects of mechanical compaction are recognised through: (1) the presence of minor crystal or grain fractures, typically on the order of less than a few hundred µm in length, (2) the development of concavo-convex grain boundaries (Fig. 3h) and (3) the rare alignment of elongate clasts. Micritised grain margins, early cements and internal clast structures are all affected by compaction. In all facies groups peloids show preferential development of concavo-convex margins (Fig. 3h), whereas elongate bioclasts such as encrusting coralline algae and larger benthic foraminifera show higher occurrences of internal deformation and fracturing. The algae, peloid and miliolid bioclastic grainstone lithofacies showed little mechanical compaction effects, with the exception of concavo-convex contacts of the peloids and one clast that has undergone minimal early cementation (Fig. 3h). The Planktonic Foraminifera Facies Group deposits have high proportions of micritic matrix with sparsely distributed bioclasts, and do not show common or pervasive compaction features (Fig. 3i). Deposits of the Coral Rich Facies Group with high abundances (>40%) of competent coral clasts show little evidence of early compaction.

6.1.6 Granular to blocky equant calcite.

Granular to blocky equant calcite is the most common diagenetic feature (94% of clasts) present in the breccia clasts, but is typically non-pervasive (<20% T.R.V in most samples). Equant cements are pore filling equidimensional calcite crystals with small (few hundred µm), irregular anhedral crystals (granular) to medium-coarse (500 µm to several mm) sub-hedral to euhedral crystals (blocky; Flügel, 2004). This cement occurs between bioclasts and infilling areas of micritic matrix or earlier fractures. These cements are typically colourless to pale-yellow in PPL, and do not commonly have inclusions or a "dusty" appearance (allowing differentiation from the granular mosaic cements (above). Equant calcite is a common feature of deposits from all facies groups and depositional settings. However, it is most pervasive in the Algal Peloidal Facies Group and the Larger Benthic Foraminifera Facies Group, in samples where granular mosaic calcite, contemporaneous calcitisation of bioclasts and mechanical compaction are rare (Fig. 3h). Granular to blocky equant calcite post-dates all prior diagenetic phases being the final porosity filling cement phase.

6.2 Post-brecciation diagenesis.

6.2.1 Mechanical compaction, dissolution seams and stylolites.

Late stage mechanical compaction of breccia clasts is recognisable from concavo-convex to sutured clast boundaries with little to no matrix preserved between contacts, and the development of dissolution seams and stylolites with suturing typically circumventing clasts (Fig. 3j). The effects of post-brecciation compaction have resulted in the Batu Gading limestone breccia developing a fitted fabric (Figs. 2c, 2d, and 2e). Mechanical compaction effects are seen in 30 of the 32 individual samples with dissolution seams and stylolites present in 66% and 50% of samples respectively. Samples that do not demonstrate mechanical compaction features are those without breccia clasts. Dissolution seams are present as smooth anastomosing seams, with stylolites having higher amplitudes (up to 2 mm). Both seams and stylolites show development from interclast sutures into circum-clast seams. Dissolution seams are typically developed where there is a higher proportion of micritic matrix on either side of the clast boundary. Stylolites are typically best developed where clasts have a high volume of early cement or competent bioclasts (e.g., corals). Both features are identifiable through the concentration of insoluble non-carbonate material, resulting in a dark-brown seam in PPL. In four samples euhedral micro-dolomite rhombs (up to a few tens of µm) have developed along dissolution seams.

6.2.2 Fractures.

Fractured fitted breccia clasts are present in 28 of 32 individual samples (Figs. 2b, 3k, and 3l). Fractures are not present in three samples which do not show evidence of brecciation and one sample composed of micrite-rich floatstone, wackestone and mudstone clasts. Linear to bifurcating fractures cross-cut the samples without observable preferred orientations, or offset of more than a few hundred µm. All of these post-brecciation fractures cross-cut breccia clast boundaries. These fractures are typically less than 200 µm wide but may be up to 1 mm in length (Fig. 3l). Fractures have been infilled by equant calcite cement, and do not show preferential development with respect to individual facies groups or lithofacies.

6.2.3 Equant calcite.

Equant calcite is the final consistent diagenetic stage observed in the Batu Gading limestone breccia. Equant calcite with a typically sub-hedral form is present in 29 of 32 individual samples where it in-fills prior fractures. Calcite crystals are 200-500 µm across and typically clear and inclusion free in PPL.

6.3 Stable isotope analysis.

Stable-isotope compositions of samples from the Batu Gading Limestone define a tight group, with low variance amongst individual values of $\delta^{18}O$. These values range from -9.77‰ to -4.12‰ V-PDB (Table 2, Fig. 4) and are similar to that expected from cements formed from seawater ($\delta^{18}O$ values of -9.96‰ to -1.37‰; discussed below). Carbon stable-isotope values range from -0.04‰ to +1.85‰ V-PDB (Table 2, Fig. 4) and occupy a narrow range consistent with or slightly more positive than the expected range of normal marine waters for SE Asia (-1‰ to +1‰ $\delta^{13}C$ V-PDB; Ali, 1995; Wilson and Evans, 2002; Madden and Wilson, 2012; 2013; Wilson et al., 2013; Arosi and Wilson, 2015).

7. Diagenetic, temperature and paleohydrologic interpretations.

Petrographic observations reveal a consistent paragenetic sequence for the diagenetic phases that have affected the Batu Gading limestone breccia, including multiple stages of cementation and replacement (Fig. 5). The Anderson and Arthur (1983) equation (Eq. (1)) provides a means to derive $\delta^{18}O$ seawater values for the region, and from this; the potential to determine the possible origins of fluids involved in cement precipitation.

$$T = 16-4.14(\delta^{18}O_{CALCITE} - \delta^{18}O_{SEAWATER}) + 0.13(\delta^{18}O_{CALCITE} - \delta^{18}O_{SEAWATER})^2 \quad (1)$$

Known regional $\delta^{18}O$‰ V-PDB values for Oligo-Miocene SE Asian marine components and cements plot within a range of -7.1‰ to -1.4‰ (Ali, 1995; Wilson and Evans, 2002; Madden and Wilson, 2012; 2013; Wilson et al., 2013; Arosi and Wilson, 2015). Several of these values are more negative than the global norm and likely represent marine components reflecting lowered marine salinities due to the significant terrestrial run-off in SE Asia (i.e., an apparent brackish signature; Tomascik et al., 1997; Wilson, 2008; Wilson et al., 2013; Arosi and Wilson, 2015). An Oligo-Miocene $\delta^{18}O$ seawater value for the region of -5.4‰ to +0.67‰ V-SMOW has been derived using this equation and the observed range of SE Asian calcitic bioclast values and an assumed ocean surface temperature of 25 °C (Neogene of coastal Borneo; Ali, 1995). The grouped calcite bioclast values from Batu Gading ($\delta^{18}O$ values of -6.7‰ to -4.9‰; Fig. 4) were not used since these fall towards the very negative end of the SE Asian bioclast values. For these end member values there is the possibility of: (1) the samples containing contaminating matrix, (2) precipitation out of equilibrium with Miocene sea water, or (3) resetting of the $\delta^{18}O$ during stabilisation by meteoric waters or elevated temperatures (cf. Madden and Wilson, 2012) Because the deposition of the Batu Gading is thought to have formed in a localised wedge-top basin it may be that the strongly negative $d^{18}O$ V-PDB values of the larger foraminifera may in part reflect a brackish signature associated with terrestrial runoff into the basin. A $\delta^{18}O$ value of -4 to -8% V-SMOW is suggested for meteoric parent fluids on the basis of $\delta^{18}O$ values of meteoric precipitation in SE Asia of -4 to -6% at low elevations and up to -8% where waters are derived from upland areas in Borneo (Anderson and Arthur 1983, Bowen and Wilkinson 2002).

The onset and development of stylolites and dissolution seams occurs in moderate to deep burial depths commonly from 500-1000 m (Finkel and Wilkinson, 1990; Lind, 1993; Railsback 1993; Nicolaides and Wallace, 1997; Machel, 2004). With the exception of the final equant cement stage (Fig. 5) all cementation pre-dates the development of dissolution seams and stylolites. Although the occurrence of dissolution seams versus stylolites may be most strongly controlled by the compacting lithologies, the prevalence of dissolution seams, is perhaps suggestive of maximum burial depth of 500 m for diagenetic features that pre-date chemical compaction (below; cf. Bathurst, 1987; 1990; Railsback, 1993; Nicolaides and Wallace, 1997; Madden and Wilson, 2012; 2013; Arosi and Wilson, 2015). Extrapolation of the geothermal gradient from Malaysian wells closest to the Batu Gading outcrops (25 °C/km; Hall, 2002) gives an estimated maximum calcite precipitation temperature of 37.5 °C for all pre-brecciation cements and up to 50 °C for post-brecciation, fracture filling cement.

8. Interpretation of diagenetic features.

8.1 Micritisation.

Micritisation of bioclasts is the first alteration process that affects samples, since micritic rims are cross-cut by all later diagenetic features. The pervasive micritisation of shallow water deposits from platform top or margin settings is consistent with endolithic micro-borers being most active in shallow-photic environments (cf., Swinchatt, 1965; Budd and Perkins, 1980; Perry and Bertling, 2000; Perry and Macdonald, 2002; Perry and Hepburn, 2008). The thickest micritic rims are developed in moderate energy deposits from inferred protected rocky shore line or seagrass deposits; consistent with an environmental control on pervasive micritisation under the influence of raised nutrient levels (Goulbric et al., 1975; Budd and Perkins, 1980; Tucker and Wright, 1990; Perry, 1998, 1999; Perry and Larcombe, 2003; Madden and Wilson, 2012; 2013).

8.2 Dissolution of selected bioclasts.

The dissolution of thin walled bioclasts and notably planktonic foraminifera is consistent with dissolution of metastable high-Mg calcite and aragonite tests (Pingitore, 1976; Eggins et al., 2003). That dissolution is most commonly seen in sub-photic, deep-water settings (Planktonic Foraminifera Facies Group) is most reasonably attributed to seafloor dissolution of thin walled bioclasts (Eggins et al., 2003), Minor early dissolution of coral skeletons may, however, also locally also be related to ingress of meteoric waters.

8.3 Syntaxial overgrowths.

Cross-cutting by fractures and pre-dating later rimming cements identifies syntaxial overgrowths as an early diagenetic process. A cloudy and inclusion rich appearance to these syntaxial overgrowth cements is consistent with their formation in a marine-phreatic environment (Flügel, 2004; Swei and Tucker, 2012). Although syntaxial overgrowths are mainly associated with echinodermata debris, the most common occurrences of overgrowth cement is not coincident with substrate availability since the amounts of echinodermata material is generally comparable between facies groups. Rather, overgrowth cements are most abundant in inferred shallow platform top deposits. This environmental association is attributed to easier pathways for flushing of precipitating pore fluids of probable marine origin in areas with open pack-grainstone textures, or more active wave/tidal flushing in the shallow platform setting (Appendix 1; Tucker and Wright, 1990; Park et al., 1992; Wilson and Evans, 2002; van der Kooij et al., 2010; Madden and Wilson, 2013).

8.4 Granular mosaic calcite and contemporaneous calcitisation.

Granular mosaic calcite retaining traces of original aragonitic skeletal structures, aggradational growth within the micritic matrix of a sample and a commonly inclusion rich appearance is indicative of neomorphism rather than dissolution and re-precipitation. Contiguous growth of cements into original porosity (calcitisation) is consistent with a neomorphic granular mosaic habit and absence of drusy cement morphologies (Hendry et al., 1999; Flügel, 2004; Madden and Wilson, 2012; 2013). Petrographic relationships reveal that neomorphism and calcitisation of original porosity took place prior to significant burial on the basis of their pre-compaction and pre-fracturing timing. Precipitation of these cements with stable-isotope values of -4.9‰ to -4.1‰ $\delta^{18}O$ V-PDB (av. -4.64‰; neomorphic replacement of coral clasts) at 25-37.5 °C and burial depths of 0-500 m (cf., Hall, 2002), suggests parent fluids of -2.6‰ to -0.1‰ $\delta^{18}O$ V-SMOW, consistent with marine fluids in a near-surface to shallow burial environment. Stable-isotope values of -0.04‰ to +0.8‰ $\delta^{13}C$ V-PDB indicate a seawater or rock-derived source of carbon with marine $\delta^{13}C$ values inherited by the precipitating fluids (Hendry et al., 1999; Madden and Wilson, 2012; 2013). Alteration of the micrite is consistent with the petrographic recognition of aggradational and patchy growth of neomorphic cements from within the micritic matrix. Stable-isotope compositions of the micritic matrix have oxygen values slightly more negative than the unaltered bioclasts at -8.9‰ to -5.9‰ $\delta^{18}O$ V-PDB (av. -7.3‰). Alteration of the micritic matrix is feasible following deposition or up to maximum burial depths (cf., Brachert and Dullo, 2000; Melim et al., 2002; Caron and Nelson, 2009). Diagenetic fluids at temperatures of 25-37.5 °C indicate parent fluid compositions of -5.3‰ to -2.8‰ $\delta^{18}O$ V-SMOW. These $\delta^{18}O$ values are consistent with alteration by marine fluids, likely at slightly higher temperatures, given that $\delta^{13}C$ values (+0.45‰ to +1.5‰ V-PDB) are in good agreement with marine carbon values. Alternatively alteration might also have been by meteoric or mixed marine-meteoric waters, but lacking a soil zone signature. .

8.5 Mechanical compaction.

The effects of mechanical compaction post-date micritisation and early formed cements as these features are affected or broken. Mechanical compaction and grain-scale fracturing of the deposits is inferred to represent compaction of largely unlithified deposits as they underwent progressive burial. The mechanical compaction and development of grain-scale fractures has been affected by deposit textures and components. In wacke-packstone lithologies of the Planktonic Foraminifera Facies Group extensive fracturing may be mitigated against by an abundance of micritic matrix and a paucity of grain-to-grain contacts (Fruth et al., 1966). Whilst breakage and compaction are common features of most facies groups the algal, peloid and miliolid bioclastic grainstone lithofacies shows almost no evidence of compaction. Representing what is likely the shallowest water deposits from Batu Gading, the miliolid rich lithofacies of the Algae Peloidal Facies Group may have been most accommodation space limited and undergone least burial prior to lithification; resulting in a paucity of compaction effects. Alternatively the very common early alteration through micritisation may in some way mitigate against grain-scale fracturing. A typical paucity of compaction effects in the Coral Rich Facies Group is attributed to the dominance of competent coral clasts that were stabilised and calcitised prior to the onset of compaction in a burial environment i.e., relatively early alteration of aragonitic components.

8.6 Granular to blocky equant calcite.

The occurrence of granular to blocky equant calcite cement between bioclasts, infilling open porosity within the micritic matrix or earlier fractures with a typically clear and inclusion free appearance indicates that this cement is separate to the prior neomorphic calcite (granular mosaic calcite). However, where relicts and inclusions of micrite occur the possibility of this cement being continued growth from areas of neomorphic replacement cannot be completely ruled out, particularly where cross-cutting relationships with other cementing phases cannot be identified. Stable-isotope compositions of the granular to blocky equant calcite have oxygen values predominantly more negative than unaltered bioclasts, neomorphic cement and the micritic matrix (-8.3‰ to -4.1‰ $\delta^{18}O$ V-PDB av. -6.8‰). Growth of this cement is likely to have taken place as the final stage of pre-brecciation diagenesis and prior to the onset of significant compaction (dissolution seams, stylolitisation and the development of a fitted breccia fabric) as it is porosity filling and post-dates prior stages of cementation. Diagenetic fluids at 25-37.5 °C suggest parent fluid compositions of -4.7‰ to -2.7‰ V-SMOW, consistent with marine parent fluids. Carbon stable-isotopic values of 0.03‰ to +1.9‰ $\delta^{13}C$ V-PDB are, as for the neomorphic cements, indicative of a seawater or rock-derived source of carbon.

8.7 Mechanical compaction, dissolution seams and stylolites.

Cross-cutting relationships place these features as post-brecciation diagenetic features. The mechanical compaction of reworked breccia clasts has produced chemical compaction features consistent with moderate to deep burial environments at depths of around 500-1000 m (Nicolaides and Wallace, 1997; Machel, 2004). It is, however, also recognised that chemical compaction features may be important at shallower levels of burial (~200 m; Mallon and Swarbrick, 2008). A moderate to deep burial environment is inferred for the Batu Gading breccia on the basis of the pervasive nature of dissolution seams and stylolites as well as the tightly fitted fabric of the breccia; which are less likely features from shallow burial depths. Although there appears to be some local substrate controls commonly under conditions of increasing burial and compaction tangential and concavo-convex to sutured contacts develop into circum-clast stylolites and seams, and locally some transitions are seen. Dissolution seams and stylolites do not generally traverse individual breccia clasts and this is suggestive of: (1) dissolution seams forming along likely calcite-clay interfaces (cf., Railsback, 1993) and (2) stylolites developing along boundaries between competent calcified clast. The minor occurrence of micro-dolomite rhombs along dissolution seams is indicative of Mg ions being locally sourced for dolomite cementation (Ali, 1995; Carnell and Wilson, 2004; Machel, 2004; Madden and Wilson, 2012; 2013).

8.8 Fracturing.

Post-brecciation fracturing is the penultimate diagenetic phase on the basis of cross-cutting relationships. However, near-contemporaneous timing with the development of the fitted fabric of the breccias is a possibility with fracturing likely representative of continued burial of the breccia.

That fracturing is present in 28 of 32 thin-sections and absent in unbrecciated and micrite-rich (floatstone, wackestone and mudstone) clasts is suggestive of mechanical fracturing preferentially affecting the most competent lithified lithologies.

8.9 Equant calcite.

Equant calcite is the final diagenetic phase recognised in the Batu Gading limestone breccia, as it in-fills the fractures that cross-cut all prior diagenetic phases. These cements are clear and inclusion free indicating that they are not neomorphic replacements of any residual micritic matrix. The stable-isotopic composition of this cement (although based on a single sample) is -8.4‰ $\delta^{18}O$ V-PDB and -0.03‰ $\delta^{13}C$ V-PDB and suggests that at temperatures of 37.5 to 50 °C (consistent with post stylolitisation burial depths of 500-1000 m and a regional geothermal gradient of 25 °C/km; Nicolaides and Wallace, 1997; Hall 2002) parent fluid compositions were -3.9‰ to -1.7‰ $\delta^{18}O$ V-SMOW, consistent with marine or modified-marine burial fluids.

9. Depositional and diagenetic summaries, comparisons with regional carbonate breccias and diagenetic trends in breccias of varied origins.

9.1 Summary of depositional environments.

The (isolated) carbonate outcrops at Batu Gading are interpreted to have been deposited in a small, wedge-top basin separate from that inferred for the better known Melinau Limestone (Fig. 1; Chai Peng et al., 2004; Wannier, 2009). Initiation of accumulation of both the Melinau and Batu Gading Limestones during the Mid to Late Eocene is interpreted to have been on rotating slices of the folded deep marine turbidites and hemipelagics of the Rajang accretionary prism (Hutchinson, 2005; Wannier, 2009). However, limited data points do not allow for spatial or structural constraints to be applied (Wannier, 2009). A 35-40 m thick Late Eocene massive limestone underlies the breccia unit at Batu Gading. The Late Eocene deposits are dominated by robust larger benthic foraminifera in pack-grain-rudstones with associated abundances of coralline red algae. These Late Eocene deposits are interpreted as shallow shoal or bank type deposits that may be consistent with a seaward platform margin or ramp-type setting (Adams, 1965; Hallock, 1979; Hallock and Glenn, 1986; Beavington-Penney and Racey, 2004), of moderate-high energy (although lower energy accumulation effects cannot be ruled out; cf. Flügel, 2004). The uncommon and typically low abundance of framework builders may suggest that for the Late Eocene aged Batu Gading Limestone corals or patch reefs may have only really been locally or sporadically present. This interpretation is in agreement with other authors who propose that pervasive, regionally widespread reef development only occurred later, i.e., during the Oligocene (Wilson and Rosen, 1998; McMonagle et al., 2011; Mihaljević et al., 2014).

Previous workers have recognised an up-sequence change in the Late Eocene Batu Gading Limestone from: (1) oblate-spheroid foraminifera dominating in the lower part of the section to (2) more elongate and lenticular forms in the upper part of the section (Abdullah and Yaw, 1993). This up-sequence variability has been interpreted as a transition from carbonate sand shoal deposition to deposition in an open shelf environment; i.e., deepening upwards within the photic zone (Abdullah and Yaw, 1993). The presence of two distinctive lithofacies within the Larger Benthic Foraminifera Facies Group observed herein, with: (1) thin flattened forms and (2) robust forms, is consistent with these earlier findings. As discussed below that both these lithofacies occur as clasts in the breccia may be related to Oligocene derivation from: (1) an erosional platform margin and/or slope, and/or (2) karstic relief and exposure of the Eocene aged foraminifera deposits of the massive limestone.

The Late Eocene massive limestones are interpreted to have been terminated by a phase of subaerial emergence that created pronounced karstic relief on emergent surfaces and the formation of caliche in restricted parts (Azhar, 1988; Abdullah and Yaw, 1993). Locally, approximately 10 m of Late Oligocene carbonate breccias unconformably overlie the massive Late Eocene limestones with breccia clasts representative of a range of shallow carbonate platform top, moderate to deep photic platform, to platform margin and slope deposits. Petrographic study of the Batu Gading limestone breccias has revealed considerable facies variability for the Oligocene platform, for which contemporaneous *in situ* shallow water deposits no longer outcrop (Table 1; Fig. 6). The coral floatstones are thought to result from localised coral and/or patch reefs development at this time. Extensive coral development and *in* situ coral frameworks are, however, both not seen and so an unrimmed, or perhaps only very locally rimmed platform setting is suggested. Extensive reworking of shallow platform material into inferred moderate to deeper-photic platform or shallow to sub-photic slope deposits is consistent with an unrimmed bank or ramp type setting that may have had a distally steepened margin (Wilson, 2002; Wilson and Vecsei, 2005). Local variable karstic relief, as identified by Abdullah and Yaw (1993), may have been important in developing protected or embayed settings and/or rocky shorelines for the development of deposits with a possible seagrass influence (Algal Peloidal Facies Group; Benedetti-Cecchi, 2001; Shears and Babcock, 2002; Reich et al., 2015).

The hypothesis that, in the absence of platform top or margin deposits inferences about both the facies variability and depositional conditions of a ‘lost’ platform will be possible from the lithic clasts of associated breccias would appear to hold for the Batu Gading limestone breccia. Detailed petrographic study identifies six broad facies groups subdivided into sixteen lithofacies representative of platform top and margin environments. However, what remains uncertain is whether any facies and/or environments might still be unrecognised from what is now a ‘lost’ carbonate system. Indeed it also remains unclear what the original spatial distributions together with their relationships was for facies present in the clasts of the breccias without *in situ* depositional facies data and in the absence of up-sequence variability data for the Batu Gading limestone. Without further field evidence of stratigraphic or lateral relationships it must be accepted that a ‘sampling’ bias might have caused under or over representation of facies.

Whilst the exact mechanisms that led to the formation of the Batu Gading limestone breccia are unknown evidence for a submarine slope breccia is seen in: (1) the relatively common occurrence of open oceanic planktonic foraminifera, (2) planktonic foraminifera-rich facies including forming the rare matrix between breccia clasts, and (3) polymict clasts representative of a range of derived lithofacies including those from moderate to deeper photic depths. A slope breccia is in keeping with postulation that differential loading by fresh sediments maintained rotation of the thrusted part of a wedge-top basin leading to local reworking down-dip (Wannier, 2009). However, on the basis of the recognition of an emergent karstic surface (Abdullah and Yaw, 1993) some clasts may have been reworked from sub-aerially exposed lithologies into the breccia. This, however, is perhaps less likely than downslope reworking for the majority of clasts on the basis of a paucity of evidence for pre-brecciation meteoric diagenesis in the derived clasts together with common evidence for deeper photic and open oceanic indicators.

9.2 Diagenetic summary

An integrated petrographic and geochemical study has identified a consistent paragenetic trend for deposits of the Batu Gading limestone breccia, and reveals some associations between diagenetic features and depositional facies (Figs. 5 and 7). Although two distinct age groupings occur, most apparent within the Larger Benthic Foraminifera Facies Group clasts, similar diagenetic trends are evident (Appendix 1). Early (pre-brecciation) diagenesis took place in a marine phreatic environment with the initial development of micritised grain margins. Micritisation was most pervasive in the inferred shallowest or partially restricted parts of the platform top and possibly in association with a rocky (probable karstic) shoreline or seagrass beds. The dissolution of thin-walled bioclasts is rare but appears to be unique to the deep-water, sub-photic deposits. The development of syntaxial overgrowth cements is a minor feature but has a strong association with environmental facies being best developed in pack-grainstone deposits of the shallow platform top to margin. The neomorphic replacement and calcitisation of bioclasts and aggradational growth of granular mosaic calcite micritic matrix took place prior to significant burial and consistent with marine fluids in near surface to shallow burial environments. Mechanical compaction features and grain breakage are common in most facies groups but absent in wacke-packstone, early cemented (neomorphic and aggradational growth of micrite) and coral rich lithologies. The final stage of pre-brecciation diagenesis is consistent with cementation of open porosity and fractures in a shallow to moderate burial environment at temperatures of up to 37.5 °C. Reworking and brecciation of the Batu Gading Limestone has resulted in a highly varied range of individual clast sizes (<1 cm to >90 cm), levels of rounding and abrasion (very poorly to well rounded; but dominantly moderately rounded to angular) and no discernible alignment of individual clasts or grading (Appendix 1). Although there is a some variability in the pre-brecciation diagenesis associated with environmental facies or environmental settings; the post-brecciation diagenetic history is less facies specific. Post-brecciation diagenesis is interpreted to have taken place at moderate to deep burial depths at temperatures of 37.5-50 °C, under the influence of dominantly marine composition burial fluids. Extensive compaction has created a fitted fabric to the breccia clasts through the development of circum-clast dissolution seams and stylolites with subsequent reduction and compaction of sedimentary fill between clasts. Mechanical fracturing and infill by equant calcite cement are the final stages in the diagenetic history of the Batu Gading limestone breccia. The early, pre-brecciation diagenesis of the clasts has effectively preserved near-original platform top and margin depositional features, with little overprinting by subsequent reworking and post-brecciation effects.

9.3 Comparisons with regional carbonate breccias.

Regionally within SE Asia, there are some descriptions of carbonate breccias to compare with the Batu Gading limestone breccia. The Tonasa Limestone Formation (Sulawesi: Wilson and Bosence, 1996; Wilson, 1996; 1999; 2000; Wilson et al., 2000), the Kedango Limestone (Borneo: Wilson et al., 2012; Madden and Wilson, 2013) and Berai Limestone (Ruby Field, Makassar Straits: Pireno et al., 2009; Tanos et al., 2013) include submarine carbonate slope breccia deposits that are potentially analogous to the Batu Gading deposits. The breccias present in each of these regional examples show some similarities and also differences in terms of textures, potential origins and diagenesis compared with the Batu Gading breccia, but differ significantly in having their contemporaneous shallow platform deposits still preserved. For the Tonasa Formation, slope carbonates include common high and low density turbidite and rare debris flow deposits reworked mainly from a tectonically active faulted platform margin forming aprons in base of slope settings. This is evidenced from interbedding of basinal marls, proximal to distal trends in sediment gravity flows away from platform margins, clast immaturity and provenance (Wilson and Bosence, 1996; Wilson, 1996; 1999; 2000; Wilson et al., 2000). Deposition of the Kedango Formation limestone breccias and rudstones (from platform top deposits along an erosional platform margin) occurred in slope to basinal environments with reworking in calciturbidites, debris flows or modified grain flows; as inferred from commonly graded bedding and interdigitation with planktonic foraminifera facies (Wilson et al., 2012; Madden and Wilson, 2013). The western margin of the Kedango Platform varied considerably along its 30 km plus length with downslope reworking occurring from: (1) distally steepened ramp, (2) bypass to erosional, partially coral fringed margin, and (3) erosional, probably faulted escarpment settings (Wilson et al., 2012). The Ruby Field breccias of the Berai Limestone underwent erosion and reworking from the platform margin in a fore-reef, toe of slope environment as debris flow fans; this has been inferred from a short transport history evidenced in the clasts, mixing of planktonic foraminifera and mounded seismic geometry (Pireno et al., 2009; Tanos et al., 2013).

Sediment gravity flow deposits from all three of these comparable examples contain abundant, large pebble to boulder sized clasts and unlithified, reworked shallow-marine bioclasts in breccias and graded pack-grainstones commonly interbedded with deeper water, low-energy, planktonic-foraminifera marls, mud-wacke-packstones and clays. Additionally, the Berai Limestone in its upper part interdigitates with, and is overlain by, pro-delta siliciclastic lithologies (Pireno *et al.,* 2009). Reworked clasts of the Tonasa, Kedango and Berai limestones reveal wide variability in sedimentary features with identifiable and varied bioclastic compositions and sedimentary textures (mudstones, wackestones, floatstones, grainstones and bindstones) representative of platform top and margin depositional settings. For the Kedango Limestone these reworked clasts do, at least in part, represent the same facies as those from the adjacent *in situ* platform top deposits (Wilson et al., 2012; Madden and Wilson, 2013), with current work potentially highlighting further similarities for the Tonasa Formation (Wilson, pers. comm. 2015).

In terms of diagenesis the Batu Gading breccia shows a similar set of features to the Tonasa and Kedango breccias, but some contrast with that from the Ruby Field breccias of the Berai Limestone. For Kedango and Tonasa micritisation of bioclastic components is common from shallow platform top or inferred lower energy seagrass environments (Madden and Wilson, 2013) with rare early marine isopachous fringing and syntaxial overgrowth cements from higher energy platform margin or slope lithofacies (Wilson and Bosence, 1996; Wilson, 1996; Wilson et al., 2000; Madden and Wilson, 2013; Arosi and Wilson, 2015). As for Batu Gading, the diagenesis of reworked Tonasa and Kedango deposits is dominated by extensive neomorphism and calcitisation by granular to blocky calcite in a marine phreatic to shallow burial environment under the influence of marine or modified-marine fluids without a specific lithological or facies control (Wilson and Bosence, 1996; Wilson, 1996; Wilson et al., 2000; Madden and Wilson, 2013; Arosi and Wilson, 2015). Sub-aerial exposure and meteoric dissolution that very locally affected clasts of the Kedango and Tonasa Limestones prior to their reworking, perhaps also rarely affected rare coral-rich deposits of the Batu Gading Limestone before they were reworked. Sub-aerial exposure and dissolution followed by vadose zone cementation has been noted in the Upper Eocene massive limestone that underlies the Batu Gading breccias (Azhar, 1988; Abdullah and Yaw, 1993). The reworked deposits of the Tonasa Limestone are commonly affected by silica cementation (dissolution-reprecipitation) related to the rapid burial of both siliceous organisms and clasts in slope to deep marine settings (Wilson and Bosence, 1996). The result of mechanical and chemical compaction in deposits from Batu Gading, Tonasa, Kedango and Berai is that of a fitted breccia fabric with pervasive development of circum-clast seams and stylolites (Wilson and Bosence, 1996; Pireno et al., 2009; Tanos et al., 2013; Madden and Wilson, 2013; Arosi and Wilson, 2015).

Unlike Batu Gading, in some of the Ruby Field limestone breccia's (MKS wells) post-brecciation (and possibly pre-brecciation) diagenetic history is characterised by extensive leaching (Pireno et al., 2009; Tanos et al., 2013). Although secondary mouldic and vuggy porosity have been partially infilled by blocky to drusy and fibrous calcite and microdolomite, the effects of ?multiple stages of, and in particular late stage burial, dissolution have resulted in high porosity with good connectivity (Pireno et al., 2009; Tanos et al., 2013). These late leaching fluids are thought to be basinal derived, perhaps associated with the early stages of hydrocarbons generation during burial, and are noted elsewhere along the margins of the Berai Platform (Tanos et al., 2013; Saller and Vijaya, 2002; Wilson, 2012; Subekti et al., 2015). While the throughput of post-brecciation burial fluids may have been enhanced in the Berai breccias, post-brecciation diagenetic effects are uncommon for the Batu Gading, Kedango and Tonasa breccias; limited to compaction effects and some late stage fracture filling cements. A paucity of diagenetic alteration (namely marine cementation), following reworking, in these deposits may be related to rapid burial in downslope settings which acts to minimise open marine circulation and cementation (e.g., Van der Kooij et al., 2010). As for other regional analogues early diagenetic variability exhibits an environment specific control in that: (1) micritisation is most prevalent in low to moderate platform top or inferred seagrass related environments, (2) minor marine cementation is developed in higher energy platform margin or slope settings and (3) compaction effects are rare in matrix rich, early stabilised or coral rich lithologies. Diagenesis for the most part is dominated by pervasive stabilisation and calcitisation of bioclasts and micrite; mitigating against later diagenetic effects and preserving the near-original depositional characteristics of the sediments. However, where there is fluid flow from compacting basinal deposits through slope or platform margin flank deposits dissolution of calcite may be enhanced, leading to effective porosity generation (Saller and Vijaya, 2002; Esteban and Taberner, 2003). Given that such variability and facies recognition can be achieved (Batu Gading, Kedango) it is likely that investigations of other reworked carbonates in the absence of well-preserved platform top or marginal deposits may prove to be a useful base from which carbonate platform variability can be studied.

9.4 Comparisons with carbonate breccias of varied origins.

Carbonate breccias with multiple and varied origins are globally well documented, however, there is a need to integrate these deposits within the context of global and local models of carbonate depositional systems (cf., Table 3; Reijmer et al., 2015). The exact mechanism that led to reworking and deposition of the Batu Gading limestone breccia is unknown but was most likely related to a slope depositional setting. By manner of diagenetic comparison, the Batu Gading limestone breccia shows comparable trends/features with submarine slope carbonate breccias from a wide variety of settings and ages. Alternative breccia origins such as intra-formational brecciation and fault brecciation are ruled-out for Batu Gading on the basis of polymict clasts (variable facies) and an absence of damage zones or extensive post-brecciation diagenetic processes (cf. Table 3 and references there in).

The diagenesis of carbonate breccias demonstrate many common traits in breccias with similar origins of formation, but significant variations where the origin of formation of the breccias varies (Table 3). Differential marine cementation is a feature of platform margin slope breccias, both pre- and early post-reworking, attributes most reasonably related to primary facies variability and flushing by seawater together with its degassing in upper slope to platform margin settings. This feature is seen, albeit rarely, not only within other Cenozoic regional examples (Tonasa: Arosi and Wilson, 2015; Kedango: Madden and Wilson, 2013; Berai: Tanos et al., 2013) but also more commonly other modern and ancient slope breccia examples (Table 3 and references therein). The facies of polymict lithoclasts reworked from platform deposits may plausibly be linked to their original depositional environments, although individual clasts may have varied diagenetic overprinting (Table 3 and references there in). The commonly pervasive development of neomorphic replacement cements over dissolution of aragonitic allochems is most likely promoted by marine fluids flushing the platform margin deposits in near-surface to shallow burial settings. Early stabilisation of metastable bioclasts, some early marine cementation in platform top or margin settings and burial in deeper slope environments, allows for lithified or semi-lithified clasts to undergo extensive burial diagenesis that may result in compaction deformation, pressure dissolution features and fitted fabrics. Pervasive effects of meteoric dissolution are features uncommon to slope margin breccias. This may, however, be a regional factors relating to limited up building potential of non-framework built, commonly Paleogene calcitic equatorial deposits (e.g., Batu Gading, Kedango, Tonasa; Wilson, 2012; Arosi and Wilson, 2015). In comparison, meteoric dissolution features are common for subaerial talus slope breccias and karstic/cavern collapse breccias and may be accompanied by geopetal matrix infiltration and meniscus or cirucm-clast cements (Table 3 and references there in). Although meteoric dissolution features are mainly lacking from the Batu Gading breccias studied here, as for the sedimentology of the deposits, it is possible that with an observed karstic surface underlying the breccias; meteoric effects may not be represented due to 'sampling' bias or under representation of lithoclasts (Azhar, 1988; Abdullah and Yaw, 1993). Extensive compaction features are typically absent from subaerial talus slope deposits but may be common in karstic and cavern collapse deposits where rapid burial under thick sedimentary sequences promote compaction. It should be noted however that extensive compaction features in cavern and karstic collapse breccias may be mitigated against by early cementation e.g., speleothems.

10. Conclusions.

The Batu Gading limestone breccia reveals a wide variability of features in terms of recognisable facies groups, lithofacies, depositional settings and diagenetic alteration. This variability has been documented for the first time through petrographic and geochemical study. Clasts of the Batu Gading limestone breccia are representative of shallow to moderate to deeper photic carbonate platform top and margin environments formed in a postulated wedge-top basin (Wannier, 2009). The local importance of rocky shorelines or perhaps localised seagrass environments, coral patch reef development and foraminiferal shoal type deposits is recognised. A submarine slope origin, perhaps with some input of clasts from emergent karstic islands is preferred for the Batu Gading breccia. This environmental interpretation is on the basis of: (1) polymict clasts from a range of shallow to deeper photic depths, (2) common planktonic foraminifera in clasts and in the rare matrix to the breccia, and (3) prior recognition of a karstified surface between Late Eocene in situ platform deposits and reworking of clasts of this age into the Late Oligocene breccia.

The sedimentological variability of the Batu Gading limestone breccia reveals a variety of primary facies for which their textures, components and local environmental settings have, at least in part, had some influence on the subsequent diagenetic history of the deposits. Facies and environment specific controls impact: (1) the degree of micritisation, (2) the presence and abundance of components, (3) component-specific effects such as syntaxial overgrowths (e.g., on echinoderms) or the potential for mechanical deformation or compaction of grains (e.g., corals versus peloids), and (4) depositional mineralogies and textures that affect the potential for stabilisation, cementation and compaction. Despite some diagenetic variability relating to primary facies the diagenesis of the Batu Gading Limestone has been dominated by pervasive stabilisation and cementation leading to a broad similarity of diagenetic features in the reworked breccia deposits. The effects of early stabilisation have mitigated against later effects of diagenesis such as dissolution or compaction allowing for recognition of platform top and margin conditions within the breccia clasts. The diagenetic characteristics of the Batu Gading deposit can be constrained in a framework of breccia origin, whereby a predominance of: (1) early and pervasive stabilisation of aragonitic components, (2) lack of post-brecciation marine cementation, (3) pervasive compaction resulting in a fitted texture and (4) paucity or lack of meteoric dissolution or cementation effects; indicate slope deposition and lithification. Comparable regional and global examples of submarine slope breccias show similar diagenetic features to the Batu Gading breccia. The results of this study, along with regional analogues, suggest the potential for reworked carbonates deposited in slope settings to be a viable way of investigating carbonate platform variability in the absence of preserved correlative platform top or margin deposits. Diagenesis of such deposits provide insight into likely setting of breccia formation, alteration both pre- and post-clast reworking, i.e., sequential changing platform to basin conditions from original deposition to burial, and a potential mechanism of distinguishing breccias of differing origins.

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12. References.

Aalto, K.R., and Dill, R.F., 1996. Late Pleistocene stratigraphy of a carbonate platform margin, Exumas, Bahamas. Sedimentary Geology 103, 129-143.

Abdullah, N.T., and Yaw, C.Y., 1993. Distribution of foraminiferal assemblages in the Upper Eocene Batu Gading Limestone, Sarawak. Proceedings of the International Symposium on Biostratigraphy of Mainland and Southeast Asia: Facies and Paleontology, Chiang Mai, Thailand, 231-242.

Adams, C.G., 1965. The foraminifera and stratigraphy of the Melinau Limestone, Sarawak, and its importance in Tertiary correlation. Quarterly Journal of the Geological Society 121, 283-338.

Adams, C.G., 1970. A reconsideration of the east Indian letter classification of the Tertiary. British Museum of (Natural History), Geology 19, 87-137.

Adams, C.G., and Haak, R., 1962. The stratigraphical succession in the Batu Gading area, Middle Baram, north Sarawak. In: Haile, N.S. (Ed.), The Geology and Mineral Resources of the Suai-Baram area, North Sarawak: Geological Survey Department, British Territories in Borneo, Memoir 13, 141-150.

Ali, M., 1995. Carbonate cement stratigraphy and timing of diagenesis in a Miocene mixed carbonate-clastic sequence, offshore Sabah, Malaysia - constraints from cathodoluminescence, geochemistry and isotope studies. Sedimentary Geology 99, 191-214.

Anderson, T.F., and Arthur, M.A., 1983. Stable isotopes of oxygen and carbon and their application to sedimentologic and paleoenvironmental problems. In: Arthur, M.A., Anderson, T.F., Kaplan, I.R., Veizer, J., and Land, L.S. (Eds.), Stable Isotopes in Sedimentary Geology, SEPM Short Course No. 10, 1-1 - 1-151.

Antonellini, M., and Mollema, P.N., 2000. A natural analog for a fractured and faulted reservoir in dolomite: Triassic Sella Group, Northern Italy. American Association of Petroleum Geologists Bulletin 84, 314-344.

Arosi, H.A., and Wilson, M.E.J., 2015. Diagenesis and fracturing of a large-scale, syntectonic carbonate platform. Sedimentary Geology 326, 109-134.

Bastesen, E., Braathen, A., Nøttveit, H., Gabrielsen, R.H., and Skar, T., 2009. Extensional fault cores in micritic carbonate – Case studies from the Gulf of Corinth, Greece. Journal of Structural Geology 31, 403-420.

Bathurst, R.G.C., 1987. Diagenetically enhanced bedding in argillaceous platform limestones: Stratified cementation and selective compaction. Sedimentology 34, 749-778.

Bathurst, R.G.C., 1990. Thoughts on the growth of stratiform stylolites in buried limestones. Sediments and Environmental Geochemistry 3-15.

Beavington-Penney, S.J., and Racey, A., 2004. Ecology of extant nummulitids and other larger benthic foraminifera: applications in palaeoenvironmental analysis. Earth Science Reviews 67, 219-265.

Beavington-Penney, S.J., Wright, V.P., and Woelkerling, Wm. J., 2004. Recognising macrophyte-vegetated environments in the rock record: a new criterion using 'hooked' forms of crustose coralline red algae.

Benedetti-Cecchi, L., 2001. Variability in abundance of algae and invertebrates at different spatial scales on rocky sea shores. Marine Ecology Progress Series 215, 79-92.

Billi, A., 2005. Grain size distribution and thickness of breccia and gouge zones from thin (<1 m) strike-slip fault cores in limestone. Journal of Structural Geology 27, 1823-1837.

Blendinger, W., 2001. Triassic carbonate buildup flanks in the Dolomites, northern Italy: breccias, boulder fabric and the importance of early diagenesis. Sedimentology 48, 919-933.

Blount, D.N., and Moore Jr, C.H., 1969. Depositional and non-depositional carbonate breccias, Chiantla Quandrangle, Quatemala. Geological Society of America Bulletin 80, 429-442.

Bowles, C.G., and Braddock, W.A., 1963. Solution breccias of the Minnelusa Formation in the Black Hills, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 475-C, p. C91-C95.

Brachert, T.C., and Dullo, W.C., 2000. Shallow burial diagenesis of skeletal carbonates: selective loss of aragonite shell material (Miocene to Recent, Queensland Plateau and Queensland Trough, NE Australia) – implications for shallow cool-water carbonates. Sedimentary Geology 136, 169-187.

Braithwaite, C.J.R., and Heath, R.A., 1992. Deposition and diagenesis of debris flows in Upper Ordovician limestones, Hadeland, Norway. Sedimentology 39, 753-767.

Budd, D.A., and Perkins, R.D., 1980. Bathymetric zonation and paleoecological significance of microborings in Puerto Rican shelf and slope sediments. Journal of Sedimentary Petrology 50, 881-904.

Carnell, A.J.H., and Wilson, M.E.J., 2004. Dolomites in SE Asia - varied origins and implications for hydrocarbon exploration. In: Braithwaite, C.J.R., Rizzi, G., and Darke, G. (Eds.), The Geometry and Petrogenesis of Dolomite Hydrocarbon Reservoirs. Geological Society of London, Special Publication 235, 255-300.

Caron, V., and Nelson, C.S., 2009. Diversity of neomorphic fabrics in New Zealand Plio-Pleistocene cool-water limestones: Insights into aragonite alteration pathways and controls. Journal of Sedimentary Research 79, 226-246.

Casabianca, D., Bosence, D., and Beckett, D., 2002. Reservoir potential of Cretaceous platform-margin breccias, central Italian Apennines. Journal of Petroleum Geology 25, 179-202.

Chai Peng, L., Shafeea Leman, M., Hassan, K., Nasib, B.M., Karim, R., 2004. Stratigraphic lexicon of Malaysia. Geological Society of Malaysia, 162 p.

Conglio, M., and Dix, G.R., 1992. Carbonate slopes. In: Walker, R.G., and James, N.P. (Eds.), Facies Models: response to seal-level change: Geological Association of Canada, St. Johns, Newfoundland, pp. 349-373.

Cook, H.E., and Enos, P. 1977. Deep-water carbonate environments – an introduction. In: Cook, H.E., and Enos, P. (Eds.), Deep-water carbonate environments: SEPM Special Publication 25, pp. 1-3.

Coplen, T.B., Brand, W.A., Gehre, M., Groning, M., Meijer, H.A.J., Toman, B., and Verkouteren, R.M., 2006. New Guidelines for d13C measurements. Analytical Chemistry 78, 2439-2441.

Crevello, P.D., and Schlager, W., 1980. Carbonate debris sheets and turbidites, Exuma Sound, Bahamas. Journal of Sedimentary Petrology 50, 1121-1148.

Davies, G.R., 1970. Carbonate bank sedimentation, eastern Shark Bay, Western Australia, AAPG Memoirs 13, 85-168.

DeCelles, P.G., and Giles, K.A., 1996. Foreland basin systems. Basin Research 8, 105-123.

Dunham, R.J., 1962. Classification of carbonate rocks according to depositional texture. In*:* Ham, W.E. (Ed.), Classification of carbonate rocks. American Association of Petroleum Geologists, Memoir 1, 108-121.

Eggins, S., De Deckker, P., and Marshall, J., 2003. Mg/Ca variation in planktonic foraminifera tests: implications for reconstructing palaeo-seawater temperature and habitat migration. Earth and Planetary Science Letters 212, 291-306.

Eliassen, A., and Talbot, M.R., 2005. Solution-collapse breccias of the Minkinfjellet and Wordiekammen Formations, Central Spitsbergen, Svalbard: a large gypsum palaeokarst system. Sedimentology 52, 775-794.

Embry, A.F. and Klovan, J.E., 1971. A late Devonian reef tract on northeastern Banks Island, Northwest Territories. Canadian Petroleum Geologist, Bulletin 19, 730-781.

Esteban, M. and Taberner, C. 2003. Secondary porosity development during late burial in carbonate reservoirs as a result of mixing and/or cooling of brines. Journal of Geochemical Exploration, 78–79, 355–359.

Ferry, S., Grosheny, D., Backert, N., and Atrops, F., 2015. The base-of-slope carbonate breccia system of Céüse (Tithonian, S-E France): Occurrence of progradational stratification in the head plug of coarse granular flow deposits. Sedimentary Geology 317, 71-86.

Finkel, E.A., and Wilkinson, B.H., 1990. Stylolitization as a source of cement in Mississippian Salem Limestone, west central Indiana. American Association of Petroleum Geologists Bulletin 74, 174-186.

Flügel, E., 2004. Microfacies of carbonate rocks, Springer, Berlin Heidelberg New York, 976 p.

Freidman, G.M., 1997. Dissolution-collapse breccias and paleokarst resulting from dissolution of evaporite rocks, especially sulfates. Carbonates and Evaporites 12, 53-63.

Fruth, L.S., Orme, G.R., and Donath, F.A., 1966. Experimental compaction effects in carbonate sediments. Journal of Sedimentary Petrology 36, 747-754.

Goulbric, S., Perkins, R.D., and Lukas, K.J., 1975. Boring microorganisms and microborings in carbonate substrates. In: Frey, R.W. (Ed.), The study of trace fossils, Springer, New York, p. 229-259.

Gradstein, F.M., Ogg, J.G., and Smith, A.G., (Eds.), 2004. A Geologic Time Scale 2004. Cambridge University Press, UK, p. 589.

Haile, N.S., 1962. The Geology and Mineral Resources of the Suai-Baram area, North Sarawak: Geological Survey Department, British Territories in Borneo, Memoir 13, 141-150.

Hall, R., 1996. Reconstructing Cenozoic SE Asia. In: Hall, R., and Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. Geological Society of London, Special Publication 106, 153-184.

Hall, R., 2002. SE Asian heat flow: Call for new data. Indonesian Petroleum Association, Newsletter 4, 20-21.

Hall, R., and Nichols, G., 2002. Cenozoic sedimentation and tectonics in Borneo: climatic influences on orogenesis. In: Jones, S.J., and Frostick, L. (Eds.), Sediment Flux to Basins: Causes, Controls and Consequences. Geological Society of London, Special Publication 191, 5-22.

Hall, R, Cottam, M.A., and Wilson, M.E.J., 2011. The SE Asian gateway: history and tectonics of the Australia-Asia collision: Geological Society, London, Special Publications 355, 1-6.

Hendry, J.P., Taberner, C., Marshall, J.D., Pierre, C., and Carey, P.F., 1999. Coral reef diagenesis records pore-fluid evolution and paleohydrology of a siliciclastic basin margin succession (Eocene South Pyrenean foreland basin, northeastern Spain). Geological Society of America Bulletin 111, 395-411.

Hopkins, J.C., 1977. Production of foreslope breccia by differential submarine cementation and downslope displacement of carbonate sands, miette and ancient wall buildups, Devonian, Canada. In: Cook, H.E., and Enos, P. (Eds.), Deep-water carbonate environments: SEPM Special Publication 25, pp. 155-170.

Hutchinson, C.S., 1996. The “Rajang accretionary prism” and “Lupar Line” problem of Borneo. In: Hall, R., and Blundell, D. (Eds.), Tectonic evolution of SE Asia. Geological Society of London, Special Publication 106, 247-261.

Hutchinson, C.S., 2005. Geology of North-West Borneo: Elsevier Science, 421 p.

Ingersoll, R.V., 2012. Tectonics of sedimentary basins, with revised nomenclature. In: Busby, C., and Azor, A. (Eds.), Tectonics of sedimentary basins: recent advances. Wiley-Blackwell, UK. 3-43.

James, N.P., 1981. Megablocks of calcified algae in the Cow Head Breccia, western Newfoundland: Vestiges of a Cambro-Ordovician platform margin. Geological Society of America Bulletin, Part 1, v. 92, 799-811.

James, N.P., and Stevens, R.K., 1986. Stratigraphy and correlation of the Cambro-Ordovician Cow Head Group, western Newfoundland. Geological Survey of Canada Bulletin 366, 143 p.

Lind, I.L., 1993. Stylolites in chalk from Leg 130, Ontong Java Plateau. In: Berger, W.H., Kroenke, J.W., and Mayer, L.A. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, 130. Ocean Drilling Program, College Station, TX, 445-451.

Loucks, R.G., 1999. Paleocave carbonate reservoirs: origins, burial-depth modifications, spatial complexity, and reservoir implications. AAPG Bulletin 83, 1795-1834.

Lunt, P., and Allan, T., 2004. A history and application of larger foraminifera in Indonesian biostratigraphy, calibrated to isotopic dating. GRDC Workshop on Micropalaeontology, 109 pp.

Machel, H.G., 2004. Concepts and models of dolomitization: A critical reappraisal. In: Braithwaite, C.J.R., Rizzi, G., and Darke, G. (Eds.), The Geometry and Petrogenesis of Dolomite Hydrocarbon Reservoirs. Geological Society of London, Special Publication 235, 7-63.

Madden, R.H.C., and Wilson, M.E.J., 2012. Diagenesis of Neogene delta-front patch reefs: Alteration of coastal, siliciclastic influenced carbonates from humid equatorial regions. Journal of Sedimentary Research 82, 871-888.

Madden, R.H.C., and Wilson, M.E.J., 2013. Diagenesis of a SE Asian Cenozoic carbonate platform margin and its adjacent basinal deposits. Sedimentary Geology 286-287, 20-38.

Madden, R.H.C., Wilson, M.E.J., and O'Shea, M., 2013. Modern fringing reef carbonates from equatorial SE Asia: An integrated environmental, sediment and satellite characterisation study. Marine Geology 344, 163-185.

Mallon, A.J., and Swarbrick, R.E., 2008. Diagenetic characteristics of low permeability, non-reservoir chalks from the Central North Sea. Marine and Petroleum Geology 25, 1097-1108.

Mazzullo, J. and Graham, A.J. (Eds.), 1988. Handbook for Shipboard Sedimentologists. ODP Technical Notes 8.

McIlreath, I.A., and James, N.P., 1978. Facies models 12: carbonate slopes. Geoscience Canada, v.5(4), 180-199.

McMechan, G.A., Loucks, R.G., Zeng, X., and Mescher, P., 1998. Ground penetrating radar imaging of a collapsed paleocave system in the Ellenburger dolomite, central Texas. Journal of Applied Geophysics 39, 1-10.

McMonagle, L.B., Lunt, P., Wilson, M.E.J., Johnson, K.G., Manning, C., and Young, J., 2011. A re-assessment of age dating of fossiliferous limestones in eastern Sabah, Borneo: implications for understanding the origins of the Indo-Pacific marine biodiversity hotspot: Palaeogeography, Palaeoclimatology, Palaeoecology 305, 28-42.

Melim, L.A., Westphal, H., Swart, P.K., Eberli, G.P., and Munnecke, A., 2002. Questioning carbonate diagenetic paradigms: evidence from the Neogene of the Bahamas. Marine Geology 185, 27-53.

Mihaljević, M., Renema, W., Welsh, K., and Pandolfi, J.M., 2014. Eocene-Miocene shallow-water carbonate platforms and increased habitat diversity in Sarawak, Malaysia. Palaios 29, 378-391.

Mustard, P.S., and Donaldson, J.A., 1990. Paleokarst breccias, calcretes, silcretes and fault talus breccias at the base of Upper Proterozoic "Windermere" strata, Northern Canadian Cordillera. Journal of Sedimentary Petrology 60, 525-539.

Mylroie, J.E., and Carew, J.L., 1990. The flank margin model for dissolution cave development in carbonate platforms. Earth Surface Processes and Landforms 15, 413-424.

Ngau, A., 1989. The geology of Batu Gading area, Middle Baram, Sarawak, Malaysia. Department of the Geological University, Malaya, 156 pp.

Nicolaides, S., and Wallace, M.W., 1997. Pressure dissolution and cementation in an Oligo-Miocene non-tropical limestone (Clifton Formation), Otway Basin, Australia. In: James, N.P., and Clarke, J.A.D. (Eds.), Cool Water Carbonates. SEPM, Special Publication 56, 249-261.

Park, R.K., Siemers, C.T., and Brown, A., 1992. Holocene carbonate sedimentation, Pulau Seribu, Java Sea: the third dimension. In: Siemers, C.T., Longman, L.W., Park, R.K., and Kaldi, J.G. (Eds.), Carbonate Rocks and Reservoirs of Indonesia, A Core Workshop. Indonesian Petroleum Association, Core Workshop Notes 2: 1-15.

Paul, D., and Skrzypek, G., 2007. Assessment of carbonate-phosphoric acid analytical technique performed using Gas Bench II in continuous flow isotope ratio mass spectrometry. International Journal of Mass Spectrometry 262, 180-186.

Perry, C.T., 1998. Grain susceptibility to the effects of microboring: implications for the preservation of skeletal carbonates. Sedimentology 45, 39-51.

Perry, C.T., 1999. Biofilm-related calcification, sediment trapping and constructive micrite envelopes: a criterion for the recognition of ancient grass-bed environments? Sedimentology 46, 33-45.

Perry, C.T., and Bertling, M., 2000. Spatial temporal patterns of macroboring within Mesozoic and Cenozoic coral reef systems. In: Insalaco, E., Skeleton, P.W., and Palmer, T.J. (Eds.), Carbonate Platform Systems: Components and Interactions. Geological Society of London, Special Publication 178, 33-50.

Perry, C.T., and Macdonald, I.A., 2002. Impacts of light penetration on the bathymetry of reef microboring communities: implications for the development of microendolithic trace assemblages. Palaeogeography, Palaeoclimatology, Palaeoecology 186, 101-113.

Perry, C.T., and Larcombe, P., 2003. Marginal and non-reef-building coral environments. Coral Reefs 22, 427-432.

Perry, C.T., and Hepburn, L.J., 2008. Syn-depositional alteration of coral reef framework through bioerosion, encrustation and cementation: Taphonomic signatures of reef accretion and reef depositional events. Earth-Science Reviews 86, 106-144.

Pingitore Jr, N.E., 1976. Vadose and phreatic diagenesis: processes, products and their recognition in corals. Journal of Sedimentary Petrology 46, 985-1006.

Pireno, G.E., Cook, C., Yulion, D., and Lestari, S., 2009. Berai carbonate debris flow as reservoir in the Ruby Field, Sebuku Block, Makassar Straits: a new exploration play in Indonesia. Proceedings of the 33rd Indonesian Petroleum Association Annual Convention and Exhibition (19 pp).

Pohler, S.M.L., and James, N.P., 1989. Reconstruction of a Lower/Middle Ordovician Carbonate Shelf margin: Cow Head Group, Western Newfoundland. Facies 21, 189-262.

Quijada, I.E., Suarez-Gonzalez, P., Benito, M.I., Lugli, S., and Mas, R., 2014. From carbonate-sulphate interbeds to carbonate breccias: The role of tectonic deformation and diagenetic processes (Cameros Basin, Lower Cretaceous, N Spain). Sedimentary Geology 312, 76-93.

Railsback, L.B., 1993. Lithologic controls on morphology of pressure-dissolution surfaces (stylolites and dissolution seams) in Paleozoic carbonate rocks from the Mideastern United States. Journal of Sedimentary Petrology 63, 513-522.

Reich, S., Di Martino, E., Todd, J.A., Wesselingh, F.P., and Renema, W., 2015. Indirect paleo-seagrass indicators (IPSIs): A review. Earth Science Reviews 143, 161-186.

Reijmer, J.J.G., Mulder, T., and Borgomano, J., 2015. Carbonate slopes and gravity deposits. Sedimentary Geology 317, 1-8.

Saller, A.H., Vijaya, S., 2002. Depositional and Diagenetic History of the Kerendan Carbonate Platform, Oligocene, Central Kalimantan, Indonesia. Journal of Petroleum Geology, 25, 123-150.

Saller, A.H., Dickson, J.A.D., and Matsuda, F., 1999. Evolution and distribution of porosity associated with subaerial exposure in Upper Paleozoic platform limestones in West Texas. AAPG Bulletin 83, 1835-1854.

Sanders, D., 2010. Sedimentary facies and progradational style of a Pleistocene talus-slop succession, Northern Calcareous Alps, Austria. Sedimentary Geology 228, 271-283.

Sanders, D.G., Osermann, M., and Kramers, J., 2010. Meteoric diagenesis of Quaternary carbonate-rocky talus slope successions (Northern Calcareous Alps, Austria). Facies 56, 27-46.

Shears, N., and Babcock, R., 2002. Marine reserves demonstrate top-down control of community structure on temperate reefs. Oecologia 132, 131-142.

Skrzypek, G., 2013. Normalization procedures and reference material selection in stable HCNOS isotope analyses – an overview. Analytical and Bioanalytical Chemistry 405, 2815-2823.

Spence, G.H., and Tucker, M.E., 1997. Genesis of limestone megabreccias and their significance in carbonate sequence stratigraphic models: a review. Sedimentary Geology 112, 163-193.

Subekti, A., Mustapha, H., Guritno, E., Smart, J., Susilo, A., Nugroho, B., Darmawan, W. and Wilson, M.E.J. 2015. New insights into the Kerendan Carbonate Platform: an Oligocene Reservoir from the Upper Kutai Basin, Kalimantan. Proceedings of the 39th Indonesian Petroleum Association. 10 p.

Swei, G.H., and Tucker, M.E., 2012. Impact of diagenesis on reservoir quality in ramp carbonates: Gialo Formation (middle Eocene), Sirt Basin, Libya. Journal of Petroleum Geology 35, 25-48.

Swennen, R., Viaene, W., and Cornelissen, C., 1990. Petrography and geochemistry of the Belle Roche Breccia (lower Visean, Belgium): evidence for brecciation by evaporite dissolution. Sedimentology 37, 859-878.

Swinchatt, J.P., 1965. Significance of constituent composition, texture, and skeletal breakdown in some recent carbonate sediments. Journal of Sedimentary Petrology 35, 71-90.

Tanos, C.A., Kupecz, J., Hilman, A.S., Ariyono, D., and Sayers, I.L., 2013. Diagenesis of carbonate debris deposits from the Sebuku Block, Makassar Strait, Indonesia. Proceedings of the 37th Indonesian Petroleum Association Annual Convention and Exhibition (18 pp).

Tarasewicz, J.P.T., Woodcock, N.H., and Dickson, J.A.D., 2005. Carbonate dilation breccias: Examples from the damage zone to the Dent Fault, northwest England. Geological Society of America Bulletin 117, 736-745.

Tomascik, T., Mah, A.J., Nontji, A., and Moosa, M.K., 1997. The Ecology of the Indonesian Seas. Oxford University Press, Singapore, 1388 p.

Tucker, M.E., and Wright, V.P., 1990. Carbonate Sedimentology, Blackwell Scientific Publications, 482 p.

Tucker, M.E., 1991. Sequence stratigraphy of carbonate-evaporite basins: models and application to the Upper Permian (Zechstein) of northeast England and adjoining North Sea. Journal of the Geological Society 148, 1019-1036.

Udchachon, M., Burrett, C., Thassanapak, H., Chonglakmani, C., Campbell, H., and Feng, Q., 2014. Depositional setting and paleoenvironment of an alatoconchid-bearing Middle Permian carbonate ramp sequence in the Indochina Terrane. Journal of Asian Earth Sciences 87, 37-55.

van Gorsel, J.T., 1988. Biostratigraphy in Indonesia: Methods, pitfalls and new directions. *Proceedings of the Indonesian Petroleum Association,* **17**th Ann. Convention, October, 275-300.

von der Borch, C.C., Grady, A.E., Eickhoff, K.H., Dibona, P., and Christie-Blick, N., 1989. Late Proterozoic Pasty Springs Canyon, Adelaide geosyncline: submarine or subaerial origin? Sedimentology 36, 777-792.

van der Kooij, B., Immenhauser, A., Steubers, T., Bahamonde Rionda, J.R., and Merino Tome, O., 2010. Controlling factors of volumetrically important marine carbonate cementation in deep slope settings. Sedimentology 57, 1491-1525.

van der Vlerk, I.M., and Umbgrove, J.H., 1927. Tertiary Gidsforaminifera van Nederladisch Oost-Indie. Wetenschappelijke Mededeelingen van de Dienst van de Mijnbouw in Nederlandsch-Oost Indie 6, 3-35.

Wannier, M., 2009. Carbonate platforms in wedge-top basins: an example from the Gunung Mulu National Park, Northen Sarawak (Malaysia): Marine and Petroleum Geology 26, 177-207.

Whalen, M.T., Eberli, G.P., Van Buchem, F.S.P., and Mountjoy, E.W., 2000. Facies models and architecture of Upper Devonian carbonate platforms (Miette and Ancient wall), Alberta, Canada. In: Homewood P.W., and Eberli, G.P. (Eds.), Genetic stratigraphy on the exploration and the production scales: Case studies from the Pennsylvanian of the Paradox Basin and the Upper Devonian of Alberta. Bulletin des Centres de Recherches et d'Exploration-Production, Elf-Aquitaine, Mémoire (2000), pp. 139-178.

Wilson, M.E.J., 1996. Evolution and hydrocarbon potential of the Tertiary Tonasa Limestone Formation, Sulawesi, Indonesia. Proceedings of the Indonesian Petroleum Association 25th Annual Convention, pp. 227-240.

Wilson, M.E.J. 1999. Prerift and synrift sedimentation during early fault segmentation of a Tertiary carbonate platform, Indonesia. Marine and Petroleum Geology. 16, (8), 825-848.

Wilson, M.E.J. 2000. Tectonic and volcanic influences on the development and diachronous termination of a tropical carbonate platform. Journal of Sedimentary Research. 70, (2), 310-324.

Wilson, M.E.J., 2002. Cenozoic carbonates in SE Asia: implications for equatorial carbonate development. Sedimentary Geology 147, 295-428.

Wilson, M.E.J., 2008. Global and regional influences on equatorial shallow marine carbonates during the Cenozoic. Palaeogeography, Palaeoclimatology, Palaeoecology 265, 262-274.

Wilson, M.E.J., 2012. Equatorial carbonates: an earth systems approach. Sedimentology 59, 1-31.

Wilson, M.E.J., and Bosence, D.W.J., 1996. The Tertiary evolution of South Sulawesi: a record in redeposited carbonates of the Tonasa Limestone Formation. In: Hall, R., and Blundell, D. (Eds.), Tectonic Evolution of Southeast Asia. Geological Society of London, Special Publication 106, 365-389.

Wilson, M.E.J., and Rosen, B.R.R., 1998. Implications of the paucity of corals in the Paleogene of SE Asia: plate tectonics or Centre of Origin. In: Hall, R., and Holloway, J.D. (Eds.), Biogeography and Geological Evolution of SE Asia. Backhuys Publishers. Amsterdam, Netherlands, pp. 165-195.

Wilson, M.E.J., and Evans, M.J., 2002. Sedimentology and diagenesis of Tertiary carbonates on the Mangkalihat Peninsula, Borneo: implications for subsurface reservoir quality. Marine and Petroleum Geology 19, 873-900.

Wilson, M.E.J., and Vecsei, A., 2005. The apparent paradox of abundant foramol facies in low latitudes: their environmental significance and effect on platform development. Earth Science Reviews 69, 133-168.

Wilson, M.E.J., Bosence, D.W.J., Limbong, A., 2000. Tertiary syntectonic carbonate platform development in Indonesia. Sedimentology 47, 395-419.

Wilson, M.E.J., Chambers, J.L.C, Evans, M.J., Moss, S.J. and Satria Nas, D. 1999. Cenozoic carbonates in Borneo: Case studies from Northeast Kalimantan. Journal of Asian Earth Science 17, 183-201.

Wilson, M.E.J., Evans, M.J., Oxtoby, N., Satria Nas, D., Donnelly, T., and Thirlwall, M., 2007. Reservoir quality, textural evolution and origin of fault-associated dolomites. American Association of Petroleum Geologists Bulletin 91, 1247-1272.

Wilson, M.E.J., Chambers, J.L.C., Manning, C., and Nas, D.S. 2012. Spatio-temporal evolution of a Tertiary carbonate platform margin and adjacent basinal deposits. Sedimentary Geology 271-272, 1-27.

Wilson, M.E.J., Chang Ee Wah, E., Dorobek, S., and Lunt, P., 2013. Onshore to offshore trends in carbonate sequence development, diagenesis and reservoir quality across a land-attached shelf in SE Asia. Marine and Petroleum Geology 45, 349-376.

Woodcock, N.H., and Mort, K., 2008. Classification of fault breccias and related fault rocks. Geological Magazine 145, 435-440.

Figures.

Figure 1. Simplified geological map of north Borneo showing the location of the study area (Batu Gading). Major outcropping and subsurface Cenozoic and modern carbonates are also shown (modified from Wilson et al., 2013).

Figure 2. (a) Outcrop view of the Batu Gading Limestone showing faulted outcrop of the ~10 m thick brecciated Late Oligocene deposits that unconformably overlie the massive limestone deposits. (b) Large two-meter blocks of Batu Gading limestone breccia that form the Miri sea defence wall. Block

in the centre of view demonstrates post-brecciation through going fracture with later in fill by calcite cement. (c) Close up of one of the Miri sea defence blocks showing the fitted fabric of the Batu Gading limestone breccia, with individual clasts of differing facies discernible: (1) Larger Benthic Foraminifera Facies Group and (2) Coral Rich Facies Group (recrystallised coral shown). (d) Fitted fabric between clasts of Larger Benthic Foraminifera Facies Group (1) and mudstone lithology likely of the Planktonic Foraminifera Facies Group (2). The development of a fitted fabric through circum clast stylolites has led to the concentration of insolubles (3). The larger benthic foraminifera in the clast shown demonstrate a thin flattened form with a width to height ratio of approximately 10:1 (1). (e) Clast of Larger Benthic Foraminifera Facies Group showing robust foraminifera with width to height ratios of approximately 2:1 (1) cross-cut by post-brecciation stylolites and fractures (2). Fractures cross-cut the fitted fabric with at least two different orientations (3).

Figure 3. Plane-polarised light thin section photomicrographs illustrating a range of diagenetic features of the Batu Gading limestone breccia. (a) Sample BG121-006-7; clast of *Discocyclina*-rich bioclastic pack-grain-rudstone of Late Eocene age. Extensive micritisation (1) of the larger foraminifera has occurred with intergranular development of inclusion-free granular equant calcite cement (2). Good preservation of minor echinoderm spines and planktonic foraminifera is also displayed (3). A post-brecciation late stage fracture cross-cuts the clast to the right of the field of view (4). (b) Sample BG121-004#1-4; clast of algal peloidal bioclastic grain-rudstone.. Pervasive micritisation of coralline algae (1) and miliolid foraminifera (2) has resulted in a high abundance of peloids. Granular equant calcite cement is well developed between allochems and appears to be contiguous with the echinoderm syntaxial overgrowth (3). Dasycladacean algae are common in this facies and may show geopetal in-fills (4). (c) Sample BG121-002-2; clast of coral bioclastic grain-pack-floatstone. Bioclasts are almost entirely micritised. An aragonitic fragment has been replaced by granular (margins; 1) to blocky (centre; 2) mosaic calcite with retention of prior micritic infills (of *Halimeda* utricles, or possible microborings in coral; 3). (d) Sample BG121-004#2-7; clast of coral, planktonic and smaller benthic foraminifera bioclastic pack-grainstone. Sample shows early syntaxial

overgrowth of echinoderm fragment (1) and minor pre-brecciation fracture infilled by later granular equant calcite cement (2). Bioclasts show little early alteration characteristics e.g., micritisation. (e) Sample BG121-016-3; clast of coral bioclastic rudstone showing pervasive neomorphism by granular mosaic calcite (1) and some contemporaneous calcitisation of coral chambers in areas not filled by micritic matrix (2). (f) Sample BG125-003; coral bioclastic pack-floatstone. Original coral structure is preserved by thick micritic rims (1) and neomorphic replacement by granular mosaic calcite (2). Neomorphic cement aggrades into contemporaneous calcitisation of the coral chamber original porosity (3). (g) Sample BG121-002-4; clast of peloid, algae and miliolid bioclastic grainstone with large dasyclad at top of field of view. Pervasive micritisation of coralline algae (1), miliolids (2) and lesser imperforate larger benthic foraminifera (3) resulting in common peloids. Patchy development of inclusion rich granular mosaic calcite within the micritic fill indicates aggradational neomorphic cement growth (4). (h) Sample BG121-001-1; clast of algae, peloidal and miliolid bioclastic grainstone. Peloids demonstrate early effects of mechanical compaction through the development of tangential to concavo-convex grain contacts. Intergranular spaces are infilled by clear blocky equant calcite. (i) Sample BG119; planktonic foraminifera mud-wackestone. Sample demonstrates micritic rich characteristics of the Planktonic Foraminifera Facies Group. Samples of this facies group do not show abundant early alteration characteristics and lack common effects of pre-brecciation mechanical compaction and cementation. (j) Sutured margins of clasts, including algal peloidal bioclastic grain-rudstone and pack-grainstone, of sample BG121-004#1. Post-brecciation mechanical compaction is represented by the fitted breccia fabric enhanced by the development of dissolution seams at clast sutures and the concentration of insoluble non-carbonate material. (k) Sample BG121-011-1; clast of *Discocyclina* rudstone from an Upper Eocene deposit with abundant flattened forms and some moderately robust forms. The aligned fabric of elongate foraminifera is cross-cut by a dissolution seam (1) and subsequent fracture (2) during post-brecciation mechanical compaction. (l) Sample BG125-008-2; clast of planktonic foraminifera bioclastic wacke-packstone. Post-brecciation fracture showing bifurcating characteristics. Fracture is infilled by late equant calcite.

Figure 4. Stable isotopic compositions of $\delta^{18}O$ V-PDB and $\delta^{13}C$ V-PDB for calcite components and cements from the Batu Gading Limestone, based on the data presented in Table 2. .

Figure 5. Paragenetic scheme for the Batu Gading limestone breccia deposits. Relative timings are based on petrographic observations (Appendix 1).

Figure 6. Inferred depositional conditions (relative energy and water depth/setting) for the recognised facies groups and lithofacies (Table 1) on the basis of petrographic observations from the Batu Gading limestone breccia. No spatial distribution of these deposits is suggested here. The two lithofacies each of the Larger Benthic Foraminifera Facies Group and the Coralline Algae Bindstone Facies Group occupy the same interpreted energy and setting and are therefore not subdivided.

Figure 7. Summary of diagenetic phases affecting the different Facies Groups of the Batu Gading limestone breccia. The paragenesis and relative abundance of each event was determined through point-counting and visual estimates of thin-sections. Cartoons display schematic representations of key petrographic features and relationships of the facies groups, lithofacies and diagenetic variability (detailed diagenetic and facies group relationships are shown in Appendix 1).

Tables.

Table 1. Subdivision, ages, characteristics and inferred depositional environments of the carbonate facies from the Batu Gading limestone breccia.

Table 2. $\delta^{13}C$‰ VPDB and $\delta^{18}O$‰ V-PDB values from samples of the Batu Gading limestone breccia. Sample numbers are directly related to detailed petrological and lithofacies data shown in Appendix 1.

Table 3. General properties of documented carbonate breccias with details of diagenetic features (mainly post-brecciation).

Appendices.

Appendix 1. Section information, sample composition, sedimentological characteristics and diagenetic features recorded in thin-sections from the Batu Gading limestone breccia (digital data repository item only).

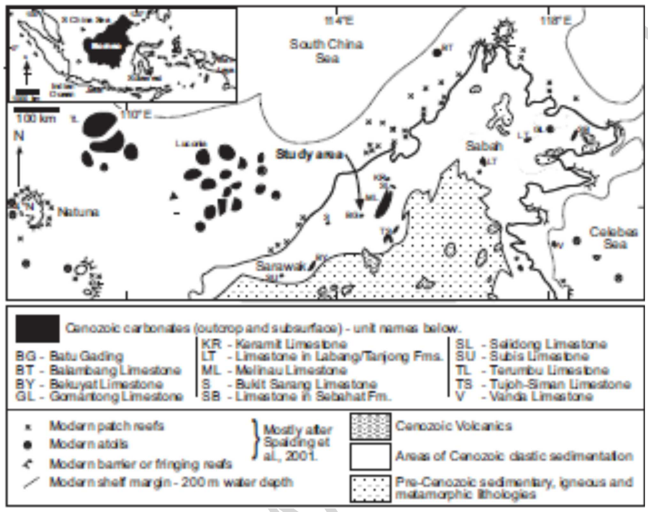

114°E
118°E
South China Sea
100 km
N
110°E
Study area
Sabah
Natuna
Celebes Sea
Sarawak
Cenozoic carbonates (outcrop and subsurface) - unit names below.
BG - Batu Gading
BT - Balambang Limestone
BY - Bekuyat Limestone
GL - Gomantong Limestone
KR - Keramit Limestone
LT - Limestone in Labang/Tanjong Fms.
ML - Melinau Limestone
S - Bukit Sarang Limestone
SB - Limestone in Sebahat Fm.
SL - Selidong Limestone
SU - Subis Limestone
TL - Terumbu Limestone
TS - Tujoh-Siman Limestone
V - Vanda Limestone
Modern patch reefs
Modern atolls
Modern barrier or fringing reefs
Modern shelf margin - 200 m water depth
Mostly after Spalding et al., 2001.
Cenozoic Volcanics
Areas of Cenozoic clastic sedimentation
Pre-Cenozoic sedimentary, igneous and metamorphic lithologies

Figure 1

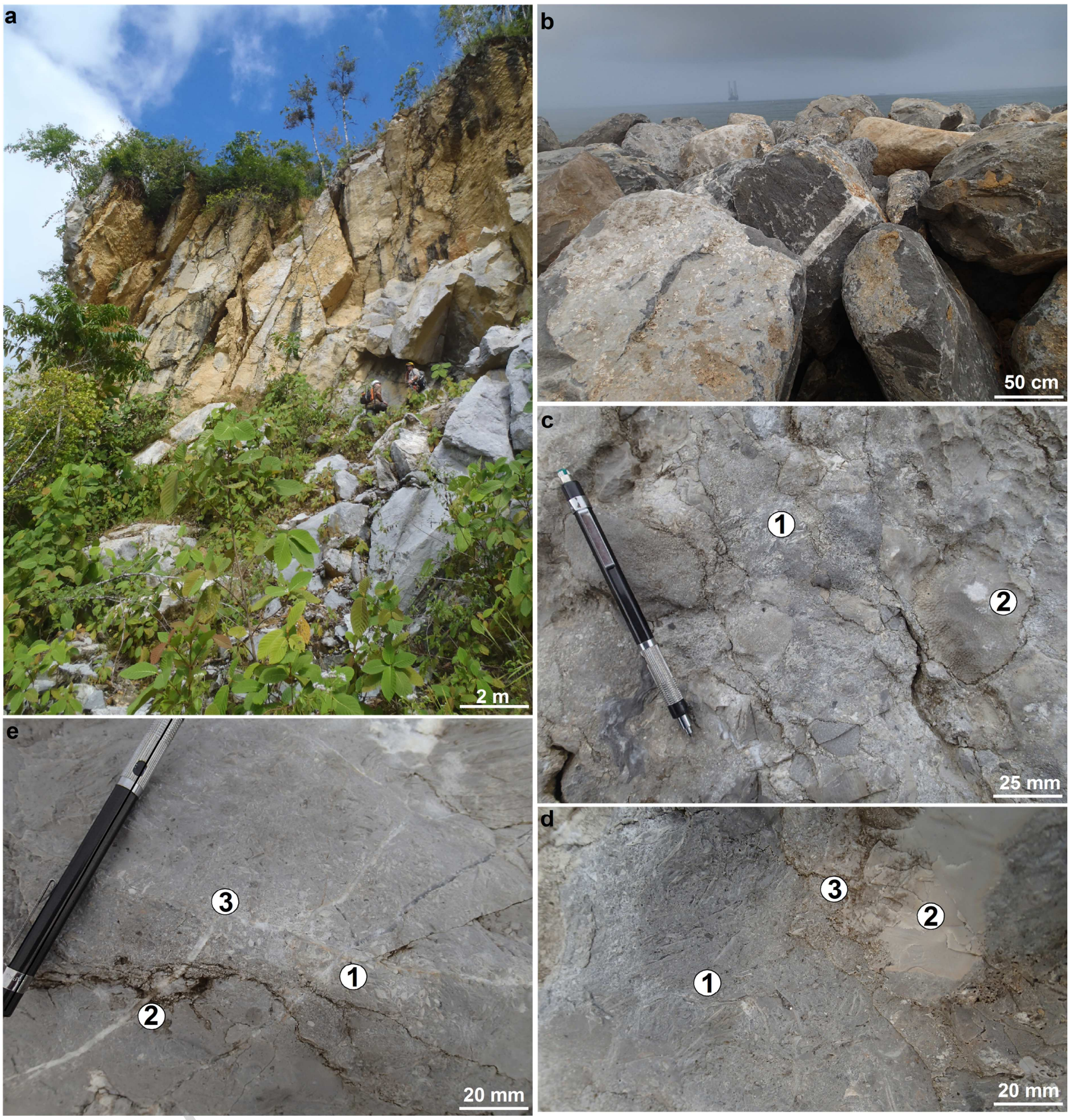


Figure 2

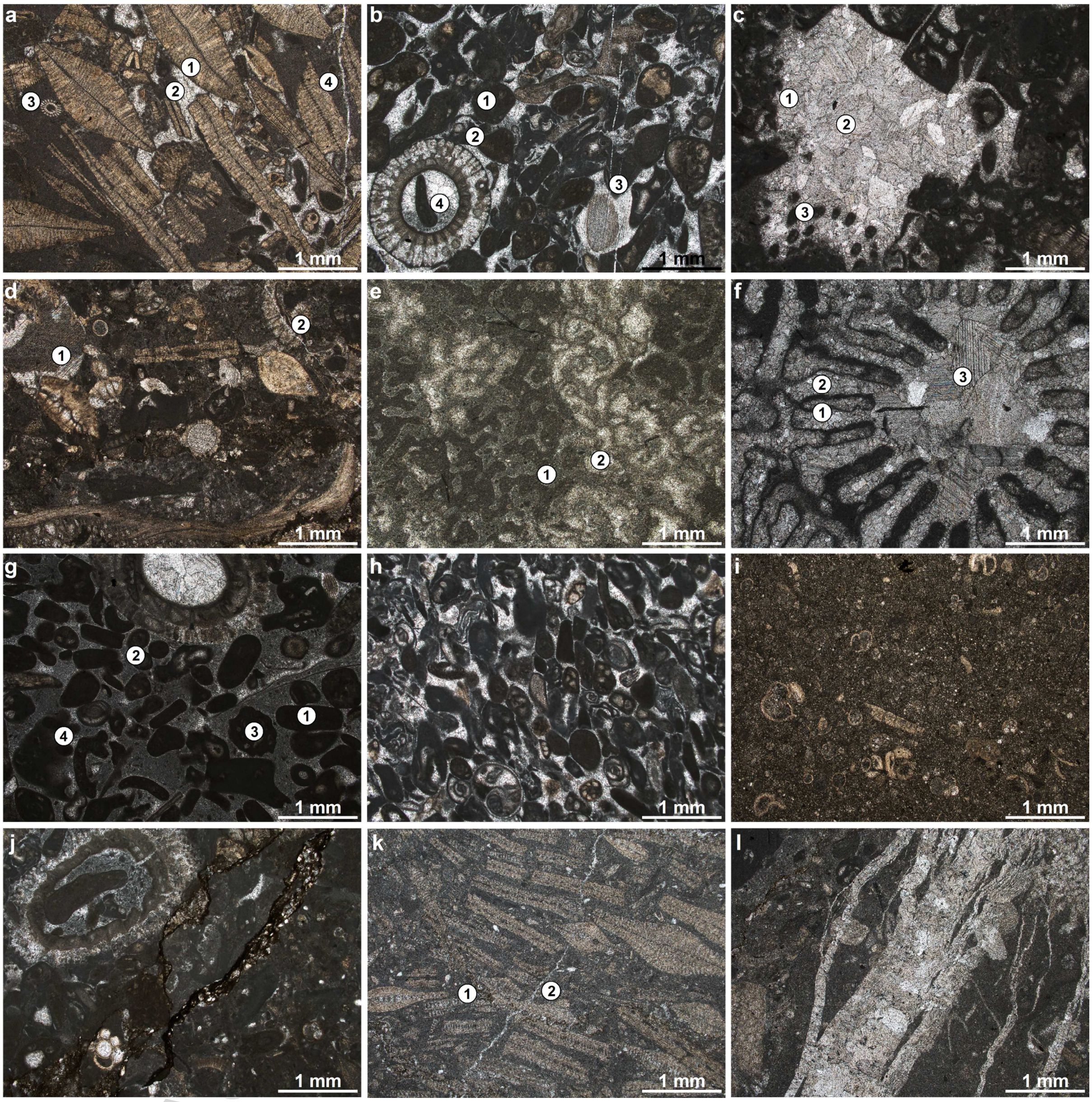
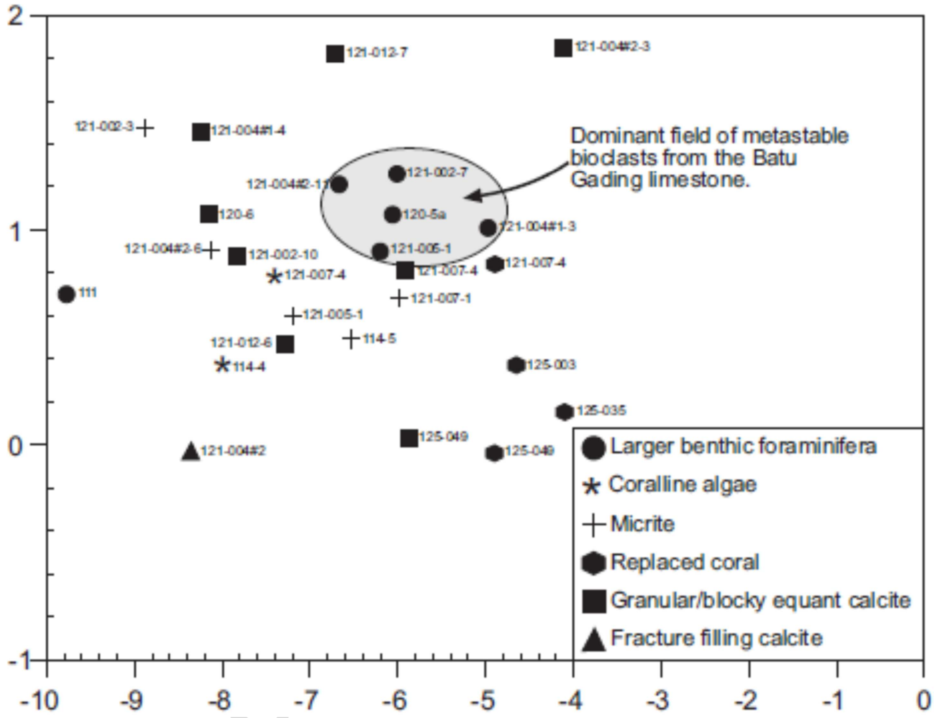


Figure 3

Figure 4



Dominant field of metastable bioclasts from the Batu Gading limestone.
Larger benthic foraminifera
Coralline algae
Micrite
Replaced coral
Granular/blocky equant calcite
Fracture filling calcite

Figure 5

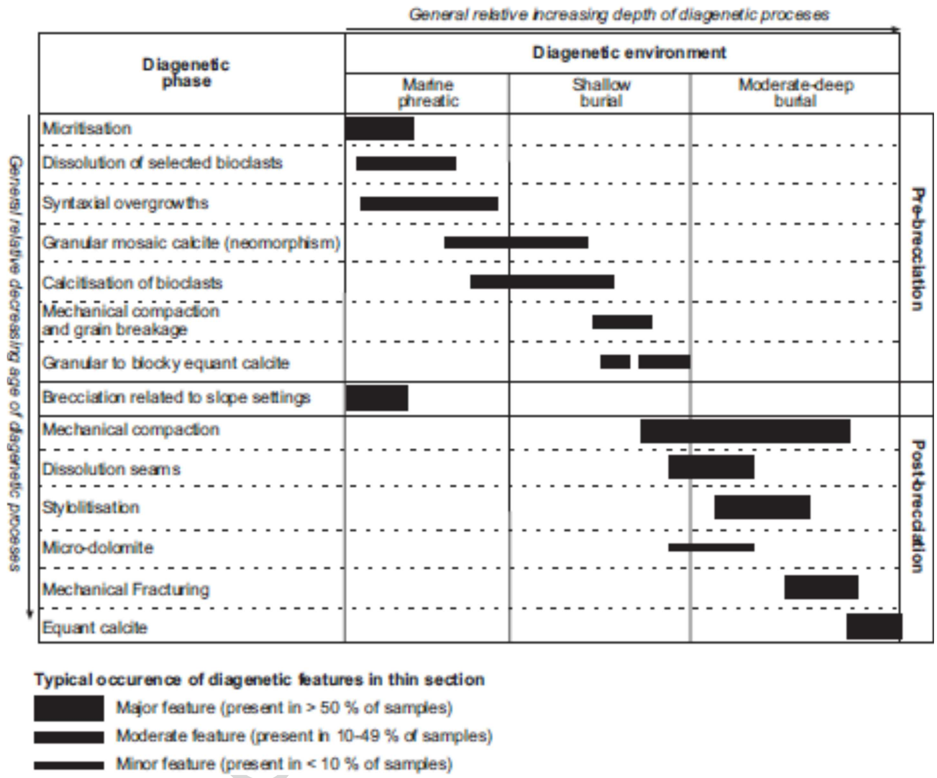

General relative increasing depth of diagenetic processes
Diagenetic phase
Diagenetic environment
Marine phreatic
Shallow burial
Moderate-deep burial
Micritisation
Dissolution of selected bioclasts
Syntaxial overgrowths
Granular mosaic calcite (neomorphism)
Calcitisation of bioclasts
Mechanical compaction and grain breakage
Granular to blocky equant calcite
Brecciation related to slope settings
Mechanical compaction
Dissolution seams
Stylolitisation
Micro-dolomite
Mechanical Fracturing
Equant calcite
Pre-brecciation
Post-brecciation
General relative decreasing age of diagenetic process
Typical occurence of diagenetic features in thin section
Major feature (present in > 50 % of samples)
Moderate feature (present in 10-49 % of samples)
Minor feature (present in < 10 % of samples)

Figure 6

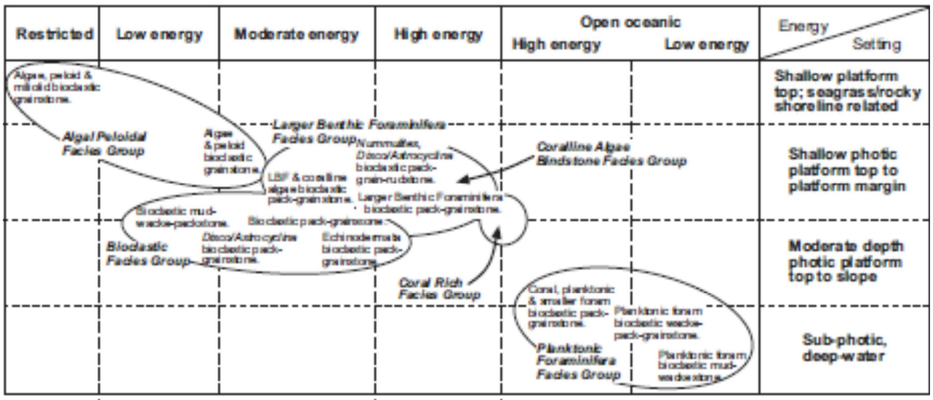

Restricted
Low energy
Moderate energy
High energy
Open oceanic
High energy
Low energy
Energy
Setting
Shallow platform top; seagrass/rocky shoreline related
Shallow photic platform top to platform margin
Moderate depth photic platform top to slope
Sub-photic, deep-water
Algal Peloidal Facies Group
Larger Benthic Foraminifera Facies Group
Nummulites, Disco/Astrocyclina bioclastic pack-grain-rudstone.
LBF & coralline algae bioclastic pack-grainstone.
Larger Benthic Foraminifera bioclastic pack-grainstone.
Coralline Algae Bindstone Facies Group
Bioclastic mud-wacke-packstone.
Bioclastic pack-grainstone.
Bioclastic Facies Group
Disco/Astrocyclina bioclastic pack-grainstone.
Echinoderm-rich bioclastic pack-grainstone.
Coral Rich Facies Group
Coral, planktonic & smaller foram bioclastic pack-grainstone.
Planktonic foram bioclastic wacke-pack-grainstone.
Planktonic Foraminifera Facies Group
Planktonic foram bioclastic mud-wackestone.

Figure 7

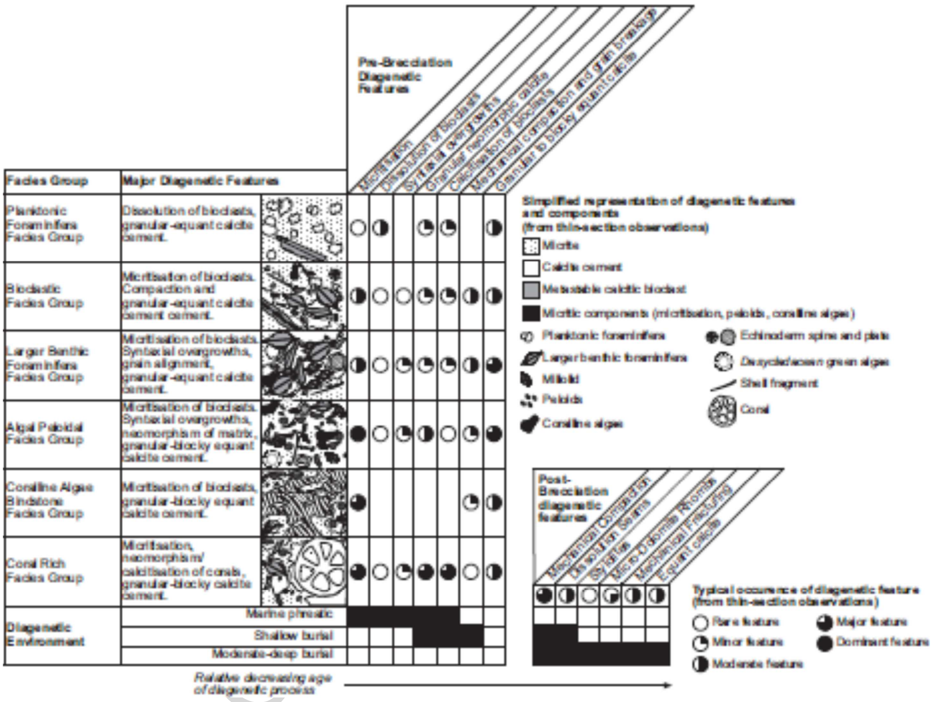

Pre-Brecciation Diagenetic Features
Micritisation
Dissolution of bioclasts
Syntaxial overgrowths
Granular neomorphic calcite
Calcitisation of bioclasts
Mechanical compaction and grain breakage
Granular to blocky equant calcite
Facies Group
Major Diagenetic Features
Planktonic Foraminifera Facies Group
Dissolution of bioclasts, granular-equant calcite cement.
Bioclastic Facies Group
Micritisation of bioclasts. Compaction and granular-equant calcite cement cement.
Larger Benthic Foraminifera Facies Group
Micritisation of bioclasts. Syntaxial overgrowths, grain alignment, granular-equant calcite cement.
Algal Peloidal Facies Group
Micritisation of bioclasts. Syntaxial overgrowths, neomorphism of matrix, granular-blocky equant calcite cement.
Coralline Algae Bindstone Facies Group
Micritisation of bioclasts, granular-blocky equant calcite cement.
Coral Rich Facies Group
Micritisation, neomorphism/ calcitisation of corals, granular-blocky calcite cement.
Diagenetic Environment
Marine phreatic
Shallow burial
Moderate-deep burial
Relative decreasing age of diagenetic process
Simplified representation of diagenetic features and components (from thin-section observations)
Micrite
Calcite cement
Metastable calcitic bioclast
Micritic components (micritisation, peloids, coralline algae)
Planktonic foraminifera
Larger benthic foraminifera
Miliolid
Peloids
Coralline algae
Echinoderm spine and plate
Dasycladacean green algae
Shell fragment
Coral
Post-Brecciation diagenetic features
Mechanical Compaction
Dissolution Seams
Stylolites
Micro-Dolomite Rhombs
Mechanical Fracturing
Equant calcite
Typical occurence of diagenetic feature (from thin-section observations)
Rare feature
Minor feature
Moderate feature
Major feature
Dominant feature

Table 1. Subdivision, characteristics and inferred depositional environment of carbonate facies and lithofacies from the Batu Gading limestone.

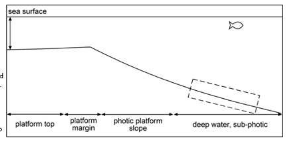
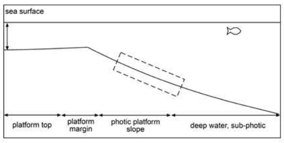
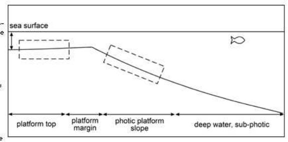
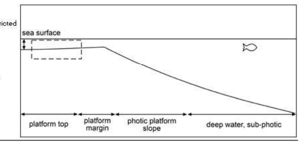
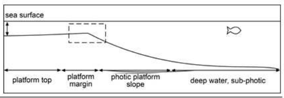
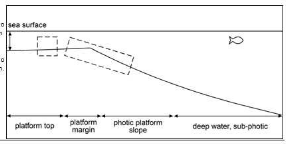
Relative facies group abundance	Facies Grou; Lithofacies	Representitive Ages	Components (% of total rock volume)	Larger Foraminifera Assemblage	Sedimentary Characteristics	Environmental Interpretation	Environmental Schematic Sketch
6%	**Planktonic Foraminifera Facies Group**						
	Planktonic Foraminifera Bioclastic Mud-Wackestone	Late Oligocene (Te1-4)	Micritic matrix (57-80%), planktonic foraminifera (14%), branching and encrusting coralline algae, encrusting foraminifera, miliolids, imperforate and perforate larger benthic and smaller benthic foraminifera (<10%), peloids may contribute ~1%.	Lepidocyclina and reworked Heterostegnia/Cycloclypeus.	Matrix supported, minimal abrasion and fragmentation of bioclasts. Little to no bioerosion.	Low energy, deep-water, sub-photic depth setting.	
	Planktonic Foraminifera Bioclastic Wacke-Pack-Grainstone	Late Oligocene (Te1-4)	Micritic matrix (48-59%), planktonic foraminifera (8-12%), branching coralline algae (4-12%), perforate larger benthic foraminifera (4-8%), minor (typically <2%) fragmented coral, mollusc fragments, echinodermata, imperforate larger benthic and smaller benthic foraminifera, miliolids and algal peloids.	Common Lepidocyclina and rare Heterostegnia/Cycloclypeus.	Matrix supported, minimal abrasion and fragmentation of bioclasts. Little to no bioerosion of components.	Low energy, deep-water, sub-photic depth setting. Some material reworked from platform top or marginal deposits.	
	Coral, Planktonic and Smaller Benthic Foraminifera Bioclastic Pack-Grainstone	Late Oligocene (Te1-4)	Micritic matrix (47%), planktonic foraminifera (8%), smaller benthic foraminifera (8%) coral (19%), minor (<2%) crinoids, branching coralline algae, encrusting foraminifera, imperforate and perforate larger benthic foraminifera.	Common Lepidocyclina.	Matrix supported, minimal abrasion and reworking of components. Moderate bioerosion; common micritised rims to corals.	Moderate-high energy reworking of platoform top or marginal deposits into sub-photic depth, deep water.	
25%	**Bioclastic Facies Group**						
	Bioclastic Mud-Wacke-Packstone	Late Oligocene (Te1-4)	Micritic matrix (50-83%), branching and encrusting coralline algae (<15%), perforate larger benthic foraminifera (<10%), uncommon fragmented corals (<10%), minor (<5%) each of molluscs, echinodermata (mostly spines), encrusting and imperforate foraminifera, smaller benthic and planktonic foraminifera, algal peloids and bryozoan.	Abundant Ledpidocyclina, less common Heterostegnia and Amphistegnia, and rare Cycloclypeus and Alveolina.	Dominantly matrix supported, variable degrees of abrasion and fragmentation; both mostly evident on branching coralline algae and LBF components. Encrustation of clasts typically minor. Bioerosion is moderately pervasive with common micritisation of coralline algae.	Low energy, normal marine photic zone. (1) Shallow platform slope or (2) moderate-deep photic depth/protected platform top depostion.	
	Bioclastic Pack-Grainstone	Late Oligocene (Te1-4) *except* for 2 clasts of Late Eocene (Tb)	Micritic matrix (20-<50%), branching coralline algae (<15%), perforate larger benthic foraminifera (5-<15%), less than 5% and typically <1-2% each of fragmented coral, molluscs (including gastropods), echniodermata (mostly spines), encrusting and imperforate foraminifera, miliolids, smaller benthic and planktonic foraminifera, algal peloids and bryozoan.	Abundant Lepidocyclina, less common Heterostegnia and Cycloclypeus, and rare Alveolina.	Matrix to clast supported fabric. Minor-moderate abrasion and moderate fragmentation of bioclasts. Minor encrustation and moderate bioerosion.	Normal marine, moderate to deep photic depths. Moderate-high energy slope or platform top.	
	Echinodermata Bioclastic Pack-Grainstone	Late Oligocene (Te1-4)	Micritic matrix (5-45%), well preserved echinoderm spines (6-11%), branching and encrusting coralline algae (>5-25%) <5% each of encrusting foraminifera, imperforate and perforate larger benthic, smaller benthic and planktonic foraminifera, miliolids and algal peloids. Lithic clasts may be locally important and contribute up to 25%.	Lepidocyclina, Heterostegnia, Cycloclypeus.	Matrix to clast supported. Minor abrasion, fragmentation and encrustation. Moderate bioerosion and micritisation of bioclasts.	Normal marine photic zone, moderate-high energy slope with some reworking of material from platform top (lithic clasts).	
	Discocyclina and Astrocyclina Bioclastic Grain-Packstone	Late Oligocene (Te1-4)	Micritic matrix (40-46%) mostly branching coralline algae (9-15%), perforate larger benthic foraminifera (4-10%), typically minor fragmented coral, imperforate foraminifera, bryozoans, algal peloids, miliolids, smaller and planktonic foraminifera (<3% each).	Discocyclina and Astrocyclina.	Matrix supported fabric. Variable degrees of abrasion, fragmentation and bioerosion.	Nomal marine photic zone, moderate-low energy slope to platform top.	
25%	**Larger Benthic Foraminifera Facies Group**						
	Nummulites, Discocyclina and Astrocyclina Bioclastic Pack-Grain-Rudstone	Late Eocene (Tb)	Perforate (9-52%) and imperforate (1-9%) larger benthic foraminifera, miliolids (1-2%), smaller benthic (1-3%) and planktonic (<1-3%) foraminifera, micritic matrix (27-51%), branching and encrusting coralline algae (1-15%), algal peloids (<5%) and minor fragmented coral, gastropods, echinodermata and encrusting foraminifera.	Nummulites, Discocylina, Biplanispira and less common Lepidocyclina, Heterostegnia, Cycloclypeus, Pelatispira, Amphistegnia and Astrocyclina.	Matrix to clast supported, minor abrasion and moderate to major fragmentation (particularly of larger foraminifera). Minor encrustation and bioerosion.	Normal marine photic zone, moderate-high energy shallow shoal or bank type deposit.	
	Larger Benthic Foraminifera Bioclastic Pack-Grainstone	Late Oligocene (Te1-4)	Perforate (8-30%) and imperforate (1-<6%) larger benthic foraminifera, miliolids (<2%), smaller benthic (<2%) and planktonic (<4%) foraminifera, branching and encrusting coralline algae (4-15%), fragmented corals (2-9%) common echinoderms (mostly spines; <5%) and minor whole and fragmented molluscs, encrusting foraminifera and algal peloids.	Lepidocyclina and less common Heterostegnia, Cycloclypeus with rare Amphistegnia and Alveolina.	Matrix to clast supported, moderate to major abrasion and fragmentation of bioclasts. Moderate encrustation and moderate bioerosion.	Normal marine, moderate to deep photic depths. Moderate-high energy slope or platform top.	
	Larger Benthic Foraminifera and Coralline Algae Bioclastic Pack-Grainstone	Late Oligocene (Te1-4)	Micritic matrix (25-44%), perforate (13-22%) and imperforate (1-<5%) larger benthic foraminifera, branching and encrusting coralline alage (15-19%), algal peloids (1-<5%), minor (typically <1-3%) molluscs, echinodermata, encrusting foraminifera and rarely coral fragments.	Lepidocyclina, Heterostegnia, Cycloclypeus and rare Pelatispira.	Matrix to clast suppoerted, minor abrasion and moderate fragmentation of bioclasts. Moderate encrustation and moderate-major bioerosion.	Normal marine, moderate to deep photic depths. Moderate energy slope or platform top. Local reworking of bioclasts.	
24%	**Algal Peloidal Facies Group**						
	Algae, Peloid and Miliolid Bioclastic Grainstone	Late Oligocene (Te1-4)	Branching and encrusting coralline algae (including dasycladacean green algae; 13-38%), algal peloids (5-28%), miliolids (5-11%), micritic matrix (7-38%) and fragmented larger benthic foraminifera (1-9%).	Lepidocyclina and Heterostegnia.	Mostly clast supported, high degree of abrasion and moderate fragmentation (mostly branching algae). Minor encrustation and pervasive micritisation of bioclasts.	Shallow platform top. Locally restricted and seagrass or rocky shoreline related.	
	Algae and Peloid Bioclastic Grainstone	Late Oligocene (Te1-4)	Micritic matrix (5-51%), branching and encrusting coralline algae (including dasycladacean green algae; 8-46%), algal peloids (5-22%) whole and fragmented perforate (1-18%) and imperforate (<1-9%) larger benthic foraminifera, corals (1-12%), echinoid spines (<5%) and minor encrusting foraminifera, miliolids, smaller benthic and planktonic foraminifera and rare bryozoan.	Lepidocyclina and Heterostegnia, uncommon Cycloclypeus, Amphistegnia and Alveolina.	Clast to matrix supported, moderate degree of abrasion, moderate fragemntation, minor encrustation and moderate to major bioerosion (higher in association with higher coralline algae abundances).	Moderate energy, shallow photic platform top.	
2%	**Coralline Algae Boundstone Facies Group**						
	Coralline Algae Grain-Pack-Boundstone	?	Encrusting coralline algae (56%), micritic matrix (17%), minor encrusting foraminifera, perforate larger benthic foraminifera and algal peloids.	Discocylina, Lepidocyclina, Heterostegnia and Amphistegina.	Bindstone fabric, pervasive micritisation of algal components.	High energy platform margin.	
	Coralline Algae Boundstone	?	Encrusting coralline algae (64-74%), micritic matrix (11-25%) minor (~1%) encrusting, imperforate and perforate larger benthic and smaller benthic foraminifera.	Lepidocyclina.	Bindstone fabric, pervasive micritisation.	High energy platform margin.	
18%	**Coral Rich Facies Group**						
	Coral Clasts	?	Fractured and microbored coral clasts (39-94%), micritic matrix (mostly infilling micro borings and chambers; <1-41%), minor encrusting coralline algae, algal peloids and bryozoans.	None.	Moderate micritisation of coral, little evidence of reworking in associated bioclasts.	Normal marine, high energy marginal to upper slope setting or shallow platform top.	
	Coral Bioclastic Grain-Pack-Floatstone	?	Fragmented coral clasts (16-59%), micritic matrix (12-67%), perforate (2-13%) and imperforate (1-4%) larger benthic foraminifera, branching and encrusting coralline algae (1-18%), algal peloids (<5%) and minor (typically <2%) fragmented and whole molluscs, encrusting foraminifera, miliolids, and smaller benthic and planktonic foraminifera.	Lepidocyclina, Heterostegnia, Cycloclypeus, Amphistegnia and Alveolina.	Matrix to clast supported, moderate abrasion and fragmentation of bioclasts, minor encrustation and pervasive micritisation of bioclasts.	Normal marine, high energy marginal to upper slope setting or shallow platform. Local reworking of bioclasts.	

Table 2. δ13C ‰ VPDB and δ18O‰ VPDB values from samples of the Batu Gading Limestones

Sample	Facies Group (c.f., Table 1)	Lithofacies (c.f., Table 1)	Component	δ^{13}C [‰, VPDB]δ^{13}C [‰, VPDB]	δ^{18}O [‰, VPDB]δ^{18}O [‰, VPDB]
BG114-4	Coral Rich Facies Group	Coral Bioclastic Grain-Pack-Floatstone	Coralline Algae	0.37	-7.99
BG114-4	Coral Rich Facies Group	Coral Bioclastic Grain-Pack-Floatstone	Coral (Granular Mosaic Calcite)	-4.24	-7.34
BG114-5	LBF Facies Group	Larger Benthic Foraminiferaand Coralline Algae Bioclastic Pack-Grainstone	Matrix	0.49	-6.53
BG120-6	LBF Facies Group	Larger Benthic Foraminifera and Coralline Algae Bioclastic Pack-Grainstone	Granular to Blocky Equant Calcite	1.07	-8.15
BG120-5a	LBF Facies Group	Nummulites, Discocyclina and Astrocyclina Bioclastic Pack-Grain-Rudstone	Larger Benthic Foraminifera	1.07	-6.06
BG121-005-1	LBF Facies Group	Larger Benthic Foraminifera Bioclastic Pack-Grainstone	Larger Benthic Foraminifera	0.90	-6.20
BG121-005-1	LBF Facies Group	Larger Benthic Foraminifera Bioclastic Pack-Grainstone	Matrix	0.60	-7.20
BG125-003	Coral Rich Facies Group	Coral Bioclastic Grain-Pack-Floatstone	Coral (Granular Mosaic Calcite)	0.37	-4.65
BG125-035	Coral Rich Facies Group	Coral Clasts	Coral (Granular Mosaic Calcite)	0.15	-4.10
BG111	LBF Facies Group	Nummulites, Discocyclina and Astrocyclina Bioclastic Pack-Grain-Rudstone	Larger Benthic Foraminifera	0.70	-9.77
BG121-002-10	Algal Peloidal Facies Group	Algae and Peloid Bioclastic Grainstone	Granular Equant Calcite	0.88	-7.83
BG121-002-7	LBF Facies Group	Larger Benthic Foraminifera Bioclastic Pack-Grainstone	Larger Benthic Foraminifera	1.26	-6.01
BG121-002-3	Bioclastic Facies Group	Bioclastic Mud-Wacke-Packstone	Matrix	1.47	-8.87
BG121-004#1-4	Algal Peloidal Facies Group	Algae and Peloid Bioclastic Grainstone	Granular Equant Calcite	1.46	-8.25
BG121-004#1-3	Algal Peloidal Facies Group	Algae and Peloid Bioclastic Grainstone	Larger Benthic Foraminifera	1.01	-4.97
BG121-004#2-3	Algal Peloidal Facies Group	Algae and Peloid Bioclastic Grainstone	Granular Equant Calcite	1.85	-4.12
BG121-004#2-11	LBF Facies Group	Larger Benthic Foraminifera Bioclastic Pack-Grainstone	Larger Benthic Foraminifera	1.21	-6.67
BG121-004#2	N/A	N/A	Fracture Fill	-0.03	-8.36
BG121-004#2-6	Bioclastic Facies Group	Bioclastic Pack-Grainstone	Matrix	0.91	-8.12
BG121-007-4	Algal Peloidal Facies Group	Algae and Peloid Bioclastic Grainstone	Coralline Algae	0.78	-7.40
BG121-007-4	Algal Peloidal Facies Group	Algae and Peloid Bioclastic Grainstone	Coral (Granular Mosaic Calcite)	0.84	-4.89
BG121-007-4	Algal Peloidal Facies Group	Algae and Peloid Bioclastic Grainstone	Granular to Blocky Equant Calcite	0.81	-5.92
BG121-007-1	Algal Peloidal Facies Group	Algae and Peloid Bioclastic Grainstone	Matrix	0.68	-5.98
BG121-	Bioclastic	Bioclastic Mud-Wacke-	Blocky Equant	0.47	-7.28

012-6	Facies Group	Packstone	Calcite		
BG121-012-7	Bioclastic Facies Group	Bioclastic Pack-Grainstone	Granular to Blocky Equant Calcite	1.82	-6.72
BG125-049	Coral Rich Facies Group	Coral Clasts	Coral (Granular Mosaic Calcite)	-0.04	-4.90
BG125-049	Coral Rich Facies Group	Coral Clasts	Granular to Blocky Equant Calcite	0.03	-5.88

Table 3. General properties of documented carbonate breccias with details of diagenetic features (mainly post-brecciation).

Breccia origin	Example Formations	Diagenesis	Some Key References
Submarine slope margin collapse related to faulting, over-steepening (and solution/karst collapse, e.g., blue holes), gravity controlled viscous mass flow, hybrid/high density sediment/fluid mass flows.	Cow Head Breccia, Newfoundland; Miette and Ancient Wall Buildups, Alberta; Tonasa Limestone, Sulawesi; Kedango Limestone, Borneo; Berai Limestone (Ruby Field), Makassar Straits; Kalvsjøen Formation, Norway; Exuma Sound, Bahamas.	Differential syn-sedimentary marine cementation possibly including fibrous fringing cements, geopetal marine sediments, some possible dissolution of aragonitic allochems with more prevalent neomorphic replacement, aggradational neomorphic growth of micrite spar. Rare replacement or infill of bioclasts by silica. Compactional deformation of matrix and semi-lithified clasts (if the latter are slope derived clasts both may be rich in planktonics). Pressure dissolution at grain boundaries and late stage dolomitisation from pervasively compacted lithologies. Fracturing common.	Hopkins, 1977; Huebert et al., 1977; Crevallo & Schlager, 1980; James, 1981; James and Stevens, 1986; Pohler and James, 1989; Spence & Tucker, 1991; Braithwaite & Heath, 1992; Aalto & Dill, 1996; Wilson and Bosence, 1996; Whalen et al., 2000; Pireno et al., 2009; Wilson et al., 2012; Madden and Wilson, 2013; Tanos et al., 2013.
Subaerial talus slope deposits: alluvial fan deposition (cohesive debris flows, sieve and flood deposits).	Hötting Breccia, Austria; Carbonate-clast breccia Pasty Springs Canyon, South Australia; Maiella carbonate platform breccias, central Italian Apennines; upper Proterozoic Windermere strata, northern Canadian Cordillera.	Lithification of fine grained clay rich matricies. Common meteoric dissolution of carbonate muds within matrix (may contain terrestrial indicators, e.g. micromammals, palynomorphs). Geopetal sedimentation of secondary matrix, and meniscus cements. Biomouldic porosity development common. Thin isopachous micritic to scalenohedral or columnar cements on lithic clasts and rarely pore lining. Locally present micro stalactites in megapores. Compactional and fracture features minor or absent.	von der Borch et al., 1989; Mustard & Donaldson, 1990; Casabianca et al., 2002; Sanders et al., 2009; Sanders, 2010.

Karstic and cavern collapse breccias: subaerial exposure of carbonates and development of associated epigenic karst.	The Bahamas; Khao Somphot Range, Thailand; Blanchard Springs Caverns, northern Arkansas; Mammoth/Flint Ridge Cave system, Kentucky; Longhorn Cavern, central Texas; Lower Ordovician and Silurian-Devonian strata of central Texas (including the Ellenburger dolomite).	Meteoric or mixing-zone dissolution excavation and cave sedimentation. Cavern collapse and breccia restructuring, differential compaction and extensive clast fracturing. Circum-granular cracks and veinlets may be present and associated with sub-aerial desiccation. Sedimentary in-fill of breccia may be accompanied by terrestrial fossils and palaeocaliche with dominant nodular fabrics. Bioclasts pervasively recrystallised or dissolved to produce biomouldic porosity. Development of circum-clast stylolites and associated pressure-dissolution cementation. Breccia matrix commonly pervasively recrystallised by calcite or (baroque) dolomite. Vuggy porosity, speleothems and flowstones may be locally present.	Mylroie & Carew, 1990; McMechan et al., 1998; Loucks, 1999 (and references therein); Saller et al., 1999: Udchachon et al., 2014.
Intra-formational breccias: collapse from evaporite dissolution.	Chintla quadrangle dolomite breccias, Guatemala; Minnelusa Formation, South Dakota and Wyoming; Belle Roche breccia, Belgium; Minkinfjellet and Wordiekammen Formations, Svalbard.	Meteoric fluids driving calcitisation and neomorphism of dolomite (delomitisation) and micritic matrix. Some dissolution of matrix. Cavity lining microcrystalline cements, sparry isopachous cements to lithic clasts enclosed by crystal-silts and clays. Breccias commonly monomict with partially fitted fabrics. Breccias with more open frameworks may be pervasively cemented by equant calcite with a drusy habit. Clasts cross-cut by sparry dolomite and some calcite veins. Possible compaction and stylolitisation features may accompany re-brecciation events. Rare silica cements.	Bowles & Braddock, 1963; Blount & Moore, 1969; Swennen et al., 1990; Tucker, 1991; Freidman, 1997; Eliassen & Talbot, 2005.

Fault breccias: including tectonic breccias.	Chintla Quadrangle Dolomite Breccias, Guatemala; Dent Fault Carboniferous Limestones, UK; Taballar Limestone, Borneo; Sella Group, Italian Central Dolomites; Gulf of Corinth, Greece; Jurassic platform limestone, Mattinata Fault Zone, Southern Italy.	Fitted fabrics of variably rotated breccia clasts. Matrix and/or open porosity is commonly pervasively cemented by sparry calcites or baroque dolomite. Compaction is variable with microdolomite rhombs possible along stylolites. Formation of fault gouge, cataclasites and damage zones that cross-cut strata with extensive fracturing and calcite or dolomite veins. Vadose zone features typically absent. Faults, fractures and associated breccia are pathways for later diagenetic fluids, e.g., dolomitising, gangue, mineralising or leaching.	Blount & Moore, 1969; Antonellini & Mollema, 2000; Tarasewicz et al., 2005; Billi, 2005; Wilson et al., 2007; Woodcock & Mort, 2008; Bastesen et al., 2009.