Department of Applied Geology

Regional versus Global Controls on the Diagenesis and Reservoir Quality of Tertiary Carbonate Platforms

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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ABSTRACT

Study of the diagenesis of carbonate platforms provides insight into basin evolution, local versus regional controlling influences and potential reservoir quality development. Despite the importance of Cenozoic carbonates in SE Asia as significant economic hydrocarbon reservoirs, there remain many aspects of the diagenesis of large-scale platforms that are almost unstudied in this tectonically active area, or indeed elsewhere in the world. This multidisciplinary study utilising field samples, microscopy and geochemistry of the Eocene to Miocene Tonasa Limestone Formation from Sulawesi, Central Indonesia, investigates three previously near-unstudied aspects of carbonate platform diagenesis. These studies are: (1) the diagenesis of large-scale syntectonic platforms, (2) the diagenetic impact of thick volcanogenic packages overlying large-scale carbonate platforms, and (3) the spatio-temporal diagenetic variability in slope and basinal deposits associated with different carbonate platform margin settings from individual carbonate platforms and their controlling influences. The implications of these three main studies for petroleum systems development, and in particular reservoir quality in large-scale carbonate platforms are also discussed.

The equatorial Tonasa carbonate platform was affected by block faulting, tilt-block rotation, differential uplift, subsidence and volcanic activity throughout its Eocene to Early Miocene history. Overall the Tonasa carbonate platform is dominated by alteration in shallow to deeper burial depths by fluids with predominantly marine precursor origins. Mechanical and chemical compaction features are common, as are a range of mainly burial-related granular mosaic, blocky and equant calcite cements. Earlier marine cements and meteoric influences are rare, being highly localised to block faulted highs and/or bathymetrically upstanding platform margin areas. Early marine micritisation of allochems was common on the platform top. Tectonic uplift together with a major oceanic throughflow current are thought to be key influences on localised karstification, meteoric diagenesis and marine cementation. The distribution and orientation of faults, fractures and calcite veins together with evidence for their relative timing are the strongest manifestation of tectonism coeval with diagenesis. There is concordance in the orientation and timing of structures affecting the Tonasa Platform with those basin-wide, with the potential for reactivation of pre-existing basement fabrics. Tectonic subsidence, including fault associated differential subsidence, controlled the degree of burial diagenesis impacting different areas of the platform. A predominance of burial diagenetic features and dearth of earlier marine or meteoric cementation is seen in other Tertiary equatorial platforms and is partly attributed to: (1) predominance of non-framework building larger benthic foraminifera and/or algae that are prone to remobilisation, have low production rates and limited potential to build to sea level, and (2) high runoff due to the equatorial humid climate contributing to lowered marine salinities in SE Asia. Underlying tectonic reasons for the preponderance of a "regional" diagenetic signature over a "syntectonic" one, fracturing excepted, are: (1) development on the flanks of a backarc basin not on typical continental crust, (2) key platform influencing structures are oblique to the main extensional direction in the basin, and (3) development in an overall subsiding tectonic regime, post-dating basin initiation. The aim is that this first part of the thesis published in the journal Sedimentary Geology will

contribute to understanding diagenetic alteration of syntectonic carbonate platforms, and those from equatorial regions.

Despite carbonate-volcanic interactions being common in the geological record the diagenetic interactions of such systems are almost unstudied. This second part of the thesis details here for the first time diagenesis of carbonate-volcanogenic units where a Cenozoic, SE Asian carbonate platform is overlain by a thick (1-2 km) Miocene volcanogenic pile with associated intrusives. Burial diagenetic effects with fluids of marine precursor origin predominate across shallow-platform, slope and basinal deposits of the syntectonic, block-faulted Tonasa carbonate Platform in Sulawesi (Wilson et al. 2000; Arosi and Wilson, 2015). Common, platform-wide late-stage stylolites/dissolution seams are probably linked to "volcanogenic overburden" from the Miocene volcanics of the Camba Formation. Aside from this, however, dynamic diagenetic interactions between the carbonates and volcanogenics are highly localised and mostly limited to the few metres to tens of metres either side of conformable formation boundaries or contacts with intrusives. Recrystallised textures and anomalously low negative value stable-isotope (C & O) values within the carbonates in proximity to intrusives are linked to higher temperatures and potential hydrocarbon maturation, perhaps associated with hydrothermal fluids (Arosi and Wilson, 2015). Where the already lithified, block-faulted upper surface of the shallow-platform carbonates are unconformably overlain, no effects of the volcanogenics different from that on the main platform are discernible on the diagenesis of the limestone. Deep-, and shallow-water carbonates that pass conformably into, or interdigitate with, the volcanogenics show more intense compaction than is seen elsewhere in the Tonasa Formation. More pervasive neomorphic replacement by very coarse bladed to mosaic calcite cements not seen elsewhere in the Tonasa Formation is also localised to shallow-water carbonates conformably overlain by the volcaniclastics. It is inferred here that increased pressures and perhaps higher temperatures associated with emplacement of the volcanogenic pile drove increased chemical compaction as well as localised fluid flow within the shallow-water carbonates driving stabilisation to coarse calcite cements. Perhaps surprisingly given the humid equatorial setting of deposition, the volcaniclastics are dominate within the volcanogenic pile commonly have a relatively fresh appearance. Possible reasons for this common paucity of alteration may include: (1) common lithic and crystal components to the volcaniclastics with a lack of reactive glassy material, (2) common interbedded clay-rich and lava flow units that may act as baffles or barriers to fluid flow, and (3) potential rapid covering by further volcaniclastics. Alteration of the volcaniclastics includes sericitisation and some calcitisation of the feldspar, some oxidation and Fe-alteration of mafic minerals, common zeolite replacement and growth into pores, and minor late calcite cementation. In keeping with other studies, alteration of the volcaniclastics is most intense where there are admixed carbonate-volcaniclastics and/or in deeper marine as opposed to terrestrial volcanogenic deposits. There is no evidence for significant exchange of fluids from the pure volcanogenics altering the pure carbonates, and *vice versa*, rather it appears fluids involved in the alteration of unlithified shallow-water carbonates and volcanogenics were mostly locally and internally sourced. This second part of the study is intended to contribute to poorly understood diagenetic variability in carbonate-volcaniclastic systems, and particularly those from the equatorial tropics.

Carbonate slope deposits are well reported yet the spatio-temporal variability in alteration and diagenesis of such deposits adjacent to different types of platform is little known. This third part of the study of slope to basinal deposits from around the equatorial syntectonic Tonasa platform in Central Indonesia; here, allows for the evaluation of differing platform margin settings, oceanographic factors and the history of basin evolution on the burial and diagenetic history of these important but little studied carbonates. Clasts of reworked Tonasa limestone represent shallow-water platform wackestone, packstone and grain/rudstone deposits that are dominated by larger benthic foraminifera. Four broadly comparable sets of diagenetic features have been identified from the Tonasa slope deposits that represent alteration following reworking and brecciation of platform margin lithologies. Mechanical compaction, cementation, silicification, glauconitisation and phosphatisation are major features of diagenesis in these reworked deposits with mechanical compaction, including mechanical breakage, plastic deformation and stylolitisation a dominant feature. Interclast carbonate cements are variable with common granular and blocky cements but also earlier pore lining cements with bladed habits. Dolomite additionally occurs in rare instances plausibly related to burial diagenesis. Silicification is a common feature that post-dates compaction effects. The recrystallisation of sponge spicules and microfossils as well as derivation from older exposures of silica-rich strata are interpreted as the source of porosity filling microcrystalline quartz and chalcedonic overlay fabrics. Glauconite pellets, bioclast-replacing glauconite and interclastic phosphate are common but low abundance features of all originally shallow water units. The broadly comparable diagenetic features of the reworked Tonasa deposits can be attributed to variable tectonic activity during the late Eocene to early Miocene; whereby the generation of accommodation space and graben infill drove greater degrees of burial and compactional diagenetic effects. Long term fault activity was a significant factor in the high rate of sediment supply (reworked carbonates), the availability of exposed silica rich lithologies and fracture networks for cementing fluid-pathways. The results of this study, along with regional analogues, suggest the growing potential for redeposited slope and basinal carbonates to be a novel way of investigating carbonate platform variability and controlling factors on their growth and diagenesis.

The Tonasa Limestone Formation as with a number of other long ranging Tertiary carbonate platforms in SE Asia is predominantly influenced by burial diagenesis with only localised influence of marine or meteoric diagenesis. The retained porosity in the Tonasa Formation, as with these other Tertiary platforms is commonly low, being generally less than 10%. Initial good primary porosity resided in high energy, shallow water grainstones but this is now mainly filled by granular mosaic and equant cement. Best porosity is now mainly seen in slope deposits that may still retain some rare to uncommon intergranular porosity. Factors that strongly influenced the general paucity of reservoir quality in the Tonasa Limestone Formation, include (1) predominance of originally calcitic bioclasts (less prone to leaching than aragonite), (2) limited subaerial exposure, (3) paucity of early marine or meteoric cements that might have mitigated against porosity loss through compaction, and (4) significant burial compaction and cementation.

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This thesis is for my children Khadeeja, Siddeeg and the little hero Mohammed.

“We sent thee not save as a mercy for the people”

Qur’an - 21:107

List of Publications Included as a Part of this Thesis

This thesis compiles a collection of research papers that were either published or under preparation at the time of writing this document. The objectives and relationship amongst the different paper are described in the introductory chapter. The final chapter summarises the papers and places them into a wider extend.

The research papers contained within this thesis are given below, with chapter 4 in preparation for submission.

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

Arosi, H.A., Wilson, M.E.J. submitted. How do thick volcanogenic piles overlying platform carbonates influence carbonate-volcanogenic diagenesis? Submitted to Sedimentology

Arosi, H.A., Wilson, M.E.J., Madden, R.H.C. (in prep). Variability in diagenesis of carbonate platform slope and basinal deposits.

The formatting of each chapter within this thesis may appear to vary, and may differ to the published from based on the requirements and formatting guidelines of each individual journal and this thesis. Due to the nature if this thesis as a composite of published manuscript there is a degree if repetition throughout.

Statement of Contribution of Others

This thesis has been supported by the Libyan Government. The individual chapters of this thesis, notably those comprising the published works listed above were undertaken in collaboration with Dr Moyra E.J. Wilson now at University of Western Australia. Samples for the entirety of this PhD have been collected by Moyra during previous field excursion. However, as the primary author of this thesis, and all published manuscripts contained within, I declare that I have been responsible for all subsequent research, analysis, interpretation and write up of these samples. A written statement of co-author contribution is provided within the Appendices at the end of this thesis.

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Date: 21/6/2016

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Date: 21/6/2016

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Chapter One

Introduction

Limited studies have been published investigating the interplay between tectonic and other influences on the development, diagenesis and reservoir quality of large-scale Cenozoic carbonate platforms in SE Asia. This is in spite of the importance of Cenozoic carbonates in SE Asia as significant economic hydrocarbon reservoirs containing about 50% of the regions hydrocarbon reserves (Howes, 1997; McClay et al., 2000; Doust and Noble, 2008). To date, many studies have in general separately concentrated on the palaeotetectonic, palaeodepositional systems or diagenetic alteration without strong linkage between these elements or their effect on carbonate reservoir quality in SE Asia region. Wilson (2002) published the first comprehensive review detailing carbonate development in Southeast Asia during the Cenozoic, and summarised the probable economic significance of Southeast Asian Cenozoic carbonates. Further region-wide evaluation of tectonic influence on carbonate reservoirs in SE Asia was by Wilson and Hall (2010), but this did not focus on the specifics of individual systems or full integration of diagenetic influences.

Tectonically, SE Asia is recognized as a highly active and complex region (Hamilton, 1979; Daly et al., 1991; Lee and Lawver, 1995; Hall, 1996, 2002; Wilson & Hall, 2010). Hall (2002) outlined three main collisional tectonic events affecting SE Asia during the Cenozoic. At 45 Ma the India - Asia collision resulted in tectonic 'reorganization' in SE Asia. The second collision was at 25 Ma between the passive margin of New Guinea and the East Philippines-Halmahera-South Caroline Arc system. Finally, Taiwan collided with the (SE) Asian arc-continent system at 5 Ma. Wilson and Rosen (1998), Wilson (2008) and Wilson and Hall (2010) evaluated and illustrated the variability of Cenozoic carbonate and coral development with respect to the plate-tectonic reconstructions of Hall (1996, 2002).

Although tectonics is a major factor controlling the carbonate reservoir development, there are a range of other factors that may have affected palaeoenvironments, past deposition and carbonate development, such as eustasy or oceanography (Perrin, 2002; Halfar and Mutti, 2005; Wilson, 1999). There is evidence that eustasy influenced carbonate deposition and diagenesis, especially in the Miocene period (Fulthorpe and Schlanger, 1989; Greenlee and Lehmann, 1993; Wilson, 2008; Wilson & et al., 2012), but this is less clear for the whole Tertiary.

The Southeast Asia region is known for its extensive reef development (Fulthorpe and Schlanger, 1989; Tomascik *et al*., 1997; Wilson, 2002), with more than 55% of the world's coral reefs occurring in this region (Muller, 1955; Wilson & Rosen, 1998). Cenozoic depositional and sedimentological data for past reefal and non-reefal carbonate successions throughout the region has been assembled and reviewed by Wilson (2002; 2008).

Wilson and Moss (1999) discussed implicitly the relationship between biogeography, hydrocarbon reservoir exploration and plate tectonic processes within palaeogeographic evaluations for Sulawesi. The first work linking between tectonic influences at varied scales on the creation, development, demise, and reservoir quality of the region's Cenozoic carbonate systems is by Wilson and Hall (2010).

Carbonate reservoirs contain nearly 50% of the world's hydrocarbon reserves and are expected to dominate future world oil production (Ramakrishnan *et al*., 2001). Carbonate reservoirs also contain almost 50% of hydrocarbon resources in the SE Asia region. The impacts of processes, such as tectonics, basin history or eustasy on the diagenesis and reservoir quality development of carbonate platforms in this area are not well understood. In SE Asia, reservoir potential in Miocene carbonate buildups is best documented, but that of larger-scale platforms whose development spans much of the Tertiary remains understudied. Meeting the demand for hydrocarbons and the high cost of oil and gas exploration has resulted in significant global challenges. Understanding the controls on deposition, diagenetic processes and their impacts on the physical properties of reservoir rocks is of key importance in the exploration for hydrocarbons in carbonate systems and for decreasing exploration risk.

Carbonate systems development, diagenesis and their physical reservoir properties (porosity and permeability) are highly responsive to a variety of potential controls. Better understanding of controlling influences is of importance in evaluating factors such as: 1) past environmental change, 2) basin history, 3) the relative impacts of regional versus global change, and 4) carbonate systems development in general. Unravelling controls on carbonates and their reservoir development is a scientific challenge, and multiple factors may be involved. For example, tectonic thrusting and tilting may cause localised uplift of carbonate platforms above the sea level, exposing them to the range of weathering processes resulting in karstification, platform collapse and down-slope re-working. Global eustatic sea level change may also cause extensive exposure of platforms and be a factor in down-slope reworking.

1.1 Aim and Objectives

The aim is this research is to assess the influence of regional versus global controls on the diagenesis and reservoir quality of Tertiary carbonate platforms. Specifically the study focused on the Eocene to Miocene Tonasa Limestone Formation of South Sulawesi, drawing comparisons with other regional and subject-specific examples. The three main objectives are:

- To evaluate controlling influences on diagenesis (post-depositional alteration) and potential reservoir quality of the Tonasa Formation, SW Sulawesi, Indonesia. Previous studies on the sedimentology and depositional evolution of the Tonasa carbonate platform have shown that tectonics was a significant influence (Wilson and Bosence, 1996; Wilson, 1999; 2000; Wilson et al., 2000). The impact of this, and other potential controls on diagenesis and reservoir potential will be investigated.

- To contribute towards understanding diagenetic alteration of volcanogenic covered and/or influenced carbonate platforms, with a focus on those from equatorial regions.

- To evaluate controlling influences on the spatio-temporal variability in diagenetic features and degree of diagenetic alteration of slope and basinal deposits adjacent to a range of platform margin types.

1.2 Thesis Structure

This thesis is presented in the form of a hybrid thesis with one chapter already published (Chapter 2; Arosi and Wilson, 2015) and another two as ‘in preparation’ for journal submission together with: (1) introduction, (2) implications for petroleum systems studies, and (3) conclusions. The three main chapters of the thesis written in paper format follow each of the main aims as outlined, with each being an original and among the ‘first-of-its-kind’ subject specific study. Chapter 2 focuses on the diagenesis and fracturing of the syntectonic platform system. Chapter 3 evaluates the impacts of emplacement of volcanogenics overlying carbonate systems. Chapter 4 concentrates on diagenetic variability of slope and basinal deposits from differing carbonate platform margin types together with their controlling influences. Appendices cover the classification and chart schemes. Appendices also include high resolution thin sections scans, photomicrographs of samples (Plain and cross polarised light and Cathodoluminescent) and photographic observation sheet. In the end of the thesis, copy of published work and the co-author contribution statement.

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Chapter Two

DIAGENESIS AND FRACTURING OF A LARGE-SCALE, SYNTECTONIC CARBONATE PLATFORM.

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Abstract

The influence of coeval tectonics on carbonate platform development is widely documented, yet the diagenesis of such syntectonic platforms is barely evaluated. An outcrop, petrographic and geochemical study details here for the first time the diagenesis of the Tonasa Limestone developed in an extensional regime in central Indonesia. This equatorial carbonate system was affected by block faulting, tilt-block rotation, differential uplift and subsidence throughout its Eocene to Early Miocene history (Wilson, 1999; Wilson et al., 2000). The Tonasa carbonate platform is dominated by alteration in shallow to deeper burial depths by fluids with predominantly marine precursor origins. Mechanical and chemical compaction features are common, as are a range of mainly burial-related granular mosaic, blocky and equant calcite cements. Earlier marine cements and meteoric influences are rare, being highly localised to block faulted highs and/or bathymetrically upstanding platform margin areas. Early marine micritisation of allochems was common on the platform top. Tectonic uplift together with a major oceanic throughflow current are thought to be key influences on localised karstification, meteoric diagenesis and marine cementation. The distribution and orientation of faults, fractures and calcite

veins together with evidence for their relative timing are the strongest manifestation of tectonism coeval with diagenesis. There is concordance in the orientation and timing of structures affecting the Tonasa Platform with those basin-wide, with the potential for reactivation of pre-existing basement fabrics. Tectonic subsidence, including fault-associated differential subsidence, controlled the degree of burial diagenesis impacting different areas of the platform. A predominance of burial diagenetic features and dearth of earlier marine or meteoric cementation is seen in other Tertiary equatorial platforms and is partly attributed to: (1) predominance of non-framework building larger benthic foraminifera and/or algae that are prone to remobilisation, have low production rates and limited potential to build to sea level, and (2) high runoff due to the equatorial humid climate contributing to lowered marine salinities in SE Asia. Underlying tectonic reasons for the preponderance of a "regional" diagenetic signature over a "syntectonic" one, fracturing excepted, are: (1) development on the flanks of a backarc basin not on typical continental crust, (2) key platform influencing structures are oblique to the main extensional direction in the basin, and (3) development in an overall subsiding tectonic regime, post-dating basin initiation. The aim here is that this study will contribute to understanding diagenetic alteration of syntectonic carbonate platforms, and those from equatorial regions.

2.1 Introduction

The development of syntectonic carbonate platforms from a range of tectonic regimes is widely documented in the literature (Burchette, 1988; Gawthorpe et al., 1994; Dorobek, 1995; 2008a; 2008b; Wilson et al., 2000; Wilson and Hall, 2010), yet the diagenesis of such platforms is poorly detailed. In the active tectonic area of SE Asia at least two-thirds of the isolated carbonate platforms are documented to have formed over faulted antecedent highs with carbonate accumulation on many of these platforms coeval with local continued tectonism; i.e., many are syntectonic (Wilson and Hall, 2010). Isolated systems in SE Asia contain 83% of the hydrocarbon reserves within the regions carbonates. With many of these platforms being tectonically influenced, there is an economic driver to better understand the variable diagenesis of syntectonic platforms and any impact on reservoir potential (Wilson and Hall, 2010). Tectonics may influence carbonate systems through uplift, differential subsidence, or active faulting (Burchette, 1988; Wilson and Hall, 2010).

Localised uplift and karstification of footwall highs and significant local variations in stratal thicknesses across platforms have all been documented for syntectonic carbonate platforms (Burchette, 1988; Rosales et al., 1994; Wilson, 1999; Wilson et al., 2000; Bachtel et al., 2004). The diagenetic details, or implications for platform alteration, of these localised karstic features or stratal thickening are generally not discussed (Rosales et al., 1994). Various studies have detailed fracture patterns in carbonate systems, but these are rarely linked to syntectonic sedimentation, and the diagenesis of such fractures remains underevaluated (Rosales et al., 1994; Cloke et al., 1999a; Van Geet et al., 2002; Breesch et al., 2009). The climatic, oceanographic and basinal context unique to any platform will also influence platform alteration and these factors may be indirectly affected by tectonics (Moore, 2001; Wilson, 2012). The major question addressed here is: to what extent does the tectonic regime influence the diagenesis of syntectonic platforms, or are regional or basinal controls more influential on the alteration of such systems?

The Eocene to Miocene Tonasa Carbonate Platform of Sulawesi, Central Indonesia is a well-documented syntectonic platform for which the influences on diagenesis of: (1) tectonics, (2) an equatorial climatic setting and (3) basin context are detailed here for the first time. Plate tectonic drift and associated changes in carbonate communities and their alteration is an additional influence on carbonate platform development (Davies et al., 1989) and diagenesis that is not documented here.

The sedimentology and evolution of the Tonasa Carbonate Platform have been previously documented, with inferred dominant controls on deposition including tectonics, volcanism, nutrients and oceanography (Wilson, 1996; 1999; 2000; Wilson and Bosence, 1996; 1997; Wilson et al., 2000; Wilson and Vecsei, 2005). However, there has been almost no prior diagenetic analysis of the Tonasa Limestone, with just minor mention of reservoir quality issues (Wilson, 1996; 2000; Wilson and Bosence, 1997). The previous sedimentary studies set the context for this diagenetic evaluation. Diagenetic "interactions" between the carbonates of the Tonasa Formation and the overlying and intruding igneous strata are the subject of a further study (Arosi et al., in prep.).

2.2 Geological Setting

Sulawesi, including the Tonasa Formation of this study, is located in the centre of the Indonesian Archipelago in the midst of one of the most complex, active tectonic regions in the world (Fig. 1; Hamilton, 1979; Hall, 1996, 2002a; Hall and Wilson, 2000; Hall et al., 2011). From the Mesozoic, and throughout the Cenozoic, SE Asia has been affected by the interaction of three main tectonic plates the: Pacific-Philippine, Indo-Australian and Eurasian plates (Hamilton, 1979; Daly et al., 1991; Hall and Wilson, 2000). Hall (2002a) outlined three main collisional tectonic events at 45, 25 and 5 Ma that resulted in tectonic 'reorganisation' within SE Asia.

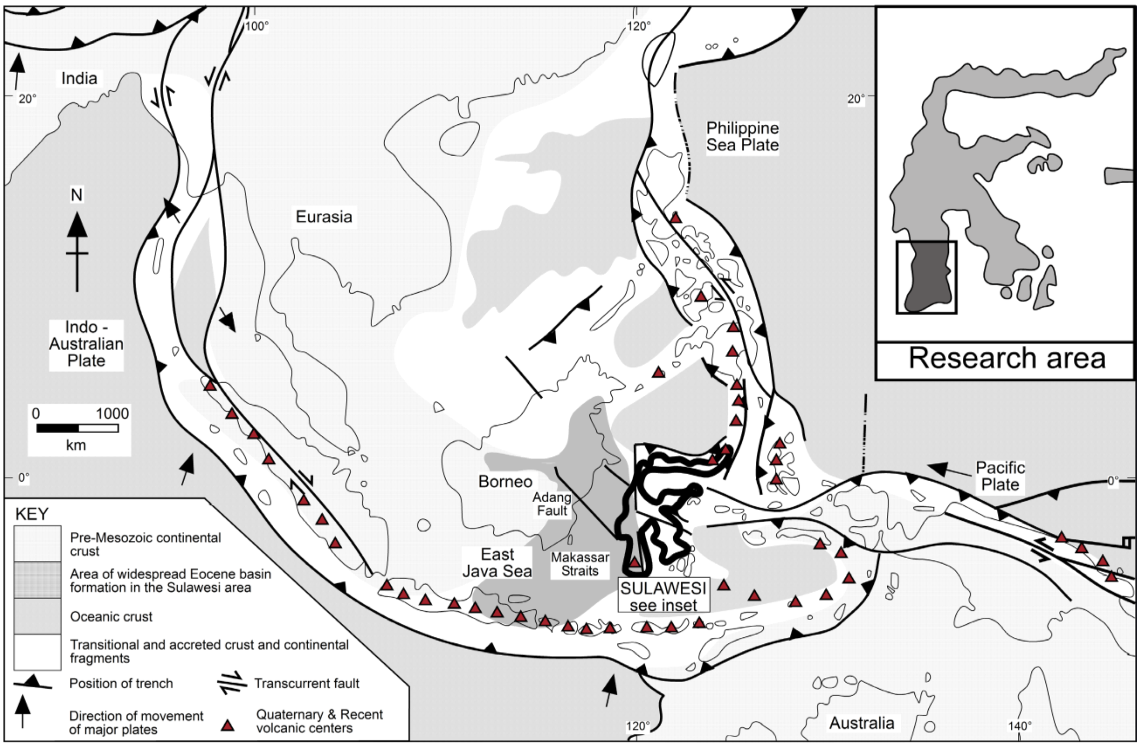

Figure 2.1. Regional tectonic setting of Sulawesi and the location of the Tertiary basinal area in Sulawesi/Borneo (from Wilson et al., 2000, modified after Daly et al., 1991; Hall, 1996; van de Weerd and Armin, 1992; Wilson, 1999). Inset shows the position of the research area within Sulawesi.

The evolution of south western Sulawesi (the South Arm) during the late Mesozoic and Cenozoic is linked to the accretion of micro-continental and oceanic fragments onto the eastern margin of the comparatively stable Eurasian plate, together with backarc rifting and volcanic arc development (Sukamto, 1975; Hamilton, 1979; van Leeuwen, 1981; Wilson and Bosence, 1997, Wilson, 1999, 2000). Relatively complete, but very different Late Cretaceous to recent stratigraphic sequences in the western and eastern halves of the South Arm reflect this complex geological evolution (Fig. 2; van Leeuwen, 1981; Wilson, 1999). The Balangbaru and Marada Formations are deep-marine forearc clastics and shales of Late Cretaceous age that overlie intersliced metamorphic, ultrabasic and sedimentary basement lithologies in the western South Arm (van Leeuwen, 1981; Hasan, 1991). By the Eocene, subduction had shifted to the east and marginal marine siliciclastics of the Malawa Formation in western South Sulawesi are associated with rifting of a broad basinal area centred on the Makassar Straits. The clastics pass transgressively upwards to carbonates of the Eocene to Miocene Tonasa Formation of this study that have predominantly shallow-water origins. During the Tertiary, accumulation of sedimentary rocks predominated in western South Sulawesi, whereas volcanic and igneous lithologies dominated to the east.

This east-west lithological subdivision occurs across a major structural divide, today demarked by the fault-bounded, NNW-SSE trending Walanae Depression (Fig. 2). The varied igneous rocks of eastern South Sulawesi include arc-related volcaniclastics, passive margin volcanics associated with the cessation of subduction, potassic volcanics linked to extension, as well as MORB-like volcanics from an accreted transtensional marginal oceanic basin (Sukamto 1982; Yuwono et al. 1987; van Leeuwen et al., 2010). Middle to late Miocene volcaniclastics and volcanics of the Camba Formation overlie the Tonasa Formation (Sukamto, 1982; Yuwono et al. 1987; Wilson, 2000). The Miocene shift in volcanism to western South Sulawesi and associated potassic igneous intrusions are linked to microcontinental collision related volcanism and post-collisional magmas (Elburg and Foden, 1999; Elburg et al., 2003).

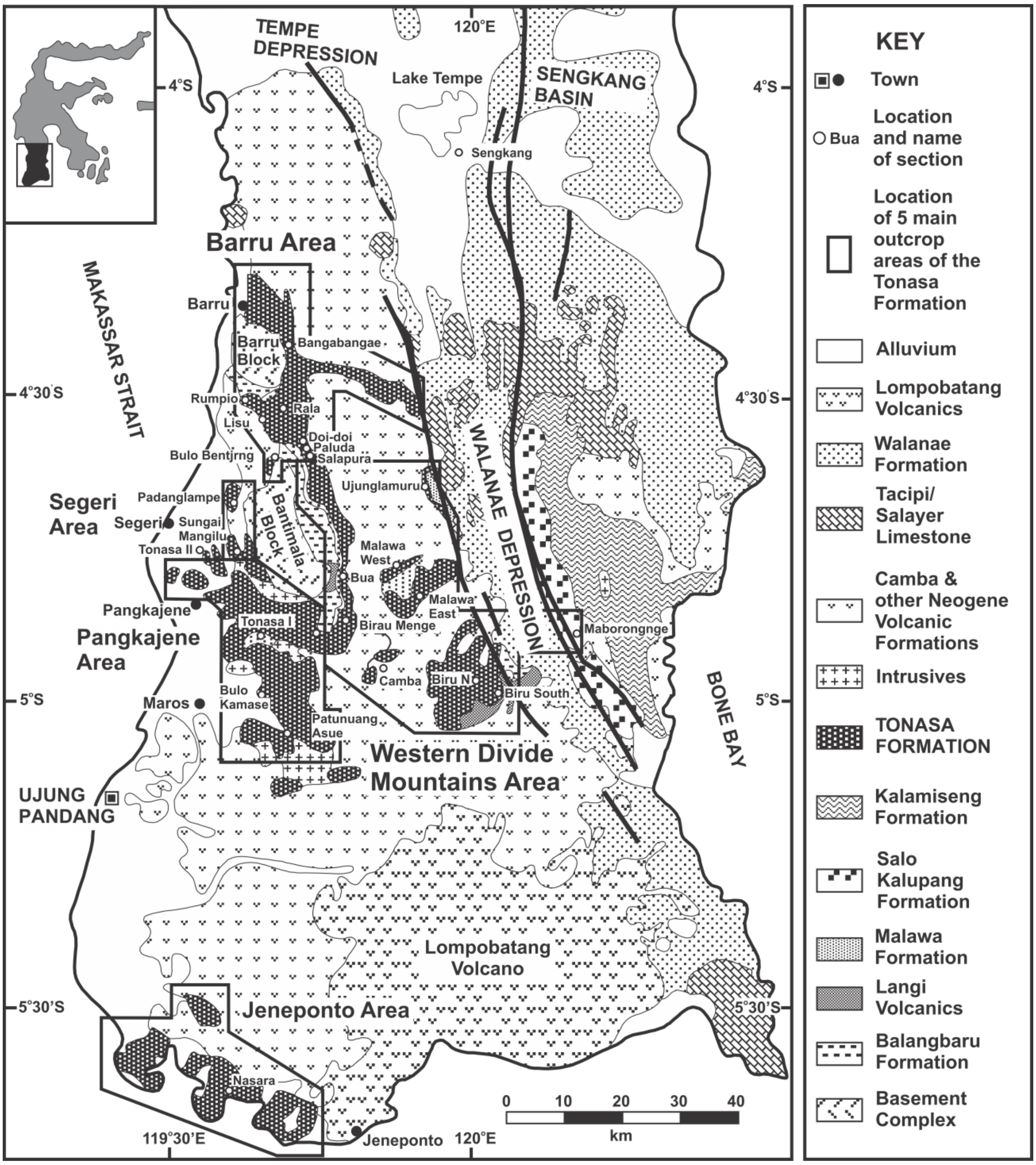

Figure 2.2. Geological map of South Sulawesi (from Wilson et al., 2000; after van Leeuwen, 1981; Sukamto, 1982; Sukamto and Supriatna, 1982; Wilson, 2000), showing the locations of the five main outcrop areas of the Tonasa Formation and the location of mentioned measured sections.

2.3 Deposition and development of the Tonasa Formation

The Early or Middle Eocene to Middle Miocene Tonasa Formation of this study comprises the main part of the Tertiary succession in the western part of South Sulawesi. The formation consists of shallow carbonate platform, associated slope and adjacent bathyal deposits that locally crop out over a 160 by 80 km north-south and east-west extent, respectively (Figs. 2, 3 and 4; Wilson and Bosence, 1996; 1997). Previous studies on the sedimentology and evolution of the Tonasa Carbonate Platform, together with evaluations of controlling influences set the context for this diagenetic study, and are briefly outlined below (Wilson, 1996; 1999; 2000; Wilson and Bosence, 1996; 1997; Wilson et al., 2000; Wilson and Vecsei, 2005).

Shallow-water deposits of the Tonasa Carbonate Platform are mainly wackestone, packstones and grain/rudstones that are dominated by larger benthic foraminifera. Other components include small benthic foraminifera, echinoid remains, coralline algae and more rarely corals (Wilson and Bosence, 1997; Wilson and Rosen, 1998; Wilson et al., 2000). Planktonic foraminifera are abundant in basinal marls. The marls interdigitate with slope and platform-fringing breccias and pack/grain/rudstones. The slope deposits contain abundant shallow-water bioclasts that were reworked downslope as well as a range of lithic clasts derived from the Tonasa and underlying formations (Wilson and Bosence, 1996; Wilson, 1999; Wilson et al., 2000).

Carbonate sedimentation of the Tonasa Formation began diachronously, with shallow-water deposits forming earliest in the northern Barru and southern Jeneponto Areas during the Early to Middle Eocene (Fig. 2; Wilson et al., 2000). By the Late Eocene shallow carbonate sedimentation had spread across much of western South Sulawesi. However, during the latter part of the Late Eocene fault segmentation resulted in rapid localised deepening and drowning of the platform in the northern Barru, eastern Segeri and westerly Western Divide Mountains Areas (Fig. 2; Wilson, 1999; Wilson et al., 2000). Some of the faults including those bounding the northern and eastern extent of main shallow platform are linked to major structural divides. These occur along strike from the NW-SE trending Adang Fault and as bounding faults to the NNW-SSE trending fault-bounded graben of the Walanae Depression, with potential involvement and reactivation of earlier basement structures (Figs. 1 and 2; van Leeuwen, 1981; Wilson and Bosence, 1996; Wilson et al., 2000). A large-scale (100 km north to south) tilted-fault-block platform with a segmented faulted northern margin (northern Barru Area) and gently dipping southern margin (southern Jeneponto Area) accumulated over 600 m of shallow water platform carbonates centred on the central Pangkajene Area (Wilson et al., 2000). Although onshore volcaniclastics cover parts of the more southerly deposits of this platform, in the area directly offshore to the west seismic data reveals the unbroken north to south nature of the coeval continuation of the platform (Letouzey et al., 1990). Up to 1100 m of shallow and mainly deep-water carbonates accumulated to the north (Barru) and south (Jeneponto) of the main platform. Areas of more complex faulting to the east and west of the main platform resulted in localised fault-block platforms and intervening small-scale basinal grabens (western Segeri and eastern Western Divide Mountains Areas on Fig. 2; Wilson et al., 2000; Wilson, 2000). Major shallow-water facies belts on the main tilt-block platform trend E-W, were aggradational and remained static through time. Low to moderate energy wackestones and packstones dominated in the north and south of the main shallow-water tilt-block platform, whereas higher energy grainstones prevailed in the central facies belt (Wilson and Bosence, 1997; Wilson et al., 2000). Water depths and energy, linked to differential subsidence/uplift together with the presence/absence of shallow shoaling protective ‘barriers’ along the westerly windward platform margin, are inferred to be important influences on the facies and biota present (Wilson and Bosence, 1997; Wilson et al., 2000). Localised subaerial exposure is inferred for the shallowest part of the main tilt-block platform on the northerly footwall high and also for some of the east-west developed block-faulted platforms (Wilson and Bosence, 1996; 1997; Wilson et al., 2000; Wilson, 2000). Mass reworking of material was common from the faulted highs into adjacent basinal graben and is often linked to phases of tectonic activity (Wilson and Bosence, 1996; Wilson, 1999; Wilson, 2000; Wilson et al., 2000). On the gently dipping southern hangingwall slope of the main tilt-block platform there was southward progradation of ramp deposits into bathyal areas during periods of tectonic quiescence and minimal subsidence (Wilson and Bosence, 1997; Wilson et al., 2000). Final demise of the platform at the end of the Early Miocene was linked to a laterally variable combination of fault-related drowning, uplift and subaerial exposure together with smothering by volcaniclastics (Wilson, 2000).

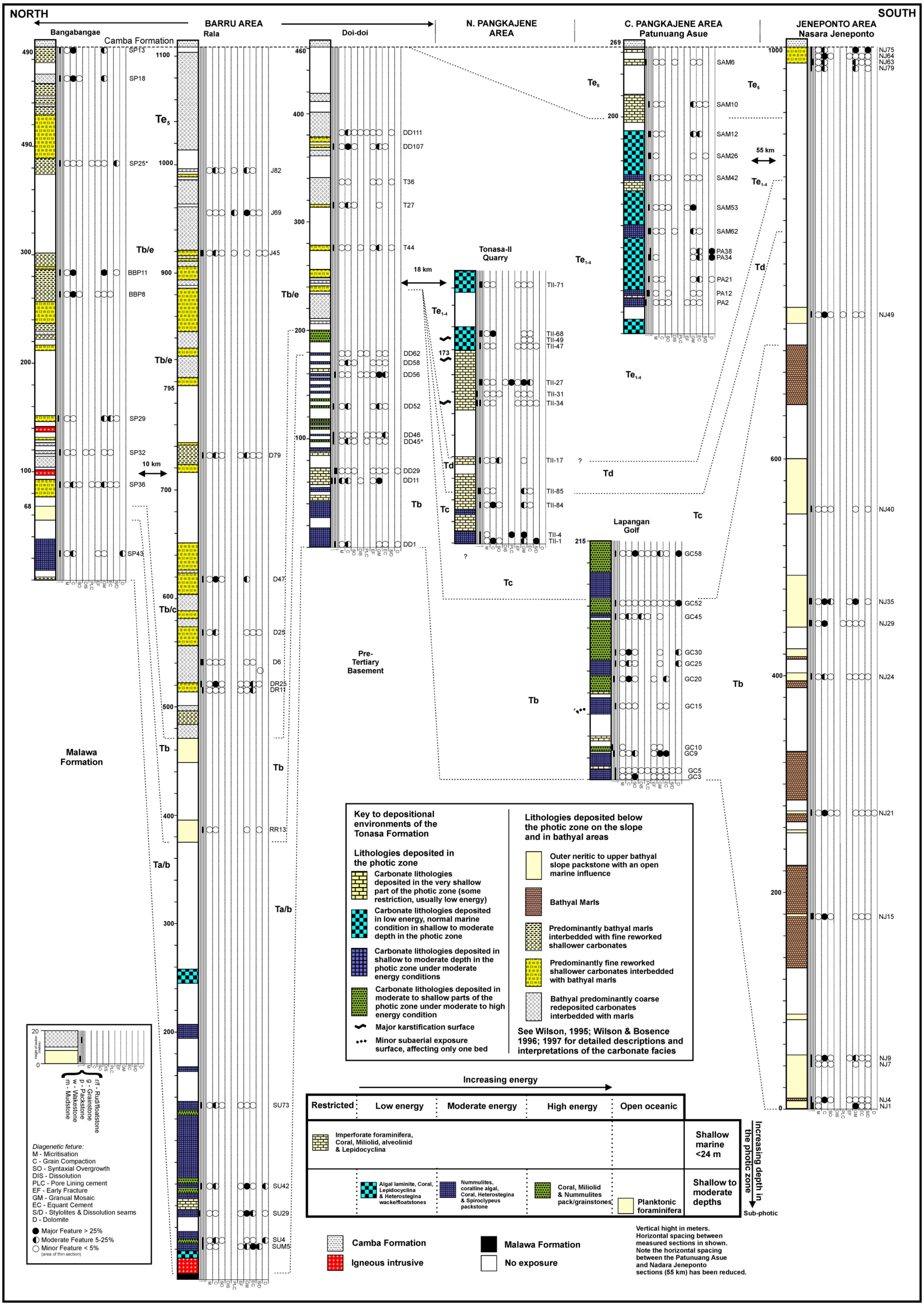

Figure 2.3. Selected summary measured sections from north to south across the main Tonasa tilt-block platform with diagenetic summaries from petrography of individual samples plotted against logged sections from Wilson et al. (2000) and Wilson (1995).

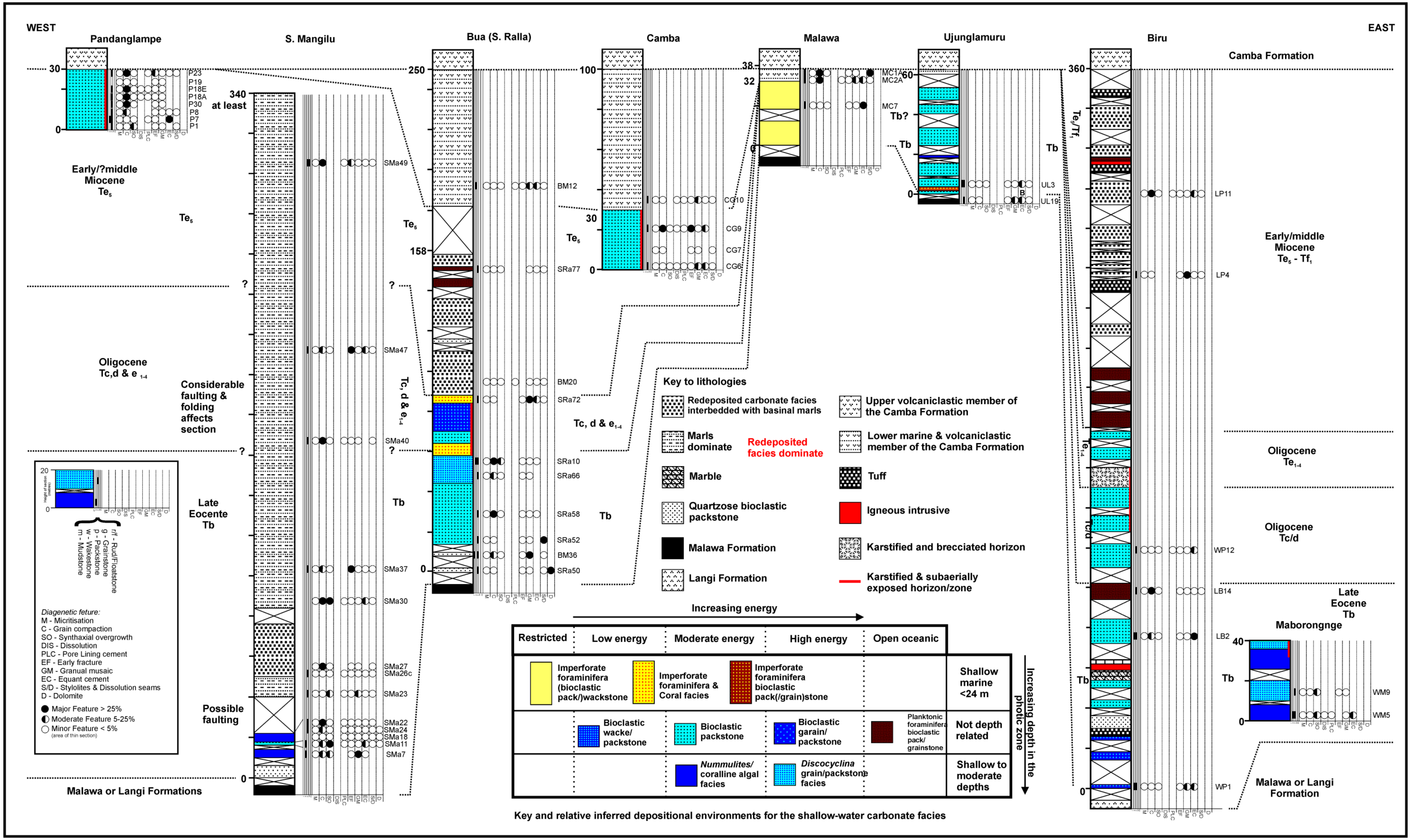

Figure 2.4. Selected summary measured sections from west to east across areas of complex block faulting in the Tonasa carbonate platform with diagenetic summaries from petrography of individual samples plotted against logged sections from Wilson et al. (2000) and Wilson (1995).

2.4 Methods

Carbonates of the Tonasa Formation are exposed as massive karstic outcrops up to 700 m high and in low riverbank exposures in western South Sulawesi. Good exposure allowed high resolution sampling, sedimentary logging, facies mapping and partial section correlation throughout the shallow water platform and adjacent basinal deposits. Eighty-one measured sections were logged (totaling >7 km of section) and of the ~1200 samples collected ~500 were thin sectioned or made into acetate peels. A subset of 153 representative thin sectioned samples that covered the full range of diagenetic features observed in the Tonasa Formation from 26 key sections were evaluated for this diagenetic study. As reported in Wilson et al. (2000) age assignments of samples were through comparison with the modified East India Letter Classification for larger benthic foraminifera (van der Vlerk and Umbgrove, 1927; Adams, 1970; Lunt and Allan, 2004) correlated against the 2004 geological timescale of Gradstein et al (2004; Figs. 3 and 4).

Lithological components, microfacies, diagenetic phases and the relative timing of diagenetic events were determined through thin-section petrography. All samples were half stained with Alizarin Red S and potassium ferricyanide to allow identification of dolomite, ferroan and non-ferroan calcite (Dickson, 1965, 1966). The relative abundance of components and diagenetic phases were recorded semi-quantitatively (visual estimates; after Mazzullo and Graham, 1988). Facies nomenclature follows the textural classification scheme of Dunham (1962), modified by Embry and Klovan (1971), with components given in lithology names where they exceed 10-15%. Nomenclature on carbonate cement morphologies follows Flügel (2004). Cold cathodoluminescent (CL) microscopy study of 32 polished sections was via a Technosyn 8200 MkII luminoscope (after Witkowski et al., 2000). Samples for CL analysis were selected to investigate the range of coarse (>250 μm) cement phases present.

Stable-isotope analysis ($\delta^{18}O$ and $\delta^{13}C$) was undertaken on 36 samples micro-drilled from the rock off-cut counterpart of the thin sections. Drilling sites matched directly to the off-cuts, correspond to a range of depositional and diagenetic features identified in thin section. Drilled samples include bioclasts, matrix and a range of cements with varied morphologies, with the later including those filling fractures. Oxygen and carbon isotope analyses were run on a VG Isocarb automated system online to a VG Isogas Prism II isotope-ratio mass spectrometer. All data have been normalised, to NBS-19: a primary carbonate standard used to define the V-PDB scale ($\delta^{13}C$ = +1.95‰, $\delta^{18}O$ = -2.2‰). In addition, replicate analyses of an internal carbonate standard (Mab2b) were reproducible to ±0.1‰.

Fractures were recorded in four ways to evaluate their orientations, and to gauge their potential relative timing with respect to carbonate sedimentation. (1) The strike orientations, and where possible dip data, for large-scale faults were recorded from field observations and the geological maps of South Sulawesi (scale: 1:250,000; Sukamto, 1982; Sukamto and Supriatna, 1982). (2) Strike and dip data were measured for millimetre to centimetre-scale aperture fractures, calcite veins (and joints) seen in outcrop during fieldwork. These small-scale features will have likely been under-recorded in all areas due to masking by heavy dripstone coating on the upstanding karstic outcrops and an algal film and/or up to 2 cm tufa-like coating on low river outcrops. (3) In thin sections, the ratio of numbers of both highly irregular and straight fractures to numbers of samples studied were recorded from key sections of all ages through *in situ* shallow platform and deeper slope to basinal deposits in all areas. Whilst not diagnostic, the highly irregular fracturing is more likely to have occurred when the deposits were semi-lithified, as opposed to fully lithified for the straight fractures. (4) In the slope breccia deposits consisting of material reworked into deeper water settings the ratio of numbers of both fractures and/or calcite filled veins constrained to within lithic clasts and those that cross-cut multiple clasts within the breccia fabric were recorded versus the number of samples studied. This latter data was recorded from thin sections through breccia units with lithic clasts of at least 5 mm across from the northern, western and eastern areas where these deposits range from Late Eocene to Miocene in age (cf. Wilson and Bosence, 1996; Wilson et al., 2000). Fractures within clasts, commonly truncated at clast margins, are present in less than 1-2% of both carbonate and non-carbonate lithic clasts in individual breccia samples. These intra-clast fractures are, nevertheless, an indication of fracturing and any associated calcite cementation occurring prior to reworking of the lithic clasts. This is as opposed to the fractures that cross-cut the fabric of the breccia that must have formed after the material was reworked and deposited downslope as the breccia units. The thin section evaluation of potential relative timing of fractures was from 164 thin sections from the key measured sections. An additional 45 thin sections of the slope deposits had clasts too small to meaningfully evaluate intra- versus extra-clast fracturing.

2.5 Results: Diagenetic Features from Petrography

Diagenetic features are described in their most common order of occurrence, as inferred from thin section petrography. There is, however, some variation in the relative timing of events between samples.

2.5.1 Micritisation

Micritisation of carbonate allochem margins pre-dates all other diagenetic features. Light to dark brown micritic rims to allochems as seen under plane-polarised light microscopy are generally between 20 and 30 µm (Fig. 5 a, b and c). Micritisation is seen in almost all thin sections, but the area of micritic rims in individual thin sections is mostly <2-5%. Grain micritisation is seen in all the different facies, but generally only as trace amounts in the basinal marls, planktonic foraminifera wacke/packstones and breccia units. Trace amounts of micritisation also occur in some shallow-water grainstones and wacke/packstone units from the Central, Northern and Eastern Areas. Samples having the most common micritisation, including micritic envelopes encircling grains with rims up to 40 µm thick, include larger benthic foraminifera wacke/packstone and coral floatstones from the Central and Eastern Areas (Fig. 5a, b and c). The CL signature of micritised rims is usually dull to non-luminescent: similar to, or slightly brighter than, the marine bioclasts they encircle.

2.5.2 Cavities and pore-lining cements

Pore-lining cements are uncommon in the Tonasa Formation, present in 19 out of 153 samples studied, with the additional samples not selected for this study containing almost none of these cements. Pores, or cavities that these cements line fall into two categories: (1) primary intergranular or shelter pores between bioclasts or lithic clasts that are on a mm- to cm-scale (Fig. 6), and (2) secondary dissolution cavities that cross cut strata and are on decimeter-scale (Fig. 7). Dissolution cavities are irregular in shape, have sharp, truncational margins with the host limestone and may be linked vertically by fractures and/or dissolution pipes.

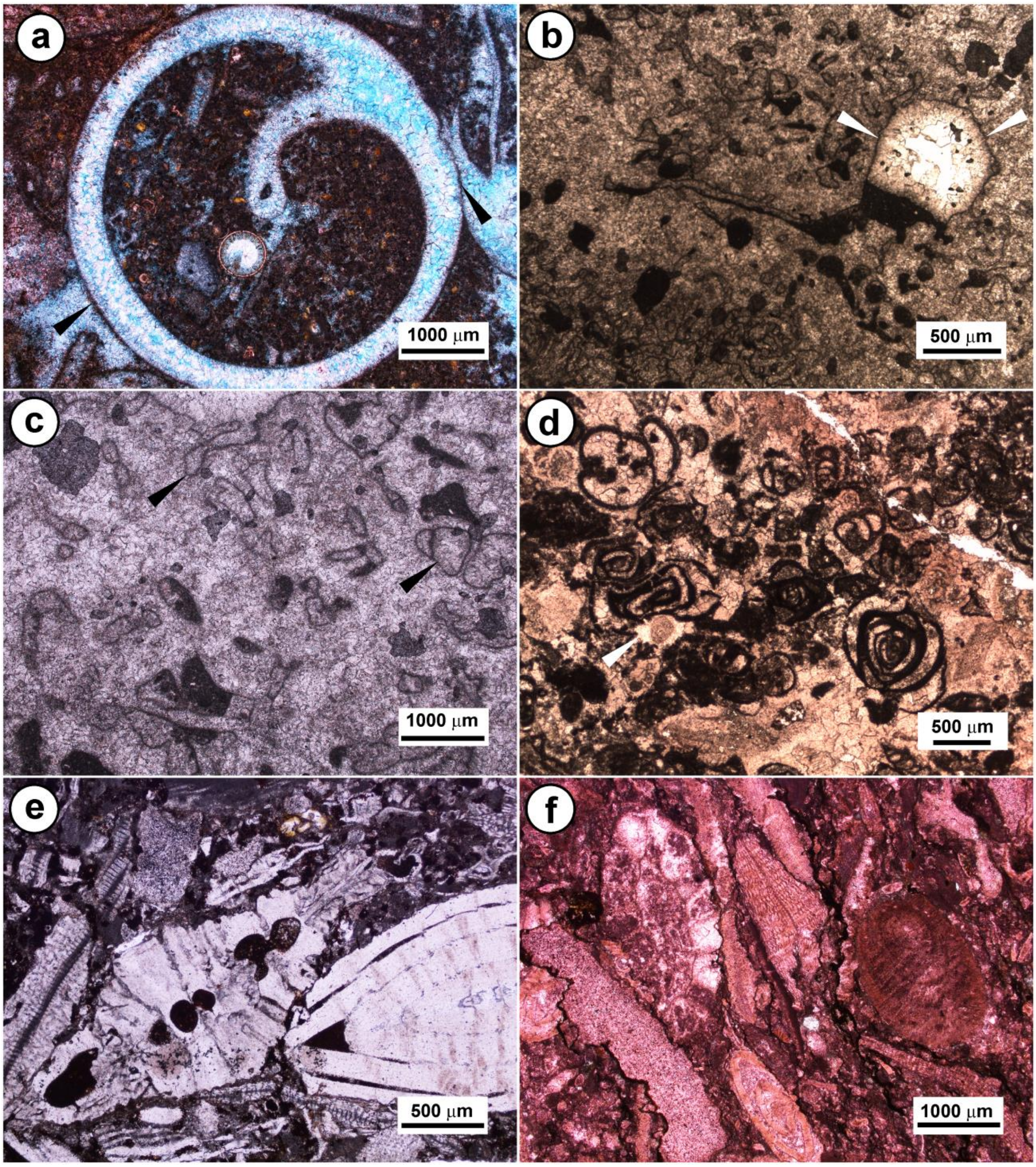

Figure 2.5. Thin-section plane polarised light photomicrographs showing (a) Micrite envelope (arrowed) encircling gastropod, the latter replaced by ferroan calcite (CG10, Eastern Area). (b and c) Micritic envelopes (arrowed), 20-30 µm thick, in coral floatstone from the Central Area (GC10). Coral skeleton is replaced by granular mosaic cement, whereas micritised cavity in coral arrowed in 'b' contains a partial micritic geopetal infill followed by bladed then blocky cement infill. (d) Imperforate foraminifera-rich grainstone from the central area (GC9) showing grain distortion of micritic-walled miliolids. Syntaxial overgrowth on echinoderm has a concavo-convex contact with adjacent distorted miliolid. Cement between grains is predominantly granular mosaic calcite, some including 'dusty' micritic areas. (e) Tangential to sutured grain contacts in shallow water larger benthic foraminifera bioclastic packstone from the Western Area (P18e). Mechanical breakage of the thin discocyclinids is common, whereas the robust *Pellatispira/?Biplanispira* (centre left) and *Nummulites* (centre right) act more like indentor grains having slightly sutured contacts with surrounding allochems. (f) Concavo-convex to sutured grain contacts in shallow water bioclastic packstone from the Eastern Area (SRa52), with swarm-like bed-parallel stylolites to dissolution seams.

These dissolution cavities were found in 4 localised areas of the Tonasa Limestone Formation (Wilson et al., 2000). (1) Associated with the northernmost faulted basement high of the Barru Block (Fig. 2) in reworked shallow-water limestone clasts derived from the northern faulted margin in the late Eocene. A few metre-scale Late Eocene shallow-water carbonate outcrops that fringe the southeasterly dip-slope of the Barru Block faulted basement high also include dissolutional cavities (Wilson and Bosence, 1996). (2) Dissolutional cavities are seen in limestone clasts reworked during the Early Miocene in a basinal graben and within *in situ* shallow-water Early Miocene limestones 2 km to the west of the graben, both in the western Segeri area. (3) Four kilometres SW of the western Segeri sections in the northernmost part of the central Pangkajene area one Late Oligocene bed of peritidal algal laminites with the overlying bed having interpreted gas escape structures are associated with reddened surfaces and irregular dissolutional cavities (Fig. 7). Late Eocene shallow carbonates in the same vicinity also contain irregular dissolutional cavities with reddened infill. (4) In the eastern area irregular dissolutional cavities are associated with erosion and tilting of strata. In the Malawa West, Ujunglamuru, Maborongnge and Bantimala measured sections Late Eocene limestones with irregular dissolutional cavities containing fine sediment are overlain by volcanics of the Camba Formation via an angular unconformity. Early Miocene shallow water carbonates at Camba have irregular dissolutional cavities of centimeter to decimeter-scale that are coated in speleothem stalagtitic and stalagmitic precipitates and containing infills of fine carbonate sediment interlaminated with layers of cave pearls (Fig. 7). The shallow-water Miocene limestones have a highly rugose upper contact with the Camba Formation at Camba and dissolution cavity infills are cut by fractures containing volcaniclastic sediment (Fig. 7). Shallow water deposits of Early Oligocene age in the Biru area bordering the western margin of the Walanae Graben have a reddened brecciated upper surface that is overlain by Late Oligocene packstones and grainstones containing planktonic foraminifera. The Bua and Birau Menge sections have irregular dissolutional cavities in Early Oligocene carbonates a few metres below an erosional and angular discordant contact with overlying Late Oligocene deposits. None of the areas with dissolution cavities can be traced for anything more than a few metres to ten metres in outcrop. In the often highly vegetated and dripstone covered upstanding karst of the Tonasa Limestone Formation it is, however, rare to be able to trace individual bed surfaces over greater extents than this. All of the irregular dissolutional cavities occur within 5 km and more usually 1-2 km of known grabenal and horst associated faults (Wilson et al., 2000).

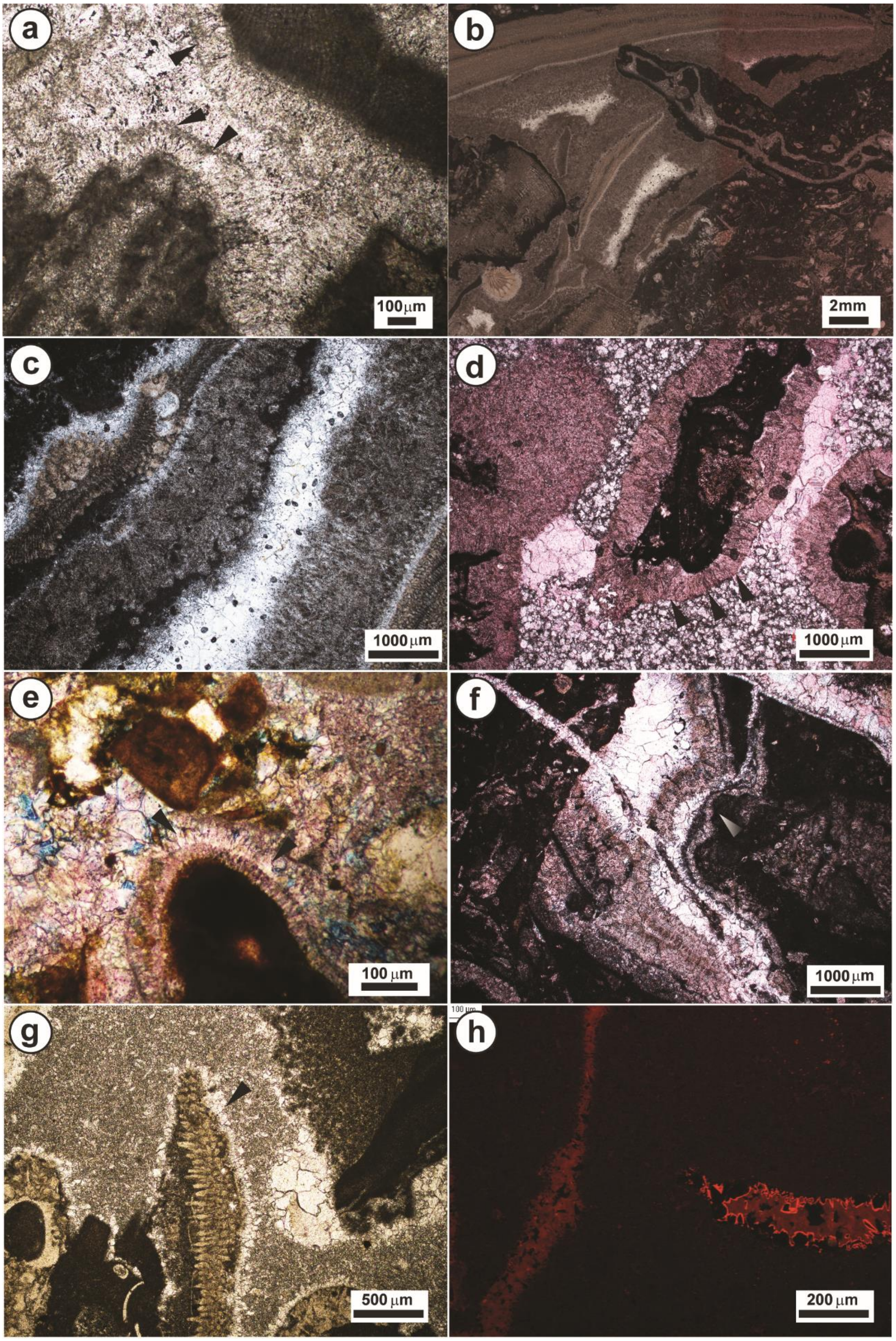

Figure 2.6: Thin-section photomicrographs of pore-lining cements from the Tonasa Platform. (a) Possible bladed to isopachous grain fringing cement with slightly micritised crystal terminations (black arrows), now replaced by granular mosaic cement (Eastern Area, CG9). (b and c) 'Turbid' radiaxial fringing cement lining cavities between bioclasts and post-dating minor clear isopachous fringing cement. Radiaxial cements are up to 2 mm long and show sweeping extinction patterns within crystals, when viewed from perpendicular to the long axis of the crystal under cross-polarised light. Radiaxial cements are post-dated by partial micritic infill in cavities then clear equant to blocky calcite cement (Western

area, SMa26c). (d) Bladed dark-pink stained, non-ferroan calcite lining irregular dissolutional cavities (arrowed). Silt-sized rhombs of dolomite (colourless) partially infill remaining pore space, with a later phase of pale-pink stained equant calcite cement infilling the remainder of the pore space (Northern area, SM^9). (e) Bladed non-ferroan cement lining intergranular pore space (arrowed). Bladed cement is pre-dated by a 'turbid' isopachous cement fringing grains (now replaced by granular mosaic cement), giving the pore-lining cements a banded appearance. Later blocky cement partially infills pore space (Western area, SMa11). (f) 'Turbid' bladed to banded cement partially infilling irregular fracture to dissolutional cavity. Bladed cement is preceded by an earlier dogtooth to blocky cement (arrowed) and micritic sediment infill. Equant to blocky cement infills later cross-cutting fractures and remaining cavity pore space (Eastern area, CG9). (g) Scalenohedral to dogtooth calcite (arrowed) lining irregular cavity. Cavity is infilled by micrite of varying darkness, with minor later blocky cement (Northern area, SP32). (h) Cathodoluminescene image with majority of image showing very dull luminescent micritic-rich sample. Curved mold after fragmented shell in right of image has blocky cement with non-luminescent character and a bright luminescent fringe. This is followed by dull luminescent pore filling cement in both the centre of the shell biomold and also the fracture, the latter in the left of the image. Non-luminescent areas within the pore filling cement areas are minor porosity, some possibly due to cement plucking during thin sectioning (Eastern area, CG7).

Included in the pore lining cements are a range of cement types that are commonly preserved as ghost textures being overprinted by later granular mosaic cement (Fig. 6a). This overprinting can render it difficult to precisely define the earlier pore lining cement phase. No pore lining cements were seen in samples from the southern Jeneponto Area. Radiaxial bladed to fibrous cements line (shelter) cavities between bioclasts or clasts in grainstone or lithoclastic facies from 4 samples associated with the platform margin in the eastern and western areas (Fig. 6b and c). Radiaxial cements have sweeping extinction patterns and crystal lengths up to 2 mm (Fig. 6c). Bladed to banded, or bladed to possible isopachous fringing cements were noted in central (1), northern (11, Fig. 6d), western (3: Fig. 6e) and eastern (2: Fig. 6a and f) area samples. These bladed and isopachous crystals fringes generally have crystal lengths less than 200 µm and occur around bioclasts in grainstone units (Fig. 6e). Longer bladed to banded crystals (up to 400 µm) fringe dissolutional cavities just in the eastern, western and northern area samples (Fig. 6d and f). Dog tooth to scalenohedral crystals are rare being present in 4 northern, 1 western and 2 eastern area samples (Fig. 6g). These dog tooth crystals are generally <200 µm and partially line dissolutional cavities (vugs to biomolds) or primary pore spaces. Micrite or crystal silts (dolomitic) may partially infill pore spaces after the pore lining cement phases (Fig. 6). Cave pearls partially infill cement lined dissolutional cavities in the eastern area (Fig. 7; after Wilson, 2000). There may be up to three phases of the same or different pore lining cements in individual samples, some separated by micrite and/or crystal silt (Fig. 6). The CL character of pore lining cements is commonly non luminescent, or more rarely slightly bright, but towards crystal margins there may be bright and dull-luminescent zones (Fig. 6h).

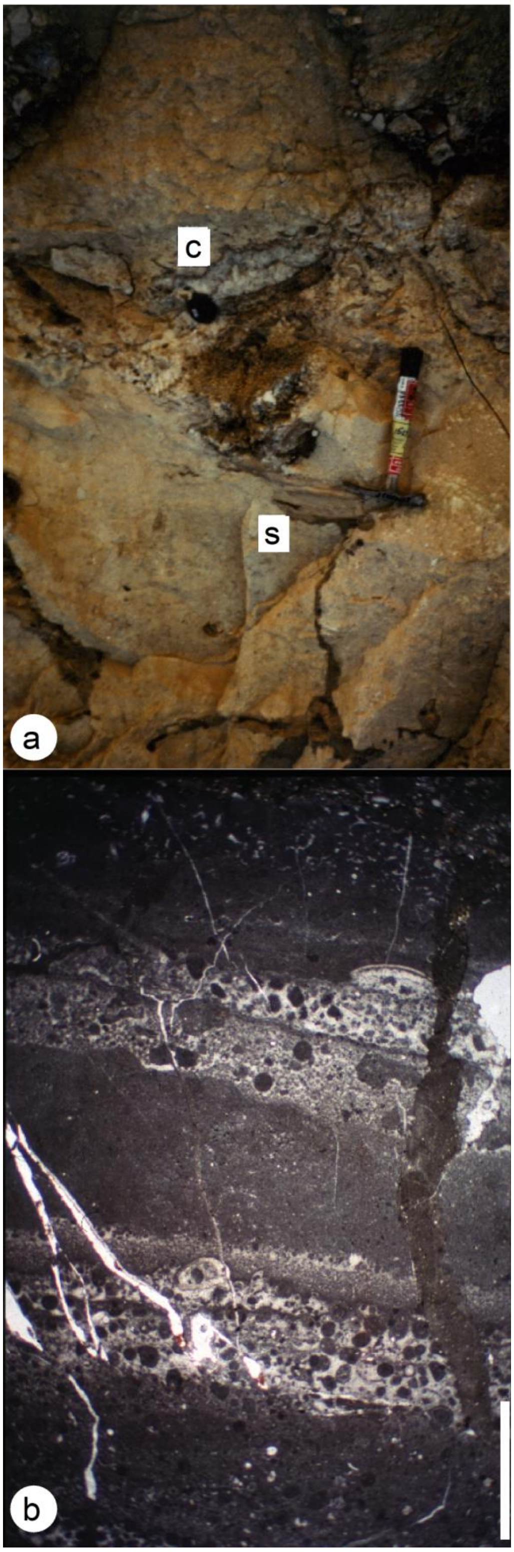

Figure 2.7. (a) Probable Tertiary karstic dissolution cavity infilled fine sediment "s" and banded calcite cement "c". (b) Photomicrograph of Miocene karstic fissure-fill sediment (including cave pearls) from the uppermost part of the Tonasa Formation in the Camba section from the eastern area. Scale bar: 0.5 mm. Laminae of micrite and cave pearls constitute most of the cavity fill. A fracture infilled with fine volcaniclastic sediment post-dates the carbonate fill of the cavity (right side of image).

2.5.3 Syntaxial overgrowths

Syntaxial overgrowth cements are noted in 101 of 153 thin sections, most commonly on echinoderm grains and rarely on larger benthic foraminifera. Overgrowth cements may both pre-date, but more commonly post-date, some of the mechanical grain packing and grain breakage features described directly below (Fig. 8a, b, c). On average syntaxial overgrowths comprises < 0.1% cement throughout the deposits of the Tonasa Platform with overgrowth thicknesses generally < 300 µm (Fig. 8d, e, f). Syntaxial overgrowth cements are most prevalent and thickest (up to 1 mm; Fig. 8b, c) in medium to coarse grained bioclastic planktonic foraminifera and graded bioclastic packstones from slope settings as well as in bioclast packstones and grainstones from the central Pangkajene Area. The echinoderm plates generally have a ‘speckled, dusty’ appearance, whereas the syntaxial cements that overgrow them are clear, to slightly turbid under plane polarised light (Fig. 8e). Cathodoluminescent imaging reveals the echinoderm grains have ‘speckled’ dull to non-luminescence, with up to four CL zones in the overgrowth cements. From oldest to youngest these CL cement zones are: (1) dull-, (2) non-, (3) bright-, to (4) bright to dull-luminescent (Fig. 8d-f).

2.5.4 Grain alignment, distortion, mechanical grain packing, grain breakage and grain suturing:

Grain distortion, mechanical grain breakage and closer grain packing, the latter including tangential and concavo-convex grain contacts, is prevalent throughout deposits of the Tonasa Platform (seen in 95% of samples studied). The degree of closer grain packing, grain breakage and sutured grain contacts is highly variable, but is most noticeable in some shallow water grainstones, larger benthic foraminifera packstones, planktonic foraminifera bioclastic packstones and breccia units (Fig. 5d, e, f). Grain distortion mostly affects micritic walled bioclasts, such as imperforate foraminifera (Fig. 5d), or marly breccia clasts. Grain breakage most commonly affects elongate grains, such as mollusc shells or flattened larger benthic foraminifera (Fig. 5e). The features described here are generally most common in the deeper Eocene and Oligocene parts of thicker sections (Figs. 3 and 4). In sections associated with deepening during fault breakthrough there is a peak in these features in deposits formed around the initial period of deepening (e.g., Rala, Figs. 3 and 4; cf. Wilson, 1999; Wilson et al., 2000).

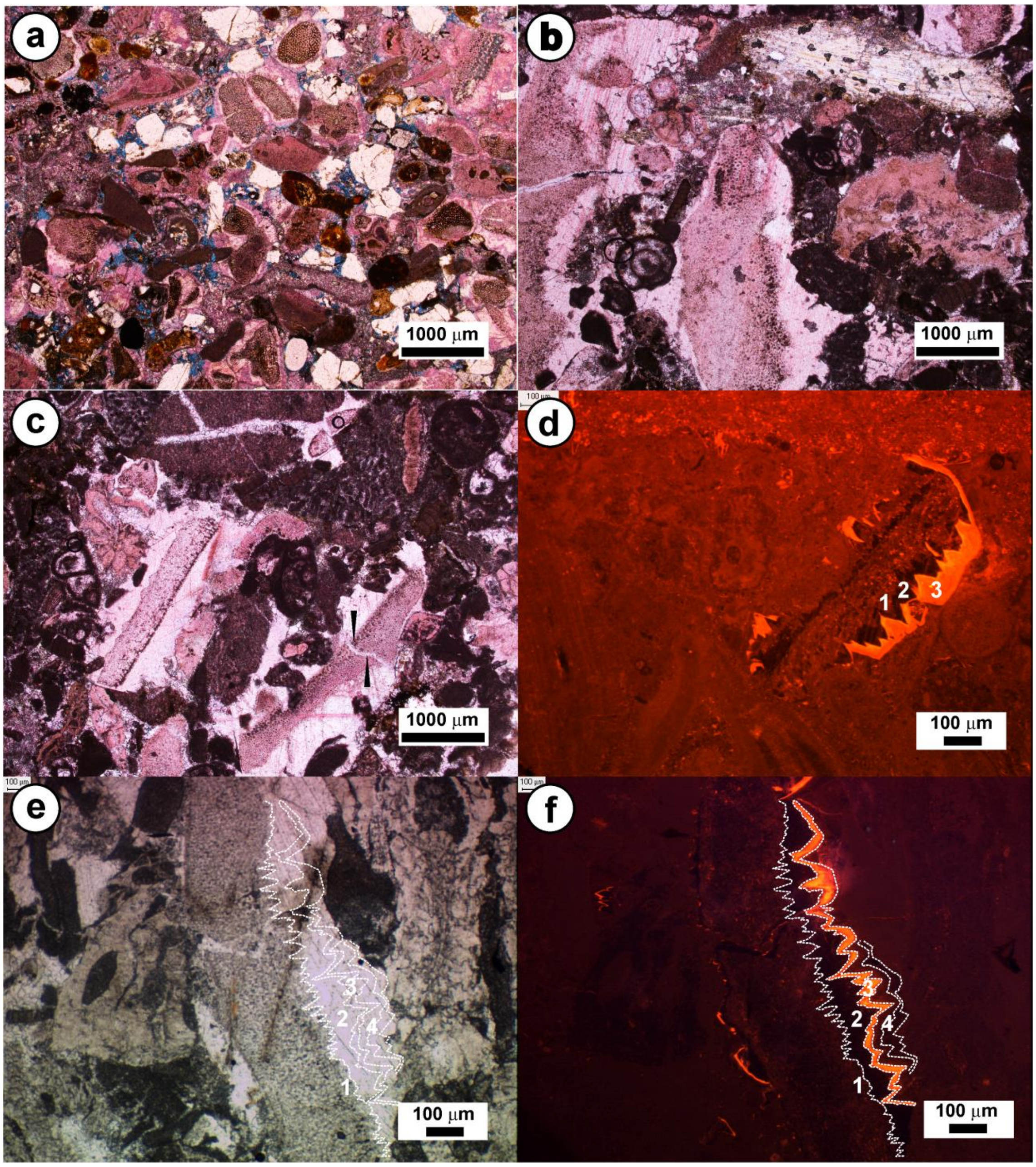

Figure 2.8. Thin-section photomicrographs show syntaxial overgrowth cements from the Tonasa Platform. (a) Clear to slightly turbid syntaxial overgrowth cement under plane polarised light in quartzose bioclastic grainstone (SMa11). Syntaxial overgrowths post-date some mechanical compaction. (b and c) Syntaxial overgrowth cements up to 1 mm thick on echinoderm material. Overgrowth cements post-date some compaction (black arrows show cement growth after grain fracturing; GC3). (d) Cathodoluminescent image (S13a) and (e and f) plane polarised light and cathodoluminescent image pair (S10a) showing CL cement zonation not visible under plane light. Sequence of CL luminescence: (1) dull-, (2) non-, (3) bright-, to (4) bright to dull-luminescent.

2.5.5 Granular mosaic calcite

Granular mosaic calcite is present as trace to common, or more rarely abundant, amounts in 90% of samples from all areas of the Tonasa Formation, i.e., this is the most common crystal type throughout the Tonasa Formation (Figs. 5b-d, 8a-d). Granular mosaic calcite is composed of roughly equidimensional small crystals (<100-300 µm, with average size ranging from 50 to 100 µm) with irregular to subhedral crystal boundaries (*sensu* Flügel, 2004; Figs. 5b-d, 9a-d). The granular calcite may be clear crystals filling pore spaces or incorporate 'dusty' micritic patches (Fig. 9a-c), or overprint earlier cement phases (Fig. 6a). Granular mosaics may also occur in place of bioclasts as regions of clear crystals or preserving 'ghost' textures of the precursor grain (Fig. 9d and e). Near complete replacement of samples by granular mosaic calcite preserving a range of these textures has occurred by non-ferroan and ferroan calcite in the northern, southern and eastern areas. Granular mosaic calcite is mostly dull-luminescent to non-luminescent. Although variable in their distribution, granular mosaic cements are most common in the Eocene and Oligocene deposits, commonly in thicker sections (Fig. 3 and 4).

2.5.6 Fracturing

Fractures here refer to through going features that cross cut more than individual grains, of which the former are grouped under mechanical grain breakage (described above). The relative timing of fractures varies, and individual samples may include multiple phases of fracturing (Figs. 9c, f and 10a, b). Fractures linking, or associated with, dissolutional cavities where fractures pre-date some cavity or fracture infill by sediment are most common in the eastern area (Fig. 9b), and more rarely occur in the northern and northern central area samples (Fig. 7). Rare samples may include multiple phases of sediment and cement infill of fractures up to 5 mm across (Fig. 6f). Other fractures not associated with cavities include sub-mm width fractures that are on a mm- to cm-scale length, commonly terminate within the sample (Figs. 9c and 10c). These fractures have irregular to diffuse margins that may merge into the groundmass. Fill of these fine scale fractures is most commonly by granular mosaic cement with crystal size commonly <100 µm (Fig. 9c). Millimetre thickness fractures and or fractures with sharp margins commonly post-date the small diffuse margined fractures and the larger-scale fractures may terminate within the thin section or be through going (Fig. 9c, f).

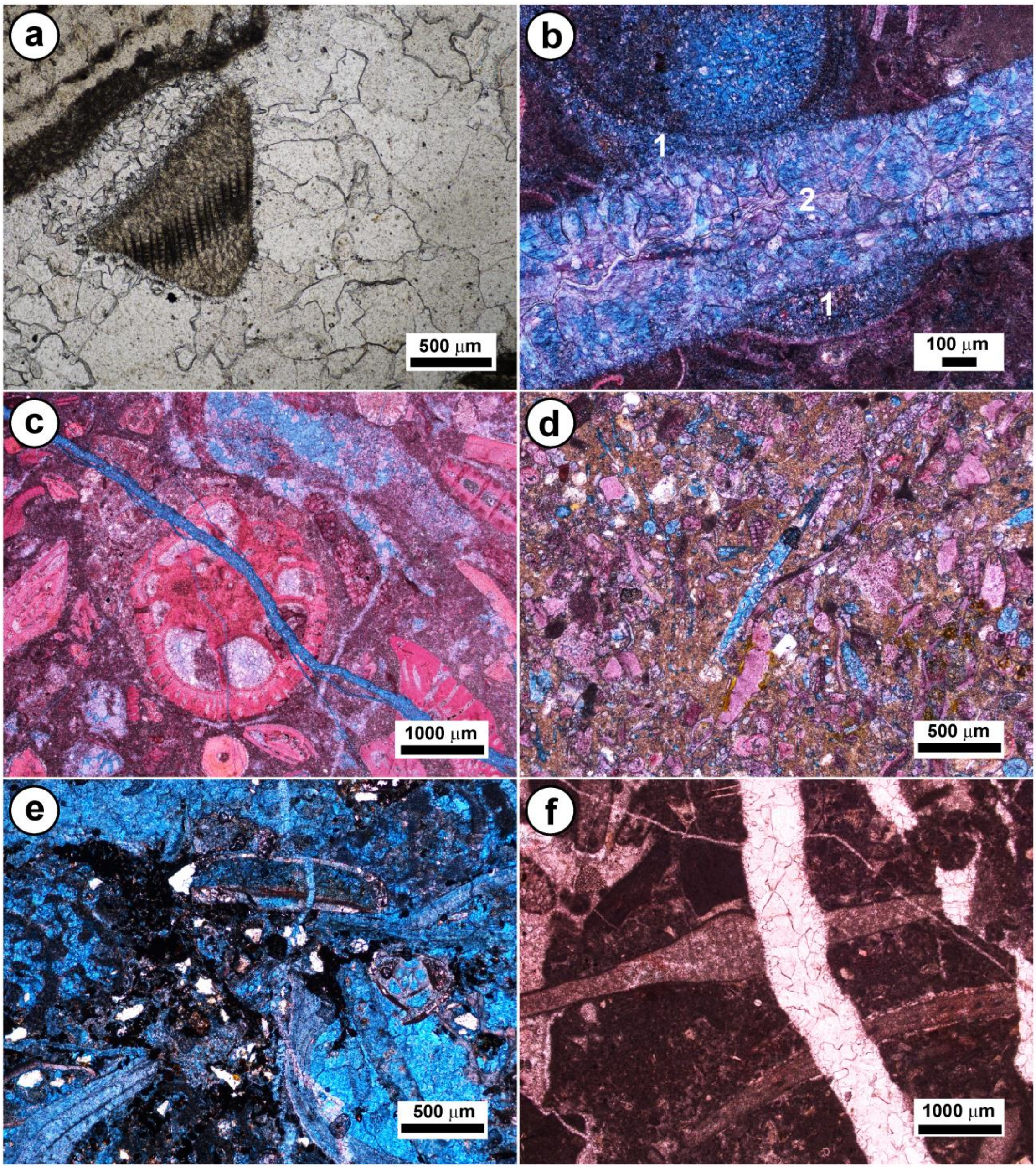

Figure 2.9. Thin-section photomicrographs show varied cement phases and fracturing from the Tonasa Platform. (a) Granular mosaic to blocky cement with clear irregular/subhedral crystal (SC6b). (b) Ferroan granular mosaic calcite replacing bioclast (1), cut by fracture, with bladed to blocky cement infilling fracture (2; MC2). (c) Pale blue stained (ferroan) granular mosaic to equant calcite replacing bioclast and micritic infill (top right), and infilling intragranular and early fracture porosity. Later fracture cross cutting all earlier features is filled by a granular mosaic to equant cement stained a darker blue than the earlier ferroan calcite (SMa47). (d) Clear, ferroan (blue-stained) granular mosaic calcite 'in place' of non-calcitic bioclasts. (e) Ferroan granular mosaic to blocky calcite replacing bioclasts (ghost texture of original wall structure preserved) and infilling adjacent porosity (BM36). (f) Sub-millimetre and millimetre-scale fractures infilled by equant to blocky cements (CG9).

The larger-scale, or sharp margined fractures commonly cross-cut earlier features including some cement phases. The sharp-margined fractures are most commonly filled with blocky to equant cements with crystal sizes up 500 µm (Fig. 9f). Up to three phases of fracturing are present in samples, including 2 phases of sharp margined fractures. Some of the sharp margined fractures infilled with equant cement terminate at stylolites, but others post-date stylolitisation (Fig. 10a and b). Displacement along fractures, most commonly on a millimetre-scale, is observed from all areas except the southern Jeneponto region (Fig. 10c). Fracture development, particularly of the fine-scale fractures may be most clearly seen under cathodoluminescent images.

2.5.7 Fault and fracture orientations and their occurrence

A number of mainly coincident trends occur in both the large-scale near-vertical faults and smaller-scale fracture (and vein) orientation data derived from the published geological maps and field measurements (Fig. 11; after Sukamto, 1982; Sukamto & Supriatna, 1982; Wilson, 1995). A dominant NW-SE trend occurs in all areas of South Sulawesi (Fig. 11). Large-scale faults with this orientation faults mainly affect the Tonasa Limestone Formation and the lower member of the Camba Formation, but do not appear to penetrate far into the upper volcanic member of the Camba Formation. A NNW-SSE trend also affects all formations (including the upper Camba Formation) in the Walanae Depression, the eastern part of South Sulawesi and the Pleistocene/Pliocene volcanics in the southern part of South Sulawesi (Fig. 11). A possible NE-SW subsidiary fault trend also occurs in western, eastern and southern parts of South Sulawesi (Fig. 11). The fault trends affecting the Pleistocene/Pliocene volcanics in the southern part of South Sulawesi appear to be more randomly oriented. Small-scale fractures and calcite filled veins in the Tonasa Limestone Formation show predominantly the same main trends as the larger-scale faults (Fig. 11). Particularly close to major faults, small-scale fracture and veins trends are commonly parallel, and also perpendicular to the strike direction of the main faults. In the northern area of the Tonasa Limestone Formation NW (-SE) trends predominate, with common NNW (-SSE) and NE (-SW) strike trends of the small-scale features. In the western and eastern areas the NNW (-SSE) and NE (-SW) to ENE (-WSW) trends predominate. Fracturing was less commonly recorded in the central and southern areas, and these fractures have more variable orientations when compared with other areas of the Tonasa Limestone Formation (Fig. 11).

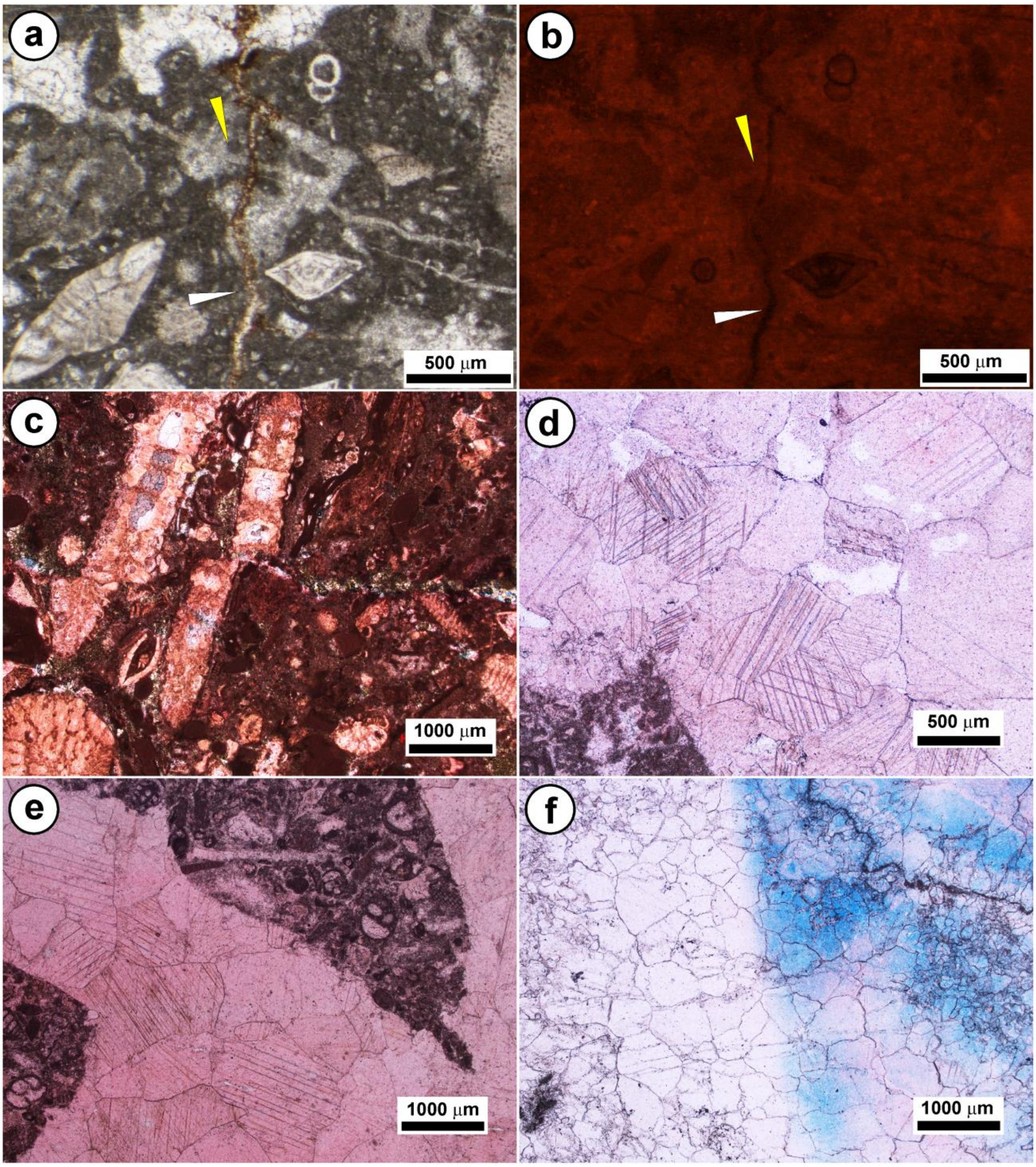

Figure 2.10. Thin-section photomicrographs showing fracturing and pore-filling cements from the Tonasa Platform. (a and b) Plane polarised light and cathodoluminescent image pair showing fracture filled by granular mosaic to equant cement (yellow arrow) and cut by other fracture with another equant cement associated with stylolites (white arrow; Sample SMa47). CL image highlights different relative timing of fracturing and their cementation. (c) Displacement along irregular fracture (SMa24). (d and e) Predominantly euhedral crystals of equant to blocky cement (up to 800 µm; LB2 and UL3, respectively). (f) Drusy to blocky cements in intragranular and biomoldic porosity after coral (CG10). Thin section photomicrograph cuts across the half stained part of the thin section (stained area to right). Micrite envelope to original coral is seen top right and part of the micritic, slightly peloidal chamber infill of the coral is seen bottom left.

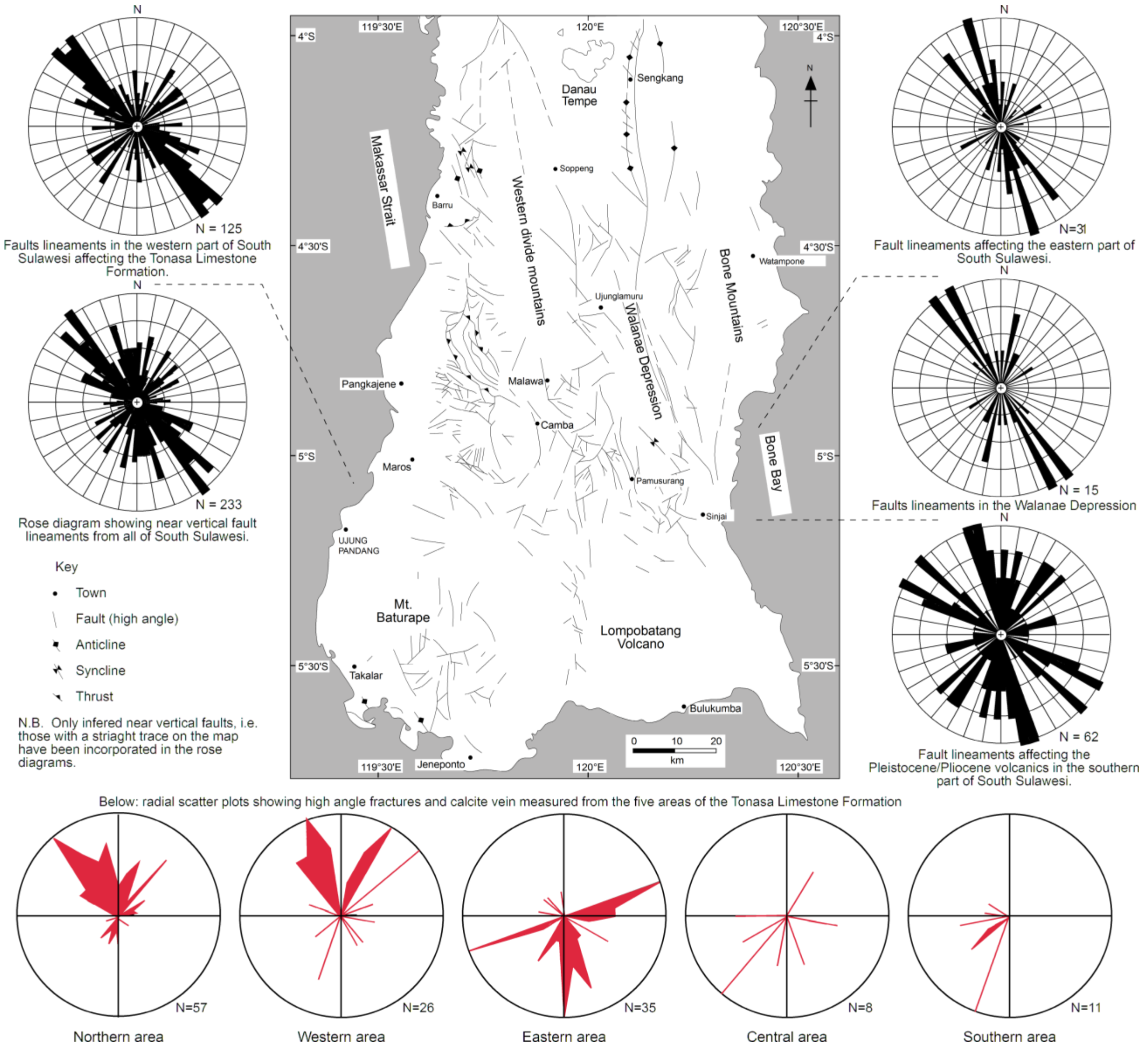

Figure 2.11. Map of South Sulawesi showing structural trends (after Sukamto, 1982; Sukamto and Supriatna, 1982; Wilson, 1995). The orientations of near vertical large-scale faults, resolvable on geological maps, from the different areas of South Sulawesi have been plotted as rose diagrams. Dip directions of faults were commonly not given on the geological maps (cf. Sukamto, 1982; Sukamto and Supriatna, 1982), consequently the strike direction of faults has been plotted as bi-directional data. The dominant fault trends in South Sulawesi are NW-SE and NNW-SSE. The small-scale fractures and/or calcite filled veins, resolvable at the outcrop scale with apertures on a centimetre to millimetre scale, for the different areas of the Tonasa Limestone Formation are plotted as radial scatter plots. Dip information for near-vertical small-scale structures was recorded in the field, consequently the strike direction of the feature is recorded uni-directionally with planar feature dipping at ninety degrees clockwise to the recorded strike direction (i.e. the 'right-hand rule'). The dominant small-scale fracture and vein trends in the Tonasa Limestone Formation are NW(-SE) and NNW(-SSE), with subsidiary trends to the NE(-SW) and NNE-SSW.

Among the in place predominantly shallow water deposits the ratio of numbers of all fractures/veins to numbers of samples studied is consistently higher by up to tenfold in the northern, eastern and western areas of the Tonasa Limestone Formation compared with the central and southern areas (Fig. 12). Only in Eocene deposits from the central area (Lapangan Golf section) does the ratio of the number of all fractures/veins approach that from other regions. In this Eocene section the higher ratio compared with other central area sections is mainly due to straight fracturing (Fig. 12). The ratio of the number of highly irregular fractures to the number of samples studied is also consistently higher by three to eight times in the northern, eastern and western areas compared with the central and southern areas of the Tonasa Limestone Formation (Fig. 12). Sediment gravity flow deposits are just found in the northern, eastern and western areas, containing material commonly derived from faulted highs (Wilson and Bosence, 1996; Wilson, 1999; Wilson et al., 2000). In all these three areas gravity flow deposits include intra-clast, calcite-filled fractures (Fig. 12). These fractures or veins are truncated at the clast margin and occur in both lithified carbonate and non-carbonate reworked clasts. Fractures or veins that cross-cut the fabric of the lithoclastic breccias are also present in many samples from the northern, eastern and western slope to basinal deposits (Fig. 12). There are no strong trends in ages of deposits compared with irregular and straight fractures or for intra- versus extra-clast fractures (Fig. 12).

2.5.8 Pore and fracture filling cements

Although granular mosaic crystals occlude some intra-, and intergranular porosity as well as some of the fine-scale fractures, this cement type is described previously. Additional crystal types that post-date and may grade from granular mosaic cements, and also fill fractures are blocky, equant, poikilotopic and rarely drusy cements (Fig. 10d-f). In less than 5% of fractures there are bladed to fibrous ‘slickencrysts’ that have their direction of elongation perpendicular or oblique to the fracture wall. All these com monly late stage cements are present in 40-60% of samples from all areas of the Tonasa Formation. Equant cements have equidimensional crystals up to 200 µm, and are euhedral, whereas blocky cements are coarser (up to 800 µm) and less equidimensional than the equant ones (*sensu* Flügel, 2004, Fig. 10d and e). Poikilotopic crystals are larger than 400 µm, enclose a number of allochems, and were seen in 4 western and northern area samples. An unequivocal sequential increase in crystal size towards pore centres typical of drusy cements was seen in just 4 samples from the western and northern areas (Fig. 10f). There is common gradation of pore filling cements from one type to another with: (1) drusy cements transitioning to blocky cements, (2) granular mosaic cements grading to equant or blocky cements, and (3) equant cements grading to blocky cements. Most cements are non-ferroan calcite, but in all areas except the central area ferroan calcite is also present in up to 15% of samples. Where there are gradational changes within samples from non-ferroan to ferroan calcite the ferroan calcite as blocky cements is most commonly the final pore filling phase. There are, however, also samples in the eastern and northern areas from near the contact with the underlying siliciclastics, or adjacent igneous rocks in which ferroan granular mosaic or more rarely drusy crystals grade to non-ferroan to blocky crystals (Figs. 9b and 10f). Near complete replacement of samples by equant calcite preserving a range of these textures has occurred by non-ferroan and ferroan calcite close to some of the igneous intrusions in the northern and eastern areas (Fig. 9e). Most of the pore filling cements described in this section are dull-luminescent, but rare non- to bright luminescent zoning is seen in some blocky cements (Fig. 6h). Although variable in their distribution, equant to blocky cements are generally most common in the deeper parts of sections (Fig. 3 and 4).

2.5.9 Stylolites and dissolution seams

A continuum of 'jagged' stylolites to 'anastomosing' dissolution seams have been recognised in different areas of the Tonasa Formation (Fig. 13a). Dissolution seams are most common in samples containing more than a few percent insolubles, mostly as clays, such as deep water marls or those close to the contact with the underlying siliciclastic Malawa Formation. Stylolites are mostly bed parallel, but also occur as circum-clast stylolites in the slope breccia units. Stylolitisation and/or seam formation usually post-dates all other diagenetic features, but can be associated with, or pre-date, some of the fracturing (Fig. 10a). Any material along stylolites and dissolution seams is generally dark in plane polarised light and usually non-luminescent under cathodoluminescence (Figs. 10a, b and 13a). As with the pore filling cements stylolites and/or dissolution seams are generally most common in the deeper parts of sections (Fig. 3 and 4).

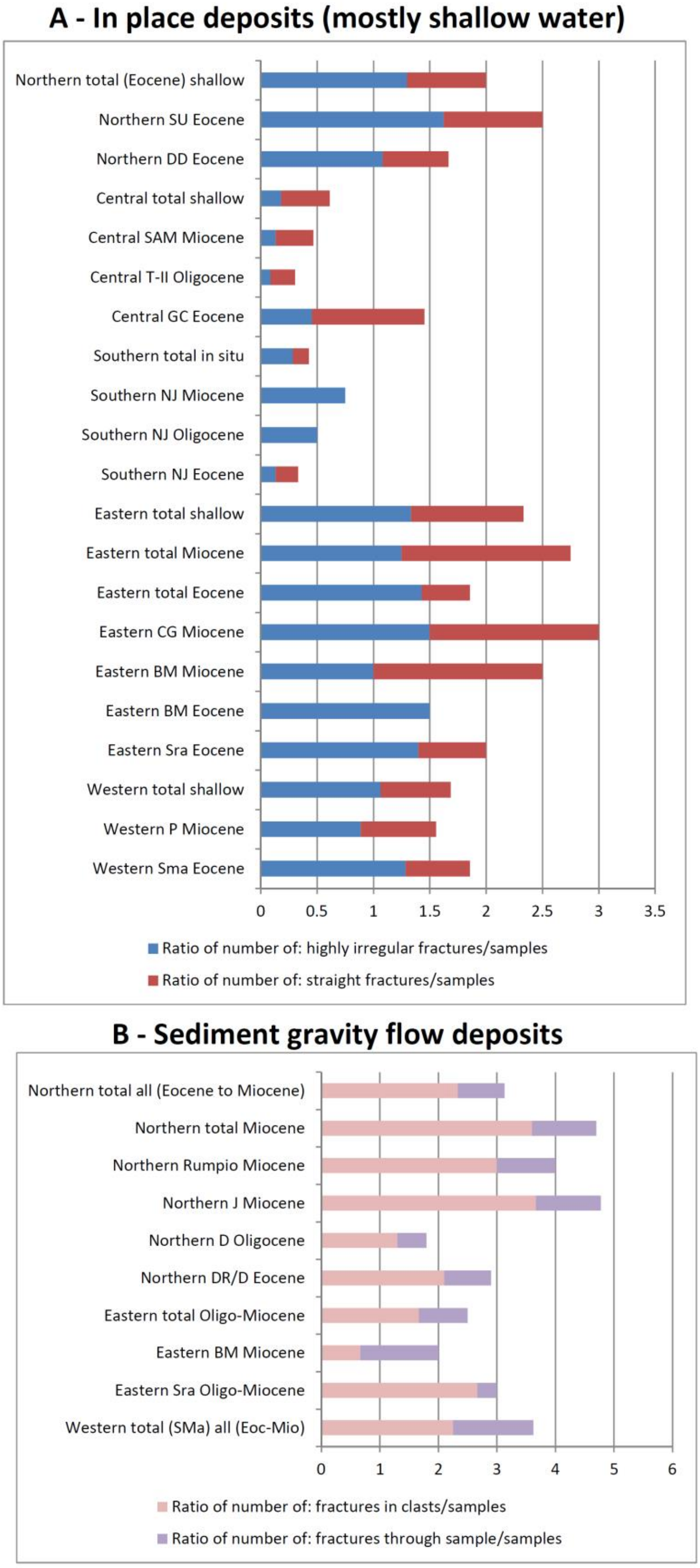

Figure 2.12. Fracture distribution and evidence for their relative timing from a study of 164 thin sections across all areas of the Tonasa Formation. (a) Ratios of numbers of highly irregular and straight fractures to the numbers of samples studied from in place, mostly shallow-water, deposits. (b) Ratios of numbers of fractures within clasts to the numbers of samples studied from sediment gravity flow deposits, with clast sizes greater than 5 mm, from the northern, eastern and western areas. Abbreviations are after the section names in the main different areas of the Tonasa Formation.

2.5.10 Dolomitisation

Dolomitisation is uncommon in the Tonasa Formation, seen in 15 out of 153 samples studied, with the additional samples not selected for this study containing almost no dolomite. Dolomite occurs as: (1) clear, intergranular rhomb shaped crystals (Fig. 13b), (2) crystal silt (crystals <50 µm across; Fig. 6d), and (3) 'dusty', mimetic or fabric replacive dolomite, the later in partially or fully dolomitised samples (Fig. 13c and d). The fully dolomitised samples are restricted to the central area (3 samples), have been affected by dissolution of bioclasts, such as foraminifera, then formation of dolomite cements and late blocky to poikilotopic non-ferroan calcite formation. CL images reveal non- to dull-luminescent mimetic dolomites followed by dolomite and calcite crystal growth that are mainly non- to dull-luminescent with bright zones (Fig. 13c and d). The dolomite crystals silts were seen in cavities from the eastern area previously fringed by earlier pore lining cements (Fig. 6d). Intergranular dolomite rhomb formation was seen in central, northern and eastern area grainstones, with rhombs up to 200 µm and showing some zoning with darker bands (PPL) and bright to non-luminescent zones in CL.

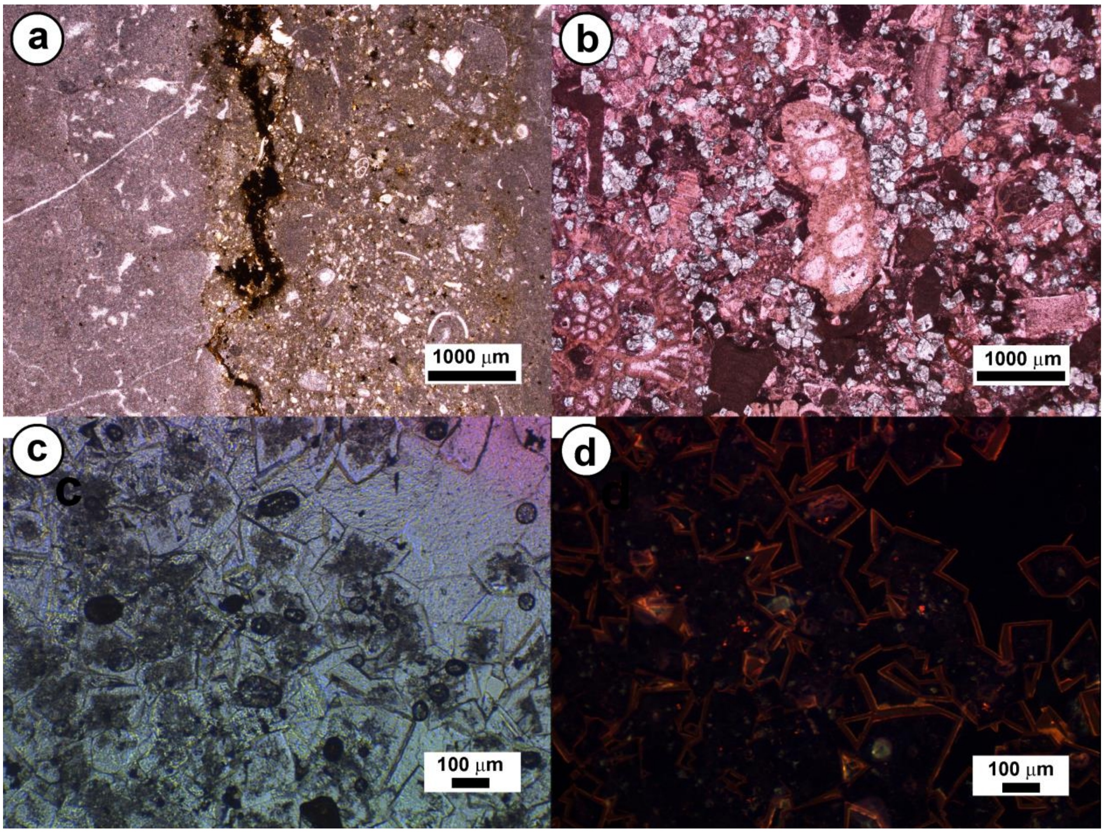

Figure 2.13. Thin-section photomicrographs showing stylolites/dissolution seams and dolomite from the Tonasa Platform. (a) Irregular stylolites to dissolution seam with concentration of insolubles along sutured interface (CG7 (b) 'Dusty' to clear, intergranular rhombic dolomite crystals (GC25). (c and d) Plane polarised light and CL image pair of fully dolomitised sample form the central area (GC58). Dusty interior to dolomite rhombs is non-luminescent with brighter 'flecks'. Clear dolomite cements forming the edges of the rhombs shows faint bright, dull, bright luminescence.

2.5.11 Stable isotope analyses

Stable isotope analysis has been run on 36 samples from across the Tonasa Limestone Formation with the exception of the southern Jeneponto area. The values of selected samples are widely scattered between 2.38‰ and –14.23‰ δ^{13}C, and from –1.71‰ to –19.68‰ of δ^{18}O (Fig. 14; Table 1). Within this stable isotopic variability three groupings and one outlier are distinguished that relate to the components and their isotopic signatures (Fig. 15). The groups are: (1) a variety of components which include dolomite, blocky calcite, micrite, micritic cavity infill after radiaxial fringing cement and large benthic foraminifera that comprise the largest group (26 samples) having values of 2.38 to -0.60‰ δ^{13}C and -1.71 to -9.47‰ δ^{18}O, (2) 4 samples including algal laminite and larger benthic foraminifera close to the algal laminite or the underlying siliciclastics with low negative values of δ^{13}C ‰ and negative δ^{18}O ‰ values ranging between -2.04 ‰ to -3.40‰ and -6.28 to -7.60‰, respectively, and (3) 5 samples including larger benthic foraminifera, pore-filling equant cement, micritic sediment infilling dissolution cavities and blocky cement with highly negative values of -9.11 to -14.23‰ δ^{13}C and -14.20 to -19.68‰ δ^{18}O. Samples from this third group all lie within 2 km of intrusive igneous stocks (with stocks exposed at the surface forming 1 to 2 km across sub-elliptical features). The outlier sample (1.79‰ δ^{13}C and -13.86‰ δ^{18}O) is from a larger benthic foraminifera (*Nummulites*) from a localised outcrop in the eastern area surrounded by siliciclastics and close the Walanae Fault Zone and igneous intrusives.

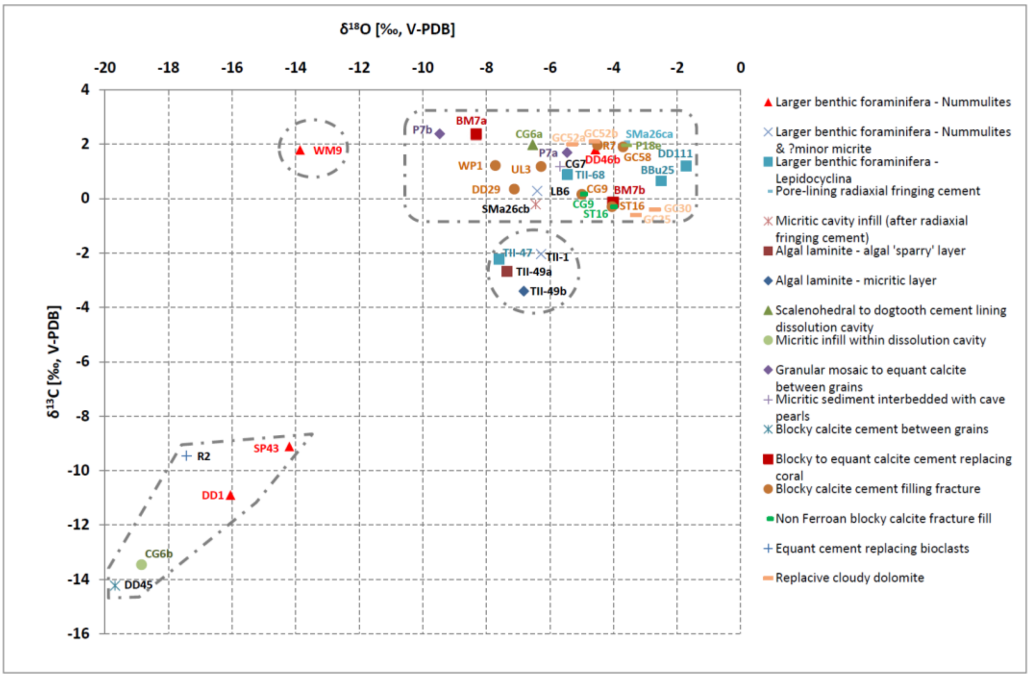

Figure 2.14. Stable isotope plot (δ^{18}O versus δ^{13}C ‰ V-PDB) of carbonate allochems, cements and matrix from the Tonasa Limestone Formation.

Table 2.1. Stable isotope results ($\delta^{18}O$ and $\delta^{13}C$ ‰ V-PDB) of analysis of carbonate allochems, cements and matrix from the Tonasa Limestone Formation.

Sample	Area/Fm	Delta 13C	Delta 18O	18OSMOW	Name
P18e	Western Area	1.96	-3.59	27.21	Larger benthic foraminifera - Nummulites
WM9	Eastern Area	1.79	-13.86	16.62	Larger benthic foraminifera - Nummulites
SP43	Northern Area	-9.11	-14.20	16.27	Larger benthic foraminifera - Nummulites
DD1	Northern Area	-10.90	-16.05	14.36	Larger benthic foraminifera - Nummulites
DD46b	Northern Area	1.81	-4.57	26.20	Larger benthic foraminifera - Nummulites
TII-1	Central Area	-2.04	-6.28	24.44	Larger benthic foraminifera - Nummulites & ?minor micrite
LB6	Eastern Area	0.28	-6.40	24.32	Larger benthic foraminifera - Nummulites & ?minor micrite
TII-68	Central Area	0.88	-5.45	25.29	Larger benthic foraminifera - Lepidocyclina
TII-47	Central Area	-2.23	-7.60	23.08	Larger benthic foraminifera - Lepidocyclina
DD111	Northern Area	1.20	-1.71	29.15	Larger benthic foraminifera - Lepidocyclina
BBu25	Northern Area	0.65	-2.51	28.32	Larger benthic foraminifera - Lepidocyclina
TII-49a	Central Area	-2.67	-7.35	23.34	Algal laminite - algal 'sparry' layer
TII-49b	Central Area	-3.40	-6.82	23.88	Algal laminite - micritic layer
SMa26ca	Western Area	2.09	-3.64	27.15	Pore-lining radiaxial fringing cement
CG6a	Eastern Area	1.98	-6.54	24.17	Scalenohedral to dogtooth cement lining dissolution cavity
SMa26cb	Western Area	-0.21	-6.45	24.26	Micritic cavity infill (after radiaxial fringing cement)
CG6b	Eastern Area	-13.46	-18.85	11.46	Micritic infill within dissolution cavity
CG7	Eastern Area	1.18	-5.68	25.06	Micritic sediment interbedded with cave pearls
P7a	Western Area	1.69	-5.46	25.28	Granular mosaic to equant calcite between grains
P7b	Western Area	2.38	-9.47	21.14	Granular mosaic to equant calcite between grains
BM7a	Eastern Area	2.37	-8.32	22.33	Blocky to equant calcite cement replacing coral
BM7b	Eastern Area	-0.14	-4.01	26.78	Blocky to equant calcite cement between grains
DD45	Northern Area	-14.23	-19.68	10.62	Blocky calcite cement between grains
DD46a	Northern Area	1.22	-5.65	25.09	Blocky calcite cement between grains
R2	Northern Area	-9.45	-17.43	12.94	Equant cement replacing bioclasts
DD29	Northern Area	0.35	-7.12	23.57	Blocky calcite cement filling fracture
R7	Northern Area	1.97	-4.50	26.27	Blocky calcite cement filling fracture
WP1	Eastern Area	1.22	-7.72	22.95	Blocky calcite cement filling fracture
UL3	Eastern Area	1.18	-6.28	24.43	Blocky calcite cement filling fracture
CG9	Eastern Area	0.16	-5.00	25.76	Non Ferroan blocky calcite fracture fill
ST16	Northern Area	-0.30	-4.05	26.73	Ferroan equant to blocky calcite fracture fill
GC58	Central Area	1.90	-3.70		Replacive cloudy dolomite
GC52a	Central Area	2.00	-5.30		Replacive cloudy dolomite
GC52b	Central Area	2.10	-4.60		Replacive cloudy dolomite
GC30	Central Area	-0.40	-2.70		Replacive cloudy dolomite
GC25	Central Area	-0.60	-3.30		Replacive cloudy dolomite

2.6 Diagenetic Interpretations

The varied diagenetic processes and cementation phases affecting the Tonasa carbonate platform are discussed below in their most common relative order of occurrence as inferred from petrographic relationships (Fig. 15). Regionally for SE Asia, known $\delta^{18}O$ V-PDB values of Oligo-Miocene marine components and marine cements plot between -1.4 to -7.1‰ (Ali, 1995; Wilson and Evans, 2002; Madden and Wilson, 2012; 2013; Wilson et al., 2013). Some of these values fall more negatively than the global norm (Tomascik et al., 1997; Wilson, 2008). The most negative values are from palaeo-inshore areas affected by terrestrial runoff, likely reflecting lower salinities and more brackish conditions compared with the global norm (Madden and Wilson, 2013; Wilson et al., 2013). Six of the 11 sampled larger benthic foraminifera from the Tonasa Formation have $\delta^{18}O$ V-PDB values between -1.71 and -6.40‰ (and slightly positive $\delta^{13}C$ values of 0.28 and 1.96‰) that are consistent with marine values for SE Asia. Using the equation of Anderson and Arthur (1983) and at seawater temperatures of 26-30˚C for modern surface waters in the Makassar Straits (Gordon, 2005; Peñaflor et al., 2009) these values from the Tonasa Formation convert to 1.4 to -4 V-SMOW. A $\delta^{18}O$ value of -6 to -4‰ V-SMOW is suggested for possible meteoric parent fluids on the basis of $\delta^{18}O$ values of meteoric precipitation in SE Asia at low elevations (Anderson and Arthur, 1983; Bowen and Wilkinson, 2002). To evaluate potential burial depths and temperatures the onset depth of stylolite and dissolution seam formation may commonly start from 500 m is utilised (Finkel and Wilkinson, 1990; Lind, 1993; Railsback, 1993; Nicolaides and Wallace, 1997). Temperature gradients of between 21 to 28˚C per kilometre have been measured in nearby subsurface wells that penetrate the Tonasa Formation (Hall, 2002b).

2.6.1 Micritisation

Micritisation is the first alteration process affecting most samples; since other diagenetic features cross-cut micrite envelopes and micritic rims to allochems. Micritic rim formation is inferred to be via infilling of microborings formed by endolithic organisms since micritisation generally encroaches into bioclasts within the Tonasa Formation (cf. Bathurst, 1966; Gunther, 1990; Perry, 1999). Common micritisation in packstones, floatstones and wackestones from platform-top deposits, but only trace amounts in slope and basinal deposits, is consistent with enhanced endolithic organism activity in shallow-water influenced by low to moderate energies (Fig. 1a and b; cf. Swinchatt, 1965; Budd and Perkins, 1980; Perry and Bertling, 2000; Perry and Macdonald, 2002; Perry and Hepburn, 2008). The thickest (40 µm) development of micrite rims in wacke/packstone and floatstones from shallow platform top and inner shallow platform environments in the eastern and central areas is consistent with shallow, warm waters but may also link to more nutrient-rich areas (cf. Golubic et al., 1975; Budd and Perkins, 1980; Perry, 1998, 1999; Perry and Larcombe, 2003). Constructional micritic envelope formation is also a possibility, and is often associated with seagrass facies that have locally been inferred for the Tonasa Platform (cf. Perry, 1999). The dull-luminescent to non-luminescent CL properties of the micritic rims and their similar CL character to the bioclasts is consistent with associated marine waters and/or oxidising pore fluids.

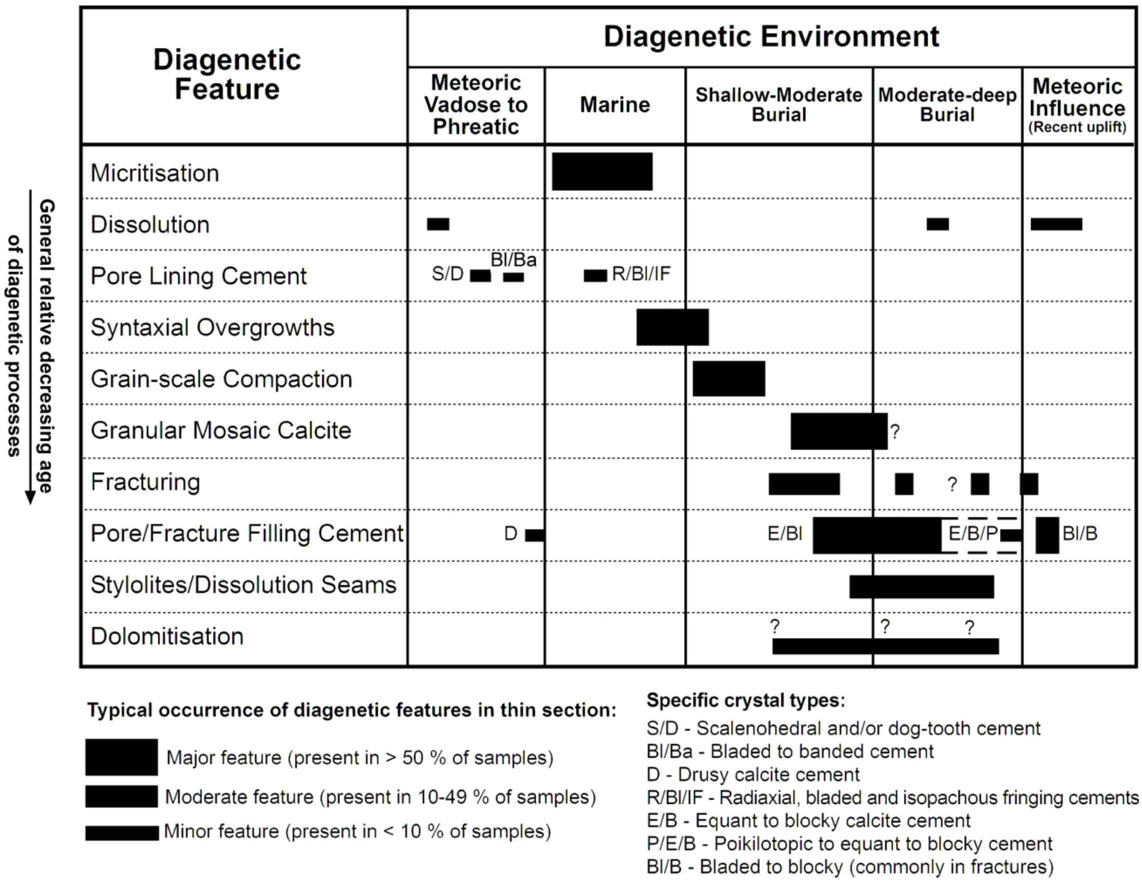

Figure 2.15. Generalised paragenetic sequence inferred for the Tonasa Limestone Formation. Relative timing of diagenetic features is inferred from petrography, but may vary slightly between samples. See text for further details on the interpreted diagenetic environment.

2.6.2 Cavities and Pore-lining cements

Pore-lining cements are very rare in the Tonasa platform; but five early cement types are associated with platform margin and/or block faulted highs areas. Some samples including these cements are now, however, present as reworked clasts in lithoclastic slope breccias. (1) The radiaxial bladed to fibrous cements are interpreted as marine cements on the basis of their growth forms, occurrence in shelter or intergranular porosity, early pre-compactional timing and geochemistry (cf. Halley and Scholle, 1985; Flügel, 2004). $\delta^{18}O$ and $\delta^{13}C$ V-PDB values of -3.6 and +2.1‰, respectively, for the one radiaxial cement sampled are consistent with the marine stable isotopic field for SE Asia. (2) The <200 μm bladed to possible isopachous fringing cements were too small to sample, but on the basis of their geometry and early timing pre-dating compaction are probably also of marine origin. These radiaxial to bladed and 'short' bladed to fringing cements are from grainstones or fringe shelter porosity in deposits close to the platform margin. Cementation is likely to be controlled by flushing of high volumes of marine waters into porous sediments along the platform margin as well as CO_2 degassing driven by high wave and tidal energy (cf. Land and Moore, 1980; Moore, 1989; Madden and Wilson, 2013). Micrite that infills some of the larger shelter pores after the pore-lining cement may have a laminated to slight peloidal character and is a feature common in other marine cavities. The rare: (3) long bladed (up to 400 μm) to banded crystals and (4) dog tooth to scalenohedral crystals are here interpreted as mainly having a probable meteoric origin on the basis of them lining dissolutional cavities, having similar forms with known meteoric cements and in some cases being post-dated by features such as cave pearls (cf. Dreybrodt, 1988; Frisia et al., 2000). One example of dogtooth to scalenohedral cement has geochemistry consistent with SMOW values of -4.5 to -3.5‰ ($\delta^{18}O$ V-PDB value of -6.54‰) at surface conditions of 25-30˚C (i.e., meteoric transitional to marine parent fluids) and carbon values most consistent with a rock or marine derived signature ($\delta^{13}C$ V-PDB value of 1.98‰). (5) Micritic sediment infilling cavities is here inferred to be of either infiltered marine sediment or of karstic infill origin. Individual interpretation of micritic infills depends on: (a) whether the sediment co-occurs with dissolution or non dissolutional cavities, (b) associations with cements of marine or meteoric origins, and (c) sometimes the micrite geochemistry (for the latter see the paragraph below). The origin of the very rare dolomite crystal silts is discussed below under dolomites. The CL signature of pore lining cement with predominantly non luminescence is consistent with oxidising conditions, with some evidence for fluctuations in geochemistry and/or redox conditions of the precipitating fluids (Moore, 2001; Boggs and Krinsley, 2006).

Evidence for potential subaerial exposure and karstification of the Tonasa Limestone Formation is highly localised to faulted highs usually within 1-2 km, but rarely up to 5 km from platform margin and/or graben bounding faults, i.e., affecting less than 2% of the platform. Indicators of subaerial exposure include: (1) irregular dissolutional cavities cross-cutting strata on a decimeter-scale, associated with, (2) in one location algal laminite and fenestral deposits, (3) speleothem stalactite and stalagmite fills, (4) banded cements, (5) cave pearl infill (6) reddened and/or brecciated surfaces, and (7) hiatal surfaces and/or angular unconformities (see also Wilson et al., 2000). Cave pearls and dog-tooth to scalenohedral cements or banded cements with speleothem geometries are distinctive of infill of karstic cavities (cf. Esteban and Klappa, 1983). The geochemical signature of these cavity infill features and the associated interlaminated micritic infill measured in this study is, however, not always distinctive of meteoric conditions. For example, although analysis of some of these features revealed negative $\delta^{13}C$ V-PDB values, 2 of the 4 analyses of this type had positive $\delta^{13}C$ V-PDB values. It may be that in regions of very limited areal extent of exposure, as is inferred here, little in the way of soil horizons may develop, and consequently there may not always be a characteristic soil-zone influenced negative carbon isotopic signature. Additionally, with the very high rates of dissolution that occur during subaerial exposure in the equatorial tropics, together with the common neomorphic replacement of early pore lining cements it is probable that a rock-derived signature (in this case of primarily marine origin) may outweigh other potential signatures (cf. Wilson, 2012). Of the localized areas with inferred subaerial exposure the timing of emergence, where constrained, is inferred to be: (1) Late Eocene – on the northern platform margin associated with the Barru Block, (2) possibly Late Eocene, but more definitely mid Oligocene and Early Miocene associated with highs surrounding the graben in the western area, and (3) around the mid Oligocene for the Birau Menge, Bua and Biru S sections and during the Early Miocene prior to the deposition of the volcaniclastics in the Camba sections all from the eastern area (cf. Wilson et al., 2000). For other sections in the eastern area (Bantimala, Malawa West, Ujunglamuru and Maborongnge) probable karstification and tilting of strata is unconstrained to during or after the Late Eocene and before the Middle Miocene (cf. Wilson et al., 2000).

2.6.3 Syntaxial overgrowths

Syntaxial overgrowth cements are an early diagenetic feature because they mainly pre-date mechanical compaction but post-date some pore-lining cements. The distribution of syntaxial overgrowths is here linked to the primary distribution of echinoderm material and more open grainy sedimentary textures with higher potential for flushing by precipitating pore fluids (cf. Madden and Wilson, 2013). Inclusion-rich, turbid syntaxial overgrowths have been linked to marine-phreatic conditions, whereas clear overgrowths may form during shallow burial, with both phases occurring in the Tonasa Formation (Tucker and Wright, 1990; Flügel, 2004; Swei and Tucker, 2012). The speckled appearance of echinoderm grains in CL partly reflects micritic or cement infill within their microporous structure. The initial dull- and predominantly non-luminescent character of the early overgrowth cement is similar to the overgrown grain and consistent with precipitation from marine oxidising fluids. The succession of CL zones from non-luminescence to bright to dull in the syntaxial overgrowths is a common zonation associated with the increasingly reducing nature of pore fluids during increasing burial (Tucker and Wright, 1990; Flügel, 2004; Boggs and Krinsley, 2006).

2.6.4 Grain alignment, distortion, mechanical grain packing, grain breakage and grain suturing

All of these burial compactional-related features formed after both micritisation and minor early cement phases (i.e., pore lining cements and some syntaxial overgrowth cements) and therefore generally pre-date full lithification of most samples (Fig. 5d). A range of point, tangential, concavo-convex and sutured contacts likely reflect increased burial compaction relative to lithification, but may also be grain and lithology influenced (Fig. 5d, e and f; Taylor, 1950; Goldhammer, 1997; Flügel, 2004). In grainy sediments this continuum from closer grain packing to pressure solution at grain contacts may occur over burial depths of 100 m up to 700 m, but such depth ranges would likely be lower for matrix-dominated samples (Goldhammer, 1997; Flügel, 2004). Grain distortion has mostly affected grains such as micritic-walled foraminifera or marl clasts that are prone to plastic deformation (cf. Madden and Wilson, 2013). Elongate bioclasts are most prone to brittle mechanical breakage. Overall the degree of grain-related compactional features is most prevalent in lithologies that: (1) experienced little early cementation, (2) contain grains or lithologies that are prone to grain breakage, grain distortion or suturing, and/or (3) were strongly affected by burial prior to full lithification. For example, breccias and planktonic foraminifera bioclastic packstones are common in the thicker successions from the northern, eastern and to a lesser extent southern and western areas that experienced the greatest (fault-related) tectonic subsidence (Wilson, 1999; Wilson et al., 2000). These lithologies typically experienced limited early cementation and contain marly clasts or micritic matrix prone to greater differential compaction compared with more competent bioclasts or lithic clasts. The prevalence of grain-scale compactional features in the deeper Paleogene parts of thicker sections and associated with deposits formed during fault-related deepening are together suggestive of the important roles of differential subsidence and overburden covering by subsequent carbonate sedimentation in generating early compactional features.

2.6.5 Granular mosaic calcite

The granular mosaic calcite is partially neomorphic to replacive in origin because it includes 'ghost' textures of earlier bioclasts or cements, or patches of micrite. Some primary calcitisation into pore space is near contiguous with neomorphism or replacement. A burial origin is inferred since granular mosaic calcite post-dates some grain compaction features, including mechanical grain breakage. Pre-dating other cementation, fracturing and compaction features (described below) a shallow burial environment of diagenesis is most likely for the granular mosaic calcite. The predominant dull-, to non-luminescent CL character of the calcite may indicate oxidising to slightly reducing pore fluids (Boggs and Krinsley, 2006), consistent with inferred shallow burial origins. Granular mosaic calcite that replaces the only known algal laminite layer from the northernmost Central area of the Tonasa Limestone has $\delta^{13}C$ V-PDB values of -2.67 and -3.40‰ indicative of soil zone process influences (cf. Hudson, 1977; Moore, 2001). The mosaic calcite must have formed very early after deposition since 'ghost' traces of the algal filaments show only minor evidence for compaction. The formation of algal laminites, their early alteration to granular mosaic calcite and $\delta^{13}C$ and $\delta^{18}O$ (-6.82 and -7.35‰ V-PDB) of the calcite are all consistent with a meteoric influence during deposition and subsequently during near surface diagenesis for this unit. A larger benthic foraminifera sampled from 2 m below the algal laminite unit (-2.23 and -7.60‰ $\delta^{13}C$ and $\delta^{18}O$ V-PDB, respectively) and one from near the contact with the underlying siliciclastics (-2.04 and -6.28‰ $\delta^{13}C$ and $\delta^{18}O$ V-

PDB, respectively) that group isotopically with the algal laminite samples are also inferred to have been influenced by meteoric fluids during near surface diagenesis. For other granular mosaic calcite that post-dates early compactional features positive $\delta^{13}C$ V-PDB values indicate a lack of soil zone processes, and that a seawater or rock-derived source of carbon with marine $\delta^{13}C$ values was inherited by the precipitating fluids (cf. Hendry et al., 1999). At shallow to moderate burial depths prior to the onset of depth of stylolite formation (around 0.5 to 1 km burial; i.e., around 35-50˚C) the $\delta^{18}O$ of -5.46 and -9.47‰ V-PDB suggest parent fluids of V-SMOW predominantly between +1.3 and -3.0, i.e., most consistent with pre-cursor marine fluids. For the $\delta^{18}O$ value of -9.47‰ V-PDB in the lower part of the potential temperature range this would convert to a V-SMOW of down to -5.4 (i.e., potentially of meteoric origin). Since the granular mosaic cements with the most negative $\delta^{18}O$ values, however, are transitional to equant calcite, and also from the centre of pores, the values from the higher part of the temperature range are considered more likely converting to V-SMOW of -2.8 (i.e., more consistent with fluids of marine origin). The most common occurrence of granular mosaic cements in the Paleogene deposits, particularly in thicker sections is likely a reflection of the influence of rates of differential subsidence and timing of overburden carbonate sedimentation in generating these shallow to moderate burial depth diagenetic phenomena (Fig. 3 and 4).

2.6.6 Fracturing

Multiple phases of fracturing with different origins have locally affected the Tonasa Limestone Formation since these features may cross-cut a diverse range of bioclasts and cements, and may be filled with varied cements and/or sediment fill. For the early fractures associated with cavities a karstic or marine collapse origin is inferred. The interpretation depended on whether cavities are: (1) on a decimetre-scale, irregular, dissolutional and filled with early meteoric pore fringing cements and cave sediments, or (2) predominantly shelter cavities, that lack dissolutional margins, are commonly on a centimetre-scale and are filled with early marine cements and sediment, respectively (see earlier pore-lining cements section). For the main non-cavity-associated group of fractures within the Tonasa Formation burial, unroofing and/or structural origins are inferred (see also section below on fracture orientations and evidence for their relative timing). The sub-millimetre scale irregular fractures with diffuse margins that are mainly filled by granular mosaic calcite likely formed in shallow burial depths during the lithification process (see granular mosaic cements above). Millimetre-scale aperture, sharp-margined, through going fractures post-date most lithification with at least 2 phases of these features. Through going fractures that link to stylolites filled with equant cements likely result from burial and/or tectonic compressional stresses (cf. Nelson, 1981; 2001). Other late fractures filled by equant to blocky cements may have burial, unroofing and/or tectonic structuration origins depending on their relative timings, orientations and later cement fills (see below).

2.6.7 Fault and fracture orientations and evidence for their relative timing

The concordance of orientation trends in small-scale fractures with those of the large-scale faults in South Sulawesi is suggestive of structural tectonic origins for many of these features (Fig. 11). The main NW-SE trend of structures that particularly predominates in the northern area parallels that of the main platform bounding faults in this area. These northern platform bounding faults also occur along strike, and with the same trend, as the large-scale regional Adang Fault (van de Weerd and Armin, 1992; Wilson, 1999). The main northern platform bounding faults were periodically active from the Late Eocene during the deposition of the Tonasa Limestone Formation and strongly influenced sedimentation patterns (Wilson and Bosence, 1996; Wilson, 1999; Wilson et al., 2000). The NW-SE structures mostly do not penetrate into strata younger than around the Early to Middle Miocene boundary (Sukamto, 1982; Sukamto and Supriatna, 1982; Wilson, 1995). The NNW-SSE trends that prevail in the eastern and western areas parallel the trend of block faulted highs and graben that developed in these areas between the Late Eocene to Early Miocene. The NNW-SSE trending faults include those associated with the Walanae Fault Zone that bound the Walanae Graben: a major structural divide separating different tectonic regions in South Sulawesi (van Leeuwen, 1981). In the field the NNW-SSE trending structures are seen to cross-cut, and therefore in part post-date other structures, including those with a NW-SE trend (Berry and Grady, 1987; Wilson, 1995). The NNW-SSE trending faults continue to be active to the present day as evidenced by recent earthquakes along the Walanae Fault Zone (e.g. Kope Mosque, that sat at the base of the ~300 m high fault scarp bounding the eastern part of the Walanae Depression was destroyed in an earthquake in the early part of this century). In the eastern area, faults with a northeasterly to easterly trend having dip-slip displacements with throws on the order of a few metres to tens of metres pre-date deposition of the Walanae Volcanics in the late Miocene (van Leeuwen, 1981).

In the southern part of South Sulawesi, faults are recorded mostly in areas close to eruptive centres of volcanoes, and locally appear to radiate from eruptive centres.

That the small-scale fractures are more common in the tectonically active northern, eastern and western areas compared with the more quiescent central and southern parts of the main platform, with many fracture trends paralleling major faults, are indications of a strong tectonic influence on fracturing. The occurrence of intra-clast fractures within shallow water lithic carbonate clasts derived from the main Tonasa platform area and reworked into slope breccia of Late Eocene to Early Miocene age are indicative of structuration during development of the Tonasa Limestone Formation, i.e., evidence for syndepositional structuration. The most common occurrence of highly irregular fractures that may have formed when deposits were semi-lithified is in the tectonically active northern, eastern and western areas, and is further suggestive of syndepositional structuration. Proximal to the major faults, small scale structures both trend parallel and perpendicular to the major faults, with those at right angles to the main faults suggestive of some dilatation parallel to major fault trends. Seismic and field relationships indicate significant normal displacements along major graben and platform margin bounding faults, but transtensional (sinistral) displacements are also inferred (Grainge and Davies, 1983; Berry and Grady, 1987; Wilson, 1995).

2.6.8 Pore and fracture filling cements

Granular mosaic cements that infill some of the sub-millimetre fractures are discussed earlier. The very rare examples of drusy cements infilling pore space may form in meteoric (or marine) phreatic to shallow burial settings, but were too small to sample for geochemical analysis. The majority of the equant to blocky cements are interpreted as shallow to deeper burial features on the basis of: (1) most being late phases of pore filling cements, (2) post-dating early compaction features, but pre-dating later compactional stylolites or dissolution seams and (3) their geochemistry. The dull-luminescent character of most of these cements is also consistent with precipitation under reducing conditions in moderate to deeper burial depths. Predominantly positive $\delta^{13}C$ V-PDB between -0.3 and +2.38‰ are consistent with precipitating fluids mainly isolated from those influenced by soil zone processes. Negative values of $\delta^{18}O$ V-PDB between -4.0 and -9.5‰ would equate to waters with V-SMOW values of +2.0 to -5.5 at moderate to shallow burial temperatures of 35-55˚C (Fig. 14; Hudson, 1977; Anderson and Arthur, 1983). Most of the blocky to equant cements are consistent with precipitation from fluids with a rock-derived and/or precursor marine fluid origin. A meteoric origin is also possible for some of the late fracture filling cements with strongly negative $\delta^{18}O$ V-PDB values, with the possibility of such a signature being linked to cementation along fractures during unroofing and present day sub-aerial exposure. The development of slickencrysts in some fracture filling cements indicates active deformation during growth of the crystals. A recrystallised larger benthic foraminifera grainstone from an isolated exposure adjacent to the major Walanae Fault Zone has highly negative -13.9‰ $\delta^{18}O$ V-PDB (1.8‰ $\delta^{13}C$ V-PDB) perhaps due to hydrothermal activity (cf. Pichler and Dix, 1996), or ?unusual fluid chemistries, along the fault zone. A separate group of 5 samples including 2 equant cements having highly negative $\delta^{18}O$ V-PDB (-14.2 to -19.7‰) and also highly negative $\delta^{13}C$ V-PDB values (-9.11 to -14.2‰) are suggestive of both high temperatures and a possible methanogenic source of carbon. All of these last 5 samples are from close to contacts with the overlying volcaniclastics or igneous intrusions and metasomatising fluids are possibly associated with the isotopic signature (cf. Pichler and Dix, 1996). The most common occurrence of pore lining cements in the deeper parts of sections attests to the importance of overburden sedimentation in influencing late burial features.

2.6.9 Stylolites and Dissolution Seams

These chemical compaction features post-date almost all other diagenetic feature on the basis of cross-cutting relationships, with the exception of some fractures and their cement infills. These features form in moderate to deep burial environments with an onset depth commonly starting around 500 m (Railsback, 1993; Nicolaides and Wallace, 1997), or may form as a result of tectonic stresses (Bathurst, 1987). In the Tonasa Limestone, the bed parallel examples are linked to burial compaction. The prevalence of stylolites and seams in northern, southern and some eastern sections correlates with where depositional thicknesses of the carbonate commonly exceed 1 km, and are subsequently covered in thick volcaniclastic piles. A continuum from dissolution seams to stylolites in clayey limestones to near pure carbonate lithologies, respectively, has been noted in a range of studies (Bathurst, 1987; 1990; Railsback, 1993; Nicolaides and Wallace, 1997). In depositional units that experience little early cementation, such as the slope breccias, grain contacts between clasts during increasing burial have developed into circum-clast stylolites (cf. Madden and Wilson, 2013). As with the pore lining cements the more common occurrence of seams and/or stylolites in the deeper parts of sections attests to the importance of overburden sedimentation in influencing late burial features.

2.6.10 Dolomitisation

The very rare dolomite seen in the Tonasa Limestone may have multiple origins, on the basis of very different occurrences. Given the complexity of potential dolomitising mechanisms and paucity of data on these dolomites only a preliminary evaluation is outlined here (cf. Warren, 2000; Carnell and Wilson, 2004; Machel, 2004). Very rare, highly localised dolomite silts infilling dissolutional cavities of karstic origin, as occur in the eastern area, have been linked in Sulawesi and elsewhere to formation in vadose meteoric environments (Fig. 14a, b; cf. Mayall and Cox, 1988; Flügel, 2004). Seawater, however, is a key source of Mg, and particularly for some of the rare dolomite silts in shelter porosity after radiaxial cement, marine fluids are the more likely dolomitizing agent (cf. Warren, 2000; Machel, 2004). Replacive dolomitisation in the fully dolomitised samples from the central area predates the onset of stylolite formation and with $\delta^{18}O$ V-PDB values of -2.7 to -5.3‰ using the equation of Land (1983) these would convert to waters with SMOW values of 0.4 to -5.2 (i.e. predominantly of marine parental fluid origins but potentially also of meteoric fluid origins; cf. Warren, 2000; Machel, 2004). A change from dull-luminescent replacive dolomite to non-luminescent dolomite cements with bright zones would be consistent with a general trend from oxidising to reducing conditions during burial with some fluctuations in geochemistry and/or redox state of dolomitised fluids (Fig. 15). The rare intergranular dolomite cements in the grainstones may also have a similar burial signature. The source of Mg for the intergranular and fully replacive dolomites may be seawater, although given that less than 1% of the platform is dolomitized there must be a local driver for the dolomitisation seen. Other potential sources of Mg are from clays in the nearby siliciclastics or perhaps more likely volcaniclastics since most partially dolomitized samples contain admixed volcaniclastics or are close to the contact with the volcaniclastics or to igneous intrusives (rich in Mg containing minerals such as biotite and locally olivine). Igneous intrusives may have provided a thermal driver for increased throughput of dolomitising fluids. This evaluation of potential dolomitising mechanisms is, however, highly speculative without further additional investigation.

2.7 Discussion

2.7.1 Summary of diagenetic features, their variability and controlling influences:

Petrographic and geochemical studies reveal that three main phases of diagenesis have affected most areas of the Eocene to Miocene Tonasa Formation prior to recent uplift and exposure (Figs. 15 and 16). The general relative order of these main diagenetic phases is: (1) surface or very near surface predominantly marine alteration, and highly localised meteoric diagenesis, (2) pervasive shallow to moderate burial grain-scale compaction and cementation/recrystallisation, and (3) common fracturing and deeper burial chemical compaction and cementation. Marine phreatic, with minor meteoric effects, through to progressively deeper burial is therefore recorded in the diagenetic features of the Tonasa Platform. As discussed below these features and their variability, or paucity thereof, predominantly link to the nature of the platform deposits, their tectonic, climatic and oceanographic context, together with the location of faulted highs, basin history and differential subsidence. Many of these same factors strongly influenced the deposition and sedimentary development of the Tonasa Platform (Wilson and Bosence, 1996; Wilson, 1999; 2000; Wilson et al., 2000). This paragenetic sequence affecting the Tonasa Limestone is similar to that from a number of Eocene to Miocene platforms in the area (Fig. 15; e.g., Berai (Saller and Vijaya, 2002), and Kedango (Wilson et al., 2012; Madden and Wilson, 2013)). These other Tertiary platforms from the neighbouring island of Borneo also show limited early (marine or meteoric) diagenesis together with prevalent neomorphism, compaction and cementation linked to shallow to deeper burial diagenesis (Saller and Vijaya, 2002; Madden and Wilson, 2013). The diagenesis of the Tonasa Limestone and other similar platforms differs markedly, however, from many Neogene systems in the region that may comprise reservoirs in the subsurface (Epting, 1980; Fulthorpe and Schlanger, 1989; Grotsch and Mercadier, 1999; Vahrenkamp et al., 2004). These Neogene reservoirs with porosities of up to 10-40% commonly have a layered development due to repeated subaerial exposure and leaching in the vadose zone, pervasive phreatic cementation, with early fabrics overprinted but commonly not masked by later diagenesis (Epting 1980; Dunn et al. 1996; Zampetti et al. 2003; Vahrenkamp et al., 2004; Wilson, 2012).

2.7.2 Early marine and meteoric diagenesis: the role of climate, tectonic highs, oceanography and the nature of platform deposits:

Although early grain micritisation occurs in most samples its prevalence in shallow-water packstones and floatstones is consistent with enhanced activity of endolithic microborers in shallow sunlit water from the platform top where wave or current activity was not a hindrance, as is inferred for much of the Tonasa Platform (Wilson et al., 2000; cf. Bathurst, 1966; Gunther, 1990). The presence of nutrients and/or seagrass facies as is common in the equatorial tropics and is locally inferred for the Tonasa platform may also promote destructive or constructive micrite envelope formation (cf. Perry, 1999; Wilson, 2012).

Pore lining cements and subsequent cavity infill fall into two categories: of marine or probable karstic origin, with all of the uncommon occurrences associated with the platform margin, faulted highs, grainstone or slope lithoclastic facies. The occurrence of marine cements in platform margin settings, many associated with probable steep-margined upstanding faulted highs is consistent with high volumes of seawater flushed through margin deposits (cf. Land and Moore, 1980; Moore, 1989; Madden and Wilson, 2013). The globally important Indonesian Throughflow, an oceanic current linking Pacific and Indian Ocean waters, has been actively flowing north to south through the Makassar Straits region since at least the Oligocene (Kuhnt et al., 2004; Gordon, 2005). The predominant occurrence of marine pore-lining cements in more northerly northern, western and eastern platform margins areas for the Tonasa Limestone, but lack of any such features from the southern margin is a probable reflection of this oceanic throughflow pathway. The comparative lack of marine cements away from the more northerly margins is perhaps due to lower than normal marine salinities common in SE Asia and associated reduced aragonite saturation linked to regionally high runoff and the equatorial setting (Wilson, 2002; 2012; Gordon, 2005). This is despite a moderate to high energy E-W trending seaway inferred for the main N-S trending Tonasa Platform area (Wilson and Bosence, 1997; Wilson et al., 2000). This paucity of marine precipitates and/or cementation is in marked contrast to other isolated platforms in more arid tropical regions (cf. Wilson, 2002; 2012). Turks-Caicos is one such platform from the more arid tropics that also has a marked E-W cross platform seaway, but this is a region of prevalent ooid formation, an allochem not found in the Tonasa Platform (Wanless and Dravis, 1989; Jones and Desroches, 1992).

Dissolutional cavities with speleothem, long bladed to banded, and scalenohedral to dogtooth cements of inferred karstic origin are restricted to northern, eastern and western areas from faulted highs (or reworked thereof). Tilting of rotated fault blocks and uplift of block faulted highs are considered instrumental in the development of these highly localised karstic features (Wilson and Bosence, 1997; Wilson, 2000; Wilson et al., 2000). On different block faulted highs the timing of localised karstification can be pinned down to: (1) during the Upper Eocene, (2) around the middle Oligocene, or (3) towards the end of the Early Miocene and just prior to volcaniclastics of the Camba Formation covering the platform (Wilson and Bosence, 1996; Wilson, 1999; 2000; Wilson et al., 2000). For other sections where there is a long hiatus, karstification may have occurred between the late Eocene and Early Miocene, and perhaps even repeatedly, although the multiple karstification events are not possible to constrain (Wilson et al., 2000). The late Eocene phase is linked to fault breakthrough of earlier reactivated basement structures and associated uplift of footwall highs (Wilson, 1999). The Early Miocene phase is linked to renewed faulting associated with the early stages of volcanism (Wilson, 2000; Wilson et al., 2000). Although around the middle Oligocene is a time of some regional structuration, sub-aerial exposure of highs may also be linked to a major eustatic sea level fall at this time (Saller et al., 1992; 1993; Wilson et al., 2000). Although much of the Tonasa Platform is aggradational remaining in photic depths throughout Eocene to Miocene deposition, it is perhaps surprising that only extremely localised subaerial exposure is inferred for the major middle Oligocene eustatic fall (of around 50 m; Haq et al., 1987). Possible reasons for this general dearth of evidence for subaerial exposure outside faulted highs are: (1) relatively slow production rates of the larger benthic foraminiferal dominated facies limiting platform building potential (0.2-0.3 m kyr^{-1} accumulation rates; Wilson et al., 2000), (2) the mobile nature of much of the platform deposits with possible truncation of sediment affected by shallow wave or current activity, as well as (3) tectonic subsidence (Wilson, 1999; Wilson et al., 2000). The preponderance of mobile deposits over framework building coral-rich deposits has been linked to the platform forming in a region of high rainfall and oceanic throughflow. In settings such as this, with a tendency towards mesotrophy low-light level oligophotic biota, including some larger benthic foraminifera and coralline algae, may be promoted (Wilson and Vecsei, 2005).

These same reasons, outlined directly above, may also be influential in the limited and highly localised occurrence of inferred subaerial exposure occurring generally within 1-2 km (rarely up to 5 km) of faulted margins and affecting less than 2% of the Tonasa platform area. Faulted highs on other syntectonic carbonate platforms are also associated with karstification (Rosales et al, 1994; Rosales, 1999; Cross and Bosence, 2008). Cretaceous platforms from Spain show karstification generally within 1-2 km (and up to 5-6 km) of faults bounding the footwall highs: i.e., similar to the Tonasa Platform (cf. Rosales et al., 1994). On these Spanish examples, however, associated with smaller-scale fault block development trending perpendicular to the rifting direction, between 10-60% of the platform area was affected by exposure during seven phases of repeated exposure over around 8 million years (Rosales et al., 1994). The eastern area of the Tonasa Limestone has fault block development on a scale most similar to the Spanish platforms but is thought to have experienced three potential phases of exposure over around 30 million years, each affecting less than 10% of the eastern platform area (Wilson et al., 2000). Extension in the eastern area probably roughly parallels the main extensional direction in the backarc basin associated with the Makassar Straits on whose eastern flank the Tonasa Platform developed (Moss and Chambers, 1999; Wilson et al., 2000). Faulting in the eastern area, however, mainly occurred from the mid Oligocene onwards and may be linked more to structuration on the Walanae Fault Zone than any rifting in the Makassar Straits (Leeuwen, 1981; Wilson et al., 2000). Across rift basins, it may be during the early synrift or on rift margin flanks that subaerial exposure of carbonates on faulted highs predominantly occurs (Rosales et al., 1994; Dorobek, 2008). i.e., subaerial exposure is not always a feature of syntectonic platforms, particularly those that formed in basin centres or after initial rifting. The Tonasa Limestone Formation developed as part of a transgressive succession slightly postdating initial back-arc basin development and on amalgamated, highly varied, intersliced basement terranes (Berry and Grady, 1987; Wakita et al., 1996). Although formed on the basin margin flanks the extensional direction of the main N-S trending tilt-block platform is oblique to that of the backarc area as a whole (Wilson, 1995; Wilson et al., 2000). Regional subsidence in South Sulawesi during the deposition of the Tonasa Limestone, based on stratal thickness data was up to 20-40 m/Ma, with higher subsidence in the adjacent Makassar Straits (Cloke et al., 1999b; Wilson et al., 2000). Inferred very limited subaerial exposure of the Tonasa Limestone Formation is likely to have been affected by platform: (1) development over an area not of “typical” continental crust, (2) accumulation in an area with extension oblique to the main regional rift direction, and (3) formation on a basin margin generally undergoing subsidence rather than flank margin uplift.

2.7.3 Mid-stage shallow to moderate burial depth diagenesis: the role of climate, tectonic highs, the nature of platform deposits and tectonic subsidence:

Syntaxial overgrowths, grain-scale compaction and granular mosaic cement all attest to the onset of burial diagenesis on predominantly unlithified deposits as they start to lithify. Aragonitic components had generally not been dissolved prior to the onset of burial diagenesis. The petrographic and geochemical evidence points towards marine, or marine-derived fluid being the main agent during mid-stage shallow to moderate depth burial diagenesis. The prevalence of this mid-stage diagenesis throughout most deposits of the Tonasa Formation is linked to the paucity of earlier marine or meteoric cementation (and/or dissolution) affecting the platform. As noted earlier this scarcity of early cements is due to the: (1) humid climatic setting and lower than global-norm marine salinity, (2) relatively slow production rates of the foraminiferal-dominated deposits and their mobile nature hindering the potential to build directly to sea level. Local variability in grain types (e.g., echinoderms and imperforate foraminifera) and sediment textures (e.g., more grainy textures and breccias) that link to environmental variability influence the degree of mid-stage diagenesis effects across the platform. Localised meteoric diagenesis is limited to areas of faulted high, including the algal laminites from the Tonasa-II section or to deposits within a few metres of the underlying siliciclastics. Outside the areas of the faulted highs, shallow water platform carbonates and shallow to deeper water successions reach thicknesses of 600 and 1100 m, respectively. Rates of tectonic subsidence and the timing of overburden carbonate sedimentation are inferred to have been influential in the abundance of mid-stage diagenetic features that link to the onset and progressive burial of the carbonates. Differential subsidence, both prior to and following fault breakthrough, controlled regional variations in subsidence, influencing the localised variability in degree of shallow to moderate burial depth diagenetic affects (cf. Wilson, 1999; Wilson et al., 2000).

2.7.4 Fault, fracture and vein distributions, their orientations and relative timing: the key impact of tectonics:

Although the Tonasa Limestone is one is the best documented examples of a syntectonic carbonate system from its sedimentary record (Wilson and Bosence, 1996; Wilson, 1999; 2000; Wilson et al., 2000), it is arguably just in the fault, fracture and vein data that the syntectonic nature of the platform is only really strongly manifest from a diagenetic perspective. The correspondence of: (1) higher occurrences of numbers of fractures, (2) more highly irregular fractures, and (3) fractures and veins within clasts of lithoclastic slope breccias all in areas of large-scale active faulting during the deposition of the Tonasa Limestone as compared with more tectonically quiescent platform areas are, collectively, direct indicators of diagenesis coeval with tectonism. There is scope for applying analysis of this type to fracture datasets from other syntectonic platforms to more fully evaluate syntectonic diagenesis. The strong concordance of fracture and vein orientation data with larger-scale fault orientation data including faults known to be active during the deposition of the Tonasa Limestone Formation is consistent with a link between synsedimentary faulting and small-scale fracturing. The predominant NW-SE and NNW-SSE trends, together with subsidiary trends of NE-SW to ENE-WSW either parallel platform margin and/or graben bounding faults, or are interpreted dilatational features perpendicular to the major faults. The predominant fault and fracture trends within South Sulawesi mirror those from the broader backarc basin region that encompasses West Sulawesi, the Makassar Straits and western Borneo. The major regional structures include the Adang Fault, Walanae Fault Zone and faults perpendicular to the predominant extensional direction in the backarc area. Regionally some of these larger-scale structures may involve reactivation of earlier basement fabrics, and including the ones linked with the Tonasa Limestone Formation, are associated with syntectonic sedimentation during the Tertiary (van de Weerd and Armin, 1992; Wilson and Bosence, 1996; Moss et al., 1997; Moss and Chambers, 1999; Wilson et al., 2012). The potential timing of fault movement inferred to have affected the Tonasa Limestone Formation in: (1) the Late Eocene, (2) possibly the mid Oligocene, and (3) during the Early Miocene is from the timing of highly localised subaerial exposure of footwall highs, but also in the record of the slope lithoclastic breccias, as well as stratal wedging and thickening (Wilson and Bosence, 1996; Wilson, 1999; 2000; Wilson et al., 2000). Regionally, although basin initiation began earlier, rifting was widespread by the Late Eocene, with some structuration inferred in the mid

Oligocene, and then again in the Early to Middle Miocene (Van de Weerd et al., 1987; Letouzey et al., 1990; Bransden and Matthews, 1992; van de Weerd and Armin, 1992; Saller et al., 1992).

The different phases of fracturing affecting individual samples may have multiple origins on the basis of their petrography and geochemistry including: early collapse or karst--related, burial-associated, tectonic-induced, or uplift-related. More systematic study of the fracturing, a tie between their orientations, relative timing data and geochemistry of any cements or sediment infills that was beyond the scope of this study is an avenue for further unraveling the histories of any syntectonic diagenesis and fracturing (cf. Guidry et al., 2007; Breesch et al., 2009; Warrlich et al., 2010; Budd et al., 2013). A study of the very highly localised and enigmatic dolomitisation is also not pursued here, but may be an avenue for further potential research (cf. Carnell and Wilson, 2004).

2.7.5 Late-stage predominantly moderate to deeper burial depth diagenesis: the role of tectonics, basin evolution, climate, tectonic highs, oceanography and the nature of platform deposits:

Most of the equant and blocky cements together with the dissolution seams and stylolites indicate that the platform was progressively affected by moderate to deeper depth burial diagenesis. As with mid-stage shallower burial diagenetic phases those associated with later burial diagenesis are commonly most pervasive in areas of greatest subsidence (e.g., the faulted graben areas) and/or where deposits had little early cementation. This predominance of burial diagenetic features dominating in large-scale Tertiary platforms is common to other SE Asian systems (Saller et al., 1992; 1993; Saller and Vijaya, 2002; Wilson et al., 1999; Wilson, 2012; Madden and Wilson, 2013). Localised evidence for early meteoric diagenesis in these other SE Asian platforms (e.g. Berai, Kedango, Kerendan, Melinau) is limited to faulted highs and/or areas with more abundant framework builders (Adams, 1965; Saller et al., 1992; 1993; Saller and Vijaya, 2002; Wilson, 2012; Madden and Wilson, 2013). The pronounced middle Oligocene eustatic sealevel fall (Haq et al., 1987) is generally only manifest on faulted and/or bathymetric highs on the platforms (Saller et al., 1992; 1993). The dominance of larger foraminiferal (and algal) deposits, their mobile nature and limited upbuilding potential have all contributed to the prevalence of burial features and paucity of earlier non-burial linked cements in Paleogene equatorial platforms (cf. Wilson, 2002; 2008;

2012). Overall, with the exception of the fracture development, it is, if anything, a regional signature similar to other long-lived Tertiary carbonate platforms in SE Asia that shines through in the diagenetic development of the Tonasa Limestone Formation as opposed to an overriding syntectonic diagenetic signature.

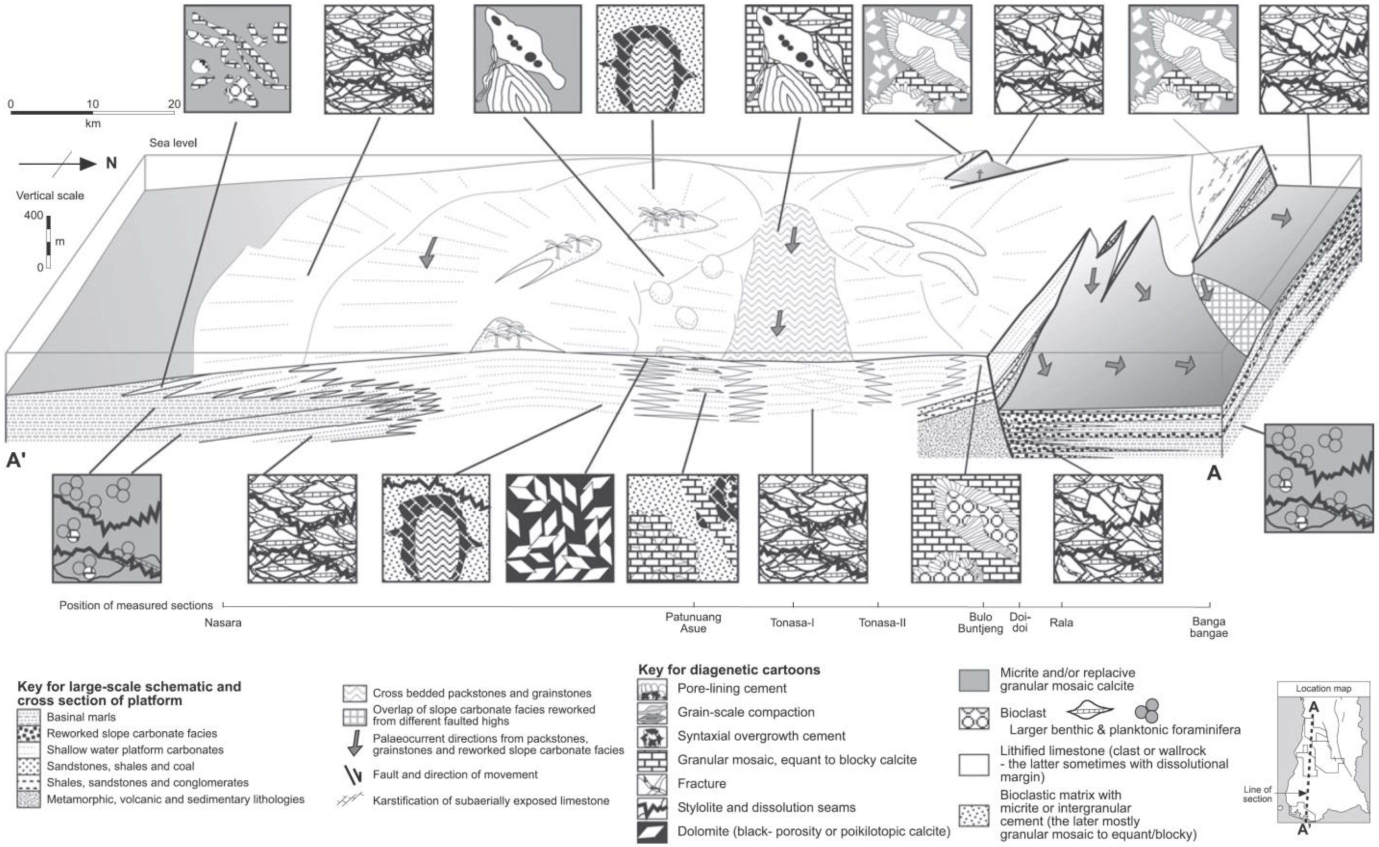

Figure 2.16. Schematic palaeoreconstruction of the main north-south trending Tonasa tilt-block platform for the Oligocene or Early Miocene (after Wilson et al., 2000). Cartoons summarise main diagenetic features affecting different parts of the platform. In general, cartoons above the reconstruction show diagenesis in shallow burial depths, whereas the overprint of deeper burial diagenesis is added on those below the main figure.

2.8 Conclusions

Diagenesis of the Eocene to Early Miocene syntectonic Tonasa carbonate platform is dominated by alteration in shallow to deeper burial depths. Burial diagenesis is evidenced by mechanical and chemical compaction, as well as a range of cements including granular mosaic, blocky and equant calcite. Earlier diagenetic features include common marine phreatic micritisation of allochems. Rare, localised evidence for meteoric diagenesis is predominantly from faulted highs. These diagenetic features in the Tonasa Limestone are similar to those from other SE Asian long-lived Tertiary carbonate platforms. The Tonasa Limestone Formation is one of the best documented syntectonic platforms from a sedimentary perspective (Wilson and Bosence, 1996; Wilson, 1999; 2000; Wilson et al., 2000). On the diagenetic side, with the exception of the fracture development, it is, however, a regional rather than strong syntectonic signature that predominates. Underlying tectonic reasons, in addition to those of non-tectonic origin listed below, are inferred to be influential in the more regional diagenetic signature predominating. (1) The platform although developing on the flanks of an extensional basin, accumulated in a backarc setting on amalgamated basement of highly varied origins. In this setting the platform would have been potentially less prone to uplift than “typical” rheologically-strong continental crust. (2) The orientation of significant synsedimentary faulting commonly influenced by earlier basement structures, was not always perpendicular to the main extensional direction in the broader basin. (3) The Tonasa Carbonate Platform formed in an extensive basinal region generally undergoing subsidence, post-dating rift basin initiation.

Tectonic uplift of faulted highs, perhaps with the overprint of eustatic sea level fall controlled highly localised karstification and meteoric diagenesis. The orientation and relative timing datasets of faulting, fracturing and calcite veining is the strongest manifestation of diagenesis coeval with tectonism in the Tonasa Limestone Formation. Orientations of both small-scale and platform bounding/ segmenting structures together with the timing of faulting are consistent with those from the broader basin, hinting at a strong regional tectonic influence. Tectonic subsidence, including fault related differential subsidence, was a key influence on the degree of burial diagenesis impacting different areas of the platform. The location of bathymetrically upstanding faulted highs together with major oceanic current systems resulted in localised marine cementation along the platform margin. The general paucity of early marine or meteoric cements is attributed to: (1) the predominance of non-framework building larger foraminifera and/or algae that have limited production rates, are prone to remobilisation, and hence limited potential to build to sea level, (2) lower than global norm marine salinities, and (3) deposition in a tectonically subsiding area. The: (1) dearth of early cementation, (2) grain associations common in mainly Paleogene carbonate platforms from SE Asia, and (3) the equatorial climate resulting in high freshwater runoff have together contributed to the predominance of burial diagenetic impacts on carbonate platforms from tectonically subsiding regions. It is hoped that studies such as this will further contribute to understanding diagenetic alteration of syntectonic carbonate platforms, and those from equatorial regions.

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Chapter Three

How do thick volcanogenic piles overlying platform carbonates influence the dynamics of carbonate-volcanogenic diagenesis?

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Abstract

Despite carbonate-volcanogenic successions being common in the geological record their diagenetic interactions are almost unstudied. This is among the first investigations detailing diagenesis associated with carbonate-volcanogenic interactions through outcrop, petrographic and geochemical analyses of a Cenozoic carbonate platform overlain by 1-2 km of Miocene volcanogenics with associated intrusives. Burial diagenesis with fluids of marine precursor origin dominates the platform-wide alteration signature of the syntectonic Tonasa Carbonate Platform in Indonesia. Aside from an inferred volcanic overburden contribution to platform-wide diagenesis, dynamic diagenetic interactions between the carbonates and volcanogenics are strongly localised, mostly limited to within tens of metres either side of conformable formation boundaries and/or contacts with intrusives. Very coarse neomorphic textures, recrystallisation and anomalously low negative $\delta^{18}O$ V-PDB values of -8 to -18‰ are localised to shallow-water carbonates conformably overlain by the volcaniclastics and those in proximity to intrusives. Deep-, and shallow-water carbonates passing conformably into, or interdigitating with, the volcanogenics show more intense compaction than is seen elsewhere in the Tonasa Formation. Where the already lithified, block-faulted upper surface of the platform

carbonates are unconformably overlain by volcanogenics, diagenesis does not differ from the background alteration signature seen throughout the main platform. It is inferred that increased pressures and high temperatures associated with emplacement of the volcanogenic pile drove localised increased chemical compaction, mineralogical stabilisation as well as thermal resetting of unlithified parts of the carbonate system. Alteration of the volcaniclastics includes sericitisation and calcitisation of the feldspars, oxidation and Fe-alteration of mafic minerals, common zeolite growth, and minor late calcite cementation. Volcaniclastic alteration is most intense in admixed carbonate-volcaniclastics and/or in deeper marine volcanogenic deposits, as opposed to those of terrestrial origins. There is no evidence for significant exchange of fluids from the pure volcanogenics altering the pure carbonates, and *vice versa*. This study is intended to contribute to poorly understood diagenetic variability in carbonate-volcanogenic systems, and particularly those from the equatorial tropics.

3.1 Introduction

Carbonate and volcaniclastic deposits are individually renowned for their commonly complex diagenetic alteration (Galloway, 1974; 1979; Davies et al., 1979; Surdam and Boles, 1979; Mathisen and McPherson, 1991; James and Choquette, 1984; Moore, 2001). Sedimentary and/or emplacement interactions are widely reported for carbonate-volcanogenic systems, yet the dynamic diagenetic interactions of such carbonate-volcanogenic systems are almost unstudied (cf. Hathway, 1995; Wilson and Lokier, 2002; Dorobek, 2008). In warm-waters, upstanding volcanic edifices are commonly colonised by reefal or other carbonate producers during periods of volcanic quiescence or on their senescence (Darwin, 1842; Dorobek, 2008; Wilson and Hall, 2010). With further igneous activity, such carbonates may be affected by: (1) intrusions, and (2) near, or (3) far-field, volcanic activity (Wilson and Lokier, 2002; Fernández-Mendiola and Garćia-Mondéjar, 2003; Dorobek, 2008; Courgeon et al., 2017). This volcanic activity may result in platforms being veneered in volcaniclastics from which carbonate production may recover, or thick volcanogenic piles that will ultimately cause the demise of the platform (cf. Fernández-Mendiola and Garćia-Mondéjar, 1995; Heikoop et al., 1996; Soja, 1996; Wilson, 2000; Mitchell, 2002; Lokier et al., 2009; Paumard et al., 2017). It is these carbonate-volcanogenic interactions and the dynamic impact they have on subsequent diagenesis that are studied here, with a focus on the impacts of thick volcanogenic piles overlying carbonate platforms. It might be expected that thick (>500 m) volcanic and/or volcaniclastic piles overlying shallow-platform deposits would have a major impact on carbonate diagenesis. However, little data is available to evaluate the themes addressed here, namely: (1) the alteration of carbonate deposits adjacent to overlying volcanogenic units, (2) the reciprocal alteration of volcanogenic deposits overlying carbonate systems, (3) the extent of any contact-related alteration, and (4) whether there are more extensive impacts on platform-wide carbonate diagenesis.

In the warm, equatorial seas of SE Asia: one of the world's most active tectonic regions, a third of the regions Cenozoic carbonate formations developed on volcanic edifices (Wilson and Hall, 2010; Fig 1). As Wilson and Hall (2010) note: for these carbonates developed around volcanic edifices "on at least one side (often all sides) the combined carbonate-volcanic feature passes laterally into deeper-water deposits. If there is a time gap between volcanic and carbonate formation this is generally <5 Myr. Carbonates may interdigitate with, and be partially contemporaneous with volcanic activity and/or erosion of volcanic material. The volcanic feature may be subaerially emergent and active or inactive (i.e. an active or dormant volcano)." The Krisna Field in the Batu Raja Formation NE of Sumatra is a productive carbonate reservoir that developed as fringing reef deposits around a volcanic edifice. Variable dissolution, cementation and dolomitisation phases are detailed for the Krisna field, yet the underlying volcanogenic rocks appear to have had minimal impact on diagenesis of the carbonate system (Park et al., 1995). An exception is the local formation of late kaolinite and minor chlorite, which may relate to breakdown of feldspars (Park et al., 1995). Other studies of carbonates overlying volcanic edifices, such as from the Pacific or Europe, similarly document minimal apparent volcanogenic influence on diagenesis of the carbonate system (Hathway, 1995; Dewit et al., 2015). A number of studies detail contemporaneous volcanogenic activity, commonly involving admixed or interdigitating volcaniclastic content in carbonate systems from SE Asia (Heikoop et al., 1996; Tomascik et al., 1997; Wilson, 2002; 2011; 2012; Wilson and Lokier, 2002) and elsewhere (Faulkner, 1989; Miller, 1989; Soja, 1990; 1993; Okhravi and Amini, 1998; Mitchell, 2002; Fernández-Mendiola and Garćia-Mondéjar, 2003; Courgeon et al., 2016; 2017). The diagenesis of these coeval carbonate-volcanogenic systems, however, is barely touched on (Fernández-Mendiola and Garćia-Mondéjar, 2003; Wilson, 2012). In many arc-associated settings or in areas of intra-plate volcanism platforms covered in thick volcanogenic deposits are detailed, but again with little documentation of associated diagenetic alteration (Fulthorpe and Schlanger, 1989; Soja, 1996; Wilson, 2000; Salomon, 2003; Dorobek, 2008).

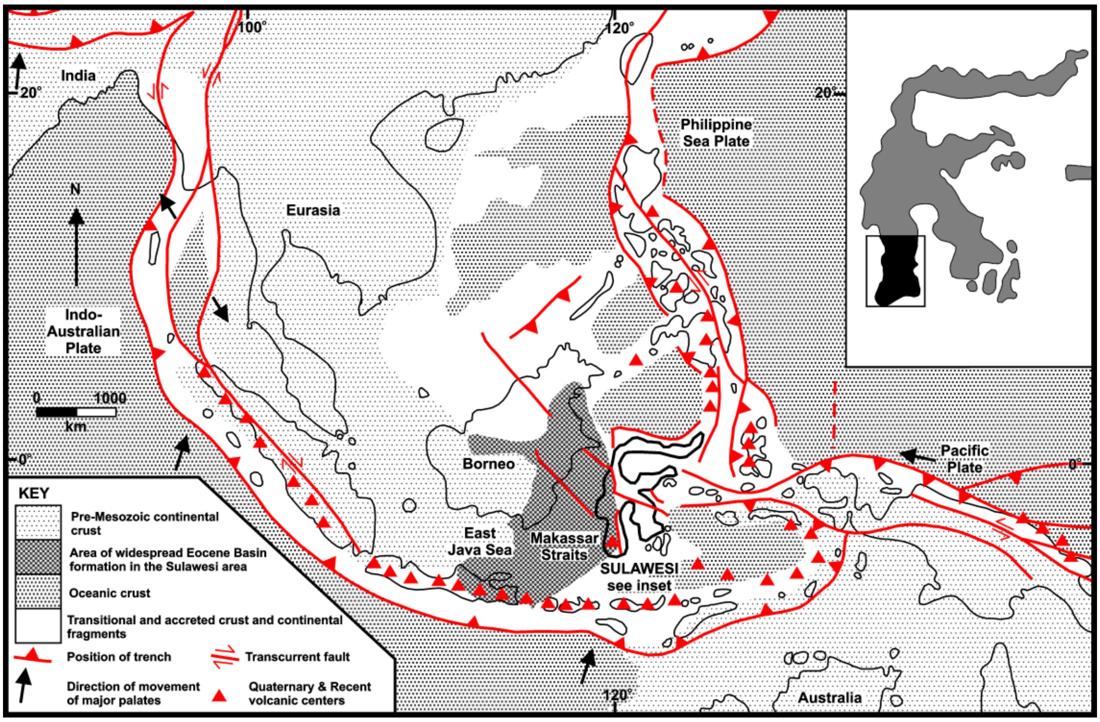

Figure 3.1 Regional tectonic setting of Sulawesi and the location of Recent volcanic centres as well as the Cenozoic basinal area in Sulawesi in which the Tonasa Limestone Formation accumulated (after Wilson, 1999; modified from Daly et al., 1991; Hall, 1996; van de Weerd and Armin, 1992). Coeval volcanism and carbonate development has been common throughout the Cenozoic in many of the areas with recent volcanic activity. Inset shows the position of the research area within Sulawesi.

The Tonasa Limestone from Central Indonesia of this study developed partly contemporaneous with laterally equivalent active volcanism and is overlain by an up to 1-2 km thick pile of volcaniclastics of the Miocene Camba Formation (Figs. 1 and 2; Wilson, 2000; Wilson et al., 2000). Previous studies on the Tonasa Carbonate Platform and its' diagenesis, outlined directly below, set the context for this diagenetic evaluation focused just on sections in proximity to overlying volcanic and/or volcaniclastics as well as those impacted by igneous intrusions[1],[2],[3] (Fig. 3: 22 measured sections; Wilson, 2000). A diagenetic study of the main carbonate deposits of the Tonasa Limestone Formation found alteration in shallow to deeper burial depths by fluids with mainly marine precursor origins predominated (Arosi and Wilson, 2015). Mechanical and chemical compaction features are common, as are a range of mainly burial-related granular mosaic, blocky and equant calcite cements. Tectonic subsidence, including fault-associated differential subsidence, controlled the degree of burial diagenesis impacting different areas of the platform. Early marine micritisation of allochems was common on the platform top. Earlier marine cements and meteoric influences are rare, being highly localised to block faulted highs and/or bathymetrically upstanding platform margin areas. The distribution and orientation of faults, fractures and calcite veins together with evidence for their

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[1] Carbonate samples were half stained with Alizarin Red S and potassium ferricyanide to allow differentiation of dolomite, ferroan and non-ferroan calcite (Dickson, 1965; 1966). The relative abundance of components and diagenetic phases were recorded semi-quantitatively (visual estimates; after Mazzullo and Graham, 1988). Facies nomenclature follows the textural classification scheme of Dunham (1962), modified by Embry and Klovan (1971), with components given in lithology names where they exceed 10-15%. Nomenclature on carbonate cement morphologies follows Flügel (2004).

[2] Biostratigraphic age assignments are through comparison with the modified East India Letter Classification for larger benthic foraminifera (van der Vlerk and Umbgrove, 1927; Adams, 1970; Lunt and Allan, 2004) correlated against the 2004 geological timescale of Gradstein et al. Planktonic foraminifera zonation follows Blow (1969; 1979), while nannofossil zonation is after Martini (1971).

[3] Stable isotopic analysis ($\delta^{18}O$ and $\delta^{13}C$) together with trace, major, rare earth element (REE) was run on key elements (cements, calcitic bioclasts and matrix) from samples both adjacent to and distal from the volcanogenics to better understand diagenetic alteration associated with carbonate-volcanogenic interactions versus those affecting the remainder of the carbonate platform. Seventy one oxygen and carbon isotope analyses were run on a GasBench II system coupled online to a stable-isotope-ratio mass spectrometer in continuous flow (Skrzypek and Paul, 2006), with all data normalised to NBS-19 (standard) and reported relative to V-PDB. External errors for $\delta^{18}O$ and $\delta^{13}C$ were ±0.1‰. Twenty-two microdrilled components were run on the ICP-MS at University of Queensland (UQ) following the methodology outlined in Yong (2013). Unfortunately the samples were mostly lost due to instrumentation failure whilst the samples were being run. Twenty six samples focusing mainly on the clayey units from around the carbonate-volcanogenic contacts were analysed for their mineralogy via X-Ray Diffraction (XRD) on a Phillips 200 (16 samples: Royal Holloway, London) and Bruker D4 (10 samples: CSIRO, Perth) fitted with Colbalt X-ray tube and a LYNXEYE detector. At Royal Holloway 10 g of sample, after adding 5 ml of hexametasodium phosphate and distilled water, evaporation and centrifuging, were subset and spread onto 3 glass slides with the first air-dried, the second glycolated, and the third heated to 550°C for 1 hour following the methodology by G. Marriner (pers. comm. 1994 after Hardy and Tucker, 1988). At CSIRO less than 1 g of sample was mixed with ethanol and spread on a glass slide and air-dried. X-Ray diffraction runs were from 5 to 90° 2Θ with an ~0.02° step size. There was no need for sample displacement correction since samples with quartz showed negligible shift.

relative timing are the strongest manifestation of tectonism coeval with diagenesis. In general, the preponderance of a “regional”, platform-wide diagenetic signature over a localised “syntectonic” one for this well-documented carbonate platform that developed coeval with active tectonics is attributed to: (1) predominance of non-framework building biota forming platform deposits that were prone to remobilization, have low production rates and limited potential to build to sea level, (2) formation in a region of lowered marine salinities due to high terrestrial runoff associated with the humid equatorial climate of SE Asia, (3) development on the flanks of a backarc basin rather than on “typical” continental crust, (4) key platform influencing structures are oblique to the main extensional direction in the basin, and (5) development in an overall subsiding tectonic regime, post-dating basin initiation (Wilson and Vecsei, 2005; Arosi and Wilson, 2015). An additional manuscript evaluates the diagenesis of the slope and basinal deposits of the Tonasa Limestone Formation (Arosi et al., in prep.). The sedimentology and evolution of the Tonasa Carbonate Platform, together with dominant controlling influences including tectonics, volcanism, nutrients and oceanography are previously documented (Wilson, 1996; 1999; 2000; Wilson and Bosence, 1996; 1997; Wilson et al., 2000; Wilson and Vecsei, 2005). The aim here is to contribute towards understanding diagenetic alteration of volcanogenic covered and/or influenced carbonate platforms, with a focus on those from equatorial regions.

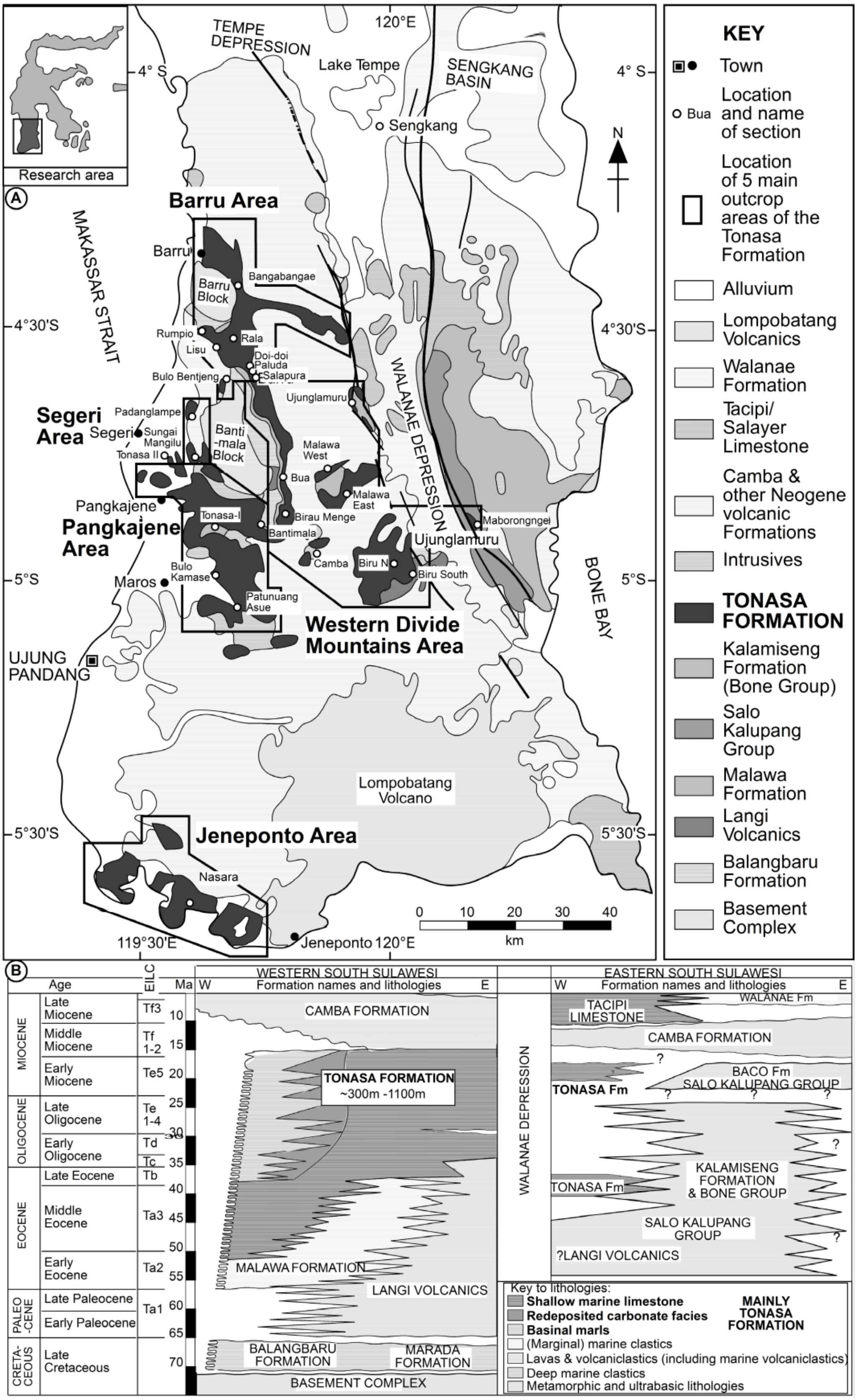

Figure 3.2 (a): Geological map and **(b)** stratigraphic sections of South Sulawesi (after van Leeuwen 1981, Sukamto 1982, Sukamto and Supriatna 1982, Wilson, 2000; van Leeuwen et al., 2010). Map shows the locations of the five main outcrop areas of the Tonasa Formation and the location of measured sections mentioned in the text.

3.2 Geological Setting

Sulawesi, including the Tonasa Formation of this study, is located in the centre of the Indonesian Archipelago in the midst of one of the most tectonically complex and volcanically active regions in the world (Fig. 1; Hamilton, 1979; Daly et al., 1991; Hall, 1996; 2002a; Wilson and Hall, 2010; Hall et al., 2011). From the Mesozoic and throughout the Cenozoic SE Asia has been affected by the interaction of three main tectonic plates, the: Pacific-Philippine, Indo-Australian and Eurasian plates (Hamilton 1979; Daly et al. 1991; Wilson and Bosence, 1996). Hall (2002a) outlined three main collisional tectonic events at 45, 25 and 5 Ma that resulted in tectonic ‘reorganization’ within SE Asia.

The evolution of south western Sulawesi (the South Arm) during the late Mesozoic and Cenozoic is linked to the accretion of micro-continental and oceanic fragments onto the eastern margin of the comparatively stable Eurasian plate, together with backarc rifting and volcanic arc development (Sukamto, 1975; Hamilton, 1979; van Leeuwen, 1981; Wilson and Bosence, 1997; Wilson, 1999, 2000). Relatively complete, but very different Late Cretaceous to recent stratigraphic sequences in the western and eastern halves of the South Arm reflect this complex geological evolution (Fig. 2; van Leeuwen, 1981; Wilson and Moss, 1999; van Leeuwen et al., 2010). The Balangbaru and Marada Formations are forearc deep-marine clastics and shales of Late Cretaceous age that overlie intersliced metamorphic, ultrabasic and sedimentary basement lithologies in the western South Arm (van Leeuwen, 1981; Hasan, 1991). By the Eocene, subduction had shifted to the east and marginal marine siliciclastics of the Malawa Formation in western South Sulawesi are associated with rifting in the Makassar Straits. The clastics pass transgressively upwards to carbonates of the Eocene to Miocene Tonasa Formation that have predominantly shallow-water origin and for which the diagenesis of the uppermost deposits of the platform are documented here. During Tertiary accumulation of sedimentary rocks in western South Sulawesi, volcanic and igneous lithologies dominated to the east of a major structural divide (the later demarked today by the north-south trending Walanae Depression). The varied igneous rocks of eastern South Sulawesi include arc-related volcaniclastics, passive margin volcanics associated with cessation of subduction, potassic volcanics linked to extension, as well as MORB-like volcanics from an accreted transtensional marginal oceanic basin

(Sukamto 1982; Yuwono et al. 1985; Elburg and Foden, 1999; van Leeuwen et al., 2010). Middle to late Miocene volcaniclastics and volcanics of the Camba Formation overlie the Tonasa Formation (Sukamto, 1982; Yuwono et al. 1985; Wilson, 2000). The Miocene shift in volcanism to western South Sulawesi and associated potassic igneous intrusions are linked to microcontinental collision related volcanism and intra-plate post-collisional (extensional) magmas (Yuwono et al., 1985; 1987; Elburg and Foden, 1999; Elburg et al., 2003; van Leeuwen et al., 2010). It is this contact between the carbonates of the Tonasa Limestone Formation and the volcaniclastics of the Camba Formation and the associated diagenesis that is detailed here. The following brief description on the geology of the Tonasa Carbonate Platform, the overlying Camba volcaniclastics and in particular the nature of the contact between the two Formations is mainly after Wilson (2000).

3.3 The Tonasa Carbonate Platform

The Tonasa Formation crops out mainly in western South Sulawesi and was deposited as a widespread area of shallow-water carbonate production, known as the Tonasa Carbonate Platform, during the early or middle Eocene to middle Miocene (~100 km N-S and ~80 km E-W; Figs. 2; Wilson et al., 2000). Detailed facies mapping and logging (81 measured sections, totalling about 7 km of section), together with petrographic (~500 thin sections and acetate peels) and biostratigraphic analysis was undertaken throughout the outcrop area of the Tonasa Formation (see footnotes 1 and 2). Larger benthic foraminifera dominate lithologies of this platform, which were deposited within the photic zone (Wilson et al., 2000; Wilson and Vecsei, 2005). Other bioclasts include coralline algae, echinoid fragments, small benthic foraminifera, and rare corals. A detailed diagenetic evaluation of a subset of 209 thin sections from 26 key measured sections allowed evaluation of the variability in Tertiary platform-wide diagenesis and its fracturing (Arosi and Wilson, 2015, see footnote 3). As described above burial diagenetic alteration mainly associated with marine precursor fluids dominates across much of the Tonasa Limestone Formation (Arosi and Wilson, 2015). Marine micritisation of bioclasts is ubiquitous in shallow platform top deposits particularly from low to moderate energy settings (Arosi and Wilson, 2015). It is predominantly only in platform margin areas associated with faulted footwall highs that localised evidence of karstification and meteoric diagenesis or marine cementation is seen (Arosi and Wilson, 2015).

The Tonasa Formation includes up to 600 m of shallow-water carbonates deposited in the main platform area (central Pangkajene area, Fig. 2; Wilson et al., 2000). Shallow-water carbonates overlain by basinal lithologies, totalling over a kilometre, were deposited to the north (Barru area) and south (Jeneponto area) of this platform. The Tonasa Carbonate Platform had a north-south extent of ~100 km. The main platform had a tilt-block morphology from Late Eocene times (Wilson, 1999; Wilson et al., 2000) and was bounded by a segmented, faulted northern platform margin (Wilson and Bosence, 1996) and a gently dipping ramp-type southern margin (Wilson and Bosence, 1997). Areas of more complex block faulting lay to the east (Western Divide Mountains area) and west (Segeri area) of the main tilt-block platform (Figs. 2 and 3; Wilson, 2000; Wilson et al., 2000). A variety of factors, including tectonics, volcanism, carbonate producers, climate, and oceanography influenced the development of the platform. Although a eustatic sea-level fall in the Oligocene may have been a contributing factor in localized subaerial exposure of the platform, the effects of eustasy are difficult to discern on this platform strongly influenced by tectonics (Wilson et al., 2000). Detailed analysis of platform and surrounding basinal deposits reveal that the Tonasa Carbonate Platform was affected by a number of phases of syndepositional tectonic activity (see below and van Leeuwen 1981; Wilson and Bosence, 1996; Wilson, 1999; 2000; Wilson et al., 2000). Most pertinent for this evaluation of alteration around the contact between the carbonates and overlying volcaniclastics Wilson (2000) concentrated on the factors controlling the diachronous demise of this platform, evaluating the relative roles of tectonics and volcanism, with Arosi and Wilson (2015) reviewing Tertiary platform-wide diagenesis.

3.4 Volcanics and Volcaniclastics of the Camba Formation

Middle to upper Miocene volcanogenics and volcaniclastics[4] overlie the Tonasa Formation and older formations, locally with an angular unconformity (Wilson, 2000; Figs. 2 and 3). These volcaniclastic sediments, igneous extrusives, and associated intrusives constitute the Camba Formation (Sukamto 1982; Sukamto and Supriatna, 1982; Yuwono et al., 1987). The surficial units of the Camba Formation accumulated in a range of continental, shallow and deep marine environments. In the eastern area of the Tonasa Limestone Formation where it borders the Walanae Depression some contemporaneous Miocene igneous activity resulted in admixing with volcaniclastics and intercalations of lava (Figure 3 (Biru section): Pake Volcanics; van Leeuwen, 1981; Elburg et al., 2002).

The lower member of the Camba Formation (Camba I Formation; Yuwono et al., 1987) is composed of tuffaceous sandstones interbedded with tuffs, sandstones, claystones, volcanic conglomerates/breccias, marls, limestones, and coal and is dated as middle to late Miocene (N9-N15; Sukamto, 1982; Sukamto and Supriatna, 1982). The dominantly volcanic upper member of the Camba Formation is also dated as middle to late Miocene on the basis of foraminifera (Sukamto, 1982) and K-Ar and fission-track dating of igneous rocks (Yuwono et al., 1987; van Leeuwen, 1981). This member includes volcanic breccias/conglomerates, lavas, and tuffs and is described here as the Camba Volcanics. Intercalated with the volcanic lithologies are marine sediments including tuffaceous sandstones, calcareous sandstones, and claystones containing disseminated plant remains (Sukamto, 1982; Sukamto and Supriatna, 1982). The lower part of the Camba Volcanics contains more volcanic breccia and lava of basaltic and andesitic composition with a calc-alkaline signature (Sukamto and Supriatna, 1982; Yuwono et al., 1987) and is thought to be equivalent to the Sopo Volcanics and affiliated volcanics described from near Biru (Fig. 2; van Leeuwen, 1981; Elburg et al., 2002). Intrusive sills and dykes within the Tonasa Limestone are mainly of basaltic, or more rarely basaltic andesitic or trachytic composition with most of these intrusions likely associated with feeder systems for

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[4]Nomenclature on the textural and compositional classification of the igneous rocks (including the lavas and intrusives) follows Gillespie and Styles (1999). The petrographic study of the volcaniclastic rocks was conducted following the classification criteria of MacKenzie et al. (1982), Fisher and Schmincke (1984), Suthren (1985), McPhie et al. (1993) and Gifkins et al. (2005).

the Camba Formation or its equivalents (Elburg and Foden, 1999). The groundmass of the intrusives are reported to be mainly glassy or microphenocrystic with some holocrystalline textures and having alkali feldspars as the main interstitial mineral (Elburg and Foden, 1999). The most mafic intrusives contain olivine, clinopyroxene and Cr-spinel, but in more evolved rocks the commonly zoned clinopyroxenes are also joined by plagioclase, sanidine, amphibole, biotite, magnetite and apatite (Elburg and Foden, 1999). Alteration effects are not reported for the intrusives. Potassium-Argon dating on a basaltic dyke and granodiorite of calc-alkaline affinity intruding the Tonasa Formation yield 17.7 Ma and 19 +/- 3.4 Ma and it is possible that initial associated formation of the Lower Camba Formation may have begun locally in the latest Early Miocene (Sukamto, 1982; Yuwono et al., 1987; Elburg et al., 2002). The upper part of the Camba Volcanics probably corresponds to the Pammesurang Volcanics, which disconformably overlies earlier successions near Biru and includes ignimbrites, lavas, tuffs, marls, and volcaniclastics (van Leeuwen, 1981). The Upper Camba Formation includes leucite basanites and tephrites, containing abundant phenocrysts of leucite, ?secondary analcite, plagioclase, titanomagnetite and in just the basanites olivine, within a finer groundmass of similar minerals (Yuwono et al., 1985). The middle to Late Miocene and younger igneous lithologies in South Sulawesi are predominantly potassic to ultra-potassic including mainly andesites, trachy-andesites, but also dacites and basalts (Yuwono et al., 1985; Elburg and Foden, 1999; Elburg et al., 2002). Elburg and Foden (1999), albeit from the younger Pliocene volcanics in South Sulawesi, noted iddingsitisation or alteration along the margins or cracks in olivine in the presence of water together with rims of fine grained Fe-Ti-oxides around hornblendes.

3.5 Carbonate-igneous contacts: their context and diagenetic alteration

The contact between the carbonates of the Tonasa Formation and the volcaniclastics of the overlying Camba Formation is extremely variable, reflecting differing reasons for diachronous carbonate platform termination. Where accessible this contact was studied in 22 measured sections distributed across western South Sulawesi (Figs. 2 & 3; Wilson, 2000). One hundred and twenty eight thin sections and acetate peels from around this contact and also associated with the intrusives from the Tonasa and Camba Formations were selected from the broader 500+ sample set to evaluate diagenetic alteration associated with igneous-carbonate interactions (see footnotes 1-3). Depositional environments from around the Tonasa-Camba contact are variable, inclusive of sub-photic to shallow-photic zone water depths and into terrestrial settings. Sections that cross the Tonasa-Camba contact include conformable or angular unconformable relationships, and for the latter there may be a major or minor (intra-Cenozoic to intra-Miocene) hiatus (van Leeuwen, 1981; Wilson, 2000; Wilson et al., 2000). Geochemical and mineralogical analyses were run on samples from at least one section crossing each of the main carbonate-volcanogenic environment-linked contact types, as well as those crossing intrusive-carbonate contacts (Figures 4 & 8; Tables 1 & 2). As noted by Wilson (2000): 'although a variety of factors influenced platform development, tectonics and volcanism were particularly important, influencing platform evolution and diachronous termination in four main ways: (1) During the Paleogene, calc-alkaline volcanic activity limited the eastward lateral extent of the platform but had little effect on carbonate sedimentation in western South Sulawesi. (2) Faulting in the latest Late Eocene resulted in segmentation of the platform and caused localized drowning in hangingwall areas and subaerial exposure on adjacent footwall highs. (3) A further phase of faulting in the Early to Middle Miocene, just prior to and during the early stages of renewed volcanism in western South Sulawesi, resulted in reactivation of faults, localized tilting of fault blocks, formation of new grabens, and subaerial exposure of faulted footwall highs. (4) In the Middle Miocene, the influx of volcaniclastics close to volcanic centres rapidly buried most of the few remaining areas of shallow-water carbonates and inhibited renewed carbonate production. However, carbonate production contemporaneous with volcanism occurred in more distal, or localised, areas shielded from volcaniclastic input.' To investigate the carbonate-igneous alteration, lithologies that cross the Tonasa-Camba boundary and their diagenetic alteration are described from regions of: (1) shallow water, to subaerially exposed, and terrestrial deposition, and (2) deep marine and slope carbonate to volcaniclastic sedimentation. For further information on the rationale for depositional interpretations refer to Wilson (2000). Lithological and chronostratigraphic correlations of selected sections that cross this contact, their key diagenetic differences from the main body of platform carbonates, and the nature of the uppermost platform development just prior to volcanism are shown on Figure 3. Figure 4 shows diagenetic and stable isotopic variability of carbonate components from key sections that cross the contact between the carbonates and the overlying volcanogenics.

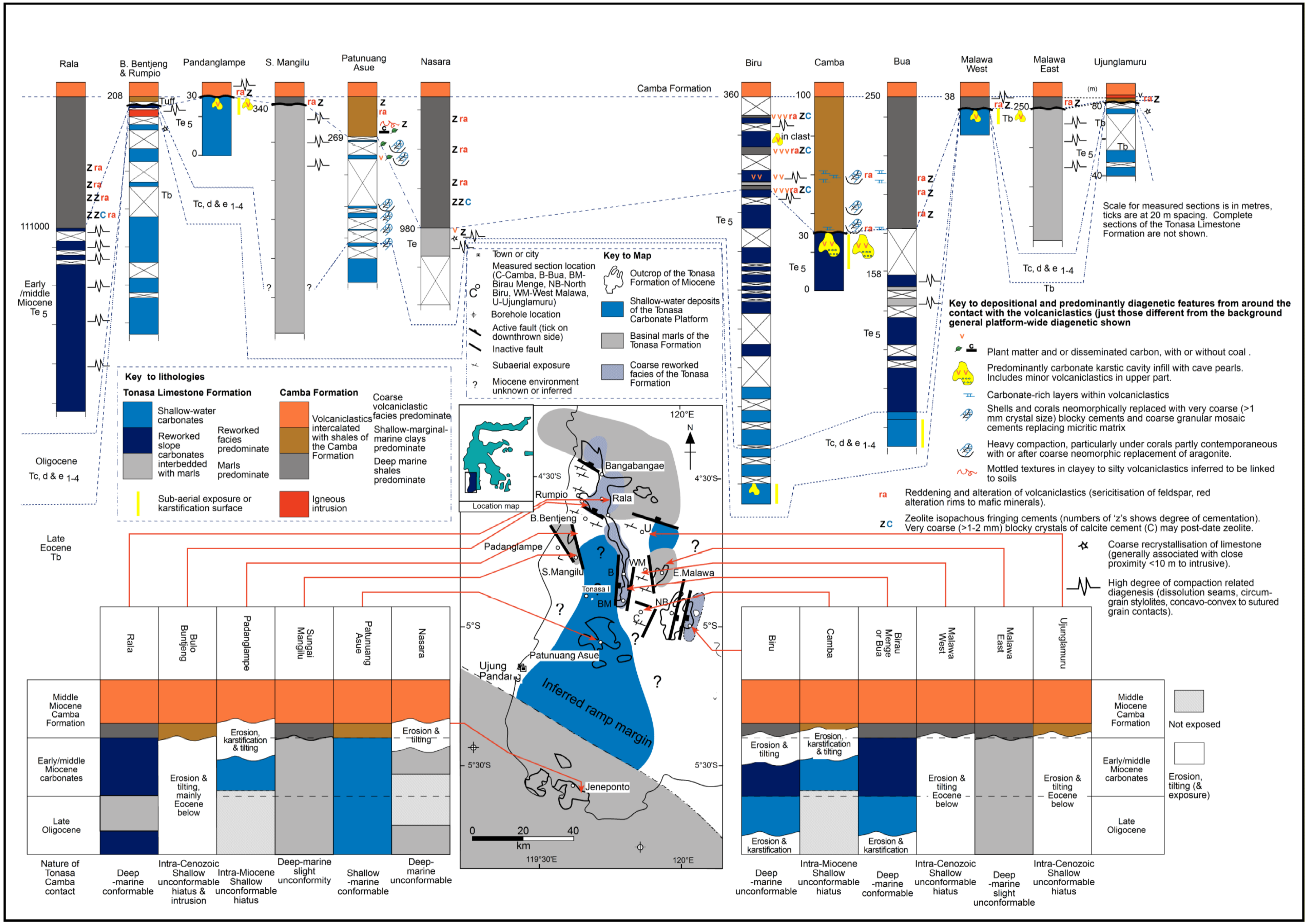

Figure 3.3 Stratigraphic sections and diagenetic alteration around the upper contact of the Tonasa Limestone Formation with the overlying volcanogenics, predominantly composed of the volcaniclastics of the Miocene Camba Formation. Figure shows lithological and chronostratigraphic correlations of selected sections that cross this contact, their key diagenetic differences from the main body of platform carbonates, and the nature of the uppermost platform development just prior to volcanism (inset map).

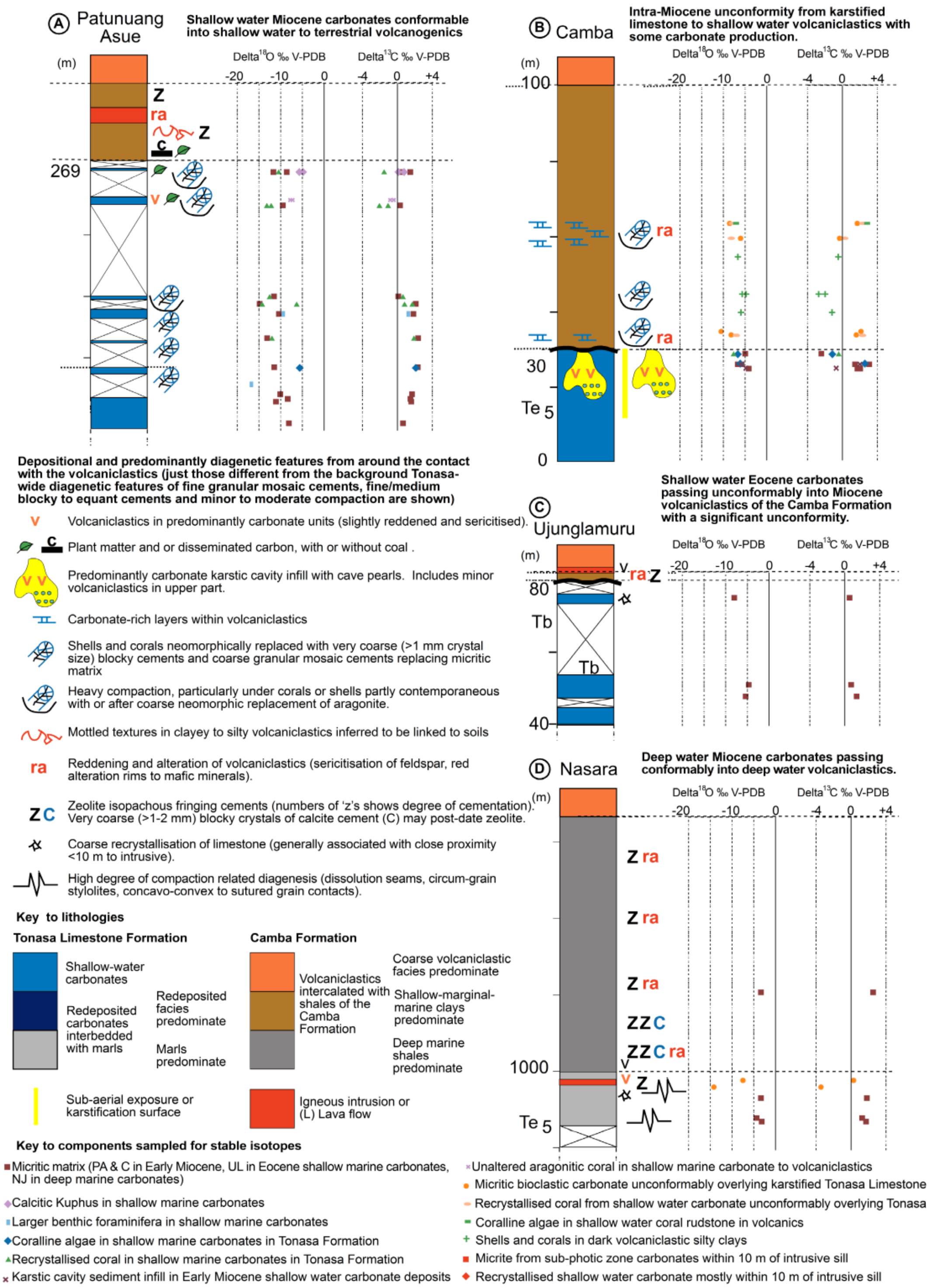

Figure 3.4 Diagenetic and stable isotopic variability of carbonate components from key sections that cross the contact between the carbonates of the Tonasa Limestone Formation and the overlying volcanogenics primarily of the Camba Formation. Sections shown are: (a) shallow water Early Miocene carbonates conformable (Patunuang Asue), and (b) unconformable (Camba) into volcanogenics, (c) shallow water Eocene carbonates with a significant unconformable hiatus into the volcanogenics (Ujunglamuru), and (d) deep water Miocene carbonates passing conformably into the volcanogenics (Nasara). Isotopic values of carbonate components in proximity to igneous intrusions (primarily from the Patunuang Asue section) are just shown on Figure 8. See Table 1 and Appendix D2 for details of components and results of stable isotopic analysed.

Table 3.1 Carbonate components analysed for stable isotopes from close to the volcanogenics. Table shows component types, their context in stratigraphic sections, $\delta^{18}O$ and $\delta^{13}C$ ‰ V-PDB results and distance from the volcanogenics.

Name	$\delta^{13}C$ [‰, VPDB]	$\delta^{18}O$ [‰, VPDB] as for calcite	Height from base of section (m), from Wilson (1995)	Stratigraphic thickness to volcanogenics (m), from Wilson (1995)	Distance from intrusive or lava flow if present in section (m), from Wilson (1995)	Sample
H-CG7-mk	-0.73	-4.66	25.00	6.00		slightly brown laminated karstic cavity infill
H-CG1-pm-a	1.82	-4.27	25.00	5.00		pink micritic matrix with few bioclasts - a
H-CG1-pm-b	2.04	-4.03	25.00	5.00		pink micritic matrix with few bioclasts - b
H-CG11-mb	1.63	-6.39	26.00	4.00		brownish bioclastic matrix
H-CG4-ccf	1.55	-6.56	26.00	4.00		very coarse blocky calcite fissure fill
H-CG6-ca	2.52	-6.48	26.00	4.00		white coralline algae in wallrock
H-CG6-gmk	2.03	-6.27	26.00	4.00		grey micritic karstic cavity infill
H-CG6-m	3.11	-6.06	26.00	4.00		white micritic matrix to limestone wallrock
H-CG2-ca	-1.10	-7.38	29.00	1.00		white coralline algae (minor micritic matrix)
H-CG2-m	-2.40	-4.88	29.00	1.00		pale brown micritic matrix (minor bioclasts)
H-CG2-rc	-0.39	-7.35	29.00	1.00		recrystalised coral
H-CG10-cc	2.31	-7.73	34.00	-4.00		recrystalised coral
H-CG10-m	1.62	-8.16	34.00	-4.00		slightly reddish micritic matrix
H-CG9-m	2.18	-10.50	35.00	-5.00		white micritic matrix
H-CG17-rc	-1.20	-5.78	40.00	-10.00		recrystalised coral, heavily compacted
H-CG18-ws-a	-2.73	-5.48	45.00	-15.00		white shells in very dark volcaniclastic matrix - a
H-CG18-ws-b	-2.04	-5.04	45.00	-15.00		white shells in very dark volcaniclastic matrix - b
H-CG25-wc	-0.47	-6.63	55.00	-25.00		white chalky coral with dark bioclastic matrix
H-CG20-rc	0.24	-8.35	60.00	-30.00		recrystalised coral
H-CG20-wm	-0.30	-6.02	60.00	-30.00		white micritic matrix in corals
H-CG24-ca	2.79	-7.32	64.00	-34.00		white coralline algae
H-CG24-m	1.77	-8.58	64.00	-34.00		pale grey bioclastic matrix
H-CG24-rc	2.36	-8.14	64.00	-34.00		recrystalised coral
H-NJ-64-pm	1.77	-3.22	987.00	-13.00	-13.00	pale grey micrite
H-NJ-72-pm	1.38	-4.24	988.00	-12.00	-36.00	pale grey micrite
H-NJ-73-pm	1.88	-3.26	993.00	-7.00	-13.50	pale grey micrite
H-NJ-70-pm	1.55	-4.14	1020.00	20.00	-8.00	pale grey micrite
H-SAM19-m	0.61	-8.19	176.80	87.60		micritic matrix
H-SAM15-m	1.53	-11.25	184.00	80.40		micritic matrix, minor bioclastics
H-SAM14-m	1.47	-8.47	185.00	79.40		cream micritic matrix, no visible bioclasts
H-SAM13-m	1.66	-10.21	186.50	77.90		petroliferous micritic matrix, minor bioclasts
H-SAM12-ca	2.23	-11.82	195.60	68.80		coralline algae
H-SAM12-mb	2.27	-11.64	195.60	68.80		brown/grey petroliferous bioclastic W/P
H-SAM11-cc-a	2.05	-12.29	205.50	58.90		recrystalised coral (?*Porites*)
H-SAM11-cc-b	1.91	-12.26	205.50	58.90		recrystalised coral (?*Porites*)
H-SAM11-mb	2.07	-13.21	205.50	58.90		micritic bioclastic matrix
H-SAM10-lb	1.18	-9.78	213.60	50.80		larger benthic foraminifera
H-SAM10-mb	1.78	-10.51	213.60	50.80		micritic bioclastic matrix

Name	δ13C [‰, VPDB]	δ18O [‰, VPDB] as for calcite	Height from base of section (m), from Wilson (1995)	Stratigraphic thickness to volcanogenics (m), from Wilson (1995)	Distance from intrusive or lava flow if present in section (m), from Wilson (1995)	Sample
H-SAM16-cc	**0.86**	**-6.40**	**217.00**	**47.40**		**recrystalised coral**
H-SAM16-mb	**2.00**	**-14.81**	**217.00**	**47.40**		**recrystalised bioclastic micritic matrix**
H-SAM16-rb	**1.66**	**-14.65**	**217.00**	**47.40**		**petroliferous recrystalised bioclast - shell**
H-SAM9-cc	**0.63**	**-12.56**	**219.50**	**44.90**		**Heavily recrystalised coral**
H-SAM9-mb	**0.09**	**-11.69**	**219.50**	**44.90**		**Micritic matrix (partly bioclastic)**
H-SAM8-cc-a	**-2.02**	**-12.55**	**250.20**	**14.20**		**recrystalised coral - a**
H-SAM8-cc-b	**-1.19**	**-13.03**	**250.20**	**14.20**		**recrystalised coral - b**
H-SAM8-m	**0.22**	**-9.61**	**250.20**	**14.20**		**Micritic matrix**
H-SAM6-ca	**-0.70**	**-7.79**	**252.00**	**12.40**		**Corals unaltered -a**
H-SAM6-cb	**-0.63**	**-7.74**	**252.00**	**12.40**		**Corals unaltered -b**
H-SAM1a-cc	**-1.51**	**-10.59**	**261.50**	**2.90**		**black heavily recrystalised coral**
H-SAM1a-m	**1.41**	**-11.74**	**261.50**	**2.90**		**pale grey petroliferous micritic matrix**
H-SAM1b-ka	**0.30**	**-5.67**	**261.50**	**2.90**		**calcitic *Kuphus* tube - a**
H-SAM1b-kb	**0.71**	**-5.32**	**261.50**	**2.90**		**calcitic *Kuphus* tube - b**
H-SAM1b-m	**0.42**	**-8.74**	**261.50**	**2.90**		**pale brown micritic matrix**
H-UL11-m	**1.41**	**-5.32**	**49.00**	**31.00**		**pale brown micrite**
H-UL12-m	**0.79**	**-4.59**	**52.00**	**28.00**		**pale grey micrite**
H-UL14-mb	**0.56**	**-7.90**	**75.00**	**5.00**	**5.00**	**micrite (bioclastic)**
H-NJ-62-pm	**-3.49**	**-14.04**	**996.00**	**-4.00**	**-4.00**	**pale grey micrite**
H-NJ-75-pm	**0.37**	**-7.33**	**997.50**	**-2.50**	**-9.00**	**pale grey micrite**
H-PA8-bm-a	**-0.28**	**-18.25**	**35.30**	**229.10**	**0.20**	**black recrystalised matrix - a**
H-PA8-bm-b	**-0.14**	**-18.18**	**35.30**	**229.10**	**0.20**	**black recrystalised matrix - b**
H-PA8-rc-a	**0.24**	**-14.78**	**36.80**	**227.60**	**2.00**	**??recrystalised coral - a**
H-PA8-rc-b	**0.32**	**-12.71**	**36.80**	**227.60**	**2.00**	**??recrystalised coral - b**
SAM48-MX	**0.72**	**-7.08**	**149.00**	**115.40**	**10.00**	**micritic matrix**
SAM52-LEP	**1.85**	**-12.10**	**127.00**	**137.40**	**4.00**	**larger benthic foraminifera Lepidocyclinid**
SAM54-ALGAE	**0.78**	**-8.89**	**118.00**	**146.40**	**13.00**	**coralline algae**
SAM54-ROT	**0.87**	**-10.32**	**118.00**	**146.40**	**13.00**	**larger benthic foraminifera rotallid (undifferentiated)**
SAM58-ALGAE	**1.21**	**-12.23**	**114.50**	**149.90**	**16.50**	**coralline algae**
SAM58-MX	**1.17**	**-12.44**	**114.50**	**149.90**	**16.50**	**micritic matrix**
SAM59-MX	**0.60**	**-6.12**	**107.00**	**157.40**	**24.00**	**micritic matrix**
SAM60-MX	**0.51**	**-4.49**	**101.00**	**163.40**	**30.00**	**micritic matrix**
H-X1-cm	**2.98**	**-6.91**	**N/A**	**~10.00**		**crystalline black marble, petroliferous**
H-X5-cm	**3.12**	**-5.90**	**N/A**	**~15.00**		**crystalline black marble, petroliferous**
H-S110-cf	**1.97**	**-5.87**	**N/A**	**N/A**	**15.00**	**recrystalised foraminifera**
H-SRa60-m	**1.98**	**-5.52**	**38.00**	**144.00**		**cream to pale grey miciritc matrix**
H-SRa68-lbf	**1.89**	**-5.28**	**68.00**	**114.00**		**larger benthic foraminifera**
H-TII68-m	**-2.71**	**-7.30**	**196.50**	**N/A**		**cream to pale grey miciritc matrix**

3.6 Diagenesis

3.6.1 Diagenesis of sections of shallow-water carbonates with or without subaerial exposure (and minor intra-Neogene hiatus) passing into shallow-water to terrestrial volcanics

Early Miocene shallow water carbonates of the Tonasa Formation pass conformably into overlying volcanics of the Camba Formation without evidence for a hiatus in the Patunuang Asue section from the Central (Pangkajene) area. Angular unconformable contacts with an intra-Neogene hiatus and evidence of subaerial exposure of the Early Miocene Tonasa Limestone prior to covering by shallow water volcaniclastics are present in the Padanglampe and Camba sections from the Western and Eastern Areas, respectively. In other accessible sections from the Central and Eastern Areas the upper surface of the shallow water Miocene carbonates is a recent erosional karstic one lacking overlying volcanics, or there is a faulted contact with the volcanics.

In the Early Miocene deposits of the Patunuang Asue section alveolinid and coral bioclastic packstones and floatstones contain a few percent slightly abraded euhedral feldspars and plant fragments 10 m below the first exposed unit of the Camba Formation: a coal. The packstones and floatstones show aggrading neomorphism of the micritic matrix and have granular mosaic ‘groundmass’ textures with interlocking matrix crystal sizes up to 100-150 µm (Fig. 5a and b). In the 100 m below the Camba Formation the $\delta^{18}O$ V-PDB values of the micritic matrix and/or its granular mosaic replacement become increasingly more negative changing from -6.2 to -8.1‰ upwards to -11.6 to -14.8‰ (Fig. 4). Corresponding $\delta^{13}C$ V-PDB are all positive varying from 0.1 to 2.3‰ with lowest values at 100 m below the contact and then again from 50 m below the contact. Coral, shell and alveolinid material is commonly replaced by blocky crystals up to 1.2 mm long, having irregular margins, and including “ghost” structures of the precursor grain (Fig. 5c and d). These relatively coarse neomorphic textures in both the groundmass and replacing individual grains are lost when the stratigraphic distance below the Camba Formation is > 60 m. The blocky replacive crystals have amongst the most negative values of $\delta^{18}O$ V-PDB within 60 m of the contact with the volcaniclastics (-10.6 to -14.7‰). Delta $\delta^{13}C$ V-PDB values of the blocky cements become less positive from 70 m (2.1‰) to 50 m (0.6‰), and negative within 30 m (-1.2 to -2.0‰), of the contact with the volcaniclastics.

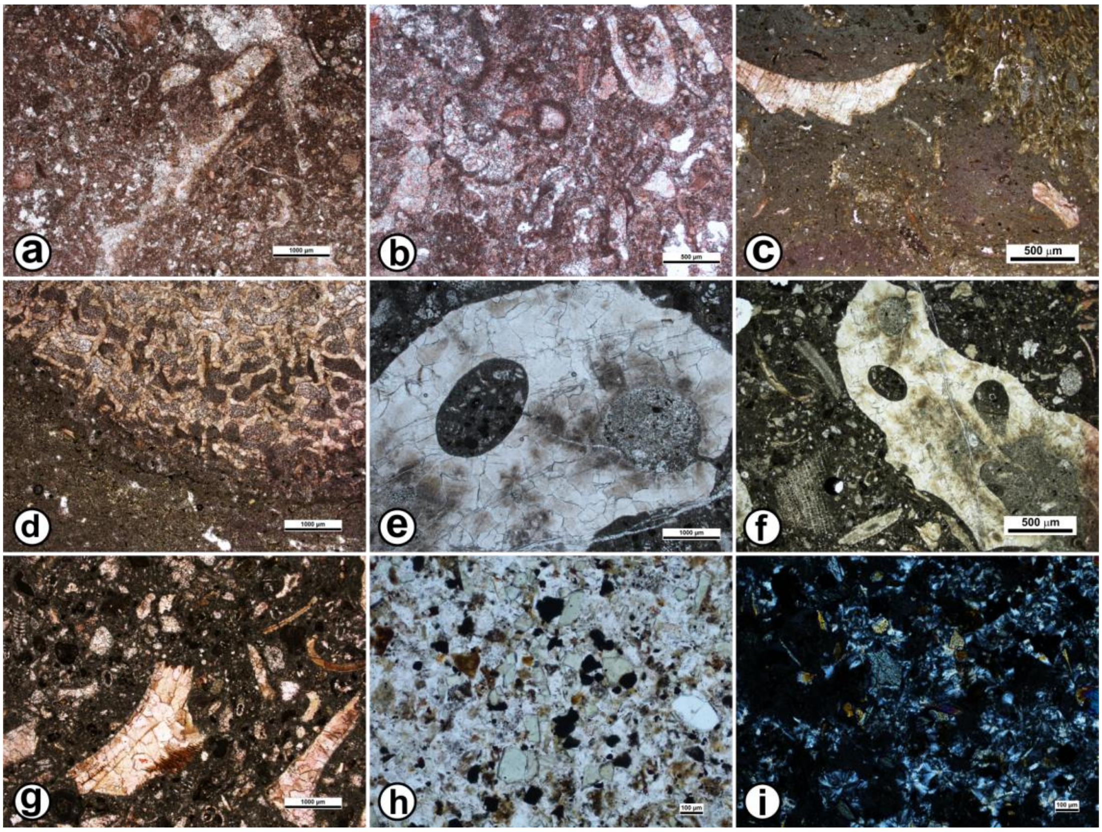

Figure 3.5 Petrographic features of the shallow-water carbonates that pass conformably upwards into the terrestrial volcaniclastics in the Patunuang Asue section: (a, b) Aggrading neomorphism and granular mosaic 'groundmass' textures with crystal sizes up to 100-150 µm (SAM1b). (c, d, e, f, g) Replacement of coral, mollusc and alveolinid material by neomorphic blocky crystals up to 1.2 mm long. Early neomorphic features post-date minor micritisation (SAM6, SAM9). (d) Neomorphism is partly contemporaneous with compaction of matrix around larger allochems (SAM6). (h, i) Volcaniclastics include abundant radiating fans of fibrous zeolite needles (up to 200 µm in length) precipitated between the grains that have low first to second order birefringence and sweeping extinction patterns. Feldspar grains may be reddened and show alteration to fine carbonate crystals or sericite at their margins and along fractures (SAM5: PPL & XPL).

In comparison low-Mg calcite *Kuphus* tubes from just below the contact into the volcanogenics that retain their original textures have $\delta^{18}O$ V-PDB vales of -5.3 and -5.7‰ with corresponding $\delta^{13}C$ V-PDB values of 0.7 to 0.3‰. The neomorphic features occurred relatively early during diagenesis post-dating minor micritisation, but pre-dating fracturing and later cement development (Fig. 5e and f). Neomorphism is, however, partly contemporaneous with compaction of matrix around larger allochems (Fig. 5d). The feldspar grains may be reddened and show alteration to fine carbonate crystals or sericite at their margins and along fractures (Fig. 5h). In the 50 metres above the coal are poorly exposed mottled pink and brown claystones interpreted as soils with volcaniclastic siltstone laminae, passing upwards into a heavily altered mafic sill or lava flow and a coarse volcaniclastic conglomerate. The laminated volcaniclastic siltstones contain subangular to angular volcanic lithic and mineral grains that include plagioclase, biotite, and augite). Subangular to sub-rounded carbonaceous and/or charcoal fragments form disseminated lamina within the siltstone. Many of the mineral grains in the siltstones are quite fresh, but the feldspars show alteration at their margin or along fractures to fine calcite or possible sericite. Montmorillionite, a smectitic clay mineral, together with illite, potassic feldspars including microcline and sanidine are seen from XRD in the clayey and silty intervals (Table 2). Some of the porphyritic igneous clasts have reddened Fe-oxidised fine matrices. There are abundant radiating fans of fibrous zeolite needles (up to 200 µm in length) precipitated between the grains with low first to second order birefringence and sweeping extinction patterns (Fig. 5h & i). The calcian, sodian, aluminium zeolite of thompsonite was identified from XRD in the one of the silty intervals, also showing calcite and montmorillionite alteration (Table 2). The mafic sill or lava flow is very altered and reddened and it is not clear how much of the alteration of this and the inferred soils occurred soon after deposition or during recent exposure. Gypsum with montmorillionite and illite are common in the mottled clayey interval together with traces of augite and potassic feldspars (from XRD; Table 2).

In both the Camba and Padanglampe sections the karstified Early Miocene packstones of the Tonasa Formation deposited in the photic zone have an angular (between 10-40°) unconformable contact with the Camba Formation. The packstones show micritisation and common granular mosaic calcite. Depositional textures and allochems generally remain recognisable with any neomorphic or recrystallization features on a similar-scale to that seen in the rest of the platform deposits (cf. Arosi and Wilson, 2015). Dissolutional karstic cavities at the top of the Tonasa Formation cross cut strata, are commonly lined by bladed to banded cements, with linking and cross-cutting fractures that have multiple phases of cavity lining cement and micrite. Following pore-lining cementation in the Camba Area the cavities are infilled by alternating micritic laminae containing ostracods with cave pearl laminae (Fig. 6a). Micritic matrix and wallrock as well karstic cavity sediment and cement infills of the Tonasa Limestone Formation at Camba have $\delta^{18}O$ V-PDB values mostly of -4.0 to -6.5‰ and predominantly positive $\delta^{13}C$ V-PDB ranging from +3.1 to -0.7‰. It is only within 1 m of the contact with the Camba Formation that more negative $\delta^{18}O$ V-PDB and $\delta^{13}C$ V-PDB values down to -7.6‰ and -2.4‰ are seen, respectively. Just in the upper part of these cavity infills micritic lamina include reddened volcaniclastic clasts as well as minor altered feldspar, and it is just in these laminae and their later cross-cutting stylolites that reddening is seen. In the Padanglampe section probable alveolar textures are additional evidence for subaerial exposure of the limestone (Wilson, 2000). The shallow water limestones of the Padanglampe sections show minor replacement by chalcedony of allochems and also silicicfication in cross cutting veins (Fig. 6b and c). In basinal grabens that developed adjacent to and contemporaneous with shallow-water carbonate production at Padanglampe there are abundant chert clasts that are admixed with lithified limestone and bioclastic material in sediment gravity flow deposits reworked into fault-bounded basins. The volcaniclastic sandstones and siltstones that overlie the Tonasa Formation at Padanglampe also contain abundant reworked chert and to a lesser extent limestone material with highly sericitised and/or reddened volcaniclastic material. Cementation by chalcedony and/or zeolites is extremely common in the volcaniclastic sandstones with fractures filled by silica (Fig 6d and e). Smectite-chlorites are abundant in the clayey intervals from XRD. Autobrecciated lava and igneous rocks within conglomerates show only minor alteration of olivines and pyroxenes with some sericitisation of feldspars (Fig. 6f and g). In the deposits that unconformably overlie the Tonasa Formation at Camba are dark claystones containing oysters and gastropods interbedded with conglomerates, graded volcaniclastic sandstones as well as coral-rich volcanogenic packstones and rudstones. From XRD the clays contain abundant smectite-illite-micas together with some calcite and potassic feldspars (Table 2). The corals, gastropods and *Halimeda* that indicate some contemporaneous carbonate production during the early stage of volcanism of the Camba Formation show very coarse (up to 1.2 mm) neomorphic replacement by blocky calcite. Although similar to the neomorphism seen in the Patunuang Asue section just below the contact with the Camba Formation this blocky calcite at Camba is ferroan rather than non-ferroan. The $\delta^{18}O$ V-PDB and $\delta^{13}C$ V-PDB values of mollusc and corals in the grey claystone are from -5.0 to -6.6‰ and -0.4 to -2.7‰, respectively (Fig. 4). In comparison coralline algae, granular mosaic cements incorporating micritic matrix, and blocky cements replacing corals in the volcanogenic packstones and rudstones are more negative in their $\delta^{18}O$

V-PDB values (-6.0 to -10.5‰) but mainly positive in their $\delta^{13}C$ V-PDB values (+2.8 to -0.3‰). Silicification of the Tonasa or Camba Formation is not seen at Camba and the degree of alteration of the volcanogenic grains is generally much less than seen at Padanglampe. Exceptions to this are where considerable bioclastic material is incorporated in the volcaniclastic siltstones or sandstones then sericitisation is common (Fig. 6h).

Table 3.2 XRD results of selected samples focused on the clayey intervals from around the Tonasa-Camba Formation (carbonate-volcanogenic contact).

Carbonate — Quartz & Mica — Clay minerals — Feldspars — Others

Unit	Sample	Calcite	Ankerite	Quartz	Mica	Muscovite	Chlorite	Kaolinite	Montmorillonite	Illite	Smectite-illite/mica	Smectite-chlorite	Mica-vermiculite	Mica-illite	Thompsonite	Analcime	Gypsum	Feldspar	Albite	Anorthite	Microcline	Sanidine	Augite	Clinochlor	Pyrite
Malawa Formation	DD21 (N)	■		■		■		■			■		■												
	MC5 (E)			■		■		■			■														
	UL39 (E)	■		■		■		■			■														
	SMa8 (W)			■				■						■											
Tonasa Formation: limestone	PA21* (C)	■	■																						
	SAM60* (C)	■																							
	SAM25* (C)	■																							
Tonasa Fn: *Discocyclina* marls	DBB12 (N)	■		■							■		■												
	RR2* (N)	■		■				■	■										■	■					
Tonasa Formation: deep water marls	D21 (N)	■		■		■	■					■	■												
	D27* (N)	■		■				■	■	■									■						
	D32* (N)	■		■				■	■	■															
	D64* (N)	■		■				■	■	■															
	D67 (N)	■		■		■					■														
	D82* (N)	■		■				■	■	■														■	
	SP17 (N)	■									■														
	MC2a (E)	■		■							■		■												
	NJ21 (S)	■		■	■							■													
	NJ74 (S)	■		■							■														
Camba Fn: Deep water claystones	SP8 (N)	■		■								■				■									
	NJ60 (S)	■		■	■		■									■		■							
Camba Fn: shallow water to terrestrial	SAM5* (C)	■							■	■					■						■		■		
	SAM7* (C)								■	■							■					■	■		■
	CG15 (E)	■									■							■							
	P18 (W)	■					■					■													
Salo Kal. Gp.	WM4 (E)	■		■	■						■							■							

For comparison 4 samples of the Eocene Malawa Formation are shown uppermost and one sample from the Paleogene volcanogenic Salo Kalumpang Group are shown at the base of the table. Where samples are from one section e.g. the Rala (RR and D samples marls and *Discocylina* marls) they are shown in younging stratigraphic order sequentially down the table. Samples marked '*' are those analysed in CSIRO with all others analysed at Royal Holloway (see footnote 3 for methodologies).

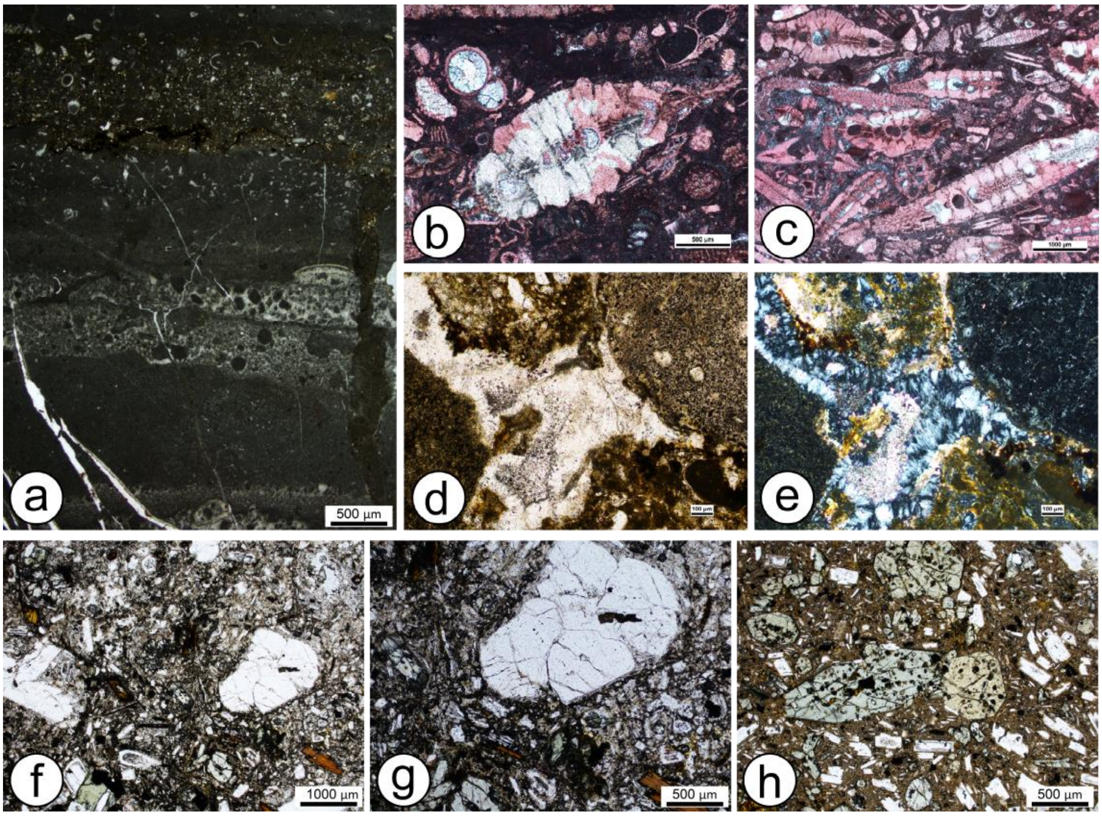

Figure 3.6 Petrographic features of the shallow-water carbonates with unconformable (intra-Miocene hiatuses into the volcaniclastics: (a) Fissure fill sediment including laminae of cave pearls, with ostracods from karstic infill at the top of the Camba section. The upper reddish laminae includes volcaniclastic material, the latter also filling the fracture on the right that cross-cuts earlier laminae (CG7). (b, c) Minor replacement by chalcedony (silicicification) of allochems in the Padanglampe section (P18I). (d, e) Cementation by chalcedony and/or zeolites in the volcaniclastic sandstones with cementation in fractures (P17). (f, g) Minor alteration of olivines, pyroxenes and some sericitisation of feldspars in autobrecciated lava and igneous rocks within conglomerates (P13). (h) Slight alteration and minor sericitisation in the volcaniclastic clast (P4).

Volcanic lithologies unconformably overlying the Miocene limestones are variable but include: volcanogenic crystal-lithic gravelly sandstones to tuffs, lithic volcanogenic conglomerates to breccias and igneous autobreccias. In many of these volcanogenic lithologies the minerals that include zoned feldspar, biotite, and clinopyroxene are relatively fresh, but in the more igneous end members show common disequilibrium textures (Fig. 6f -h). Some of the grains such as biotites show darker Fe-?Ti-oxidised margins, with common zoned feldspar and resorbtion textures at their margins (cf. Elburg and Foden, 1999). These disequilibrium igneous textures are inherent features of changing, or mixing, magma compositions during crystallisation rather than alteration features. Very minor sericitisation of feldspar is seen and there may be reddening and alteration (including slight sericitisation of, and devitrification of the groundmass. Euhedral crystals, including clinopyroxenes may include inclusions and/or altered areas of other minerals, e.g. possible glassy and opaque inclusions, with some alteration along brittle intra-crystal fractures).

3.6.2 Diagenesis of sections of shallow-water carbonates passing unconformably into shallow-water to terrestrial volcanics with a significant hiatus

In the SW part of the Northern Barru Area (3 sections) together with the Ujunglamuru (2 sections), Malawa West and Biru North sections from the Eastern Area the Camba Formation unconformably overlies Paleogene shallow-water carbonates, i.e., there is a significant hiatus between the formations. Uplift, tilting and periods of non-deposition or erosion during block faulting are inferred for all these sections prior to volcanism (Wilson, 2000).

In almost all Paleogene sections of shallow-water deposits of the Tonasa Limestone that are unconformably overlain by the Camba Formation the limestone diagenesis is similar to that seen in shallow platform deposits more distant from the contact with the volcaniclastics. That is, micritisation, followed by granular mosaic calcite and sometimes later equant or blocky cements developed to a comparable degree as in the rest of the platform (cf. Arosi and Wilson, 2015). As an example $\delta^{18}O$ V-PDB and $\delta^{13}C$ V-PDB values of the Tonasa Limestone Formation within 31 m of the unconformable contact with the Camba Formation at Ujunglamuru are -4.6 to -5.3‰ and +0.7 to +1.4‰, respectively, i.e., similar to that of the majority the Paleogene platform carbonate deposits (Fig. 4; Arosi and Wilson, 2015, Loche and Wilson, submitted). Only very rarely and generally closest to contacts with lavas in the Camba Formation are there samples of the limestones where the original textures and calcitic bioclasts are starting to be lost through recrystallization to granular mosaic to equant cements. In these recrystallised examples such as within 5 m of the contact at Ujunglamuru $\delta^{18}O$ V-PDB values tend to be more negative (down to -7.9‰) and $\delta^{13}C$ V-PDB values less positive (to 0.6‰) than many of the Palaeogene platform carbonates. Evidence for karstification was not seen at all these unconformable contacts and where karstic cavities were noted they did not include any volcaniclastic material in the infills. Overlying volcaniclastic and/or igneous material is generally quite fresh but may show some sericitisation of feldspar, reddening of minerals and intergranular zeolite cements in sandstones.

3.6.3 Diagenesis of sections mainly of shallow-water carbonates affected by igneous intrusions

Seven of the 81 measured sections through the Tonasa Limestone Formation include small-scale igneous intrusions. These intrusives are predominantly sills of mainly basaltic composition between 3-10 m thick, but also include minor dykes generally on a decimetre-scale. Sections with intrusives sills are mainly in the Central Area, including Oligocene (Patunuang Asue, Karaengta, Bantimurung, Bulo Tedong) and Eocene deposits (Tonasa-I Quarry; Wilson, 1995). Larger-scale igneous "stocks" up to 6 km across intrude the Tonasa Formation in the Central Area within 2 km of the Siloro 3, Bulo Bodong, Balocci and Patunuang Asue sections. In the northern area igneous sills intrude the Malawa Formation or Camba Formation just below or above the Tonasa Formation in two sections each, respectively (Banga-bangae, Rala and Rumpio, Bulo Buntjeng). In the Northern Area only the Salapuro section includes an igneous sill within Eocene deposits of the Tonasa Formation. Igneous stocks up to 2 km across intrude the Tonasa Formation within 2 km of some Northern (Salo Cinee, Wanuwaru, Bulo Dua, Doi-doi-Bulo Buntjeng and Dam Sadjang), Western (Padanglampe) and Eastern Area (Biru, Camba, Malawa) sections. In the Eastern Area a sill intrudes late Eocene carbonates in the Biru section (van Leeuwen, 1981). An igneous sill intrudes the Camba Formation within 1-30 m of the contact with the underlying Tonasa Formation in the Southern Area.

Within 4 m of the metre-scale predominantly basaltic sills and <1 m of the decametre-scale rare dykes the Tonasa Limestone shows a range of alteration features that are distinct from the background diagenesis of the platform as a whole (cf. Arosi and Wilson, 2015). These alteration effects associated with the intrusives include replacement of coral, mollusc and *Halimeda* fragments by coarse blocky cements (to 800 µm), with some retaining "ghost" textures of the original allochems, and abundant granular mosaic cements partially replacing matrix (Fig. 7a and b). Limestone lithologies may appear black or reddened and "crystalline" and have a strong petroliferous odour not present in other samples more distant from the intrusives. XRD of unaltered limestone and the recrystallised examples adjacent to the sills all show calcite as the almost exclusive component (Table 2). In fine grained lithologies from below the sills lithologies may be highly "recrystallised" and show abundant anastomosing fine-scale seams, with or without concentrations of carbonaceous or oily residues at seam interfaces (Fig. 7c). Close to sills of up to 8 m thickness that step up through the Patunuang Asue section limestones with recrystallised textures have $\delta^{18}O$ and $\delta^{13}C$ signature between -8.9 to -18.3‰ and +1.9 to -0.3‰ V-PDB, respectively[5] (Fig. 8). Some of these same alteration features and a distinctive negative $\delta^{18}O$ and $\delta^{13}C$ signature (between -14.2 to -19.7‰ and -9.1 and -14.2‰ V-PDB, respectively) are present in the Tonasa Limestone Formation within 1-2 km of some of the larger scale-stocks (Arosi and Wilson, 2015). Very close to the sills and within a few hundred metres of the stocks matrix and allochems, including calcitic larger benthic foraminifera may be replaced by interlocking mosaics of equant calcite crystals up to 50 and 200 µm, respectively (Fig. 7d).

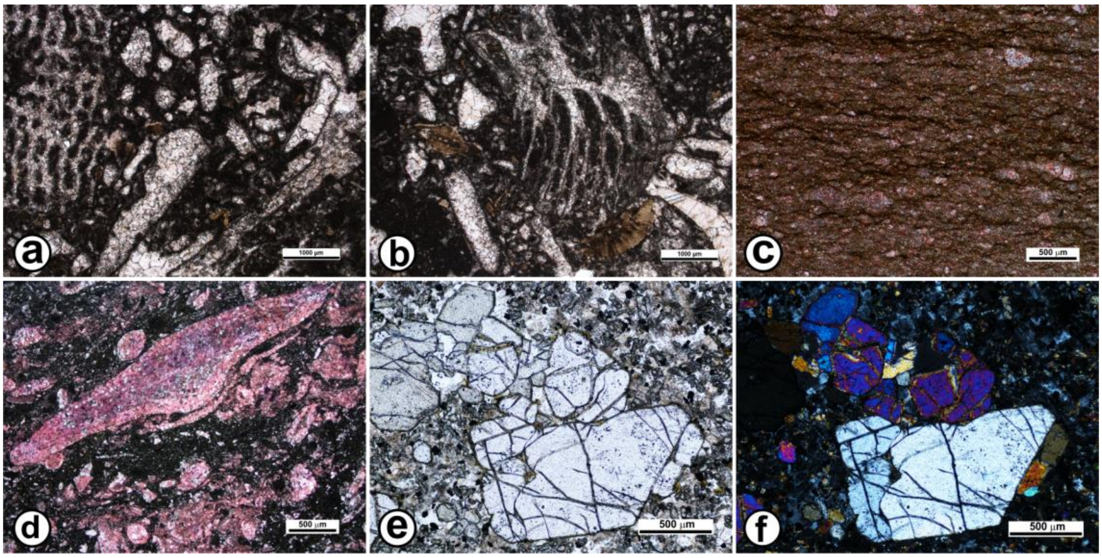

Figure 3.7 Petrographic features of the carbonates in proximity to intrusives and their diagenetic alteration: (a, b) Replacement of coral, mollusc and *Halimeda* fragments by coarse blocky cements (to 800 µm), with some retaining "ghost" textures of the original allochems. Abundant granular mosaic cements partially replaces matrix (PA6). (c) Organic-rich anastomosing fine-scale seams in fine grained lithologies from directly below the sills in the Patunuang Asue section (PA5). (d) Larger benthic foraminifera may be replaced by interlocking mosaics of equant calcite crystals up to 50 and 200 µm very close to the sills and within a few hundred metres of the stocks (R2). (e, f) Minor alteration around crystal margins, slight serpentinisation and alteration of olivine margins and fractures together with some sericitisation of the feldspars (NJ61).

[5] Although highly negative δ18O values occur up to 30 m below some of the outcropping sills, sills 'step-up' through the Pantunuang Asue sections and samples with the strongly negative anomalies are thought to be much closer to the sills horizontally to sub-vertically than they appear in a 'vertical' sense from road-cut sections.

The sills are generally porphyritic to microphenocrystic basalts to basaltic andesites having a glassy to microphenocrystic groundmass dominated by feldspars. Phenocrysts include feldspars (commonly zoned) with pyroxenes (including clinopyroxene) and sometimes olivine. Away from intense surface weathering of the sills, minerals are relatively fresh, but show minor alteration around crystal margins and slight serpentinisation and alteration of olivine margins and fractures together with some sericitisation of the feldspars (Fig. 7e and f).

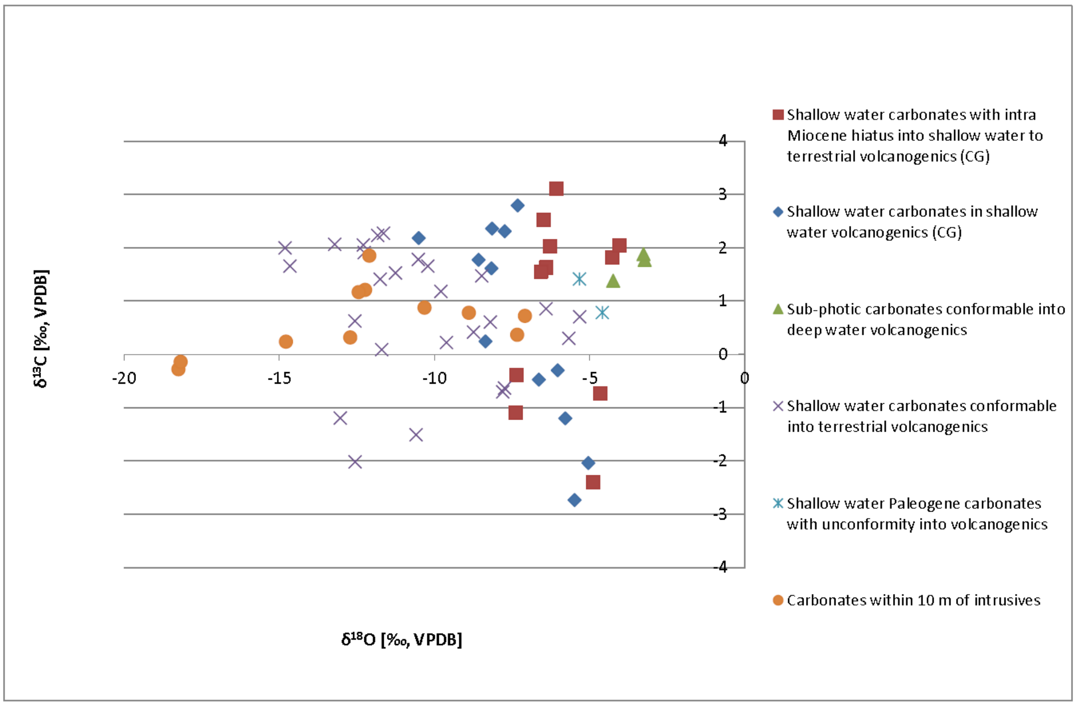

Figure 3.8 Stable isotopic cross plot of $\delta^{18}O$ against $\delta^{13}C$ ‰ V-PDB results for all carbonate components from close to the contact with, or within, the volcanogenics. There is a generally increasingly negative $\delta^{18}O$ ‰ V-PDB trend moving from deep-water carbonate deposits, to shallow-water already lithified carbonates associated with hiatuses, into shallow water within volcanogenics, to shallow-water conformable with volcanogenics and then associated with intrusives. This increasingly negative $\delta^{18}O$ ‰ V-PDB trend is interpreted to mainly reflect increasing temperatures associated with shallowing water depths, then increasing temperatures during diagenesis associated with emplacement of the volcanogenics.

3.6.4 Diagenesis of sections with deep water and slope carbonates passing into deep water volcaniclastics.

In many sections where it was possible to study the contact between the Tonasa and Camba Formations deep water and slope carbonates pass conformably or without a significant hiatus into deep water volcaniclastics (11 sections). In the North and Eastern areas 8 thick successions of deep marine marls (NN4-NN5; early to middle Miocene) interbedded with slope lithoclastic breccias containing abundant reworked shallow water carbonate lithic clasts and/or bioclastic material pass either sharply or gradationally over a few metres into the Lower Member of the Camba Formation. In the Southern Area 3 sections of marls interbedded with planktonic foraminifera bioclastic wacke/packstones are overlain with a very slight angular unconformity by volcaniclastics of the Lower Camba Formation (shown as an amalgamated section on Fig. 4). Outer ramp deposits are inferred for a southern gently dipping margin to the Tonasa Platform and it is not clear whether there was slight tectonic tilting or a change in depositional slope on the change to volcaniclastic sedimentation (Wilson and Bosence, 1997; Wilson, 2000). From XRD marls of the Tonasa Formation are dominated by calcite and some quartz as well as illite. Different trace components in the marls include kaolinite and montmorillionite in the northern area, smectite-chlorite and smectite-illite in the southern and eastern areas, respectively (Table 2). The deep water deposits of the Camba Formation in all these sections consist of dark grey bioturbated mudstones interbedded with rippled and/or graded volcaniclastic siltstones to gravelly volcanogenic sandstones or conglomerate/ breccias and tuffaceous units (Wilson, 2000). Although there may be some transition, XRD results together with the stratigraphy show a relatively ‘rapid’ change from marls of the Tonasa Formation into the volcaniclastic claystones. The claystones of the Camba Formation contain only minor calcite, together with quartz, feldspars, abundant smectite-chlorite, or smectite-illite combinations as well as the sodian, aluminium zeolite of analcime (Table 2).

Carbonates of deep water and slope origin at the top of the Tonasa Formation consist of marls and planktonic foraminifera wacke/packstones interbedded with (graded) bioclastic planktonic foraminifera packstones, and commonly graded (lithic) bioclastic packstones together with lithic conglomerates and breccias. The latter deposits are sediment gravity flow units rich in shallow water debris, lithified carbonate and non-carbonate clasts reworked downslope from commonly faulted platform margins. Collectively, the sediment gravity flow, outer ramp deposits (Southern Area) and background basinal deposits close to the volcaniclastic contact show moderate to very high levels of burial compaction influence (Fig. 9a). This is manifest as circum granular stylolites in the breccias and common concavo-convex to sutured grain contacts in the more bioclastic and planktonic foraminifera-rich deposits. Anastomosing dissolution seams and/or stylolite “swarms” showing the most intense compaction are most common in sections near the contact below igneous sills or flows, but may be present in any of the lithologies (Fig.9b). This degree of compaction in the Tonasa Formation close to the contact is equal to, or more intense than, that seen in the lower parts of the sections within the slope and basinal deposits (cf. Arosi and Wilson, 2015). In the southern area near Jeneponto micritic matrix in planktonic foraminifera packstones and marls near the contact have among some of the least negative $\delta^{18}O$ V-PDB within the Tonasa Limestone Formation (between -3.2 to -4.2‰ and $\delta^{13}C$ V-PDB values of +1.4 to +1.9‰ (Fig. 4; cf. Loche and Wilson, submitted). More negative $\delta^{18}O$ V-PDB values (-7.3 and -14.0‰) are seen in the deep water deposits from around the contact where deposits are less than 9 m from intrusives (corresponding $\delta^{13}C$ V-PDB values of +0.4 and -3.49‰: Fig. 4).

In a number of sections there is admixing of the carbonate and volcaniclastic material over a few metres to more rarely 10s of metres. Where there is volcaniclastic material in the more marly units, sericitisation of fine matrix can be intense, and both sericitisation and calcite replacement may affect feldspars, but many of the other volcanogenic minerals, such as pyroxenes may have a relatively fresh appearance or slight alteration rims (Fig. 9c). Planktonic foraminifera commonly show grain-scale compaction in these deposits and may show intra-test growth of zeolites or glauconite, with the former either pre- or post-dating compaction (Fig. 9d and e). Some deposits are a welded and highly altered mixture of recrystallized and crushed planktonic foraminifera and carbonate material with altered volcanogenic components within laminar “stringers” of devitrified glass (Fig.9f). In sandy to gravelly mixes of carbonates and volcanogenics carbonate material may be recrystallized or retain its original textures, with volcanogenic material showing common to intense alteration. This alteration includes sericitisation and/or calcitisation of feldspars and any fine matrix, devitrification of glass, alteration rims up to 0.2–2 mm to lithic and mineral grain boundaries. Growth of zeolites as both pore lining cements and some grain replacement may be abundant post-dating some compaction. Blocky pore-lining calcite cement growth to 300 µm long may post-date zeolite growth. In one section in the Northern Area large reworked marl clasts up to 60 cm in size are strongly contorted within volcanogenic breccias. Within a few metres to tens of metres from the base of the Camba

Formation carbonate material is predominantly lost. These volcanogenic units show similar, but less intense diagenesis to the admixed units. This alteration includes compaction, sericitisation, some grain margin alteration, and zeolite formation (Fig. 9g and h). Calcite formation, although present, is much rarer than in the admixed units. Where igneous textures are present in clasts or as sills, away from grain or igneous body margins, there may be little alteration, other than some sericitisation. Vesicular textures where present have vesicles lined by zeolites (up to 200 µm) followed by pore-filling blocky calcite cements (Fig. 9i).

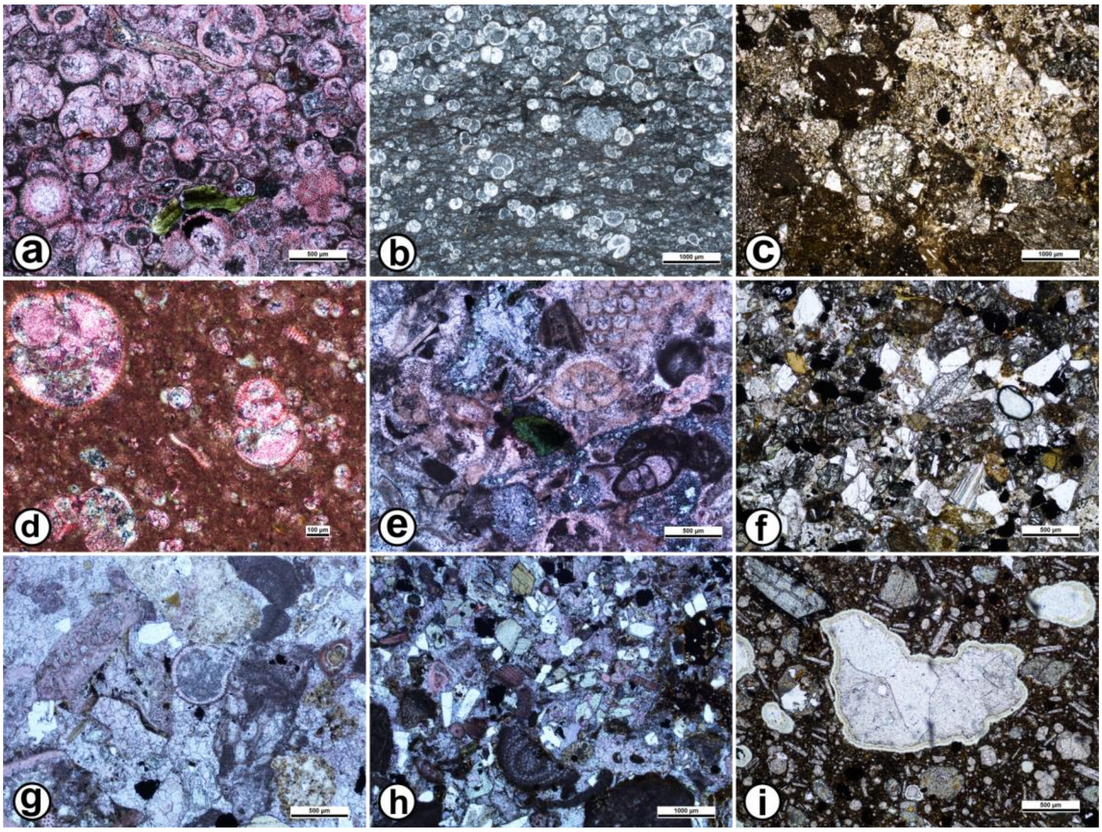

Figure 3.9 Petrographic features of the deep-water and slope carbonates that pass conformably into marine volcaniclastics: (a, b) Outer ramp deposits and background basinal deposits close to the volcaniclastic contact show moderate to very high levels of burial compaction influence (SRa25, NJ75). (b) Anastomosing dissolution seam "swarm" showing the most intense compaction in sections near the contact below igneous sills or flows (NJ75). (c) Admixing of the carbonate and volcaniclastic material over a few metres to more rarely 10s of metres from the upper carbonate contact or the transition to >50% volcaniclastics (SP10). (d, e) Planktonic foraminifera and bioclastic deposits show local glauconite and possible zeolites (some intra-test) either pre- or post-dating compaction (SP12, R14). (f, g, h) Locally strongly compacted and altered mixture of recrystallized and crushed planktonic foraminifera and carbonate material with altered volcanogenic components including some devitrified glass (SP15, BM12). Alteration of the admixed units includes some compaction, sericitisation, some grain margin alteration, and zeolite formation. (i) Vesicular textures where present have vesicles lined by zeolites (to 200 µm) followed by pore-filling blocky calcite cements (J107A).

3.7 Interpretation

The Anderson and Arthur (1983) equation (Eq. (1)) provides a means to derive $\delta^{18}O$ seawater values or temperatures for the region, and from this; the potential to determine the possible origins of fluids and temperatures involved in cement precipitation and diagenetic alteration.

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

The low-Mg calcite *Kuphus* 'tubes' are shallow-water bivalves thought to secrete their tube walls in equilibrium with ambient waters and are therefore useful for dating or paleoenvironmental studies (Ortega-Ariza & Franseen, 2011; Ortega-Ariza et al., 2015). Those retaining their original layered wall structure in the Early Miocene deposits at the top of the carbonate succession in the Patunuang Asue section are probably *Kuphus polythalamia* and from microscopy appear unaltered (almost the only original low Mg calcite preserved components in the studied samples). These calcitic feeding tubes up to 1 m in length are common in mangrove assemblages, or other marine settings with decaying wood. Temperatures in these shallow to intertidal, tidally-influenced mangrove settings in SE Asia vary seasonally from 26-31 °C (Primavera, 1998). Salinities in such settings may be that of the regional marine values, whilst brackish to higher-salinity conditions occur in riverine and island-associated mangroves, respectively (Tomascik et al., 1997; Primavera, 1998; pers. obs.). The values of the *Kuphus* tubes in the Tonasa Formation at -5.7‰ to -5.3‰ fall within the known values for Oligo-Miocene SE Asian marine components and cements of -7.1‰ to -1.4‰ V-PDB $\delta^{18}O$ (Ali, 1995; Wilson and Evans, 2002; Madden and Wilson, 2012, 2013; Wilson et al., 2013). The *Kuphus* values from the Tonasa falling towards the more negative end of the SE Asian range are consistent with relative warm, protected and perhaps brackish conditions consistent with their probable shallow coastal setting. The $\delta^{18}O$ V-PDB Kuphus values and temperatures of 26-31 °C would equate to V-SMOW water values of -2.0 to -3.4‰.

Least altered larger benthic foraminifera from the Tonasa Formation have $\delta^{18}O$ V-PDB values between −1.7 and −6.4‰ (and slightly positive $\delta^{13}C$ values of 0.3 and 2.0‰) that are consistent with marine values for SE Asia (Arosi and Wilson, 2015). Using the equation of Anderson and Arthur (1983) and at seawater temperatures of 26–30 °C for modern surface waters in the Makassar Straits off South Sulawesi (Gordon, 2005; Peñaflor et al., 2009) these values from the Tonasa Formation convert to V-SMOW water values of +1.4 to −4.1‰. Loche and Wilson (submitted) report a continuum of V-PDB $\delta^{18}O$ for least altered Eocene components in the Tonasa Formation varying sequentially from around -1.7‰ in planktonic foraminifera-rich deposits to -7.3‰ in increasingly shallower to very shallow photic depth deposits (for samples not showing negative trending $\delta^{13}C$ values). The surface water temperatures of 26-30 °C in the Makassar Straits decease at depth showing a steep thermocline between 75 m water depth (26-28 °C) dropping to 10-12 °C by 300m (Gordon, 2005). For the Spermonde Shelf, the modern continuation of what would have been the Tonasa carbonate platform, sea surface water temperatures are 28.5 °C decreasing to about 26 °C around 20 m water depth (Storm, 1989). Sea water salinities on the Spermonde Shelf are 31-32 ‰, but within 4 km of the coast in areas of river discharge the fresher water 'head' may be as low as 20‰ (Storm, 1989). Kuhnt et al. (2004) suggest that thermal stratification in the Makassar Straits region for the Miocene may have been similar to the present day, but with a deeper cooler element prior to the Miocene. Oligo-Miocene least altered components from the Tonasa Formation show a similar spread to those of the Eocene deposits, but more negative trending oxygen isotopic values are associated with localised meteoric diagenesis as well as proximity to intrusions (Arosi and Wilson, 2015; this paper; Loche and Wilson, in prep.) Several of the SE Asian and Tonasa specific 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). A $\delta^{18}O$ value of −6 to −4‰ V-SMOW is suggested for possible meteoric parent fluids on the basis of $\delta^{18}O$ values of meteoric precipitation in SE Asia at low elevations (Anderson and Arthur, 1983; Bowen and Wilkinson, 2002). Meteoric V-SMOW water values down to -8‰ are reported for SE Asia from higher elevations (Anderson and Arthur, 1983; Bowen and Wilkinson, 2002), such as might occur during the Miocene formation of the 'Camba' volcanic arc in South Sulawesi during the termination of the Tonasa Carbonate Platform.

3.7.1 Alteration of the shallow water carbonates that pass conformably into volcaniclastics and those close to intrusives

The shallow water Miocene carbonates in the Patunuang Asue section that pass conformably into the overlying Camba Formation show a more prevalent impact of early neomorphism, associated with some early compaction, than is seen in the majority of the rest of the Tonasa Limestone (cf. Arosi and Wilson, 2015). Blocky cements that replace coral, shell and alveolinid material retaining "ghost" textures of the precursor grain and having crystal sizes up to 1.2 mm with irregular margins generally have very different pore-filling character elsewhere in the Tonasa Formation (lack "ghost" textures, crystal sizes up to 800 µm with sharp crystal boundaries; Arosi and Wilson, 2015). These replacive calcite crystals in conformable sections into the Camba Formation with values of up to -10.6 to -14.8‰ $\delta^{18}O$ V-PDB if attributed just to higher temperatures would equate to values of ~50-135 °C, with the more negative values forming above 85 °C. There must be a strong thermal impact on the highly negative $\delta^{18}O$ signatures of the replacive features since the recorded V-PDB values would not be feasible from meteoric and/or burial related thermal influences in isolation (Thermal gradients of 21-28 °C per km of overburden reported for nearby subsurface wells; Hall, 2002b; Arosi and Wilson, 2015). Some brackish to meteoric additional contribution is, however, inferred for the conformable top of the carbonate section in the Patunuang Asue section due to the increasingly less positive to negative $\delta^{13}C$ V-PDB values approaching the volcanogenic contact. This prevalence of relatively coarse neomorphic replacement of both allochems and matrix together with early compaction of allochems into matrix and their geochemical signatures is mainly attributed to elevated pressures and temperatures associated with close temporal emplacement and accumulation of the overlying Camba Formation. New experimental studies show very coarse neomorphic recrystallisation can be reproduced at temperatures exceeding 100 °C (Pederson et al., 2017). Due to preservation of 'ghost' precursor textures of corals and molluscs, emplacement of the Camba Formation occurred prior to lithification and aragonite stabilisation of the uppermost shallow water deposits of the Tonasa Limestone.

The volcaniclastic grains in the Patunuang Asue section although quite fresh show alteration including sericitisation, some alteration of mafic grain margins and zeolites rimming pore spaces consistent with the alteration seen in other non-marine volcaniclastic sections (Mathisen and McPherson, 1991). The zeolites as pore rimming cements, albeit of limited lengths up to 200 µm are a commonly reported feature associated with dissolution of volcanic glass and low temperature precipitation under the presence of meteoric waters (Glanzman and Rytuba, 1979; Mathisen and McPherson, 1991; Ibrahim and Hall, 1996). Limited alteration of the volcaniclastic deposits may be linked to the lack of fluids constantly "bathing" the subaerially exposed volcaniclastics, their covering by more volcaniclastics and a predominance of lithic and crystal components over glassy elements (cf. Glanzman and Rytuba, 1979; Mathisen and McPherson, 1991; Vitali et al., 1995). It is only in the shallow-water to coastal grainy sections associated with some admixed bioclastic material that the calcian zeolite Thompsonite is found in the volcanogenics suggestive of local fluid remobilisation of calcite. The coals and mottled claystones that comprise the basal 30 m of the outcropping Camba Formation in the Patunuang Asue section may also have acted as a barrier or baffle to carbonate-rich fluids derived from the underlying Tonasa Formation more significantly affecting the Camba Formation. Downward and lateral groundwater flow patterns from terrestrial charge on formation of emergent volcanoes likely also acted contra to wholesale movement of calcite rich fluids into the volcanogenics. Gypsum in the mottled interpreted soil horizons although difficult to tie to an early diagenetic timing may be locally linked to evaporation in the strongly seasonal climate.

Close to contacts with igneous intrusives shallow-water limestones also show marked recrystalisation and compaction effects. Whilst similar to diagenetic affects in the conformable stratal transition to volcanogenics alteration associated with intrusions is consistent with the onset and development of contact metamorphism. The highly negative $\delta^{18}O$ V-PDB values of recrystalisation features between -8.9 to -19.6‰ adjacent to intrusives must be mainly linked to increased thermal effects with calculated temperatures of up to 120-200 °C (Arosi and Wilson, 2015; or from $\delta^{18}O$ V-PDB as negative as -18.3‰ in this study temperatures of up to 110-180 °C, cf. Anderson & Arthur, 1983). Both recrystalisation and enhanced chemical compaction below sills is therefore linked to higher temperatures and potentially pressures associated with igneous emplacement. Contact metamorphism is evidenced by recrystallisation of calcitic bioclasts to equant mosaics of calcite crystals whereas elsewhere in the platform deposits it is the originally aragonitic bioclasts that are affected by recrystalisation. The anomalously low negative oxygen and locally also carbon values in limestones proximal to intrusives compared with the rest of the platform are linked to higher temperatures and potential localised hydrocarbon maturation, perhaps associated with hydrothermal fluids (Arosi and Wilson, 2015). Although some of the igneous sills show chilled margins having smaller crystal within a few tens of centimetres of the contact the paucity of diagenetic alteration to the igneous minerals is suggestive of limited fluid flow from the limestones into the intrusives. *Vice versa*, preliminary results from elemental analyses are not indicative of significant volcanogenic-derived elemental exchange from either intrusives or the volcanogenic pile into the carbonates.

3.7.2 Alteration of carbonates unconformably overlain by volcaniclastics

Where shallow water carbonates of the Tonasa are unconformably overlain by volcanogenics of the Camba Formation the limestones are inferred to have been previously lithified since there is no additional impact of the overlying volcaniclastics on the diagenesis of the carbonates different from the rest of the platform. Geochemical $\delta^{18}O$ V-PDB signatures of the limestones close to unconformable contacts are directly comparable with those of the least altered marine components throughout the Tonasa Formation (Arosi and Wilson, 2015; Loche and Wilson, submitted). There is no strong evidence for elemental exchange between the volcanogenics and carbonates or *vice versa*. Only locally associated with karstified uppermost platform surface is there potential for some meteoric influence (cf. Arosi and Wilson, 2015 and here inferred from the $\delta^{13}C$ V-PDB signatures of some karstic infill and proximal wallrock results: Table 1). It is only very locally where elevated temperature and possibly pressures associated with igneous and or volcanogenic emplacement have caused additional recrystallization to the degree where the textures and calcitic bioclasts are starting to be lost. Recrystallised samples close to intrusives at the top of the Ujunglamuru section with $\delta^{18}O$ V-PDB of -7.9‰ are suggestive of an ~20 °C increase in temperature compared with the background limestone component signatures (-4.6 to -5.3‰ V-PDB).

Localised carbonate production resumed contemporaneous with volcanogic emplacement and post-dating the unconformity. The very coarse replacive calcite of ferroan mineralogy in these mixed deposits locally links to elevated temperatures associated with volcanogenic emplacement, but also early neomorphic replacement of aragonite lacking evidence for elevated temperatures with local sourcing of Fe from the volcaniclastics. Values of $\delta^{18}O$ V-PDB as negative as -10.5‰ in coarse blocky neomorphic replacement of corals and molluscs within the volcaniclastics of the Camba section are suggestive of an ~30 °C increase in temperature compared with the background admixed carbonate-volcaniclastic component signatures (-5.0 to -6.0‰ V-PDB). The geochemical signatures of ferroan fine-scale recrystalisation of carbonate components in thick shaley volcaniclastic sections is suggestive of buffering from elevated temperatures, but some fluid interaction with the Fe-rich volcaniclastic matrix (cf. Hendry et al., 1999; Madden & Wilson, 2012).

Minor volcanic material present just in the upper parts of karstic cavity infills associated with the highly rugose upper surface of the Tonasa Limestone in the Camba area have only resulted in very localised and minimal alteration through reddening of the associated limestone. Silicicfication in the Padanglampe section is associated with abundant reworked chert derived from the basement, probably exposed at faulted margins. It may be that elevated temperatures and pressures associated with volcanogenic emplacement enhanced silica dissolution from the reworked cherts and its precipitation and/or replacement in both the limestone and the volcaniclastics. The relatively limited alteration of the igneous and volcanogenic material is suggestive of very limited fluid flow from the carbonates into the volcaniclastics. It is mainly in sections that contain reworked admixed carbonate and/or chert material as well as originally porous sandstones where most alteration has occurred (see also shallow-water conformable sections).

3.7.3 Alteration of deep-water basinal and slope carbonates conformably overlain by volcaniclastics

The deep water basinal and slope carbonates close to the contact with the overlying volcaniclastics as with other comparable deposits from the Tonasa Formation are dominated by burial diagenetic features (cf. Arosi and Wilson, 2015).

Reasons for the strong impact of burial compaction on these particular deposits are: (1) little early cementation with compaction occurring prior to lithification, and (2) may contain grains or lithologies, such as marls, that are prone to compaction (cf. Arosi and Wilson, 2015). Throughout the deeper water deposits of the Tonasa Formation some of the most intense burial compaction related diagenesis is seen close to the contact with the overlying Camba Formation. This is suggestive of increased rates of overlying sedimentation (i.e. associated with volcaniclastic influx) and potentially (2) increased pressures and temperatures associated with emplacement of the volcanogenic lithologies. Stable oxygen isotopes, however, indicate that bioclastic components in deep-water carbonates passing upwards into deep water volcaniclastics are buffered from elevated temperatures having signatures comparable with other similar deposits throughout the Tonasa Formation. Exceptions are when the deep water carbonates are within a few metres of intrusives where $\delta^{18}O$ V-PDB values of -7.3 and -14.0‰ in carbonate components are suggestive of ~20-60 °C increase in temperature compared with the background deep water carbonate deposit component signatures (-3.2 to -4.2‰ V-PDB). The relationship of "swarms" of stylolites and/or dissolution seams in the Tonasa Formation below igneous sills or flows is also consistent with increased burial compaction prior to full lithification associated with volcanogenic emplacement.

In the admixed volcaniclastic-carbonate lithologies around the contact between formations in deep-water systems the degree of alteration and cementation is more intense than from other environmental settings associated with the contact. This alteration is particularly marked in gravelly sands and includes sericitisation or calcitisation of feldspars, devitrification of glass, and alteration rims to volcanogenic grains. Together with the precipitation of zeolites and calcite cements, all of the diagenetic features are relatively low temperature alteration effects that occur in the presence of fluids (Mathisen and McPherson, 1991; Vitali et al., 1995). Being bathed in seawater (to fluids perhaps altered during burial) since deposition and with the potential for locally sourced calcite-rich fluids associated with chemical compaction of the carbonates appears to have maximised alteration associated with deposits at the contact between the two formations. Analcime the sodian zeolite that rims pores is, however, suggestive that calcite is either locally derived associated with feldspar alteration or perhaps related to latter burial diagenesis rather than early circulation of calcian-rich fluids. Alteration effects are commonly greatest in lithologies with precursor intergranular porosity that most likely had the best potential to allow fluid flow, as in the gravelly sandstones. Welded structures and local crushing and/or alteration of grains therein are linked to emplacement of still hot, but probably rapidly quenched, volcaniclastic airfall material followed by their settling and reworking through the marine water column as tuff deposition (i.e., epiclastic to hydroclastic). On subsequent volcanogenic input of the Camba Formation, admixed carbonate material is generally lost up section. These pure volcanogenic deposits show less alteration and in particular less calcite cementation and/or replacement suggestive of limited interchange of diagenetic fluids derived from the Tonasa Formation into the bulk of the overlying volcaniclastics.

3.8 Discussion:

3.8.1 Impact of volcanogenic emplacement on the diagenesis of platform carbonates and reciprocal alteration of volcanogenics

Significant thicknesses (up to 1-2 km) of volcaniclastic deposits of the Camba Formation directly overlying platform deposits of the Tonasa Formation appear to have had relatively limited impact on diagenesis of the carbonate system. Diagenesis is generally limited to: (1) localised "baking" and/or contact metamorphism in shallow water carbonates unconformably overlain or intruded by igneous flows or sills, (2) enhanced recrystallisation, and locally chemical compaction of near contemporaneous or contemporaneous shallow-water carbonate deposition associated with conformable or intra-Neogene minor hiatuses into volcanogenic emplacement, and (3) enhanced burial compaction effects with maximum alteration of deeper-marine section that pass from carbonates into volcaniclastics. Late burial diagenesis in the form of stylolite and/or dissolution seam formation does affect much of the Tonasa Formation and was likely influenced by covering in the thick volcaniclastic pile (Arosi and Wilson, 2015). Aside from this, however, diagenesis of much of the shallow-water system including unconformably overlain carbonates very close to the contact show little to no diagenetic influence associated with the overlying volcaniclastics because the carbonates were already lithified prior to volcanogenic emplacement. Cretaceous chalk of the Giants Causeway Area in

Northern Ireland shows very similar limited contact baking associated with emplacement of lava flows and sills of Tertiary volcanogenics channelled via palaeo sea caves and erosional sea stacks. Generally the chalk only shows alteration and recrystallisation within 1-2 m of the emplaced volcanogenic flows or sills. Scholle (1974) in a study comparing diagenetic alteration of Cretaceous chalks across Europe suggested, however, that those from Northern Ireland have undergone more extreme compaction and are consequently “harder” than seen elsewhere. These enhanced compaction and recrystallisation effects adjacent to igneous dykes were both linked to diagenesis associated with proximity to volcanogenics (Scholle, 1974). The highly negative $\delta^{18}O$ (‰ V-PDB) of carbonates from near the intrusions in the Tonasa Formation are suggestive of “baking” or hydrothermal fluids linked with emplacement, (Arosi and Wilson, 2015; cf. Pichler and Dix, 1996) although there is not evidence for significant elemental exchange. Associated highly negative ‰ $\delta^{13}C$ V-PDB and a petroliferous odour are also suggestive of localised baking and maturation of organic-rich material (cf. Mathisen and McPherson, 1991; Arosi and Wilson, 2015). Lava flows or other volcanogenic units overlying carbonate systems have been noted as playing the part of effective seals or strainers for aggressive waters, such as meteoric ones (i.e., in the latter case waters filtered through the volcanogenic pile lessen the aggressiveness; Salomon, 2003; Robins et al., 2011). Where there is weathering of basaltic overlying lithologies, however, the neogenesis of montmorillonite appears to be particularly favourable in the progression of dissolution of underlying limestones (Salomon, 2003).

Higher temperatures and pressures associated with emplacement of volcanogenic units are inferred to have resulted in recrystallisation and compaction effects of unlithified carbonate soon after their deposition. For shallow water carbonates at Patunuang Asue and those from above the unconformity at Camba aragonitic corals and molluscs had not been stabilised to calcite prior to volcanogenic emplacement. Rather, the very coarse neomorphic replacement is associated with increased temperatures and also linked with enhanced chemical compaction. For the sections that pass into terrestrial to perhaps very shallow marine volcanogenics much of volcaniclastic material is relatively fresh and there is little evidence for fluids derived from the underlying carbonates significantly modifying the volcanogenics. The relatively limited impact of the volcanogenic emplacement to alteration of lithified or unlithified shallow-water carbonate material together with occurrence of potential baffles or barriers to fluid flow in the lower part of the Camba Formation all probably limited influence on carbonate-volcanogenic diagenetic interactions. A number of authors have shown the common occurrence of zeolites as early pore rimming cements in volcaniclastic sediments from non-marine settings (Galloway, 1974; 1979; Davies et al., 1979; Surdam and Boles, 1979; Mathisen and McPherson, 1991; Ibrahim and Hall, 1996). It is perhaps surprising, however, that other early diagenetic alteration features such as common clay rims and coats, dissolution of glass or dissolution of feldspars reported from other terrestrial volcaniclastic units are not more abundant in the terrestrial deposits of the Camba Formation (Galloway, 1974; 1979; Davies et al., 1979; Surdam and Boles, 1979; Mathisen and McPherson, 1991). The relative freshness of the terrestrial Camba material is perhaps even more surprising given the humid equatorial climate that the volcaniclastics are likely to have developed under (Moss and Wilson, 1998; Wilson, 2008; 2011). The fact that volcanics of the Camba Formation are predominantly not glassy, but crystal- or lithic-rich may have contributed to their "freshness". Also, perhaps rapid volcaniclastic sedimentation of 1-2 km of deposits in <5-10 Ma, with initial volcaniclastic deposition apparently quickly smothering most remaining shallow-water carbonate production, together with the presence of local baffles and/or barriers within the volcanogenics, such as soils or lava flows may have contributed to the relatively fresh appearance of much of the volcaniclastic material in the Camba Formation.

The more intense compaction and alteration seen in deep-water sections of the Tonasa Limestone that pass upwards into the Camba Formation is consistent with: (1) a lack of lithification of the slope and deep-water deposits and also (2) the diagenesis reported from other marine volcaniclastic units (cf. Mathisen and McPherson, 1991; Arosi and Wilson, 2015). Clayey alteration rims and zeolites are early diagenetic features with some alteration of feldspars and later calcite cements reported around the Tonasa-Camba contact and from other marine volcaniclastics (Mathisen and McPherson, 1991). However, the general paucity of glassy elements or textures in the Camba Formation and its burial to depths around 2 km are, however, probable influences in the lack of complete recrystallisation and /or associated very common late dissolution as seen in other deep-water volcaniclastic successions buried in excess of a few km (cf. Mathisen and McPherson, 1991; Wilson et al., 2003). Grain-scale alteration of the deep-water deposits with admixed carbonate-volcaniclastic material is the most marked out of all the environmental settings in the Tonasa-Camba systems. Inferred reasons for this are the: (1) the lack of early cementation but common chemical compaction in the upper part of the Tonasa Formation, (2) deposits bathed in fluids since deposition, (3) close juxtaposition of reactive volcanogenic minerals with potential "reactor" marine clays and carbonates, (4) enhanced pressures and temperatures associated with emplacement of volcanogenics together with the pressure of the overlying water column. It is suggested that on subsequent volcanogenic input in which marine deposits of the Camba Formation have generally lost admixed carbonate material this paucity of local carbonate material results in less alteration of the volcaniclastics. Alteration of marine volcaniclastics of the Camba Formation are, however, still comparable with that seen in other marine volcaniclastic deposits and there is no strong evidence for elemental exchange between the volcanogenics and carbonates (cf. Mathisen and McPherson, 1991). Further analysis beyond the scope of this study could address variability in the volcaniclastics, together with their diagenetic variability, such as a including more systematic investigation of the zeolites or geochemical analysis of crystals and cements. Overall, however, it is inferred there is limited interchange of altering fluids from the carbonates into the volcaniclastics, and *vice versa*, near their contact.

3.9 Conclusions

Despite carbonate-volcanic interactions being common in marine areas with plate-margin or intra-plate volcanism the diagenetic interactions of such carbonate-volcanogenic systems are almost unstudied. This research addresses the: (1) alteration of carbonate deposits adjacent to overlying volcanogenic units, (2) the reciprocal alteration of volcanogenic deposits overlying carbonate systems, (3) the extent of any contact-related alteration and (4) whether there are more extensive impacts on platform-wide carbonate diagenesis. An outcrop, petrographic and geochemical study details here for the first time diagenesis of carbonate-volcanogenic units where 1-2 km thickness of volcaniclastics and associated intrusives of the Miocene Camba Formation overlie, or are in contact with, Cenozoic carbonates of the Tonasa Limestone Formation, Sulawesi, Indonesia.

3.9.1 Broad diagenetic impacts of the overlying volcanogenic pile and intrusives on the carbonate platform - Platform, slope and basinal deposits up to 1.2 km thick of the syntectonic Tonasa carbonate Platform were strongly influenced by block faulting and tilting during their development (Wilson et al., 2000). The effects of burial diagenesis by fluids of marine precursor origins predominate across the platform (Arosi and Wilson, 2015). It is likely that common late stage compactional stylolites and dissolution seams were influenced by the thickness of the overlying volcanogenic pile. Aside from this widespread "volcanogenic overburden affect" dynamic diagenetic interactions between the carbonates and volcanogenics are highly localised and mostly limited to the few metres to tens of metres either side of conformable formation boundaries or contacts with intrusive sills. In regions of larger igneous stocks (1-2 km diametre) carbonates within 1-2 km of the intrusive contact may have a crystalline appearance and show anomalously low negative oxygen and also carbon values compared with the rest of the platform (Arosi and Wilson, 2015). The low negative values are linked to higher temperatures and potential hydrocarbon maturation, perhaps associated with hydrothermal fluids.

3.9.2 Local diagenetic interactions at the carbonate-volcaniclastic contacts - Where the Tonasa Limestone Formation is unconformably overlain by the Camba Formation there are no discernible effects of the volcaniclastics on the diagenesis of the limestone, with the exception of where there are associated intrusives. It is inferred the overlying volcanogenic strata had little impact on the already lithified bulk of the shallow-water platform deposits prior to their deposition over the block faulted topography of the top of the platform. Shallow-water carbonates that pass conformably into, or interdigitate with, the volcanogenics show more pervasive neomorphic replacement by very coarse bladed to mosaic calcite cements and also localised more intense compaction than is seen elsewhere in the Tonasa Formation. The inference here is that the higher temperatures associated with emplacement of the volcanogenic pile together with increased pressures drove increased chemical compaction and fluid flow driving stabilisation to coarse calcite cements. There is no evidence for significant exchange of fluids from the volcanogenics altering the carbonates, and *vice versa*, rather it appears fluids involved in the alteration of unlithified shallow-water carbonates were locally and internally sourced. Deep water slope and basinal deposits of the Tonasa Formation close to the contact with the overlying Camba Formation are also strongly affected by compaction with chemical compaction of predominantly unlithified units linked to increased pressures and temperatures associated with emplacement of the overlying volcaniclastics.

3.9.3 Diagenesis of the volcaniclastics and the influence of environments and proximity to carbonates - Perhaps surprisingly given the humid equatorial setting of deposition the volcaniclastics of the Camba Formation commonly have a relatively fresh appearance. Possible reasons for this common paucity of alteration may include: (1) common lithic and crystal components to the volcaniclastics with a lack reactive glassy material, (2) common interbedded clayey and lava flow units that may act as baffles or barriers to fluid flow, and (3) potential rapid covering by further volcaniclastics. Alteration of the volcaniclastics includes sericitisation and some calcitisation of the feldspar, some oxidation and Fe-alteration of mafic minerals, common zeolite replacement and growth into pores and minor late calcite cementation. In keeping with other studies alteration of the volcaniclastics is most intense where there are admixed carbonate-volcaniclastics and/or in deeper marine deposits. Again localised fluid flow for alteration in the volcaniclastics is inferred with little noticeable fluid mixing between the carbonates and volcaniclastics. It is hoped this study will contribute to poorly understood diagenetic variations in carbonate-volcaniclastic systems, and particularly those from the equatorial tropics.

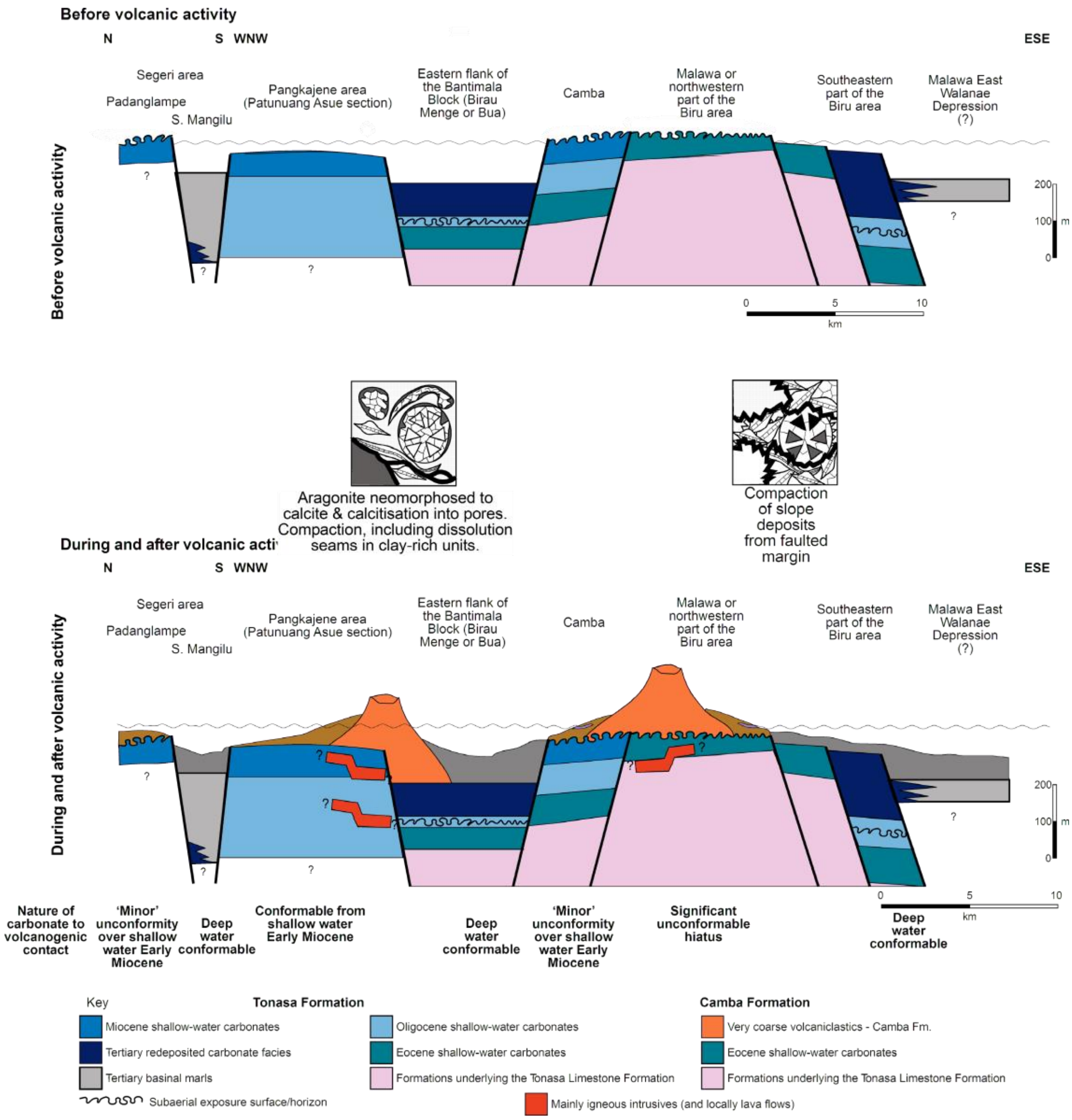

Figure 3.10 Summary figure showing schematic east-west cross-sections through the Tonasa Carbonate system just before (uppermost) and after (lowermost) volcanogenic emplacement. Central part of the panel shows diagenetic features of the carbonate and volcanogenic deposits from around the contact between the different formations. For the carbonate schematics just features differing from that of the main platform carbonates are mainly illustrated.

3.10 Acknowledgements

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Chapter Four

VARIABILITY IN DIAGENESIS OF CARBONATE PLATFORM SLOPE AND BASINAL DEPOSITS

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Abstract

The sedimentology of carbonate slope deposits are widely described yet the spatio-temporal variability in the alteration and diagenesis of such deposits adjacent to different types of platform is little known. This petrographic study of slope to basinal deposits from around the equatorial syntectonic Tonasa platform in Central Indonesia allows for the evaluation of differing platform margin settings, oceanographic factors and the history of basin evolution on the burial and diagenetic history of these important but little studied carbonates. Clasts of reworked Tonasa limestone represent shallow-water platform wackestone, packstone and grain/rudstone deposits that are dominated by larger benthic foraminifera. Four broadly comparable sets of diagenetic features have been identified from the carbonate slope deposits that represent alteration following reworking and brecciation of platform margin lithologies. Mechanical compaction, cementation, silicification and glauconitisation and phosphatisation are the main diagenetic features in these reworked deposits with mechanical compaction, including mechanical breakage, plastic deformation and stylolites being the dominant feature. Interclast carbonate cements are variable with common granular and blocky cements but also earlier pore lining cements with bladed habits. Dolomite additionally occurs in rare instances probably related to burial diagenesis. Silicification is a common feature that post-dates compaction effects. The recrystallisation of sponge spicules and microfossils as well as

derivation from older exposures of silica-rich strata are interpreted as the source of porosity filling microcrystalline quartz and chalcedonic overlay fabrics. Glauconite pellets, bioclast replacing glauconite and interclastic phosphate are common but low abundance features of all originally shallow water units. The broadly comparable diagenetic features of the reworked Tonasa deposits can be attributed to variable tectonic activity during the late Eocene to early Miocene; whereby the generation of accommodation space and graben infill drove greater degrees of burial and compactional diagenetic effects. Long term fault activity was a significant factor in the high rate of sediment supply (reworked carbonates), the availability of exposed silica rich lithologies and fracture networks for cementing fluid-pathways. The results of this study, along with regional analogues, suggest the potential for diagenetic variability within slope deposits associated with differing: platform margin settings, oceanographic conditions, accommodation space, sedimentation rates, and the nature of any reworked material.

4.1 Introduction

The depositional features of carbonate slope deposits are relatively well documented with significant literature on controlling influences (e.g., Coniglio and Dix, 1992; Wilson and Bosence, 1996; Reijmer et al., 2015). Although the diagenesis of carbonate slope to basinal deposits are broadly reported, the spatio-temporal variability in alteration around different types of platform margins remains poorly known. Evaluated here are the potential impacts of differing platform margin settings, oceanographic factors, together with the history of basin evolution, its subsequent infill and burial on the diagenesis of slope to basinal deposits from around an equatorial syntectonic platform in Central Indonesia (Wilson and Bosence, 1996; 1997; Wilson, 1999; 2000; Wilson et al., 2000).

Slope to basinal carbonate deposits show common burial compaction effects, varying from mechanical grain-scale breakage as well as closer grain packing, to chemical compaction features, such as stylolites and dissolution seams. Where there is downslope reworking of bioclastic and/or lithic debris, circum-clast stylolites and fitted fabrics may develop (Wilson and Bosence, 1996; Madden et al., 2017). Fracturing may occur, such as through platform margin instability, differential compaction, or hydrofracturing, some of which for syntectonic platforms may be linked to tectonism (Arosi and Wilson, 2015). Burial cementation, such as by equant cements, that is often near concomitant with chemical pressure dissolution may form in primary and /or secondary porosity, including in fractures (Arosi and Wilson, 2015). Cementation between downslope reworked clasts or bioclasts, as well as in background deeper-water sediments is therefore commonly from fluids of marine derivation with a rock or sediment derived signature. Cement types and their origins, developed in the slope and basinal deposits may differ quite significantly from those within any reworked clasts, the latter recording the earlier evolution of platform and commonly the diagenetic history of the platform top (cf. Madden et al., 2017). Late burial leaching or corrosion is a feature of some platform flank and slope deposits with corrosive fluids thought to be basinal derived, perhaps associated with the early stages of hydrocarbon generation during burial (Saller and Vijaya, 2002; Esteban and Taberner, 2003 Wilson, 2012; Tanos et al., 2013; Subekti et al., 2015). Overall, these are the commonly reported diagenetic features of slope and basinal deposits that together with specific depositional fabrics and components appear to be distinctive of slope sediment gravity flows deposits as compared with breccias of differing origins (e.g., karstic, intraformational or fault breccias; cf., Madden et al., 2017).

In a broad platform-wide study of diagenesis of the Cenozoic syntectonic Tonasa carbonate platform encompassing shallow-platform and adjacent slope to basinal deposits. Arosi and Wilson (2015) noted some initial differences in the degree of development of diagenetic features and their spatio-temporal variability from the slope to basinal deposits. In particular, 'the prevalence of compactional features in the deeper Paleogene parts of thicker sections and associated with deposits formed during fault-related deepening were together suggestive of the important roles of differential subsidence and overburden covering by subsequent carbonate sedimentation in generating early compactional features' (Arosi and Wilson, 2015). This work further details the poorly documented topic of spatio-temporal variability in diagenesis and degree of alteration of slope to basinal deposits from around an individual carbonate platform. The Tonasa Limestone Formation from Sulawesi of the earlier work (Arosi and Wilson, 2015) was considered ideal for this study since well-exposed slope to basinal deposits showing initial diagenetic variability formed adjacent to well-documented but varied platform margin types. The range of platform margin types documented for the Tonasa Platform include active faulted escarpment margins and less active probably bypass margin and ramp-type margins (Wilson and Bosence, 1996; 1997; Wilson, 1999; 2000; Wilson et al., 2000). The specific aims of this study are therefore to: (1) evaluate the spatio-temporal variability in diagenetic features and degree of diagenetic alteration of slope and basinal deposits adjacent to a range of platform margin types from an individual carbonate system. (2) To assess the potential controlling influences on these diagenetic differences of slope to basinal deposits. Such influences on diagenetic variability may include: (a) lithological variability in the slope to basinal deposits, (b) degree, and nature of subsidence generation, slope angles and subsequent infill of basinal areas and (c) local oceanographic/climatic setting of platform margins.

4.2 Geological setting

The Eocene to Early Miocene Tonasa Carbonate Platform of Sulawesi is located in the centre of the Indonesian Archipelago. These carbonates developed in one of the most complex, active tectonic regions of the world as part of a transgressive succession on the eastern flank of a broad 'backarc' basin centred on the Makassar Straits (Fig. 1, 2; Hamilton, 1979; Hall, 1996, 2002a; Hall and Wilson, 2000; Hall et al., 2011). Extensive tectonism and associated volcanism throughout the Mesozoic and Cenozoic in SE Asia is linked to the convergence of three main tectonic plates (Pacific-Philippine, Indo-Australian and Eurasian plates) interacting with smaller intervening micro-continental and oceanic fragments (Fig. 1; Hall, 1996, 2002a; Hall and Wilson, 2000; Hall et al., 2011).

The evolution of south western Sulawesi during the late Mesozoic and Cenozoic is linked to the accretion of micro-continental and oceanic fragments onto the eastern margin of the comparatively stable Eurasian plate, together with backarc rifting and volcanic arc development (Sukamto, 1975; Hamilton, 1979; van Leeuwen, 1981;Wilson and Bosence, 1997; Wilson, 1999, 2000). Relatively complete, but very different Late Cretaceous to recent stratigraphic sequences in the western and eastern halves of the South Arm reflect this complex geological evolution (Fig. 2; van Leeuwen, 1981; Wilson, 1999). The Balangbaru and Marada Formations are deep-marine forearc clastics and shales of Late Cretaceous age that overlie intersliced metamorphic, ultrabasic and sedimentary basement lithologies in the western South Arm (Fig. 2; van Leeuwen, 1981; Hasan, 1991). By the Eocene, subduction had shifted to the east and marginal marine siliciclastics of the Malawa Formation in western South Sulawesi are associated with rifting of a broad basinal area centred on the Makassar Straits. The clastics pass transgressively upwards into carbonates of the Eocene to Miocene Tonasa Formation of this study that have predominantly shallow-water origins. Faulting linked to both regional and local structuration segmented this broad shallow-water carbonate producing area of the Tonasa Formation in south Sulawesi into block and basin topography from the latter part of the Late Eocene onwards (Wilson and Bosence, 1996; Wilson, 1999, 2000; Wilson et al., 2000) This segmentation of the broad carbonate system through faulting led to considerable variability in: intra-, and extra-platform basins, their adjacent platform margin types, depositional settings, and to a certain extent variability in diagenetic processes affecting the carbonate systems of Sulawesi (Wilson, 1999; Wilson et al., 2000; Arosi and Wilson, 2015).

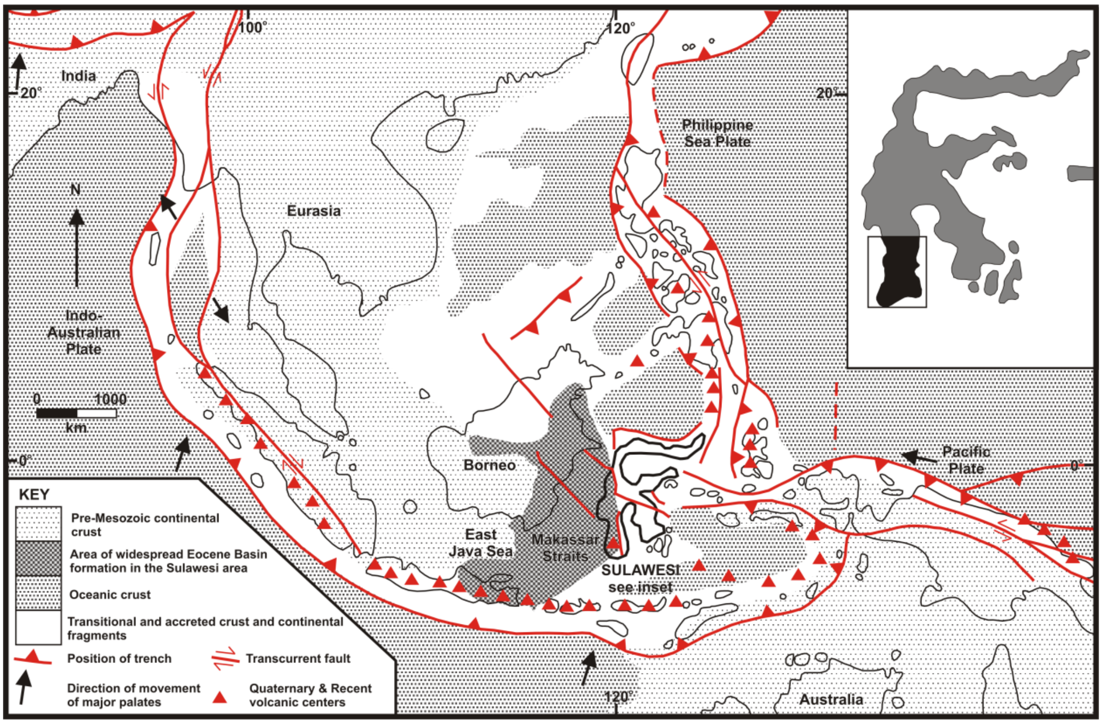


Figure 4.1. Regional tectonic setting of Sulawesi and the location of the Tertiary basinal area in Sulawesi/Borneo (from Wilson et al., 2000, modified after Daly et al., 1991; Hall, 1996; van de Weerd and Armin, 1992; Wilson, 1999). Inset shows the position of the research area within Sulawesi.

During the Tertiary, accumulation of sedimentary rocks predominated in western South Sulawesi, whereas volcanic and igneous lithologies dominated to the east. This east-west lithological subdivision occurs across a major structural divide, today demarked by the fault-bounded, NNW-SSE trending Walanae Depression (Fig. 2). The various igneous rocks of eastern South Sulawesi include arc-related, passive margin volcanics associated with the cessation of subduction, potassic volcanics linked to extension, as well as MORB like volcanics from an accreted transtensional marginal oceanic basin (Sukamto, 1982; Yuwono et al., 1987; van Leeuwen et al., 2010). Middle to late Miocene volcanogenics of the Camba Formation overlie the Tonasa Formation (Sukamto, 1982; Yuwono et al., 1987; Wilson, 2000). The Miocene shift in volcanism to western South Sulawesi and associated potassic igneous intrusions are linked to micro-continental collision related volcanism and post-collisional magmas (Fig. 2; Elburg and Foden, 1999; Elburg et al., 2003).

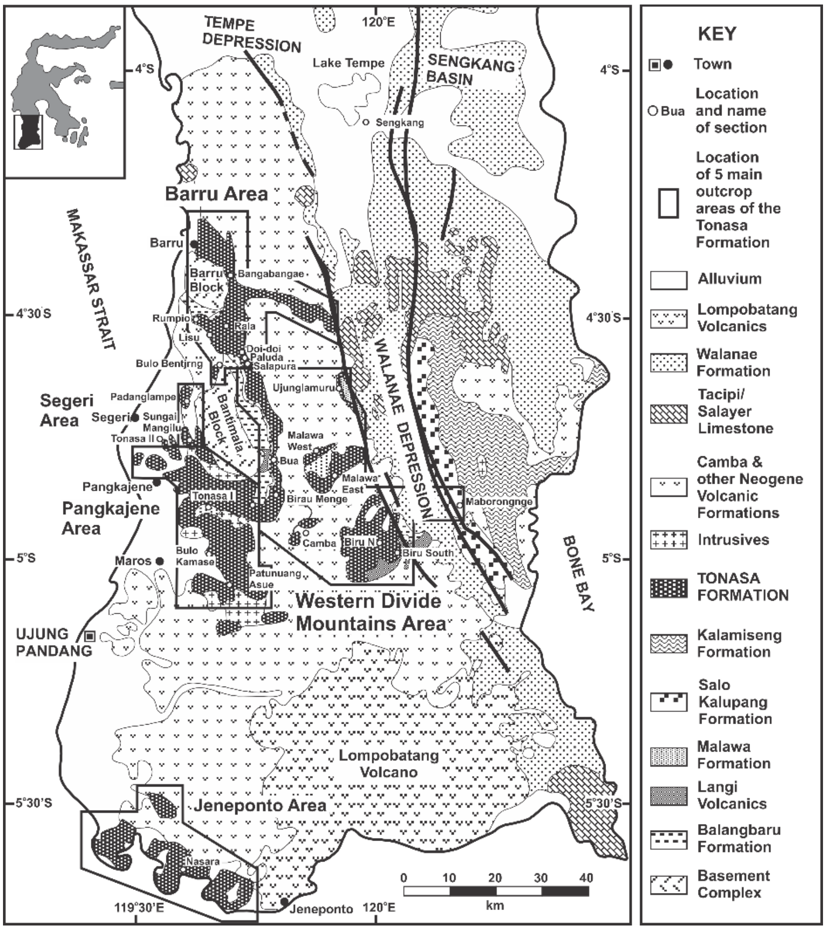


Figure 4.2. Geological map of South Sulawesi (from Wilson et al., 2000; after van Leeuwen, 1981; Sukamto, 1982; Sukamto and Supriatna, 1982; Wilson, 2000), showing the locations of the five main outcrop areas of the Tonasa Formation and the location of mentioned measured sections.

4.3 Deposition and development of the Tonasa Formation and its adjacent slope to basinal deposits

The Early or Middle Eocene to Middle Miocene Tonasa Formation of this study comprises the main part of the Tertiary succession in the western part of South Sulawesi (Fig. 2). The formation consists of shallow carbonate platform, associated slope and adjacent bathyal deposits that locally crop out over a 160 by 80 km north-south and east-west extent, respectively (Figs. 2; Wilson and Bosence, 1996, 1997). Previous studies on the sedimentology, evolution and platform-wide diagenetic variability of the Tonasa Carbonate Platform, together with evaluations of controlling influences set the context for this diagenetic study of the slope to basinal deposits, and are briefly outlined above and below (Wilson, 1996; 1999, 2000; Wilson and Bosence, 1996, 1997; Wilson et al., 2000; Wilson and Vecsei, 2005; Arosi and Wilson, 2015). Shallow-water deposits of the Tonasa Carbonate Platform are mainly wackestones, packstones and grain/rudstones that are dominated by larger benthic foraminifera. Other components include small benthic foraminifera, echinoid remains, coralline algae and more rarely corals (Wilson and Bosence, 1997; Wilson and Rosen, 1998; Wilson et al., 2000). Planktonic foraminifera are abundant in basinal marls. The marls interdigitate with slope and platform-fringing breccias and pack/grain/rudstones. The slope deposits contain abundant shallow water bioclasts that were reworked downslope as well as a range of lithic clasts derived from the Tonasa and underlying formations (Wilson and Bosence, 1996; Wilson, 1999; Wilson et al., 2000). Carbonate sedimentation of the Tonasa Formation began diachronously, with shallow-water deposits forming earliest in the northern Barru and southern Jeneponto Areas during the Early to Middle Eocene (Fig. 2; Wilson et al., 2000). By the Late Eocene shallow carbonate sedimentation had spread across much of western South Sulawesi. However, during the latter part of the Late Eocene fault segmentation resulted in rapid localised deepening and drowning of the platform in the northern Barru, eastern Segeri and westerly Western Divide Mountains Areas (Fig. 2; Wilson, 1999; Wilson et al., 2000). Some of the faults including those bounding the northern and eastern extent of main shallow platform are linked to major structural divides. These occur along strike from the NW-SE trending Adang Fault and as bounding faults to the NNW-SSE trending fault-bounded graben of the Walanae Depression, with potential involvement and reactivation of earlier basement structures (Fig. 2; van Leeuwen, 1981; Wilson and Bosence, 1996; Wilson et al., 2000). A large-scale (100 km north to south) tilted-fault-block platform with a segmented faulted northern margin (northern Barru Area) and gently dipping southern margin (southern Jeneponto Area) accumulated over 600 m of shallow water platform carbonates centred on the central Pangkajene Area (Wilson et al., 2000). Although onshore volcanogenics cover parts of the more southerly deposits of this platform, in the area directly offshore to the west seismic data reveal the predominantly unbroken north to south nature of the coeval continuation of the platform (Letouzey et al., 1990). Up to 1100 m of shallow and mainly deep-water carbonates accumulated to the north (Barru) and south (Jeneponto) of the main platform. Areas of more complex faulting to the east and west of the main platform resulted in localised fault-block platforms and intervening small-scale basinal grabens (western Segeri and eastern Western Divide Mountains Areas on Fig. 2; Wilson et al., 2000; Wilson, 2000). Major shallow-water facies belts on the main tilt-block platform trend E-W, were aggradational and remained static through time. Low to moderate energy wackestones and packstones dominated in the north and south of the main shallow-water tilt-block platform, whereas higher energy grainstones prevailed in the central facies belt (Wilson and Bosence, 1997; Wilson et al., 2000). Water depths and energy, linked to differential subsidence/uplift together with the presence/absence of shallow shoaling protective ‘barriers’ along the westerly windward platform margin, are inferred to be important influences on the facies and biota present (Wilson and Bosence, 1997; Wilson et al., 2000). Localised subaerial exposure is inferred for the shallowest part of the main tilt-block platform on the northerly footwall high and also for some of the eastwest developed block-faulted platforms (Wilson and Bosence, 1996, 1997; Wilson, 2000; Wilson et al., 2000). Mass reworking of material was common from the faulted highs into adjacent basinal graben and is often linked to phases of tectonic activity (Wilson and Bosence, 1996; Wilson, 1999; Wilson, 2000; Wilson et al., 2000). On the gently dipping southern hanging wall slope of the main tilt-block platform, there was southward progradation of ramp deposits into bathyal areas during periods of tectonic quiescence and minimal subsidence (Wilson and Bosence, 1997; Wilson et al., 2000). Final demise of the platform at the end of the Early Miocene was linked to a laterally variable combination of fault-related drowning, uplift and subaerial exposure together with smothering by volcaniclastics (Wilson, 2000).

4.4 Local development of the Tonasa Platform focused on the adjacent slope to basinal deposits

Throughout the late Eocene to early Miocene, shallow water deposits were dominant in western South Sulawesi. During the Late Eocene, larger benthic foraminifera grainstones, packstones and wackestones were deposited in the Pangkajene and Western Divide areas, while in the eastern area, foraminiferal packstones to grainstone were deposited, nevertheless there is no significant evidence that indicates whether shallow-water deposits extended continuously into eastern South Sulawesi during the earliest Paleogene or whether isolated shoals built up around the easterly volcanic arc (Wilson and Bosence, 1996). Thick shallow water carbonates (~400 m) formed in the Rala area in the north of the Tonasa platform, that deepen into ~700 m of Late Eocene to Early Miocene deeper water slope to basinal deposits. These strata totalling ~1100 m of sediments accumulated in a hanging wall graben and demonstrate a deepening upwards trend (Figs. 2, 3, and 4a). In contrast, Eocene thinner, shallowing upwards sediments were laterally and simultaneously deposited in Doi-Doi and Bangabangae areas closer to footwall highs prior to their subsequent drowning as hanging wall areas relative to adjacent neighbouring ‘conjugate’ fault systems (Wilson and Bosence, 1996; Wilson, 1999). Later, open marine outer shelf and slope sediments such as planktonic foraminiferal bioclastic packstones and grainstones overlaid the shallow water deposits in the Barru area. Late pre-rift/early syn-rift quartzose sequences formed on footwall highs with variable thickness. In the latest late-Eocene, thick sequences of basinal marl covered the bioclastic units of the Barru area. Because of the active normal faults that bordered the Tonasa Platform, breccias to coarse grain/packstones including reworked lithics of carbonates, siliciclastic, volcaniclastics and metamorphics from the underlying formations of South Sulawesi and adjacent shallow platform deposits are interbedded with the basinal marl sequences (Wilson & Bosence, 1996). The northern margin of the Tonasa Carbonate Platform was a segmented escarpment margin (Fig. 4), where the faults were active from the latest late-Eocene through to the middle Miocene (Wilson, 1999; Wilson et al., 2000). The same scenario in the Barru area had repeated in Segeri area, where the accumulation of shallow marine sequences of packstones and grainstones contain abundant large benthic foraminifera overlaid by facies consisting of marls and reworked carbonates (Fig. 2; Wilson et al., 2000).

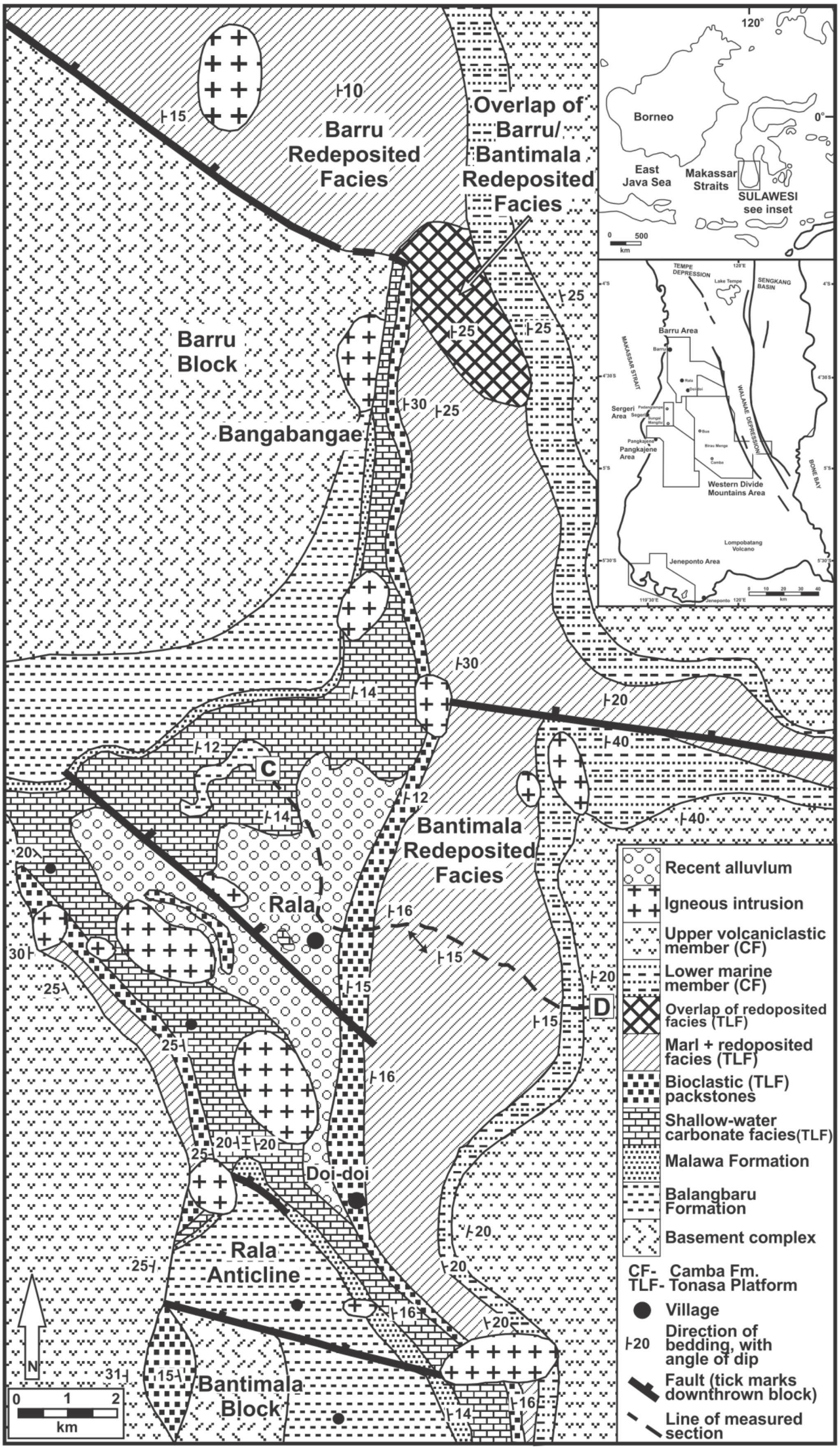


Figure 4.3. Geological map of the Barru area (modified after Wilson and Bosnce, 1996). Palaeocurrent data from the redeposited facies are shown as arrows and rose diagrams.

Towards the east, shallow marine carbonates crop out in the Western Divide area. During or after the late Eocene and before the middle Miocene these sequences were locally tilted and exposed to subaerial processes. Towards the east, shallow water Oligocene deposits outcrop in the Biru Area and alongside the eastern Bantimala Block edge (Figs. 2, 3 and 4; van Leeuwen, 1981; Wilson, 2000; Wilson et al., 2000). These Western Divide Area successions have been locally exposed to subaerial processes and/or eroded on block faulted highs or are affected by deepening in fault bounded grabens. By the late Oligocene to Early Miocene, open marine influenced marls, packstones and grainstones interdigitate with slope breccia deposits bordering the eastern margin of the Bantimala Block and also the western margin of the Walanae Depression (van Leeuwen, 1981; Wilson, 2000; Wilson et al., 2000). On the southern margin of the Tonasa Platform, outer ramp packstones to basinal planktonic foraminifera wackestones and marls dominate (Wilson and Bosence, 1997).

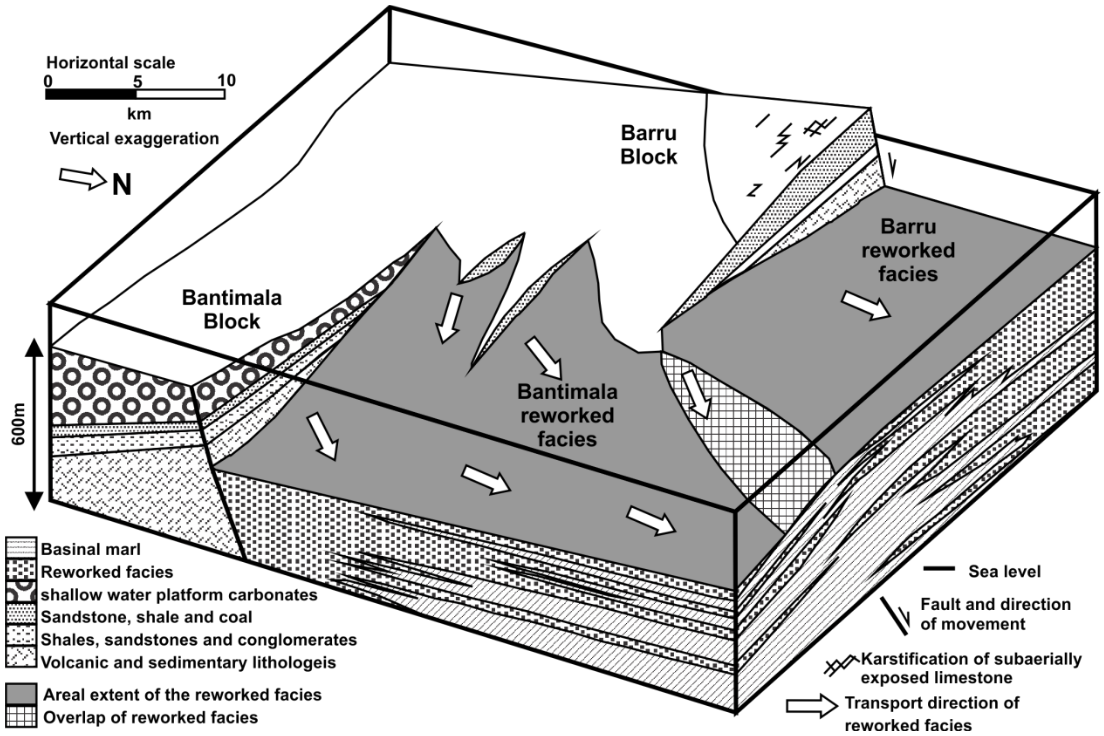


Figure 4.4. Block diagram showing the preferred reconstruction if the northern margin of the Tonasa Platform in the Barru area during the late Eocene (modified after Wilson and Bosence, 1996). Two tectonically active, major NW-SE trending normal faults are separated by an east-dipping relay ramp. The area is thought to have been tilted gently towards the east.

4.5 Diagenetic study of the Tonasa Platform slope and adjacent basin deposits

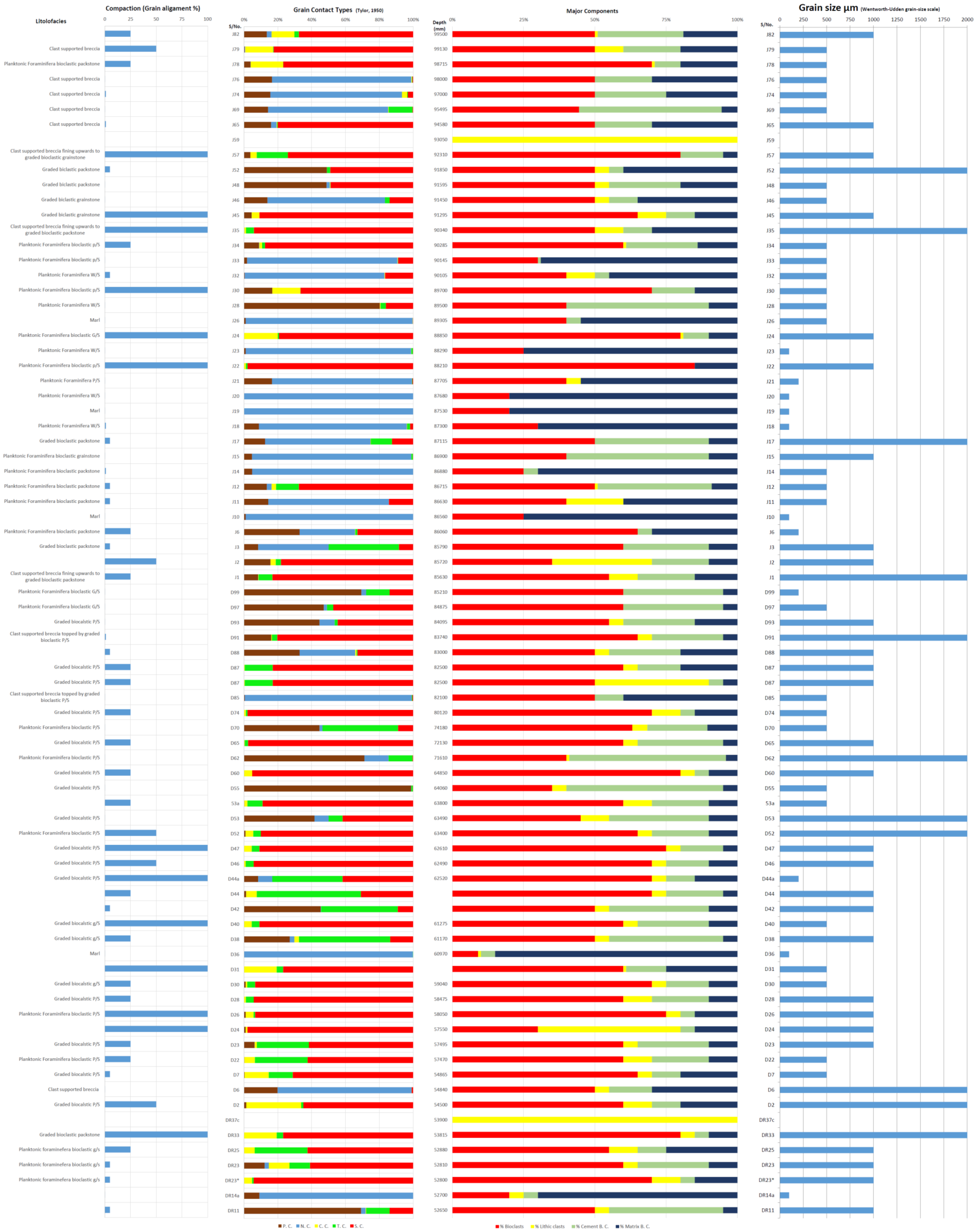
Slope and basinal deposits of the Tonasa Platform are found in four different areas (Figs. 2, 3 and 4). These are associated with the northerly faulted escarpment margin to the main N-S oriented tilt-block platform (Barru Area), the faulted escarpment to bypass margins of westerly and easterly block faulted grabens (Segeri and Western Divide Mountains), and on the southern ramp-type margin of the main N-S trending tilt-block platform (Jeneponto Area). Due to time, constraints at the end of the thesis just samples from the first three settings were studied but the intention is to include samples from the southern area for a broader manuscript to be submitted to a journal. Greater than 600 m thickness of reworked sediments interbedded with basinal marls crop out in the Rala section of the Barru area. The two sections located in the Western Divide area in the east and Segeri in the west include upwards of 200 m of slope to basinal deposits (Wilson, 1995; Wilson and Bosence, 1996). Petrographic study of 119 selected thin-sections was conducted to determine the abundance of components, clast types and determine depositional textures and evidence of clast reworking. Sample description follows the textural classification criteria of Dunham (1962) as well as Flügel (2004) to characterise cement morphologies and diagenetic features. Compaction and grain-contact features have been described following the classification scheme of Taylor (1950). Grain size descriptions and rock nomenclature has been identified using the Wentworth-Udden grain-size scale.

4.6 Results and interpretation

Four broadly comparable sets of diagenetic features have been identified from across the Rala section, Western Divide and Segeri deposits: (1) mechanical compaction, (2) cementation, (3) silicification and (4) glauconitisation and phosphatisation. These features are presented below in order of their relative decreasing abundance (Fig. 5 and Appendix E)**.**

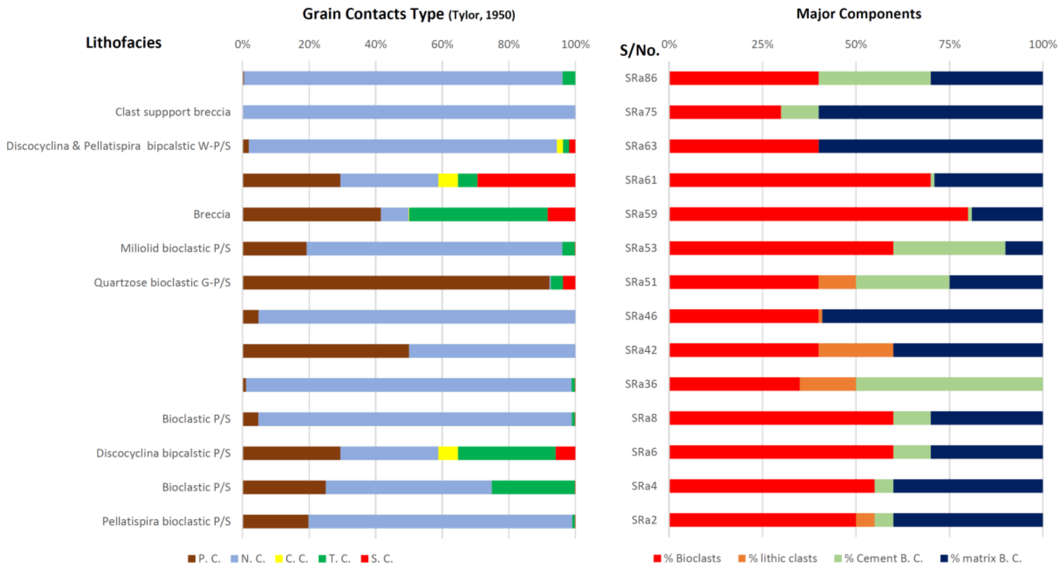
4.6.1 Mechanical Compaction and its relative features

Mechanical compaction is seen in 99 of 119 thin-sections with variable pervasiveness from rare to dominant diagenetic feature (Figs. 5a, b and c). In deposits from the Rala section, where thick successions of reworked deposits have accumulated, mechanical compaction is mostly dominant in packstone and wackestone facies (Fig. 6a). Compaction features are rarely present in grainstones facies (Fig. 6b) and negligible in mudstone and marl facies (Fig. 6c). The prevalence of compaction features are relatively variable based on lithological components (composition) of individual samples. Samples that have high percentage of early submarine cements (below) are recognised by a paucity of compaction feature (Meyers, 1978; Arosi and Wilson, 2015; Fig. 6b). In the Western Divide and Segeri areas, compaction is present in packstone and grainstone units but with low abundance (<25%) (Fig. 6d). The relative timing of compaction is variable with respect to cementation (below). Individual allochems show common deformation features including: grain reorientation, breakage and plastic deformation (Fig. 6e). Such features are abundant in shallow water packstone/wackestone units. Bioclastic grains have undergone variable degrees of fragmentation and deformation (Figs. 6a and e). Mechanical compaction occurred under burial conditions, where high pressure was produced by overburden (Goldhammer, 1997). Grain contact types are highly variable, both throughout the Rala section and between areas. Sutured contacts are the dominant contact type between grains in shallow water units (Figs. 5a and 6f) and are abundant in packstone/wackestones facies. Grain suturing is also seen in grainstones, planktonic foraminifera bioclastic units and clast-supported breccia units.



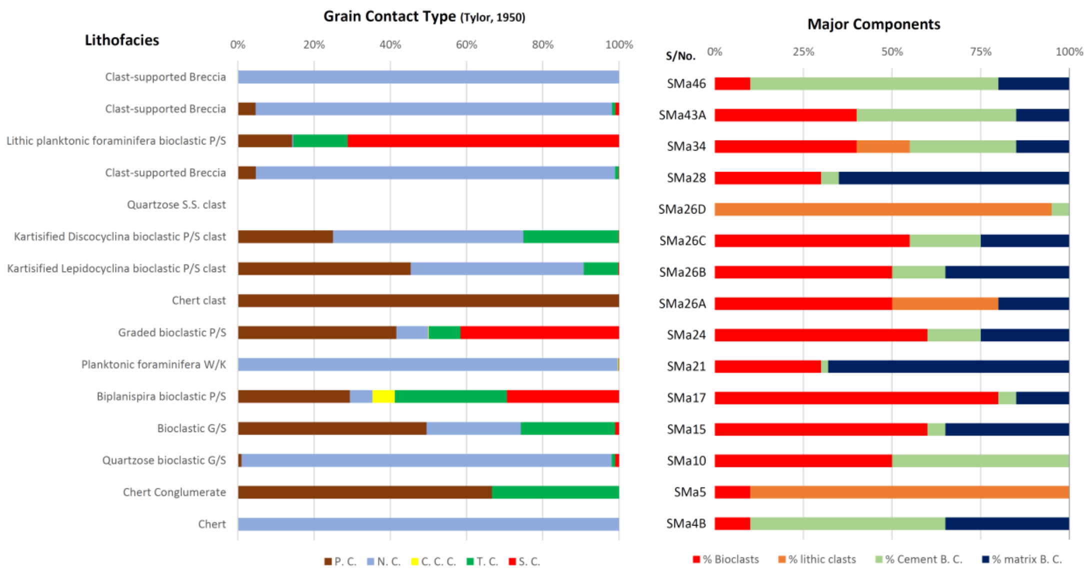
(a)

Figure 4.5.a Statistic diagram of diagenetic feature ratios shows the petrographic observation of 83 thin sections from Rala Section (P.C. = Point contact, N.C. = No-contact, C.C. = Concavo-convex contacts, T.C. = Tangential contact and S.C. = Sutured contact).



(b)

Figure 4.5.b Statistic diagram of diagenetic feature ratios shows the petrographic observation of 14 thin sections from Western Divide area. (P.C. = Point contact, N.C. = No-contact, C.C. = Concavo-convex contacts, T.C. = Tangential contact and S.C. = Sutured contact).



(c)

Figure 4.5.c. Statistic diagram of diagenetic feature ratios shows the petrographic observation of 17 thin sections from Segeri area. (P.C. = Point contact, N.C. = No-contact, C.C. = Concavo-convex contacts, T.C. = Tangential contact and S.C. = Sutured contact).

Sutured contacts are predominant in samples that have a low abundance (<30%) of early calcite cement and/or matrix between clasts. This feature is attributed to burial compaction (Goldhamer, 1997; Flügel, 2004; Arosi and Wilson, 2015) and/or may result from an increase in differential pressure solution (Taylor, 1950). Tangential and concavo-convex contacts are uncommon features but present in all areas and with variable percentages between 5% - 40% in the Rala section, 5% - 30% in the Western Divide and 1% - 25% in the Segeri areas (Figs. 5a, b, c and 7a). No-contact type is uncommon in the Rala section with higher abundance in the upper part (Figs. 5a and 6b), whilst it is predominant in the Western Divide and Segeri areas (Figs. 5b, c and 7b). No-contact grain type mainly appears in shallow water grainstone units or deeper in marl units. This may be a result of the early cementation and lithification pre-dating compaction stage (Meyers, 1978; Adams et al., 2000; Arosi and Wilson, 2015; Madden et al., 2017). Point contact type is present throughout the Rala section but with variable percentage (Figs. 5a and 7c). This type is more common in Eastern and Western areas (Figs. 5b and c). Additional to overburden pressure, grain contact types may be influenced by grain shape, original packing and lithology of sediments texture (Taylor, 1950; Meyers, 1978; Adams et al., 2000).

Fragmentation of breccia clasts is generally common throughout all areas. Fragmentation is evident from bioclastic breccias consisting of variably reworked benthic foraminifera, coralline algae and a wide range of lithoclastic grains such as quartz and igneous phenocrysts (Fig. 7d ; Wilson and Bosence, 1996). Fragments of pre-existing calcite cements are also found in all areas (Fig. 7e). Cements are usually composed of granular or blocky calcite cement. Carbonate breccias are angular to sub-angular with clasts ranging in size from very fine sand to fine pebbles. Some bioclast fragments have a preserved micritic envelope (Fig. 7f). Two types of silica-rich lithoclast are recognised: (1) rocks derived from reworking of basement rocks (e.g. cherts or quartzo-feldspathic schists; Fig. 8d) and (2) the terrigenous sediment influx, which deposited the quartzose sandstone units (Fig. 9a). In the Rala section, quartz is also present as reworked lithoclastic grains (Fig. 10d) or as an individual crystal in shallow water facies (Fig. 10e). The wide extent of fragment type, variety of grain size and angularity of clasts are features reasonably attributed reworking from fault platform margins (Blount and Moore, 1969; Wilson and Bosence, 1996).

Stylolites are abundant in wacke/packstones units (Figs. 8a and b). Wispy and anastomosing dissolution seams are more prevalent in fine grained (micritic) facies (Fig. 8a). Stylolites in some thin sections are also associated with silicification (Fig. 8c; and below). Stylolites are also seen in grainstone samples with percentage > 10% of igneous phenocrysts (Fig. 8d). Dissolution seams are relatively common from deposits in all areas. Arosi and Wilson (2015) attribute these chemical compaction features to burial compaction.

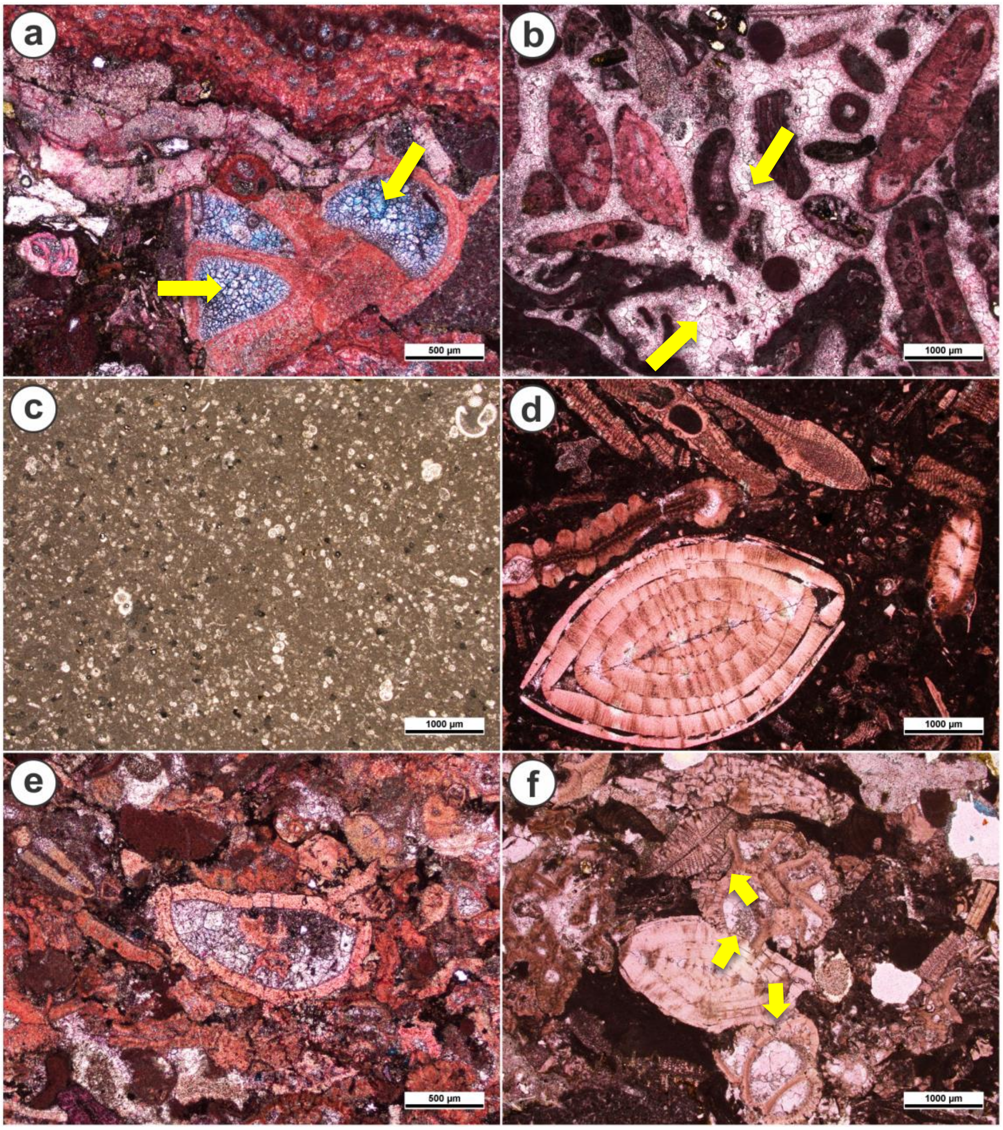


Figure 4.6. Thin-section plane polarised light photomicrographs showing (a) bioclast breakage and grain distortion as a result of mechanical compaction. Ferroan granular calcite cement (blue) filled the chambers of benthic foraminifera (arrows). (J45s). (b) Paucity of compaction feature in facies that have a high percentage of early submarine cements. Early granular (20-30 µm) and pore-lining cements precipitated intra- and inter-clast in grainstone facies (arrows). (J69). (c) Minor or negligible compaction feature in mudstone and marl facies (J23). (d) Compaction feature in packstone/grainestone facies (SRa61). (e) Deformation features including: grain reorientation, breakage and plastic deformation. The sample also shows brecciation and fragmentation of bioclasts (J22). (f) Sutured contacts type between grains in shallow water units (arrows) (DR23).

Mechanical fractures are rarely observed. The average width of these fractures is 100 µm cross-cutting all fabrics and components of the sample (Figs. 8e and 8f). These late-fractures are filled by ferroan to non-ferroan granular calcite cement (Fig. 8e). In one sample from the Western area, fractures in a quartzose sandstone unit are filled with twinned blocky calcite cement (Fig. 8f). Although fractures are rarely seen in these sections, they are plausibly evidence for tectonic activity (Arosi and Wilson 2015). Fracturing is most commonly observed to post-date compaction and silicification (Fig. 9a), however; it is not possible to deduce the specific timing of these features based on the varied cross-cutting characteristics observed (Arosi and Wilson, 2015). Rather, fracturing likely occurred as syn- and post-burial diagenetic features.

4.6.2 Cementation

Additional to compaction, the dominant diagenetic feature that is seen in thin-sections of reworked deposits is calcite cement. Ferroan to non-ferroan granular mosaic calcite is present within lithoclastic deposits in 75% of thin-sections and mostly in the northern (37%) in the middle part of Rala section with average 25% of thin sections component, as inter and intra-clast cement. Granular crystals are anhedral to subhedral and average 100 µm in size (*sensu* Flügel, 2004; Figs. 8a and b). Blocky calcite cement is present with crystals size average around 500 µm. Crystals are pink stained (non-ferroan) and twinned (Fig. 9b). Speckled echinoderm grains with twinned syntaxial overgrowth is generally common in the Rala section (Fig. 7d). Ferroan to non-ferroan neomorphic granular calcite is rarely seen in the Western and Eastern Areas. Ferroan calcite is most common in the lower to middle sets out of the three main packages of coarse downslope reworked deposits in the Rala section (where ferroan calcite is seen in 35% of the deposits overall and on average making up 25% of samples). The distribution of this ferroan calcite appears to be most strongly associated with units that contain significant reworked siliciclastic material (much derived from basement that includes both mafic and silicic components). Locally grains are partly or completely recrystallised by granular calcite (Fig. 9c). Pore-lining cements commonly exist in grainstone units (Fig. 6b). Cementation timing may be variable with cements that have formed with more than one generation, e.g., preserved pore-rimming non-ferroan bladed/granular calcite cement is post-dated by ferroan granular calcite cement that precipitated between/into grains after compaction (Fig. 9d). In the western area, three generations of calcite cements are found: (1) preserved syntaxial overgrowths, (2) ferroan to non-ferroan calcite cement, (3) pale crystals of calcite cement (Fig. 9e). Furthermore, some ?intra-grain pores are filled with granular cement (Fig. 9f). Granular/blocky calcite cements also filled fractures in the last diagenetic stage after compaction and silicification (Fig. 8f and Fig. 9a). Granular, blocky and syntaxial overgrowth cements may be associated with shallow burial diagenesis (Tucker and Wright, 1990; Flügel, 2004; Swei and Tucker, 2012). Melim et al., (1995) found that, in Bahamas the blocky cement formed late in marine burial diagenesis after compaction (e.g. Scholle and Halley, 1985; Choquette and James,1990). Furthermore, twining feature in blocky and syntaxial overgrowth calcite cements is linked to high pressure that had been concentrated in carbonate units (Adams et al., 2000).

Dolomite is only found in 9 samples from the northern area in the Rala section. Dusty euhedral rhomb-shaped dolomite is seen in 3 samples from the upper part (Fig. 7e), 1 from the middle and 1 from the lower parts of the section (Fig. 10a). Rhomb shaped replacive dolomite is seen in 2 samples from the upper part (Fig. 10b) and 1 sample from the middle part of the section. This dolomitisation is a minor feature and postdating some burial compaction, without further geochemical study the dolomitising mechanism is not further speculated on here (Warren, 2000; Flugel, 2004; Carnell and Wilson, 2004; Machel, 2004). The replacive dolomitisation seen in the shallow platform deposits of the Tonasa Formation may be linked to burial diagenesis (Arosi and Wilson, 2015).

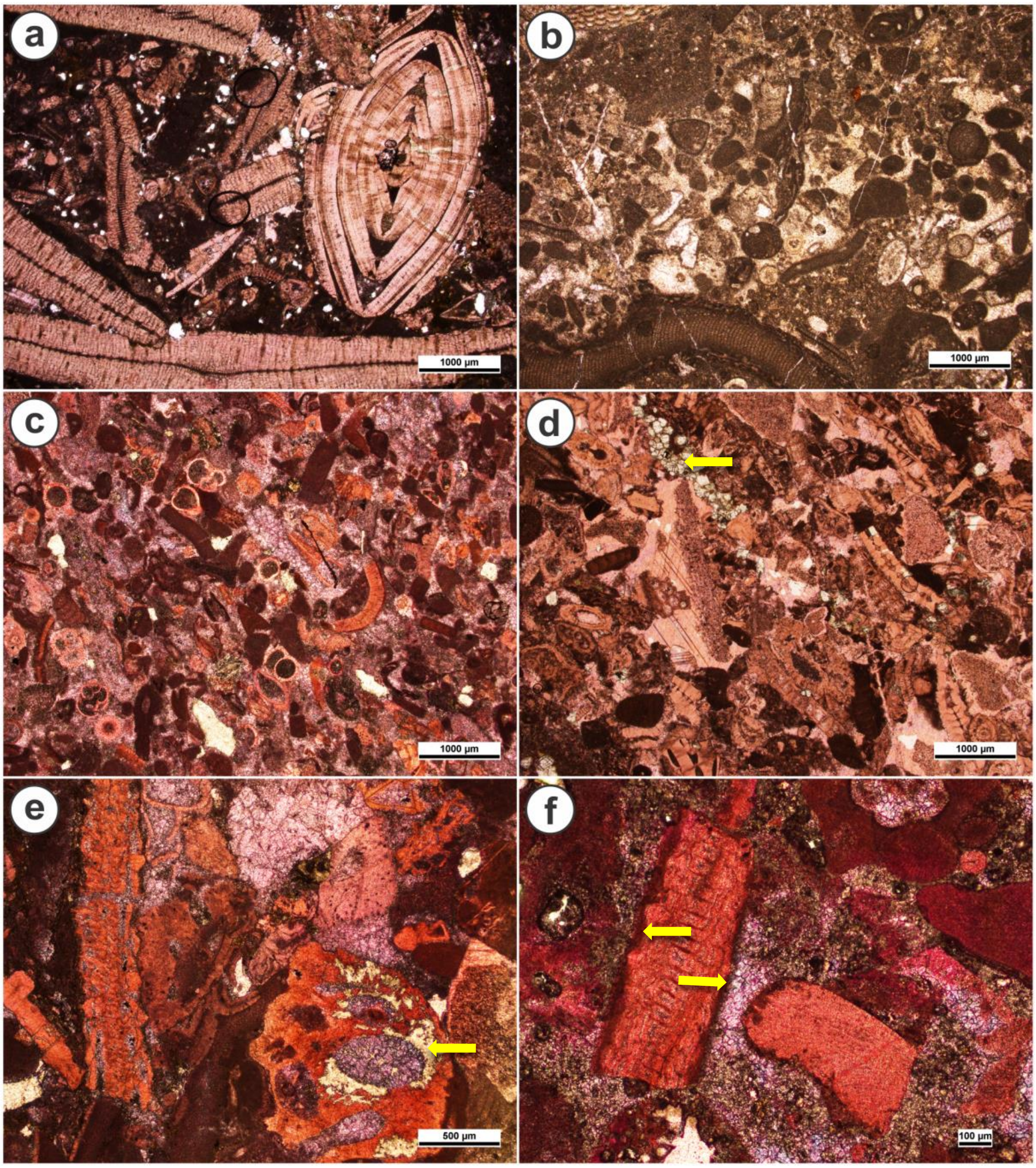


Figure 4.7. Thin-section plane polarised light photomicrographs showing (a) Tangential and concavo-convex contacts types (SRa6). (b) No-contact type from eastern area (SMa26). (c) Point contact type between grains (D55). (d) Fragment of 'speckled' echinoderm bioclasts with preserved twinned syntaxial overgrowth cement in packstones unit. This photo shows dusty euhedral rhomb-shaped dolomite (arrow) (J57). (e) Fragments of pre-existing calcite cements. Selective silicification is also seen in this sample (arrow) (D52). (f) Preserved micritic envelope (arrow) (D53).

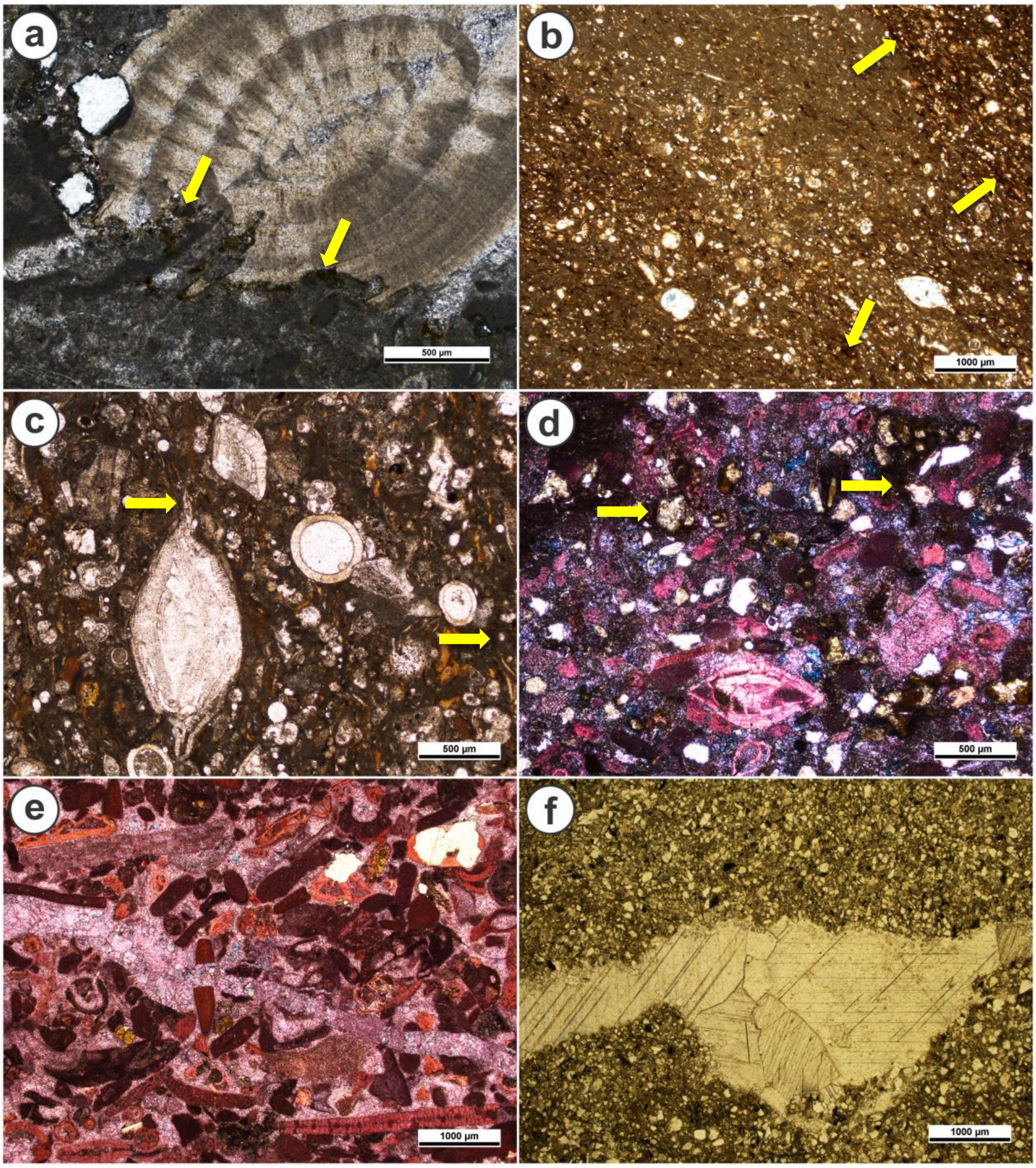


Figure 4.8. Thin-section plane polarised light photomicrographs showing (a, b) Wispy and anastomosing dissolution seams in wacke/packstones units (D85, J20). (c) Stylolites associated with silicification. Some skeletons are replaced by lutecite silicification (J32). (d) Stylolites in grainstones from the Eastern area associated with igneous lithoclastics (SRa51). (e) Fracture width averaging about 100 µm cross-cutting all fabrics and components of the sample. Fractures are filled by granular calcite cement (D62). (f) Fractures in a quartzose sandstone unit are filled with twinned blocky calcite cement in one sample from the Western area (SMa26D).

4.6.3 Silicification

Silicification is most widely present throughout the Rala section. Selective silicification is common in shallow water packstone/wackestone units (Fig. 7e). Shells are partly to completely replaced by lutecite silicification. In some cases, pores between and within clasts were infilled with microcrystalline granular quartz

(Fig. 8c) and mosaic quartz (Fig. 10c). Fabric-replacing chalcedony is only seen in the northern area (Fig. 9f; Wilson, 1966). Silicification is also been noticed association with ferroan calcite cement especially in the lower part of Rala section, this may open a new door for future research. Silicification happened after compaction but before fracturing and late granular calcite cement. The source of silica probably came from sponge spicules and microfossils, although derivation from silica-rich older strata exposed and reworked from the faulted northern margin is another possibility (Wilson and Bosence, 1996). Hesse (1989) suggested that the presence of chalcedonic fabric is an indication of tectonic activity, whereas pore space is opened resulting from tectonic deformation. Silicification not only appears in reworked deposits in the Tonasa Platform, but also many of other ancient reworked slope carbonates (Gawthorpe, 1986; Bustillo and Ruiz-Ortiz, 1987; Coniglio 1987; Eberli, 1987; Reijmer and Everaars, 1991; Herbig and Bender, 1992). The rapid burial of reworked sediments may be the main reason for dissolving siliceous shales in sea water (Bustillo and Ruiz-Ortiz, 1987).

4.6.4 Glauconitisation and Phosphatisation

Two types of glauconite are recognised in shallow water packstone/grainstone units. Glauconite pellets were precipitated into and between bioclasts with light green colour, or as a 'ghost' mineral which replaced bioclasts. Glauconite is seen in 15 samples from the middle part of Rala section in the north (Fig. 10f), 1 sample from Western Divide in the east and 1 sample from the Segeri section in the west. Phosphate is seen in all shallow water and reworked units. It occurs in all areas, but is more dominant in the Rala section. Phosphates are yellow to brown and formed between clasts. Phosphate is usually associated with glauconite. The glauconitisation commonly appears in restricted to marine environments with low sedimentation rate with depth ranges between 100 and 300 m. (Jimenez-Millan et al., 1998). Also, the presence of phosphate is a strong evidence of restricted environment with high salinity of sea water (Cody and Hull, 1980; Moller, 1988, Jimenez-Millan et al., 1998). In Tonasa Platform, Wilson and Bosence (1996) found that the presence of miliolids, gastropods and large alveolinids is an indication for minor restriction environment. Wilson (1999) suggested that foraminifera wackestones facies deposited in localised restriction and fluctuations in salinity in the basal tens of metres of the Rala and Doi-doi sections. The combination of glauconite and phosphate is not only present in the Tonasa Formation, but they are often found together in different ages of marine deposits (Odin and Letolle, 1980; Carson and Crowley, 1993).

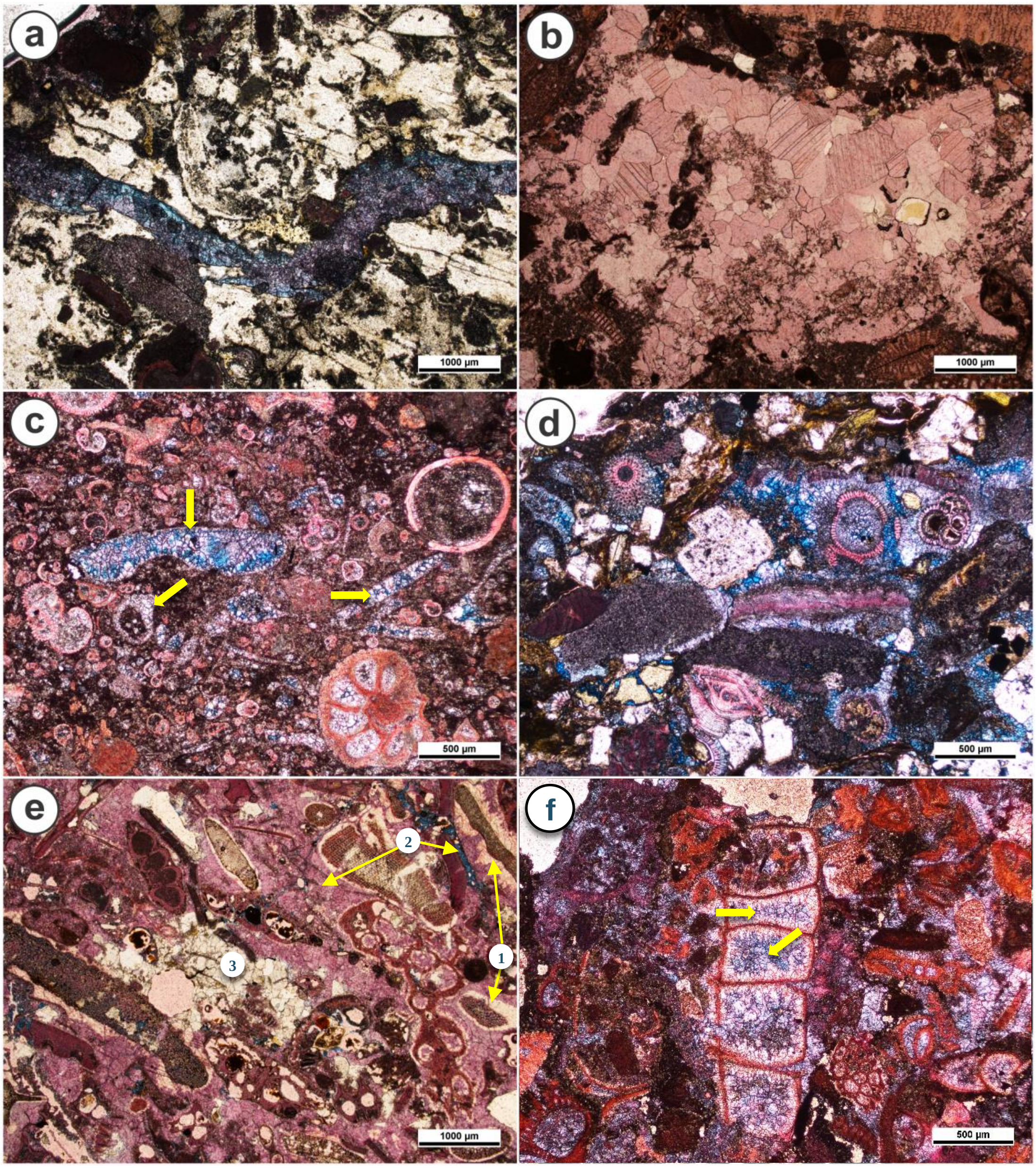


Figure 4.9. Thin-section plane polarised light photomicrographs showing (a) Fracture post-dates compaction and chalcedonic overlay fabric silicification with pore filled by later ferroan granular calcite cement. (D87). (b) Pink stained and twinned blocky calcite cement (~500 µm), twining might be linked to the burial pressure. (c) Ferroan neomorphic granular calcite (arrowed). (d, e) Different generation of calcite cement, preserved non-ferroan bladed granular calcite cement with later ferroan granular calcite cement (J2). Three generations of calcite cements are found as shown in photo (e) : (1) preserved syntaxial overgrowth, (2) Ferroan to non-ferroan calcite cement, and (3) crystals of calcite cement (SMa10). (f) Granular cement infilled intra-grain pores (arrows) (D87).

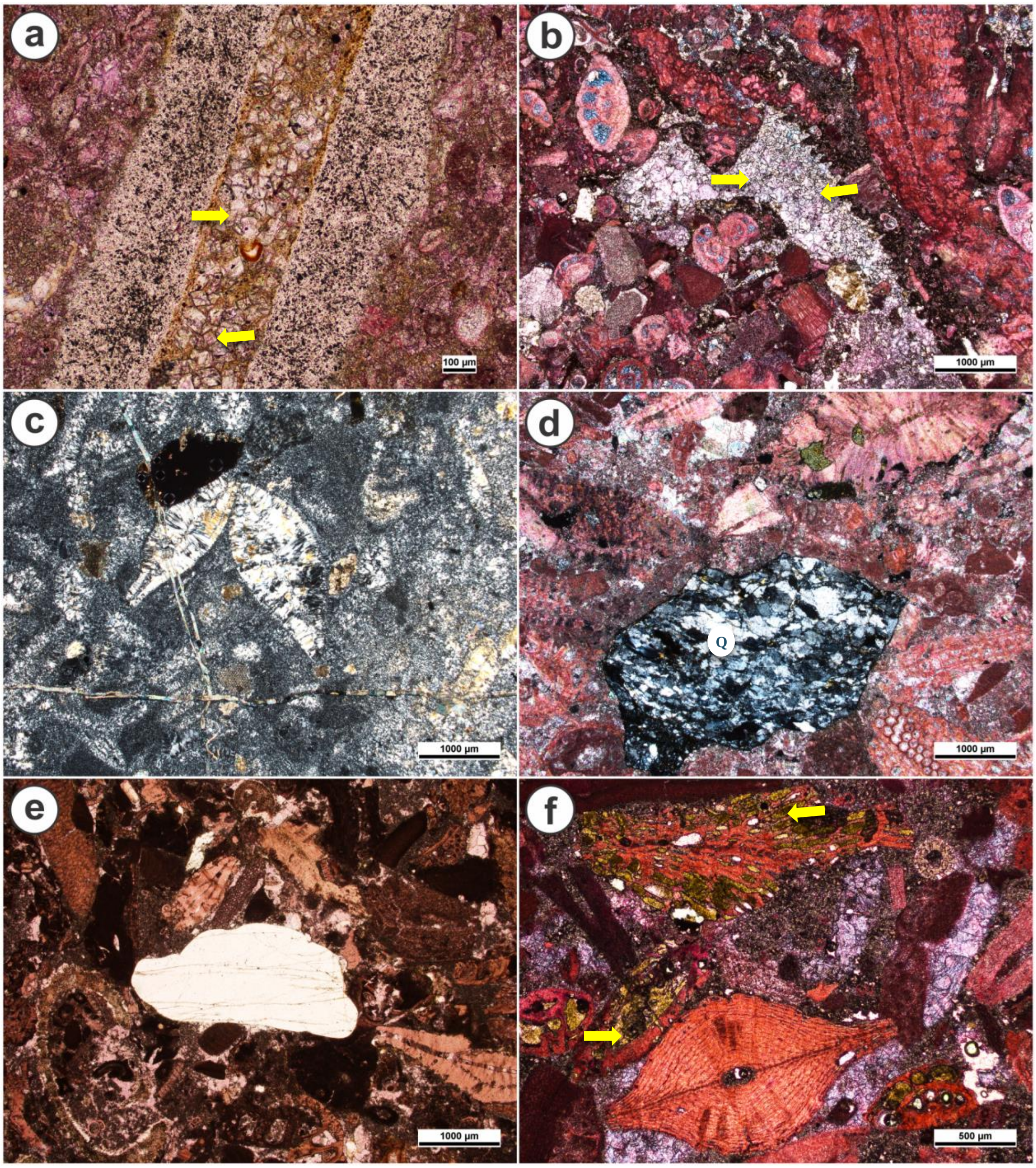


Figure 4.10. Thin-section plane polarised light photomicrographs showing (a) Dusty euhedral rhomb-shaped dolomite from the lower part of Rala section (DR14). (b) Replacive dolomite from the upper part of Rala section (J45). (c) Mosaic quartz infilling pores between clasts from the lower part of Rala section (DR11-XPL). (d) Reworked lithoclastic grains containing quartz crystals in the Rala section (J1-XPL). (e) An individual quartz crystal with bioclastic fragments in shallow water facies (DR25). (f) Ghost glauconite (light green) replaced the bioclasts shells (arrows) from the middle part of Rala section in the north (D53).

4.7 Discussion

The variability of lithological components, differential burial compaction and variations of cementation timing influence the different diagenetic stages affecting the late Eocene to early Miocene slope and basinal deposits of the Tonasa Carbonate Platform.

4.7.1 Diagenetic comparison between slope to basin deposits and the adjacent shallow platform of the Tonasa Formation

The diagenetic features in slope-basinal deposits, in terms of presence and abundance, although similar to that of the shallow-water platform vary in terms of amounts. Mechanical compaction is seen in 80% of all thin-sections from slope-basin deposits. In the Rala section, mechanical compaction is dominant in packstone and wackestone facies, but with low abundance in Western Divide and Segeri areas (<25%). compaction features are rather variable based on lithological components of individual samples. Mechanical compaction and sutured contact here are controlled by grain type, shape and original texture. Mechanical compaction is also seen in some of the shallow water deposits, such as those including flattened larger benthic foraminifera that are particularly prone to breakage on compaction.

Micritisation is generally seen in almost all thin sections and all different facies throughout the Tonasa Platform, with <5% in individual thin sections. Calcite cement is mostly dominanting in slope to basinal carbonate deposits which include: granular cement, blocky calcite and syntaxial overgrowths. Syntaxial overgrowth cements are mostly noted on echinoderm grains in both shallow and slope to basinal carbonate deposits. Speckled echinoderm grains with twinned overgrowth cements may both pre-date, but more commonly post-date, some of the mechanical compaction.

The granular mosaic calcite is seen 75% of thin-sections from the slope and basin deposits. This percentage is slightly less than the percentages seen throughout deposits of the whole platform (90% of samples). Blocky calcite cement where present in slope and basinal deposits is mostly similar to that in the rest of the platform deposits in terms of crystals size $\geq$ 500 µm, pink stained and twinned.

Ferroan to non-ferroan neomorphic granular calcite is rarely seen in Western and Eastern Areas slope and basin deposits, whilst in the northern Rala section is present with percentage of 35%. Most cements are non-ferroan calcite, but in all areas except the central area ferroan calcite is also present in up to 15% of samples. Ferroan calcite is most common in the eastern and northern areas from near the contact with the underlying siliciclastics, or where adjacent to igneous rocks where ferroan granular mosaic or more rarely drusy crystals grade to non-ferroan to blocky crystals. A local source for the iron is therefore inferred from the clastics or volcanogenics. Silicification is much more common in the northern and western slope deposits than elsewhere throughout the platform, likely reflecting a local, perhaps basement lithology, source of silica.

Stylolites, are commonly abundant in fine grained facies, but also it is present in grainstones unit associated with igneous phenocrysts from the slope and basin settings. Stylolites and dissolution seams are noticed in deep water facies, such as marls, and circum-clast stylolites are particular common in slope breccia units. Elsewhere throughout the Tonasa Formation stylolites or dissolution seams are common close to the underlying siliciclastic units of the Malawa Formation, whereas stylolites are more common in the shallow water platform deposits.

4.7.2 Influence of tectonic and volcanic activities on diagenesis in reworked carbonates

The frequent appearance of breccia units in the upper part of the Rala section with a variety of grain sizes and very angular grains indicates continuation of faulting activity until early/middle Miocene (Wilson and Bosence, 1996; Wilson, 1999; Wilson et al., 2000). Furthermore, large thicknesses of these reworked sediments (> 500 m) showed long term faulting activity (cf., Bluont and Moore, 1969; Kepper, 1981; Hurst and Surlyk, 1984; Martini et al., 1986; Eberli 1987; Burchette, 1988; Eaton and Robertson, 1993). As a result of normal fault movement the previous deposits were exposed subaerially, eroded and redeposited in slope to basinal settings of the northern Tonasa platform (Wilson and Bosence, 1996). The presence of 'old' diagenetic features such as cavity lining cements and sediment infill within the reworked clasts is a possible indication for subaerial exposure of footwell highs in the northern area (Arosi and Wilson, 2015). Twining feature, blocky and syntaxial overgrowth cement are significant indications of overburden pressure in carbonate units in burial environments (Tucker and Wright, 1990; Adams et al., 2000; Flügel, 2004; Swei and Tucker, 2012; Arosi and Wilson, 2015). In addition, the interbedding of marl with coarse redeposited facies such as quartzose, igneous lithic clast units were deriving from major active normal fault bordering the Tonasa platform (Wilson and Bosence, 1996; Wilson et al., 2000). Additional to the high sedimentation rate, faulting activity also caused great subsidence which allowed for the accumulating of significant thicknesses (>200 m) of reworked deposits (Arosi and Wilson, 2015).

Although, the main source of silica in the Rala section may be sponge spicules or microfossil tests (Wilson and Bosence, 1996), there is another possibility for different sources of silica, because this phenomenon is only seen throughout the reworked deposits (Wilson and Bosence, 1996). This probably refers to inorganic sources of silica. Banks (1970) has found three different sources of inorganic silica: (1) hypersaline marine water with fluctuating pH. This source may be a significant source of silica, whereas the other evidence for high salinity of seawater is the presence of phosphate (Cody & Hull, 1980; Moller, 1988, Jimenez-Millan et al., 1998). (2) Lithological source of silica would be acceptable as well, because quartz is found in reworked sediments and quartzose units or lithic clasts that occur throughout the Rala section, and (3) Hydrothermal jasperoid deposits. Hesse (1989) also mentioned to waters from volcanic hydrothermal as a source of silica, but this theory is neglected here because there are other sections in Tonasa Platform such as Doi-doi section that are very close to the igneous bodies but the silicification is not seen throughout them (Wilson and Bosence, 1996).

4.7.3 Influence of burial processes on diagenesis in reworked carbonates

The variety of common diagenetic features such as compaction, stylolites/dissolution seams, and syntaxial overgrowth and blocky cements can be linked to burial conditions (Goldhammer, 1997). Burial diagenesis is predominant in large-scale Tertiary platforms in the SE Asia region (Saller et al., 1992; 1993; Wilson et al., 1999; Saller and Vijaya, 2002; Wilson et al., 1999; Wilson, 2012; Madden and Wilson, 2013). The great thickness of reworked sediments produced a high pressure on these deposits. Twining feature in blocky and syntaxial overgrowth calcite cements is linked to high pressure that had been concentrated in carbonate units (Adams et al., 2000). Mechanical compaction usually appears in the early stage of burial diagenesis (Goldhammer, 1997). Meyers (1980) had found that sediments could be affected by mechanical compaction with depth less than 107 m. This led to shallow burial processes being involved in the main factors of mechanical compaction, however, stylolites and dissolution seams are mainly formed by deeper burial processes. Silicification can also happen during the mid-stage of burial diagenesis, where the pressure solution of quartz with clay minerals such as smectite transforms to release a source of silica (Hesse, 1987).

4.7.4 Influence of lithological and biological components on diagenesis in reworked carbonates

The variability of lithological components controlled many of the diagenetic features. Lithoclastic, bioclastic types and grain shapes have influenced the intensity of compaction and the variation of grain contacts type throughout the areas. In samples that contain a high percentage of bioclasts (>50%), the sutured contact type is usually dominant. These facies are present throughout the Rala section but with more abundance in the lower part in shallow water deposits of late Eocene age (Wilson and Bosence, 1996). In grainstone and clast-supported breccia units, submarine and meteoric calcite cement played a significant role in preventing the effects of compaction (Meyers, 1978, 1980; Adams et al, 2000; Figs. 6b and d). As a resulting of preventing compaction, no-point contacts type is present, being more frequent in the upper part of the Rala section that was deposited during the early to middle Miocene (Wilson and Bosence, 1996). Grain contact types might be controlled by grain shape, grains packing and lithology of sediments rather than burial compaction (Taylor, 1950; Meyers, 1978, 1980; Adams et al., 2000). Because of faulting and uplift of basement rocks, K- feldspathic-rich rocks (in addition to silica-rich ones) were reworked into the carbonate slope deposits. This mineral is a common source of glauconite (Odin and Matter 1981, Dasgupta at el., 1990; Deb and Fukuoka, 1998; Bandopadhyay, 2007; Banerjee et al. 2008; Chattoraj et al. 2008). K mineral also could be a reason for modifying smectitic materials to phosphate (Stille & Clauer, 1994; Jimenez-Millan et al., 1998). Porosity here was not significant factor that can cause any change in diagenetic features because it is only < 1 -2%.

4.8 Conclusions

- Compaction and granular calcite cement are the common diagenetic features that have been seen in downslope reworked carbonates of the Tonasa Platform.
- Cementation is common within the thinsection components with only average % 25.
- The variability of original and clasts type and lithological components is a significant factor controlling the intensity of compaction.
- Tectonic activity, associated generation of accommodation space as well as graben sedimentary infill may affect the degree of burial diagenesis affecting the reworked carbonates.
- Long term faulting activity was a significant factor that influenced directly or indirectly the diagenesis of the reworked carbonate. Uplift and subsidence created differential accommodation space and high rates of sediments supply impacting the degree of compaction of deposits. Faulting also resulted in the localised subaerial exposure of the basement highs in western Segeri and eastern Western Divide Mountains Areas as evidenced in reworked clasts derived from the platform margin. Additionally fracturing, differing types of water influx and varied sediment supply are associated with the faulting.
- The variation in diagenetic features seen in the three areas and throughout the Rala section are partly linked to lithological and textural differences.

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Chapter Five

DIAGENETIC STUDY OF THE TONASA PLATFORM AND IMPLICATIONS FOR HYDROCARBON EXPLORATION

Carbonate reservoirs produce about 50% of hydrocarbons worldwide (Ramakrishnan *et al*., 2001); furthermore, they represent almost 50% of hydrocarbon resources in the SE Asia region (Howes, 1997). More than 80% of these resources within carbonates are accumulated in isolated carbonate platforms (Wilson, 2002; Wilson and Hall, 2010). Carbonate rocks are commonly strongly influenced by diagenesis, yet this may result in increased or decreased porosity and permeability. This chapter explores to what extent diagenesis has impacted reservoir quality in the Tonasa Platform but also the general hydrocarbon prospectively in South Sulawesi. Since much of the Tonasa Platform now crops out onshore the formation does not comprise a viable reservoir in these areas, but may provide useful analogue data for other subsurface systems.

Reservoir properties are highly impacted by different types of diagenetic processes that influence porosity and permeability. These properties are very essential for the best performance and development of the oil or gas reservoirs. For example, completely cemented layers may act as internal seals and in some cases diagenetic processes preserve and increase the reservoir porosity. Therefore, comprehensively understanding the diagenetic history of carbonates is essential for better characterizing and predicting their reservoir potential.

5.1 Summary of reservoir quality in the Tonasa Limestone Formation and comparison with other Cenozoic SE Asian carbonate systems

The Tonasa Limestone Formation as with a number of other long ranging Tertiary carbonate platforms in SE Asia is predominantly influenced by burial diagenesis with only localised influence of marine or meteoric diagenesis (Adams, 1965; 1970; Saller and Vijaya, 2002; Wilson et al., 2012; Madden and Wilson, 2013). The retained porosity in the Tonasa Formation, as with these other Tertiary platforms is commonly low, being generally less than 10%. This differs significantly from other mainly Neogene-aged systems that were strongly affected by subaerial exposure, together with vadose and phreatic meteoric conditions, but may also have been overprinted by further diagenesis. These Neogene platforms have good to excellent, but commonly highly variable porosity, ranging between 10 and 40% that locally renders them excellent hydrocarbon reservoirs (Epting, 1980; Fulthorpe and Schlanger, 1989; Grötsch and Mercadier, 1999; Vahrenkamp et al., 2004). Factors that strongly influenced the general paucity of reservoir quality in the Tonasa Limestone Formation, include (1) predominance of calcitic bioclasts (less prone to leaching than aragonite), (2) limited subaerial exposure, (3) paucity of early marine or meteoric cements that might have mitigated against porosity loss through compaction, and (4) significant burial compaction and cementation (cf., Wilson, 1996; 2012).

The primary porosity and permeability of shallow water deposits of Tonasa Platform was locally high, as in for example the higher-energy, shallow-water grainstones units, however, this was commonly significantly reduced by later diagenesis (Wilson, 1995). Intergranular or intragranular porosity generally contains very limited marine cements, instead commonly containing significant granular to equant cements that formed in shallow to deeper burial depths, probably associated with burial under a thick volcaniclastic pile (Wilson, 1996; Arosi and Wilson, 2015). It may be, however, that primary porosity may be retained in similar deposits that have not been affected by adverse pore occluding diagenetic processes (Wilson, 1996).

In comparison, the slope facies composed of reworked lithic and bioclastic material may retain some primary porosity in the Tonasa Limestone Formation if primary porosity is not completely lost during burial compaction. As quoted from Wilson (1996): These slope facies ‘derived from block faulted footwall areas may be both porous and permeable, indicated by circum-granular stylolites and some preserved primary intergranular porosity. Although concentrations of argillaceous material around clasts in some beds may lead to reduced permeability. Downslope reworked facies, abutting impermeable basement and platform lithologies, are thought to form the most suitable hydrocarbon reservoir within the Tonasa Limestone Formation and indeed traces of hydrocarbons do occur (such as in the Salo Cinee section; Wilson, 1995). Overlying marine clays may form effective seals with underlying coal deposits providing a potential source (cf. Phillips, et al., 1991; Coffield, et al., 1993). This study suggests that redeposited carbonate facies may form effective hydrocarbon reservoirs in otherwise tight foraminiferal dominated carbonates. Fulthorpe and Schlanger (1989) recognized that in seismically active areas, carbonate megaturbidites could provide pathways for the migration of hydrocarbons, or act as reservoirs.' Late burial leaching or corrosion is a feature of some platform flank and slope deposits with corrosive fluids thought to be basinal derived, perhaps associated with the early stages of hydrocarbon generation during burial (Saller and Vijaya, 2002; Esteban and Taberner, 2003; Pireno et al., 2009; Wilson, 2012; Tanos et al., 2013; Subekti et al., 2015). Such late burial leaching is a possibility for porosity enhancement in slope and margin deposits of the Tonasa Platform, but although noted regionally (Saller and Vijaya, 2002; Pireno et al., 2009; Tanos et al., 2013) was not evidenced at outcrop in the Tonasa Formation. As discussed below, fractures in the Tonasa Limestone Formation, although commonly cemented, may retain some secondary porosity.

Diverse diagenetic processes have affected the carbonate facies of Tonasa Platform near concomitant with, and post-dating deposition during the Eocene to Early Miocene. Tectonic, volcanic activity, sea level change and faulting system together have all impacted the chemical and physical properties of carbonate rocks of Tonasa Platform and their quality in terms of porosity and permeability. Four main stages of diagenesis can be distinguished for the Tonasa Limestone Formation; (1) meteoric diagenesis and/or subaerial exposure, (2) fracturing, (3) marine, and (4) burial diagenesis. These stages are characterized by different diagenetic processes and different degrees of reservoir facies modification. The best interparticle and mouldic porosity values are found in the shallow larger foraminifera dominated lithofacies associations. However, in some cases the cementation has plugged and occluded the pore spaces which destroyed the reservoir quality.

5.2 Impacts of meteoric diagenesis on reservoir properties of the Tonasa Carbonates

Early phases of diagenesis normally occur within the eogenetic zone where sediments are altered by near surface processes including meteoric dissolution (Ali, 2010). Dissolution by meteoric waters may affect carbonate rocks during uplift events and such meteoric dissolution may be particularly prevalent in the equatorial tropics (Wilson, 2002; 2012). In most case meteoric water has a positive impact on carbonate reservoirs as they create excellent mouldic porosity. Dissolution by meteoric water during the uplifting is considered to be a major porosity-forming process. However, in the Tonasa carbonate rocks meteoric influences are rare seen, being highly localised to block faulted highs and/or bathymetrically upstanding platform margin areas. The areal extent and/or volume of the Tonasa Limestone Formation affected by meteoric process comprise less than 1% of the formation. Where dissolutional cavities have formed the paucity of aragonitic bioclasts generally resulted in little moldic porosity, instead cavities that formed are commonly lined by blocky to dog-tooth or scalenohedral cements and commonly include sediment infill. Due to this cement and sediment infill, there little net gain in porosity is seen in area affected by subaerial exposure in the Tonasa Formation. The dog tooth cements were probable meteoric origin as they are lining dissolutional cavities and having same forms meteoric cements.

5.3 Impacts of marine diagenesis on reservoir properties of the Tonasa Carbonates

Early marine cementation is likely to be controlled by flushing of high volumes of marine waters into porous sediments along the platform margin as well as CO_2 degassing driven by high wave and tidal energy (cf. Land and Moore, 1980; Moore, 1989; Madden and Wilson, 2013). Marine cementation is generally minor and mostly limited to platform margin areas of the Tonasa Formation, such as the northern margin likely to be most strongly impacted by the Indonesia Through Flow Current. Locally these cements although pore occluding may if not too pervasive mitigate against later compaction effects. Relict porosity, however in the Tonasa Limestone Formation is commonly filled by later burial cements. The general paucity, however, of marine cements throughout much of the Tonasa Formation may be linked to the relatively low marine salinities compared with global averages due to runoff into the Makassar Straits (Wilson, 2002; 2012). Micritisation that is a common marine diagenetic process affecting the lower energy shallow water platform deposits of the Tonasa Formation may have lowered intergranular porosity.

5.4 Impacts of burial diagenesis on reservoir properties of the Tonasa Carbonates

A quantitative study of compaction in Mississippian coarse-grained skeletal grainstones and cement-rich packstones over a region of about 25,000 km^2 of south western New Mexico has shown that intergranular compaction was a major process of porosity destruction in more than 90% of all coarse grainstones and packstones. These deposits accumulated with at least 42 percent primary intergranular porosity (Meyers and Hill, 1983). Thus, burial compaction is a major porosity-killing diagenetic process. In the

Tonasa Formation, burial diagenesis is noticed through mechanical and chemical compaction. It is also evidenced by different types of cements including granular mosaic, blocky and equant calcite cement. Burial diagenesis in its various manifestations is the key reason for the Tonasa Limestone Formation having generally low reservoir quality. Burial compaction effects are thought to have been the overriding diagenetic overprint on the formation due to: (1) a paucity of biotic frameworks or early cements mitigating against compaction, and (2) burial under >1 km of overlying combined carbonate and volcanogenic pile

5.5 Impacts of tectonic activity and fracturing on reservoir quality of the Tonasa Platform

The influence of tectonics on carbonate platform development is widely documented, yet the diagenesis of such syntectonic platforms is barely evaluated. The Tonasa Limestone developed in an extensional regime in central Indonesia. Wilson (1999) and Wilson et al. (2000) documented that the Tonasa equatorial carbonate system was affected by block faulting, tilt-block rotation, differential uplift and subsidence throughout its Eocene to Early Miocene history. Tectonic uplift together with a major oceanic through flow current are thought to be key influences on localised karstification, meteoric diagenesis and marine cementation. The distribution and orientation of faults, fractures and calcite veins together with evidence for their relative timing are the strongest manifestation of tectonism coeval with diagenesis. There is concordance in the orientation and timing of structures affecting the Tonasa Platform with those basin-wide, with the potential for reactivation of pre-existing basement fabrics. Tectonic subsidence, including fault-associated differential subsidence, controlled the degree of burial diagenesis impacting different areas of the platform.

Fractures that resulted from compaction or tectonism normally enhance reservoir potential through increasing the porosity and by linking the pores which will increase the permeability. Fractures forming secondary porosity have been noticed across the area of Tonasa platform in different facies including shallow water deposits with more concentration in Eocene deposits. These fractures have varied width and are occasionally associated with karstic cavities although many are probably tectonic in origin. Karstification is associated with highly localised tectonic uplift and subaerial exposure of block faulted highs in the Tonasa Platform (Arosi and Wilson, 2015). In the

Tonasa Platform, large-scale near-vertical NW-SE and ~N-S trend faults cross-cut the Tonasa Platform and these trends are also seen in the small-scale fracture patterns (Sukamto, 1982; Sukamto and Supriatna, 1982; Wilson, 1995, Arosi and Wilson, 2015). Some of the fractures are multistage and crosscut each other (Arosi and Wilson, 2015). Many of the fractures are occluded, or partially occluded by later cements and there may be little net gain in porosity or permeability associated with these features in the Tonasa Formation.

5.6 Volcanogenic reservoir quality and volcanogenic impacts on petroleum systems development in South Sulawesi with regional comparisons

Hydrocarbon reservoirs in volcaniclastics are far less common than in carbonates and sandstones. However, oil and gas are commercially produced from or associated with them in different place in the world. Productive volcaniclastics are most often of Tertiary age, but examples as old as Permian are known. Most of the productive fields are located along past or present subduction zone volcanic-arc tracts. These include the ancient volcanic belts of the former Soviet Union (Georgia, Azerbaijan), Australia and China, as well as the present-day "ring of fire" which rims the Pacific Basin (Indonesia, Japan, New Zealand and Argentina). Petroleum exploration in Africa, northern Europe, South America and Asia have resulted in commercial hydrocarbon discoveries from within volcaniclastic deposits (Schull, 1988; Brook and Glennie, 1987; Schott, 1982; Fitzgerald et al., 1990; Bee, 1982; Mathisen and McPherson, 1991). Although volcaniclastics of Tertiary and Quaternary age are very common throughout Indonesia, commercial hydrocarbon discoveries within the region in these deposits are, however, quite rare (Willumsen and Schiller, 1994).

Indonesian volcaniclastic reservoir examples include the Jatibarang Formation which produce oil and gas from the Jatibarang Field, NW Java (Eocene–Oligocene). The long abandoned Kuti and Metatu Fields were discovered near Surabaya in Northeast Java (Pleistocene) (Soetantri et al, 1973; Willumsen and Schiller, 1994). The Kuti Field produced 0.75 MMBO from Pleistocene tuffaceous sandstone while Metatu produced 0.3 MMBO from the same Pleistocene volcaniclastics and from underlying Pliocene calcarenites (Soetantri et al, 1973). The Krisna Field from the Batu Raja Formation in NE Sumatra is an example of a carbonate reservoir that developed as a fringing reef around a volcanic edifice (Park et al., 1995; Wilson and Hall, 2010).

Variable dissolution, cementation and dolomitisation phases are detailed for the Krisna field, yet the underlying volcanogenic rocks appear to have had minimal impact on diagenesis of the carbonate system (Park et al., 1995).

The Samgori Field in Georgia, the former Soviet Union, represents the largest volcaniclastic oil field described in the available literature. The field has produced over 165 MMBO since its discovery in 1974 from hydrothermally altered tuffs and tuffaceous sandstones. The porosity is reportedly mostly secondary and the result of zeolitization and fracturing (Grinberg et al, 1991; Patton, 1993).

In volcaniclastics, the variation of facies, their components and diagenesis determines the quality of any potential hydrocarbon reservoirs (Mathisen and McPherson, 1991). The diversity of volcaniclastic facies formed in proximal to distal settings, together with the nature of the volcanism impacts sediment composition, which somewhat controls diagenetic processes. The components of volcaniclastic rocks are chemically unstable and very susceptible to alter diagenetically. These alterations of volcaniclastic minerals may produce a high amount of cements such as calcite, clays and zeolites that can occlude pores (Surdam and Boles, 1979; Davies et al, 1979; Galloway, 1979). Volcaniclastic sediments typically undergo rapid early diagenesis at shallow depths and low temperatures because of the abundance of unstable glass and mineral grains. Although this can destroy primary porosity through compaction and cementation, later diagenesis can create secondary porosity through dissolution (Mathisen and McPherson, 1991). Thus, the ability of volcaniclastic deposits to serve as hydrocarbon traps depends on the coincidence of porosity preservation and generation processes with the time of hydrocarbon migration (Mathisen and McPherson, 1991).

Recent studies of Pliocene and Pleistocene volcaniclastics from the Porong-1 and WD-8 wells and various outcrops within onshore East Java, show that volcaniclastic sandstones can provide high quality reservoirs (Willumsen and Schiller, 1994). Conolly (1985) and Hawlader (1990) have mentioned that the oil and gas production is from within Mesozoic volcaniclastics in the Surat and Bowen Basins of Australia, with further untested potential in these new reservoir fairways. Mathisen (1984) describes excellent reservoir quality in shallow Plio-Pleistocene volcaniclastics from the Philippines. The high porosity is attributed to a combination of non-marine deposition, shallow burial (400-900m), early grain dissolution and high pore-fluid flow rates. Mathisen and McPherson (1991) present a good review of the various factors that control porosity preservation and destruction in volcaniclastic sandstones. They indicate that the most favourable conditions are achieved in reworked, distal non-marine, epiclastic and pyroclastic fall deposits with shallow burial, high geothermal gradients and high-rate pore water flow.

The Late Miocene Kerek Formation in East Java contains turbidite sandstones and conglomerates composed of a mixture of volcaniclastic and calcareous bioclastic sediments (de Gcnevraye and Samuel, 1972; van Gorse1 and Troelstra, 1981). The porosity observed in outcrop is generally less than 5-10% due to early calcite cementation brought about largely by the abundance of calcareous bioclasts. Calcite and other cements such as zeolite and clays are the major cause of poor reservoir quality in other examples such as Neogene volcaniclastics from Slovakia (Reed and Gipson, 1991) and are derived sands from Alaska (Galloway, 1979) and New Zealand (Surdam and Boles, 1979). In these examples the cements were formed as a result of early diagenetic alteration of the volcaniclastic sediments.

5.7 Impact of volcanogenic emplacement on petroleum systems development in South Sulawesi

The key impact on diagenesis of shallow-water deposits of the Tonasa Limestone Formation that pass conformably up into shallow-water deposits of the Camba Formation is aggrading neomorphism in the form of cementation and stabilisation of fine grained matrix by granular calcite and formation of much larger than normal neomophic calcite cements replacing aragonitic components such as corals (i.e., crystals larger than seen elsewhere in the Tonasa Limestone Formation). This overriding neomophic alteration close to shallow-water contacts is attributed to elevated temperatures and pressures associated with the overlying volcanogenic pile. The neomorphic alteration together with some volcaniclastic input in Early Miocene shallow-water carbonates collectively results in very low reservoir quality in these deposits adjacent to the contact with the overlying volcaniclastics. Where deep water slope to basinal deposits of the Tonasa Formation pass conformable into overlying volcanogenics, reservoir quality in the carbonates is also commonly low due to pervasive compaction. Pervasive compaction effects are attributed to burial of uncemented carbonate sediments during probable rapid burial by volcaniclastics.

Alteration of components such as feldspars that may be admixed in the uppermost carbonates is common in these marine deposits and resultant cements including calcite also negatively impact reservoir potential. Volcanogenics overlying earlier karstified surfaces in the Tonasa Limestone Formation have little impact on reservoir quality of the karstified deposits, but karst infill tend to have low reservoir potential due to some inclusion of volcaniclastics and development of calcite cements. Where intrusives or lavas are emplaced into the carbonate strata or lower part of the volcanogenic pile the nearby carbonates show common recrystallisation (i.e. towards marble) and chemical compaction can be intense with development of anastomosing seams. These metasediments generally have low reservoir quality associated with recrystallisation. Highly localised generation of hydrocarbons is associated with the intrusives as evidenced by remnant hydrocarbons, petroliferous odours and a distinctive strongly negative oxygen and carbon isotopic signature.

5.8 Impact of diagenetic alteration of the volcaniclastics on their reservoir potential

The maximum alteration of the volcaniclastic deposits in the form of alteration of feldspars, sericitisation and cementation by calcite or zeolite occurs in the volcaniclasts that accumulated in marine settings in the Camba Formation. The zeolites as pore rimming cements, albeit of limited lengths up to 200 µm are a commonly reported feature associated with dissolution of volcanic glass and low temperature precipitation under the presence of meteoric or marine waters (Glanzman and Rytuba, 1979; Mathisen and McPherson, 1991; Ibrahim, and Hall, 1996). In general, cementation caused a lowering of the porosity of the rocks which in turn lowers the reservoir quality. It seems likely that in South Sulawesi, the presence of fluids accelerated alteration of the volcaniclastics thereby negatively impacting reservoir potential. Where sedimentation rates of the volcaniclastics was high it may be that baffling effects of clay-rich and tuffaceous layers locally limited fluid throughput hindering alteration of the volcaniclastics despite the humid climatic setting that these deposits formed under.

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Chapter Six

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

6.1.1 Diagenesis and fracturing of a large-scale, syntectonic carbonate platform

Diagenesis of the Eocene to Early Miocene syntectonic Tonasa carbonate platform is dominated by alteration in shallow to deeper burial depths. Burial diagenesis is evidenced by mechanical and chemical compaction, as well as a range of cements including granular mosaic, blocky and equant calcite. Earlier diagenetic features include common marine phreatic micritisation of allochems. Rare, localised evidence for meteoric diagenesis is predominantly from faulted highs. These diagenetic features in the Tonasa Limestone are similar to those from other SE Asian long-lived Tertiary carbonate platforms. The Tonasa Limestone Formation is one of the best documented syntectonic platforms from a sedimentary perspective (Wilson and Bosence, 1996; Wilson, 1999; 2000; Wilson et al., 2000). On the diagenetic side, with the exception of the fracture development, it is, however, a regional rather than strong syntectonic signature that predominates. Tectonic setting, faulting and subsidence (listed below), in addition of non-tectonic influences, are inferred to be influential in the more regional diagenetic signature predominating. (1) The platform although developing on the flanks of an extensional basin, accumulated in a backarc setting on amalgamated basement of highly varied origins. In this setting the platform would have been potentially less prone to uplift than “typical” rheologically-strong continental crust. (2) The orientation of significant synsedimentary faulting commonly influenced by earlier basement structures, was not always perpendicular to the main extensional direction in the broader basin. (3) The Tonasa Carbonate Platform formed in an extensive basinal region generally undergoing subsidence, post-dating rift basin initiation.

Tectonic uplift of faulted highs, perhaps with the overprint of eustatic sea level fall controlled highly localised karstification and meteoric diagenesis. The orientation and relative timing datasets of faulting, fracturing and calcite veining is the strongest manifestation of diagenesis coeval with tectonism in the Tonasa Limestone Formation. Orientations of both small-scale and platform bounding/ segmenting structures together with the timing of faulting are consistent with those from the broader basin, hinting at a strong regional tectonic influence. Tectonic subsidence, including fault related differential subsidence, was a key influence on the degree of burial diagenesis impacting different areas of the platform. The location of bathymetrically upstanding faulted highs together with major oceanic current systems resulted in localised marine cementation along the platform margin. The general paucity of early marine or meteoric cements is attributed to: (1) the predominance of non-framework building larger foraminifera and/or algae that have limited production rates, are prone to remobilisation, and hence limited potential to build to sea level, (2) lower than global norm marine salinities, and (3) deposition in a tectonically subsiding area and lack of common eustatic sea level falls. The: (1) dearth of early cementation, (2) grain associations common in mainly Paleogene carbonate platforms from SE Asia, and (3) the equatorial climate resulting in high freshwater runoff have together contributed to the predominance of burial diagenetic impacts on carbonate platforms from tectonically subsiding regions. It is hoped that studies such as this will further contribute to understanding diagenetic alteration of syntectonic carbonate platforms, and those from equatorial regions.

6.1.2 How do thick volcanic and/or volcaniclastic piles overlying platform carbonates influence the dynamics of carbonate-volcaniclastic diagenesis?

Despite carbonate-volcanic interactions being common in marine areas with plate-margin or intra-plate volcanism, the diagenetic interactions of such carbonate-volcanogenic systems are almost unstudied. This research addresses the: (1) alteration of carbonate deposits adjacent to overlying volcanogenic units, (2) the reciprocal alteration of volcanogenic deposits overlying carbonate systems, (3) the extent of any contact-related alteration and (4) whether there are more extensive impacts on platform-wide carbonate diagenesis. An outcrop, petrographic and geochemical study details here for the first time diagenesis of carbonate-volcanogenic units where 1-2 km thickness of volcaniclastics and associated intrusives of the Miocene Camba Formation overlie, or are in contact with, Tertiary carbonates of the Tonasa Limestone Formation, Sulawesi, Indonesia.

Broad diagenetic impacts of the overlying volcanogenic pile and intrusives on the carbonate platform - Platform, slope and basinal deposits up to 1.2 km thick of the syntectonic Tonasa carbonate Platform were strongly influenced by block faulting and tilting during their development (Wilson et al. 2000). The effects of burial diagenesis by fluids of marine precursor origins predominate across the platform (Arosi and Wilson, 2015). It is likely that common late stage compactional stylolites and dissolution seams were influenced by the thickness of the overlying volcanogenic pile. Aside from this widespread "volcanogenic overburden affect" dynamic diagenetic interactions between the carbonates and volcanogenics are highly localised and mostly limited to the few metres to tens of metres either side of conformable formation boundaries or contacts with intrusive sills. In regions of larger igneous stocks (1-2 km diametre) carbonates within 1-2 km of the intrusive contact may have a crystalline appearance and show anomalously low negative oxygen and also carbon values compared with the rest of the platform (Arosi and Wilson, 2015). The low negative values are linked to higher temperatures and potential hydrocarbon maturation, perhaps associated with hydrothermal fluids.

Local diagenetic interactions at the carbonate-volcaniclastic contacts - Where the Tonasa Limestone Formation is unconformably overlain by the Camba Formation, apart from where there are associated intrusives, there are no discernible effects of the volcaniclastics on the diagenesis of the limestone. It is inferred the overlying volcanogenic strata had little impact on the already lithified bulk of the shallow-water platform deposits prior to their deposition over the block faulted topography of the top of the platform. Shallow-water carbonates that pass conformably into, or interdigitate with, the volcanogenics show more pervasive neomorphic replacement by very coarse bladed to mosaic calcite cements and also localised more intense compaction than is seen elsewhere in the Tonasa Formation. The inference here is that the increased pressures and perhaps higher temperatures associated with emplacement of the volcanogenic pile drove increased chemical compaction and fluid flow driving stabilisation to coarse calcite cements. There is no evidence for significant exchange of fluids from the volcanogenics altering the carbonates, and *vice versa*, rather it appears fluids involved in the alteration of unlithified shallow-water carbonates were locally and internally sourced. Deep water slope and basinal deposits of the Tonasa Formation close to the contact with the overlying Camba Formation are also strongly affected by compaction with chemical compaction of predominantly unlithified units linked to increased pressures and temperatures associated with emplacement of the overlying volcaniclastics.

Diagenesis of the volcaniclastics and the influence of environments and proximity to carbonates - Perhaps surprisingly given the humid equatorial setting of deposition the volcaniclastics of the Camba Formation commonly have a relatively fresh appearance. Possible reasons for this common paucity of alteration may include: (1) common lithic and crystal components to the volcaniclastics with a lack reactive glassy material, (2) common interbedded clay rich and lava flow units that may act as baffles or barriers to fluid flow, and (3) potential rapid covering by further volcaniclastics. Alteration of the volcaniclastics includes sericitisation and some calcitisation of the feldspar, some oxidation and Fe-alteration of mafic minerals, common zeolite replacement and growth into pores and minor late calcite cementation. In keeping with other studies alteration of the volcaniclastics is most intense where there are admixed carbonate-volcaniclastics and/or in deeper marine deposits. Again localised fluid flow for alteration in the volcaniclastics is inferred with little noticeable fluid mixing between the carbonates and volcaniclastics. It is hoped this study will contribute to poorly understood diagenetic variations in carbonate-volcaniclastic systems, and particularly those from the equatorial tropics.

6.1.3 Variability in diagenesis of carbonate platform slope and basinal deposits

- Compaction and granular calcite cement are the common diagenetic features that have been seen in downslope reworked carbonates of the Tonasa Platform.
- Cementation is common within the thinsection components with only average % 25.
- The variability of original and clasts type and lithological components is a significant factor controlling the intensity of compaction.

- Tectonic activity, associated generation of accommodation space as well as graben sedimentary infill may affect the degree of burial diagenesis affecting the reworked carbonates.
- Long term faulting activity was a significant factor that influenced directly or indirectly the diagenesis of the reworked carbonate. Uplift and subsidence created differential accommodation space and high rates of sediments supply impacting the degree of compaction of deposits. Faulting also resulted in the localised subaerial exposure of the basement highs in western Segeri and eastern Western Divide Mountains Areas as evidenced in reworked clasts derived from the platform margin. Additionally fracturing, differing types of water influx and varied sediment supply are associated with the faulting.
- The variation in diagenetic features seen in the three areas and throughout the Rala section are partly linked to lithological and textural differences.

6.2 Suggestions for future work

- More detailed geochemical study could be undertaken of fracture infills to better evaluate fluid flow and relative to development of fractures and multi-stage fracturing.
- More work could be done on the geochemistry of the volcaniclastics of the Camba Formation that was beyond the scope of this study.
- The source of the silica in the slope deposits is still uncertain. This may open a new future research direction.
- Further geochemical study to better understand the dolomitising mechanism may be another future research avenue.
- Geochemistry of selected least altered components, together with palaeoecology and facies analysis is being used to characterise local and regional scale environmental and/or climatic change throughout the Cenozoic deposits of the Tonasa Limstone Formation (Marco Loche's PhD thesis, in preparation).

Chapter Seven

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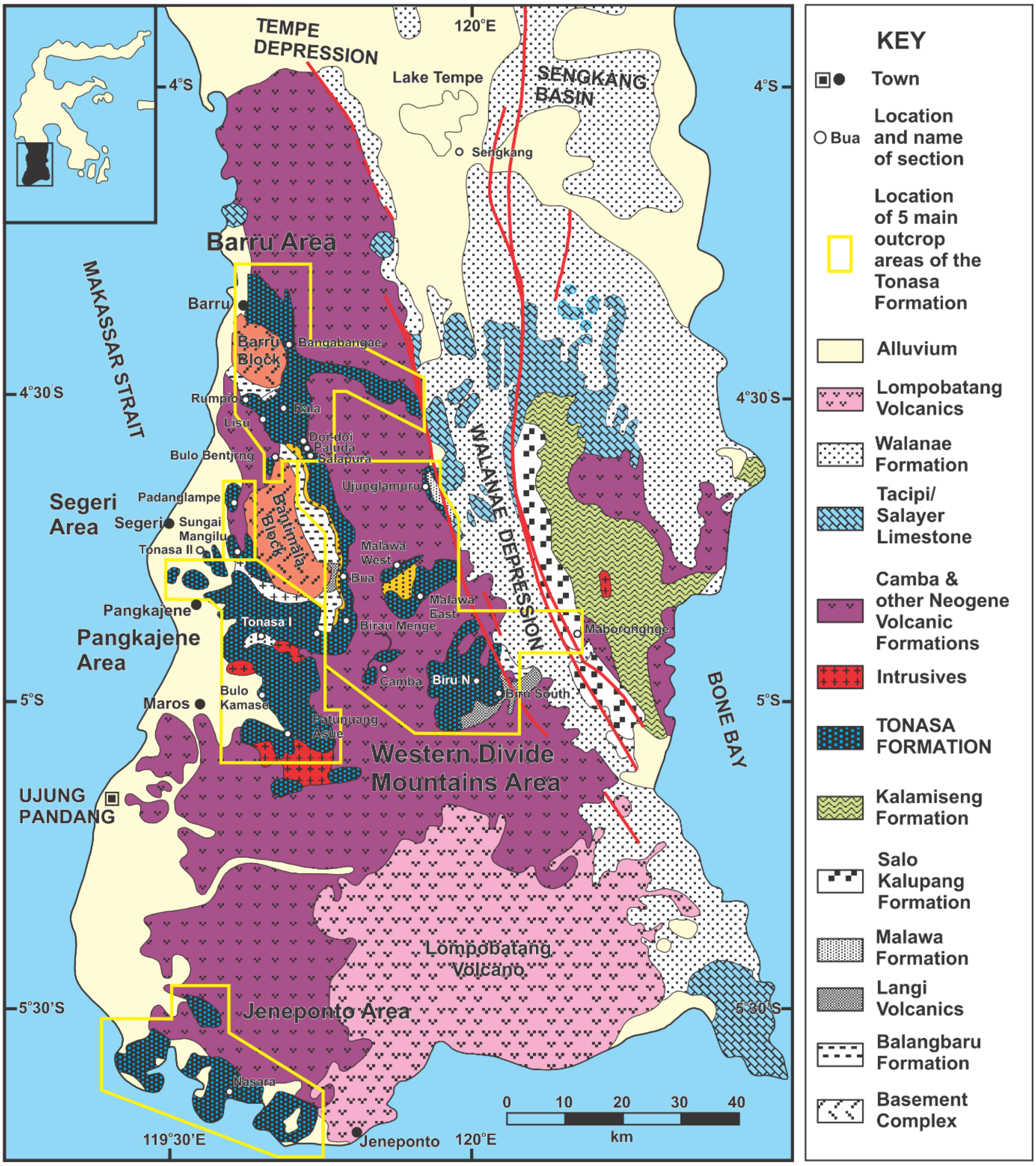
APPENDICES

APPENDIX A

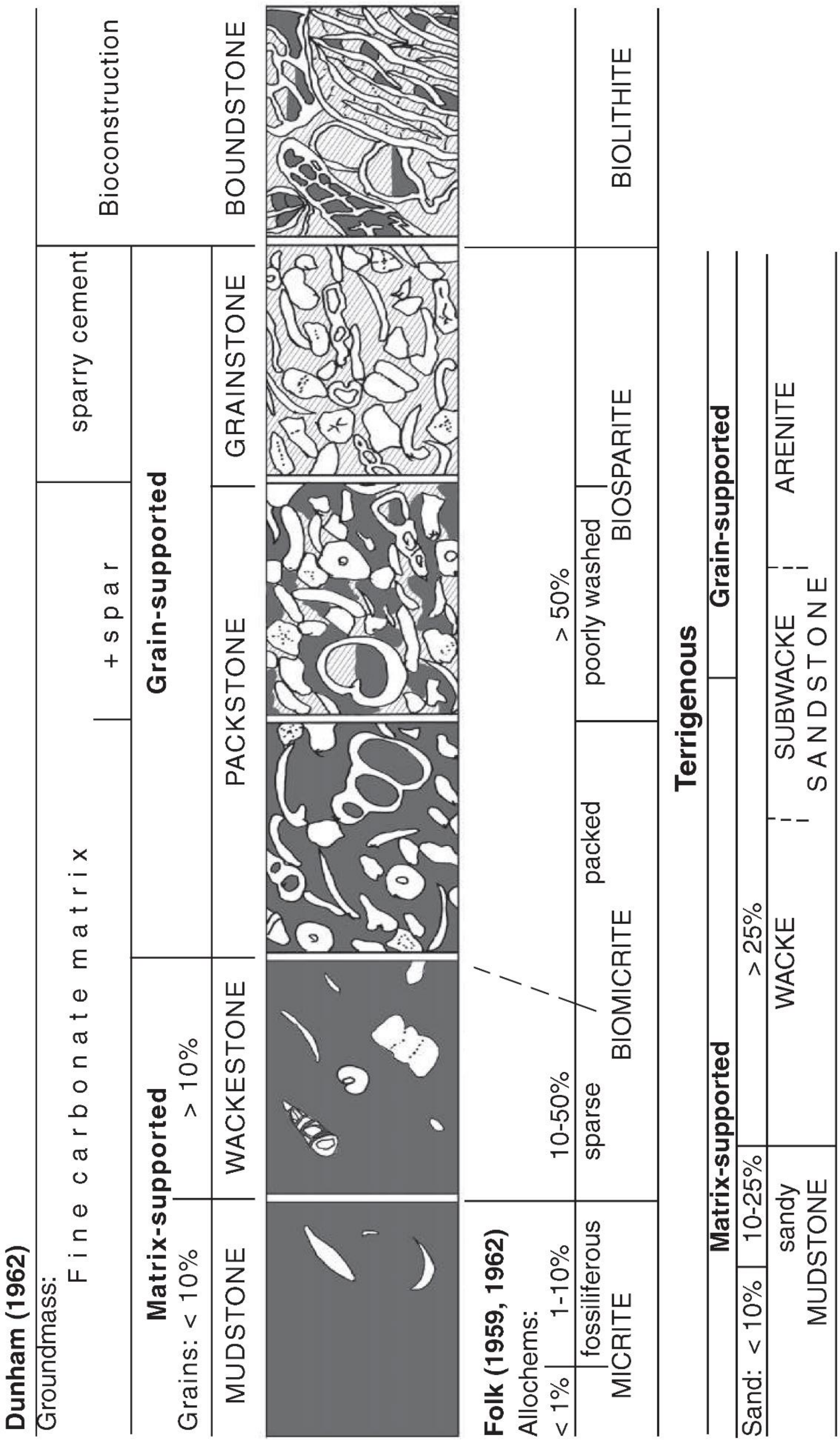
Geological map of South Sulawesi



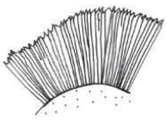
Appendix A: Geological map of South Sulawesi (modified after Wilson et al., 2000; after van Leeuwen, 1981; Sukamto, 1982; Sukamto and Supriatna, 1982; Wilson, 2000), showing the locations of the five main outcrop areas of the Tonasa Formation and the location of mentioned measured sections.

APPENDIX B

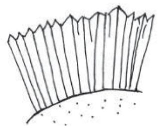
Classification and charts Schemes



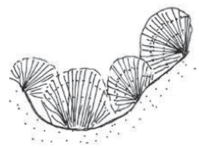
B1: Limestone classification scheme (Flugel, 2004)



Acicular: Needle-like crystals, growing normal to the substrate. Crystals elongated parallel to the c-axis, exhibiting straight extinction. Terminations are pointed or chisel-shaped, twinning is common. Width < 10 μm, length about 100 μm and more. Often forming isopachous crusts. Predominantly aragonite, but also Mg-calcite. Marine phreatic. Pl. 31/2, Pl. 34/1.

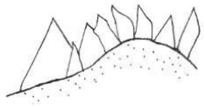


Fibrous: Fibrous crystals, growing normal to the substrate. Crystals show a significant length elongation, usually parallel to the c-axis. Crystal shape is needle-like or columnar (length to width ratio > 6:1, width > 10 μm). Size commonly fine to medium crystalline. Often forming isopachous crusts; common in inter- and intraparticle pores. Aragonite or High-Mg calcite. Mostly marine-phreatic, but also meteoric-vadose and marine-vadose (columnar crystal shape). Syn.: Radial fibrous. Pl. 2/4, Pl. 31/1-2, Pl. 32/1-4, Pl. 50/6.

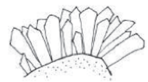


Botryoidal: Pore-filling cement made of individual and coalescent mamelons exhibiting discontinuous horizons, e.g. dust lines ranging in size from tens of microns to several centimeters. The cement consists of individual and compound fans, which in turn are composed of elongated euhedral fibers with a characteristic sweeping extinction in cross-polarized light. Aragonite. Usually marine (common in cavities of reefs and steep seaward slopes), but also known from burial environments. Syn.: Spherulitic. Pl. 145/1-3.

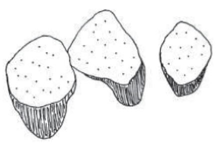
Radiaxial fibrous: Large, often cloudy and turbid, inclusion-rich calcite crystals with undulose extinction. Size medium to coarse crystalline. Sometimes extending several millimeters in length, usually about 30 to 300 μm. Crystal length/width ratio 1:3 to 1:10. Crystals show a pattern of subcrystal units. Within each subcrystal that diverges away from the substrate an opposing pattern of distally-convergent optic axes occurs, caused by a curvature of cleavage and twin lamellae. Undulose extinction of subcrystals or subcrystal units are used in distinguishing three radiaxial subtypes (see text). Often forming isopachous crusts. Phreatic-marine and burial. Pl. 27/2, Pl. 34/2; Fig. 7.9.



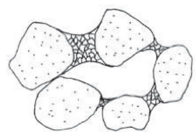
Dog tooth: Sharply pointed acute calcite crystals of elongated scalenohedral or rhombohedral form, growing normal and subnormal to the substrate (grain surfaces, atop earlier cements). Crystals are a few tens to a few hundred micrometers long and have acute and sometimes blunted terminations. Often meteoric and shallow-burial but also marine-phreatic and hydrothermal. Syn.: Bladed scalenohedral cement, bladed prismatic calcite cement, dentate cement, scalenohedral calcite cement. Pl. 2/3, Pl. 31/5-6, Pl. 34/8.



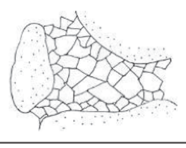
Bladed: Crystals that are not equidimensional and not fibrous. They correspond to elongate crystals somewhat wider than fibrous crystals (length/width ratio between 1.5:1 to 6:1) and exhibiting broad flattened and pyramid-like terminations. Crystal size up to 10 μm in width and between less than 20 and more than 100 μm in length. Crystals increase in width along their length. Commonly forming thin isopachous fringes on grains. Usually High-Mg calcite but also aragonite. Marine-phreatic (abundant in shallow-marine settings) and marine-vadose. Pl. 33/1, 3, 5, 8; Pl, 34/7.



Dripstone: Pendant cement characterized by distinct thickening of cement crusts beneath grains or under the roofs of intergranular and solution voids. The cement forms on droplets beneath grains after the bulk of the mobile water has drained out of the pores, leaving a thicker water film at the lower surface of the grains. Forms typically gravitational, beard-like patterns. Predominantly calcite. Formed below the zone of capillarity and above the water table within the meteoric-vadose zone (often associated with meniscus cement), but also in the meteoric-phreatic and sporadically in marine-vadose diagenetic environments (e.g. inter- and supratidal, and beachrocks: aragonitic dripstone cement). Syn.: Gravitational cement, microstalactitic cement, microstalactitic druse cement, stalactitic cement. Pl. 34/6, Pl. 126/1.



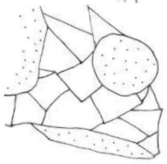
Meniscus: Calcite cement precipitated in meniscus style at or near grain-to-grain contacts in pores containing both air and water. Exhibits a curved surface below grains. Resulting intergranular pores have a rounded appearance due to the meniscus effect. Characteristically formed in the meteoric-vadose zone but may also occur in the phreatic-meteoric and the vadose-marine environment (beachrock). Pl. 14/1, Pl. 32/5-6, Pl. 33/4, Pl. 126/1.



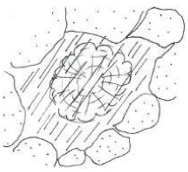
Drusy: Void-filling and pore-lining cement in intergranular and intraskeletal pores, molds and fractures, characterized by equant to elongated, anhedral to subhedral non-ferroan calcite crystals. Size usually >10 μm. Size increases toward the center of the void. Displays a characteristic fabric (see Fig. 7.12). Near-surface meteoric as well as burial environments. Syn.: Drusy calcite spar mosaic, drusy equant calcite mosaic. Pl. 10/2.

B3a: Cement types, part 1 (Flugel, 2004)

Granular: Calcite cement consisting of relatively equidimensional pore-filling small crystals. Common in interparticle pores, generally without distinct substrate control. Formed in meteoric-vadose, meteoric-phreatic and burial environments. Can also originate from recrystallization of pre-existing cements. Pl. 10/2.

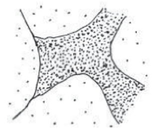


Blocky: Calcite cement consisting of medium to coarse-grained crystals without a preferred orientation. Characterized by variously sized crystals (tens of microns to several millimeters), often showing distinct crystal boundaries. Xenotopic and hypidiotopic crystal fabrics common. High-Mg calcite or Low-Mg calcite. Typically in meteoric (meteoric phreatic and vadose) and burial environments; rare in marine hardgrounds and reefs. Precipitated after the dissolution of aragonite cements or grains or as late diagenetic cement filling remaining pore space. Blocky textures can also originate from recrystallization of pre-existing cements. Pl. 20/1, Pl. 28/2, Pl. 34/1.



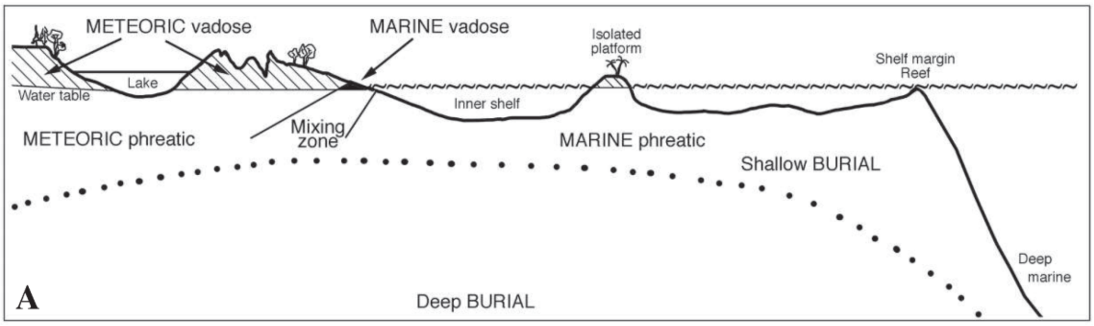
Syntaxial calcite overgrowth cement: Substrate-controlled overgrowth around a host grain made by a single crystal (usually High-Mg calcitic echinoderm fragments). Overgrowth often in crystallographic lattice continuity with the host grain. Echinoderm overgrowth is often zoned. Color differences between the skeletal grain and the overgrowth cement can be conspicuous. Overgrowth cements from near-surface marine, vadose-marine and meteoric-phreatic environments are inclusion-rich and cloudy, in contrast to clear overgrowth from deep burial environments Syn.: Grain overgrowth cement, syntaxial echinoderm cement, syntaxial cement rim, syntaxial overgrowth rim cement. Pl. 31/3-4, Pl. 34/3-4, Pl.144/5; Fig. 7.10.

Peloidal microcrystalline cement: Characterized by a peloidal (or pelleted) fabric composed of tiny peloids (size <100 μm) within a microcrystalline calcite matrix. The peloids consist of micrite-sized crystals bearing a radiating halo. Shallow-marine. Common in modern and ancient reefs. Possible interpretations: Chemical and/or microbially induced precipitation (Sect. 4.2.2). Pl. 8/5.



Microcrystalline or micrite cement: Micron-sized curved rhombic crystals. Forms thin coatings around grains, lines intraskeletal pores, fills pores completely or constructs bridges between grains (contributing to meniscus cement). Mg-calcite. Micritic cement fringes should be distinguished from micrite envelopes (Sect. 4.2.3). Often associated with peloidal cements. Pl. 31/3-4, Pl. 32/1-4, Pl. 33/2.

B3a: Cement types, part 1 (Flugel, 2004)

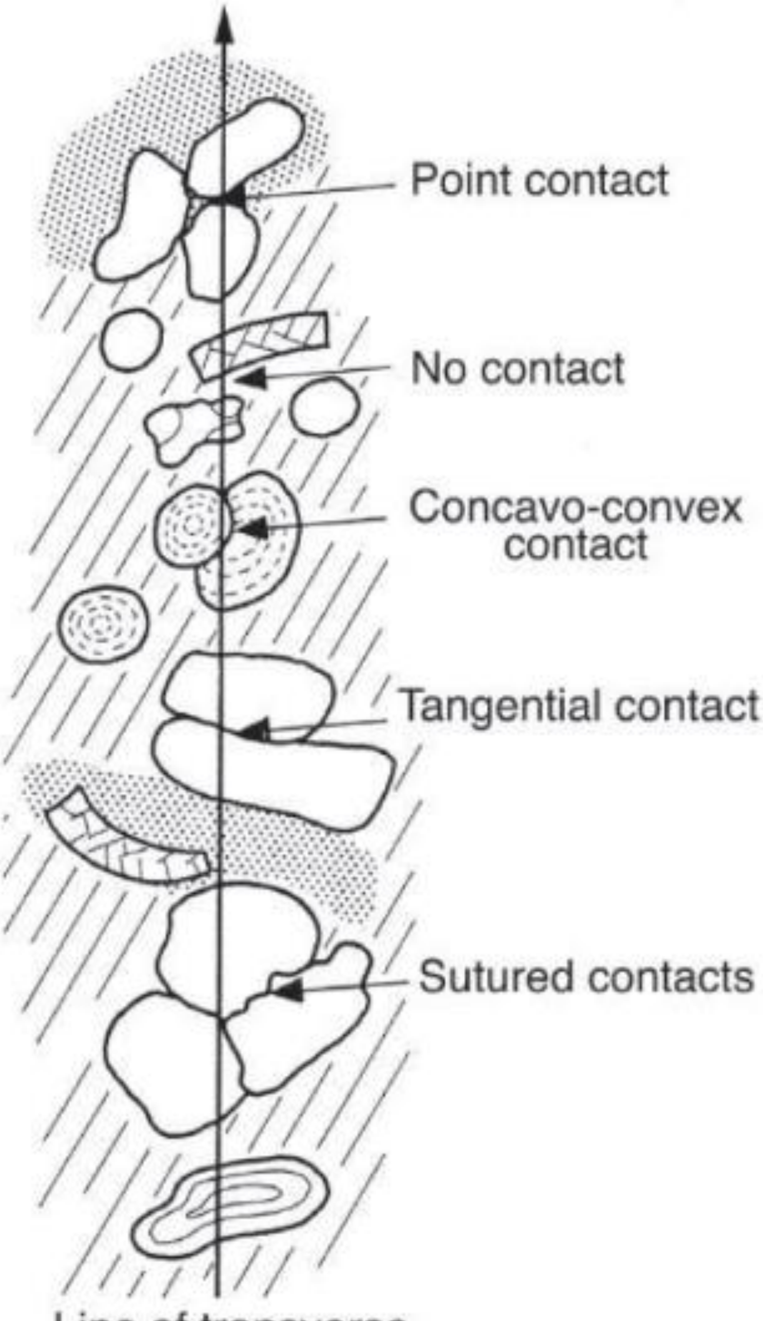


Diagenetic environment	Location	Pore Filling	Processes	~ Time needed
Meteoric vadose environment	Above water table, between land surface and meteoric phreatic zone	Pores filled with freshwater and/ or air	*Solution zone* (soil): Extensive solution; removal of aragonite; formation of vugs. *Precipitation zone* (near surface): Minor cementation	10^3 - 10^5 years
Meteoric phreatic environment	Below water table, may tend downwards 100s of meters	Pores filled with freshwater	*Solution zone* (e.g. sinkholes, caves): Solution; formation of molds and/or vugs. *Active zone* (upper part of meteoric phreatic environment): Dissolution of aragonite and Mg-calcite; rapid and diverse cementation; precipitation of calcite; creation of molds and vugs. *Stagnant zone* (deeper part and in arid climates): Little cementation; stabilization of aragonite and Mg-calcite	10^3 -10^5 up to 10^6 - 10^7 years
Marine phreatic environment	On the shallow or deep sea floor or just below	Pores filled with marine water	*Shallow-marine environment:* Waters oversaturated with respect to $CaCO_3$; rapid cementation by aragonite and Mg-calcite; diverse cement types. *Deep-marine and cold-water environments:* Waters undersaturated with respect to $CaCO_3$; strong dissolution of aragonite and calcite at two dissolution levels	10^1 - 10^4 years
Burial environment **B**	Subsurface beneath reach of surface-related processes, down to realm of low-grade metamorphism. May tend downwards 1000s of meters	Pores filled with brines of varying salinity, from brackish to highly saline	*Shallow burial* (first few meters fo tens of meters) and *deeper burial* (sediment overburden of hundreds to thousands of meters): Physical compaction; chemical compaction (pressure solution); cementation; porosity reduction	10^6 -10^8 years

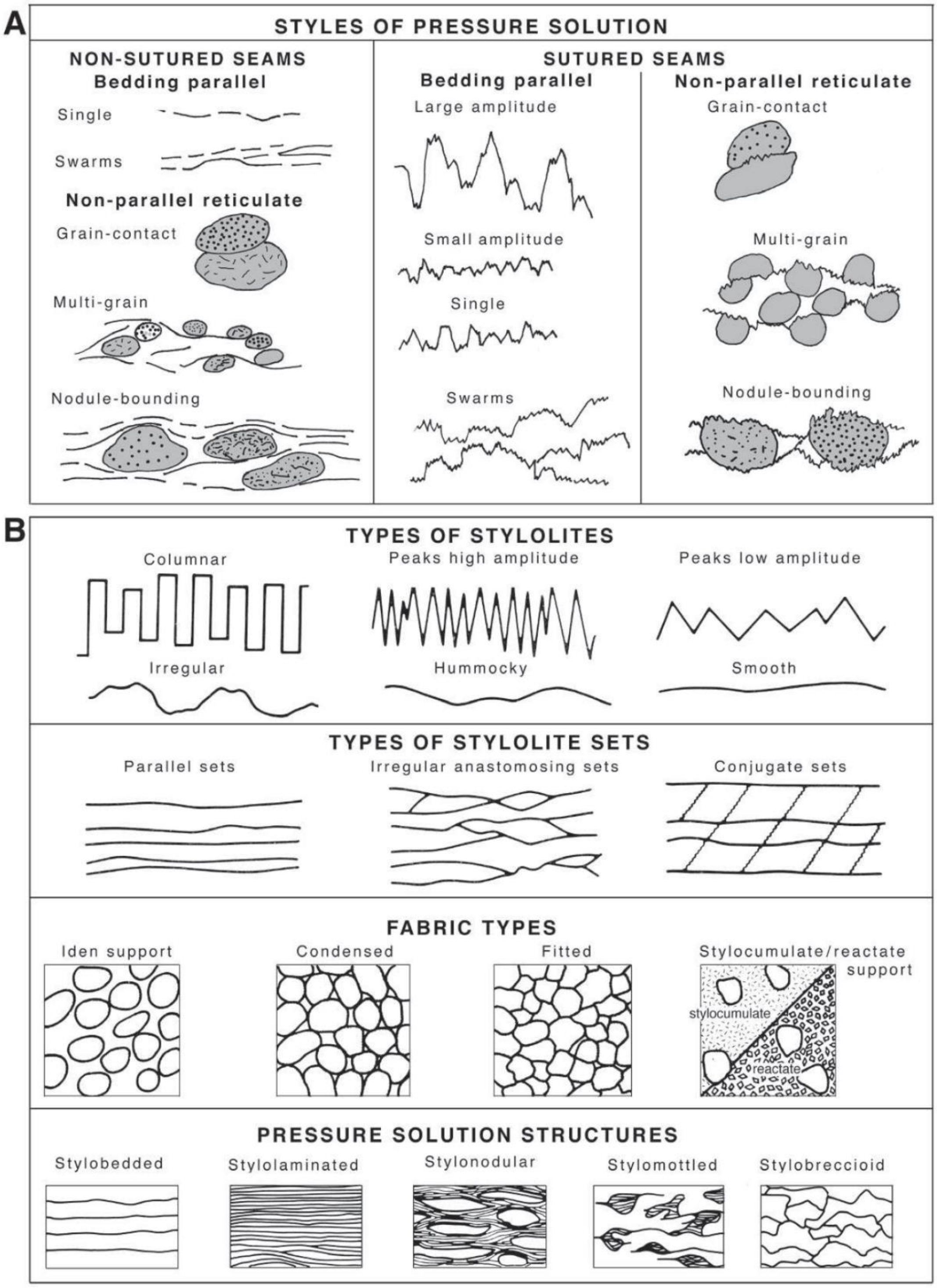
Fig. 7.2. *Major diagenetic environments.* **A** – Simplified scheme. Many of the studies dealing with the diagenesis of carbonate rocks are environment-specific and concentrate on processes affecting particular hydrogeochemically defined diagenetic environments. Carbonate diagenesis operates in the *meteoric environment*, the *marine environment* and the *burial environment*. In the *meteoric environment* pore space is occupied by freshwater and air (*meteoric vadose zone* above water table; hatched) or by freshwater (*meteoric phreatic zone*). The *marine-vadose zone* at the land-sea boundary and the *mixing zone* in coastal areas and shallow near-coastal subsurface exhibits meteoric and marine criteria. In the *marine phreatic environment* water is supersaturated with respect to $CaCO_3$ in shallow seas and undersaturated in cold and deep seas. The subsurface *burial environment* comprises the subsurface beneath the reach of surface-related processes down to the realm of low-grade metamorphism. Conventionally *shallow burial* and *deep burial* are differentiated. The term *near-surface diagenesis* refers to processes at or close to the sea floor and in the meteoric environment within the reach of surface-related processes related to depositional or weathering interfaces. Here, cementation is highly facies-specific. The terms eogenic, mesogenic and telegenic, introduced by Choquette and Pray (1970), refer to early near-surface, burial and uplift/unconformity-related processes (Sect. 7.3.2).

B – Major processes occurring in different diagenetic environments. The time involved in diagenetic processes varies significantly in different diagenetic zones. Early diagenetic solution/precipitation processes in meteoric vadose and shallow marine phreatic environments need far less time than late diagenetic deeper burial diagenesis, which can last millions of years. Similarly, unconformity-related meteoric phreatic processes may continue over very long time intervals. Early cementation in intertidal and shallow subtidal environments occurs within a range of almost recent to several tens to a few thousand years. Synsedimentary botryoidal cements on marginal slopes of platforms may grow over several tens of years, resulting in synsedimentary stabilization of steep carbonate slope deposits at or above angles of repose (Grammer et al. 1993).

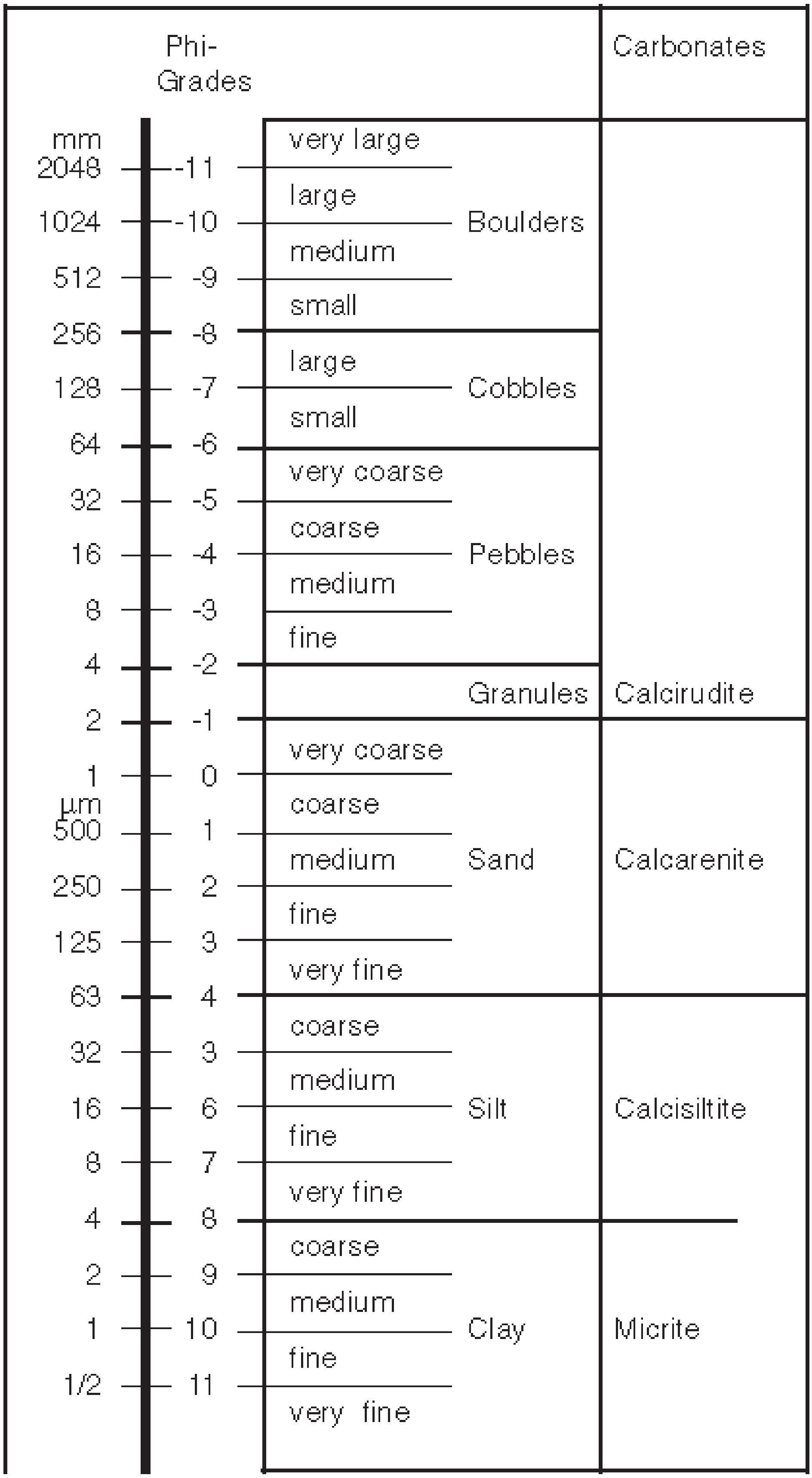
B3: Diagenetic environments and process (Flugel, 2004)



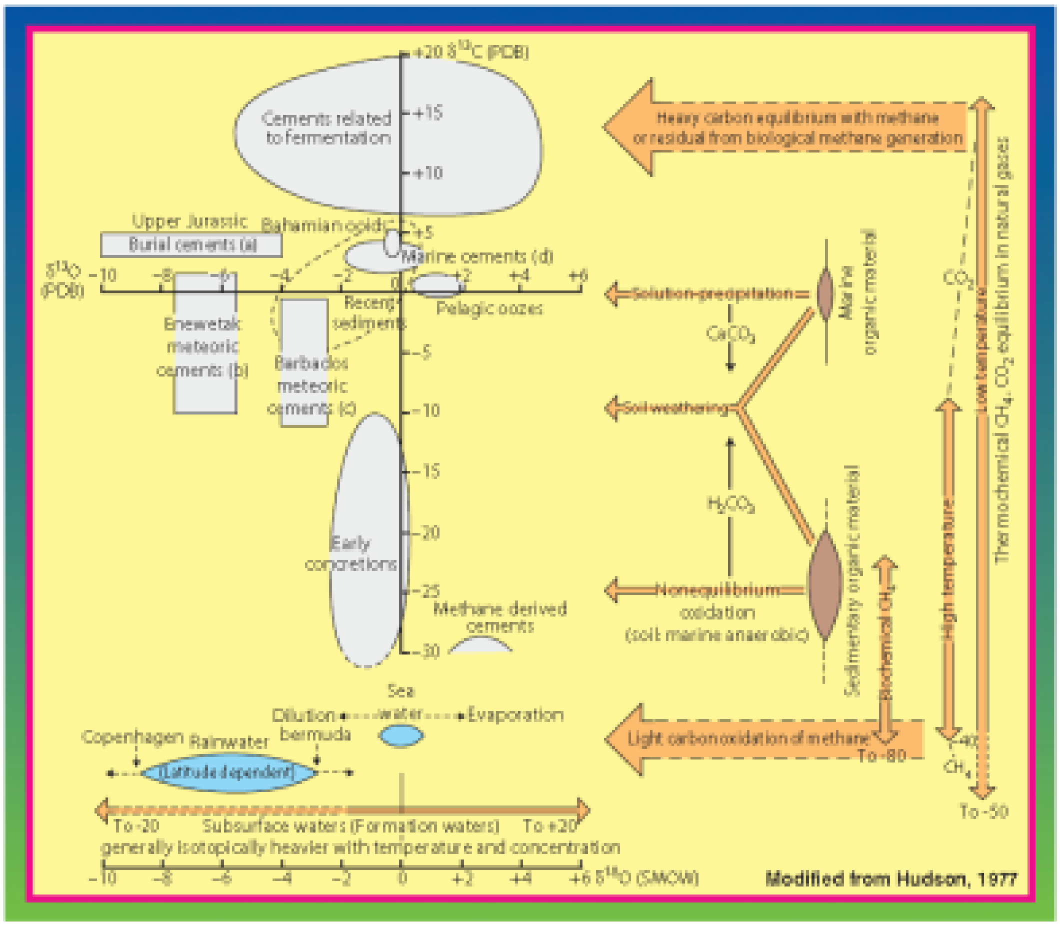
B4: Grain contact types according to (Tylor, 1950, Flugel, 2004)



B5: Pressure solution terminology (Flugel, 2004)



B6: Grain size scale (Flugel, 2004)



B7: Crossplot of carbon and oxygen isotopic compositions of some carbonate sediments, cements, and limestones showing distribution field of specific depositional and diagenetic environments. (Moore and Wade, 2013)

APPENDIX C

PETROGRAPHIC OBSERVATIONS AND PHOTOMICROGRAPHS RELATING TO CHAPTER 3

Appendix C1: Petrographic observations of samples relating to Chapter 2

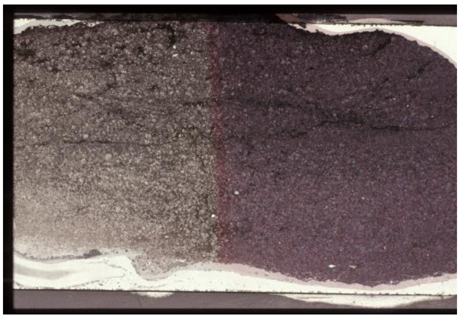
Section	Sample	Age Notes	Lithology (based on outcrop and thin section observations)	Micritization	Mechanical Bioclast / Grain Compaction	Syntaxial Overgrowth	Dissolution	Pore-Lining Cement (DT- Dog tooth, Bl- Bladed	Early Fracturing	Granular Mosaic Neomorphic Calcite (Fe- Ferroan)	Equante Calcite D - Drusy	Equante Calcite G - Granular	Equante Calcite B - Blocky	Dissolution Seams (se) - Stylolites (st)	Dolomite
BARRU AREA - Doi-Doi	T27	Tb-e	Planktonic foraminifera bioclastic grainstone	1	2										
BARRU AREA - Doi-Doi	T36	Tb-e	Marl	1	2									SE3	
BARRU AREA - Doi-Doi	T44	Tb-e	Planktonic foraminifera bioclastic grainstone	1	2				4	5				SE7	
BARRU AREA - Doi-Doi	DD111	Tb-e	Clast-supported breccia	1	2	3		4DT	4	5			6	ST7	
BARRU AREA - Doi-Doi	DD107	Tb-e	Bioclastic grainstone	1	2	3			4	5		6			
BARRU AREA - Doi-Doi	DD62	Tb-e	Clast-supported breccia	1	2			4DT		4			5		
BARRU AREA - Doi-Doi	DD56	Ta/b	Nummulites bioclastic packstone	1	2			4	3	4			4/5		6
BARRU AREA - Doi-Doi	DD58	Tb		1	2	3			5	4			6		
BARRU AREA - Doi-Doi	DD52	Eocene	Nummulites bioclastic packstone	1	2						3		8		
BARRU AREA - Doi-Doi	DD46	Eocene	Nummulites & quartzose grainstone	1	2	3		4Bl	4	5			5		
BARRU AREA - Doi-Doi	DD45	Eocene	Nummulites & quartzose grainstone	1	2	3				4			5		
BARRU AREA - Doi-Doi	DD29	Eocene	Nummulites & quartzose grainstone	1	2	3		6Bl	4	5			6		7
BARRU AREA - Doi-Doi	DD11	Ta/b	Imperforate foraminifera & coral bioclastic pack/floatstone	1	2				3	4					
BARRU AREA - Doi-Doi	DD1	Eocene	Nummulites bioclastic packstone	1	2					3		4			5
Rumpio	R2	Ta/b	Bioclastic pack/rudstone	1	2							3		SE4	
Rumpio	R6	Ta/b	Nummulites bioclastic grainstone	1	2	3				4				SE6	
Rumpio	R7	Tb/f	Clast-supported breccia	1	2	3			4	5			5/6		6
Salo Cinee	SC6B	Tb-f	Limestone clast from breccia: Nummulites and Discocyclina bioclastic packstone	1	2	3		5Bl	4	5			6		
Salo Maraung	SMA2	Tb-f	Discocyclina & Biplanispira bioclastic packstone	1	2	3			4			5	5		
Salo Maraung	SMA6	Tb-f	Discocyclina & Biplanispira bioclastic packstone	1	2	3			4	5		5/6		ST7	
Salo Maraung	SMA8	Tb-f	Karstified Discocyclina & Biplanispira bioclastic packstone	1	2			3Bl		3/4	4		4	SE5	
Salo Maraung	SMA9	Tb-f	Breccia Clast (?serpentinite)	1	2			3Bl					5		4Silt
Salo Tinre	ST16	Tb-f	Karstified bioclastic packstone	1	2	3		4Bl	4	5			5/6		
BARRU AREA - Bangabangae	SP13	Tb-e	Shale matric-supported limestone conglomerate	1	2					3					
BARRU AREA - Bangabangae	SP18	Tb-e	Graded bioclastic grainstone fining upward to a packstone	1	3	2				4					
BARRU AREA - Bangabangae	SP25	Tb-e	Silicified planktonic foraminifera bioclastic packstone	1	2	3		4Bl	5	6				ST4	
BARRU AREA - Bangabangae	BBP11	Tb-e	Planktonic foraminifera packstone	1	2					3				4SE	
BARRU AREA - Bangabangae	BBP8	Tb-e	Planktonic foraminifera bioclastic packstone	1	2	3			4	5			5		
BARRU AREA - Bangabangae	SP29	Tb	Bioclastic grainstone	1	2					3		4	4	5	
BARRU AREA - Bangabangae	SP32	Tb	Biplanispira & Pellatispira bioclastic packstone	1	2			3DT		4			5		
BARRU AREA - Bangabangae	SP36	Tb	Clast-supported breccia overlain by graded bioclastic packstone	1	2	3		5	4	5	6	6		SE6	
BARRU AREA - Bangabangae	SP43	Eocene	Nummulites bioclastic packstone	1	2				3	4					5
Bete - B. Bintjeng	DC11	Tb	Pellatispira & algal bioclastic pack/boundstone	1	2	3				4		4/5			
Bete - B. Bintjeng	DC10	Tb	Pellatispira & coralline algal bioclastic pack/grainstone	1	2	3			4	5			5		
Bete - B. Bintjeng	DC2	Tb	Pellatispira & coralline algal bioclastic pack/grainstone	1	2	3			4	5			5		
BARRU AREA - Rala	J82	Te	Clast-supported breccia	1	2	3		4Bl		4			4		
BARRU AREA - Rala	J69	Td-e	Clast-supported breccia	1	2	3		4Bl		4/5	5	5		ST6	
BARRU AREA - Rala	J45	Td-e	Graded bioclastic grainstone fining upward to a packstone	1	2	3		4		4				SE5	6
BARRU AREA - Rala	D79	Tb/c	Planktonic foraminifera bioclastic packstone	1	2	3			4	4		5	5	SE6	
BARRU AREA - Rala	D47	Tb/c	Graded bioclastic packstone	1	2	3				4			5		
BARRU AREA - Rala	D25	Tb	Clast-supported breccia overlain by graded bioclastic packstone	1	2					4			4	SE5	
BARRU AREA - Rala	D6	Late Eocene	Graded bioclastic grainstone fining upward to a packstone	1	2	3			5	4			6		
BARRU AREA - Rala	DR25	Late Eocene	Planktonic foraminifera bioclastic grainstone	1	2	3			4	5			6	SE7	
BARRU AREA - Rala	DR11	Late Eocene	Graded bioclastic packstone	1	2	3			4				5		
BARRU AREA - Rala	RR13	Ta/b	Planktonic foraminifera packstone	1	2					3				SE5	
BARRU AREA - Rala	SU73	Eocene	Bioclastic grainstone	1	2	3			4				5		
BARRU AREA - Rala	SU42	Eocene	Nummulites & coralline algal bioclastic grainstone	1	2				3	4			5		6
BARRU AREA - Rala	SU29a	Eocene	Bioclastic coral floatstone	1	2				3	4			5		6
BARRU AREA - Rala	SU4a	Eocene	Bioclastic packstone	1	2	3				4			5		6
BARRU AREA - Rala	SUM5	Eocene	Bioclastic packstone	1	2				4	3			5	SE6	
S. PANGKAJENE - Patunuang Asue	SAM6	Miocene	Coral bioclastic floatstone	1	2					3			4		
S. PANGKAJENE - Patunuang Asue	SAM10	Miocene	Bioclastic packstone	1	2					3	4	4	4	5	
S. PANGKAJENE - Patunuang Asue	SAM12	Oligocene	Coral & alveolinid bioclastic wacke/packstone	1	2					3	4	4	4		
S. PANGKAJENE - Patunuang Asue	SAM26	Oligocene	Bioclastic wacke/packstone	1						2				3	
S. PANGKAJENE - Patunuang Asue	SAM42a	Oligocene	Bioclastic wackestone	1	2	3			4	5		5			
S. PANGKAJENE - Patunuang Asue	SAM53	Oligocene	Bioclastic packstone	1	2					3					
S. PANGKAJENE - Patunuang Asue	SAM62	Oligocene	Heterostegina & Spiroclypeus wacke/packstone	1	2					3		3			
S. PANGKAJENE - Patunuang Asue	PA38	Oilgocene	Dolomitised bioclastic wackestone												
S. PANGKAJENE - Patunuang Asue	PA34	Oilgocene	Bioclastic wacke/packstone	1						2			3		
S. PANGKAJENE - Patunuang Asue	PA21	Oilgocene	Coral & Heterostegina bioclastic packstone	1	2					3	4	4	4		5
S. PANGKAJENE - Patunuang Asue	PA12	Oilgocene	Brecciated mudstone with bioclastic pack/grainstone infill	1		2				3	4		4		
S. PANGKAJENE - Patunuang Asue	PA2	Oilgocene	Coral, lithoclast & Heterostegina bioclastic rudstone	1	2	3			4	5	6	6	6		
N. PANGKAJENE - Tonasa-II Quarry	TII-85	Oilgocene	Miliolid & alveolinid bioclastic pack/grainstone	1	2					3		4			
N. PANGKAJENE - Tonasa-II Quarry	TII-84	Oligocene	Bioclastic packstone	1	2	3				4		5			
N. PANGKAJENE - Tonasa-II Quarry	TII-71	Oligocene	Lepidocyclina & Heterostegina bioclastic wacke/packstone	1	2			Bl	3	4	5	5	5		
N. PANGKAJENE - Tonasa-II Quarry	TII-68	Oligocene	Lepidocyclina & Heterostegina bioclastic wacke/packstone	1	2					3		3			
N. PANGKAJENE - Tonasa-II Quarry	TII-49	Oligocene	Algal laminite												
N. PANGKAJENE - Tonasa-II Quarry	TII-47	Oligocene	Lepidocyclina & Heterostegina bioclastic packstone	1	2				3	4		5		6	
N. PANGKAJENE - Tonasa-II Quarry	TII-34	Oligocene	Coral, miliolid, alveolinid & Lepidocyclina bioclastic float/packstone	1	2				3	4		5	5	6	
N. PANGKAJENE - Tonasa-II Quarry	TII-31	Oligocene	Lepidocyclina & coral bioclastic floatstone	1	2	3			4	5	6		6		
N. PANGKAJENE - Tonasa-II Quarry	TII-27	Oligocene	Miliolid, alveolinid & Lepidocyclina bioclastic wacke/packstone	1	2			Bl	3	4	5	5	5		
N. PANGKAJENE - Tonasa-II Quarry	TII-17	Oligocene	Miliolid, alveolinid & Lepidocyclina bioclastic packstone	1	2	3				4		5			
N. PANGKAJENE - Tonasa-II Quarry	TII-4	Oligocene	Bioclastic packstone	1				Bl		2					
N. PANGKAJENE - Tonasa-II Quarry	TII-1	Oligocene	Bioclastic packstone	1	2	3				4				ST5	
C. PANGKAJENE - Lapangan Golf	GC58	Early Oligcene	Dolomite	1	2	3			4	5		5	5		
C. PANGKAJENE - Lapangan Golf	GC52	Late Eocene	Dolomite										1		2
C. PANGKAJENE - Lapangan Golf	GC45	Late Eocene	Bioclastic packstone	1	2	3				4					
C. PANGKAJENE - Lapangan Golf	GC30	Late Eocene	Dolomitised Discocyclina & Pellatispira bioclastic packstone	1	2	3				4					5
C. PANGKAJENE - Lapangan Golf	GC25	Late Eocene	Dolomitised bioclastic packstone	1	2	3				4					5
C. PANGKAJENE - Lapangan Golf	GC20	Late Eocene	Bioclastic grainstone	1	2	3			4		5		5		
C. PANGKAJENE - Lapangan Golf	GC15	Late Eocene	Bioclastic packstone	1	2	3		Bl		4	5		5		
C. PANGKAJENE - Lapangan Golf	GC10	Late Eocene	Coral bioclastic floatstone	1					2	3					

C. PANGKAJENE - Lapangan Golf	GC9	late Eocene	Miliolid bioclastic grainstone	1	2	3			4	5			5		
C. PANGKAJENE - Lapangan Golf	GC5	late Eocene	Bioclastic packstone												
C. PANGKAJENE - Lapangan Golf	GC3	late Eocene	Bioclastic packstone	1	2	3			4	5		5			
Patunuang Asue	P1	Te1-4 Oilgocene	Bioclastic packstone	1	2	3			4					4	
Patunuang Asue	P8	Te1-4 Oilgocene	Planktonic foraminifera bioclastic packstone	1	2					4	4	4	4	SE4	
Patunuang Asue	P7	Te1-4 Oilgocene	Bioclastic pack/grainstone	1	2	3		Bl	4	5			5		
Patunuang Asue	P18-A	Te1-4 Oilgocene	Breccia clast: Karstified coral & coralline algal floatstone	1	2	3			4	5Fe				SE4	
Patunuang Asue	P18-E	Te1-4 Oilgocene	Breccia clast: Discocyclina bioclastic packstone	1	2	3			4						
Patunuang Asue	P19	Te1-4 Oilgocene	Clasts supported breccia	1	2	3			4	6					
Patunuang Asue	P22	Te1-4 Oilgocene	Planktonic foraminifera packstone	1	2	3			3	4Fe		4		SE3	
Patunuang Asue	P23	Te1-4 Oilgocene	Clasts supported breccia	1	2	3			5		6	6	6	SE4	
Patunuang Asue	P30	Te1-4 Oilgocene	Bioclastic packstone	1	2	3			5	4					
Patunuang Asue	SMa7	Te1-4 Oilgocene	Bioclastic grainstone	1	2	3				4	4	4	4		
Patunuang Asue	SMa11	Te1-4 Oilgocene	Quartzose bioclastic grainstone	1	2	3		Bl	4	5	5		5	SE6	??
Patunuang Asue	SMa18	Te1-4 Oilgocene	Coralline algal bioclastic packstone	1	2	3			4		5		5		
Patunuang Asue	SMa22	Te1-4 Oilgocene	Discocyclina bioclastic packstone	1	2	3			5Fe		6		6	SE4	
Patunuang Asue	SMa23	Te1-4 Oilgocene	Silicified planktonic foraminifera bioclastic packstone							Fe				SE	
Patunuang Asue	SMa24	Te1-4 Oilgocene	Graded bioclastic packstone	1	2	3			4			7	5		
Patunuang Asue	SMa26c	Te1-4 Oilgocene	Breccia clast: Karstified Discocyclina bioclastic packstone	1	2	3			4Fe	5	5	5	5	SE6	
Patunuang Asue	SMa27	Te1-4 Oilgocene	Clasts supported breccia	1	2	3			5					SE4	
Patunuang Asue	SMa37	Te1-4 Oilgocene	Graded bioclastic packstone	1	2	3			4		5	5	5		
Patunuang Asue	SMa40	Te1-4 Oilgocene	Planktonic foraminifera packstone	1	2	3			5					SE4	
Patunuang Asue	SMa47	Te1-4 Oilgocene	Planktonic foraminifera packstone	1	2	3					6	4	6		
Patunuang Asue	SMa47a	Te1-4 Oilgocene	Planktonic foraminifera packstone	1		2						2		SE	
Patunuang Asue	SMa49	Te1-4 Oilgocene	Planktonic foraminifera wacke/packstone	1	2				4Fe		2	5	5	SE6	
Patunuang Asue	SMa30	Te1-4 Oilgocene		1	2	3			5		6		6	SE4	
Camba	CG6	E-M Miocene	Karstified coral bioclastic pack/floatstone	1	2	3		DT	4	6/7	7	7	7	ST8	
Camba	CG7	E-M Miocene	Laminated karst filling sediment	1	2				3					ST5	
Camba	CG9	E-M Miocene	Karstified bioclastic packstone	1	2	3		DT	4		6		6		
Camba	CG10		Karstified bioclastic packstone	1	2			Bl	3	4/5	5/6	5/6	5/6	SE7	
Bua (S. Ralla)	BM12		Arkosic bioclastic grainstone	1	2	3			4	6	6/7	6/7	6/7	SE8	
Bua (S. Ralla)	BM20	E-M Miocene	Clasts supported breccia	1	2	3		R		4	4/5	4/5	4/5		
Bua (S. Ralla)	BM36	late Eocene	Coral quartzose bioclastic rud/packstone	1	2	3			6	4				SE5	
Ujunglamuru	UL3	late Eocene	Miliolid bioclastic pack/grainstone	1	2	3		Bl	4	5	5/6		5/6		
Ujunglamuru	UL19		Miliolid & coral bioclastic packstone	1	2				4	5		5/6	5/6	ST3	
Malawa	MC1A	late Eocene	Arkosic planktonic foraminifera bioclastic packstone	1	2	3								ST5	
Malawa	MC2A	late Eocene	Recrystallised bioclastic packstone	1	2				3	4	4/58	4/5	4/5/8	SE6	
Malawa	MC7	late Eocene	Karstified miliolid bioclastic packstone	1	2	3			4	5/6	6		6		
Maborongnge	WM5	late Eocene	Discocyclina & Pellatispira bioclastic pack/grainstone	1	2	3		DT			5		5		
Maborongnge	WM9	late Eocene	Pellatispira bioclastic packstone	1	2	3			4			5			
Biru	WP1	late Eocene	Quartzose bioclastic pack/grainstone	1	2	3			4	4/5	5		5		
Biru	WP12	Oligocene	Altered miliolid bioclastic packstone	1	2	3			4	5	5/6		5/6		
Biru	LP11	E-M Miocene	Clasts supported breccia	1	2	3		Bl	4	5	5/6		5/6	ST7	
Biru	LP4	L-M Miocene	Volcaniclastic bioclastic packstone	1	2				3	4		4/5	4/5	SE6	
Biru	LB14	Late Eocene	Planktonic foraminifera bioclastic packstone	1	2	3			4		5		5	SE6	
Biru	LB2	late Eocene	Bioclastic pack/grainstone	1	2	3			4	5	5/6		5/6		
Bua (S. Ralla)	SRa77	Early Miocene	Planktonic foraminifera bioclastic packstone	1	2	3				4Fe	8	4/5/8	8	SE6	
Bua (S. Ralla)	SRa72	Oligocene	Miliolid & coral bioclastic pack/floatstone	1	2				3	4		/4/5	4/5		
Bua (S. Ralla)	SRa66	late Eocene	Pellatispira bioclastic packstone	1	2	3			4						
Bua (S. Ralla)	SRa58	late Eocene	Discocyclina bioclastic packstone	1	2	3		Bl	4		5	5			
Bua (S. Ralla)	SRa52	late Eocene	Discocyclina & Nummulites bioclastic packstone	1	2				3	4				ST7	
Bua (S. Ralla)	SRa50	Late Eocene	Dolomitised quartzose bioclastic packstone	1	2				3	4				SE6	7
Bua (S. Ralla)	SRa10	late Eocene	Discocyclina & Pellatispira bioclastic pack/grainstone	1	2	3			4		5	5	5		
Nasara Jeneponto	NJ79	NN4-5 early-middle Miocene	Coarse planktonic foraminifera packstone	1	2					4				ST5	
Nasara Jeneponto	NJ76	?Early to Middle Miocene	Medium arenaceous (volcaniclastic) planktonic foraminifera packstone	1	2	3				4		4		SE5	
Nasara Jeneponto	NJ75	NN4-5 early-middle Miocene	Coarse planktonic foraminifera packstone	1	2					3				4	
Nasara Jeneponto	NJ71	?Early to Middle Miocene	Medium arenaceous (volcaniclastic) planktonic foraminifera packstone		1				1					ST	
Nasara Jeneponto	NJ64	NN4-5 early-middle Miocene	Coarse bioclastic planktonic foraminifera packstone	1	2	3			4	5		5	5	ST6	
Nasara Jeneponto	NJ63	NN4-5 early-middle Miocene	Medium planktonic foraminifera wacke/packstone	1	2					3			3	ST4	
Nasara Jeneponto	NJ49	Oligocene	Coarse bioclastic planktonic foraminifera packstone	1	2	3				4		5			
Nasara Jeneponto	NJ40	NP18-20 Late Eocene	Medium arenaceous bioclastic packstone	1	2	3				4Fe				SE5	
Nasara Jeneponto	NJ35	late Eocene	Medium arenaceous bioclastic pack/grainstone	1	2	3			4	5Fe				SE6	
Nasara Jeneponto	NJ29	late Eocene	Coarse arenaceous bioclastic pack/grainstone	1	2	3			4	5Fe		6	6		
Nasara Jeneponto	NJ24	NP18-20 Late Eocene	Coarse arenaceous bioclastic planktonic foraminifera packstone	1	2	3			4	5		5	5	SE6	
Nasara Jeneponto	NJ21	late Eocene	Coarse bioclastic packstone	1	2	3				5	6	6	6	SE7	8
Nasara Jeneponto	NJ15	NP17-20 Late Eocene	Fine planktonic foraminifera bioclastic wacke/packstone	1	2	3				4	4	4		SE5	
Nasara Jeneponto	NJ9	late Eocene	Coarse bioclastic planktonic foraminifera packstone	1	2	3			4	5			5	SE6	
Nasara Jeneponto	NJ7	late Eocene	Fine planktonic foraminifera bioclastic packstone	1	2	3				4				SE5	
Nasara Jeneponto	NJ4	late Eocene	Coarse bioclastic planktonic foraminifera packstone	1	2	3			4	5		5	5	SE6	
Nasara Jeneponto	NJ1	late Eocene	Altered planktonic foraminifera wacke/packstone	1					2				4	SE3	

Dominant >
Abundant 25% - 50%
Common 5% - 25%
Present 1% - 5%
Rare 0.1% - 1 %
Trace < 0.1%

Appendix C2: Thin Section photomicrographs of samples relating to Chapter 2

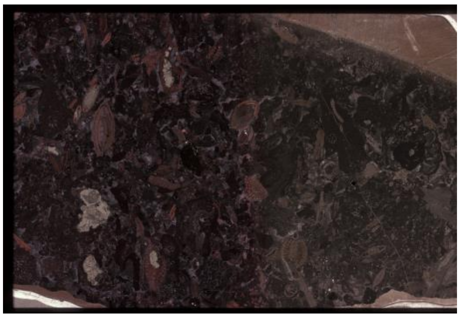
BBP8



BBP11

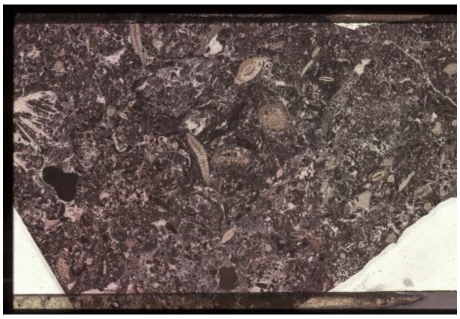
D25

D47

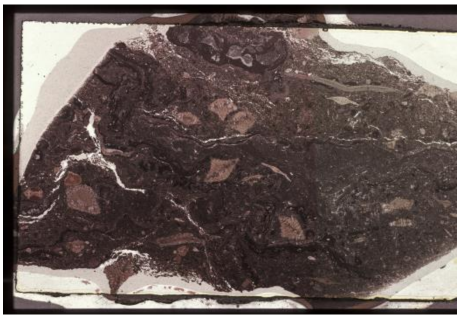


D79

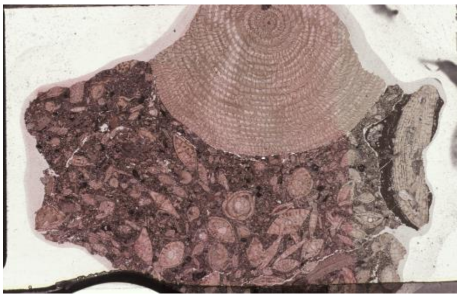
DC2



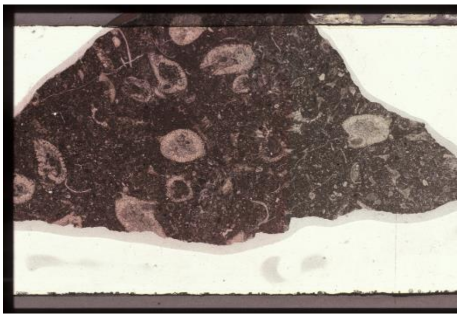
DC10



DC11



DD1



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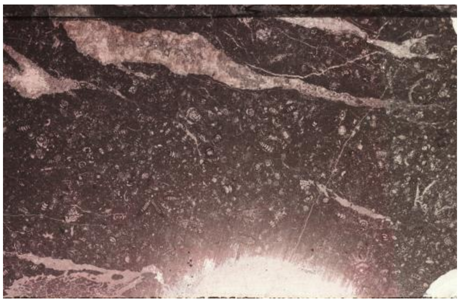

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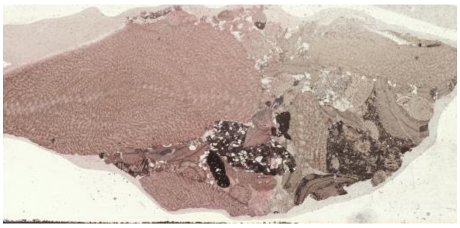
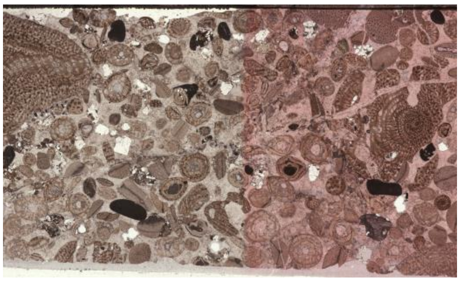


DD45



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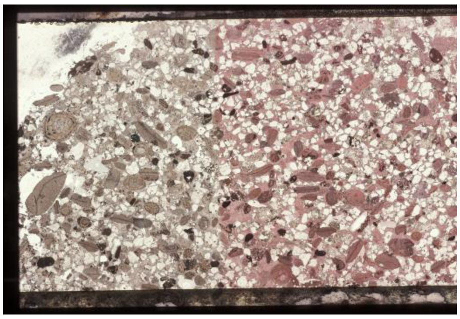

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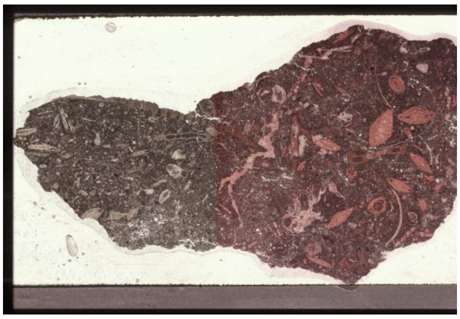

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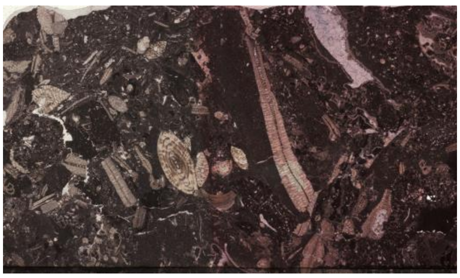

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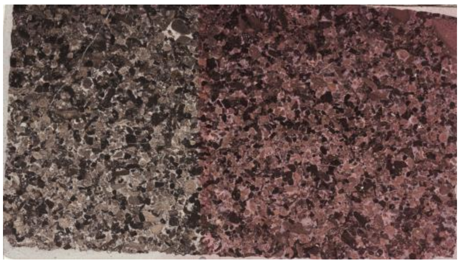
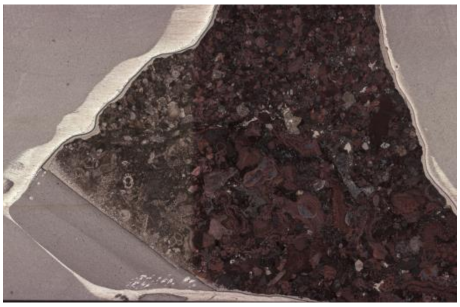
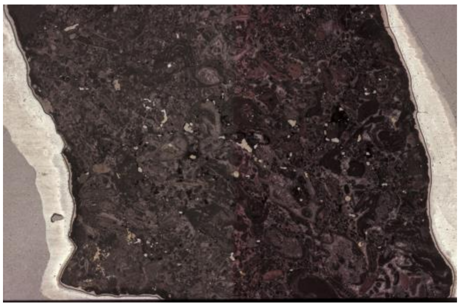


DD107

DD111



J45



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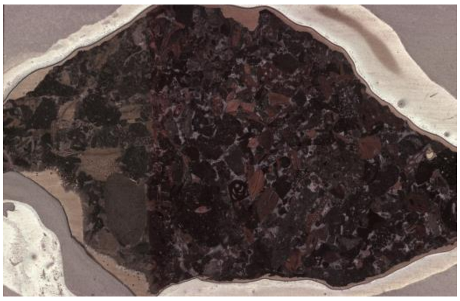

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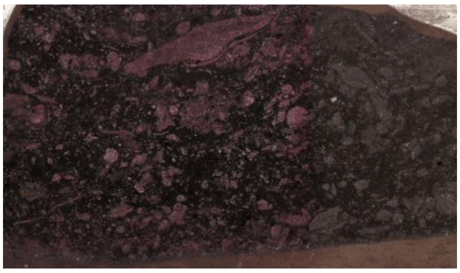
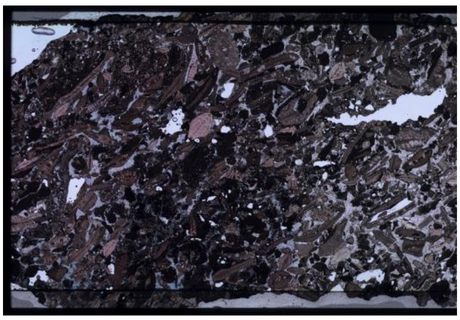


R2

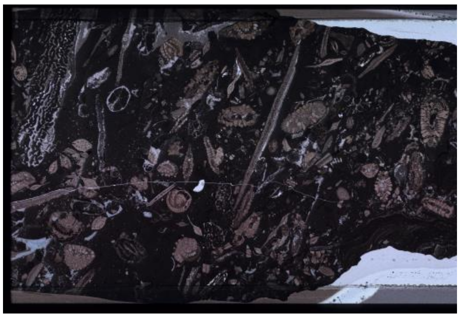
R6

R7

SC6b

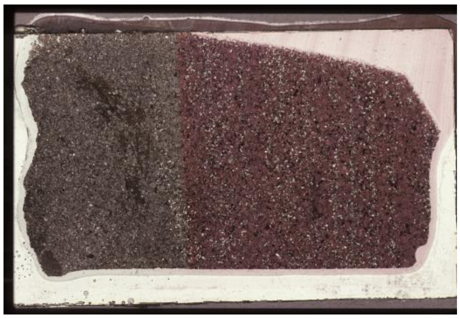


SM^2


SM^6


SM^8


SM^9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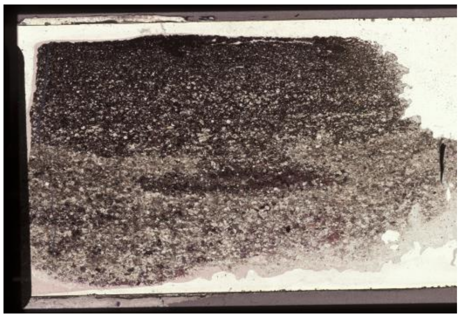
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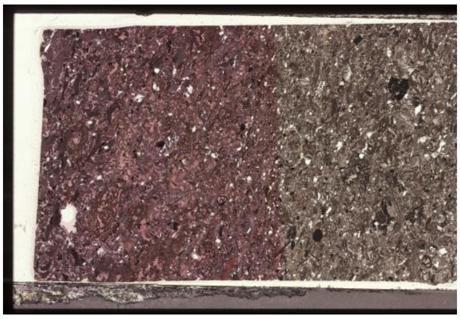
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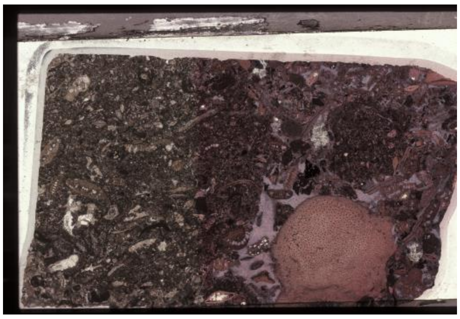
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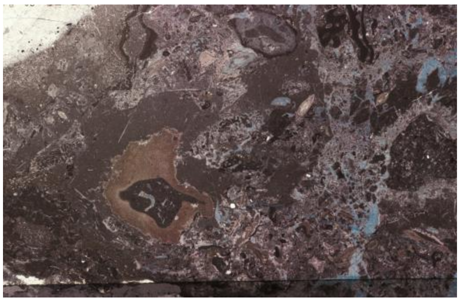
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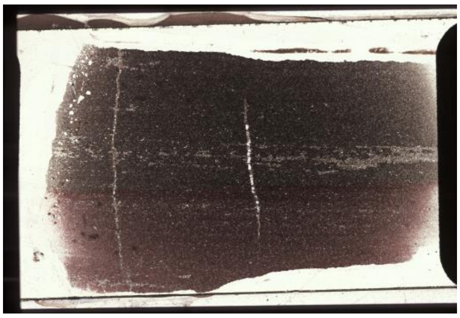
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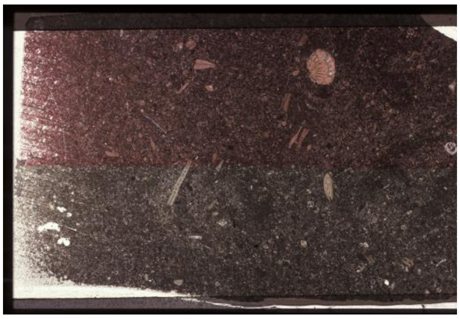
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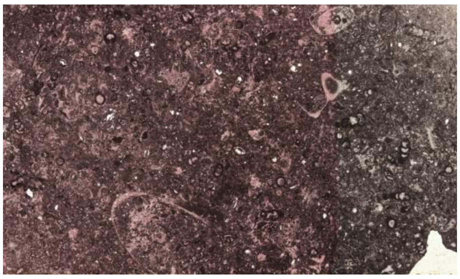
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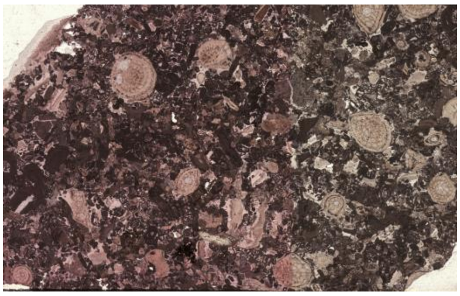
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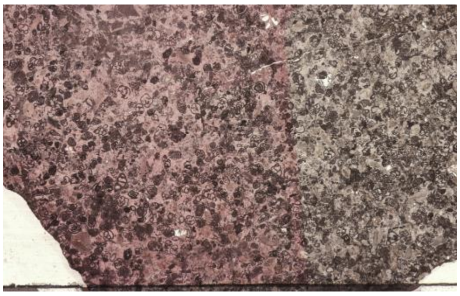
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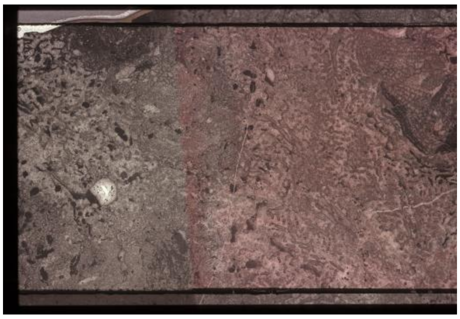
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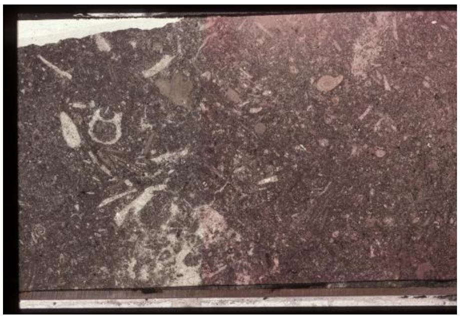
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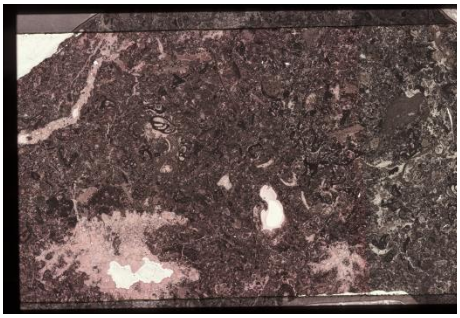
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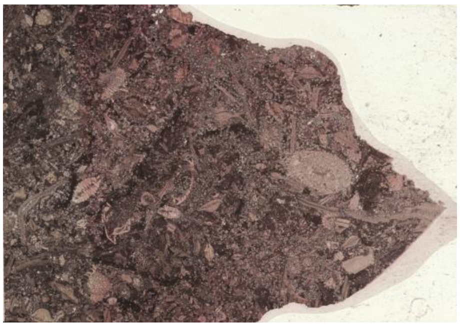
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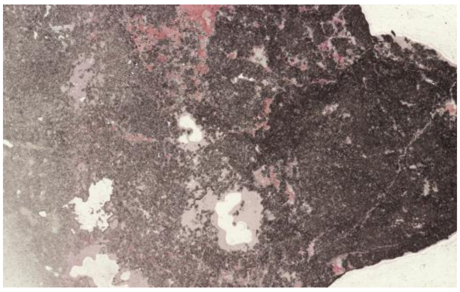
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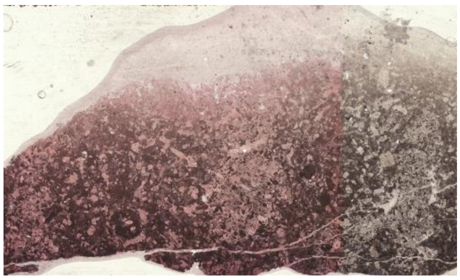
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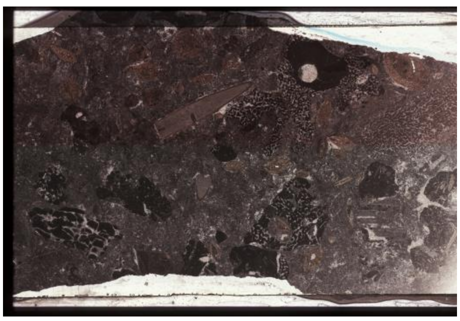
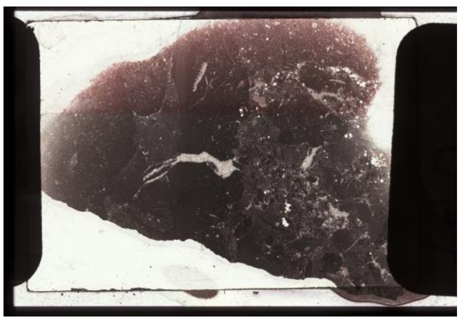
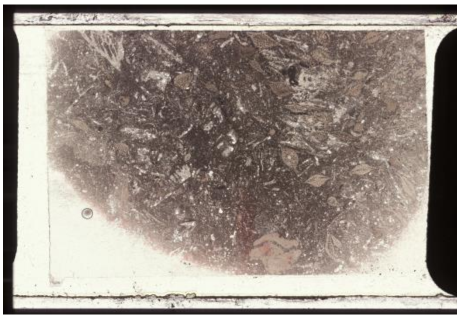
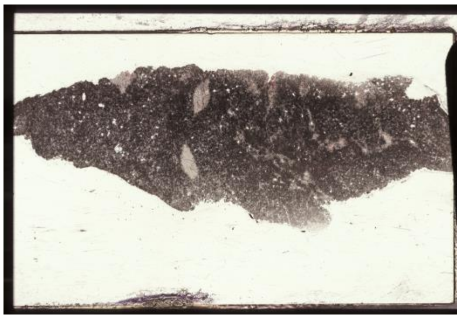




PA2 PA12





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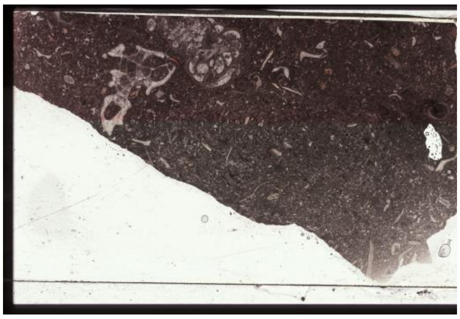
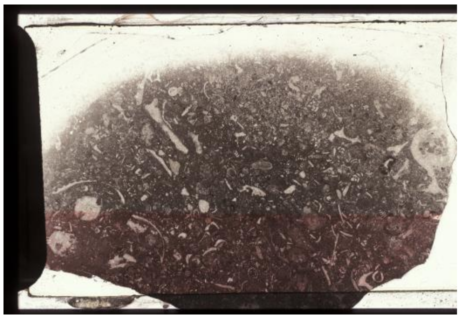
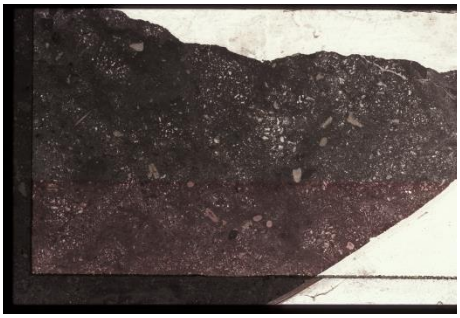
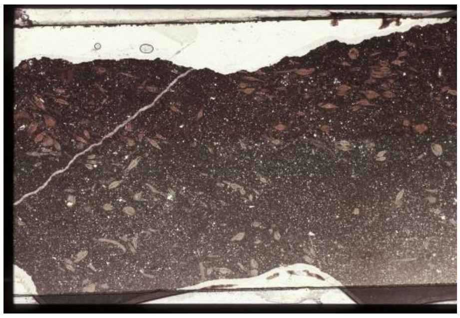


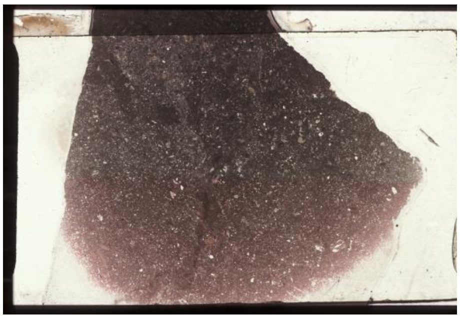


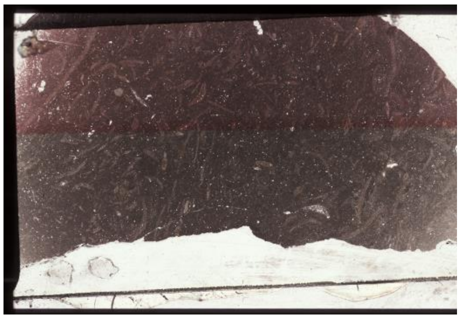
SAM10 SAM12



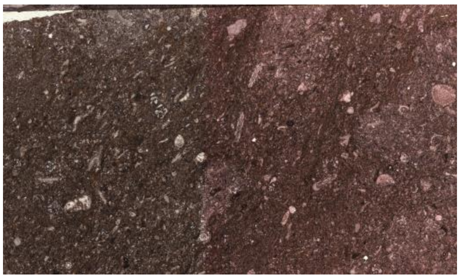


SAM26 SAM42a

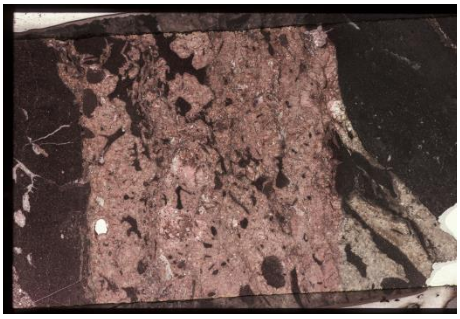




SAM53 SAM62

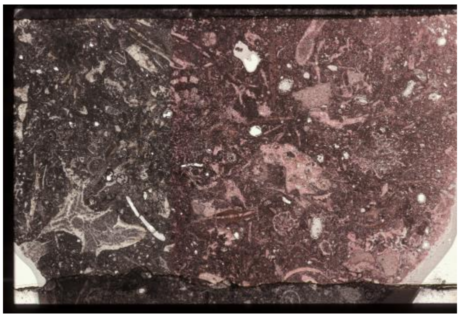


TII-1



TII-4

TII-17



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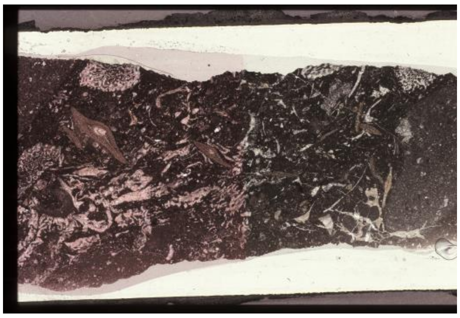
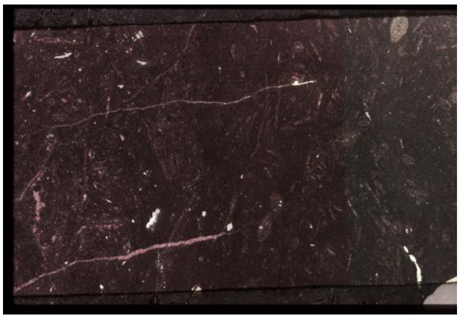


TII-31

TII-47

TII-49



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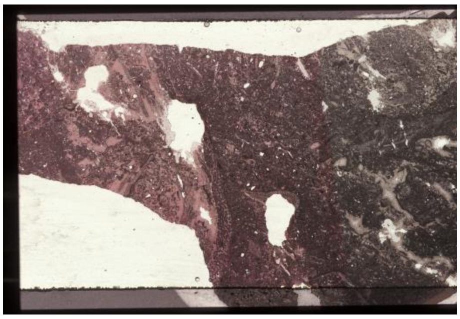
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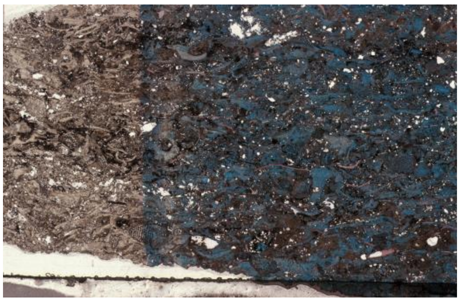
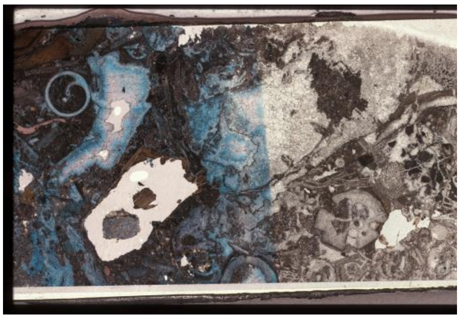

BM36


CG7


CG9

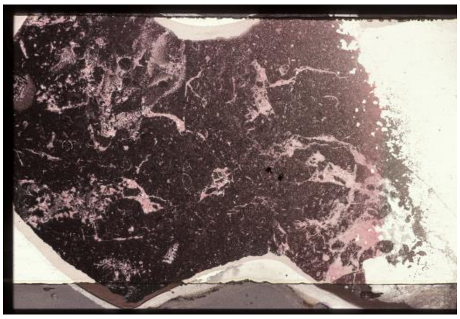

CG10


LB2


LB14


LP4

MC1A



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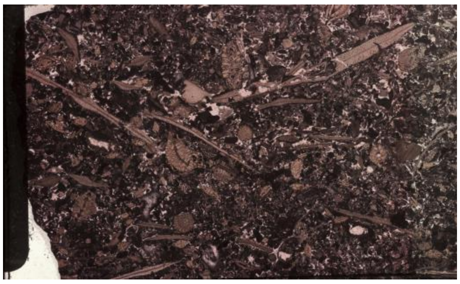
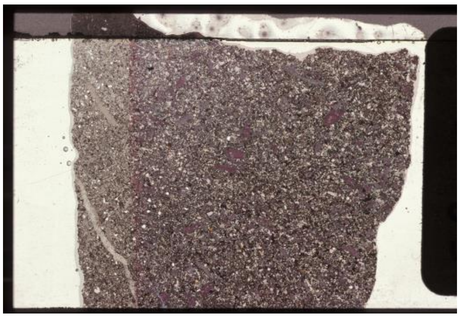


SRa10



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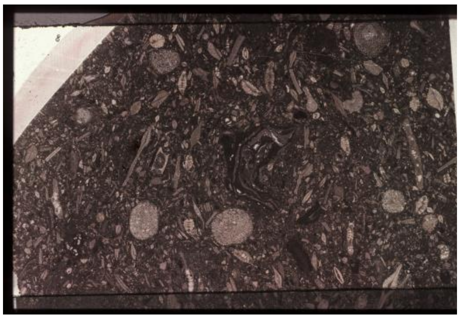

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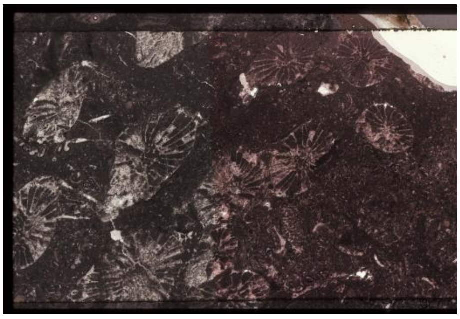

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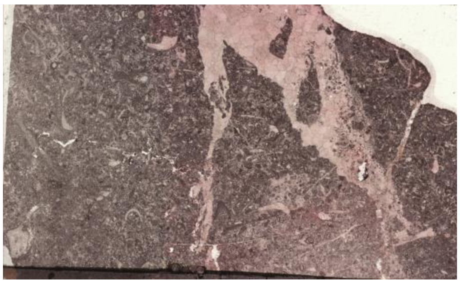
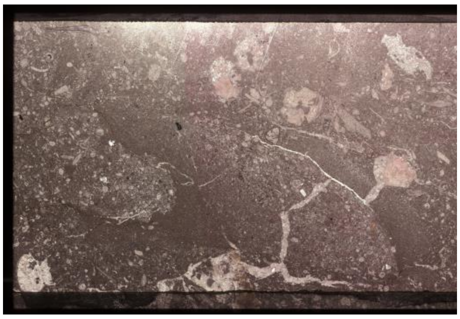


UL3



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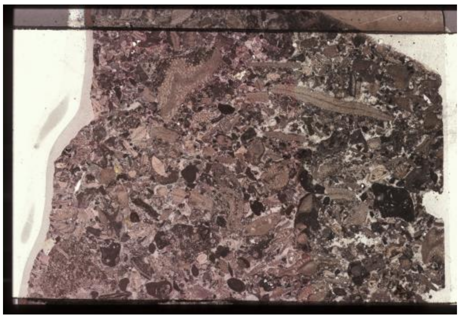
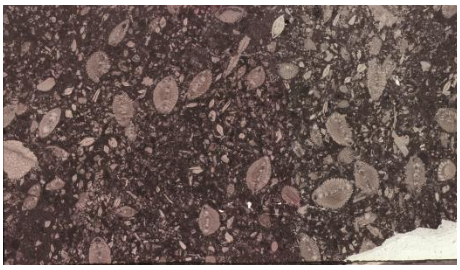


WM5



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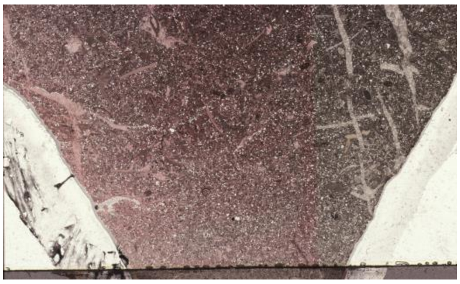

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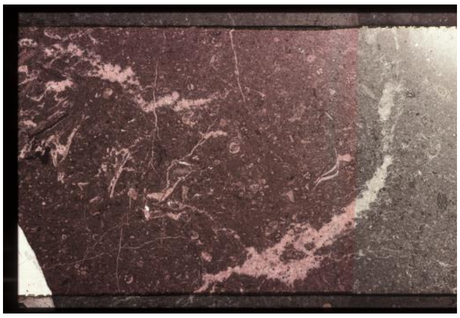

WP12

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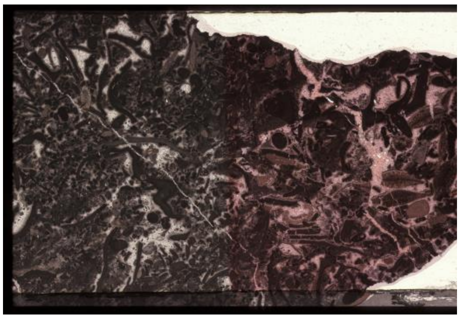
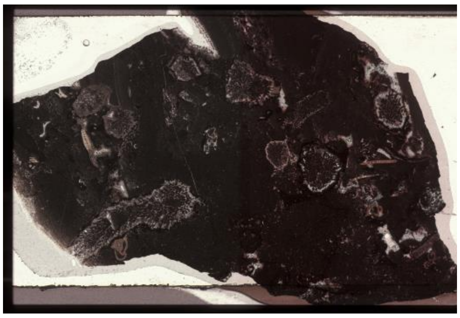


P7

P8



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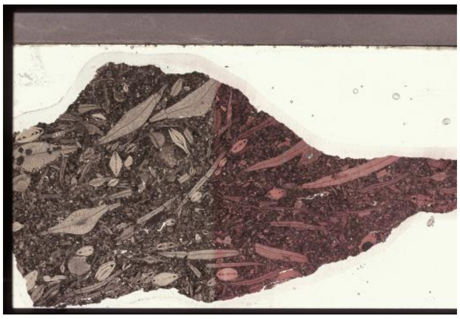
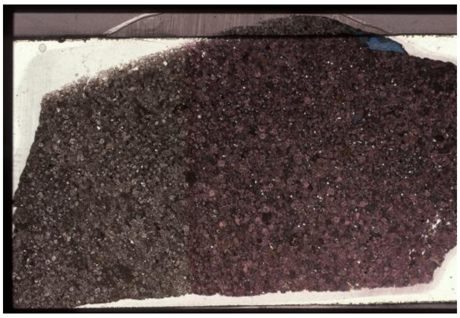


P18E

P19



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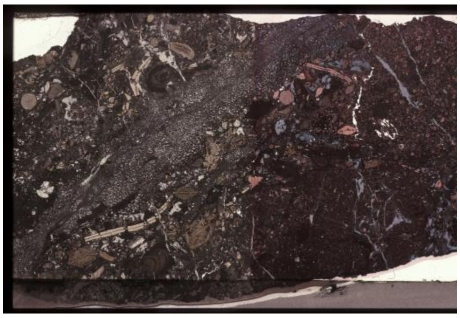
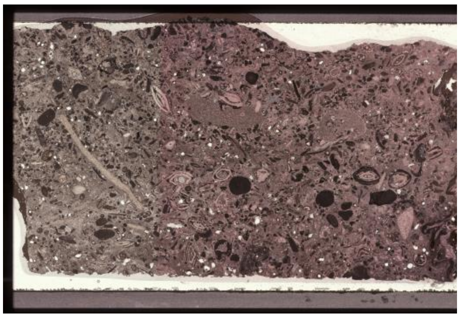


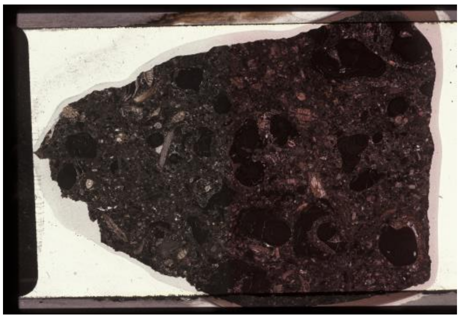
P23

P30



SMa7

SMa11



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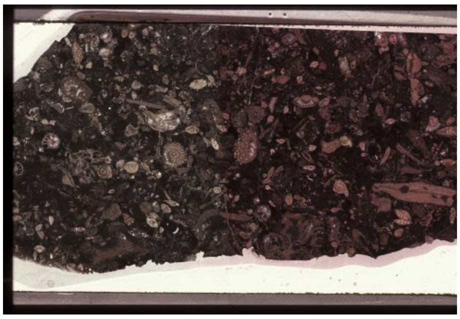
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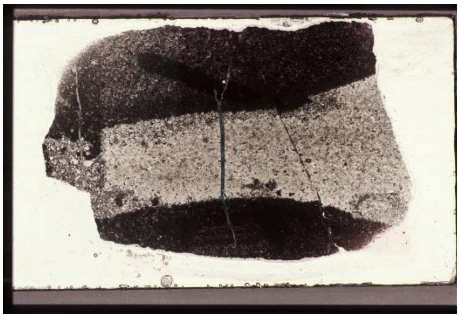
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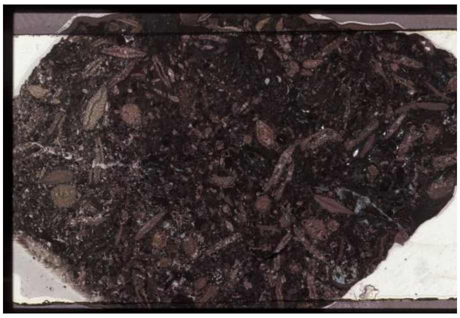
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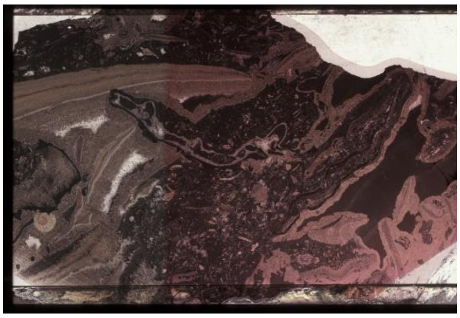
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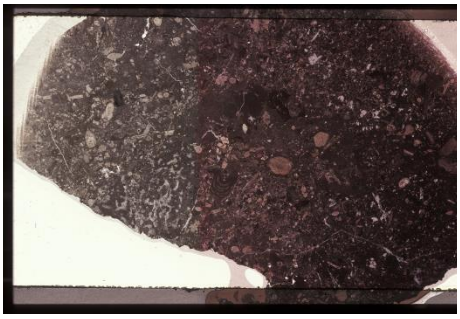
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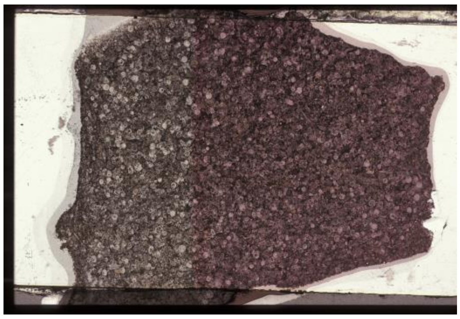
SMa30


SMa37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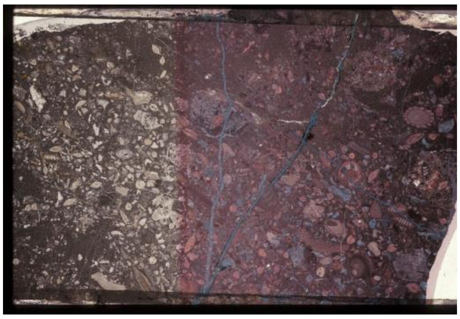
SMa47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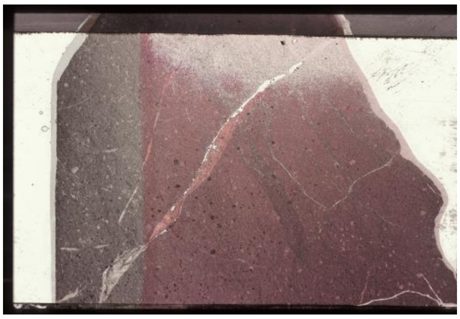
SMa49


NJ75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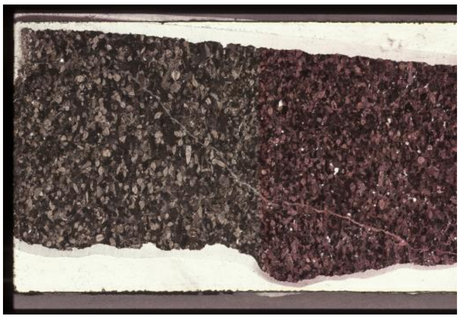
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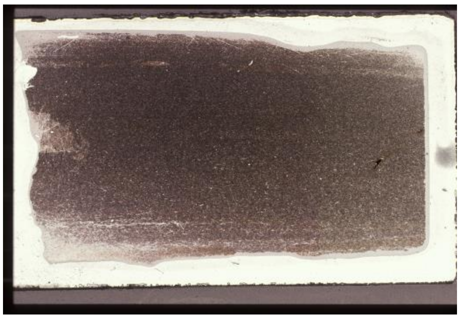
NJ7


NJ9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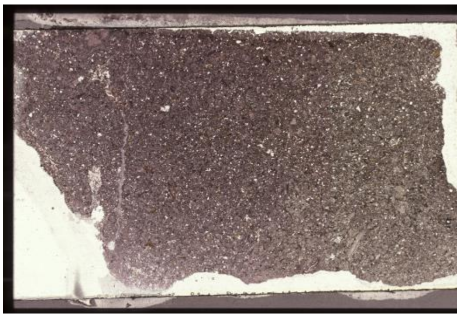
NJ21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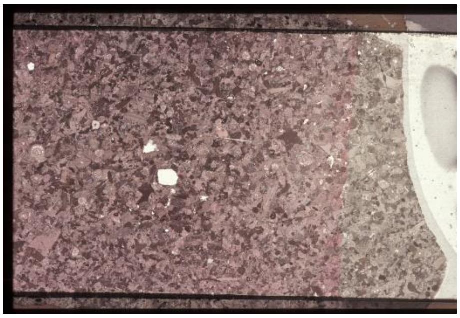
NJ29


NJ35


NJ40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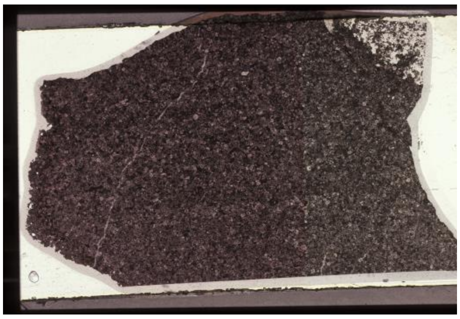
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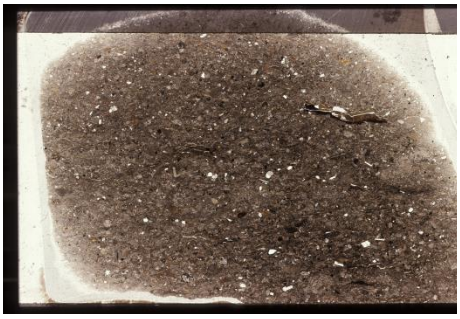
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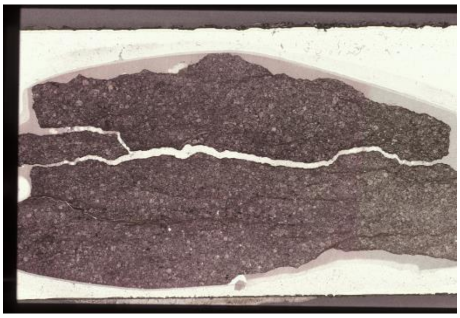

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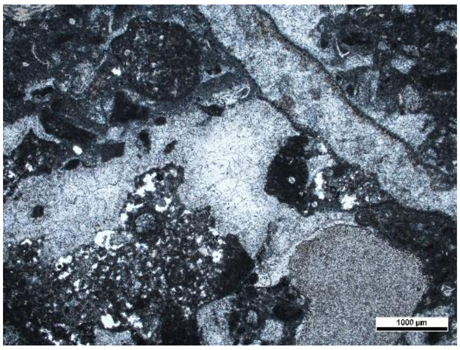
NJ76



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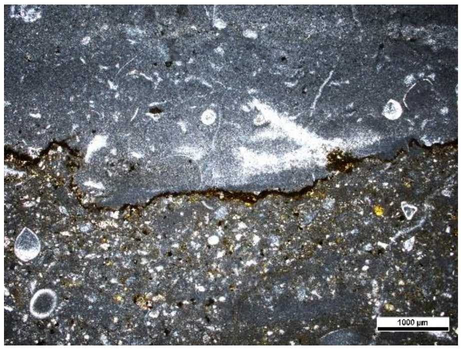

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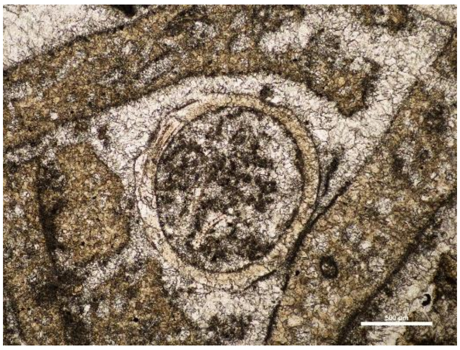
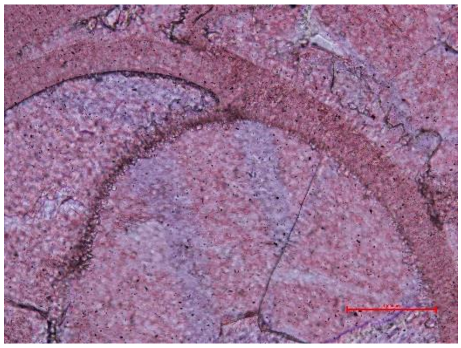

CG10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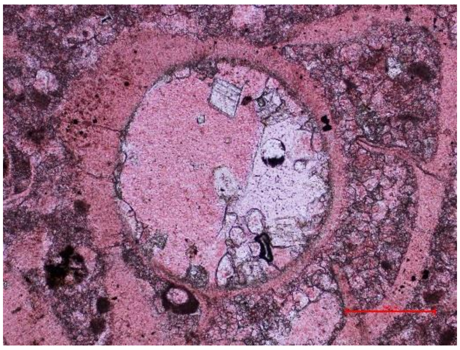
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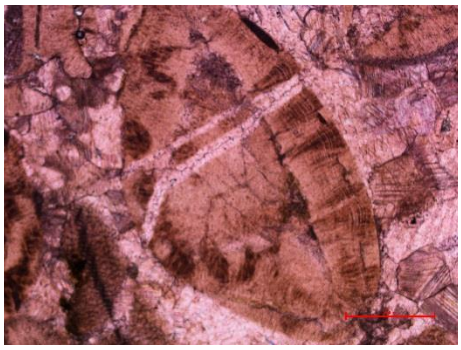
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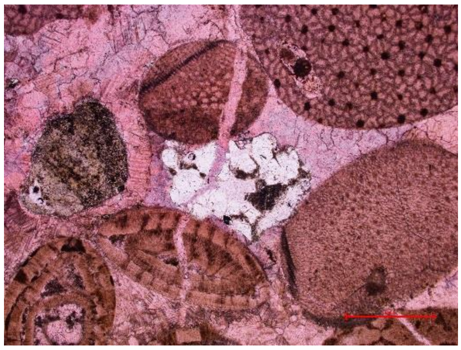
DD46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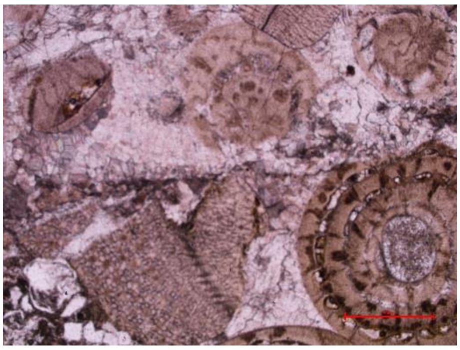
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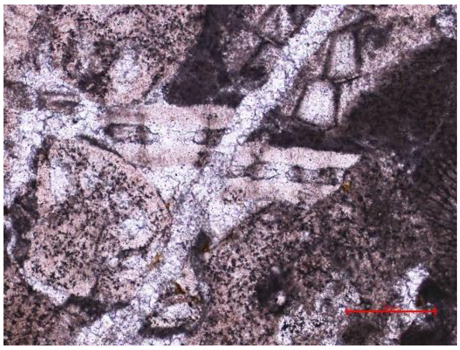
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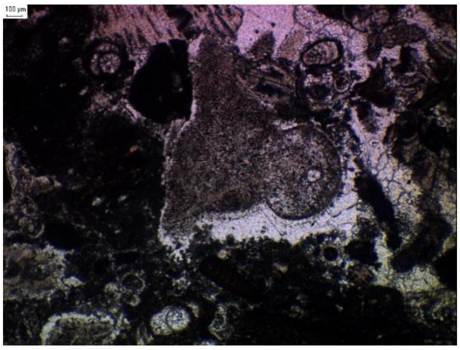
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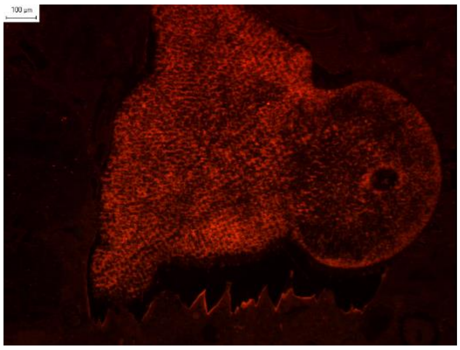
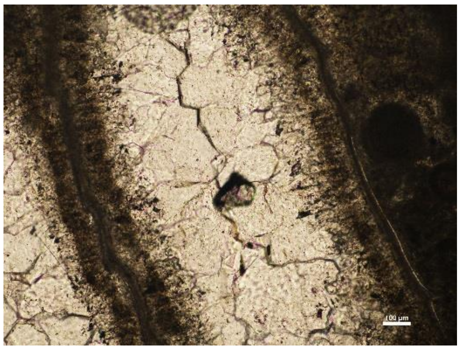

J82-CL


J82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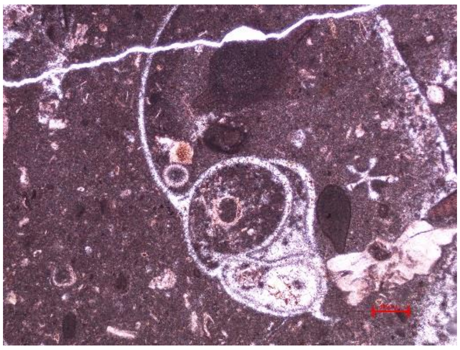
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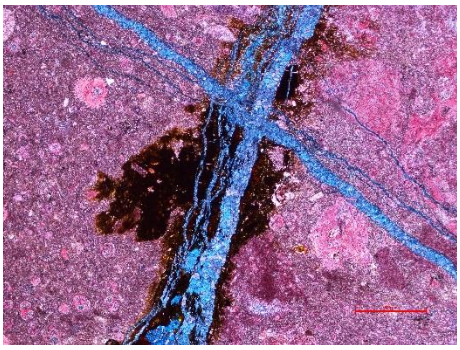
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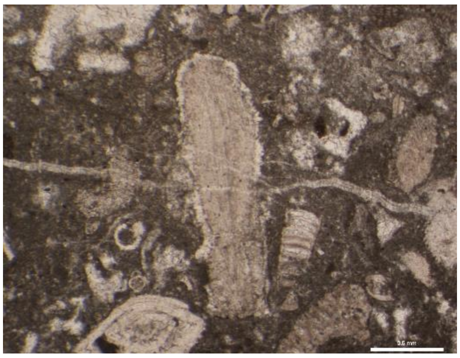
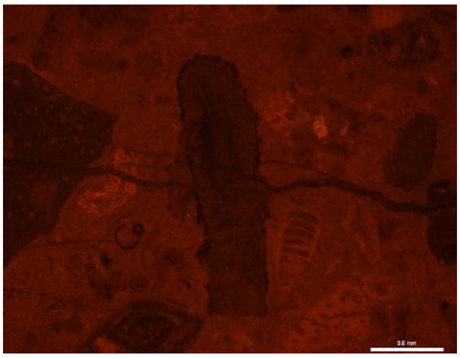


SMa47b



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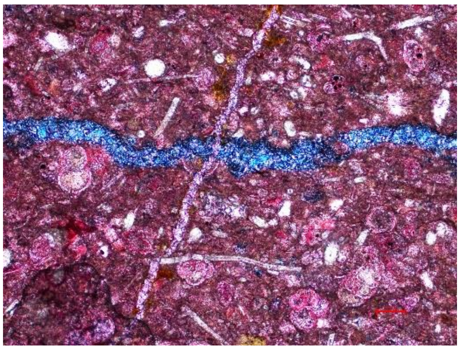

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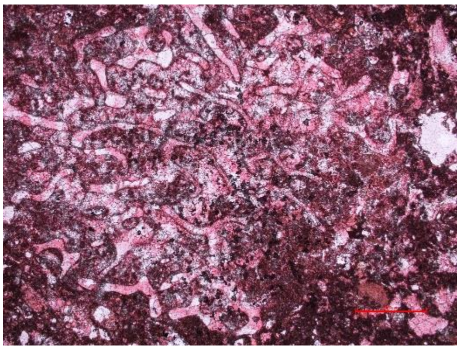


TII-21

APPENDIX D

PETROGRAPHIC OBSERVATIONS AND PHOTOMICROGRAPHS RELATING TO CHAPTER 3

Appendix D1: Petrographic observations of samples relating to Chapter 3

Appendix D2: Table of Carbonate components analysed for stable isotopes from close to the volcanogenics. Table shows component types, their context in stratigraphic sections, $\delta^{18}O$ and $\delta^{13}C$ ‰ V-PDB results and distance from the volcanogenics.

Appendix D3: Thin Section photomicrographs of samples relating to Chapter 3

Appendix D1: Petrographic observations of samples relating to Chapter 3

Section	Sample	Age Notes	Lithology (based on outcrop and thin section observations)	Micritization	Pore-lining cement	Syntaxial Overgrowth (Selected Bioclasts - SB)	Mechanical Bioclast / Grain Compaction	Mechanical Fracturing	Dissolution	Granular Mosaic Neomorphic Calcite (D - Drusy, F - Ferroan, X -	D - Drusy	G - Granular	B - Blocky	Stylolites	Dolomitisation	Olivine	Pyroxene	Quartz	Feldspar	Volcanic Glass	Zeolite	Terrestial Material	Hematite ?	Bioclasts	Phenocryst	Grain Size	Alteration	overgrowth	Crystal Shape	Crystallinity	Texture
Patunuang Asue	P33	Te1-4 Oilgocene	Bioclastic packston	e+r	D																										
Patunuang Asue	P32	Te1-4 Oilgocene	Planktonic Fora. Bioclastic packstone	e																											
Patunuang Asue	P28	Te1-4 Oilgocene	Miliolid bioclastic packstone	e+r*	D	*	*			*			*																		
Patunuang Asue	P24	Te1-4 Oilgocene	Diorite																							Inquigranular	H		Eu-Sub	hyp	Porphyritic
Patunuang Asue	P22	Te1-4 Oilgocene	Planktonic Fora. packstone	e	R(F)							F																			
Patunuang Asue	P20	Te1-4 Oilgocene	Bioclastic packstone	e+r	D(F)					F		F	F												*						
Patunuang Asue	P18 l	Te1-4 Oilgocene	Discocyclina & Biplanispira bioclastic packstone	e	D		*																								
Patunuang Asue	P18 g	Te1-4 Oilgocene	Altred introsive																												
Patunuang Asue	P17	Te1-4 Oilgocene	Volcaniclastic conglomerate																							Inquigranular	M		an	hyp	Porphyritic
Patunuang Asue	P16??	Te1-4 Oilgocene	Volcaniclastic siltstone																												
Patunuang Asue	P13	Te1-4 Oilgocene	Volcaniclastic conglomerate																								M			hc	Porphyritic
Patunuang Asue	P13+	Te1-4 Oilgocene	Volcaniclastic conglomerate																							Inquigranular	M		Eu-Sub	hc	Porphyritic
Patunuang Asue	P12??	Te1-4 Oilgocene	Replaced by silica																												
Patunuang Asue	P10	Te1-4 Oilgocene	Altered breccia packstone	r											??																
Patunuang Asue	P5	Te1-4 Oilgocene	bioclastic packstone	r*	B*			*		*																					
Patunuang Asue	P4	Te1-4 Oilgocene	Diorite																							Inquigranular	L		Eu-Sub	hyp	Porphyritic
Salo Maraung	SM^7	Tb-f	Granite																							Inquigranular			eu-sub	hc	
Salo Maraung	SM^11	Tb-f	Serpentinite																												
Salo Maraung	SM^9b	Tb-f	marble												?					?											
BARRU AREA - Bangabangae	SP10	Tb	Volcaniclastic ss.																												Porphyritic
BARRU AREA - Bangabangae	SP9	Tb	Volcaniclastic ss.																							F	L		sub	hc	
BARRU AREA - Bangabangae	SP11	Tb	Volcaniclastic ss.																							F	M		sub	hc	
BARRU AREA - Bangabangae	SP12	Tb	Shale matrix supported limestone cong.	e														?													
BARRU AREA - Bangabangae	SP14	Tb	Volcaniclastic ss.																								M				Porphyritic
BARRU AREA - Bangabangae	SP15	Tb	Volcaniclastic ss.																												Porphyritic
BARRU AREA - Rala	J108																									M	L		Sub	hc	Porphyritic
BARRU AREA - Rala	J107																									M	L		Sub		Porphyritic
BARRU AREA - Rala	J107B																									M	L		Sub		Porphyritic
BARRU AREA - Rala	J106		Volcaniclastic packstone	e																						F	M		AN		
Rumpio	R13	Tb/f	Volcaniclastic Cong. & ss.																							VF	L		Eu-sub	hc	
Rumpio	R13?	Tb/f	Volcaniclastic Cong. & ss.																?	?						Inquigranular	L		Eu-sub	hc	Porphyritic
Rumpio	R10	Tb/f	igneous intrusion																							Inquigranular	L		Eu-sub	hc	Porphyritic
Rumpio	R	Tb/f																								Inquigranular	L		Eu-sub	hc	Porphyritic
Rumpio	R16	Tb/f		e+r	R																										
Rumpio	R11	Tb/f	Clast supported breccia	e+r																											
Rumpio	R17	Tb/f		e																											
Rumpio	R14	Tb/f	Reworkd carbonate clast	e																											
Bua (S. Ralla)	SRa35	Late Eocene																								M					Porphyritic
Bua (S. Ralla)	SRa34	Late Eocene	Volcaniclastic ss.																							F					
Bua (S. Ralla)	SRa28	Late Eocene	Volcaniclastic Cong.																							Inquigranular	M				
Bua (S. Ralla)	SRa27	Late Eocene	Volcaniclastic Siltstone																							F	M				
Bua (S. Ralla)	SRa31	Late Eocene	Volcaniclastic Siltstone																							F	L				
Bua (S. Ralla)	SRa25	Late Eocene		e																											
Bua (S. Ralla)	SRa78	Late Eocene	Packstone/grainstone	e	D																										
Malawa	MC1	Late Eocene	Arkosic P.Fora. Bioclastic packstone	e	D																										
Malawa	MC8	Late Eocene	Miliolid bioclastic packstone	e+r																							F		Eu-sub		
Malawa	MC1A	Late Eocene																													
Bua (S. Ralla)	BM11	E-M Miocene	Volcaniclastic ss.																					?		Inquigranular	M				
Bua (S. Ralla)	BM3	E-M Miocene	Clast-supported breccia	e+r	D																										
Bua (S. Ralla)	BM5	E-M Miocene	Planktonic Fora. Bioclastic packstone																												
Bua (S. Ralla)	BM12	E-M Miocene	Arkosic bioclastic grainstone	e																							H				
S. PANGKAJENE - Patunuang Asue	SAM5	Miocene	Coal																							F	M		An		
S. PANGKAJENE - Patunuang Asue	SAM1B	Miocene	Alveolinid bioclastic packstone	e+r																											
S. PANGKAJENE - Patunuang Asue	SAM8	Miocene	Coral bioclastic floatstone	r																											
S. PANGKAJENE - Patunuang Asue	SAM9	Miocene	Alveolinid bioclastic packstone	e																											
S. PANGKAJENE - Patunuang Asue	PA6	Oilgocene	Coral, lithoclast & Heterostegina rudstone	r																											
S. PANGKAJENE - Patunuang Asue	PA9	Oilgocene	Mudstone/wackstone	e																											
S. PANGKAJENE - Patunuang Asue	PA5	Oilgocene	Mudstone																												
Nasara Jeneponto	NJ70	NN4-5 early-middle Miocene	Volcaniclastic conglomerate																												Porphyritic
Nasara Jeneponto	NJ69	NN4-5 early-middle Miocene																								V.F	M		AN		
Nasara Jeneponto	NJ68	NN4-5 early-middle Miocene	Volcaniclstic SS																												Porphyritic
Nasara Jeneponto	NJ61	NN4-5 early-middle Miocene	Diorite																		?					Inquigranular	L		Sub		
Nasara Jeneponto	NJ60	NN4-5 early-middle Miocene																								F	L		Sub		
Nasara Jeneponto	NJ71	NN4-5 early-middle Miocene	Volcaniclastic ss																												
Nasara Jeneponto	NJ75	NN4-5 early-middle Miocene	Planktonic fora. Packstone	e																							L				
Nasara Jeneponto	NJ76	NN4-5 early-middle Miocene	Arakosic fora. Packstone																								L			hh	

Cyrestal Shape		
Eu	Euhedral	Completely bounded
Sub	Subhedral	sime bounded
An	Anhedral	Lack

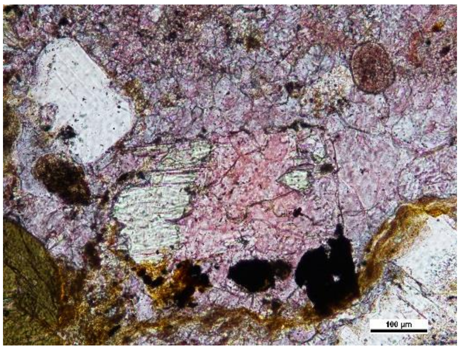
Crystallinity		
100% crystrals		100% glass
holocyrtalline	hypohyline	holohyline
hc	hyp	hh

Grain Size	Crystal diameters	
Fine	<1mm	F
Medium	1-5mm	M
Coarse	>5mm	C
Mixed	Inquigranular	

Name	$\delta^{13}C$ [‰, VPDB]	$\delta^{18}O$ [‰, VPDB] as for calcite	Height from base of section (m), from Wilson (1995)	Stratigraphic thickness to volcanogenics (m), from Wilson (1995)	Distance from intrusive or lava flow if present in section (m), from Wilson (1995)	Sample	Comments
H-CG7-mk	-0.73	-4.66	25.00	6.00		slightly brown laminated karstic cavity infill	from karst filling laminated mud/packstone
H-CG1-pm-a	1.82	-4.27	25.00	5.00		pink miciritc matrix with few bioclasts - a	from pink Bioclastic wacke/packstone at top of karst
H-CG1-pm-b	2.04	-4.03	25.00	5.00		pink miciritc matrix with few bioclasts - b	from pink Bioclastic wacke/packstone at top of karst
H-CG11-mb	1.63	-6.39	26.00	4.00		brownish bioclastic matrix	from bioclastic pac/grainstone
H-CG4-ccf	1.55	-6.56	26.00	4.00		very coarse blocky calcite fissure fill	from calcite spar filling karstic cavity
H-CG6-ca	2.52	-6.48	26.00	4.00		white coralline algae in wallrock	from karstified coral bioclastic packstone
H-CG6-gmk	2.03	-6.27	26.00	4.00		grey micritic karstic cavity infill	from karstified coral bioclastic packstone
H-CG6-m	3.11	-6.06	26.00	4.00		white micritic matrix to limestone wallrock	from karstified coral bioclastic packstone
H-CG2-ca	-1.10	-7.38	29.00	1.00		white coralline algae (minor miciritc matrix)	from Bioclastic pack/grainstone
H-CG2-m	-2.40	-4.88	29.00	1.00		pale brown micritic matrix (minor bioclasts)	from Bioclastic pack/grainstone
H-CG2-rc	-0.39	-7.35	29.00	1.00		recrystalised coral	from Bioclastic pack/grainstone
H-CG10-cc	2.31	-7.73	34.00	-4.00		recrystalised coral	from bioclastic packstone overlying Tonasa Formation
H-CG10-m	1.62	-8.16	34.00	-4.00		slightly reddish micritic matrix	from bioclastic packstone overlying Tonasa Formation
H-CG9-m	2.18	-10.50	35.00	-5.00		white micritic matrix	from bioclastic packstone overlying Tonasa Formation
H-CG17-rc	-1.20	-5.78	40.00	-10.00		recrystalised coral, heavily compacted	from coral bioclastic pack/grainstone with volcaniclastics
H-CG18-ws-a	-2.73	-5.48	45.00	-15.00		white shells in very dark volcaniclastic matrix - a	from altered coral volcaniclastic conglomerate
H-CG18-ws-b	-2.04	-5.04	45.00	-15.00		white shells in very dark volcaniclastic matrix - b	from altered coral volcaniclastic conglomerate
H-CG25-wc	-0.47	-6.63	55.00	-25.00		white chalky coral with dark bioclastic matrix	from coral rudstone
H-CG20-rc	0.24	-8.35	60.00	-30.00		recrystalised coral	from coral volcaniclastic rudstone/conglomerate
H-CG20-wm	-0.30	-6.02	60.00	-30.00		white micritic matrix in corals	from coral volcaniclastic rudstone/conglomerate
H-CG24-ca	2.79	-7.32	64.00	-34.00		white coralline algae	from coral rudstone
H-CG24-m	1.77	-8.58	64.00	-34.00		pale grey bioclastic matrix	from coral rudstone
H-CG24-rc	2.36	-8.14	64.00	-34.00		recrystalised coral	from coral rudstone
H-NJ-64-pm	1.77	-3.22	987.00	-13.00	-13.00	pale grey micrite	from planktonic foraminifera packstone
H-NJ-72-pm	1.38	-4.24	988.00	-12.00	-36.00	pale grey micrite	from planktonic foraminifera packstone
H-NJ-73-pm	1.88	-3.26	993.00	-7.00	-13.50	pale grey micrite	from marl, >10 m from 3 m thick diorite sill
H-NJ-70-pm	1.55	-4.14	1020.00	20.00	-8.00	pale grey micrite	from clast in noramlly graded volcaniclastic conglomerate in Camba Fm, 8 m from diorite sill
H-SAM19-m	0.61	-8.19	176.80	87.60		micritic matrix	from *Spiroclypeus*bioclastic wacke/packstone
H-SAM15-m	1.53	-11.25	184.00	80.40		micritic matrix, minor bioclastics	from Bioclastic wackestone
H-SAM14-m	1.47	-8.47	185.00	79.40		cream micritic matrix, no visible bioclasts	from Bioclastic wacke/packstone
H-SAM13-m	1.66	-10.21	186.50	77.90		petroliferous micritic matrix, minor bioclasts	from Bioclastic wackestone
H-SAM12-ca	2.23	-11.82	195.60	68.80		coralline algae	from coral and alveolinid bioclastic wacke/packstone
H-SAM12-mb	2.27	-11.64	195.60	68.80		brown/grey petroliferous bioclastic W/P	from coral and alveolinid bioclastic wacke/packstone
H-SAM11-cc-a	2.05	-12.29	205.50	58.90		recrystalised coral (?*Porites*)	from altered coral floatsone
H-SAM11-cc-b	1.91	-12.26	205.50	58.90		recrystalised coral (?*Porites*)	from altered coral floatsone
H-SAM11-mb	2.07	-13.21	205.50	58.90		micritic bioclastic matrix	from altered coral floatsone
H-SAM10-lb	1.18	-9.78	213.60	50.80		larger benthic foraminifera	from bioclastic packstone

H-SAM10-mb	1.78	-10.51	213.60	50.80		micritic bioclastic matrix	from bioclastic packstone
H-SAM16-cc	0.86	-6.40	217.00	47.40		recrystalised coral	from coral bioclastic floatstone
H-SAM16-mb	2.00	-14.81	217.00	47.40		recrystalised bioclastic micritic matrix	from coral bioclastic floatstone
H-SAM16-rb	1.66	-14.65	217.00	47.40		petroliferous recrystalised bioclast - shell	from coral bioclastic floatstone
H-SAM9-cc	0.63	-12.56	219.50	44.90		Heavily recrystalised coral	from Alveolinid bioclastic pack/rudstone
H-SAM9-mb	0.09	-11.69	219.50	44.90		Micritic matrix (partly bioclastic)	from Alveolinid bioclastic pack/rudstone
H-SAM8-cc-a	-2.02	-12.55	250.20	14.20		recrystalised coral - a	from coral bioclastic floatstone
H-SAM8-cc-b	-1.19	-13.03	250.20	14.20		recrystalised coral - b	from coral bioclastic floatstone
H-SAM8-m	0.22	-9.61	250.20	14.20		Micritic matrix	from coral bioclastic floatstone
H-SAM6-ca	-0.70	-7.79	252.00	12.40		Corals unaltered -a	from coral bioclastic floatstone with volcaniclastics
H-SAM6-cb	-0.63	-7.74	252.00	12.40		Corals unaltered -b	from coral bioclastic floatstone with volcaniclastics
H-SAM1a-cc	-1.51	-10.59	261.50	2.90		black heavily recrystalised coral	from coral in Alveolinid bioclastic pack/rudstone at contact
H-SAM1a-m	1.41	-11.74	261.50	2.90		pale grey petroliferous micritic matrix	from Alveolinid bioclastic pack/rudstone
H-SAM1b-ka	0.30	-5.67	261.50	2.90		calcitic *Kuphus* tube - a	from Alveolinid bioclastic pack/rudstone
H-SAM1b-kb	0.71	-5.32	261.50	2.90		calcitic *Kuphus* tube - b	from Alveolinid bioclastic pack/rudstone
H-SAM1b-m	0.42	-8.74	261.50	2.90		pale brown micritic matrix	from Alveolinid bioclastic pack/rudstone
H-UL11-m	1.41	-5.32	49.00	31.00		pale brown micrite	from bioclastic packstone
H-UL12-m	0.79	-4.59	52.00	28.00		pale grey micrite	from bioclastic packstone
H-UL14-mb	0.56	-7.90	75.00	5.00	5.00	micrite (bioclastic)	from pale brown recrystalised packstone/marble
H-NJ-62-pm	-3.49	-14.04	996.00	-4.00	-4.00	pale grey micrite	from planktonic foraminifera packstone, 4 m from diorite sill
H-NJ-75-pm	0.37	-7.33	997.50	-2.50	-9.00	pale grey micrite	from planktonic foraminifera packstone, 9 m from 3 m thick diorite sill
H-PA8-bm-a	-0.28	-18.25	35.30	229.10	0.20	black recrystalised matrix - a	affected by contact metamorphism directly above 2 m thick igneous sill
H-PA8-bm-b	-0.14	-18.18	35.30	229.10	0.20	black recrystalised matrix - b	affected by contact metamorphism directly above 2 m thick igneous sill
H-PA8-rc-a	0.24	-14.78	36.80	227.60	2.00	??recrystalised coral - a	affected by contact metamorphism 2 m above 2 m thick igneous sill overlying PA8
H-PA8-rc-b	0.32	-12.71	36.80	227.60	2.00	??recrystalised coral - b	affected by contact metamorphism 2 m above 2 m thick igneous sill overlying PA8
SAM48-MX	0.72	-7.08	149.00	115.40	10.00	micritic matrix	from bioclastic wacke/packstone, 10 m above 8 m thick gabbroic sill, but sill may be much further as sill below steps down through strata at least 150 m away
SAM52-LEP	1.85	-12.10	127.00	137.40	4.00	larger benthic foraminifera Lepidocyclinid	from Lepidocyclinid wacke/floatstone. 4m directly below 8 m gabbroic sill
SAM54-ALGAE	0.78	-8.89	118.00	146.40	13.00	coralline algae	from bioclastic packstone, 13 m below 8 m thick gabbroic sill, but sill may be closer horizontally as steps up through strata
SAM54-ROT	0.87	-10.32	118.00	146.40	13.00	larger benthic foraminifera rotallid (undifferentiated)	from bioclastic packstone, 13 m below 8 m thick gabbroic sill, but sill may be closer horizontally as steps up through strata
SAM58-ALGAE	1.21	-12.23	114.50	149.90	16.50	coralline algae	from bioclastic packstone, 16.5 m below 8 m thick gabbroic sill, but sill may be closer horizontally as sill steps up through strata
SAM58-MX	1.17	-12.44	114.50	149.90	16.50	micritic matrix	from bioclastic packstone, 16.5 m below 8 m thick gabbroic sill, but sill may be closer horizontally as sill steps up through strata
SAM59-MX	0.60	-6.12	107.00	157.40	24.00	micritic matrix	from bioclastic wacke/packstone, 24 m below 8 m thick gabbroic sill, but sill may be closer horizontally as sill steps up through strata
SAM60-MX	0.51	-4.49	101.00	163.40	30.00	micritic matrix	from carbonate mudstone, 30 m below 8 m thick gabbroic sill, but sill may be closer horizontally as sill steps up through strata
H-X1-cm	2.98	-6.91	N/A	~10.00		crystalline black marble, petroliferous	from crystalline marble
H-X5-cm	3.12	-5.90	N/A	~15.00		crystalline black marble, petroliferous	from crystalline marble
H-S110-cf	1.97	-5.87	N/A	N/A	15.00	recrystalised foraminifera	from bioclastic packstone top Senggareng section
H-SRa60-m	1.98	-5.52	38.00	144.00		cream to pale grey miciritc matrix	from *Discocyclina*bioclastic pack/rudstone
H-SRa68-lbf	1.89	-5.28	68.00	114.00		larger benthic foraminifera	from miliolid and coral bioclastic pack/floatstone
H-TII68-m	-2.71	-7.30	196.50	N/A		cream to pale grey miciritc matrix	from *Heterostegina* & *Lepidocyclina* bioclastic wackestone

Appendix D2: Thin Section photomicrographs of samples relating to Chapter 3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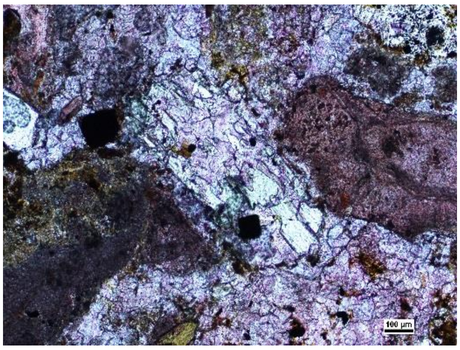
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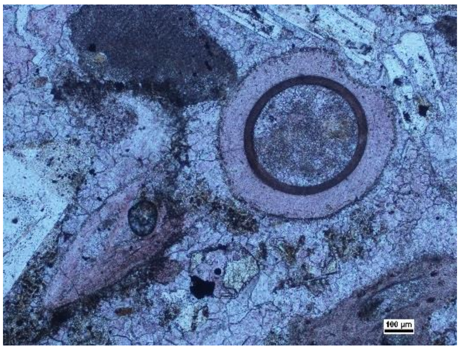
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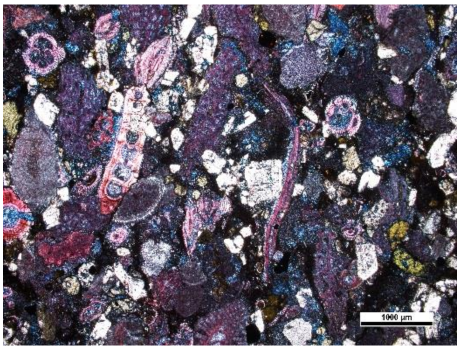
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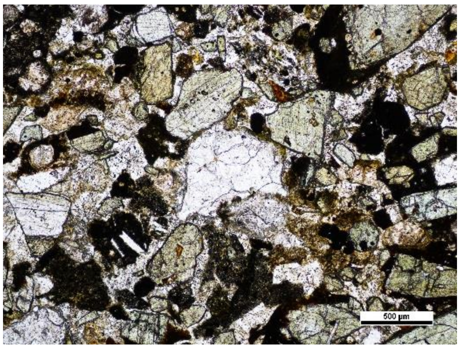
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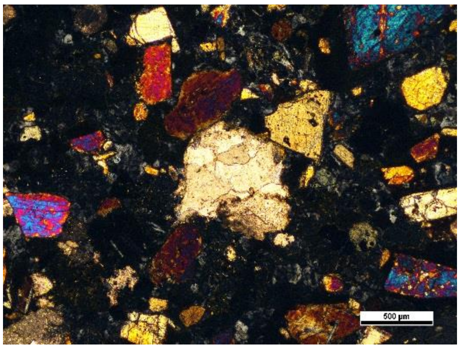
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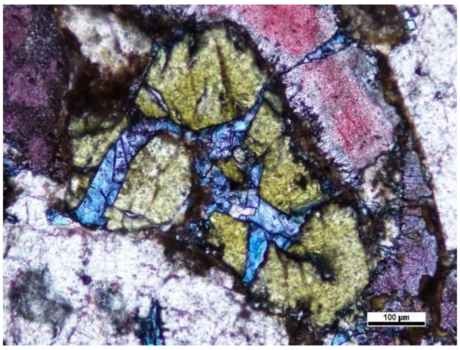
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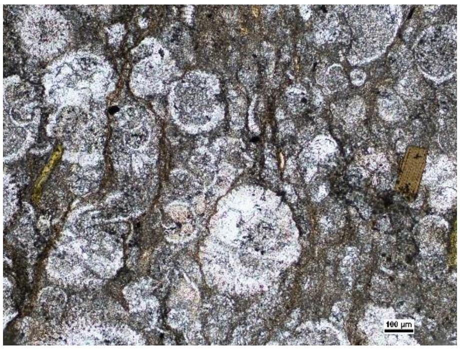
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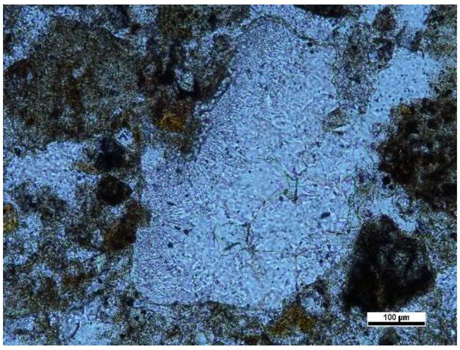
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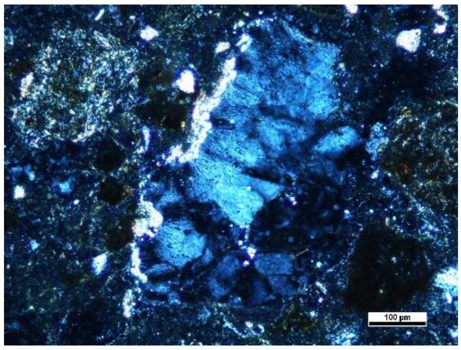
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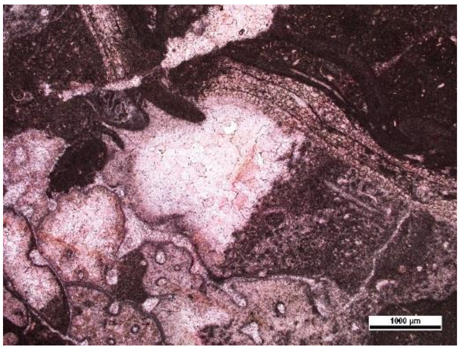
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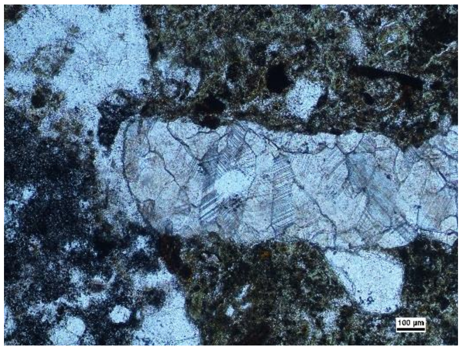
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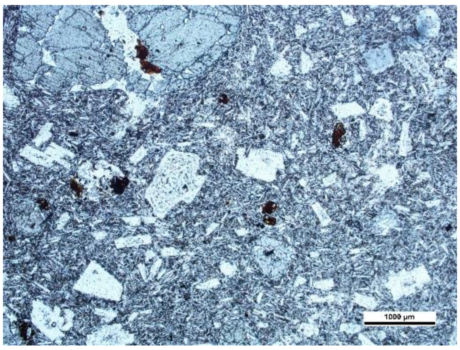
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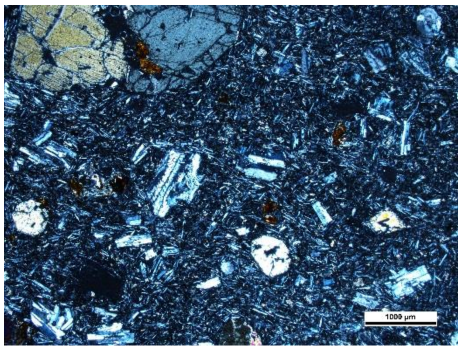
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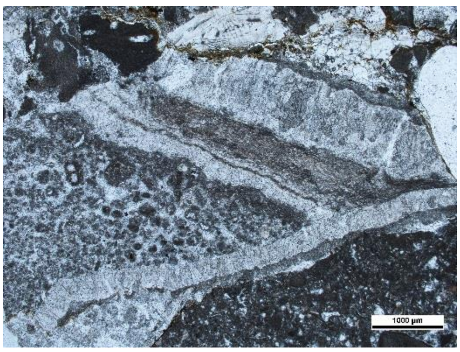
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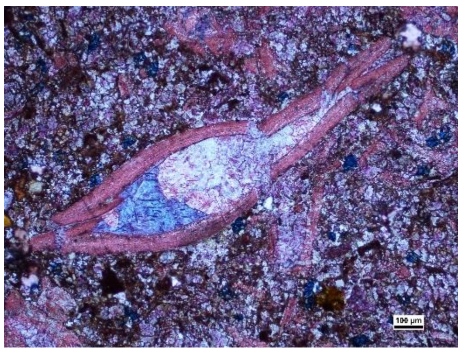
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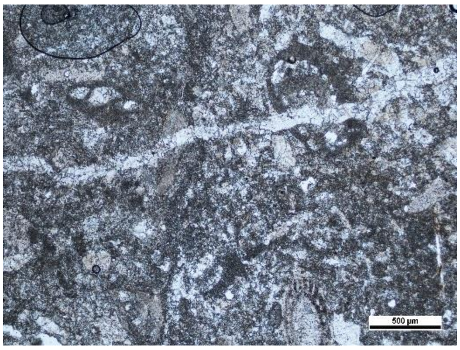

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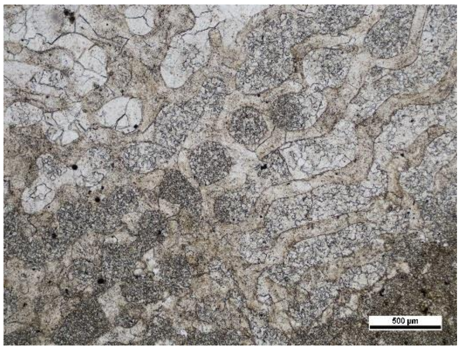

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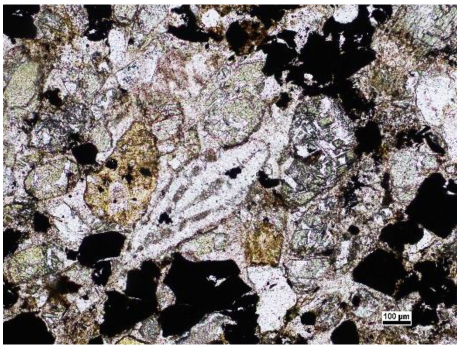

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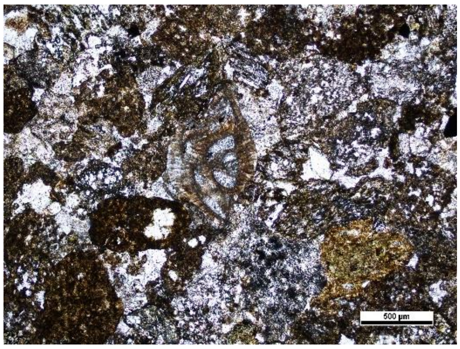

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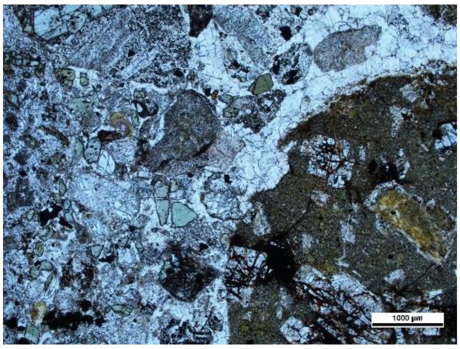

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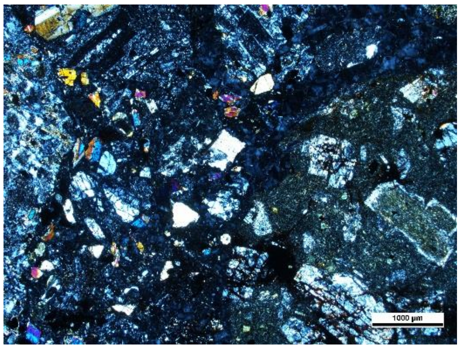

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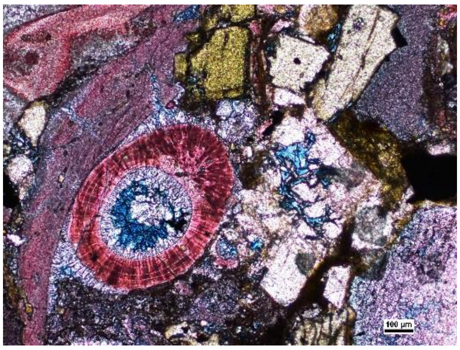

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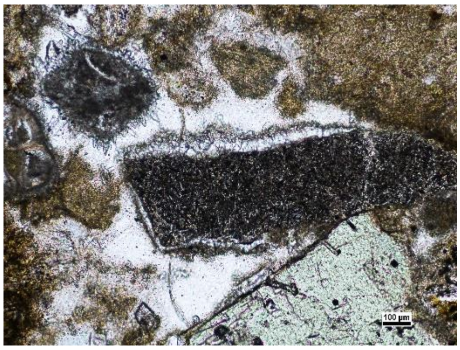


SRa35

APPENDIX E

PETROGRAPHIC OBSERVATIONS AND PHOTOMICROGRAPHS RELATING TO CHAPTER 4

Appendix E1: Petrographic observations of samples relating to Chapter 4

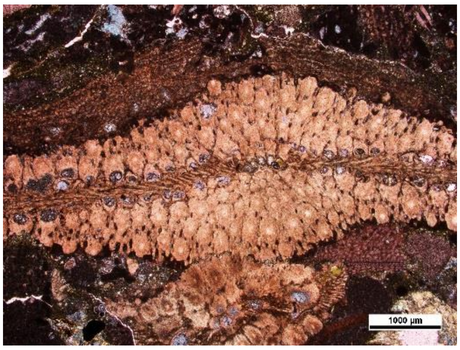
Sample No.			Thickness (cm)	Lithology	Thin-section Lithology	% Bioclasts	% Lithic clasts	% Cement B. C.	% Matrix B. C.	Total	% Silicification	Compaction (Grain alligament)	Mechanical Breackage	Grain contact types					Sum of contacts	Normalised grain contacts %					Cement types B. C.	Silicification	Fragmentation	Abrasion	Diagenesis within clasts (preservation)	Stylolites and Dissolution	Grain size μm	Remarks
	Base	Top												P. C.	N. C.	C.C.C.	T. C.	S. C.		P. C.	N. C.	C. C.	T. C.	S. C.								
J82	99500				Packstone	50	1	30	19	100		25		5	1	5	1	25	37	13.51	2.70	13.51	2.70	67.57	GR/DS/BK/DT				Syn/BL		C. Sand	
J79	99130	99385	255	Clast supported breccia	Packstone	50	10	20	20	100		50		0.1	0.1	5	0.1	25	30.3	0.33	0.33	16.50	0.33	82.51	GR(F)/NMP/FB				Syn		M. Sand	Silica
J78	98715	98820	105	Planktonic Foraminifera bioclastic packstone	Packstone	70	1	9	20	100		25		5	0.1	25	0.1	100	130.2	3.84	0.08	19.20	0.08	76.80	GR/FB				Syn		M. Sand	
J76	98000	98400	400	Clast supported breccia	Packstone	50	0	20	30	100		0.1		5	25	0.1	0.1	0.1	30.3	16.50	82.51	0.33	0.33	0.33	Dol/DT/GR /NMP/BK				Syn	0.1	M. Sand	
J74	97000	97500	500	Clast supported breccia	Grainstone	50	0	25	25	100		1		5	25	1	0.1	1	32.1	15.58	77.88	3.12	0.31	3.12	GR/RF/Syn					0.1	M. Sand	
J69	95495			Clast supported breccia	Grainstone	40	0	45	5	90		0.1		5	25	0.1	5	0.1	35.2	14.20	71.02	0.28	14.20	0.28	GR/RF				Syn		M. Sand	
J65	94580		-94580	Clast supported breccia	Packstone	50	0	20	30	100		1		5	1	0.1	0.1	25	31.2	16.03	3.21	0.32	0.32	80.13	Dol/DS/				GR		C. Sand	
J59	93050	93600	550				100			100				0	0	0	0	0	100	0.00	0.00	0.00	0.00	0.00								Q
J57	92310	92500	190	Clast supported breccia fining upwards to graded bioclastic grainstone	Packstone	80	0	15	5	100		100		5	0	5	25	100	135	3.70	0.00	3.70	18.52	74.07	Syn/DT/ Dol/BK/GR				Syn		C. Sand	
J52	91850	92000	150	Graded biclastic packstone	Packstone	50	5	5	40	100	1	5		25			1	25	51	49.02	0.00	0.00	1.96	49.02	GR				Syn	0.1	V.C. Sand	Glauconite
J48	91595	91715	120	Graded biclastic packstone		50	5	25	20	100		0.1		25	1	0.1	0.1	25	51.2	48.83	1.95	0.20	0.20	48.83	GR				Syn		M. Sand	
J46	91450	91595	145	Graded biclastic grainstone	Wackestone	50	5	10	35	100	1	0.1		5	25		1	5	36	13.89	69.44	0.00	2.78	13.89	BK/ GR (F) / Dol				Syn	0.1	M. Sand	
J45	91295	91450	155	Graded biclastic grainstone	Packstone	65	10	10	15	100		100		5		5		100	110	4.55	0.00	4.55	0.00	90.91	Dol/ GR				GR(F)/DT/RF/Syn	0.1	C. Sand	Q
J35	90340	90420	80	Clast supported breccia fining upwards to graded bioclastic packstone	Packstone	50	10	10	30	100		100		0.1	0.1	1	5	100	106.2	0.09	0.09	0.94	4.71	94.16	GR (F)/ Dol				Syn	1	V.C. Sand	silica
J34	90285	90340	55	Planktonic Foraminifera bioclastic p/S	Packstone	60	1	25	14	100		25		5	0.1	1	1	50	57.1	8.76	0.18	1.75	1.75	87.57	GR (F)				Syn	5	M. Sand	Glauconite
J33	90145	90205	60	Planktonic Foraminifera bioclastic p/S	Wackestone	30	0	1	69	100		0.1		1	50	0.1	0.1	5	56.2	1.78	88.97	0.18	0.18	8.90	GR (F)				Syn/ Radixial		M. Sand	
J32	90105	90145	40	Planktonic Foraminifera W/S	Wackestone	40	10	5	45	100	50	5		0.1	25	0.1		5	30.2	0.33	82.78	0.33	0.00	16.56	NMP					50	M. Sand	replaced by silica
J30	89700	89760	60	Planktonic Foraminifera bioclastic p/S	Packstone	70	0	15	15	100		100		25		25	0.1	100	150.1	16.66	0.00	16.66	0.07	66.62	BK/ GR (F)				Syn/BL	25	M. Sand	
J28	89500	89615	115	Planktonic Foraminifera W/S	Wackestone	40	0	50	10	100		0.1		25		0.1	1	5	31.1	80.39	0.00	0.32	3.22	16.08	GR/ Syn				Micritisation / Grnaular / Syn		M. Sand	Glauconite
J26	89305	89390	85	Marl	Mudstone	40	0	5	55	100		0.1	T	1	100	0.1	0.1	0.1	101.3	0.99	98.72	0.10	0.10	0.10	NMP (F)				GR		M. Sand	Neomor
J24	88850	88950	100	Planktonic Foraminifera bioclastic G/S	Packstone	80	1	9	10	100		100		0.1		25	1	100	126.1	0.08	0.00	19.83	0.79	79.30	GR		P	A	GR/ Syn	5	C. Sand	Glauconite
J23	88290	88350	60	Planktonic Foraminifera W/S	Wackestone	25	0		75	100		0.1		1	100	0.1	1	0.1	102.2	0.98	97.85	0.10	0.98	0.10	GR				GR/radixial fib	25	V.F. Sand	
J22	88210	88250	40	Planktonic Foraminifera bioclastic p/S	Packstone	85	0	0	15	100		100		0.1		1	1	100	102.1	0.10	0.00	0.98	0.98	97.94	FB / GR		C	A	Syn	5	C. Sand	Glauconite
J21	87705	87950	245	Planktonic Foraminifera P/S	Mudstone	40	5		55	100	50	0.1		5	25		0.1	0.1	30.2	16.56	82.78	0.00	0.33	0.33		A	T			25	F. Sand	Glauconite
J20	87680	87705	25	Planktonic Foraminifera W/S	Mudstone	20	0		80	100	10	0.1		0.1	100				100.1	0.10	99.90	0.00	0.00	0.00			R			100	V.F. Sand	
J19	87530	87590	60	Marl	Mudstone	20	0		80	100		0.1		0.1	100				100.1	0.10	99.90	0.00	0.00	0.00						25	V.F. Sand	
J18	87300			Planktonic Foraminifera W/S	Mudstone	30	0		70	100		1		5	50	0.1	1	1	57.1	8.76	87.57	0.18	1.75	1.75			T		GR	5	V.F. Sand	
J17	87115	87210	95	Graded bioclastic packstone	Grainstone	50	0	40	10	100		5		5	25	0.1	5	5	40.1	12.47	62.34	0.25	12.47	12.47	GR/BK/Syn				Syn		V.C. Sand	
J15	86900	86990	90	Planktonic Foraminifera bioclastic grainstone		40	0	50	10	100		0.1		5	100		1	0.1	106.1	4.71	94.25	0.00	0.94	0.09	GR/BK/Syn						C. Sand	
J14	86880	86900	20	Planktonic Foraminifera bioclastic packstone	Wackestone	25	0	5	70	100		1		5	100				105	4.76	95.24	0.00	0.00	0.00					GR	1	M. Sand	
J12	86715	86780	65	Planktonic Foraminifera bioclastic packstone	Grainstone	50	1	40	9	100		5		5	1	1	5	25	37	13.51	2.70	2.70	13.51	67.57	GR/BK/Syn				Syn		M. Sand	Glauconite
J11	86630	86695	65	Planktonic Foraminifera bioclastic packstone	Wackestone	40	20	0	40	100	75	5		5	25			5	35	14.29	71.43	0.00	0.00	14.29					GR (F)	25	M. Sand	REPLACED BY SILICA
J10	86560	86630	70	Marl	Mudstone	25	0		75	100		0.1		1	100				101	0.99	99.01	0.00	0.00	0.00					GR		V.F. Sand	
J6	86060	86115	55	Planktonic Foraminifera bioclastic packstone	Packstone	65	0	5	30	100		25		25	25	0.1	1	25	76.1	32.85	32.85	0.13	1.31	32.85	GR				GR	25	F. Sand	
J3	85790	85850	60	Graded bioclastic packstone	Grainstone	60	0	30	10	100	5	5		5	25		25	5	60	8.33	41.67	0.00	41.67	8.33	GR/DT/BK/BL				Syn		C. Sand	
J2	85720	85740	20			35	35	20	10	100		50		5		1	1	25	32	15.63	0.00	3.13	3.13	78.13	GR (F)				Syn/FB/GR	1	C. Sand	Ignoues phenocryst/
J1	85630	85720	90	Clast supported breccia fining upwards to graded bioclastic packstone	Packstone	55	10	20	15	100	1	25		5		0.1	5	50	60.1	8.32	0.00	0.17	8.32	83.19	GR/BK/Syn/RF						V.C. Sand	Glauconite
D99	85210	85230	20	Planktonic Foraminifera bioclastic G/S	Grainstone	60	0	35	5	100		0.1		25	1		5	5	36	69.44	2.78	0.00	13.89	13.89	GR/BK/BL/DT/NMP						F. Sand	Glauconite
D97	84875	84895	20	Planktonic Foraminifera bioclastic G/S	Grainstone	60	0	35	5	100		0.1		25	1		2	25	53	47.17	1.89	0.00	3.77	47.17	GR / BK / Syn/ DT				Syn		M. Sand	Glauconite
D93	84095	84200	105	Graded biocalstic P/S	Grainstone	55	5	25	15	100		0.1		25	5		1	25	56	44.64	8.93	0.00	1.79	44.64	GR/DT/BL				Syn/BL/GR		C. Sand	Q
D91	83740	83900	160	Clast supported breccia topped by graded bioclastic P/S	Packstone	65	5	25	5	100	1	1		5		0.1	1	25	31.1	16.08	0.00	0.32	3.22	80.39	GR				GR/Syn	0.1	V.C. Sand	
D88	83000	83050	50		Packstone	50	5	25	20	100		5		5	5	0.1	0.1	5	15.2	32.89	32.89	0.66	0.66	32.89	GR/BK				FB/GR/Syn	0.1	C. Sand	
D87	82500	82590	90	Graded biocalstic P/S	Packstone	60	5	15	20	100		25				0.1	5	25	30.1	0.00	0.00	0.33	16.61	83.06	GR				Syn		C. Sand	
D87	82500	82590	90	Graded biocalstic P/S	Packstone	50	40	5	5	100		25				0.1	5	25	30.1	0.00	0.00	0.33	16.61	83.06	GR (F)				Syn/GR		C. Sand	replaced by silica
D85	82100	82220	120	Clast supported breccia topped by graded bioclastic P/S	Packstone	50	0	10	40	100		0.1		0.1	25		0.1	0.1	25.3	0.40	98.81	0.00	0.40	0.40	GR/dol					0.1	M. Sand	
D74	80120	80150	30	Graded biocalstic P/S	Packstone	70	10	5	15	100	1	25		0.1		1	1	100	102.1	0.10	0.00	0.98	0.98	97.94	GR (F)					1	M. Sand	phenocryst replaced by calcite /ignoues phenocryst
D70	74180	74230	50	Planktonic Foraminifera bioclastic P/S	Packstone	60	5	20	10	95		0.1		25	1		25	5	56	44.64	1.79	0.00	44.64	8.93	GR (F)				Syn	0.1	M. Sand	
D65	72130	72190	60	Graded biocalstic P/S	Packstone	60	5	30	5	100	1	25		0.1		0.1	1	50	51.2	0.20	0.00	0.20	1.95	97.66	GR (F)/Syn				Syn/GR/BL	5	C. Sand	
D62	71610	71680	70	Planktonic Foraminifera bioclastic P/S	Grainstone	40	1	55	4	100		0.1	*	25	5		5	0.1	35.1	71.23	14.25	0.00	14.25	0.28	GR/BL/DT/NMP/Syn						V.C. Sand	
D60	64850	64910	60	Graded biocalstic P/S	Packstone	80	5	5	10	100	1	25				5		100	105	0.00	0.00	4.76	0.00	95.24	GR/Dol				Syn/GR		C. Sand	
D55	64060	64120	60	Graded biocalstic P/S	Grainstone	35	5	55	5	100		0.1		100	0.1		1	0.1	101.2	98.81	0.10	0.00	0.99	0.10	GR/NMP/				Micritic env*/Syn	0.1	M. Sand	silica
53a	63800	63810	10		Packstone	60	10	20	10	100		25		0.1		1	5	50	56.1	0.18	0.00	1.78	8.91	89.13	GR (F)				GR/Syn	5	M. Sand	Q
D53	63490	63600	110	Graded biocalstic P/S	Packstone	45	10	35	10	100		0.1		25	5		5	25	60	41.67	8.33	0.00	8.33	41.67	GR/BK/NMP (F)				Syn/BL		V.C. Sand	Q/Glauconite
D52	63400	63405	5	Planktonic Foraminifera bioclastic P/S	Packstone	65	5	20	10	100	5	50		1		5	5	100	111	0.90	0.00	4.50	4.50	90.09	GR (F)/BL				Syn/BL	1	V.C. Sand	Q/??
D47	62610	62695	85	Graded biocalstic P/S	Packstone	75	5	15	5	100		100				5	5	100	110	0.00	0.00	4.55	4.55	90.91	GR (F) /BK				Syn	0.1	C. Sand	Quartz
D46	62490	62510	20	Graded biocalstic P/S	Packstone	70	5	15	10	100	5	50				1	5	100	106	0.00	0.00	0.94	4.72	94.34	GR (F)				Syn/BL/GR	5	C. Sand	Q
D44a	62520	62540	20	Graded biocalstic P/S	Packstone	70	5	10	15	100		100		5	5		25	25	60	8.33	8.33	0.00	41.67	41.67	GR					25	F. Sand	
D44					Packstone	70	5	20	5	100	1	25		1		5	50	25	81	1.23	0.00	6.17	61.73	30.86	GR (F)				Syn	5	C. Sand	Q
D42					Grainstone	50	5	35	10	100		5		25	0.1		25	5	55.1	45.37	0.18	0.00	45.37	9.07	GR (F)				Syn	0.1	C. Sand	Silica
D40	61275	61285	10	Graded biocalstic g/S	Packstone	60	5	25	10	100	1	100				5	5	100	110	0.00	0.00	4.55	4.55	90.91	GR (F)				Syn	5	M. Sand	Glauconite
D38	61170	61210	40	Graded biocalstic g/S	Grainstone	50	5	40	5	100		25		50	5	5	100	25	185	27.03	2.70	2.70	54.05	13.51	GR (F)				Syn	0.1	C. Sand	Glauconite
D36	60970	60990	20	Marl	Mudstone	9	1	5	85	100		0.1		0.1	100		0.1		100.2	0.10	99.80	0.00	0.10	0.00	GR (F)					0.1	V.F. Sand	
D31			0		Packstone	60	1	14	25	100		100		0.1		25	5	100	130.1	0.08	0.00	19.22	3.84	76.86	GR (F)				Syn/BL	0.1	M. Sand	
D30	59040	59100	60	Graded biocalstic g/S	Packstone	70	5	15	10	100		25		1		1	5	100	107	0.93	0.00	0.93	4.67	93.46	GR (F)				Syn/BL*	25	M. Sand	
D28	58475	58500	25	Graded biocalstic P/S	Packstone	60	10	20	10	100	1	25		0.1		1	5	100	106.1	0.09	0.00	0.94	4.71	94.25	GR (F)				Syn/GR	5	C. Sand	Silica
D26	58050	58170	120	Planktonic Foraminifera bioclastic P/S	Packstone	75	5	5	15	100	1	100		1		5	1	100	107	0.93	0.00	4.67	0.93	93.46	GR (F)				Syn/ GR	5	C. Sand	Silica
D24	57550	57557	7		Packstone	30	50	5	15	100	50	100		1		1		100	102	0.98	0.00	0.98	0.00	98.04	GR (F)??	50%			GR (F)	1	C. Sand	Silica
D23	57495	57510	15	Graded biocalstic P/S	Grainstone	60	5	25	10	100		25		5	0.1	1	25	50	81.1	6.17	0.12	1.23	30.83	61.65	GR/BK (F)				Syn	25	C. Sand	Gluconite/silica
D22	57470	57495	25	Planktonic Foraminifera bioclastic P/S	Packstone	60	10	20	10	100	1	25		0.1		5	25	50	80.1	0.12	0.00	6.24	31.21	62.42	GR (F)				Syn	5	M. Sand	Gluconite
D7	54865	54950	85	Graded biocalstic P/S	Packstone	65	5	10	20	100		5		0.1		5	5	25	35.1	0.28	0.00	14.25	14.25	71.23	GR/BK (F)				Syn		M. Sand	Q
D6	54840	54865	25	Clast supported breccia	Grainstone	50	5	15	30	100	15	0.1		25	100		0.1	1	126.1	19.83	79.30	0.00	0.08	0.79	GR / BK(F)				Syn		V.C. Sand	Igneuos
D2	54500	54550	50	Graded biocalstic P/S	Packstone	60	10	10	20	100	1	50		1		25	1	50	77	1.30	0.00	32.47	1.30	64.94	GR/BK				Syn/BK		V.C. Sand	Q
DR37c	53900						100			100									0	#####	#####	#####	#####	####								q
DR33	53815	54020	205	Graded bioclastic packstone	Packstone	80	5	5	10	100	2	100				25	5	100	130	0.00	0.00	19.23	3.85	76.92	GR (F)				Syn/	0.1	V.C. Sand	silica
DR25	52880	52890	10	Planktonic foraminefera bioclastic g/s	Packstone	55	10	10	25	100		25				5	25	50	80	0.00	0.00	6.25	31.25	62.50	GR/BK/Syn				Syn/	0.1	C. Sand	Q
DR23	52810	52830	20	Planktonic foraminefera bioclastic g/s	Grainstone	60	5	25	10	100		5		5	1	5	5	25	41	12.20	2.44	12.20	12.20	60.98	*BK/Syn/DT/gra				Syn/		C. Sand	Q
DR23*	52800		-52800	Planktonic foraminefera bioclastic g/s	Packstone	70	10	5	15	100	5	5				5	1	100	106	0.00	0.00	4.72	0.94	94.34	GR/ DT/Syn/BK				Syn/	0.1	C. Sand	Q/replaced by siclica
DR14a	52700		-52700		Mudstone	20	5	5	70	100		0.1		5	50				55	9.09	90.91	0.00	0.00	0.00	GR/BK/ NMP/Dol*?				GR	0.1	V.F. Sand	
DR11	52650		-52650		Grainstone	50	5	40	5	100		5		25	1	0.1	5	5	36.1	69.25	2.77	0.28	13.85	13.85	GR/ BK/Syn/ DT				Syn/BL		C. Sand	Q/replaced by siclica
D47b							100																									Q
D49B							100																		GR							Q
D51B							100																									IG
D84							100														GR					?		Q

Sample No.			Thickness (cm)	Lithology		% Bioclasts	% lithic clasts	% Cement B. C.	% matrix B. C.	Total	% Silicification	Compaction (Grain alligament)	Mechanical Breackage	Grain contact types						Normalised grain contacts %					Cement types B. C.	Silicification	Fragmentation	Abrasion	Diagenesis within clasts (preservation)	Dissolution Seams	Grain size µm	Remarks
	Base	Top												P. C.	N. C.	C.C.C.	T. C.	S. C.	Sum	P. C.	N. C.	C. C.	T. C.	S. C.								
SRa86			0		Grainstone	40		30	30	100				0.1	25		1		26.1	0.38	95.79	0.00	3.83	0.00	GR				Syn		C. Sand	
SRa75	12000	13700	1700	Clast suppport breccia	Wackestone	30		10	60	100				0.1	100				100.1	0.10	99.90	0.00	0.00	0.00	GR				Syn		F. Sand	
SRa63	4570	4595	25	Discocyclina & Pellatispira bipcalstic W-P/S	Packstone	40			60	100				1	50	1	1	1	54	1.85	92.59	1.85	1.85	1.85							V.C. Sand	
SRa61	3900	4450	550		Packstone	70		1	29	100				5	5	1	1	5	17	29.41	29.41	5.88	5.88	29.41	GR				syn		Granules	
SRa59	2800	3180	380	Breccia	Packstone	80		1	19	100				25	5	0.1	25	5	60.1	41.60	8.32	0.17	41.60	8.32	GR				syn		V.C. Sand	
SRa53	1310	1740	430	Miliolid bioclastic P/S	Grainstone	60		30	10	100				25	100		5	0.1	130.1	19.22	76.86	0.00	3.84	0.08	GR/BL						C. Sand	
SRa51	600	710	110	Quartzose bioclastic G-P/S	Grainstone	40	10	25	25	100				25	0.1		1	1	27.1	92.25	0.37	0.00	3.69	3.69	GR/syn				syn		F. Sand	Q/Glauconite
SRa46			0		Wackestone	40	1		59	100				5	100				105	4.76	95.24	0.00	0.00	0.00					GR		F. Sand	
SRa42			0		Packstone	40	20	0	40	100				25	25				50	50.00	50.00	0.00	0.00	0.00					syn/GR		F. Sand	IG phenocrysts
SRa36			0		Grainstone	35	15	50		100				1	100		1	0.1	102.1	0.98	97.94	0.00	0.98	0.10	GR/NMP/BK				syn/BL		C. Sand	IG phenocrysts
SRa8	3690	3890	200	Bioclastic P/S	Packstone	60		10	30	100				5	100		1	0.1	106.1	4.71	94.25	0.00	0.94	0.09	BK				Syn		M. Sand	
SRa6	3300	3490	190	Discocyclina bipcalstic P/S	Packstone	60		10	30	100				25	25	5	25	5	85	29.41	29.41	5.88	29.41	5.88	GR/Syn				syn		V.C. Sand	
SRa4	2800	3100	300	Bioclastic P/S	Packstone	55		5	40	100				25	50		25	0.1	100.1	24.98	49.95	0.00	24.98	0.10	GR				Syn		M. Sand	
SRa2	0	470	470	Pellatispira bioclastic P/S	Packstone	50	5	5	40	100				25	100		1	0.1	126.1	19.83	79.30	0.00	0.79	0.08	GR				Syn		C. Sand	Q

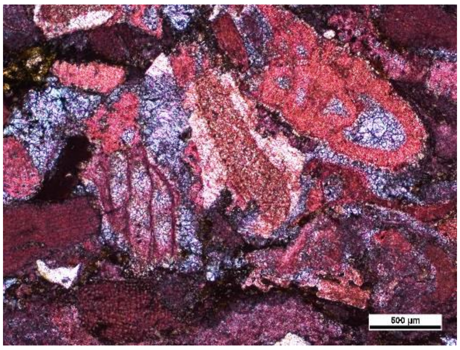
Sample No.	Lithology		% Bioclasts	% lithic clasts	% Cement B. C.	% matrix B. C.	Total	% Silicification	Compaction (Grain allignment)	Mechanical Breackage	Grain contact types						Normalised grain contacts %					Cement types B. C.	Silicification	Fragmentation	Abrasion	Diagenesis within clasts (preservation)	Dissolution Seams	Grain size µm	Remarks
											P. C.	N. C.	C. C. C.	T. C.	S. C.	Sum	P. C.	N. C.	C. C. C	T. C.	S. C.								
SMa46	Clast-supported Breccia		10		70	20	100					100				100	0.00	100.00	0.00	0.00	0.00	GR/ BK (F)/ DS/BL						F. Sand	
SMa43A	Clast-supported Breccia	Grainstone	40		45	15	100				5	100		1	1	107	4.67	93.46	0.00	0.93	0.93	GR/BK/DT/Syn				BL		C. Sand	
SMa34	Lithic planktonic foraminifera bioclastic P/S	Grainstone	40	15	30	15	100				5	0.1		5	25	35.1	14.25	0.28	0.00	14.25	71.23	GR/BK				Syn		M. Sand	IG phenocrysts /Glauconite/crystals replaced by calcite
SMa28	Clast-supported Breccia	Packstone	30		5	65	100				5	100		1	0.1	106.1	4.71	94.25	0.00	0.94	0.09	BK/GR				BK?/BL		C. Sand	
SMa26D	Quartzose S.S. clast			95	5		100									0						BK						V.F. Sand	Q
SMa26C	Kartisified Discocyclina bioclastic P/S clast	Packstone	55		20	25	100				25	50		25	0.1	100.1	24.98	49.95	0.00	24.98	0.10	BK/GR/BL						V.C. Sand	
SMa26B	Kartisified Lepidocyclina bioclastic P/S clast	Packstone	50		15	35	100				25	25		5	0.1	55.1	45.37	45.37	0.00	9.07	0.18	BK/ GR						C. Sand	
SMa26A	Chert clast		50	30		20	100	100			100					100	100.00	0.00	0.00	0.00	0.00							V.F. Sand	
SMa24	Graded bioclastic P/S	Packstone	60		15	25	100				25	5	0.1	5	25	60.1	41.60	8.32	0.17	8.32	41.60	GR (F)				Syn		C. Sand	
SMa21	Planktonic foraminifera W/K	Wackestoe	30		2	68	100	25			0.1	100	0.1	0.1	0.1	100.4	0.10	99.60	0.10	0.10	0.10	GR						V.F. Sand	Reolaced by silica
SMa17	Biplanispira bioclastic P/S	Packstone	80		5	15	100				25	5	5	25	25	85	29.41	5.88	5.88	29.41	29.41	GR				Syn		Granules	
SMa15	Bioclastic G/S	Packstone	60		5	35	100				50	25		25	1	101	49.50	24.75	0.00	24.75	0.99	GR				Syn		M. Sand	
SMa10	Quartzose bioclastic G/S		50		50		100				1	100		1	1	103	0.97	97.09	0.00	0.97	0.97	GR / BK / Syn				Syn/BL/GR		V.C. Sand	
SMa5	Chert Conglumerate		10	90			100				50	0	0	25	0	75	66.67	0.00	0.00	33.33	0.00							F. Pebbles	
SMa4B	Chert		10		55	35	100				0.1	100				100.1	0.10	99.90	0.00	0.00	0.00	GR						F. Sand	
SMa3	Altered diorite			99	1		100									0						GR						M. Sand	IG
SMa1	Quartzose S.S.			97	3		100									0						GR						M. Sand	Q

Appendix E2: Thin Section photomicrographs of samples relating to Chapter 4

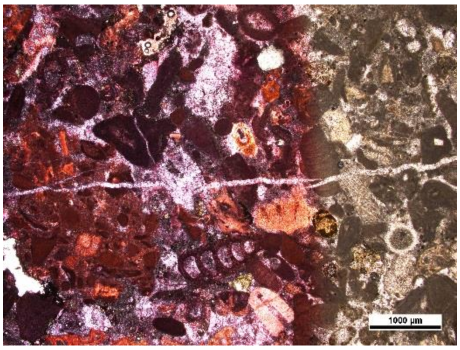
D2



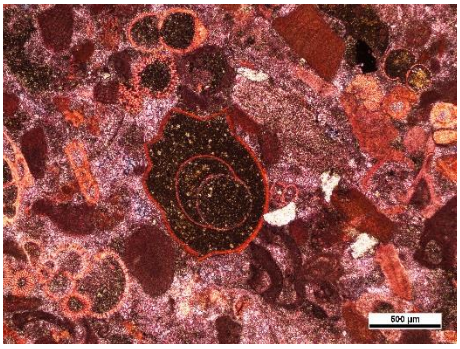
D2



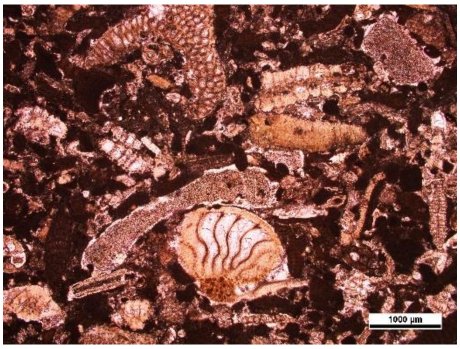
D22



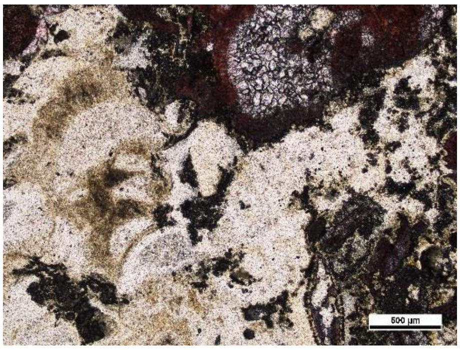
D42



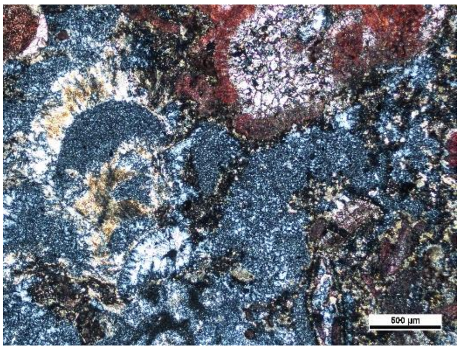
D55



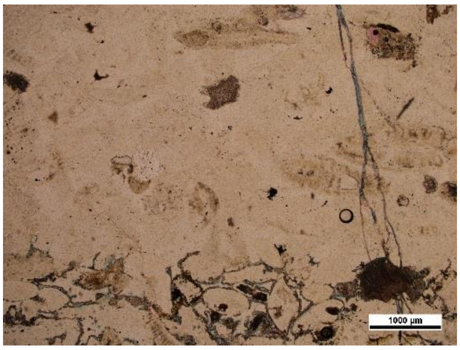
SMa17

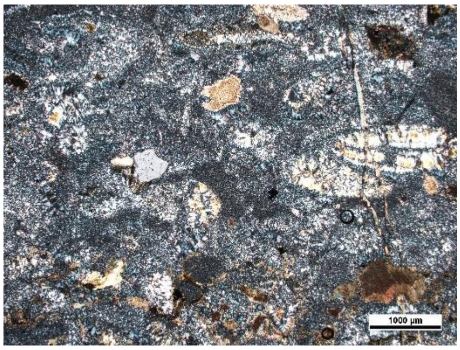


D87



D87-XPL


DR11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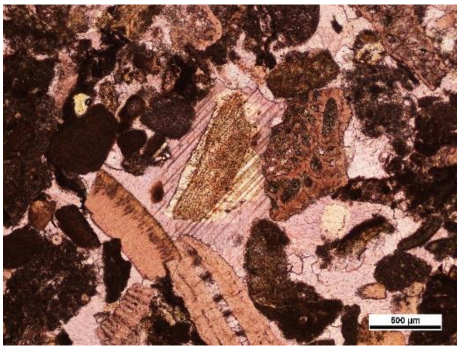
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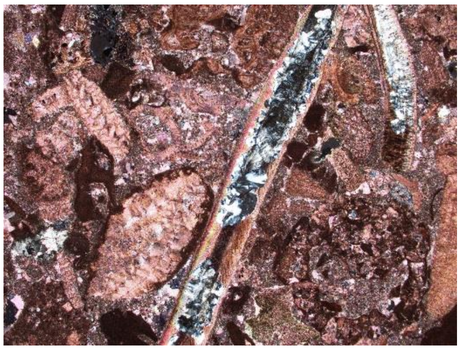
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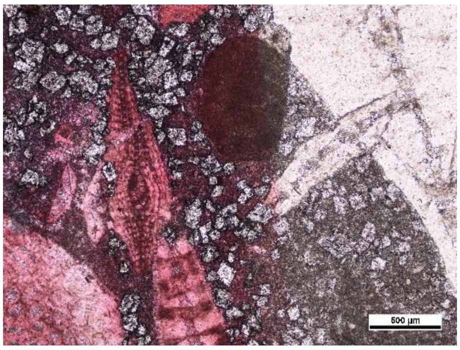
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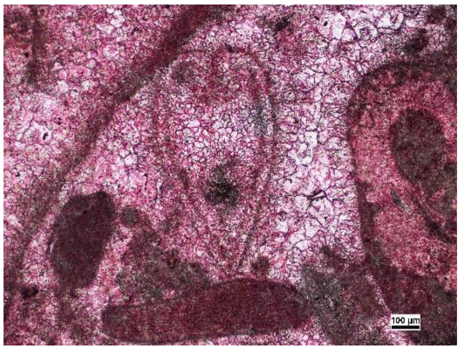
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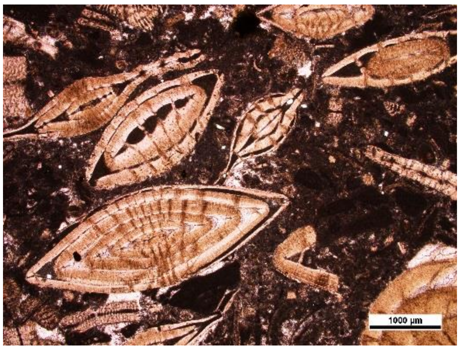
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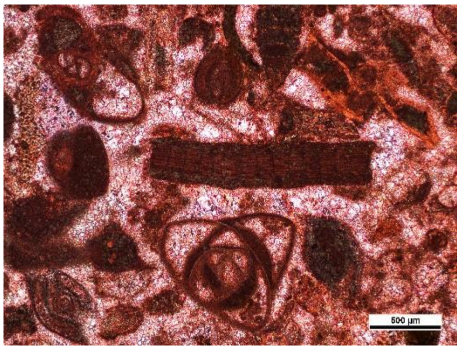
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APPENDIX F

STATEMENT OF THE CONTRIBUTION OF OTHERS

To Whom It May Concern

I, **Hamed Ali Hadi Arosi**, contributed to all aspects of research including, but not limited to, primary data collection, data processing and analysis, figure drafting and writing for the co-authored publications/chapters entitled:

(1) "Diagenesis and fracturing of a large-scale, syntectonic carbonate platform"

(2) "How do thick volcanogenic piles overlying platform carbonates influence the dynamics of carbonate-volcanogenic diagenesis?."

(3) "Variability in diagenesis of carbonate platform slope and basinal deposits."

Hamed A.H. Aros

Date: 21st June, 2016

A realistic breakdown of the contribution by each author for each respective chapter listed above is as follows:

(1) Hamed A.H. Arosi 70%
Dr. Moyra E.J. Wilson 30%

(2) Hamed A.H. Arosi 70%
Dr. Moyra E.J. Wilson 30%

(3) Hamed A.H. Arosi 90%
Dr. Moyra E.J. Wilson 5%
Dr. Robert H.C. Madden 5%

We, as co-author and supervisors to Hamed, endorse that the level of contributions indicated above are accurate.

MEJ WILSON

Date: 21st June, 2016

RHC MADDEN

Date: 21st June, 2016

APPENDIX G

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Diagenesis and fracturing of a large-scale, syntectonic carbonate platform

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ABSTRACT

The influence of coeval tectonics on carbonate platform development is widely documented, yet the diagenesis of such syntectonic platforms is barely evaluated. An outcrop, petrographic and geochemical study details here for the first time the diagenesis of the Tonasa Limestone Formation developed in an extensional regime in central Indonesia. This equatorial carbonate system was affected by block faulting, tilt-block rotation, differential uplift and subsidence throughout its Eocene to Early Miocene history (Wilson, 1999; Wilson et al., 2000). The Tonasa carbonate platform is dominated by alteration in shallow to deeper burial depths by fluids with predominantly marine precursor origins. Mechanical and chemical compaction features are common, as are a range of mainly burial-related granular mosaic, blocky and equant calcite cements. Earlier marine cements and meteoric influences are rare, being highly localised to block faulted highs and/or bathymetrically upstanding platform margin areas. Early marine micritisation of allochems was common on the platform top. Tectonic uplift together with a major oceanic throughflow current are thought to be key influences on localised karstification, meteoric diagenesis and marine cementation. The distribution and orientation of faults, fractures and calcite veins together with evidence for their relative timing are the strongest manifestation of tectonism coeval with diagenesis. There is concordance in the orientation and timing of structures affecting the Tonasa Platform with those basin-wide, with the potential for reactivation of pre-existing basement fabrics. Tectonic subsidence, including fault-associated differential subsidence, controlled the degree of burial diagenesis impacting different areas of the platform. A predominance of burial diagenetic features and dearth of earlier marine or meteoric cementation is seen in other Tertiary equatorial platforms and is partly attributed to: (1) predominance of non-framework building larger benthic foraminifera and/or algae that are prone to remobilisation, have low production rates and limited potential to build to sea level, and (2) high runoff due to the equatorial humid climate contributing to lowered marine salinities in SE Asia. Underlying tectonic reasons for the preponderance of a “regional” diagenetic signature over a “syntectonic” one, fracturing excepted, are: (1) development on the flanks of a backarc basin not on typical continental crust, (2) key platform influencing structures are oblique to the main extensional direction in the basin, and (3) development in an overall subsiding tectonic regime, post-dating basin initiation. The aim here is that this study will contribute to understanding diagenetic alteration of syntectonic carbonate platforms, and those from equatorial regions.

1. Introduction

The development of syntectonic carbonate platforms from a range of tectonic regimes is widely documented in the literature (Burchette, 1988; Gawthorpe et al., 1994; Dorobek, 1995, 2008a, 2008b; Wilson et al., 2000; Wilson and Hall, 2010), yet the diagenesis of such platforms is poorly detailed. In the active tectonic area of SE Asia at least two-thirds of the isolated carbonate platforms are documented to have formed over faulted antecedent highs with carbonate accumulation on many of these platforms coeval with local continued tectonism; i.e., many are syntectonic (Wilson and Hall, 2010). Isolated systems in SE Asia contain 83% of the hydrocarbon reserves within the regions carbonates. With many of these platforms being tectonically influenced there is an economic driver to better understand the variable diagenesis of syntectonic platforms and any impact on reservoir potential (Wilson and Hall, 2010). Tectonics may influence carbonate systems through uplift, differential subsidence, or active faulting (Burchette, 1988; Wilson and Hall, 2010). Localised uplift and karstification of footwall highs and significant local variations in stratal thicknesses across platforms have all been documented for syntectonic carbonate platforms (Burchette, 1988; Rosales et al., 1994; Wilson, 1999; Wilson et al., 2000; Bachtel et al., 2004). The diagenetic details, or implications for platform alteration, of these localised karstic features or stratal thickening are generally not discussed (Rosales et al., 1994). Various studies have detailed fracture patterns in carbonate systems, but these are rarely linked to syntectonic sedimentation, and the diagenesis of such fractures remains underevaluated (Rosales et al., 1994; Cloke et al., 1999a; Van Geet et al., 2002; Breesch et al., 2009). The climatic, oceanographic and basinal context unique to any platform will also influence platform

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alteration and these factors may be indirectly affected by tectonics (Moore, 2001; Wilson, 2012). The major question addressed here is: to what extent does the tectonic regime influence the diagenesis of syntectonic platforms, or are regional or basinal controls more influential on the alteration of such systems?

The Eocene to Miocene Tonasa Carbonate Platform of Sulawesi, Central Indonesia, is a well-documented syntectonic platform for which the influences on diagenesis of: (1) tectonics, (2) an equatorial climatic setting and (3) basin context are detailed here for the first time. Plate tectonic drift and associated changes in carbonate communities and their alteration is an additional influence on carbonate platform development (Davies et al., 1989) and diagenesis that is not documented here.

The sedimentology and evolution of the Tonasa Carbonate Platform have been previously documented, with inferred dominant controls on deposition including tectonics, volcanism, nutrients and oceanography (Wilson, 1996, 1999, 2000; Wilson and Bosence, 1996, 1997; Wilson et al., 2000; Wilson and Vecsei, 2005). However, there has been almost no prior diagenetic analysis of the Tonasa Limestone, with just minor mention of reservoir quality issues (Wilson, 1996, 2000; Wilson and Bosence, 1997). The previous sedimentary studies set the context for this diagenetic evaluation. Diagenetic "interactions" between the carbonates of the Tonasa Formation and the overlying and intruding igneous strata are the subject of a further study (Arosi et al., in prep.).

2. Geological setting

Sulawesi, including the Tonasa Formation of this study, is located in the centre of the Indonesian Archipelago in the midst of one of the most complex, active tectonic regions in the world (Fig. 1; Hamilton, 1979; Hall, 1996, 2002a; Hall and Wilson, 2000; Hall et al., 2011). From the Mesozoic, and throughout the Cenozoic, SE Asia has been affected by the interaction of three main tectonic plates the: Pacific-Philippine, Indo-Australian and Eurasian plates (Hamilton, 1979; Daly et al., 1991; Hall and Wilson, 2000). Hall (2002a) outlined three main collisional tectonic events at 45, 25 and 5 Ma that resulted in tectonic 'reorganisation' within SE Asia.

The evolution of south western Sulawesi (the South Arm) during the late Mesozoic and Cenozoic is linked to the accretion of microcontinental and oceanic fragments onto the eastern margin of the comparatively stable Eurasian plate, together with backarc rifting and volcanic arc development (Sukamto, 1975; Hamilton, 1979; van Leeuwen, 1981; Wilson and Bosence, 1997; Wilson, 1999, 2000). Relatively complete, but very different Late Cretaceous to recent stratigraphic sequences in the western and eastern halves of the South Arm reflect this complex geological evolution (Fig. 2; van Leeuwen, 1981; Wilson, 1999). The Balangbaru and Marada Formations are deep-marine forearc clastics and shales of Late Cretaceous age that overlie intersliced metamorphic, ultrabasic and sedimentary basement lithologies in the western South Arm (van Leeuwen, 1981; Hasan, 1991). By the Eocene, subduction had shifted to the east and marginal marine siliciclastics of the Malawa Formation in western South Sulawesi are associated with rifting of a broad basinal area centred on the Makassar Straits. The clastics pass transgressively upwards to carbonates of the Eocene to Miocene Tonasa Formation of this study that have predominantly shallow-water origins. During the Tertiary, accumulation of sedimentary rocks predominated in western South Sulawesi, whereas volcanic and igneous lithologies dominated to the east. This east-west lithological subdivision occurs across a major structural divide, today demarked

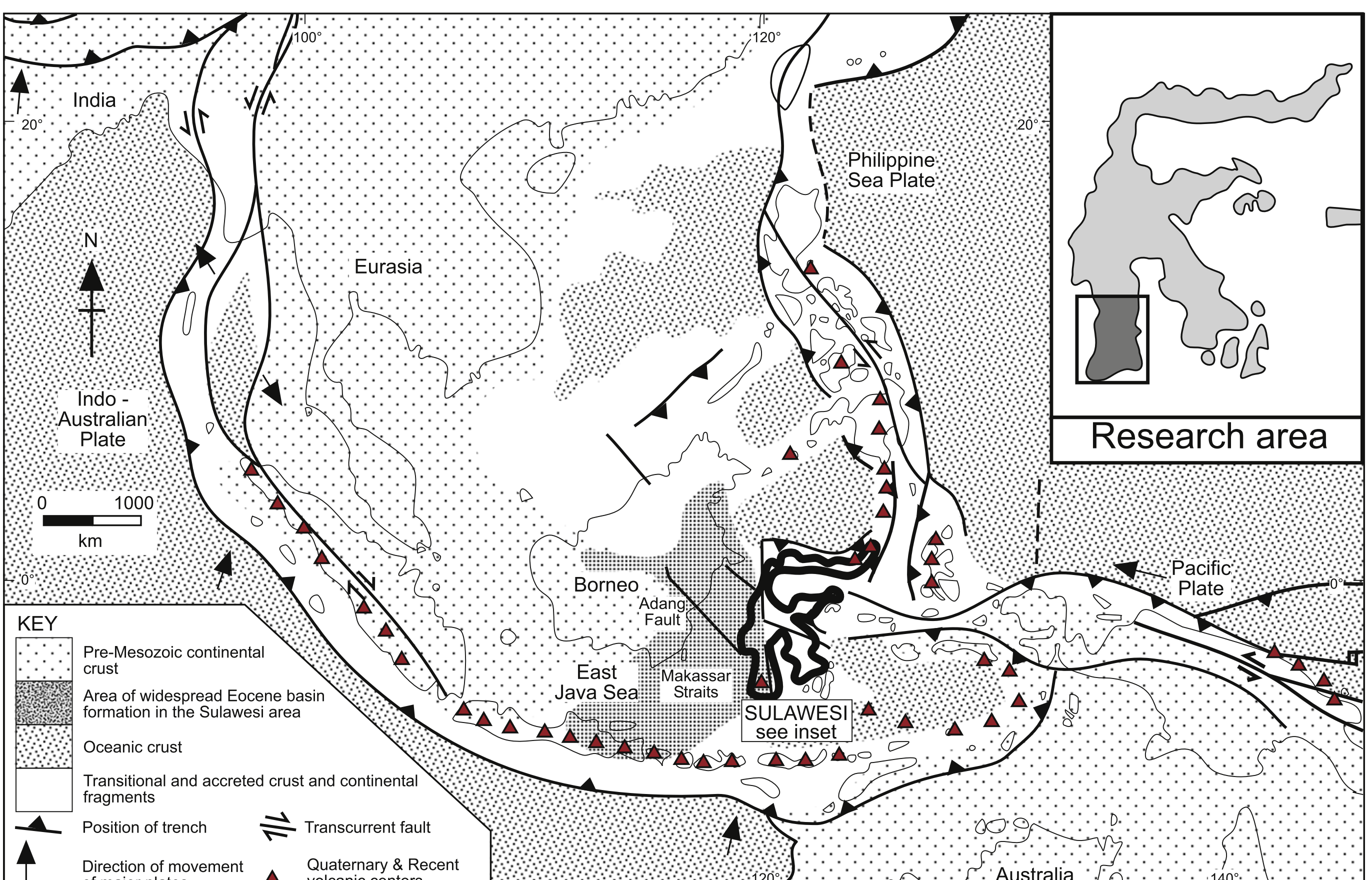

Fig. 1. Regional tectonic setting of Sulawesi and the location of the Tertiary basinal area in Sulawesi/Borneo (from Wilson et al., 2000, modified after Daly et al., 1991; Hall, 1996; van de Weerd and Armin, 1992; Wilson, 1999). Inset shows the position of the research area within Sulawesi.

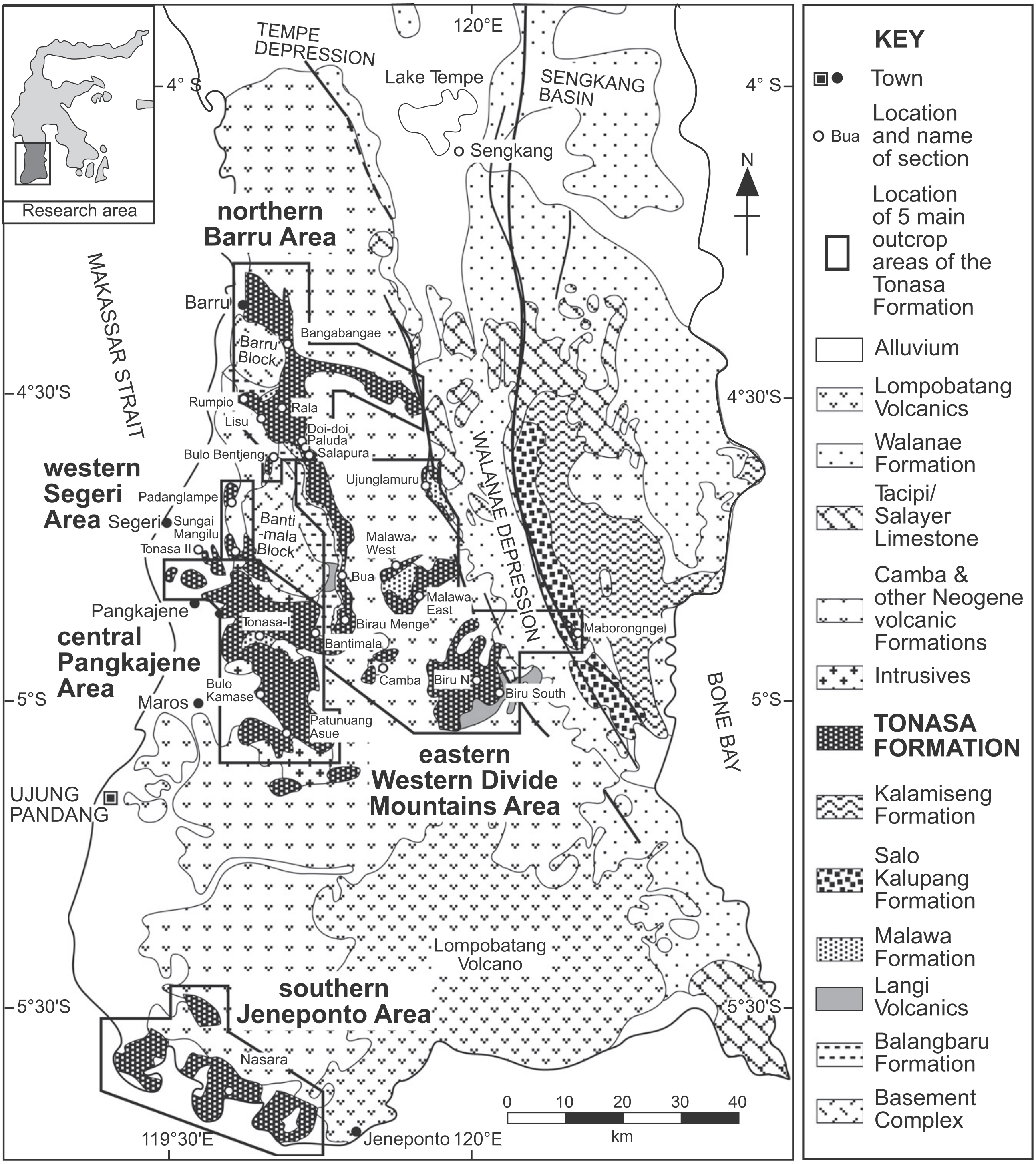

Fig. 2. Geological map of South Sulawesi (from Wilson et al., 2000; after van Leeuwen, 1981; Sukamto, 1982; Sukamto and Supriatna, 1982; Wilson, 2000), showing the locations of the five main outcrop areas of the Tonasa Formation and the location of mentioned measured sections.

by the fault-bounded, NNW-SSE trending Walanae Depression (Fig. 2). The varied igneous rocks of eastern South Sulawesi include arc-related volcaniclastics, passive margin volcanics associated with the cessation of subduction, potassic volcanics linked to extension, as well as MORB-like volcanics from an accreted transtensional marginal oceanic basin (Sukamto, 1982; Yuwono et al., 1987; van Leeuwen et al., 2010). Middle to late Miocene volcaniclastics and volcanics of the Camba Formation overlie the Tonasa Formation (Sukamto, 1982; Yuwono et al., 1987; Wilson, 2000). The Miocene shift in volcanism to western South Sulawesi and associated potassic igneous intrusions are linked to microcontinental collision related volcanism and post-collisional magmas (Elburg and Foden, 1999; Elburg et al., 2003).

3. Deposition and development of the Tonasa Formation

The Early or Middle Eocene to Middle Miocene Tonasa Formation of this study comprises the main part of the Tertiary succession in the western part of South Sulawesi. The formation consists of shallow carbonate platform, associated slope and adjacent bathyal deposits that locally crop out over a 160 by 80 km north-south and east-west extent,

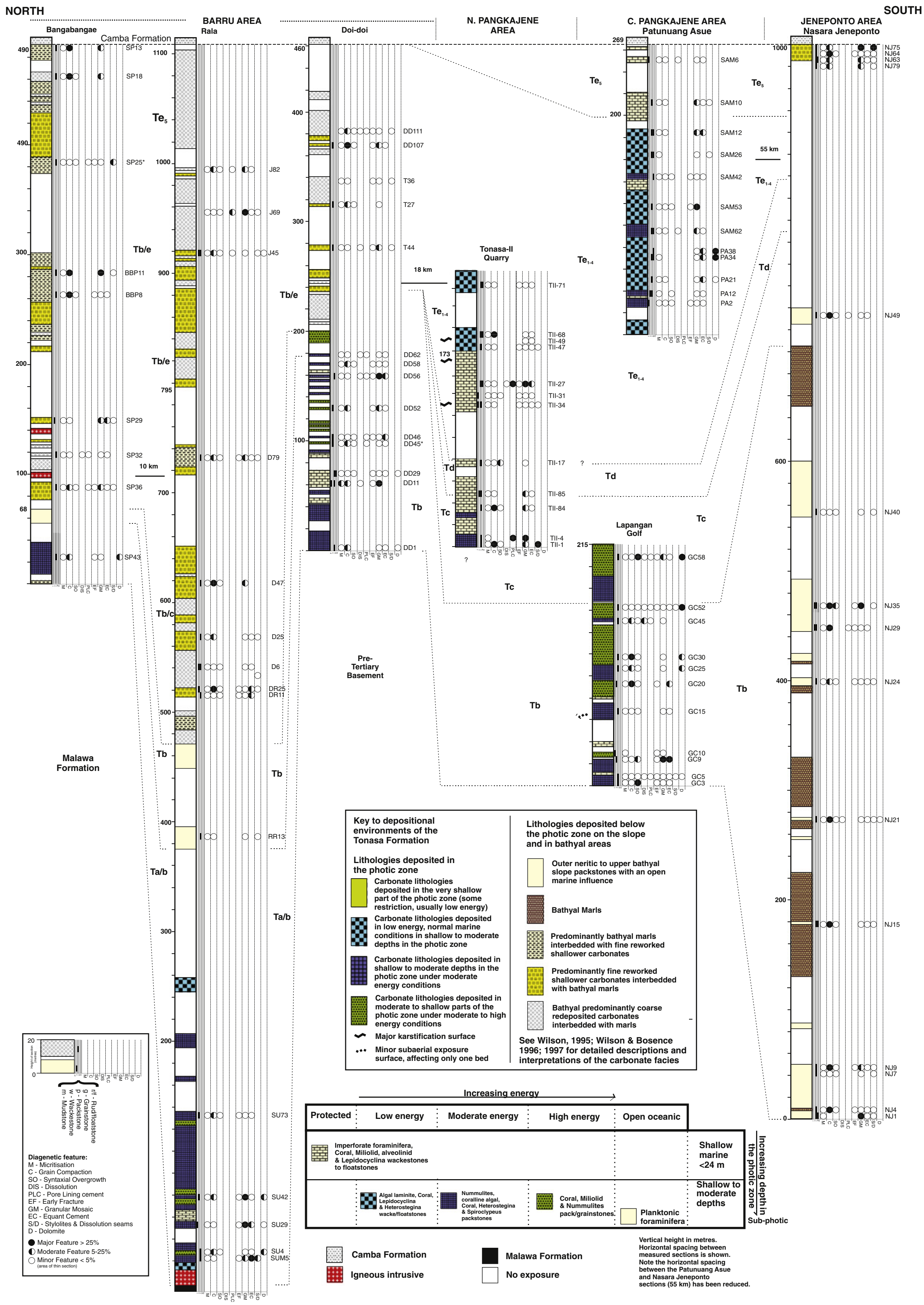

Fig. 3. Selected summary measured sections from north to south across the main Tonasa tilt-block platform with diagenetic summaries from petrography of individual samples plotted against logged sections from Wilson et al. (2000) and Wilson (1995).

respectively (Figs. 2, 3, 4; Wilson and Bosence, 1996, 1997). Previous studies on the sedimentology and evolution of the Tonasa Carbonate Platform, together with evaluations of controlling influences set the context for this diagenetic study, and are briefly outlined below (Wilson, 1996; 1999, 2000; Wilson and Bosence, 1996, 1997; Wilson et al., 2000; Wilson and Vecsei, 2005).

Shallow-water deposits of the Tonasa Carbonate Platform are mainly wackestones, packstones and grain/rudstones that are dominated by larger benthic foraminifera. Other components include small benthic foraminifera, echinoid remains, coralline algae and more rarely corals (Wilson and Bosence, 1997; Wilson and Rosen, 1998; Wilson et al., 2000). Planktonic foraminifera are abundant in basinal marls. The marls interdigitate with slope and platform-fringing breccias and pack/grain/rudstones. The slope deposits contain abundant shallow-water bioclasts that were reworked downslope as well as a range of lithic clasts derived from the Tonasa and underlying formations (Wilson and Bosence, 1996; Wilson, 1999; Wilson et al., 2000).

Carbonate sedimentation of the Tonasa Formation began diachronously, with shallow-water deposits forming earliest in the northern Barru and southern Jeneponto Areas during the Early to Middle Eocene (Fig. 2; Wilson et al., 2000). By the Late Eocene shallow carbonate sedimentation had spread across much of western South Sulawesi. However, during the latter part of the Late Eocene fault segmentation resulted in rapid localised deepening and drowning of the platform in the northern Barru, eastern Segeri and westerly Western Divide Mountains Areas (Fig. 2; Wilson, 1999; Wilson et al., 2000). Some of the faults including those bounding the northern and eastern extent of main shallow platform are linked to major structural divides. These occur along strike from the NW-SE trending Adang Fault and as bounding faults to the NNW-SSE trending fault-bounded graben of the Walanae Depression, with potential involvement and reactivation of earlier basement structures (Figs. 1, 2; van Leeuwen, 1981; Wilson and Bosence, 1996; Wilson et al., 2000). A large-scale (100 km north to south) tilted-fault-block platform with a segmented faulted northern margin (northern Barru Area) and gently dipping southern margin (southern Jeneponto Area) accumulated over 600 m of shallow water platform carbonates centred on the central Pangkajene Area (Wilson et al., 2000). Although onshore volcaniclastics cover parts of the more southerly deposits of this platform, in the area directly offshore to the west seismic data reveals the predominantly unbroken north to south nature of the coeval continuation of the platform (Letouzey et al., 1990). Up to 1100 m of shallow and mainly deep-water carbonates accumulated to the north (Barru) and south (Jeneponto) of the main platform. Areas of more complex faulting to the east and west of the main platform resulted in localised fault-block platforms and intervening small-scale basinal grabens (western Segeri and eastern Western Divide Mountains Areas on Fig. 2; Wilson et al., 2000; Wilson, 2000). Major shallow-water facies belts on the main tilt-block platform trend E-W, were aggradational and remained static through time. Low to moderate energy wackestones and packstones dominated in the north and south of the main shallow-water tilt-block platform, whereas higher energy grainstones prevailed in the central facies belt (Wilson and Bosence, 1997; Wilson et al., 2000). Water depths and energy, linked to differential subsidence/uplift together with the presence/absence of shallow shoaling protective 'barriers' along the westerly windward platform margin, are inferred to be important influences on the facies and biota present (Wilson and Bosence, 1997; Wilson et al., 2000). Localised subaerial exposure is inferred for the shallowest part of the main tilt-block platform on the northerly footwall high and also for some of the east-west developed block-faulted platforms (Wilson and Bosence, 1996, 1997; Wilson, 2000; Wilson et al., 2000). Mass reworking of material was common from the faulted highs into adjacent basinal graben and is often linked to phases of tectonic activity (Wilson and Bosence, 1996; Wilson, 1999; Wilson, 2000; Wilson et al., 2000). On the gently dipping southern hangingwall slope of the main tilt-block platform there was southward progradation of ramp deposits into bathyal areas during periods of tectonic quiescence and minimal subsidence (Wilson and Bosence, 1997; Wilson et al., 2000). Final demise of the

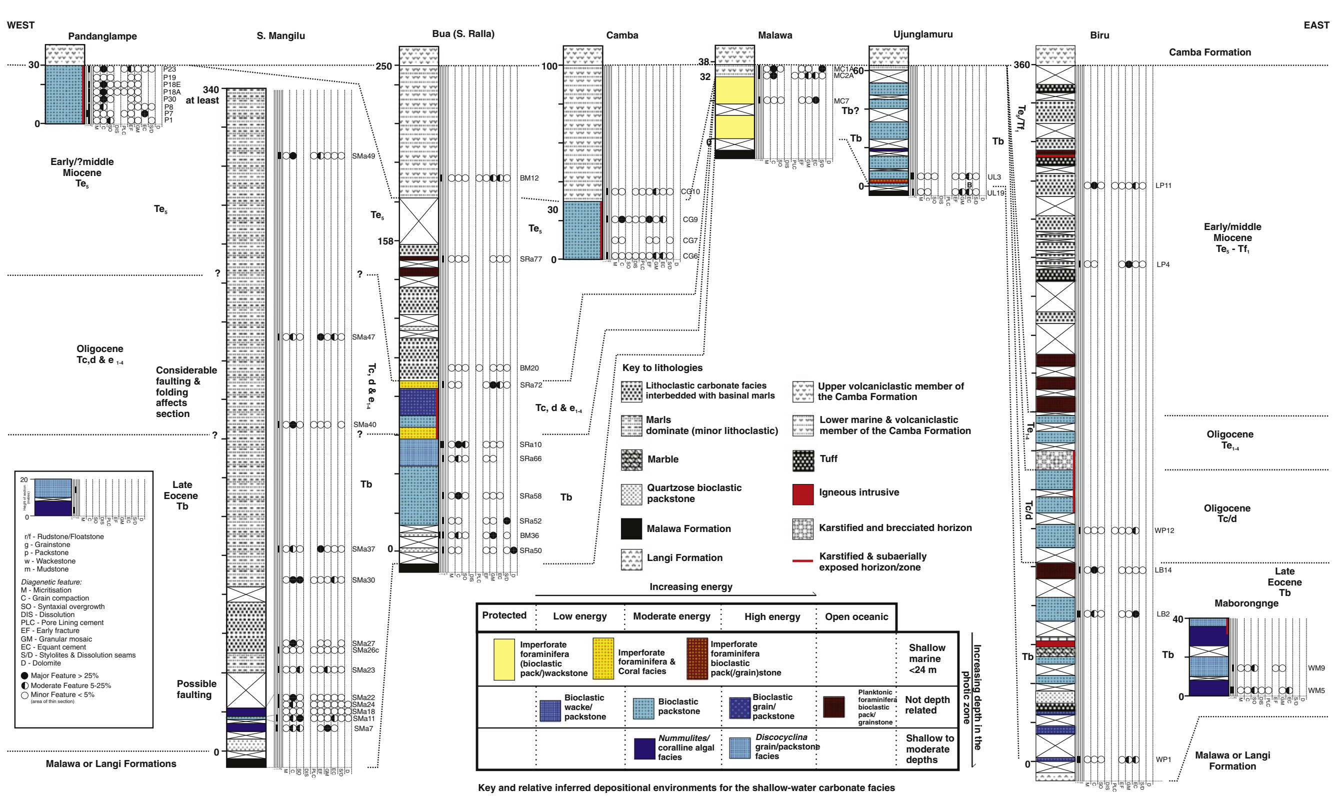

Fig. 4. Selected summary measured sections from west to east across areas of complex block faulting in the Tonasa carbonate platform with diagenetic summaries from petrography of individual samples plotted against logged sections from Wilson et al. (2000) and Wilson (1995).

platform at the end of the Early Miocene was linked to a laterally variable combination of fault-related drowning, uplift and subaerial exposure together with smothering by volcaniclastics (Wilson, 2000).

4. Methods

Carbonates of the Tonasa Formation are exposed as massive karstic outcrops up to 700 m high and in low riverbank exposures in western South Sulawesi. Good exposure allowed high resolution sampling, sedimentary logging, facies mapping and partial section correlation throughout the shallow water platform and adjacent basinal deposits. Eighty-one measured sections were logged (totaling >7 km of section) and of the ~1200 samples collected ~500 were thin sectioned or made into acetate peels. A subset of 153 representative thin sectioned samples that covered the full range of diagenetic features observed in the Tonasa Formation from 26 key sections were evaluated for this diagenetic study. As reported in Wilson et al. (2000) age assignments of samples were through comparison with the modified East India Letter Classification for larger benthic foraminifera (van de Vlerk and Umbgrove, 1927; Adams, 1970; Lunt and Allan, 2004) correlated against the 2004 geological timescale of Gradstein et al (2004; Figs. 3, 4).

Lithological components, microfacies, diagenetic phases and the relative timing of diagenetic events were determined through thin-section petrography. All samples were half stained with Alizarin Red S and potassium ferricyanide to allow identification of dolomite, ferroan and non-ferroan calcite (Dickson, 1965, 1966). The relative abundance of components and diagenetic phases were recorded semi-quantitatively (visual estimates; after Mazzullo and Graham, 1988). Facies nomenclature follows the textural classification scheme of Dunham (1962), modified by Embry and Klovan (1971), with components given in lithology names where they exceed 10–15%. Nomenclature on carbonate cement morphologies follows Flügel (2004). Cold cathodoluminescent (CL) microscopy study of 32 polished sections was via a Technosyn 8200 MkII luminoscope (after Witkowski et al., 2000). Samples for CL analysis were selected to investigate the range of coarse (>250 μm) cement phases present.

Stable-isotope analysis ($\delta^{18}O$ and $\delta^{13}C$) was undertaken on 36 samples micro-drilled from the rock off-cut counterpart of the thin sections. Drilling sites matched directly to the off-cuts, correspond to a range of depositional and diagenetic features identified in thin section. Drilled samples include bioclasts, matrix and a range of cements with varied morphologies, with the later including those filling fractures. Oxygen and carbon isotope analyses were run on a VG Isocarb automated system online to a VG Isogas Prism II isotope-ratio mass spectrometer. All data have been normalised to NBS-19: a primary carbonate standard used to define the V-PDB scale ($\delta^{13}C = +1.95‰$, $\delta^{18}O = -2.2‰$). In addition, replicate analyses of an internal carbonate standard (Mab2b) were reproducible to $\pm 0.1‰$.

Fractures were recorded in four ways to evaluate their orientations, and to gauge their potential relative timing with respect to carbonate sedimentation. (1) The strike orientations, and where possible dip data, for large-scale faults were recorded from field observations and the geological maps of South Sulawesi (scale: 1:250,000; Sukamto, 1982; Sukamto and Supriatna, 1982). (2) Strike and dip data were measured for millimetre to centimetre-scale aperture fractures, calcite veins (and joints) seen in outcrop during fieldwork. These small-scale features will have likely been under-recorded in all areas due to masking by heavy dripstone coating on the upstanding karstic outcrops and an algal film and/or up to 2 cm tufa-like coating on low river outcrops. (3) In thin sections, the ratio of numbers of both highly irregular and straight fractures to numbers of samples studied were recorded from key sections of all ages through *in situ* shallow platform and deeper slope to basinal deposits in all areas. Whilst not diagnostic, the highly irregular fracturing is more likely to have occurred when the deposits were semi-lithified, as opposed to fully lithified for the straight fractures. (4) In the slope breccia deposits consisting of material reworked into deeper water settings the ratio of numbers of both fractures and/or calcite filled veins constrained to within lithic clasts and those that cross-cut multiple clasts within the breccia fabric were recorded versus the number of samples studied. This latter data was recorded from thin sections through breccia units with lithic clasts of at least 5 mm across from the northern, western and eastern areas where these deposits range from Late Eocene to Miocene in age (cf. Wilson and Bosence, 1996; Wilson et al., 2000). Fractures within clasts, commonly truncated at clast margins, are present in less than 1–2% of both carbonate and non-carbonate lithic clasts in individual breccia samples. These intraclast fractures are, nevertheless, an indication of fracturing and any associated calcite cementation occurring prior to reworking of the lithic clasts. This is as opposed to the fractures that cross-cut the fabric of the breccia that must have formed after the material was reworked and deposited downslope as the breccia units. The thin section evaluation of potential relative timing of fractures was from 164 thin sections from the key measured sections. An additional 45 thin sections of the slope deposits had clasts too small to meaningfully evaluate intra- versus extra-clast fracturing.

5. Results: diagenetic features from petrography

Diagenetic features are described in their most common order of occurrence, as inferred from thin section petrography. There is, however, some variation in the relative timing of events between samples.

5.1. Micritisation

Micritisation of carbonate allochem margins pre-dates all other diagenetic features. Light to dark brown micritic rims to allochems as seen under plane-polarised light microscopy are generally between 20 and 30 μm (Fig. 5a, b and c). Micritisation is seen in almost all thin sections, but the area of micritic rims in individual thin sections is mostly <2–5%. Grain micritisation is seen in all the different facies, but generally only as trace amounts in the basinal marls, planktonic foraminifera wacke/packstones and breccia units. Trace amounts of micritisation also occurs in some shallow-water grainstones and wacke/packstone units from the Central, Northern and Eastern Areas. Samples having the most common micritisation, including micritic envelopes encircling grains with rims up to 40 μm thick, include larger benthic foraminifera wacke/packstone and coral floatstones from the Central and Eastern Areas (Fig. 5a, b and c). The CL signature of micritised rims is usually dull to non-luminescent: similar to, or slightly brighter than, the marine bioclasts they encircle.

5.2. Cavities and pore-lining cements

Pore-lining cements are uncommon in the Tonasa Formation, present in 19 out of 153 samples studied, with the additional samples not selected for this study containing almost none of these cements. Pores, or cavities that these cements line fall into two categories: (1) primary intergranular or shelter pores between bioclasts or lithic clasts that are on a mm- to cm-scale (Fig. 6), and (2) secondary dissolution cavities that cross cut strata and are on decimeter-scale (Fig. 7). Dissolution cavities are irregular in shape, have sharp, truncational margins with the host limestone and may be linked vertically by fractures and/or dissolution pipes. These dissolution cavities were found in 4 localised areas of the Tonasa Limestone Formation (Wilson et al., 2000). (1) Associated with the northernmost faulted basement high of the Barru Block (Fig. 2) in reworked shallow-water limestone clasts derived from the northern faulted margin in the late Eocene. A few metre-scale Late Eocene shallow-water carbonate outcrops that fringe the southeasterly dip-slope of the Barru Block faulted basement high also include dissolutional cavities (Wilson and Bosence, 1996). (2) Dissolutional cavities are seen in limestone clasts reworked during the Early Miocene in a basinal graben and within *in situ* shallow-water Early Miocene limestones 2 km to

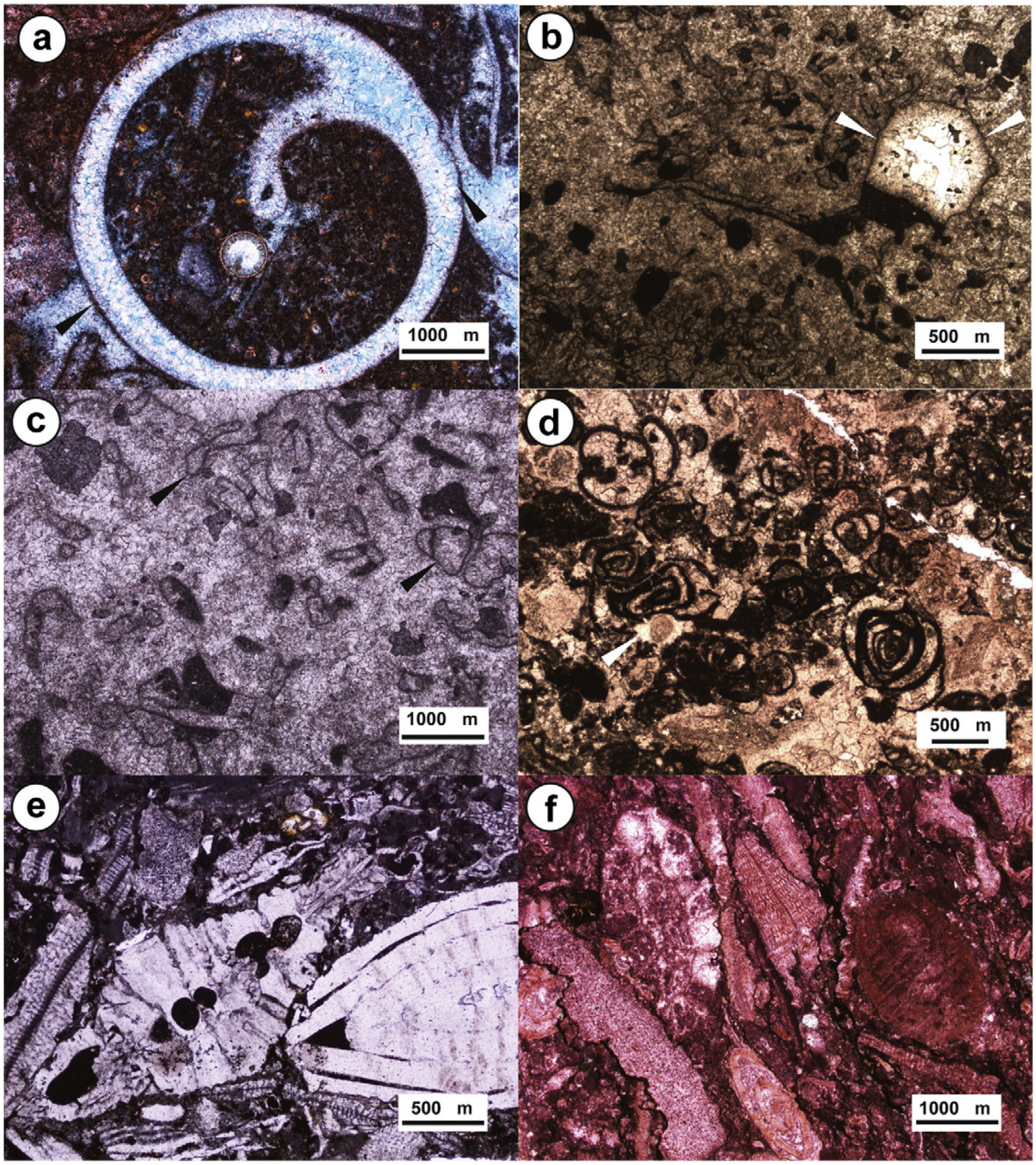

Fig. 5. Thin-section plane polarised light photomicrographs showing (a) Micrite envelope (arrowed) encircling gastropod, the latter replaced by ferroan calcite (CG10, Eastern Area). (b and c) Micritic envelopes (arrowed), 20–30 μm thick, in coral floatstone from the Central Area (GC10). Coral skeleton is replaced by granular mosaic cement, whereas micritised cavity in coral arrowed in 'b' contains a partial micritic geopetal infill followed by bladed then blocky cement infill. (d) Imperforate foraminifera-rich grainstone from the central area (GC9) showing grain distortion of micritic-walled miliolids. Syntaxial overgrowth on echinoderm has a concavo-convex contact with adjacent distorted miliolid. Cement between grains is predominantly granular mosaic calcite, some including 'dusty' micritic areas. (e) Tangential to sutured grain contacts in shallow water larger benthic foraminifera bioclastic packstone from the Western Area (P18e). Mechanical breakage of the thin discocyclinids is common, whereas the robust *Pellatispira*/?*Biplanispira* (centre left) and *Nummulites* (centre right) act more like indentor grains having slightly sutured contacts with surrounding allochems. (f) Concavo-convex to sutured grain contacts in shallow water bioclastic packstone from the Eastern Area (SRa52), with swarm-like bed-parallel stylolites to dissolution seams.

the west of the graben, both in the western Segeri area. (3) Four kilometres SW of the western Segeri sections in the northernmost part of the central Pangkajene area one Late Oligocene bed of peritidal algal laminites with the overlying bed having interpreted gas escape structures are associated with reddened surfaces and irregular dissolutional cavities (Fig. 7). Late Eocene shallow carbonates in the same vicinity also contain irregular dissolutional cavities with reddened infill. (4) In the eastern area irregular dissolutional cavities are associated with erosion and tilting of strata. In the Malawa West, Ujunglamuru, Maborongnge and Bantimala measured sections Late Eocene limestones with irregular dissolutional cavities containing fine sediment are overlain by volcanics of the Camba Formation via an angular unconformity. Early Miocene shallow water carbonates at Camba have irregular dissolutional cavities of centimeter to decimeter-scale that are coated in speleothem stalagtitic and stalagmitic precipitates and containing infills of fine carbonate sediment interlaminated with layers of cave pearls (Fig. 7). The shallow-water Miocene limestones have a highly rugose upper contact with the Camba Formation at Camba and dissolution cavity infills are cut by fractures containing volcaniclastic sediment (Fig. 7). Shallow water deposits of Early Oligocene age in the Biru area bordering the western margin of the Walanae Graben have a reddened brecciated upper surface that is overlain by Late Oligocene packstones and grainstones containing planktonic foraminifera. The Bua and Birau Menge sections have irregular dissolutional cavities in Early Oligocene carbonates a few metres below an erosional and angular discordant contact with overlying Late Oligocene deposits. None of the areas with dissolution cavities can be traced for anything more than a few metres to ten metres in outcrop. In the often highly vegetated and dripstone

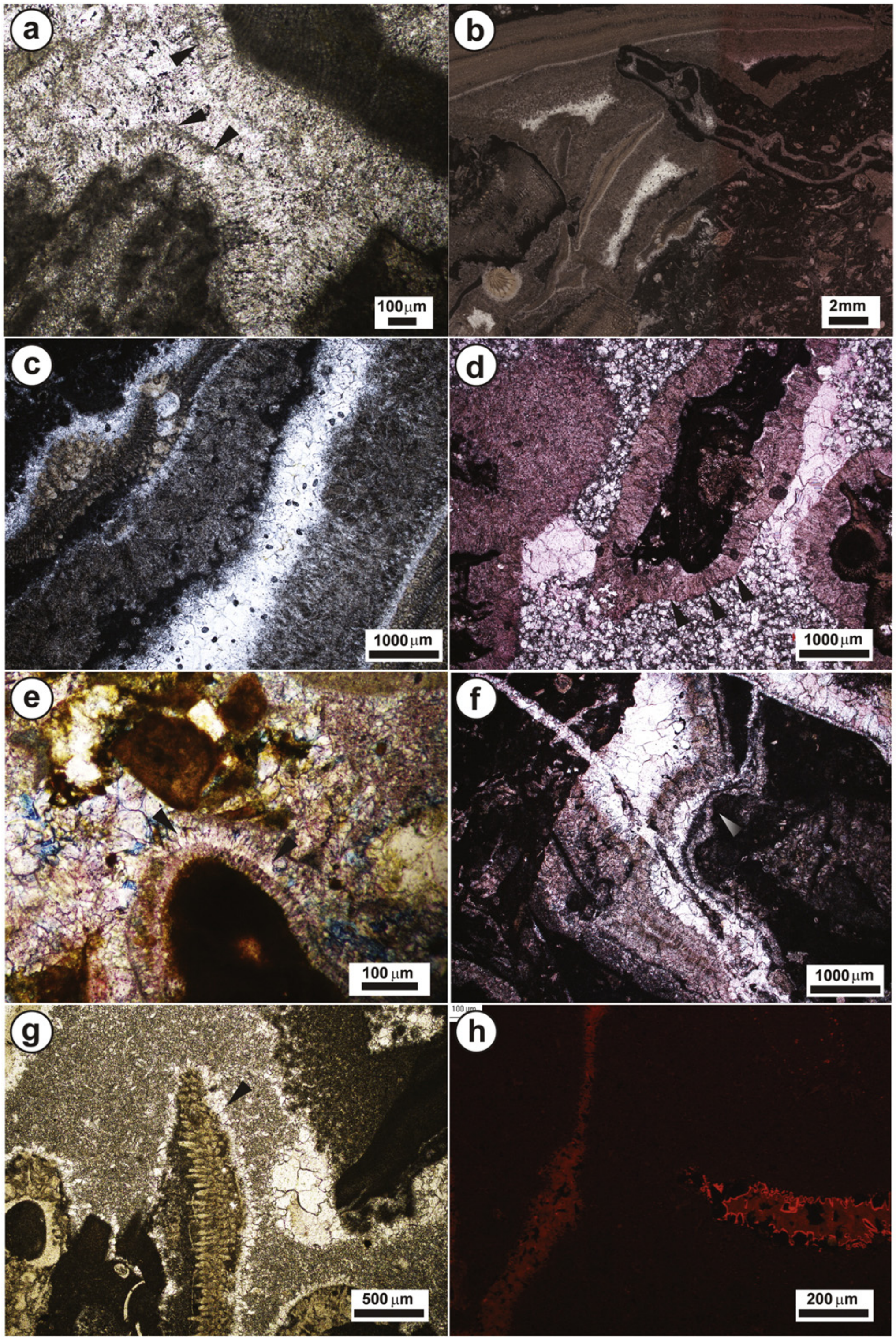

Fig. 6. Thin-section photomicrographs of pore-lining cements from the Tonasa Platform. (a) Possible bladed to isopachous grain fringing cement with slightly micritised crystal terminations (black arrows), now replaced by granular mosaic cement (Eastern Area, CG9). (b and c) 'Turbid' radiaxial fringing cement lining cavities between bioclasts and post-dating minor clear isopachous fringing cement. Radiaxial cements are up to 2 mm long and show sweeping extinction patterns within crystals, when viewed from perpendicular to the long axis of the crystal under cross-polarised light. Radiaxial cements are post-dated by partial micritic infill in cavities then clear equant to blocky calcite cement (Western area, SMa26c). (d) Bladed dark-pink stained, non-ferroan calcite lining irregular dissolutional cavities (arrowed). Silt-sized rhombs of dolomite (colourless) partially infill remaining pore space, with a later phase of pale-pink stained equant calcite cement infilling the remainder of the pore space (Northern area, SM^9). (e) Bladed non-ferroan cement lining intergranular pore space (arrowed). Bladed cement is pre-dated by a 'turbid' isopachous cement fringing grains (now replaced by granular mosaic cement), giving the pore-lining cements a banded appearance. Later blocky cement partially infills pore space (Western area, SMa11). (f) 'Turbid' bladed to banded cement partially infilling irregular fracture to dissolutional cavity. Bladed cement is preceded by an earlier dogtooth to blocky cement (arrowed) and micritic sediment infill. Equant to blocky cement infills later cross-cutting fractures and remaining cavity pore space (Eastern area, CG9). (g) Scalenohedral to dogtooth calcite (arrowed) lining irregular cavity. Cavity is infilled by micrite of varying darkness, with minor later blocky cement (Northern area, SP32). (h) Cathodoluminescene image with majority of image showing very dull luminescent micritic-rich sample. Curved mold after fragmented shell in right of image has blocky cement with non-luminescent character and a bright luminescent fringe. This is followed by dull luminescent pore filling cement in both the centre of the shell biomold and also the fracture, the latter in the left of the image. Non-luminescent areas within the pore filling cement areas are minor porosity, some possibly due to cement plucking during thin sectioning (Eastern area, CG7).

covered upstanding karst of the Tonasa Limestone Formation it is, however, rare to be able to trace individual bed surfaces over greater extents than this. All of the irregular dissolutional cavities occur within 5 km and more usually 1–2 km of known grabenal and horst associated faults (Wilson et al., 2000).

Included in the pore lining cements are a range of cement types that are commonly preserved as ghost textures being overprinted by later granular mosaic cement (Fig. 6a). This overprinting can render it difficult to precisely define the earlier pore lining cement phase. No pore lining cements were seen in samples from the southern Jeneponto Area. Radiaxial bladed to fibrous cements line (shelter) cavities between bioclasts or clasts in grainstone or lithoclastic facies from 4 samples associated with the platform margin in the eastern and western areas (Fig. 6b and c). Radiaxial cements have sweeping extinction patterns and crystal lengths up to 2 mm (Fig. 6c). Bladed to banded, or bladed to possible isopachous fringing cements were noted in central (1), northern (11, Fig. 6d), western (3: Fig. 6e) and eastern (2: Fig. 6a and f) area samples. These bladed and isopachous crystals fringes generally have crystal lengths less than 200 μm and occur around bioclasts in grainstone units (Fig. 6e). Longer bladed to banded crystals (up to 400 μm) fringe dissolutional cavities just in the eastern, western and northern area samples (Fig. 6d and f). Dog tooth to scalenohedral crystals are rare being present in 4 northern, 1 western and 2 eastern area samples (Fig. 6g). These dog tooth crystals are generally <200 μm and partially line dissolutional cavities (vugs to biomolds) or primary pore spaces. Micrite or crystal silts (dolomitic) may partially infill pore spaces after the pore lining cement phases (Fig. 6). Cave pearls partially infill cement lined dissolutional cavities in the eastern area (Fig. 7; after Wilson, 2000). There may be up to three phases of the same or different pore lining cements in individual samples, some separated by micrite and/or crystal silt (Fig. 6). The CL character of pore lining cements is commonly non luminescent, or more rarely slightly bright, but towards crystal margins there may be bright and dull-luminescent zones (Fig. 6h).

5.3. Syntaxial overgrowths

Syntaxial overgrowth cements are noted in 101 of 153 thin sections, most commonly on echinoderm grains and rarely on larger benthic foraminifera. Overgrowth cements may both pre-date, but more commonly post-date, some of the mechanical grain packing and grain breakage features described directly below (Fig. 8a, b, c). On average syntaxial overgrowths comprises <0.1% cement throughout the deposits of the Tonasa Platform with overgrowth thicknesses generally <300 μm (Fig. 8d, e, f). Syntaxial overgrowth cements are most prevalent and thickest (up to 1 mm; Fig. 8b, c) in medium to coarse grained bioclastic planktonic foraminifera and graded bioclastic packstones from slope settings as well as in bioclast packstones and grainstones from the central Pangkajene Area. The echinoderm plates generally have a ‘speckled, dusty’ appearance, whereas the syntaxial cements that overgrow them are clear, to slightly turbid under plane polarised light (Fig. 8e). Cathodoluminescent imaging reveals the echinoderm grains have ‘speckled’ dull to non-luminescence, with up to four CL zones in the overgrowth cements. From oldest to youngest these CL cement zones are: (1) dull-, (2) non-, (3) bright-, to (4) bright to dull-luminescent (Fig. 8d–f).

5.4. Grain alignment, distortion, mechanical grain packing, grain breakage and grain suturing

Grain distortion, mechanical grain breakage and closer grain packing, the latter including tangential and concavo-convex grain contacts, is prevalent throughout deposits of the Tonasa Platform (seen in 95% of samples studied). The degree of closer grain packing, grain breakage and sutured grain contacts is highly variable, but is most noticeable in some shallow water grainstones, larger benthic foraminifera packstones, planktonic foraminifera bioclastic packstones and breccia units (Fig. 5d–f). Grain distortion mostly affects micritic walled bioclasts, such as imperforate foraminifera (Fig. 5d), or marly breccia clasts. Grain breakage most commonly affects elongate grains, such as mollusc shells or flattened larger benthic foraminifera (Fig. 5e). The features described here are generally most common in the deeper Eocene and Oligocene parts of thicker sections (Figs. 3, 4). In sections associated with deepening during fault breakthrough there is a peak in these features in deposits formed around the initial period of deepening (e.g., Rala, Figs. 3 and 4; cf. Wilson, 1999; Wilson et al., 2000).

5.5. Granular mosaic calcite

Granular mosaic calcite is present as trace to common, or more rarely abundant, amounts in 90% of samples from all areas of the Tonasa Formation, i.e., this is the most common crystal type throughout the Tonasa Formation (Figs. 5b–d, 8a–d). Granular mosaic calcite is composed of roughly equidimensional small crystals (<100–300 μm, with average size ranging from 50 to 100 μm) with irregular to subhedral crystal boundaries (*sensu* Flügel, 2004; Figs. 5b–d, 9a–d). The granular calcite may be clear crystals filling pore spaces or incorporate ‘dusty’ micritic patches (Fig. 9a–c), or overprint earlier cement phases (Fig. 6a). Granular mosaics may also occur in place of bioclasts as regions of clear crystals or preserving ‘ghost’ textures of the precursor grain (Fig. 9d and e). Near complete replacement of samples by granular mosaic calcite preserving a range of these textures has occurred by non-ferroan and ferroan calcite in the northern, southern and eastern areas. Granular mosaic calcite is mostly dull-luminescent to non-luminescent. Although variable in their distribution, granular mosaic cements are most common in the Eocene and Oligocene deposits, commonly in thicker sections (Fig. 3, 4).

5.6. Fracturing

Fractures here refer to through going features that cross cut more than individual grains, of which the former are grouped under mechanical grain breakage (described above). The relative timing of fractures varies, and individual samples may include multiple phases of fracturing (Figs. 9c, f, 10a, b). Fractures linking, or associated with, dissolutional cavities where fractures pre-date some cavity or fracture infill by sediment are most common in the eastern area (Fig. 9b), and more rarely occur in the northern and northern central area samples (Fig. 7). Rare samples may include multiple phases of sediment and cement infill of fractures up to 5 mm across (Fig. 6f). Other fractures not associated with cavities include sub-mm width fractures that are on a mm- to cm-scale length, commonly terminate within the sample (Figs. 9c, 10c). These fractures have irregular to diffuse margins that may merge into the groundmass. Fill of these fine-scale fractures is most commonly by granular mosaic cement with crystal size commonly <100 μm (Fig. 9c). Millimetre thickness fractures and or fractures with sharp margins commonly post-date the small diffuse margined fractures and the larger-scale fractures may terminate within the thin section or be through going (Fig. 9c, f). The larger-scale, or sharp margined fractures commonly cross-cut earlier features including some cement phases. The sharp-margined fractures are most commonly filled with blocky to equant cements with crystal sizes up 500 μm (Fig. 9f). Up to three phases of fracturing are present in samples, including 2 phases of sharp margined fractures. Some of the sharp margined fractures infilled with equant cement terminate at stylolites, but others post-date stylolitisation (Fig. 10a and b). Displacement along fractures, most commonly on a millimetre-scale, is observed from all areas except the southern Jeneponto region (Fig. 10c). Fracture development, particularly of the fine-scale fractures may be most clearly seen under cathodoluminescent images.

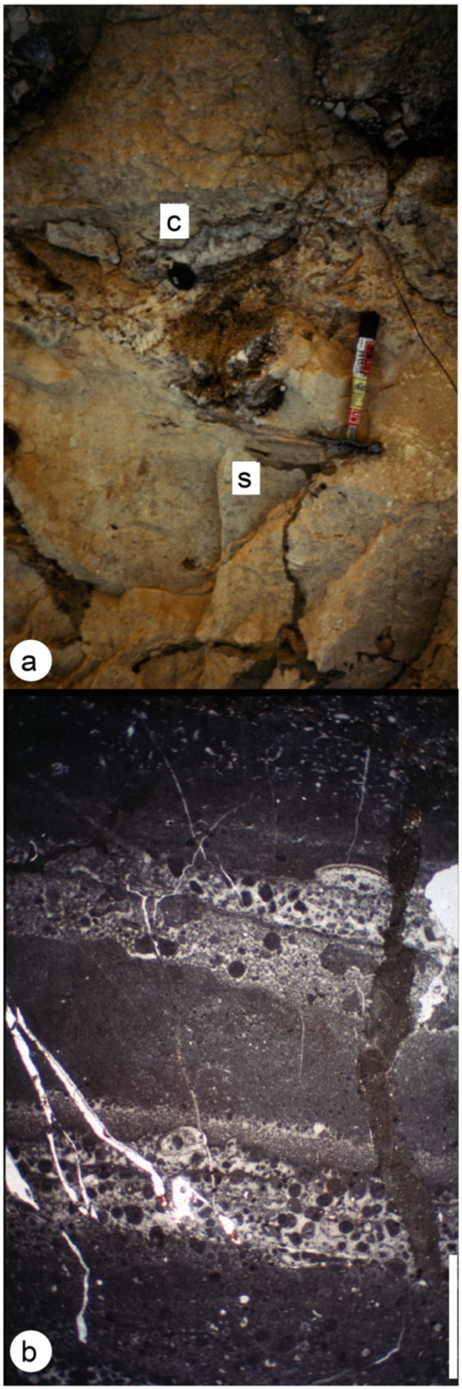

Fig. 7. (a) Probable Tertiary karstic dissolution cavity infilled with fine sediment "s" and banded calcite cement "c". (b) Photomicrograph of Miocene karstic fissure-fill sediment (including cave pearls) from the uppermost part of the Tonasa Formation in the Camba section from the eastern area. Scale bar: 0.5 mm. Laminae of micrite and cave pearls constitute most of the cavity fill. A fracture infilled with fine volcaniclastic sediment post-dates the carbonate fill of the cavity (right side of image).

5.7. Fault and fracture orientations and their occurrence

A number of mainly coincident trends occur in both the large-scale near-vertical faults and smaller-scale fracture (and vein) orientation data derived from the published geological maps and field measurements (Fig. 11; after Sukamto, 1982; Sukamto and Supriatna, 1982; Wilson, 1995). A dominant NW-SE trend occurs in all areas of South Sulawesi (Fig. 11). Large-scale faults with this orientation faults mainly affect the Tonasa Limestone Formation and the lower member of the Camba Formation, but do not appear to penetrate far into the upper volcanic member of the Camba Formation. A NNW-SSE trend also affects all formations (including the upper Camba Formation) in the Walanae Depression, the eastern part of South Sulawesi and the Pleistocene/Pliocene volcanics in the southern part of South Sulawesi (Fig. 11). A possible NE-SW subsidiary fault trend also occurs in western, eastern and southern parts of South Sulawesi (Fig. 11). The fault trends affecting the Pleistocene/Pliocene volcanics in the southern part of South Sulawesi appear to be more randomly oriented. Small-scale fractures and calcite filled veins in the Tonasa Limestone Formation show predominantly the same main trends as the larger-scale faults (Fig. 11). Particularly close to major faults, small-scale fracture and veins trends are commonly parallel, and also perpendicular to the strike direction of the main faults. In the northern area of the Tonasa Limestone Formation NW (-SE) trends predominate, with common NNW (-SSE) and NE (-SW) strike trends of the small-scale features. In the western and eastern areas the NNW (-SSE) and NE (-SW) to ENE (-WSW) trends predominate. Fracturing was less commonly recorded in the central and southern areas, and these fractures have more variable orientations when compared with other areas of the Tonasa Limestone Formation (Fig. 11).

Among the in place predominantly shallow water deposits the ratio of numbers of all fractures/veins to numbers of samples studied is consistently higher by up to tenfold in the northern, eastern and western areas of the Tonasa Limestone Formation compared with the central and southern areas (Fig. 12). Only in Eocene deposits from the central area (Lapangan Golf section) does the ratio of the number of all fractures/veins approach that from other regions. In this Eocene section the higher ratio compared with other central area sections is mainly due to straight fracturing (Fig. 12). The ratio of the number of highly irregular fractures to the number of samples studied is also consistently higher by three to eight times in the northern, eastern and western areas compared with the central and southern areas of the Tonasa Limestone Formation (Fig. 12). Sediment gravity flow deposits are just found in the northern, eastern and western areas, containing material commonly derived from faulted highs (Wilson and Bosence, 1996; Wilson, 1999; Wilson et al., 2000). In all these three areas gravity flow deposits include intra-clast, calcite-filled fractures (Fig. 12). These fractures or veins are truncated at the clast margin and occur in both lithified carbonate and non-carbonate reworked clasts. Fractures or veins that cross-cut the fabric of the lithoclastic breccias are also present in many samples from the northern, eastern and western slope to basinal deposits (Fig. 12). There are no strong trends in ages of deposits compared with irregular and straight fractures or for intra- versus extra-clast fractures (Fig. 12).

5.8. Pore and fracture filling cements

Although granular mosaic crystals occlude some intra-, and intergranular porosity as well as some of the fine-scale fractures, this cement type is described previously. Additional crystal types that post-date and may grade from granular mosaic cements, and also fill fractures are blocky, equant, poikilotopic and rarely drusy cements (Fig. 10d–f). In less than 5% of fractures there are bladed to fibrous 'slickencrysts' that have their direction of elongation perpendicular or oblique to the fracture wall. All these commonly late stage cements are present in 40–60% of samples from all areas of the Tonasa Formation. Equant cements have equidimensional crystals up to 200 μm, and are euhedral, whereas blocky cements are coarser (up to 800 μm) and less equidimensional than the equant ones (*sensu* Flügel, 2004, Fig. 10d and e). Poikilotopic crystals are larger than 400 μm, enclose a number of allochems, and were seen in 4 western and northern area samples. An unequivocal sequential increase in crystal size towards pore centres typical of drusy cements was seen in just 4 samples from the western and northern areas (Fig. 10f). There is common gradation of pore filling cements from one

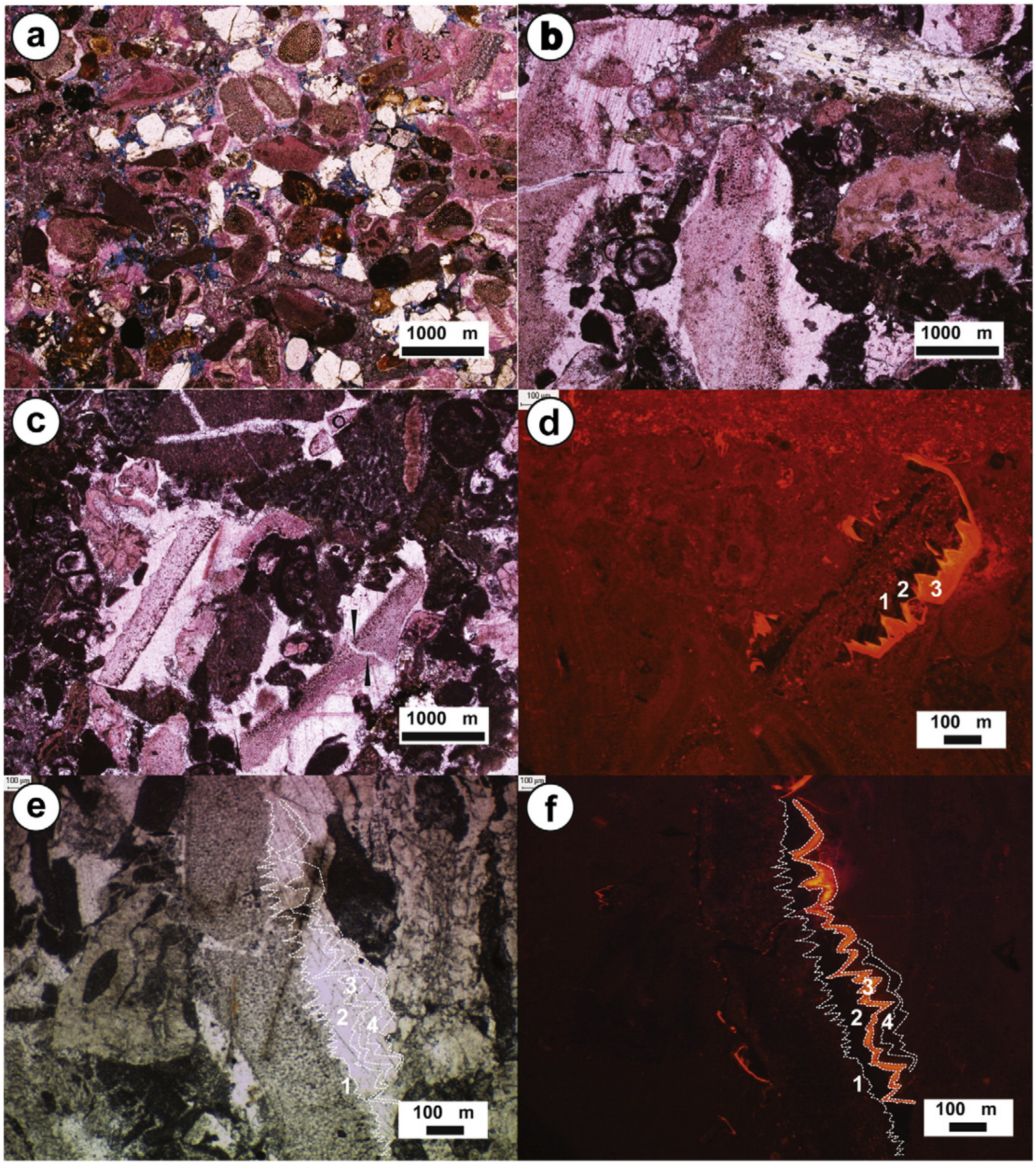

Fig. 8. Thin-section photomicrographs show syntaxial overgrowth cements from the Tonasa Platform. (a) Clear to slightly turbid syntaxial overgrowth cement under plane polarised light in quartzose bioclastic grainstone (SMa11). Syntaxial overgrowths post-date some mechanical compaction. (b and c) Syntaxial overgrowth cements up to 1 mm thick on echinoderm material. Overgrowth cements post-date some compaction (black arrows show cement growth after grain fracturing; GC3). (d) Cathodoluminescent image (S13a) and (e and f) plane polarised light and cathodoluminescent image pair (S10a) showing CL cement zonation not visible under plane light. Sequence of CL luminescence: (1) dull-, (2) non-, (3) bright-, to (4) bright to dull-luminescent.

type to another with: (1) drusy cements transitioning to blocky cements, (2) granular mosaic cements grading to equant or blocky cements, and (3) equant cements grading to blocky cements. Most cements are non-ferroan calcite, but in all areas except the central area ferroan calcite is also present in up to 15% of samples. Where there are gradational changes within samples from non-ferroan to ferroan calcite the ferroan calcite as blocky cements is most commonly the final pore filling phase. There are, however, also samples in the eastern and northern areas from near the contact with the underlying siliciclastics, or adjacent igneous rocks in which ferroan granular mosaic or more rarely drusy crystals grade to non-ferroan to blocky crystals (Figs. 9b, 10f). Near complete replacement of samples by equant calcite preserving a range of these textures has occurred by non-ferroan and ferroan calcite close to some of the igneous intrusions in the northern and eastern areas (Fig. 9e). Most of the pore filling cements described in this section are dull-luminescent, but rare non- to bright luminescent zoning is seen in some blocky cements (Fig. 6h). Although variable in their distribution, equant to blocky cements are generally most common in the deeper parts of sections (Fig. 3, 4).

5.9. Stylolites and dissolution seams

A continuum of 'jagged' stylolites to 'anastomosing' dissolution seams have been recognised in different areas of the Tonasa Formation (Fig. 13a). Dissolution seams are most common in samples containing more than a few percent insolubles, mostly as clays, such as deep water marls or those close to the contact with the underlying siliciclastic Malawa Formation. Stylolites are mostly bed parallel, but also occur as circum-clast stylolites in the slope breccia units. Stylolitisation and/or seam formation usually post-dates all other diagenetic features, but can be associated with, or pre-date, some of the fracturing (Fig. 10a). Any material along stylolites and dissolution seams is generally dark in plane polarised light and usually non-luminescent under cathodoluminescence (Figs. 10a, b, 13a). As with the pore filling

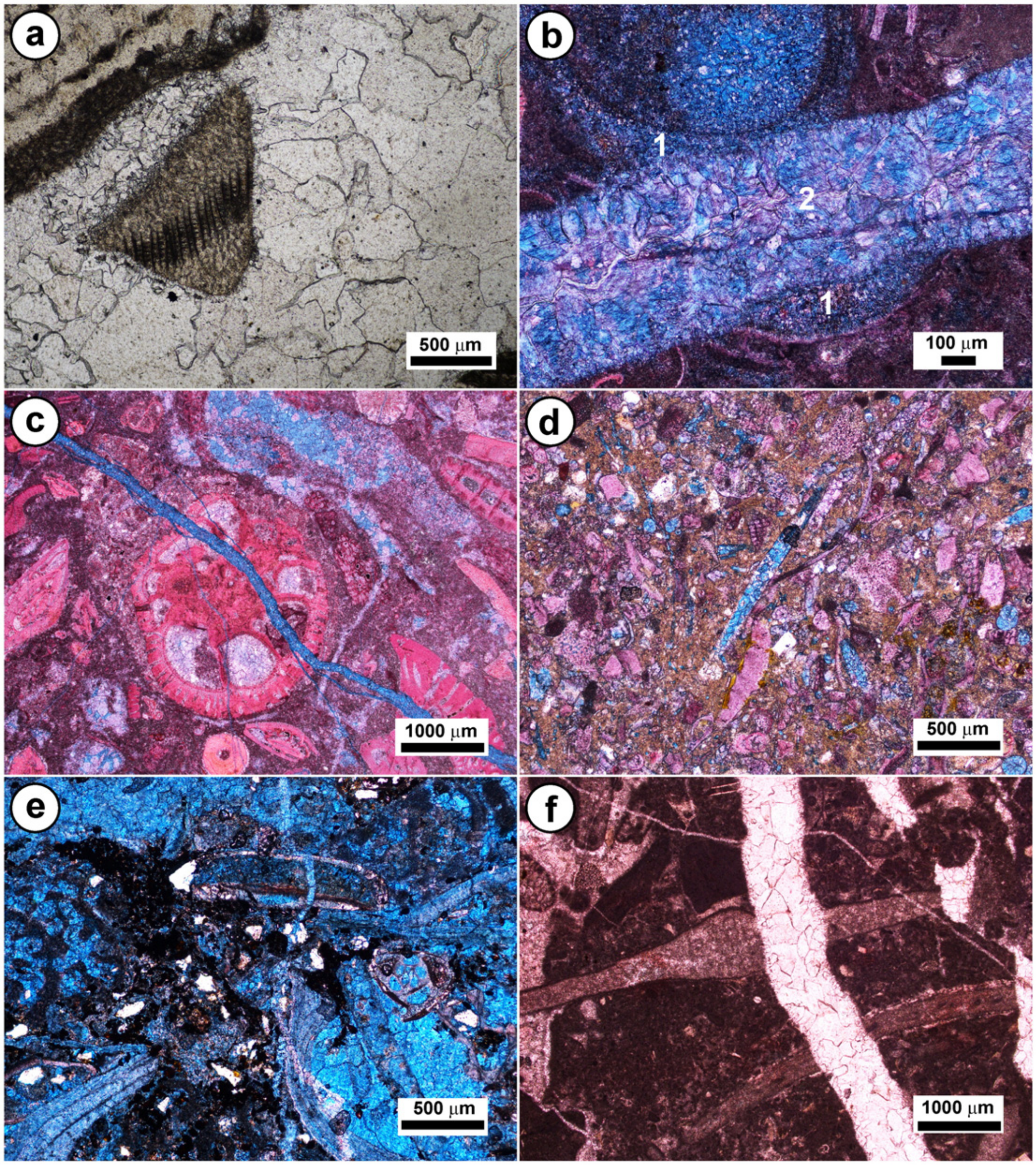

Fig. 9. Thin-section photomicrographs show varied cement phases and fracturing from the Tonasa Platform. (a) Granular mosaic to blocky cement with clear irregular/subhedral crystals (SC6b). (b) Ferroan granular mosaic calcite replacing bioclast (1), cut by fracture, with bladed to blocky cement infilling fracture (2; MC2). (c) Pale blue stained (ferroan) granular mosaic to equant calcite replacing originally aragonitic bioclast and micritic infill (top right), and infilling intragranular and early fracture porosity. Calcitic bioclasts, including foraminifera, are non-ferroan calcite (pink stain). Later fracture cross cutting all earlier features is filled by a granular mosaic to equant cement stained a darker blue than the earlier ferroan calcite (SMa47). (d) Clear, ferroan (blue-stained) granular mosaic calcite 'in place' of non-calcitic bioclasts. (e) Ferroan granular mosaic to blocky calcite replacing bioclasts (ghost texture of original wall structure preserved) and infilling adjacent porosity (BM36). (f) Sub-millimetre and millimetre-scale fractures infilled by equant to blocky cements (CG9).

cements stylolites and/or dissolution seams are generally most common in the deeper parts of sections (Fig. 3, 4).

5.10. Dolomitisation

Dolomitisation is uncommon in the Tonasa Formation, seen in 15 out of 153 samples studied, with the additional samples not selected for this study containing almost no dolomite. Dolomite occurs as: (1) clear, intergranular rhomb shaped crystals (Fig. 13c), (2) crystal silt (crystals <50 μm across; Fig. 6d), and (3) 'dusty', mimetic or fabric replacive dolomite, the later in partially or fully dolomitised samples (Fig. 13c and d). The fully dolomitised samples are restricted to the central area (3 samples), have been affected by mimetic, 'dusty' dolomite formation, followed by dissolution of bioclasts, such as foraminifera, then formation of dolomite cements and late blocky to poikilotopic non-ferroan calcite formation. CL images reveal non- to dull-luminescent mimetic dolomites followed by dolomite and calcite crystal growth that are mainly non- to dull-luminescent with bright zones (Fig. 13c and d). The dolomite crystals silts were seen in cavities from the eastern area previously fringed by earlier pore lining cements (Fig. 6d). Intergranular dolomite rhomb formation was seen in central, northern and eastern area grainstones, with rhombs up to 200 μm and showing some zoning with darker bands (PPL) and bright to non-luminescent zones in CL.

6. Results: Stable isotope analyses

Stable isotope analysis has been run on 36 samples from across the Tonasa Limestone Formation with the exception of the southern Jeneponto area. The values of selected samples are widely scattered between 2.38‰ and −14.23‰ $\delta^{13}C$, and from −1.71‰ to −19.68‰ of $\delta^{18}O$ (Fig. 14; Table 1). Within this stable isotopic variability three groupings and one outlier are distinguished that relate to the

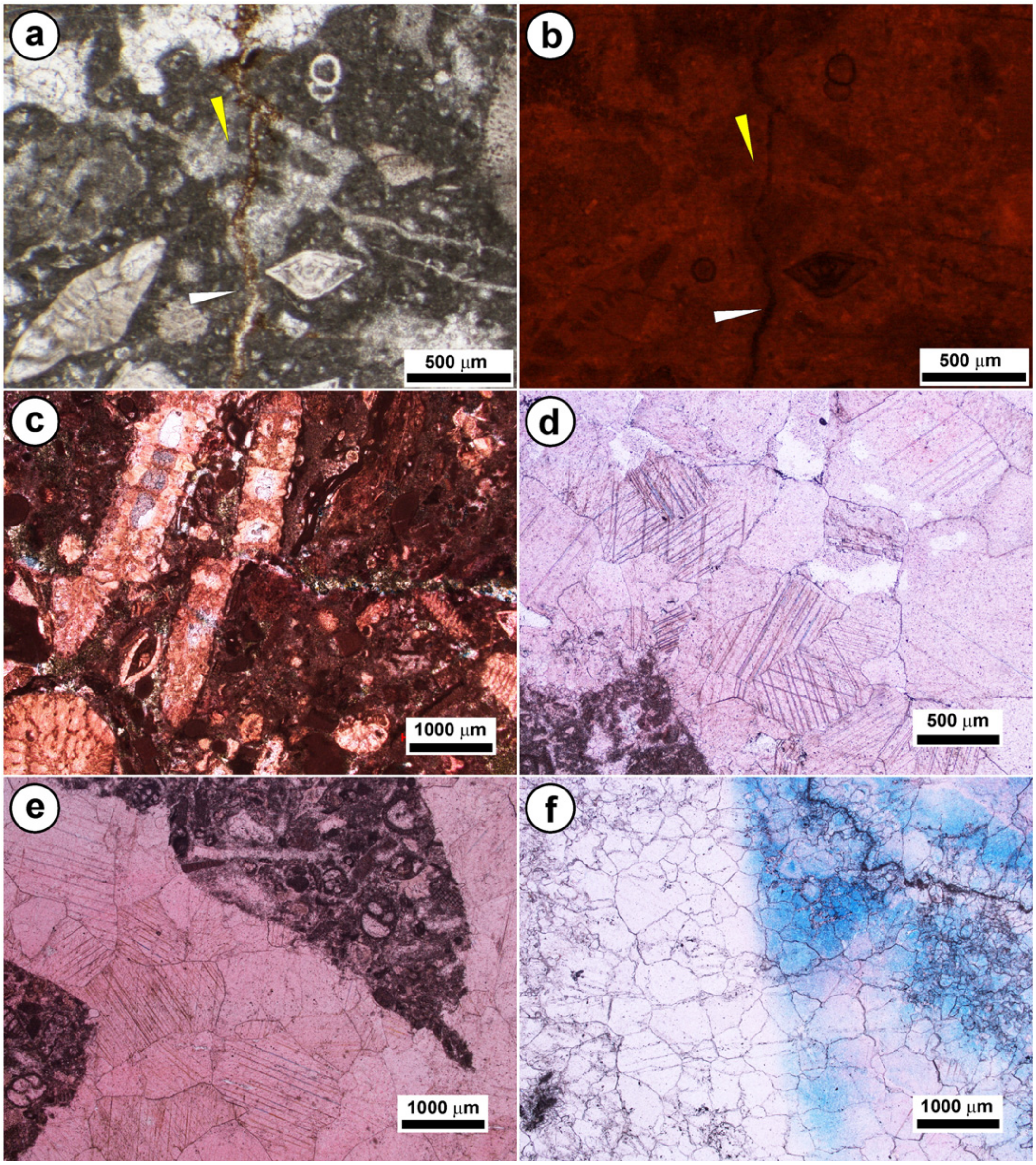

Fig. 10. Thin-section photomicrographs showing fracturing and pore-filling cements from the Tonasa Platform. (a and b) Plane polarised light and cathodoluminescent image pair showing fracture filled by granular mosaic to equant cement (yellow arrow) and cut by other fracture with another equant cement associated with stylolites (white arrow; Sample SMa47). CL image highlights different relative timing of fracturing and their cementation. (c) Displacement along irregular fracture (SMa24). (d and e) Predominantly euhedral crystals of equant to blocky cement (up to 800 μm; LB2 and UL3, respectively). (f) Drusy to blocky cements in intragranular and biomoldic porosity after coral (CG10). Thin section photomicrograph cuts across the half stained part of the thin section (stained area to right). Micrite envelope to original coral is seen top right and part of the micritic, slightly peloidal chamber infill of the coral is seen bottom left.

components and their isotopic signatures (Fig. 15). The groups are: (1) a variety of components which include dolomite, blocky calcite, micrite, micritic cavity infill after radiaxial fringing cement and large benthic foraminifera that comprise the largest group (26 samples) having values of 2.38 to −0.60‰ δ^{13}C and −1.71 to −9.47‰ δ^{18}O, (2) 4 samples including algal laminite and larger benthic foraminifera close to the algal laminite or the underlying siliciclastics with low negative values of δ^{13}C ‰ and negative δ^{18}O ‰ values ranging between −2.04 ‰ to −3.40‰ and −6.28 to −7.60‰, respectively, and (3) 5 samples including larger benthic foraminifera, pore-filling equant cement, micritic sediment infilling dissolution cavities and blocky cement with highly negative values of −9.11 to −14.23‰ δ^{13}C and −14.20 to −19.68‰ δ^{18}O. Samples from this third group all lie within 2 km of intrusive igneous stocks (with stocks exposed at the surface forming 1 to 2 km across sub-elliptical features). The outlier sample (1.79‰ δ^{13}C and −13.86‰ δ^{18}O) is from a larger benthic foraminifera (*Nummulites*) from a localised outcrop in the eastern area surrounded by siliciclastics and close the Walanae Fault Zone and igneous intrusives.

7. Diagenetic interpretations

The varied diagenetic processes and cementation phases affecting the Tonasa carbonate platform are discussed below in their most common relative order of occurrence as inferred from petrographic relationships (Fig. 15). Regionally for SE Asia, known δ^{18}O V-PDB values of Oligo-Miocene marine components and marine cements plot between −1.4 to −7.1‰ (Ali, 1995; Wilson and Evans, 2002; Madden and Wilson, 2012, 2013; Wilson et al., 2013). Some of these values fall more negatively than the global norm (Tomascik et al., 1997; Wilson, 2008). The most negative values are from palaeo-inshore areas affected by terrestrial runoff, likely reflecting lower salinities and more brackish conditions compared with the global norm (Madden and Wilson, 2013;

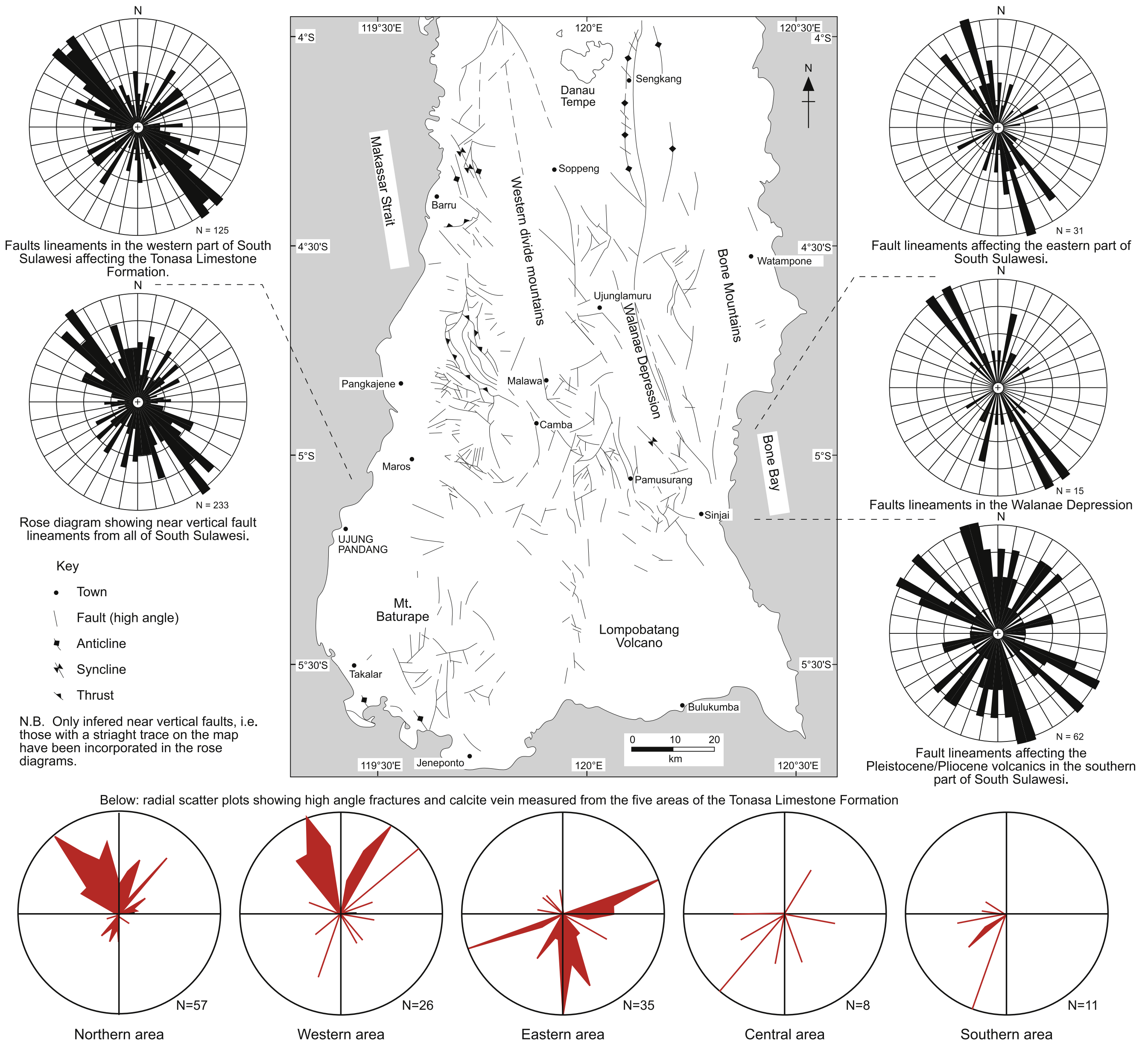

Fig. 11. Map of South Sulawesi showing structural trends (after Sukamto, 1982; Sukamto and Supriatna, 1982; Wilson, 1995). The orientations of near vertical large-scale faults, resolvable on geological maps, from the different areas of South Sulawesi have been plotted as rose diagrams. Dip directions of faults were commonly not given on the geological maps (cf. Sukamto, 1982; Sukamto and Supriatna, 1982), consequently the strike direction of faults has been plotted as bi-directional data. The dominant fault trends in South Sulawesi are NW-SE and NNW-SSE. The small-scale fractures and/or calcite filled veins, resolvable at the outcrop scale with apertures on a centimetre to millimetre scale, for the different areas of the Tonasa Limestone Formation are plotted as radial scatter plots. Dip information for near-vertical small-scale structures was recorded in the field, consequently the strike direction of the feature is recorded uni-directionally with the planar feature dipping at ninety degrees clockwise to the recorded strike direction (i.e. the 'right-hand rule'). The dominant small-scale fracture and vein trends in the Tonasa Limestone Formation are NW(-SE) and NNW(-SSE), with subsidiary trends to the NE(-SW) and NNE-SSW.

Wilson et al., 2013). Six of the 11 sampled larger benthic foraminifera from the Tonasa Formation have $\delta^{18}O$ V-PDB values between −1.71 and −6.40‰ (and slightly positive $\delta^{13}C$ values of 0.28 and 1.96‰) that are consistent with marine values for SE Asia. Using the equation of Anderson and Arthur (1983) and at seawater temperatures of 26–30 °C for modern surface waters in the Makassar Straits (Gordon, 2005; Peñaflor et al., 2009) these values from the Tonasa Formation convert to 1.4 to −4 V-SMOW. A $\delta^{18}O$ value of −6 to −4‰ V-SMOW is suggested for possible meteoric parent fluids on the basis of $\delta^{18}O$ values of meteoric precipitation in SE Asia at low elevations (Anderson and Arthur, 1983; Bowen and Wilkinson, 2002). To evaluate potential burial depths and temperatures the onset depth of stylolite and dissolution seam formation may commonly start from 500 m is utilised (Finkel and Wilkinson, 1990; Lind, 1993; Railsback, 1993; Nicolaides and Wallace, 1997). Temperature gradients of between 21 to 28 °C per kilometre have been measured in nearby subsurface wells that penetrate the Tonasa Formation (Hall, 2002b).

7.1. Micritisation

Micritisation is the first alteration process affecting most samples; since other diagenetic features cross-cut micrite envelopes and micritic rims to allochems. Micritic rim formation is inferred to be via infilling of microborings formed by endolithic organisms since micritisation generally encroaches into bioclasts within the Tonasa Formation (cf. Bathurst, 1966; Gunther, 1990; Perry, 1999). Common micritisation in packstones, floatstones and wackestones from platform-top deposits, but only trace amounts in slope and basinal deposits, is consistent with enhanced endolithic organism activity in shallow-water influenced by low to moderate energies (Fig. 1a and b; cf. Swinchatt, 1965; Budd and Perkins, 1980; Perry and Bertling, 2000; Perry and Macdonald, 2002; Perry and Hepburn, 2008). The thickest (40 μm) development of micrite rims in wacke/packstone and floatstones from shallow platform top and inner shallow platform environments in the eastern and central areas is consistent with shallow, warm waters but may also link to more nutrient-rich areas (cf. Golubic et al., 1975; Budd and Perkins, 1980; Perry, 1998, 1999; Perry and Larcombe, 2003). Constructional micritic envelope formation is also a possibility, and is often associated with seagrass facies that have locally been inferred for the Tonasa Platform (cf. Perry, 1999). The dull-luminescent

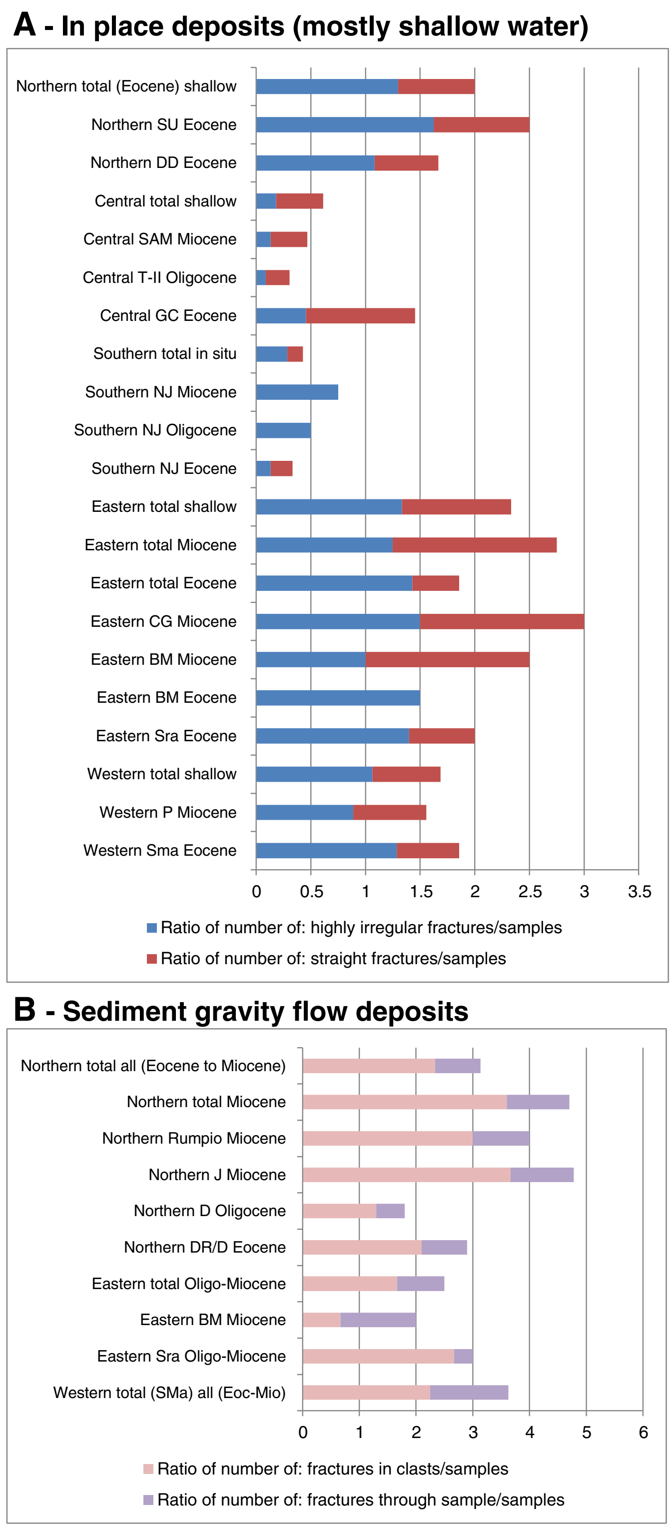

Fig. 12. Fracture distribution and evidence for their relative timing from a study of 164 thin sections across all areas of the Tonasa Formation. (a) Ratios of numbers of highly irregular and straight fractures to the numbers of samples studied from in place, mostly shallow-water, deposits. (b) Ratios of numbers of fractures within clasts to the numbers of samples studied from sediment gravity flow deposits, with clast sizes greater than 5 mm, from the northern, eastern and western areas. Abbreviations are after the section names in the main different areas of the Tonasa Formation.

to non-luminescent CL properties of the micritic rims and their similar CL character to the bioclasts is consistent with associated marine waters and/or oxidising pore fluids.

7.2. Cavities and pore-lining cements

Pore-lining cements are very rare in the Tonasa platform; but five early cement types are associated with platform margin and/or block faulted high areas. Some samples including these cements are now, however, present as reworked clasts in lithoclastic slope breccias. (1) The radiaxial bladed to fibrous cements are interpreted as marine cements on the basis of their growth forms, occurrence in shelter or intergranular porosity, early pre-compactional timing and geochemistry (cf. Halley and Scholle, 1985; Flügel, 2004). Delta δ^{18}O and δ^{13}C V-PDB values of −3.6 and +2.1‰, respectively, for the one radiaxial cement sampled are consistent with the marine stable isotopic field for SE Asia. (2) The <200 μm bladed to possible isopachous fringing cements were too small to sample, but on the basis of their geometry and early timing pre-dating compaction are probably also of marine origin. These radiaxial to bladed and 'short' bladed to fringing cements are from grainstones or fringe shelter porosity in deposits close to the platform margin. Cementation is likely to be controlled by flushing of high volumes of marine waters into porous sediments along the platform margin as well as CO_2 degassing driven by high wave and tidal energy (cf. Land and Moore, 1980; Moore, 1989; Madden and Wilson, 2013). Micrite that infills some of the larger shelter pores after the pore-lining cement may have a laminated to slight peloidal character and is a feature common in other marine cavities. The rare: (3) long bladed (up to 400 μm) to banded crystals and (4) dog tooth to scalenohedral crystals are here interpreted as mainly having a probable meteoric origin on the basis of them lining dissolutional cavities, having similar forms with known meteoric cements and in some cases being post-dated by features such as cave pearls (cf. Dreybrodt, 1988; Frisia et al., 2000). One example of dogtooth to scalenohedral cement has geochemistry consistent with SMOW values of −4.5 to −3.5 (δ^{18}O V-PDB value of −6.54‰) at surface conditions of 25–30 °C (i.e., meteoric transitional to marine parent fluids) and carbon values most consistent with a rock or marine derived signature (δ^{13}C V-PDB value of 1.98‰). (5) Micritic sediment infilling cavities is here inferred to be of either infiltered marine sediment or of karstic infill origin. Individual interpretation of micritic infills depends on: (a) whether the sediment co-occurs with dissolution or non dissolutional cavities, (b) associations with cements of marine or meteoric origins, and (c) sometimes the micrite geochemistry (for the latter see the paragraph below). The origin of the very rare dolomite crystal silts is discussed below under dolomites. The CL signature of pore lining cement with predominantly non luminescence is consistent with oxidising conditions, with some evidence for fluctuations in geochemistry and/or redox conditions of the precipitating fluids (Moore, 2001; Boggs and Krinsley, 2006).

Evidence for potential subaerial exposure and karstification of the Tonasa Limestone Formation is highly localised to faulted highs usually within 1–2 km, but rarely up to 5 km from platform margin and/or graben bounding faults, i.e., affecting less than 2% of the platform. Indicators of subaerial exposure include: (1) irregular dissolutional cavities cross-cutting strata on a decimeter-scale, associated with, (2) in one location algal laminite and fenestral deposits, (3) speleothem stalactite and stalagmite fills, (4) banded cements, (5) cave pearl infill (6) reddened and/or brecciated surfaces, and (7) hiatal surfaces and/or angular unconformities (see also Wilson et al., 2000). Cave pearls and dog-tooth to scalenohedral cements or banded cements with speleothem geometries are distinctive of infill of karstic cavities (cf. Esteban and Klappa, 1983). The geochemical signature of these cavity infill features and the associated interlaminated micritic infill measured in this study is, however, not always distinctive of meteoric conditions. For example,

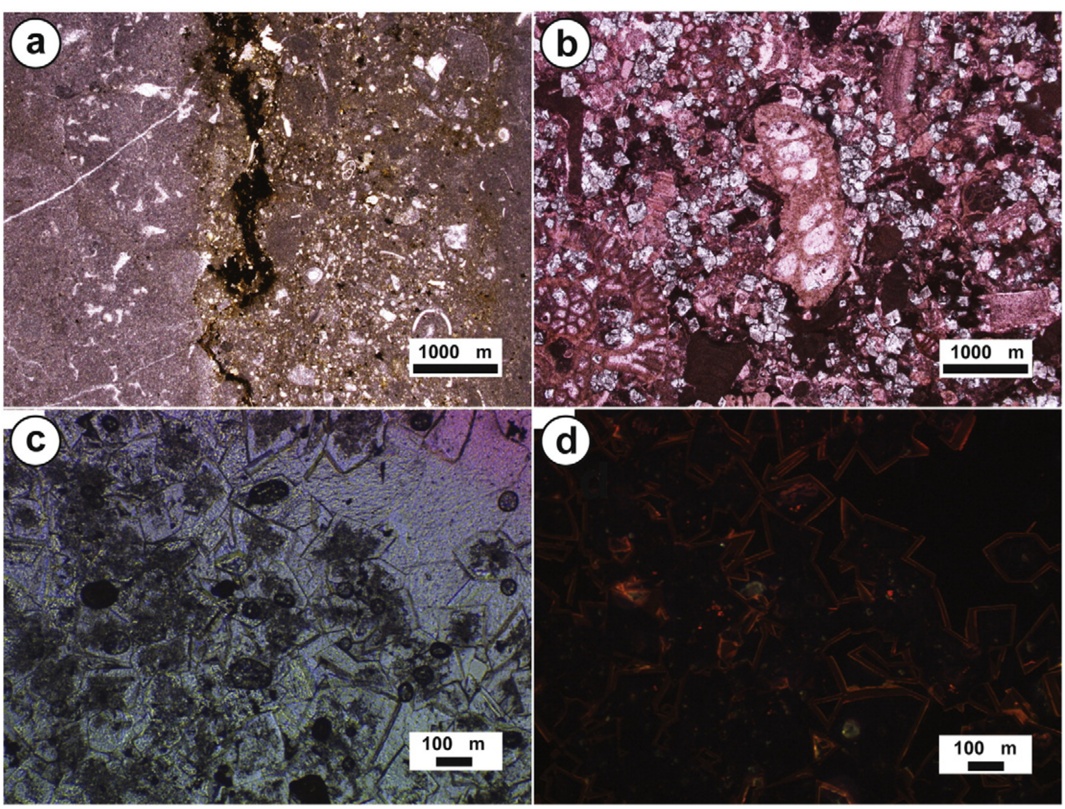

Fig. 13. Thin-section photomicrographs showing stylolites/dissolution seams and dolomite from the Tonasa Platform. (a) Irregular stylolites to dissolution seam with concentration of insolubles along sutured interface (CG7). (b) 'Dusty' to clear, intergranular rhombic dolomite crystals (GC25). (c and d) Plane polarised light and CL image pair of fully dolomitised sample from the central area (GC58). Dusty interior to dolomite rhombs is non-luminescent with brighter 'flecks'. Clear dolomite cements forming the edges of the rhombs shows faint bright, dull, bright luminescence.

although analysis of some of these features revealed negative $\delta^{13}C$ V-PDB values, 2 of the 4 analyses of this type had positive $\delta^{13}C$ V-PDB values. It may be that in regions of very limited areal extent of exposure, as is inferred here, little in the way of soil horizons may develop, and consequently there may not always be a characteristic soil-zone influenced negative carbon isotopic signature. Additionally, with the very high rates of dissolution that occur during subaerial exposure in the equatorial tropics, together with the common neomorphic replacement of early pore lining cements it is probable that a rock-derived signature (in this case of primarily marine origin) may outweigh other potential signatures (cf. Wilson, 2012). Of the localized areas with inferred subaerial exposure the timing of emergence, where constrained, is inferred to be: (1) Late Eocene – on the northern platform margin associated with the Barru Block, (2) possibly Late Eocene, but more definitely mid Oligocene and Early Miocene associated with highs surrounding the graben in the western area, and (3) around the mid Oligocene for the Birau Menge, Bua and Biru S sections and during the Early Miocene prior to the deposition of the volcaniclastics in the Camba sections all from the eastern area (cf. Wilson et al., 2000). For other sections in the eastern area (Bantimala, Malawa West, Ujunglamuru and Maborongnge) probable karstification and tilting of strata is unconstrained to during or after the Late Eocene and before the Middle Miocene (cf. Wilson et al., 2000).

7.3. Syntaxial overgrowths

Syntaxial overgrowth cements are an early diagenetic feature because they mainly pre-date mechanical compaction but post-date some pore-lining cements. The distribution of syntaxial overgrowths is here linked to the primary distribution of echinoderm material and more open grainy sedimentary textures with higher potential for flushing by precipitating pore fluids (cf. Madden and Wilson, 2013). Inclusion-rich, turbid syntaxial overgrowths have been linked to marine-phreatic conditions, whereas clear overgrowths may form during shallow burial, with both phases occurring in the Tonasa Formation (Tucker and Wright, 1990; Flügel, 2004; Swei and Tucker, 2012). The speckled appearance of echinoderm grains in CL partly reflects micritic or cement infill within their microporous structure. The initial dull- and predominantly non-luminescent character of the early overgrowth cement is similar to the overgrown grain and consistent with precipitation from marine oxidising fluids. The succession of CL zones from non-luminescence to bright to dull in the syntaxial overgrowths is a common zonation associated with the increasingly reducing nature of pore fluids during increasing burial (Tucker and Wright, 1990; Flügel, 2004; Boggs and Krinsley, 2006).

7.4. Grain alignment, distortion, mechanical grain packing, grain breakage and grain suturing

All of these burial compactional-related features formed after both micritisation and minor early cement phases (i.e., pore lining cements and some syntaxial overgrowth cements) and therefore generally predate full lithification of most samples (Fig. 5d). A range of point, tangential, concavo-convex and sutured contacts likely reflect increased burial compaction relative to lithification, but may also be grain and lithology influenced (Fig. 5d, e and f; Taylor, 1950; Goldhammer, 1997; Flügel, 2004). In grainy sediments this continuum from closer grain packing to pressure solution at grain contacts may occur over burial depths of 100 m up to 700 m, but such depth ranges would likely be lower for matrix-dominated samples (Goldhammer, 1997; Flügel, 2004). Grain distortion has mostly affected grains such as micritic-walled foraminifera or marl clasts that are prone to plastic deformation (cf. Madden and

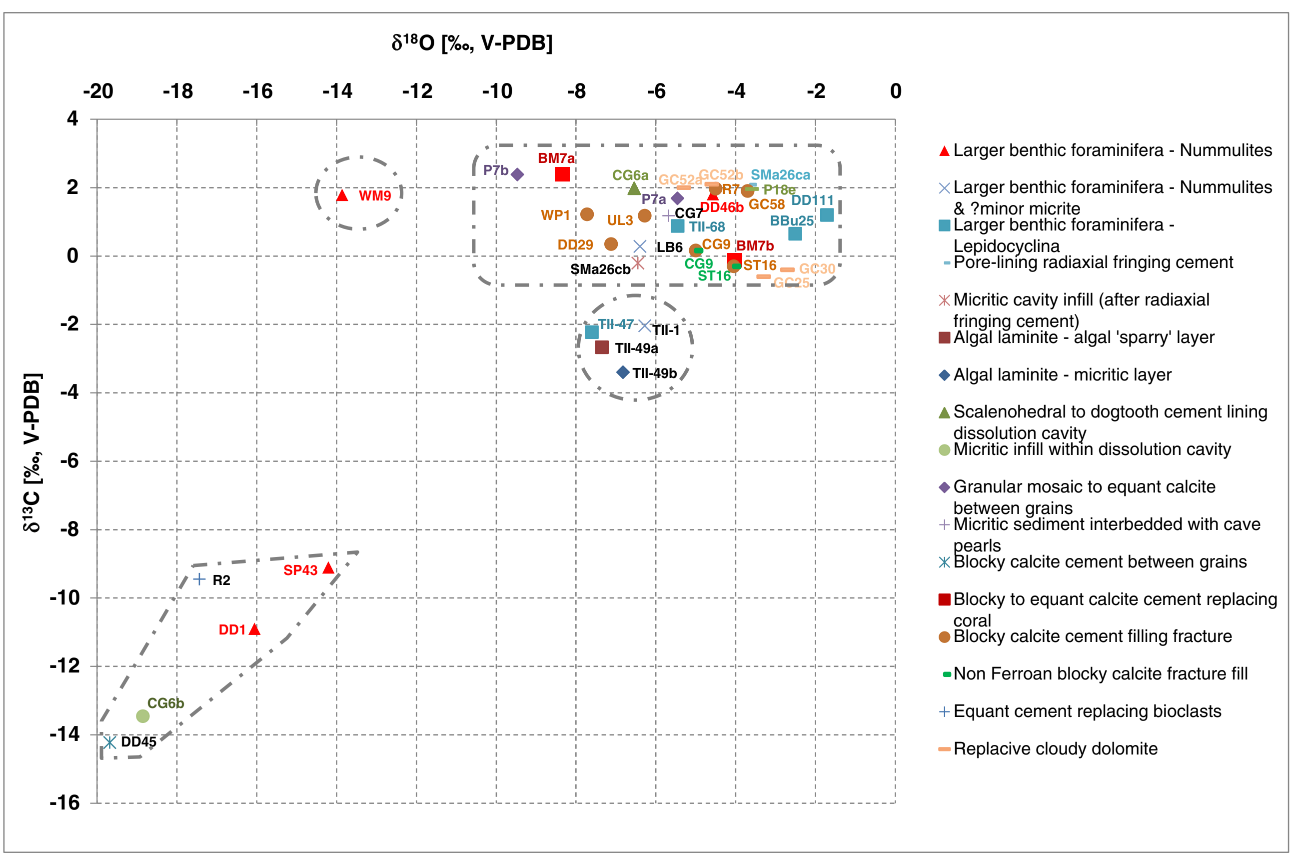

Fig. 14. Stable isotope plot ($\delta^{18}O$ versus $\delta^{13}C$ ‰ V-PDB) of carbonate allochems, cements and matrix from the Tonasa Limestone Formation.

Table 1
Stable isotope results ($\delta^{18}O$ and $\delta^{13}C$ ‰ V-PDB) of analyses of carbonate allochems, cements and matrix from the Tonasa Limestone Formation.

Sample	Area/Fm.	Delta 13C	Delta 18O	18OSMOW	New names
P18e	Western Area	1.96	−3.59	27.21	Larger benthic foraminifera – Nummulites
WM9	Eastern Area	1.79	−13.86	16.62	Larger benthic foraminifera – Nummulites
SP43	Northern Area	−9.11	−14.20	16.27	Larger benthic foraminifera – Nummulites
DD1	Northern Area	−10.90	−16.05	14.36	Larger benthic foraminifera – Nummulites
DD46b	Northern Area	1.81	−4.57	26.20	Larger benthic foraminifera – Nummulites
TII-1	Central Area	−2.04	−6.28	24.44	Larger benthic foraminifera – Nummulites & ?minor micrite
LB6	Eastern Area	0.28	−6.40	24.32	Larger benthic foraminifera – Nummulites & ?minor micrite
TII-68	Central Area	0.88	−5.45	25.29	Larger benthic foraminifera – Lepidocyclina
TII-47	Central Area	−2.23	−7.60	23.08	Larger benthic foraminifera – Lepidocyclina
DD111	Northern Area	1.20	−1.71	29.15	Larger benthic foraminifera – Lepidocyclina
BBu25	Northern Area	0.65	−2.51	28.32	Larger benthic foraminifera – Lepidocyclina
TII-49a	Central Area	−2.67	−7.35	23.34	Algal laminite – algal 'sparry' layer
TII-49b	Central Area	−3.40	−6.82	23.88	Algal laminite – micritic layer
SMa26ca	Western Area	2.09	−3.64	27.15	Pore-lining radiaxial fringing cement
CG6a	Eastern Area	1.98	−6.54	24.17	Scalenohedral to dogtooth cement lining dissolution cavity
SMa26cb	Western Area	−0.21	−6.45	24.26	Micritic cavity infill (after radiaxial fringing cement)
CG6b	Eastern Area	−13.46	−18.85	11.46	Micritic infill within dissolution cavity
CG7	Eastern Area	1.18	−5.68	25.06	Micritic sediment interbedded with cave pearls
P7a	Western Area	1.69	−5.46	25.28	Granular mosaic to equant calcite between grains
P7b	Western Area	2.38	−9.47	21.14	Granular mosaic to equant calcite between grains
BM7a	Eastern Area	2.37	−8.32	22.33	Blocky to equant calcite cement replacing coral
BM7b	Eastern Area	−0.14	−4.01	26.78	Blocky to equant calcite cement between grains
DD45	Northern Area	−14.23	−19.68	10.62	Blocky calcite cement between grains
DD46a	Northern Area	1.22	−5.65	25.09	Blocky calcite cement between grains
R2	Northern Area	−9.45	−17.43	12.94	Equant cement replacing bioclasts
DD29	Northern Area	0.35	−7.12	23.57	Blocky calcite cement filling fracture
R7	Northern Area	1.97	−4.50	26.27	Blocky calcite cement filling fracture
WP1	Eastern Area	1.22	−7.72	22.95	Blocky calcite cement filling fracture
UL3	Eastern Area	1.18	−6.28	24.43	Blocky calcite cement filling fracture
CG9	Eastern Area	0.16	−5.00	25.76	Non Ferroan blocky calcite fracture fill
ST16	Northern Area	−0.30	−4.05	26.73	Ferroan equant to blocky calcite fracture fill
GC58	Central Area	1.90	−3.70		Replacive cloudy dolomite
GC52a	Central Area	2.00	−5.30		Replacive cloudy dolomite
GC52b	Central Area	2.10	−4.60		Replacive cloudy dolomite
GC30	Central Area	−0.40	−2.70		Replacive cloudy dolomite
GC25	Central Area	−0.60	−3.30		Replacive cloudy dolomite

Wilson, 2013). Elongate bioclasts are most prone to brittle mechanical breakage. Overall the degree of grain-related compactional features is most prevalent in lithologies that: (1) experienced little early cementation, (2) contain grains or lithologies that are prone to grain breakage, grain distortion or suturing, and/or (3) were strongly affected by burial prior to full lithification. For example, breccias and planktonic foraminifera bioclastic packstones are common in the thicker successions from the northern, eastern and to a lesser extent southern and western areas that experienced the greatest (fault-related) tectonic subsidence (Wilson, 1999; Wilson et al., 2000). These lithologies typically experienced limited early cementation and contain marly clasts or micritic matrix prone to greater differential compaction compared with more competent bioclasts or lithic clasts. The prevalence of grain-scale compactional features in the deeper Paleogene parts of thicker sections and associated with deposits formed during fault-related deepening are together suggestive of the important roles of differential subsidence and overburden covering by subsequent carbonate sedimentation in generating early compactional features.

7.5. Granular mosaic calcite

The granular mosaic calcite is partially neomorphic to replacive in origin because it includes 'ghost' textures of earlier bioclasts or cements, or patches of micrite. Some primary calcitisation into pore space is near contiguous with neomorphism or replacement. A burial origin is inferred since granular mosaic calcite post-dates some grain compaction features, including mechanical grain breakage. Predating other cementation, fracturing and compaction features (described below) a shallow burial environment of diagenesis is most likely for the granular mosaic calcite. The predominant dull-, to non-luminescent CL character of the calcite may indicate oxidising to slightly reducing pore fluids (Boggs and Krinsley, 2006), consistent with inferred shallow burial origins. Granular mosaic calcite that replaces the only known algal laminite layer from the northernmost Central area of the Tonasa Limestone has $\delta^{13}C$ V-PDB values of −2.67 and −3.40‰ indicative of soil zone process influences (cf. Hudson, 1977; Moore, 2001). The mosaic calcite must have formed very early after deposition since 'ghost' traces of the algal filaments show only minor evidence for compaction. The formation of algal laminites, their early alteration to granular mosaic calcite and $\delta^{13}C$ and $\delta^{18}O$ (−6.82 and −7.35‰ V-PDB) of the calcite are all consistent with a meteoric influence during deposition and subsequently during near surface diagenesis for this unit. A larger benthic foraminifera sampled from 2 m below the algal laminite unit (−2.23 and −7.60‰ $\delta^{13}C$ and $\delta^{18}O$ V-PDB, respectively) and one from near the contact with the underlying siliciclastics (−2.04 and −6.28‰ $\delta^{13}C$ and $\delta^{18}O$ V-PDB, respectively) that group isotopically with the algal laminite samples are also inferred to have been influenced by meteoric fluids during near surface diagenesis. For other granular mosaic calcite that post-dates early compactional features positive $\delta^{13}C$ V-PDB values indicate a lack of soil zone processes, and that a seawater or rock-derived source of carbon with marine $\delta^{13}C$ values was inherited by the precipitating fluids (cf. Hendry et al., 1999). At shallow to moderate burial depths prior to the onset of depth of stylolite formation (around 0.5 to 1 km burial; i.e., around 35–50 °C) the $\delta^{18}O$ of −5.46 and −9.47‰ V-PDB suggest parent fluids of V-SMOW predominantly between +1.3 and −3.0, i.e., most consistent with precursor marine fluids. For the $\delta^{18}O$ value of −9.47‰ V-PDB in the lower part of the potential temperature range this would convert to a V-SMOW of down to −5.4 (i.e., potentially of meteoric origin). Since the granular mosaic cements with the most negative $\delta^{18}O$ values, however, are transitional to equant calcite, and also from

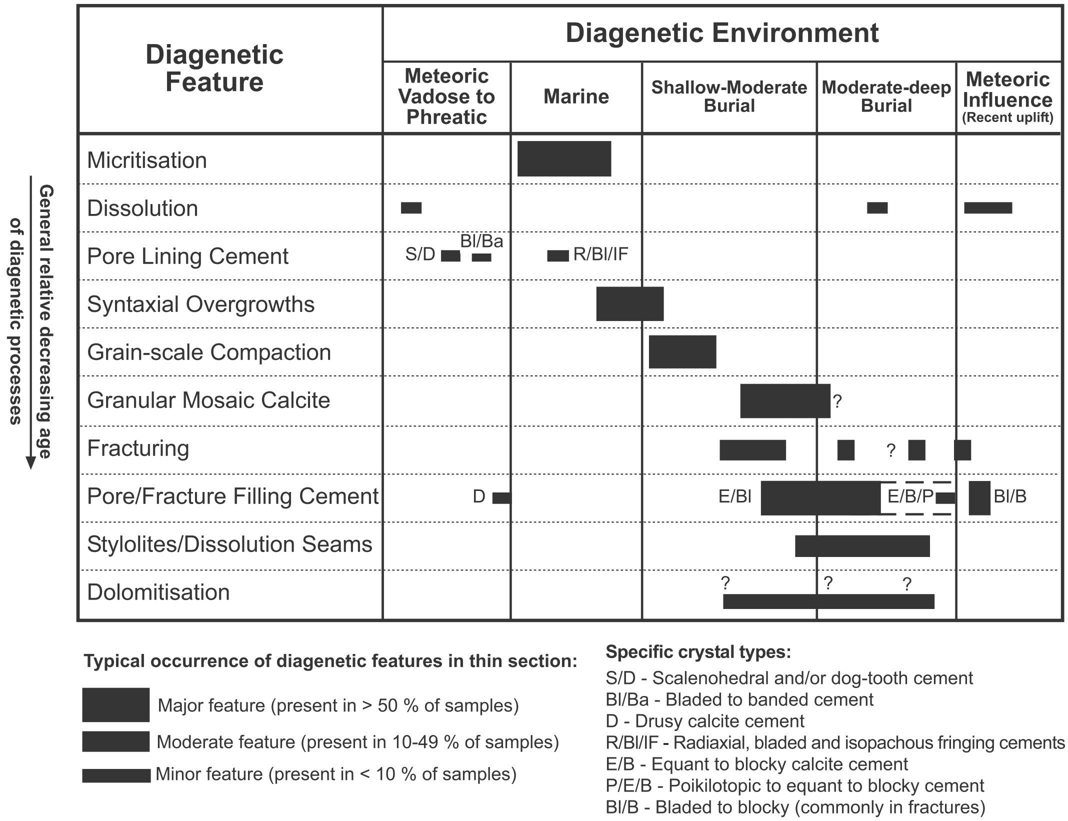

Fig. 15. Generalised paragenetic sequence inferred for the Tonasa Limestone Formation. Relative timing of diagenetic features is inferred from petrography, but may vary slightly between samples. See text for further details on the interpreted diagenetic environment.

the centre of pores, the values from the higher part of the temperature range are considered more likely converting to V-SMOW of −2.8 (i.e., more consistent with fluids of marine origin). The most common occurrence of granular mosaic cements in the Paleogene deposits, particularly in thicker sections is likely a reflection of the influence of rates of differential subsidence and timing of overburden carbonate sedimentation in generating these shallow to moderate burial depth diagenetic phenomena (Fig. 3, 4).

7.6. Fracturing

Multiple phases of fracturing with different origins have locally affected the Tonasa Limestone Formation since these features may cross-cut a diverse range of bioclasts and cements, and may be filled with varied cements and/or sediment fill. For the early fractures associated with cavities a karstic or marine collapse origin is inferred. The interpretation depended on whether cavities are: (1) on a decimetre-scale, irregular, dissolutional and filled with early meteoric pore fringing cements and cave sediments, or (2) predominantly shelter cavities, that lack dissolutional margins, are commonly on a centimetre-scale and are filled with early marine cements and sediment, respectively (see earlier pore-lining cements section). For the main non-cavity-associated group of fractures within the Tonasa Formation burial, unroofing and/or structural origins are inferred (see also section below on fracture orientations and evidence for their relative timing). The sub-millimetre scale irregular fractures with diffuse margins that are mainly filled by granular mosaic calcite likely formed in shallow burial depths during the lithification process (see granular mosaic cements above). Millimetre-scale aperture, sharp-margined, through going fractures post-date most lithification with at least 2 phases of these features. Through going fractures that link to stylolites filled with equant cements likely result from burial and/or tectonic compressional stresses (cf. Nelson, 1981, 2001). Other late fractures filled by equant to blocky cements may have burial, unroofing and/or tectonic structuration origins depending on their relative timings, orientations and later cement fills (see below).

7.7. Fault and fracture orientations and evidence for their relative timing

The concordance of orientation trends in small-scale fractures with those of the large-scale faults in South Sulawesi is suggestive of structural tectonic origins for many of these features (Fig. 11). The main NW-SE trend of structures that particularly predominates in the northern area parallels that of the main platform bounding faults in this area. These northern platform bounding faults also occur along strike, and with the same trend, as the large-scale regional Adang Fault (van de Weerd and Armin, 1992; Wilson, 1999). The main northern platform bounding faults were periodically active from the Late Eocene during the deposition of the Tonasa Limestone Formation and strongly influenced sedimentation patterns (Wilson and Bosence, 1996; Wilson, 1999; Wilson et al., 2000). The NW-SE structures mostly do not penetrate into strata younger than around the Early to Middle Miocene boundary (Sukamto, 1982; Sukamto and Supriatna, 1982; Wilson, 1995). The NNW-SSE trends that prevail in the eastern and western areas parallel the trend of block faulted highs and graben that developed in these areas between the Late Eocene to Early Miocene. The NNW-SSE trending faults include those associated with the Walanae Fault Zone that bound the Walanae Graben: a major structural divide separating different tectonic regions in South Sulawesi (van Leeuwen, 1981). In the field the NNW-SSE trending structures are seen to cross-cut, and therefore in part post-date other structures, including those with a NW-SE trend (Berry and Grady, 1987; Wilson, 1995). The NNW-SSE trending faults continue to be active to the present day as evidenced by recent earthquakes along the Walanae Fault Zone (e.g. Kope Mosque, that sat at the base of the ~300 m high fault scarp bounding the eastern part of the Walanae Depression was destroyed in an earthquake in the early part of this century). In the eastern area, faults with a northeasterly to easterly trend having dip-slip displacements with throws on the order of a few metres to tens of metres pre-date deposition of the Walanae Volcanics in the late Miocene (van Leeuwen, 1981). In the southern part of South Sulawesi faults are recorded mostly in areas close to eruptive centres of volcanoes, and locally appear to radiate from eruptive centres.

That the small-scale fractures are more common in the tectonically active northern, eastern and western areas compared with the more quiescent central and southern parts of the main platform, with many fracture trends paralleling major faults, are indications of a strong tectonic influence on fracturing. The occurrence of intra-clast fractures within shallow water lithic carbonate clasts derived from the main Tonasa platform area and reworked into slope breccia of Late Eocene to Early Miocene age are indicative of structuration during development of the Tonasa Limestone Formation, i.e., evidence for syndepositional structuration. The most common occurrence of highly irregular fractures that may have formed when deposits were semi-lithified is in the tectonically active northern, eastern and western areas, and is further suggestive of syndepositional structuration. Proximal to the major faults small scale structures both trend parallel and perpendicular to the major faults, with those at right angles to the main faults suggestive of some dilatation parallel to major fault trends. Seismic and field relationships indicate significant normal displacements along major graben and platform margin bounding faults, but transtensional (sinistral) displacements are also inferred (Grainge and Davies, 1983; Berry and Grady, 1987; Wilson, 1995).

7.8. Pore and fracture filling cements

Granular mosaic cements that infill some of the sub-millimetre fractures are discussed earlier. The very rare examples of drusy cements infilling pore space may form in meteoric (or marine) phreatic to shallow burial settings, but were too small to sample for geochemical analysis. The majority of the equant to blocky cements are interpreted as shallow to deeper burial features on the basis of: (1) most being late phases of pore filling cements, (2) post-dating early compaction features, but pre-dating later compactional stylolites or dissolution seams and (3) their geochemistry. The dull-luminescent character of most of these cements is also consistent with precipitation under reducing conditions in moderate to deeper burial depths. Predominantly positive δ^{13}C V-PDB between -0.3 and $+2.38$‰ are consistent with precipitating fluids mainly isolated from those influenced by soil zone processes. Negative values of δ^{18}O V-PDB between -4.0 and -9.5‰ would equate to V-SMOW values of $+2.0$ to -5.5 at moderate to shallow burial temperatures of 35–55 °C (Fig. 14; Hudson, 1977; Anderson and Arthur, 1983). Most of the blocky to equant cements are consistent with precipitation from fluids with a rock-derived and/or precursor marine fluid origin. A meteoric origin is also possible for some of the late fracture filling cements with strongly negative δ^{18}O V-PDB values, with the possibility of such a signature being linked to cementation along fractures during unroofing and present day sub-aerial exposure. The development of slickencrysts in some fracture filling cements indicates active deformation during growth of the crystals. A recrystalised larger benthic foraminifera grainstone from an isolated exposure adjacent to the major Walanae Fault Zone has highly negative -13.9‰ δ^{18}O V-PDB (1.8‰ δ^{13}C V-PDB) perhaps due to hydrothermal activity (cf. Pichler and Dix, 1996), or ?unusual fluid chemistries, along the fault zone. A separate group of 5 samples including 2 equant cements having highly negative δ^{18}O V-PDB (-14.2 to -19.7‰) and also highly negative δ^{13}C V-PDB values (-9.11 to -14.2‰) are suggestive of both high temperatures and a possible methanogenic source of carbon. All of these last 5 samples are from close to contacts with the overlying volcaniclastics or igneous intrusions and metasomatising fluids are possibly associated with the isotopic signature (cf. Pichler and Dix, 1996). The most common occurrence of pore lining cements in the deeper parts of sections attests to the importance of overburden sedimentation in influencing late burial features.

7.9. Stylolites and dissolution seams

These chemical compaction features post-date almost all other diagenetic feature on the basis of cross-cutting relationships, with the exception of some fractures and their cement infills. These features form in moderate to deep burial environments with an onset depth commonly starting around 500 m (Railsback, 1993; Nicolaides and Wallace, 1997), or may form as a result of tectonic stresses (Bathurst, 1987). In the Tonasa Limestone the bed parallel examples are linked to burial compaction. The prevalence of stylolites and seams in northern, southern and some eastern sections correlates with where depositional thicknesses of the carbonate commonly exceed 1 km, and are subsequently covered in thick volcaniclastic piles. A continuum from dissolution seams to stylolites in clayey limestones to near pure carbonate lithologies, respectively, has been noted in a range of studies (Bathurst, 1987; 1990; Railsback, 1993; Nicolaides and Wallace, 1997). In depositional units that experience little early cementation, such as the slope breccias, grain contacts between clasts during increasing burial have developed into circum-clast stylolites (cf. Madden and Wilson, 2013). As with the pore lining cements the more common occurrence of seams and/or stylolites in the deeper parts of sections attests to the importance of overburden sedimentation in influencing late burial features.

7.10. Dolomitisation

The very rare dolomite seen in the Tonasa Limestone may have multiple origins, on the basis of very different occurrences. Given the complexity of potential dolomitising mechanisms and paucity of data on these dolomites only a preliminary evaluation is outlined here (cf. Warren, 2000; Carnell and Wilson, 2004; Machel, 2004). Very rare, highly localised dolomite silts infilling dissolutional cavities of karstic origin, as occur in the eastern area, have been linked in Sulawesi and elsewhere to formation in vadose meteoric environments (Fig. 14a, b; cf. Mayall and Cox, 1988; Flügel, 2004). Seawater, however, is a key source of Mg, and particularly for some of the rare dolomite silts in shelter porosity after radiaxial cement, marine fluids are the more likely dolomitizing agent (cf. Warren, 2000; Machel, 2004). Replacive dolomitisation in the fully dolomitised samples from the central area predates the onset of stylolite formation and with δ^{18}O V-PDB values of -2.7 to -5.3‰ using the equation of Land (1983) these would convert to SMOW values of 0.4 to -5.2 (i.e. predominantly of marine parental fluid origins but potentially also of meteoric fluid origins; cf. Warren, 2000; Machel, 2004). A change from dull-luminescent replacive dolomite to non-luminescent dolomite cements with bright zones would be consistent with a general trend from oxidising to reducing conditions during burial with some fluctuations in geochemistry and/or redox state of dolomitised fluids (Fig. 15). The rare intergranular dolomite cements in the grainstones may also have a similar burial signature. The source of Mg for the intergranular and fully replacive dolomites may be seawater, although given that less than 1% of the platform is dolomitized there must be a local driver for the dolomitisation seen. Other potential sources of Mg are from clays in the nearby siliciclastics or perhaps more likely volcaniclastics since most partially dolomitized samples contain admixed volcaniclastics or are close to the contact with the volcaniclastics or to igneous intrusives (rich in Mg containing minerals such as biotite and locally olivine). Igneous intrusives may have provided a thermal driver for increased throughput of dolomitising fluids. This evaluation of potential dolomitising mechanisms is, however, highly speculative without further additional investigation.

8. Discussion

8.1. Summary of diagenetic features, their variability and controlling influences

Petrographic and geochemical studies reveal that three main phases of diagenesis have affected most areas of the Eocene to Miocene Tonasa Formation prior to recent uplift and exposure (Figs. 15 and 16). The general relative order of these main diagenetic phases is: (1) surface or very near surface predominantly marine alteration, and highly localised meteoric diagenesis, (2) pervasive shallow to moderate burial grain-scale compaction and cementation/recrystallisation, and (3) common fracturing and deeper burial chemical compaction and cementation. Marine phreatic, with minor meteoric effects, through to progressively deeper burial is therefore recorded in the diagenetic features of the Tonasa Platform. As discussed below these features and their variability, or paucity thereof, predominantly link to the nature of the platform deposits, their tectonic, climatic and oceanographic context, together with the location of faulted highs, basin history and differential subsidence. Many of these same factors strongly influenced the deposition and sedimentary development of the Tonasa Platform (Wilson and Bosence, 1996; Wilson, 1999, 2000; Wilson et al., 2000). This paragenetic sequence affecting the Tonasa Limestone is similar to that from a number of Eocene to Miocene platforms in the area (Fig. 15; e.g., Berai (Saller and Vijaya, 2002), and Kedango (Wilson et al., 2012; Madden and Wilson, 2013)). These other Tertiary platforms from the neighbouring island of Borneo also show limited early (marine or meteoric) diagenesis together with prevalent neomorphism, compaction and cementation linked to shallow to deeper burial diagenesis (Saller and Vijaya, 2002; Madden and Wilson, 2013). The diagenesis of the Tonasa Limestone and other similar platforms differs markedly, however, from many Neogene systems in the region that may comprise reservoirs in the subsurface (Epting, 1980; Fulthorpe and Schlanger, 1989; Grötsch and Mercadier, 1999; Vahrenkamp et al., 2004). These Neogene reservoirs with porosities of up to 10–40% commonly have a layered development due to repeated subaerial exposure and leaching in the vadose zone, pervasive phreatic cementation, with early fabrics overprinted but commonly not masked by later diagenesis (Epting, 1980; Dunn et al., 1996; Zampetti et al., 2003; Vahrenkamp et al., 2004; Wilson, 2012).

8.2. Early marine and meteoric diagenesis: the role of climate, tectonic highs, oceanography and the nature of platform deposits

Although early grain micritisation occurs in most samples its prevalence in shallow-water packstones and floatstones is consistent with enhanced activity of endolithic microborers in shallow sunlit water from the platform top where wave or current activity was not a hindrance, as is inferred for much of the Tonasa Platform (Wilson et al., 2000; cf. Bathurst, 1966; Gunther, 1990). The presence of nutrients and/or seagrass facies as is common in the equatorial tropics and is locally inferred for the Tonasa platform may also promote destructive or constructive micrite envelope formation (cf. Perry, 1999; Wilson, 2012).

Pore lining cements and subsequent cavity infill fall into two categories: of marine or probable karstic origin, with all of the uncommon occurrences associated with the platform margin, faulted highs, grainstone or slope lithoclastic facies. The occurrence of marine cements in platform margin settings, many associated with probable steep-margined upstanding faulted highs is consistent with high volumes of seawater flushed through margin deposits (cf. Land and Moore, 1980; Moore, 1989; Madden and Wilson, 2013). The globally important Indonesian Throughflow, an oceanic current linking Pacific and Indian Ocean waters, has been actively flowing north to south through the Makassar Straits region since at least the Oligocene (Kuhnt et al., 2004; Gordon, 2005). The predominant occurrence of marine pore-lining cements in more northerly northern, western and eastern platform margins areas for the Tonasa Limestone, but lack of any such features from the southern margin is a probable reflection of this oceanic throughflow pathway. The comparative lack of marine cements away from the more northerly margins is perhaps due to lower than normal marine salinities common in SE Asia and associated reduced aragonite saturation linked to regionally high runoff and the equatorial setting (Wilson, 2002, 2012; Gordon, 2005). This is despite a moderate to high energy E-W trending seaway inferred for the main N-S trending Tonasa Platform area (Wilson and Bosence, 1997; Wilson et al., 2000). This paucity of marine precipitates and/or cementation is in marked contrast to other isolated platforms in more arid tropical regions (cf. Wilson, 2002, 2012). Turks-Caicos is one such platform from the more arid tropics that also has a marked E-W cross platform seaway, but this is a region of prevalent ooid formation, an allochem not found in the Tonasa Platform (Wanless and Dravis, 1989; Jones and Desrochers, 1992).

Dissolutional cavities with speleothem, long bladed to banded, and scalenohedral to dogtooth cements of inferred karstic origin are restricted to northern, eastern and western areas from faulted highs (or reworked thereof). Tilting of rotated fault blocks and uplift of block faulted highs are considered instrumental in the development of these highly localised karstic features (Wilson and Bosence, 1997; Wilson, 2000; Wilson et al., 2000). On different block faulted highs the timing of localised karstification can be pinned down to: (1) during the Upper Eocene, (2) around the middle Oligocene, or (3) towards the end of the Early Miocene and just prior to volcaniclastics of the Camba Formation covering the platform (Wilson and Bosence, 1996; Wilson, 1999, 2000; Wilson et al., 2000). For other sections where there is a long hiatus, karstification may have occurred between the late Eocene and Early Miocene, and perhaps even repeatedly, although the multiple karstification events are not possible to constrain (Wilson et al., 2000). The late Eocene phase is linked to fault breakthrough of earlier reactivated basement structures and associated uplift of footwall highs (Wilson, 1999). The Early Miocene phase is linked to renewed faulting associated with the early stages of volcanism (Wilson, 2000; Wilson et al., 2000). Although around the middle Oligocene is a time of some regional structuration, sub-aerial exposure of highs may also be linked to a major eustatic sea level fall at this time (Saller et al., 1992, 1993; Wilson et al., 2000). Although much of the Tonasa Platform is aggradational remaining in photic depths throughout Eocene to Miocene deposition, it is perhaps surprising that only extremely localised subaerial exposure is inferred for the major middle Oligocene eustatic fall (of around 50 m; Haq et al., 1987). Possible reasons for this general dearth of evidence for subaerial exposure outside faulted highs are: (1) relatively slow production rates of the larger benthic foraminiferal dominated facies limiting platform building potential (0.2–0.3 m kyr^{-1} accumulation rates; Wilson et al., 2000), (2) the mobile nature of much of the platform deposits with possible truncation of sediment affected by shallow wave or current activity, as well as (3) tectonic subsidence (Wilson, 1999; Wilson et al., 2000). The preponderance of mobile deposits over framework building coral-rich deposits has been linked to the platform forming in a region of high rainfall and oceanic throughflow. In settings such as this, with a tendency towards mesotrophy low-light level oligophotic biota, including some larger benthic foraminifera and coralline algae, may be promoted (Wilson and Vecsei, 2005).

These same reasons, outlined directly above, may also be influential in the limited and highly localised occurrence of inferred subaerial exposure occurring generally within 1–2 km (rarely up to 5 km) of faulted margins and affecting less than 2% of the Tonasa platform area. Faulted highs on other syntectonic carbonate platforms are also associated with karstification (Rosales et al, 1994; Rosales, 1999; Cross and Bosence, 2008). Cretaceous platforms from Spain show karstification generally within 1–2 km (and up to 5–6 km) of faults bounding the footwall highs: i.e., similar to the Tonasa Platform (cf. Rosales et al., 1994). On these Spanish examples, however, associated with smaller-scale fault block development trending perpendicular to the rifting direction, between 10–60% of the platform area was affected by exposure during seven phases of repeated exposure over around 8 million years (Rosales et al., 1994). The eastern area of the Tonasa Limestone has fault block development on a scale most similar to the Spanish platforms but is thought to have experienced three potential phases of exposure over around 30 million years, each affecting less than 10% of the eastern platform area (Wilson et al., 2000). Extension in the eastern area probably roughly parallels the main extensional direction in the backarc basin associated with the Makassar Straits on whose eastern flank the Tonasa Platform developed (Moss and Chambers, 1999; Wilson et al., 2000). Faulting in the eastern area, however, mainly occurred from the mid Oligocene onwards and may be linked more to structuration on the Walanae Fault Zone than any rifting in the Makassar Straits (van Leeuwen, 1981; Wilson et al., 2000). Across rift basins, it may be during the early synrift or on rift margin flanks that subaerial exposure of carbonates on faulted highs predominantly occurs (Rosales et al., 1994; Dorobek, 2008a, 2008b). I.e., subaerial exposure is not always a feature of syntectonic platforms, particularly those that formed in basin centres or after initial rifting. The Tonasa Limestone Formation developed as part of a transgressive succession slightly postdating initial back-arc basin development and on amalgamated, highly varied, intersliced basement terranes (Berry and Grady, 1987; Wakita et al., 1996). Although formed on the basin margin flanks the extensional direction of the main N-S trending tilt-block platform is oblique to that of the backarc area as a whole (Wilson, 1995; Wilson et al., 2000). Regional subsidence in South Sulawesi during the deposition of the Tonasa Limestone, based on stratal thickness data was up to 20–40 m/Ma, with higher subsidence in the adjacent Makassar Straits (Cloke et al., 1999b; Wilson et al., 2000). Inferred very limited subaerial exposure of the Tonasa Limestone Formation is likely to have been affected by platform: (1) development over an area not of "typical" continental crust, (2) accumulation in an area with extension oblique to the main regional rift direction, and (3) formation on a basin margin generally undergoing subsidence rather than flank margin uplift.

8.3. Mid-stage shallow to moderate burial depth diagenesis: the role of climate, tectonic highs, the nature of platform deposits and tectonic subsidence

Syntaxial overgrowths, grain-scale compaction and granular mosaic cement all attest to the onset of burial diagenesis on predominantly unlithified deposits as they start to lithify. Aragonitic components had generally not been dissolved prior to the onset of burial diagenesis. The petrographic and geochemical evidence points towards marine, or marine-derived fluid being the main agent during mid-stage shallow to moderate depth burial diagenesis. The prevalence of this mid-stage diagenesis throughout most deposits of the Tonasa Formation is linked to the paucity of earlier marine or meteoric cementation (and/or dissolution) affecting the platform. As noted earlier this scarcity of early cements is due to the: (1) humid climatic setting and lower than global-norm marine salinity, (2) relatively slow production rates of the foraminiferal-dominated deposits and their mobile nature hindering the potential to build directly to sealevel. Local variability in grain types (e.g., echinoderms and imperforate foraminifera) and sediment textures (e.g., more grainy textures and breccias) that link to environmental variability influence the degree of mid-stage diagenesis effects across the platform. Localised meteoric diagenesis is limited to areas of faulted high, including the algal laminites from the Tonasa-II section or to deposits within a few metres of the underlying siliciclastics. Outside the areas of the faulted highs, shallow water platform carbonates and shallow to deeper water successions reach thicknesses of 600 and 1100 m, respectively. Rates of tectonic subsidence and the timing of overburden carbonate sedimentation are inferred to have been

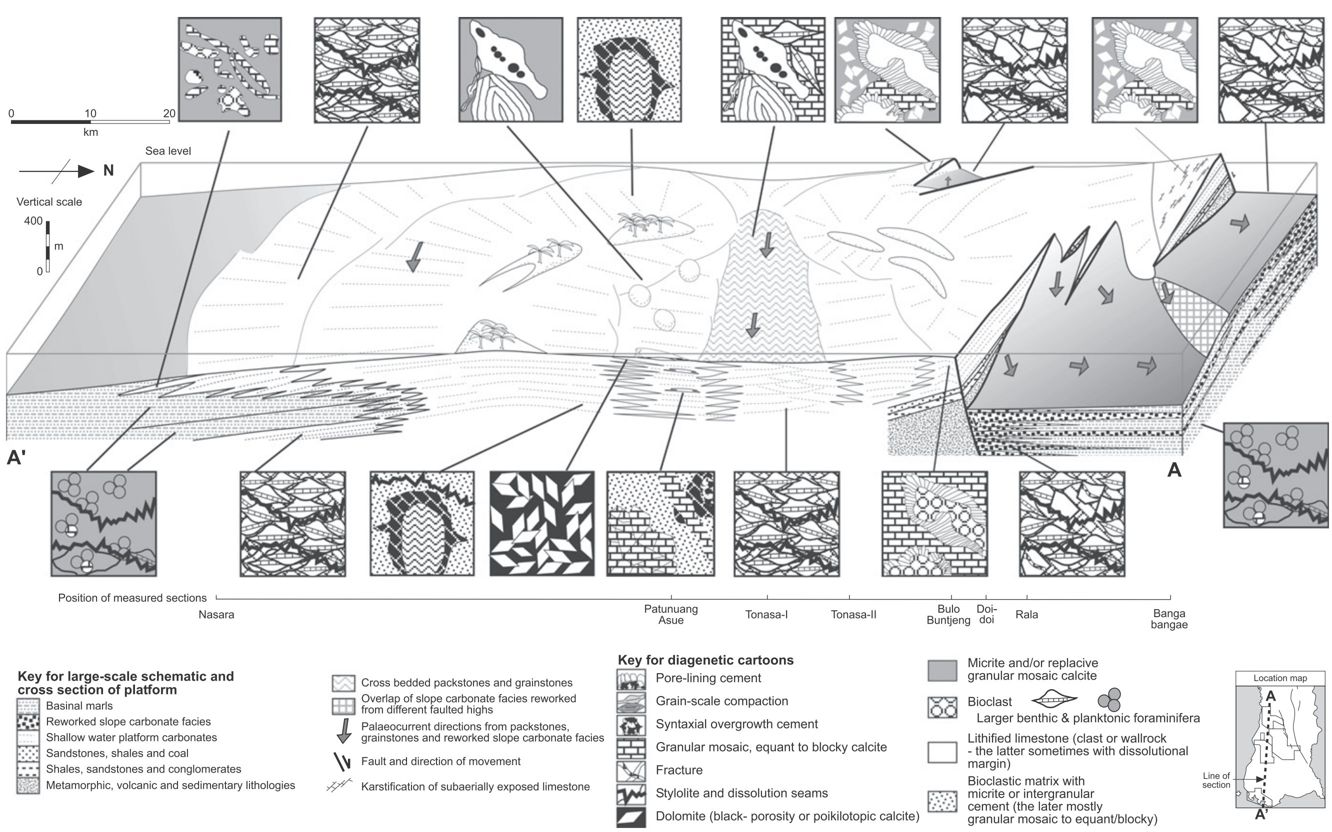

Fig. 16. Schematic palaeoreconstruction of the main north-south trending Tonasa tilt-block platform for the Oligocene or Early Miocene (after Wilson et al., 2000). Cartoons summarise main diagenetic features affecting different parts of the platform. In general, cartoons above the reconstruction show diagenesis in shallow burial depths, whereas the overprint of deeper burial diagenesis is added on those below the main figure.

influential in the abundance of mid-stage diagenetic features that link to the onset and progressive burial of the carbonates. Differential subsidence, both prior to and following fault breakthrough, controlled regional variations in subsidence, influencing the localised variability in degree of shallow to moderate burial depth diagenetic affects (cf. Wilson, 1999; Wilson et al., 2000).

8.4. Fault, fracture and vein distributions, their orientations and relative timing: the key impact of tectonics

Although the Tonasa Limestone is one is the best documented examples of a syntectonic carbonate system from its sedimentary record (Wilson and Bosence, 1996; Wilson, 1999, 2000; Wilson et al., 2000), it is arguably just in the fault, fracture and vein data that the syntectonic nature of the platform is only really strongly manifest from a diagenetic perspective. The correspondence of: (1) higher occurrences of numbers of fractures, (2) more highly irregular fractures, and (3) fractures and veins within clasts of lithoclastic slope breccias all in areas of large-scale, active faulting during the deposition of the Tonasa Limestone as compared with more tectonically quiescent platform areas are, collectively, direct indicators of diagenesis coeval with tectonism. There is scope for applying analysis of this type to fracture datasets from other syntectonic platforms to more fully evaluate syntectonic diagenesis. The strong concordance of fracture and vein orientation data with larger-scale fault orientation data including faults known to be active during the deposition of the Tonasa Limestone Formation is consistent with a link between synsedimentary faulting and small-scale fracturing. The predominant NW-SE and NNW-SSE trends, together with subsidiary trends of NE-SW to ENE-WSW either parallel platform margin and/or graben bounding faults, or are interpreted dilatational features perpendicular to the major faults. The predominant fault and fracture trends within South Sulawesi mirror those from the broader backarc basin region that encompasses West Sulawesi, the Makassar Straits and western Borneo. The major regional structures include the Adang Fault, Walanae Fault Zone and faults perpendicular to the predominant extensional direction in the backarc area. Regionally some of these larger-scale structures may involve reactivation of earlier basement fabrics, and including the ones linked with the Tonasa Limestone Formation, are associated with syntectonic sedimentation during the Tertiary (van de Weerd and Armin, 1992; Wilson and Bosence, 1996; Moss et al., 1997; Moss and Chambers, 1999; Wilson et al., 2012). The potential timing of fault movement inferred to have affected the Tonasa Limestone Formation in: (1) the Late Eocene, (2) possibly the mid Oligocene, and (3) during the Early Miocene is from the timing of highly localised subaerial exposure of footwall highs, but also in the record of the slope lithoclastic breccias, as well as stratal wedging and thickening (Wilson and Bosence, 1996; Wilson, 1999, 2000; Wilson et al., 2000). Regionally, although basin initiation began earlier, rifting was widespread by the Late Eocene, with some structuration inferred in the mid Oligocene, and then again in the Early to Middle Miocene (van de Weerd et al., 1987; Letouzey et al., 1990; Bransden and Matthews, 1992; van de Weerd and Armin, 1992; Saller et al., 1992).

The different phases of fracturing affecting individual samples may have multiple origins on the basis of their petrography and geochemistry including: early collapse or karst–related, burial-associated, tectonic-induced, or uplift-related. More systematic study of the fracturing, a tie between their orientations, relative timing data and geochemistry of any cements or sediment infills that was beyond the scope of this study is an avenue for further unraveling the histories of any syntectonic diagenesis and fracturing (cf. Guidry et al., 2007; Breesch et al., 2009; Warrlich et al., 2010; Budd et al., 2013). A study of the very highly localised and enigmatic dolomitisation is also not pursued here, but may be an avenue for further potential research (cf. Carnell and Wilson, 2004).

8.5. Late-stage predominantly moderate to deeper burial depth diagenesis: the role of tectonics, basin evolution, climate, tectonic highs, oceanography and the nature of platform deposits

Most of the equant and blocky cements together with the dissolution seams and stylolites indicate that the platform was progressively affected by moderate to deeper depth burial diagenesis. As with mid-stage shallower burial diagenetic phases those associated with later burial diagenesis are commonly most pervasive in areas of greatest subsidence (e.g., the faulted graben areas) and/or where deposits had little early cementation. This predominance of burial diagenetic features dominating in large-scale Tertiary platforms is common to other SE Asian systems (Saller et al., 1992, 1993; Wilson et al., 1999; Saller and Vijaya, 2002; Wilson, 2012; Madden and Wilson, 2013). Localised evidence for early meteoric diagenesis in these other SE Asian platforms (e.g. Berai, Kedango, Kerendan, Melinau) is limited to faulted highs and/or areas with more abundant framework builders (Adams, 1965; Saller et al., 1992, 1993; Saller and Vijaya, 2002; Wilson, 2012; Madden and Wilson, 2013). The pronounced middle Oligocene eustatic sealevel fall (Haq et al., 1987) is generally only manifest on faulted and/or bathymetric highs on the platforms (Saller et al., 1992; 1993). The dominance of larger foraminiferal (and algal) deposits, their mobile nature and limited upbuilding potential have all contributed to the prevalence of burial features and paucity of earlier non-burial linked cements in Paleogene equatorial platforms (cf. Wilson, 2002; 2008; 2012). Overall, with the exception of the fracture development, it is, if anything, a regional signature similar to other long-lived Tertiary carbonate platforms in SE Asia that shines through in the diagenetic development of the Tonasa Limestone Formation as opposed to an overriding syntectonic diagenetic signature.

9. Conclusions

Diagenesis of the Eocene to Early Miocene syntectonic Tonasa carbonate platform is dominated by alteration in shallow to deeper burial depths. Burial diagenesis is evidenced by mechanical and chemical compaction, as well as a range of cements including granular mosaic, blocky and equant calcite. Earlier diagenetic features include common marine phreatic micritisation of allochems. Rare, localised evidence for meteoric diagenesis is predominantly from faulted highs. These diagenetic features in the Tonasa Limestone are similar to those from other SE Asian long-lived Tertiary carbonate platforms. The Tonasa Limestone Formation is one of the best documented syntectonic platforms from a sedimentary perspective (Wilson and Bosence, 1996; Wilson, 1999, 2000; Wilson et al., 2000). On the diagenetic side, with the exception of the fracture development, it is, however, a regional rather than strong syntectonic signature that predominates. Underlying tectonic reasons, in addition to those of non-tectonic origin listed below, are inferred to be influential in the more regional diagenetic signature predominating. (1) The platform although developing on the flanks of an extensional basin, accumulated in a backarc setting on amalgamated basement of highly varied origins. In this setting the platform would have been potentially less prone to uplift than "typical" rheologically-strong continental crust. (2) The orientation of significant synsedimentary faulting commonly influenced by earlier basement structures, was not always perpendicular to the main extensional direction in the broader basin. (3) The Tonasa Carbonate Platform formed in an extensive basinal region generally undergoing subsidence, post-dating rift basin initiation.

Tectonic uplift of faulted highs, perhaps with the overprint of eustatic sea level fall controlled highly localised karstification and meteoric diagenesis. The orientation and relative timing datasets of faulting, fracturing and calcite veining is the strongest manifestation of diagenesis coeval with tectonism in the Tonasa Limestone Formation. Orientations of both small-scale and platform bounding/ segmenting structures together with the timing of faulting are consistent with those from the broader basin, hinting at a strong regional tectonic influence. Tectonic subsidence, including fault related differential subsidence, was a key influence on the degree of burial diagenesis impacting different areas of the platform. The location of bathymetrically upstanding faulted highs together with major oceanic current systems resulted in localised marine cementation along the platform margin. The general paucity of early marine or meteoric cements is attributed to: (1) the predominance of non-framework building larger foraminifera and/or algae that have limited production rates, are prone to remobilisation, and hence limited potential to build to sea level, (2) lower than global norm marine salinities, and (3) deposition in a tectonically subsiding area. The: (1) dearth of early cementation, (2) grain associations common in mainly Paleogene carbonate platforms from SE Asia, and (3) the equatorial climate resulting in high freshwater runoff have together contributed to the predominance of burial diagenetic impacts on carbonate platforms from tectonically subsiding regions. It is hoped that studies such as this will further contribute to understanding diagenetic alteration of syntectonic carbonate platforms, and those from equatorial regions.

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