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STRATIGRAPHY AND SEDIMENTOLOGY OF THE MZAMBA FORMATION IN THE EASTERN CAPE, SOUTH AFRICA

By

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In

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DECLARATION

I, Zamampondo Susela, declare this dissertation to be my own unaided work. Where other sources of information have been used, they have been acknowledged and referenced. It is being submitted for the Degree of Master of Science at the University of Fort Hare, Alice. It has not been submitted before for any degree or examination in any other university.

Zamampondo Susela

May 2014

University of Fort Hare

DEDICATION

To the pillars of my life: my God, my parents, sisters, brothers and friends.

Walking with You through this journey has given me strength.

Daddy, you are everything to me, my hero, thank you for inspiring me, believing in me and giving me support in every way possible.

Mom, thank you for having faith in me and teaching me never to give up. You have given me so much. Your love kept me going.

Lusanda, Lelethu, Abulele, Aphelele, thank you for understanding me and for the continued support. Without you, I wouldn’t have made it this far.

Wandile, you always said “you can make it”, thank you for the advice, support, understanding and love.

We made it!

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ABSTRACT

This research project is aimed at providing new information to the stratigraphy, sedimentology, palaeontology and diagenesis of the Mzamba Formation. The study area is located at the south of Port Edward, Eastern Cape. The methodologies employed in this study include field geological investigation and sampling, stratigraphic measurement and logging, thin-section microscope study, powder samples of XRD analysis, and SEM-EDX analysis of rock textures and mineral compositions.

The stratigraphy of the Mzamba Formation can be divided into three newly established members, i.e. the Lower Conglomerate Member, Middle Silt/Mudstone-Shell Bed Member and Upper Mudstone-Shell Bed Member with a total thickness of 31.26m in an inland borehole and 30.05m in the field measurement. The Lower Conglomerate Member is 2.65m thick and consists of pebbly conglomerate with coarse sandstone, shell fragments and silicified wood trunks, representing shallow marine nearshore deposits. The Middle Silt/Mudstone and Shell Bed Member is 9.5 m thick and consists of black mudstone and fine-grained siltstone alternated with medium grained pecten beds, which was deposited in a storm influenced deeper marine environment. The Upper Mudstone-Shell Bed Member is 17.9m thick and is made up of fine-mudstones with articulated pecten layers which were deposited in a deep and quiet marine environment.

Petrology studies showed that the Mzamba Formation consists of mixed sediments of carbonate and siliciclastic rocks. Siliciclastic rocks include pebbly conglomerates, medium to coarse sandstones and fine-grained mudstones, whereas carbonate rocks include packstone, wackstone and grainstone (pecten beds). The formation shows cyclical pattern of a series fining-upward cyclicities, changing from bottom conglomerate to sandstone, then upward repeated series of cyclotherms from pecten bed to mudstone.

Mineralogy of the Mzamba Formation consists of terrigenous minerals of quartz, orthoclase, plagioclase, muscovite and various igneous and metamorphic rock-lithics, clay minerals of smectite, illite and sericite, and carbonate minerals of calcite and dolomite; with minor diagenetic minerals of pyrite, glauconite, hematite, gypsum, albite and organic maceral of vitrinite. Heavy minerals of garnet, zircon and rutile are minor minerals in the strata, which were detrital in origin.

Mzamba Formation is a fossiliferous sequence, and contains both fauna and flora fossils in the strata. The pecten beds host well-preserved bivalve, gastropod, brachiopoda, ammonite, and echinoderm; whereas trace fossils of coprolites, burrows and tracks, as well as plant fossils of silicified wood trunks were also found in the formation. Some new fossil species were collected and studied, which include Bivalve: Pteriaceae, Pinnacea and Ostreacea; Gastropod: Cerithiacea and Mesogastopoda; Echinoderm: Echinocystoidea and Crinoidea. The benthonic species predominate in the lower part in the succession, whilst the planktonic species are abundant in the upper part of the sequence, which points to increase in water depths of the depositional environment.

Based on lithology, sedimentary structures, and stratum architecture, seven different facies have been distinguished. Facies A (*Flat bedded pebbly conglomerate*), Facie B (*Cross-bedded coarse calcareous sandstone facies*), Facies C (*Burrowed sandstone facies),* Facies D (*Shell-fragmental fine-grained calcareous sandstone facies*), Facies E (*Horizontal bedded* c*alcareous mudstone facies),* Facies F (*Calcareous patch reef*), Facies G (Wash out r*eef facies*). Wash out reef facies is rich in algae, bivalve shells, broken oysters, coral fragments and small pebbles.

Four types of cements were found in the Mzamba Formation, including calcite, smectite, illite and quartz. Calcite cement can be further classified into two types, micrite calcite cement and sparite calcite cement. The clay cement consists of smectite and illite and mainly occurs as matrix. The isopachous rim calcite and bright isopachous rim of silica cements indicate diagenesis in a marine phreatic zone. Authigenic minerals which formed in early diagenetic stage include quartz, plagioclase, glauconite and organic maceral of vitrinite. Three stages of diagenesis have been recognised in the sequence, i.e. syndiagenesis, early and late diagenesis. Glauconite pellets and worm faecal pellets were formed in syndiagenetic stage; cementation and authigenic minerals were formed in early diagenetic stage; whereas clay mineral conversion of smectite to illite, quartz overgrowth, bioclast recrystallization and calcite replacement took place during late diagenetic stage.

The pebbly conglomerate at the bottom of the Mzamba Formation represents high energy deposits in a shallow marine environment; the grain-size gradually becomes finer in the middle succession and finest mudstone facies at the top of the succession, which represents deep marine deposits. Meanwhile, benthonic fossils are dominant in the bottom succession while plankton fossils are more abundant in the top succession. These features indicate that the Mzamba Formation constitutes a perfect transgression sequence, and the depositional environments started from shallow marine near shore environment, and gradually shifted to a deep marine quiet water environment.

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CHAPTER 1 INTRODUCTION

1.1 Background Information

The Mzamba Formation is a fossiliferous sequence of Cretaceous age. Investigations on the fossil content on the Cretaceous rocks of Zululand and Natal gave rise to the term Mzamba Formation. Garden (1855) provided the first general account of the exposures, then a number of studies followed by other geologists. The deposits have been described in varying degrees by other authors. Rogers and Schwarz (1902) described the outcrop at Mzamba in some detail, and attempted to determine field relationships. They found out that there is faulted contact with the Natal group. Lithological evidence showed that the section consisted of 13 beds, and shell beds were impersistant throughout.

The first description of the microfauna from the Cretaceous rocks of the Transkei was produced by Chapman (1904); cited from Greyling 1991. He described 18 species of foraminifera and 7 species of ostracoda. Further studies were conducted, and more species were recognized, citing their specific locations. Valuable contributions have been made to the knowledge of stratigraphy and palaeontology. The most recent reference to the Mzamba Formation was from two borehole data that were drilled by a Transkei Mining Corporation, just a few kilometers south west of the Mzamba River.

1.2 Location of study area

The study area is situated along the coast of the Sun Coast Casino beach, south of Port Edward, Eastern Cape Province. The area covers approximately 3kilometers along the beach, and is found about 4kilometers from the Sun Coast Hotel. It stretches to the West of the Casino and the area contains a thickness of Cretaceous sediments to a maximum of 31.26m high, as recovered from the borehole logs drilled around Mzamba. The population is made up of Pondo people, one of the Xhosa people tribes. These people live and work here. Mzamba and Port Edward mark the northernmost boundary of the Transkei Wild Coast, and fall into the famous Pondoland Centre of Endernism and is a great Tourism attraction destination.

Accessibility is generally fair, with exception of some exposures on the coast, which are only accessible in low tide; otherwise they can be totally covered by sea water.

The area is a summer rainfall area with most rainfall occurring in the spring and summer months. The region experiences cool sub-tropical conditions, whilst the neighbouring Province the KwaZulu Natal is considered as warm sub-tropical. The area generally experiences more extreme inland temperatures to milder temperatures and higher rainfall along the coast. The winters are mild and generally pleasant.

Mzamba area is dominated by a smooth coastal-plain surface. Rivers in this region have cut impressive gorges straight through the sandstone region to the sea. Along the Pondoland coast a regional uplift south of the Msikaba River to the Mthamvuna River in the north has influenced the landform, therefore resulting in a number of coastal terraces descending in steps towards the sea.

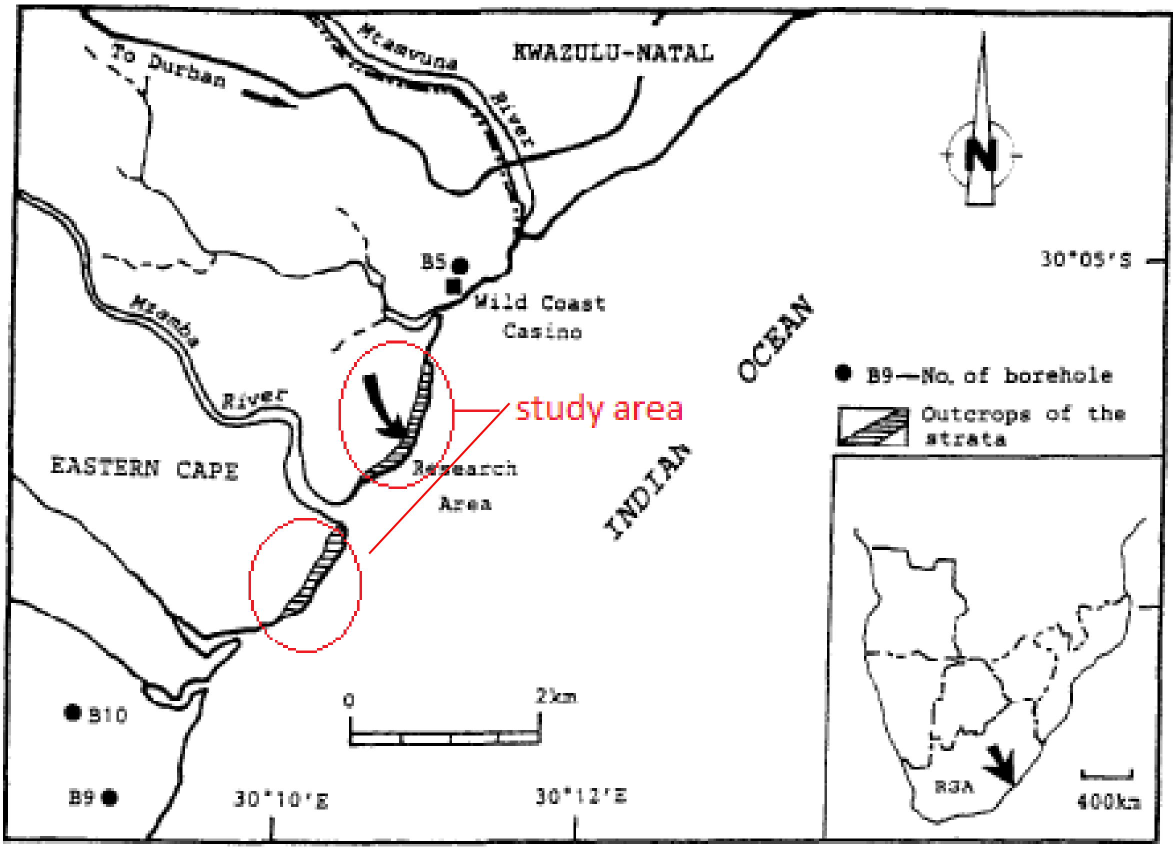


Figure 1: Location of study area and boreholes drilled in the Mzamba area (extracted from Liu and Greyling, 1996).

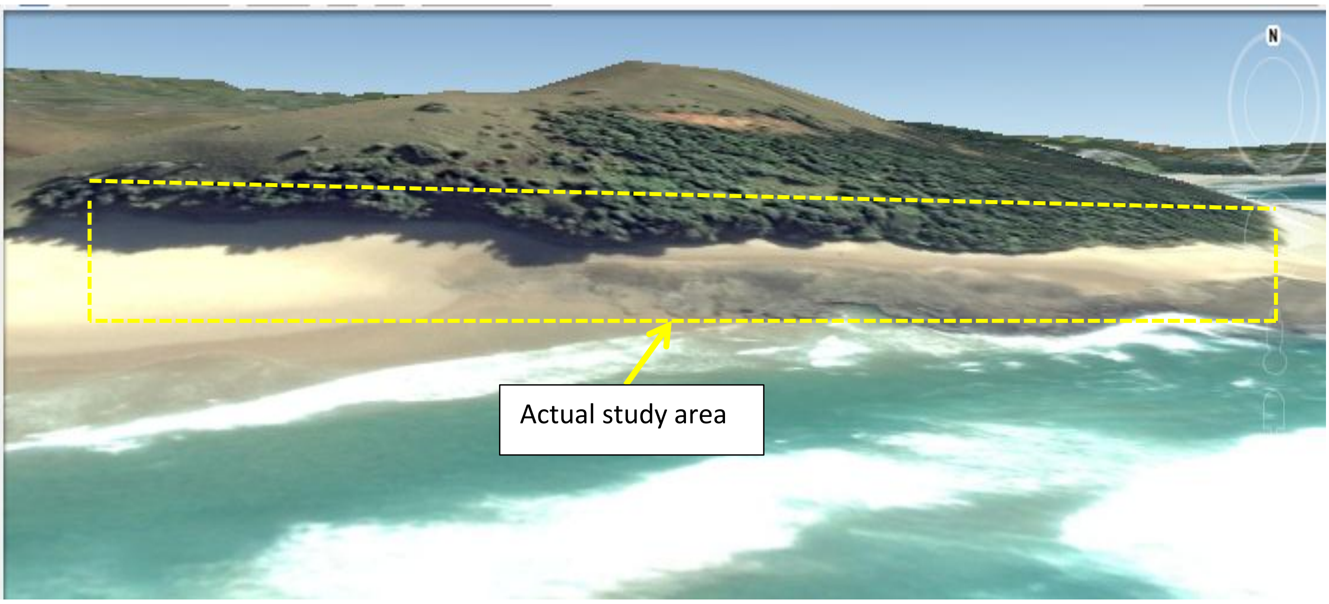


Figure 2: Satellite image showing the topography of the area (created from Google Earth, 2014).

1.3 Research Questions

The project will focus on answering the following research questions:

i) What are the sedimentary facies of the sequence?
ii) What new fossils can be discovered in the succession?
iii) What is the depositional environment of the sequence?
iv) Can a complete stratigraphic section be achieved?

1.4 Problem Statement

There were a number of previous studies on Mzamba Formation; these studies mainly focus on stratigraphic description, and palaeontology (Greyling, (1991), Liu & Greyling, (1996) Mathew and McCarthy (1988), There is very limited literature which dealt with petrology, sedimentary facies and depositional environments, and there was no publication which contributed to the detailed diagenetic environment and processes. Therefore, Mzamba Formation is an understudied sequence, much research and work need to be done, particularly, the sedimentary facies, and diagenesis including cementation, diagenetic environments and diagenetic pathway are still not understood and need to be investigated.

1.5 Aim of the study

Work has not been done extensively in the Formation, judging from the number of publications on the area. The main aim of my thesis research project is to identify and investigate different sedimentary facies, depositional environments (marine or continental environment), fossil types and percentage of constituents, and its diagenetic environment and processes.The main aim of this study is therefore to investigate the stratigraphic sequence and construct a stratigraphic column, the sedimentary facies, and particularly the diagenetic environment and processes. Sedimentary facies include the classification of rocks according to texture, grain size, colour and the sedimentary structures present. Diagenetic studies include diagenetic textures, cement types and the diagenetic pathway.

The aims of this study also include the following:-

- To measure the stratigraphic sections and establish the stratigraphic vertical column of the Mzamba Formation in the study areas;
- To identify the different rocks types and recognize its petrographic characteristics;
- To identify different types of sedimentary structures and fossils which were occurred in the sequence;
- To study the different types of the sedimentary facies of the succession and to restore the depositional environments for the Mzamba Formation;
- To investigate the mineral compositions and partially the authigenic minerals during diagenesis.
- To investigate the diagenetic textures, cement types and the diagenetic environments of the sediments;

1.6 Rationale

The purpose of this research is based on the following:

1. The Mzamba Formation is an understudied sequence, therefore, with that in mind, this project includes detailed work on the area.
2. No study of this kind has been done on the Formation.

3. The results of this research will add significantly on the existing literature and can be used for academic purposes.
4. The supervisor knowledge and expertise will be used to complete the research.

CHAPTER 2 LITERATURE REVIEW

2.1. Introduction

The Mzamba Formation is an understudied sedimentary sequence of Cretaceous Age (Liu & Greyling, 1996). The sequence lacks literature, and much studies still need to be undertaken. The first person to describe the succession was Garden (1855, cited from Liu and Greyling, 1996), followed by descriptions by several other geologists, including Giesback (1871), Woods (1906), Du Toit (1912), Plows (1921), Rennie (1929), Dingle (1969, 1985), Kennedy and Klinger (1975), and Klinger and Kennedy (1980). The previous studies that have been conducted dealt mainly with stratigraphy (Greyling, 1996) and palaeontology (Mathew and McCarthy (1998) and Cooper and Greyling (1996), which led to the realization that the formation is a marine unit of upper Cretaceous age. The exact age of the formation remains debatable due to lack of isotope age study.

Biostratigraphic work on the Cretaceous deposits of Zululand and Natal led to a proposal by Kennedy and Klinger (1972, 1975, 1979; cited from Greyling 1991) for the acceptance of the lithostratigraphic term “Mzamba Formation”. Greyling (1991) studied the stratigraphy and palaeontology as her MSc project. Mathew and McCarthy (1988) investigated the orientation of fossil logs and pebbles around Mzamba River-mouth. Liu and Greyling (1996) studied the grain-size distribution and cementation of the Mzamba Formation, and they focused on some aspects of the depositional mechanism and diagenesis of the sediments.

2.2. General and Regional Geology

In Southern Africa, Upper Cretaceous rocks are mostly encountered as narrow, discontinuous coastal strips along the southeastern shores of the subcontinent, from Mozambique to the Transkei; whereas the Mzamba Formation is restricted only along the coastline outcrops from Port Edward to East London (Greyling, 1991). The Upper Cretaceous Mzamba Formation lays uncomformably on Lower Palaeozoic quartz-arenite of the Msikaba Formation, Natal Group or Upper Palaeozoic diamictite of Dwyka Group (Liu and Greyling, 1996). At the Mzamba River mouth the Cretaceous strata comprise calcareous fine-grained sandstones interbedded with shelly limestone and mudstone beds. The limestone at the lowermost bed of the sequence is conglomeratic, ranging in grain-size from granule to pebbles and it contains abundant fossil wood which now have been strongly silicified. The limestones are also crowded with several other species of bivalves, gastropods and echinoderm, whilst the less resistant strata appear to be sparsely fossiliferous. The latter hosts a variety of ammonites, brachiopoda and some other microfossils, as well as small crinoidea and spongy, which often occurred in small clusters (Greyling, 1991).

The beds can be traced upstream along the Mzamba River mouth upward for about one kilometer, where an in situ contact between fossiliferous sediment and Natal Group sandstone was encountered. There were also two boreholes drilled inland south of the Mzamba River, at which Cretaceous sediments were encountered (Fig. 1). The thickest development of the succession is found from an inland borehole (Borehole 9, 31.26m in Fig. 1); and maximum visible surface-exposures are along the coast immediately north of the Mzamba estuary. Cretaceous sediments were penetrated some distance south of the Mphalane River, where the sediments are resting on Natal Group strata. On the Natal coast, from Trafalgar Beach to Port Edward, sporadic small outcrops of fossiliferous Cretaceous beds were encountered, with a basal conglomerate resting on a surface of charnockites of the Margate Metamorphic Complex (Du Toit, 1912; Dingle et al., 1983; cited from Greyling 1991).

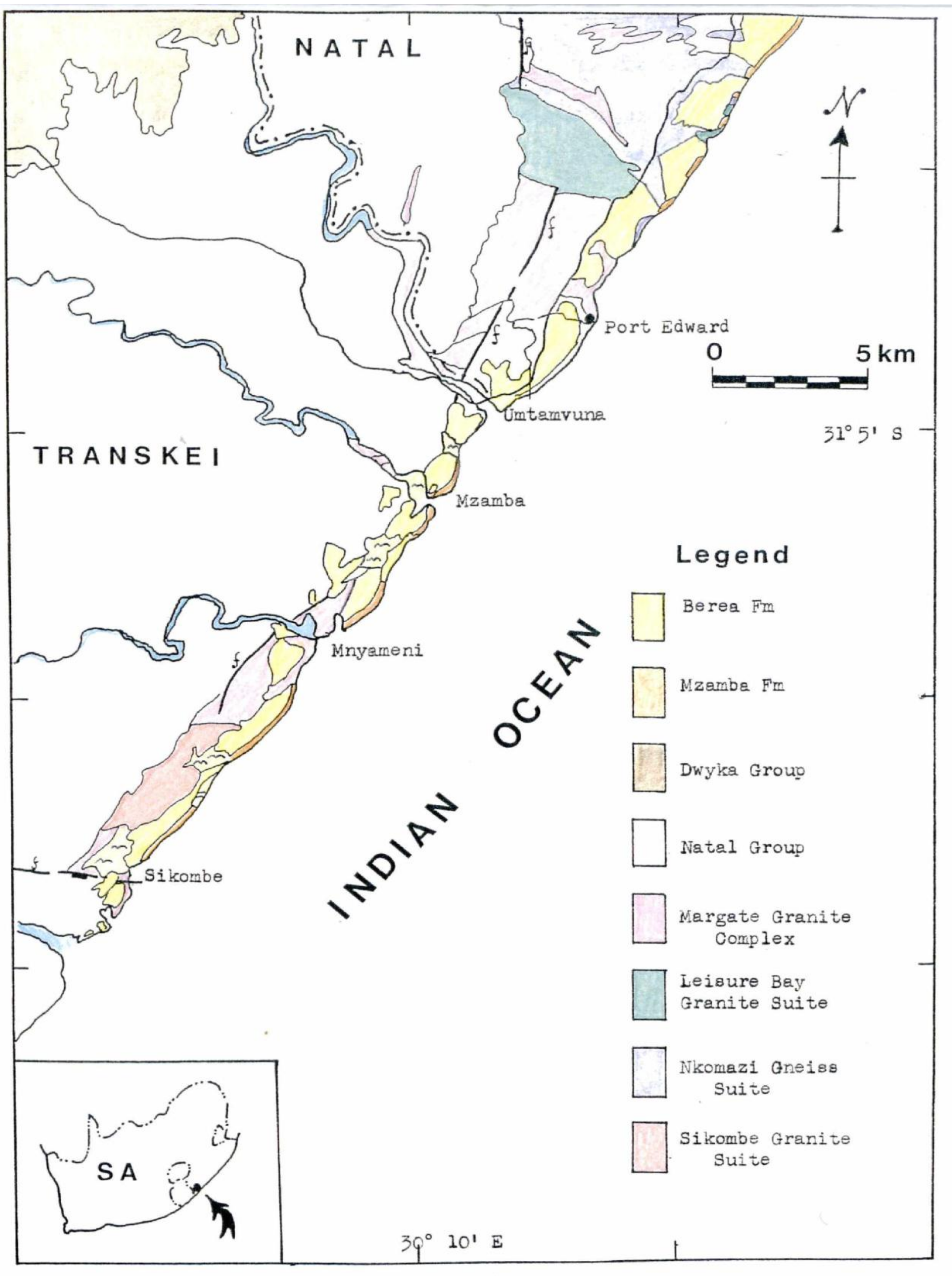


Figure 3: Geological map of northeastern Transkei (extracted from Greyling, 1991).

2.3. Stratigraphy of the Mzamba Formation

The stratigraphy of the Mzamba Formation is best exposed along the cliff of the Mzamba River mouth, south of Port Edward. Description of the stratigraphy is based on the outcrop as it appears. The beds strike N50°E and dip 2-6°, therefore it occurs nearly horizontal. Cyclical sedimentation on different scales is evident throughout the succession. Greyling (1991), and Liu and Greyling (1996) noted that there are more than twelve fining-upward cyclotherms above the lower-most pebbly conglomerate making up the major part of the succession. The cycles are composed of cross-bedded shelly limestone, overlain by massive, bioturbated, and fine-grained, calcareous sandstone with interbedded shelly horizons. The interbedded shelly horizons form minor fining-upward cycles within the major cycles. Each of the cyclotherms comprises a packstone/wackstone and a very fine argillaceous sandstone subunit at the top. The two different lithologies recognized in each major cycle are characterized by remarkable consistency in their internal structuring, bed thickness, and fossil preservation on a large scale (Greyling, 1991).

Greyling (1991), Liu and Greyling (1996) divided the succession into 12 units (Fig. 4), as exposed in the stratotype area in Mzamba River mouth, south of Port Edward:-

Unit1: this is the lowermost bed in the succession. It is made up of massive, fine-grained, calcareous sandstone with a pebbly conglomerate at the bottom. It is discontinuously exposed, and it is partially exposed at very low tide and could be totally merged in the sea water during high tide period. It is fossiliferous, with large fossilized wood, randomly orientated shell-fragments, and chert and sandstone pebbles concentrated in clusters.

Unit 2: this unit overlies unit 1 with a sharp contact zone. It comprises hard, well cemented, medium to coarse-grained sandy limestone. This unit attains a thickness of about 0.66m and it is exposed at low tide along the coastline. The unit fines upwards. Quartzite and hornfels pebbles are scattered throughout the unit.

Unit 3: this is the first unit that is continuously exposed along the coastal cliff during normal tide range. It is 1.46m thick and consists of soft, friable, greenish-brownish fine-grained, calcareous sandstone. Concretions occur discontinuously at the top of the unit. There is a horizontal layering of shells at the base.

Unit 4: this unit is 23cm thick, and is a hard, brown, cross-bedded, medium to coarse-grained calcareous sandstone. Sparsely scattered pebbles are present in the strata, which are well rounded and elongated, but not flat. Fossil density is very high, containing a large proportion of shell species.

Unit 5: this is a unit of brown-weathering, friable, fine-grained, calcareous sandstone, with interbedded shelly horizons. It attains a thickness of 1,20m, but varies in thickness across the study area. Two well-sorted shell beds persist over the total length of the outcrop.

Unit 6: this unit is 53cm thick; it has brown, medium-grained, well-cemented, sandy limestone with erosive lower contacts. The limestone unit is not well defined, as compared with the limestone in the lower part of the succession. Shell density is very high and pebbles occur sparsely in the unit.

Unit 7: this unit attains a thickness of 3m. It is a composite unit that is soft, brownish-weathering, fine-grained, calcareous sandstone which is blue-greyish when it was fresh. The unit was interbedded with shell lags.

Unit 8: from this unit onwards, till the last unit, they are mostly inaccessible, and severe weathering of the cliff makes their accessibility risky. Therefore, observations were made at a distance. This unit is composed of hard, buff-colored, sandy limestone, with a scoured bottom contact. The unit is 25cm and is fossiliferous, with well-sorted coarse shell debris that is randomly orientated at the base of the unit.

Unit 9: this is a unit of 1.50m thickness; fossiliferous, comprising of brown-weathering argillaceous sandstone, with an even bottom contact.

Unit 10: this is a badly degraded unit which consists of 30cm of light brown, shelly limestone displaying low-angle cross bedding. The bottom contact is sharp.

Unit 11: this unit is 3.20m thick, with a sharp contact with the underlying unit, even though it’s clear that the unit underwent extensive weathering, the unit is brown weathering, fine-grained sandstone, with a shelly horizon.

Unit 12: unit 12 is comprised of sandy limestone, with a thickness of 30cm and is in sharp uneven contact with the underlying unit. It is hard, buff-coloured with low angle cross-crossing.

Unit 13: this unit measures 2.30m and it is the last composite unit at this type section. It is friable, greyish-brown, calcareous sandstone that is fine-grained and fossiliferous. A discontinuous concretionary horizon occurs at the base of the unit.

Unit 14: it is a well cemented unit of light brown, sandy limestone with a thickness of 35cm. it has a sharp, erosive, lower contact with the underlying unit. The lower part of the unit is packed with coarse shell debris, and the unit fines upwards into horizontally bedded gritty sandstone.

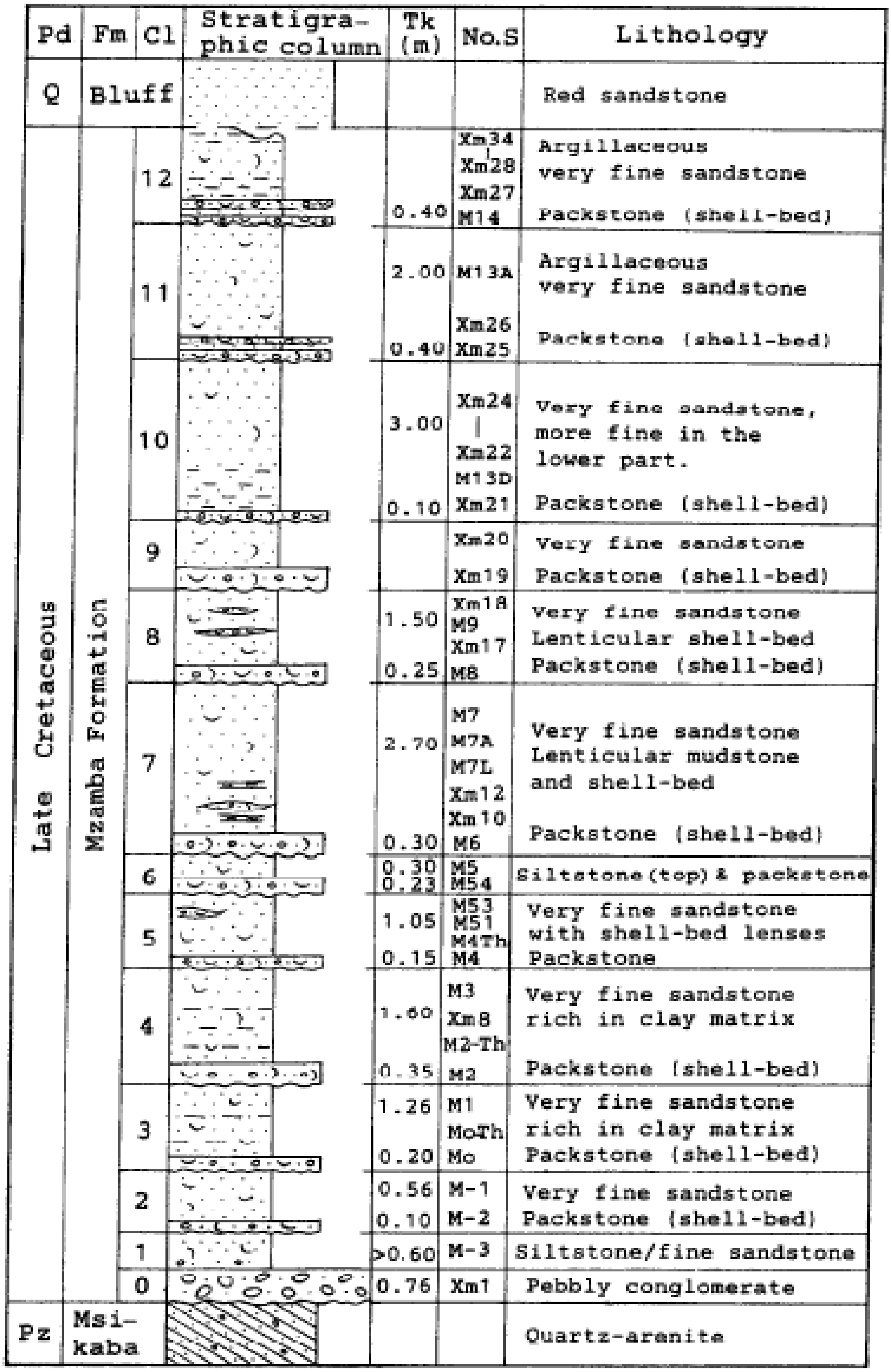


Figure 4: Stratigraphic column of the Mzamba Formation (from Liu and Greyling, 1996). Pd=Period; Fm= Formation; Cl= Cycle; Tk=Thickness; Q= Quaternary; Pz= Palaeozoic.

2.4. Paleontology of the Mzamba Formation

Britannica Concise Encyclopedia defines palaeontology as the scientific study of life of the geologic past, which involves analyzing preserved animal fossils as well as plants fund in rocks. It is mainly focused on all aspects of the biology of ancient life forms: their species, shape and structure, evolutionary patterns, taxonomic relationships with each other and with modern species, its geographic distribution, and interrelationships with the environments. Paleontology has played a vital role in reconstructing the Earth's history and has provided evidence to support the theory of evolution. Palaeontology studies also assists in reconstructing the age of a succession and the depositional environments, and through palaeontological evidence, it has been concluded that Mzamba Formation is an Upper Cretaceous shallow-marine succession

There has been extensive research on the different species found in the Mzamba. Palaeontology of the Mzamba Formation was first studied by Baily in 1855, and then was studied by numerous workers. Silicified wood and large vertebrate remains also occur throughout the succession. Initial studies of the Mzamba foraminifera were by Chapman (1904, 1923), more recently late Cretaceous foraminifera of the KwaZulu-Natal Basin and other coastal outcrops have been detailed by Smitter (1956), De Gasparis (1968), Lambart (1971, 1973), Stapleton (1975), and Wright (1998) (cited from McMillan, 2008). Makrides (1979) comprehensively examined the benthic and planktonic foraminifera of the Mzamba succession, and on the basis of differences in the foraminiferal assemblages was able to divide the succession into Santonian and Campanion portions. Cooper and Greyling (1996) listed benthic and planktonic foraminifera assemblages identified from the Mzamba Formation temporary exposure of the Campanion succession in excavations for a new car-park at the Wild Coast Casino. The following species were found at the Mzamba cliff: Dicarinella asymmetrical, Sigalia deflaensis and Sigalia sp. These species occur intermittently, and they support the age dating previously gained from the ammonites by Kennedy & Klinger (1980).

The gastropod and bivalve fauna were first described by Woods (1906) and Rennie (1929), modern revision of the ammonite fauna have been undertaken by Van Hoepen (1965) and Kennedy and Klinger (1975, 1980). Ammonite of the family Pachydiscidae occurs in the Santonian-Campanion Mzamba Formation in Pondoland (Kennedy & Klinger, 1922). Makrides

(1979) provided descriptions of the foraminifera and Dingle (1969, 1980, 1981, and 1985) published extensively on the ostracoda fauna. Greyling (1991) investigated the fauna of the Mzamba Formation. Fauna lists of all Mzamba species are included in the appendix.

McMillan (2003) gave a comprehensive review of the foraminiferal stratigraphy of the Cretaceous successions in South Africa, which also included the Mzamba Formation. He proposed an Early Santonian age for the lower half of the formation, and an Early Campanian age for the upper half. The stratigraphic position of the unconformity, however, was not established and it should exist between the Early Santonian and the Early Camapanian (Maria et al., 2009). The calcareous nannofossil assemblage identified in Mzamba Formation includes 73 species. The study concluded that the palaeoenvironment conditions were generally unfavourable for the development of calcareous nannoplankton, this was because nannofossils were found to be extremely rare throughout the section. However, species occur more frequently in the lower part of the section.

Cooper (2002) conducted investigations on Palaeolophid and Liostreine Oysters (Bivalvia: Ostreidae) from the Cretaceous of southeast Africa, and he noted two species that occur in the Mzamba Formation. These are:

a) **Rastellum deshayesi**

   Locality- from lower stratigraphic levels (Lower to Middle Santonian) of the Mzamba Formation at its strototype, and from excavations of the Mzamba Formation at the Wild Coast Casino.

   Palaeoecology- this species occurs in the lower, high-energy part of the Mzamba Formation, associated with conglomeritic tempestites, hummocky cross-stratification, fossil logs and diverse heterodont bivalves, including numerous pterotrigoniines and diverse gastropods. Deposition was in an offshore neritic setting, well above storm wave base, suggesting an inner shelf environment. In view of the scarcity of these oysters, it seems likely they represent an allochthonous component, flushed in from nearer-shore environments by storm activity.

b) **Curvostrea tevesthensis**

   Locality- the lower half of the Mzamba Formation at its stratotype, in strata of Middle Santonian age.

   Palaeontology- this species occurs in the lower part of the Mzamba Formation in the background siltstones associated with proximal to medial tempestites, suggesting a mid-shelf environment.

2.5. Lithology and Diagenesis

Diagenesis encompasses all natural changes in sediments occurring from the moment of sediment deposition, continuing through compaction, lithification and beyond—stopping shortly at the time of the onset of metamorphism.

The limitary boundary between diagenesis and metamorphism is not precise in terms of pressure or temperature, nor is there a sharp boundary between diagenesis and weathering (Ali et al., 2010). Diagenesis is both complex and easily misunderstood because natural systems of water, geochemistry, climate and a variety of other factors drive these processes (Nobles, 2010).

Relatively few studies have dealt with diageneis, however, Liu & Greyling (1996) investigated the grain-size distribution and the cementation processes of the Mzamba Formation. Conclusions on the study revealed the grain-size distribution of two major lithofacies, the packstone facies and very fine sandstone facies. The results of grain-size analysis reveal the influence of storm events during deposition. The packstone lithofacies shows characteristics of a wide range of grain-size variation, negative skewness and bimodal grain-size distribution, reflecting the mixed nature of the sediments that were presumably formed by storm, the current and suspension processes. The very fine sandstone lithofacies showed a narrow range of grain-size variation and moderate to good sorting, reflecting a much simpler depositional mechanism by current and suspension process only.

Their study included the investigation of cements found in the Mzamba sediments, and four types of cements were identified 1) carbonate (calcite), 2) clay (smectite & illite), 3) phosphate (carbonate flourapatite) and 4) hydrocarbon (bitumen). Among these four kinds of cement, eight different cementation textures were also distinguished. Diagenetic environments were distinguished, which included the marine phreatic, meteoric phreatic, meteoric vadose and burial diagenetic environments, which were implicated from the four kinds of cements and the eight types of cementation textures encountered.

With the above knowledge of what has been done already in the area concerning diagenesis, this research project will focus on investigating the mineral composition and partially authigenic minerals during diagenesis, find more/ new cement types if possible, and lastly establish diagenetic environments of the study through microscope studies.

The Mzamba Formation contains both siliciclastic and carbonate rocks; therefore, the following literature is a summary of diagenesis of carbonates.

Most carbonate sediments are deposited under marine conditions, although carbonate rocks can also form under some non-marine conditions. Diagenesis of carbonates begins at deposition and continues during burial and uplift .When carbonates are brought into contact with waters of varying chemical composition, they have a great susceptibility to mineralogical and textural change, cementation and dissolution (www.sepmstrata.org). Carbonate minerals are generally more susceptible to dissolution, crystallization and replacement than most silicate minerals. For an example, an original aragonite mud may be altered to calcite completely during early diagenesis or burial (Boggs, Jr, 2001). Thus, diagenesis is greatest near the sediment surface and during shallow burial, where most variation in mineralogical composition of the carbonates and ground waters occurs. As carbonates are buried more deeply, they are commonly in equilibrium with the adjacent subsurface waters; nevertheless, significant diagenetic changes can occur (Machel, 1999).

2.6 Regimes of Carbonate Diagenesis

I. The seafloor and shallow-marine subsurface regime which is characterized mainly by marine waters of normal salinity, although hypersaline waters are present in the evaporative environments.

II. The meteoric regime is distinguished by the presence of freshwater. It includes the unsaturated, vadose zone above the water table and the phreatic zone, or saturated zone below the water table.

III. The deep subsurface zone. In the deep subsurface, sediment pores are filled with waters that were either marine or meteoric waters in the beginning. The composition of deep pore water is commonly different, however, from either marine or meteoric waters owing to burial modification.

2.6.1. Diagenetic Processes and Changes

2.6.1.1. Biogenic Alteration

Organisms present in carbonate depositional environments rework sediment by burrowing, boring, and sediment-ingesting activities. These activities tend to destroy primary sedimentary structures in carbonate sediments and leave behind mottled bedding and other kinds of organic traces. Many kinds of small organisms such as fungi, bacteria and algae create microborings in skeletal fragments and other carbonate grains. Fine grained aragonite may then precipitate into these holes. This boring and micrite-precipitation process may be so intensive in some warm-water environments that carbonate grains are reduced almost completely to micrite, a process called micritization. If boring is less intensive, then only a thin micrite rim or micrite envelope may be produced around the grain. Larger organisms such as gastropoda and shrimp create macroborings in skeletal grains and carbonate substrates and other organisms such as fish and mollusks may break down carbonate grains in various ways to smaller pieces (Boggs Jr, 2001).

2.6.1.2. Cementation

Cementation is a very important process in all diagenetic realms. On the ocean floor, cementation usually occurs mainly in warm-water areas within the pore spaces of grain-rich sediments or in cavities. Reefs, carbonate sand shoals on the margins of platforms, and carbonate beach sands are favored areas for early cementation. Seafloor cement is commonly aragonite, less commonly high-magnesium calcite. Seafloor cement can take several textural forms. Isopachous rinds, which completely surround grains, forms under subaqueous conditions whereby the grains are constantly surrounded by water. Aragonite cements may also occur as a mesh of needles or as fibrous radial crystals that have a botryoidal form. In the meteoric realm, dissolution is a more important process than cementation; however, cementation does occur. The cement is almost exclusively calcite. Calcite cementation may also take place during deep burial, although the conditions that control cementation at depth are poorly understood.

Cementation occurs during the formation of oolites, grapestones, and hardened pellets. For example, the oolites occurring in high energy zones are formed by the precipitation of calcium carbonate around a nucleus. Grapestones, found to the lee of oolite shoals in a quieter water setting, are formed by the precipitation of carbonate cement at points of contact between sand-sized grains and by partial disaggregation of cemented crusts by storms. Further evidence of cementation is the hardening of pellets on open shelf environment, whereas in protected water environment of the hardened pellet zone on the Great Bahama Bank, lime mud pellets remain uncemented (www.sepmstata.org).

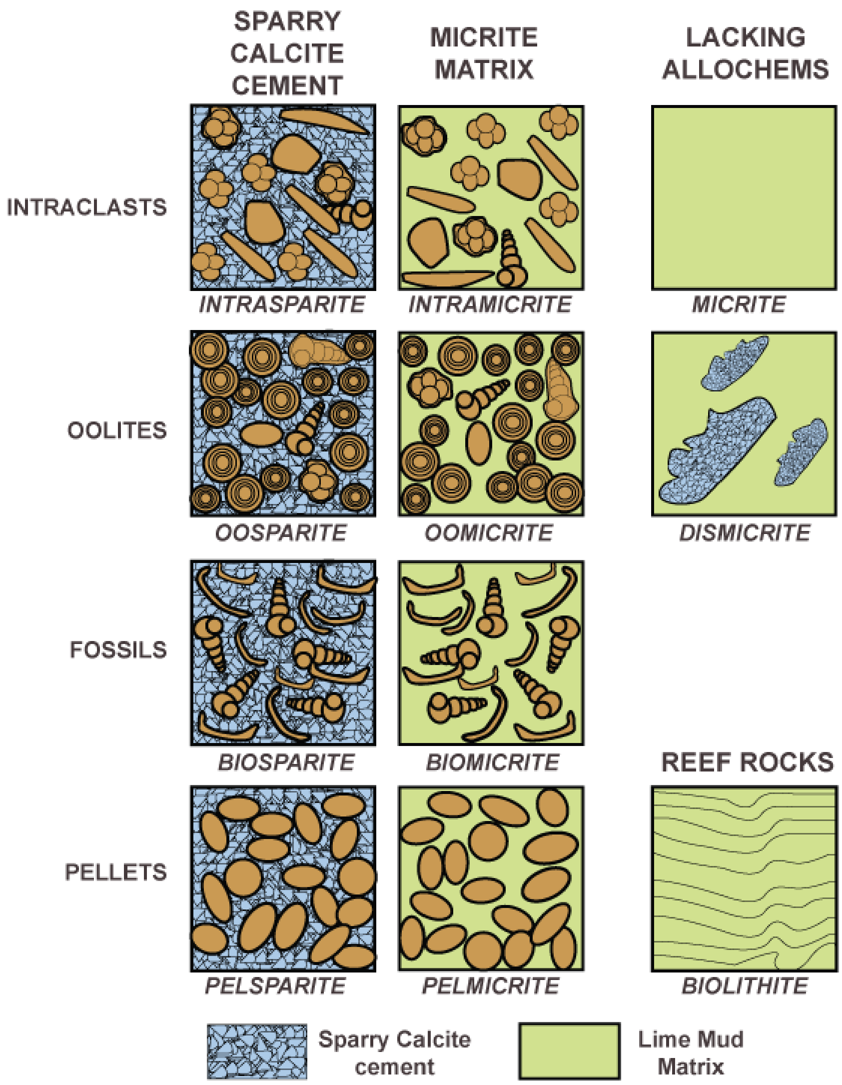


Figure 5: Components of carbonate rocks (from SEPM STRATA, 2013)

2.6.1.3. Dissolution

Cementation is a very common diagenetic process in carbonate rocks, yet, some-what paradoxically so is dissolution. Dissolution of carbonate minerals requires conditions essentially opposite to those that lead to cementation. Dissolution is favored by unstable mineralogy, cool temperatures, and low pH pore waters that are undersaturated with calcium carbonate. Dissolution takes place especially in chemically aggressive pore waters highly charged with carbon dioxide and/or organic acids. Dissolution tends to be concentrated particularly along the water table, which accounts for the common presence of caves in carbonate rocks at the level of the water table.

2.6.1.4. Neomorphism

Neomorphism is a term used to cover the overall processes of inversion and recrystallization. Inversion is the change of one mineral to its polymorph, such as aragonite to calcite. Inversion strictly takes place in the dry (solid) state. During diagenesis, most aragonite is eventually changed to calcite. Recrystallization refers to the change in size or shape of a crystal, with little or no change in chemical composition or mineralogy. Neomorphism may occur in all three diagenetic realms but is particularly important in the meteoric and subsurface diagentic environments. Neomorphism may affect both carbonate grains and micrite and usually increases crystal sizes.

2.6.1.5. Replacement

Replacement involves the dissolution of one mineral and the nearly simultaneous precipitation of another mineral of different composition in its place. Replacement of calcium carbonate minerals by other minerals is a common diagenetic process. Replacement may occur in all diagenetic environments. Dolomitization of calcium carbonate sediments is one kind of replacement process.

2.7. Carbonate Classification

Two carbonate classification systems are in common use, one is by R.L Folk (1962) and the second is by R.J Dunham (1962). Carbonate rock classifications have been changed rapidly, as compared with sandstone classifications.

2.7.1. Folk Classification (1962)

Folk’s classification requires definite knowledge of the kinds and abundances of carbonate grains (allochems) and the relative abundance of micrite and sparry calcite cement. The classification requires the following steps to be followed: 1) Determine the relative abundance of carbonate grains (allochems) as a percentage of the total rock, that is, >10 percent grains or < 10 percent grains. 2) Determine the relative abundance of micrite and sparry calcite cement, that is sparry calcite abundance > micrite abundance or micrite > sparry calcite. 3)Normalize the carbonate grain types to 100 percent grains, that is determine the abundance of each major kind of carbonate grain (intraclast, ooids, pellets, oncoids, fossils) as a percentage of total grains. 4) Enter the appropriate row in the classification: a) if intraclasts exceed 25% of total grains, the rock is an intraclastic limestone b) if the intraclasts make up less than 25% of total grains, but ooids exceeds 25%, the rock is an oolitic limestone. 5) Select the appropriate name on the basis mentioned above.

The rock name is derived by combining the appropriate abbreviation for the dominant allochem (e.g intra for intraclast) with the abbreviation for micrite (mic) or sparry calcite cement (spar) as seen to be appropriate. To this name a suffix is added denoting the dominant size of the carbonate grains. The suffix is either –ite, shortened from arenite (Fig. 6).

		INTERSTITIAL MATERIAL	
		Micrite Matrix	Spar Cement
ALLOCHEMS	Fossils	Biomicrite	Biosparite
	Oolites	Oomicrite	Oosparite
	Pellets	Pelmicrite	Pelsparite
	Intraclasts	Intramicrite	Intraaparite

Figure 6: Folk's (1962) classification.

Limestones that contain 10% or less carbonate grains are micritic limestones. For limestones containing 1-10 percent grains, Folk assigns names based on dominant grain type. Biogenic limestones that that were bound together at the time of deposition e.g. coral reef rock, are called biolithites. Folk classification can also be used for dolomites. He suggests that fine-grained primary dolomites be classified with limestone. Such fine-grained dolomite is called dolomicrite.

Folk also provides a textural maturity classification for limestones that is based on the percentage of carbonate grains in the total rock and the relative abundance of micrite and sparry calcite.

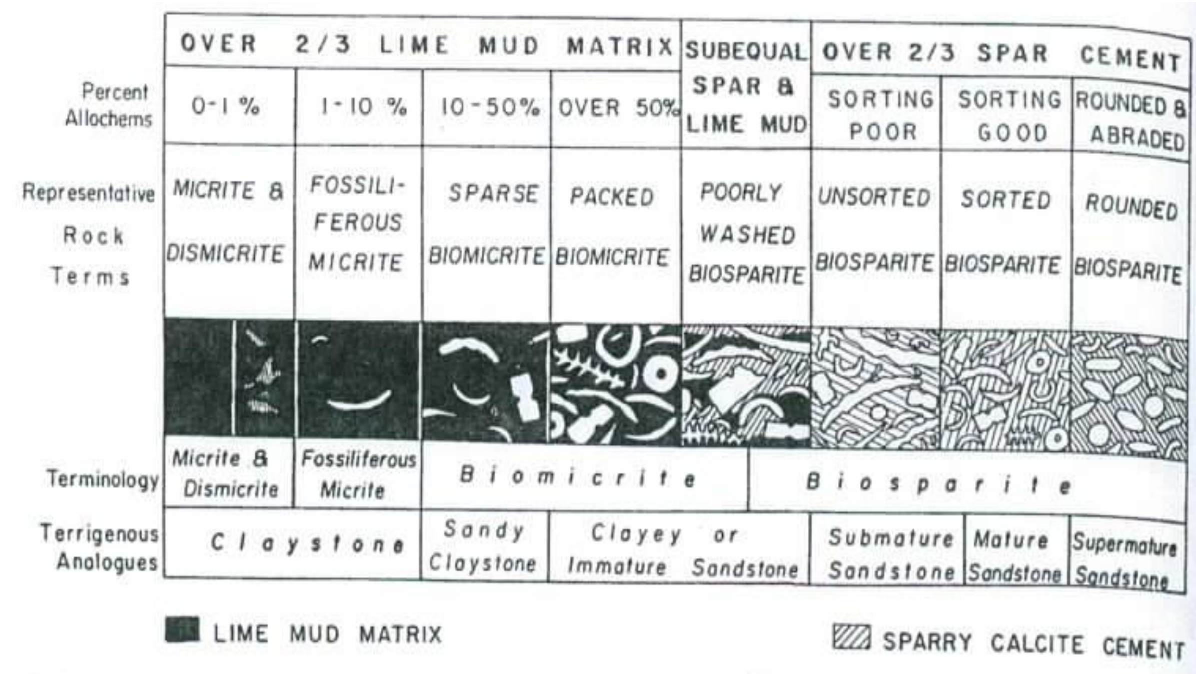


Figure 7: Textural maturity classification of Folk (1962) (extracted from Tucker & Wright, 1990)

2.7.2. Dunham's Classification (1962)

Dunham's 1962 classification focuses upon depositional textures rather than upon the identity of specific kinds of carbonate grains. In order to use this classification, one must first determine if the original constituents of the limestone were or were not bound together at the time of deposition. For rocks composed of components not bound together during deposition, the rocks are further divided into those that contain lime mud (micrite) and those that lack mud. Rocks that contain lime mud are either mud-supported or grain-supported. Mud supported limestones are mudstones, if they contain less than 10% carbonate grains, and wackestone if they contain some micrite and matrix are packstone. Grain-supported limestones that lack mud matrix are grainstones. Grain-supported grainstones that lack mud matrix are boundstone.

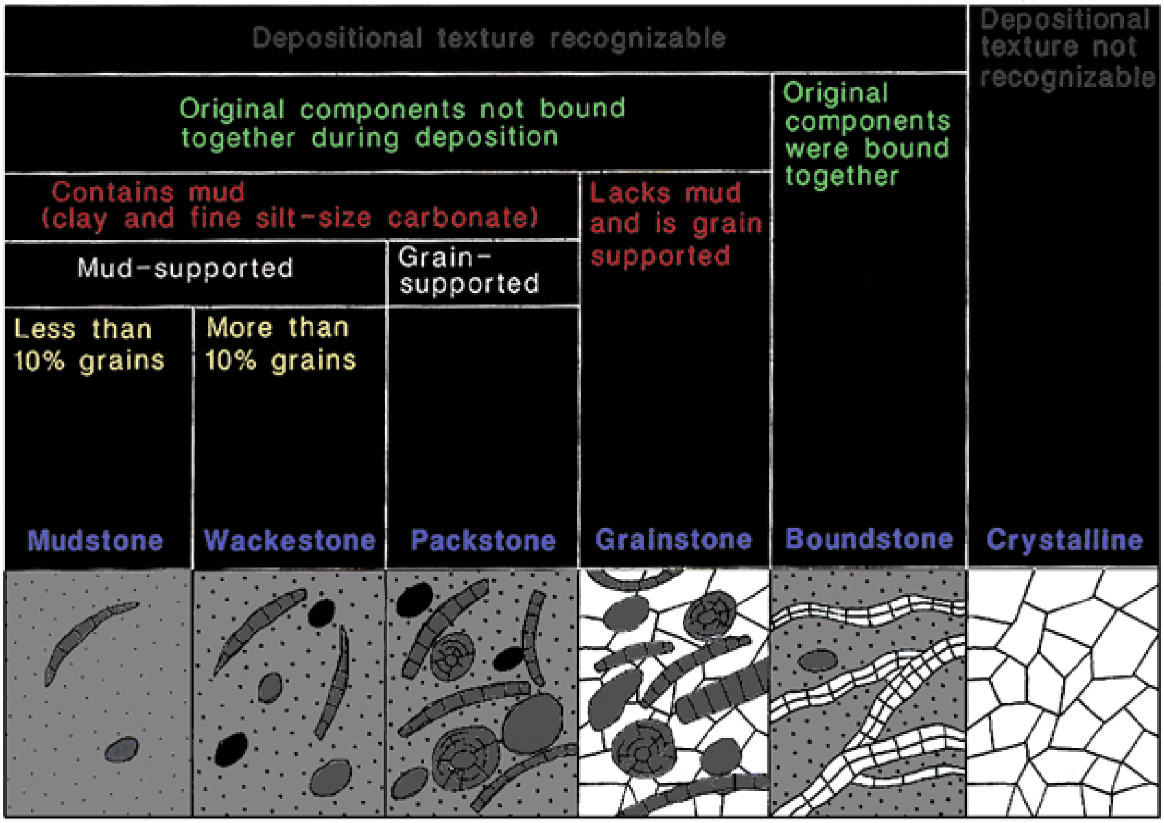


Figure 8: Dunham's (1962) classification of limestones, with schematic diagrams of each rock type (extracted from Tucker & Wright, 1990).

2.8. Conclusion

Previous work was mainly concentrated on the stratigraphy and palaeontology of the Mzamba Formation. There is limited previous research and publications related to sedimentology of the Mzamba Formation; particularly it is lack of research on its sedimentary facies, depositional environments and diagenesis. Therefore, this research project is aimed at the weak point of the previous work, and is to provide a new insight into sedimentary facies, depositional environments and diagenesis of the Mzamba Formation. Of course, we are also going to provide new work on the stratigraphic aspects. This thesis will contribute to the present knowledge and attempt to provide new and more detailed information to the studies of Mzamba Formation.

Diagenesis plays a vital role in controlling hydrocarbon exploration, production and field management. Diagenesis can affect the ways in which geologists and engineers interpret, evaluate and develop hydrocarbon reservoirs. Therefore, this research is further aimed at providing a detailed diagenetic study of the sequence since diagenetic changes have a major effect on porosity and permeability of groundwater and hydrocarbon reservoirs, therefore, this research may be of economic significance for exploration of hydrocarbon and groundwater hosted in the sediments.

CHAPTER 3 METHODOLOGY

The methodology employed in this study is closely related to the aims and tasks of the project. To address the tasks of this research, the following methodologies have been employed:

3.1 Field geological investigation

Field exposures of the Mzamba Formation were observed and data was documented. The following observations where made:

- Measurements were taken to construct the stratigraphic succession of the Mzamba Formation along the coastal cliff located in the south of Port Edward.
- Identification of lithological variation of the strata, sedimentary structures presenting in the formation, and particularly the grain-size changes and the biological features of the sequence.
- Field measurement of bedding occurrence, i.e. Dip directions and dip angle were recorded.
- Systematically collecting rock samples during field visits where it was possible.
- Field photos were also taken.

3.2 Sample preparation

Rock samples were systematically collected from the study area, and the samples were selected for making thin-sections.

Powder samples for XRD were prepared in the lab, whereby rock samples were broken into chips using a hammer. The chips were further crushed manually to fine powder using a pestle and mortar.

Rock chips for SEM analysis were prepared by cutting the rocks using a hammer, acquiring a near-flat surface on one side. The near-flat surface is glued to a glass slide and left for a few minutes to dry. The slide was then mounted on a carbon coating machine, and the samples were coated with multiple coats of carbon.

3.3 Laboratory Work

3.3.1 Thin Section Analysis

50 thin sections were created and analyzed. Microscopy-petrography was undertaken to identify lithologies and rock types of the rocks, cement types and cementation textures of the rocks. Constituent minerals and cements were identified. Recrystallization, neomorphism, dissolution, replacement textures and processes were also analysed. Identification of the diagenetic environments and establishment of the diagenetic pathway for the sediments was done. Microscope photographs were taken to illustrate the different minerals and diagenetic textures present. The optical study was conducted using a Reflected Light Microscope.

3.3.2 SEM study

Scanning Electron Microscopy was employed for micro-analysis of mineral types and diagenetic textures since the high-magnification properties of the SEM analysis and its Energy Dispersive X-ray (EDX) facilities. Surface textures of rocks were analyzed using small, near-flat pieces of the natural rock surfaces and the samples were carbon coated. Observations were made using SEM, model JEOL JSM-6390LVwith a working voltage of 15KV and it uses the secondary electron detector. Minerals and textures of the four samples from the study area were investigated to assist in lithology and diagenetic modification.

3.3.3 XRD analysis

Four samples from the research area, two mudstones and two sandstones were chosen. The samples were crushed to powder form using a pestle and mortar. X-ray powder diffraction, using X-ray detection Model D8 Advance machine, the scanning angle range is 2 Thetha and is between 0-80^{o}, scanning speed being 30/min and the software package Diffrac.Suite was used to analyze the samples. This was conducted in order to verify the presence of minerals observed under petrographical microscope, and more importantly, to identify new and unrecognized minerals, also the crystalline properties of a mineral, such as clay mineral crystallinity. XRD provides unambiguous mineral identification and data interpretation is straight forward.

3.3.4. Grain Size Measurements

In this study, grains were measured using the microscope. This will help in classifying the rock types of the formation. Two classification schemes were used, the Folk's (1962) Classification and Dunhamm's (1962) Classification because the rocks of the Mzamba are carbonates, specifically limestone, as well as mixed siliciclastic sedimentary rocks.

CHAPTER 4 STRATIGRAPHY

4.1. Introduction

Stratigraphy is a branch of geology dealing with the form, arrangement, geographic distribution, chronologic succession, classification, correlation, and mutual relationships of rock strata, especially sedimentary rocks (McGraw, 2003). Mostly here, the vertical and horizontal distribution of the Mzamba Formation will be studied. Stratigraphy is based on the principle of superposition, which states that in a normal sequence of rock layers the youngest is on top and the oldest at the bottom. Location exposure of rock sequences are studied in the field, and after considering such factors as the average rate of deposition of the different rocks, their composition, the width and extent of the strata, the fossils contained, and the periods of uplift and erosion, it is only then that the geological history of the sequence is reconstructed. There are other stratigraphic classifications that are used such as lithostratigraphy, biostratigraphy, chronostratigraphy and magnetostratigraphy.

The stratigraphy of the Mzamba Formation is clearly observable in the cliffs of the Mzamba River mouth. The outcrops of the Mzamba Formation are now not extensively exposed; it is covered by sand dunes and bushes. Description of the stratigraphy is based on the outcrop as it appears at the locality. Three sections were measured, and the longest section is about 10m high, and the other exposures are sparsely distributed along the coastal area. The locality has evident large-scale fining upward cycles of cross-bedded shelly limestone, overlain by massive bioturbated, fine-grained calcareous sandstone with interbedded shelly horizons. Near the bottom, there is a conglomerate bed which is rich in fossils and different sizes of pebbles. Three sections were measured to help describe the lithology and construct the stratigraphic column.

4.2. Detailed Stratigraphy

The stratigraphic sections of the Mzamba Formation are well exposed along the coastal cliff. It shows alternating coarse fossil-rich packstone bed with fine fossil-poor mudstone bed, which constitutes a various thickness of multiple upward fining cyclotherms in the field. Cyclical sedimentation is evident, but it has different scale and it is evident throughout the type section. Each cyclotherm is composed of different rock unit with different lithologies, sedimentary structures and fossil contents. The two differing lithologies that were recognized in each cycle are characterized by consistency in the bed thickness, internal structure and the fossil reservation. The type section is located on the beach at the south of Wild Coast Sun near Port Edward, and is described as below.

4.2.1. Measured section 1-The type section

Unit 1

This is the lowermost bed in the section and is clearly exposed. The bed attains a thickness of 2.55m. This conglomerate is fossiliferous, with randomly orientated small to medium-sized chert and sandstone pebbles, some laminated siltstone pebbles are also found. At the type section, the pebbles are varied between 1-10cm in grain size, and the conglomerate contains calcium and clay minerals as cement. The fossils that are found here are well preserved, which include bivalve, gastropod and oyster fossils, as well as silicified wood trunks as large as 35cm in diameter which were orientated alignment in a west-east direction.

Unit 2

This unit attains a thickness of 10cm, and it overlies unit 1 with a scoured bottom contact surface. At the type section this massive sandstone bed is fine-grained, soft and grey-green in colour. The bed is strongly bioturbated, with well-developed burrows. Sedimentary structures including parallel bedding and lamination are prevalent, indicating the sediments were deposited in a relatively deep water environment. The unit is fossiliferous with small-medium sized shells that are concentrated in clusters.

Unit 3

This mudstone bed unit overlies unit 2 with an uneven erosional bottom contact. This unit extends all the way to the beach. It is fine-grained and grayish-blue in colour. It attains a thickness of 12cm, and keeps increasing in the southward direction. Inside the mudstone bed, there are dispersed shell fragments. The unit is exposed at low tide along the coastline. The section starts fining upwards from this mudstone bed unit.

Unit 4

This unit attains a thickness of 18cm, it overlies unit 3 with a scour erosional bottom contact. It is a hard, brownish, massive-bedded, medium-grained pecten bed. This unit is fossiliferous and the shells have not suffered extensive abrasion and removing, and therefore are clearly observable in the original growing position at which they were deposited. Gastropoda, bivalve, sponge and oyster fossils are among the most abundant species in the strata. The different species tend to be concentrated in clusters. The bottom bounding surfaces are erosional.

Unit 5

This is a rather thick unit of very fine–grained mudstone bed, with a thickness of 37cm. The contact with Unit 4 is gradational. Bioturbated shells are common. Low relief hummocky cross-stratification has also been noted in this unit. Horizontal and vertical burrows are encountered; the shell fragments in the strata are generally small and occur randomly. This bed thickens slightly southward. This unit is laterally the most persistent succession and can be traced continuously for about 500m.

Unit 6

This unit overlies Unit 5 and the bottom contact is erosional. It attains a thickness of 10cm and slightly decreases in thickness as going to southward along the succession. This pecten bed is well-cemented and is concentrated of the fossils as clusters, and the bed is persisting horizontally. The fossils are well preserved. The bed is thin bedded and the rock is coarse grained and is mostly made up of shell fragmental fossils with the shell fragment to mud ratio being 80%.

Unit 7

This is a 32cm thick, grayish-blue, fine to medium-grained mudstone bed. It is well defined in the bottom boundary with very fine shell fragments setting in matrix. The shell fragments are dislocated and dispersed evenly throughout the bed. The mudstone bed with the underlying rock (Unit 6) constitutes a fining upward cycle.

Unit 8

This unit attains a thickness of 15cm. It is medium-grained and contains lesser fossils as compared to all the other pecten beds. This pecten bed contains eroded and dislocated shell fragmental fossils which are not clearly observable. The fossils are poorly sorted and are horizontally orientated.

Unit 9

This is the thickest mudstone bed found in the succession of the Mzamba Formation, nowhere else does it appear so thick. It is 68cm thick, soft, fine-grained, and grayish-blue in colour. It contains small to medium-sized shell fragments that are randomly orientated.

Unit 10

This pecten bed is 12cm thick, which overlies the Unit 9 with an erosional bottom contact. It contains abundant fossils that are orientated horizontally and distributed in clusters. The most abundant fossil species are bivalve, gastropoda and oyster fragmental fossils.

Unit 11

This unit overlies Unit 10 with a clearly visible erosional bottom contact surface. This mudstone bed unit is 22cm in thickness, it is hard, fine-grained, and laminated, with shell fragments occurred in the bed which are slightly coarser than matrix and are horizontally orientated.

Unit 12

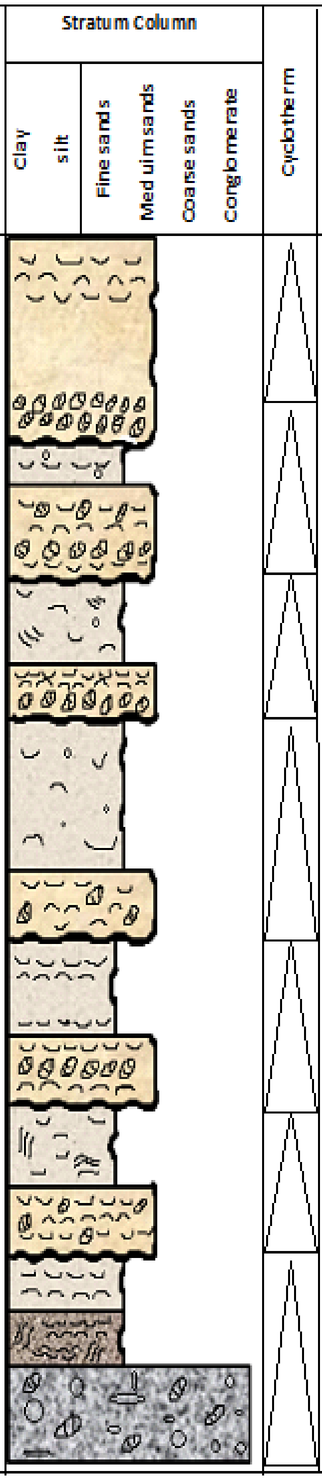
This unit attains a thickness of 31cm. It is a rather thick bedded, medium-grained unit, and is rich in well preserved shell fragmental fossils. This pecten bed is hard, brownish and overlies the Unit 11 with a sharp erosional bottom surface. The fossils are concentrated in clusters, and are sometimes aligned as threadlines or stripes. The most abundant species include oysters, gastropod and bivalves.

Unit 13

This is a highly weathered mudstone rock unit that attains a thickness of 7cm. It is blue-grey, fine-grained, and bounded by a sharp but even bottom contact with the Unit 12. It can be continuously traced for about 200m in southward direction. It contains less shell fragments and the shell fragments tend to be smaller in size, and are orientated very randomly.

Unit 14

This is the top unit of the succession. It is easily accessible even in high tides. It is overlain by thick vegetated sands and bushes. It has a sharp but even bottom contact surface with the underlying unit. This is a 70cm thick, hard, buff-coloured rock unit, with low-relief hummocky cross-stratification. This fine-grained pecten bed contains fossils that are horizontally orientated at the lower part, and shell fragments are dispersed unevenly near the top.



Strata No.	Thickness (m)	Sedimentary Structure	Lithology
14	0.70	Medium-grained, contains fossils that are horizontally orientated at the lower part, and shell fragments are dispersed unevenly near the top.	Pecten bed, hard, buff-coloured, strata has low-relief hummmocky cross-stratification, the top is overlain by thick vegetated sands & bushes.
13	0.07	Contains lesser shell fragments.	Highly weathered mudstone bed, fine-grained, blue-grey in colour.
12	0.31	Rich in well preserved fossils.	Thick-bedded pecten ned that is meduim-grained. It is hard, brownish in colour.
11	0.22	Cross-bedded mudstone bed, contains shell fragments.	Mudstone bed, hard, fine-grained and has some laminations.
10	0.12	Rich in fossils that are horizontally orientated, and are in clusters.	Pecten bed, meduim-grained and light in colour.
9	0.68	Small to meduim-sized shells that are randomly orientated.	Mudstone bed, grayish-blue in colour, soft and fine-grained.
8	0.15	Contains eroded & dislocated shell fragmental fossils.	Medium-grained pecten bed, brownish in colour.
7	0.32	Very fine shell fragments setting in matrix.	Mudstone bed, grayish-blue in colour and is fine to meduim-grained.
6	0.10	Clustered, preserved shell fragments.	Pecten bed, thin-bedded, well-cemented and coarse-grained.
5	0.37	Shell fragments, horizontal & vertical burrows.	Mudstone bed, very fine-grained, has low relief hummocky cross-stratification.
4	0.18	Rich in bivalvs, gastropods & oyster fossils.	Meduim-grained pecten bed, hard, brownish in colour and is massive bedded.
3	0.12	Dispersed shell fragments.	Mudstone bed, fine-grained and is grayish-blue in colour.
2	0.10	Fossiliferous, with burrows.	Massive sandstone bed, fine-grained, gray-greenish in colour.
1	0.22	Fossiliferous, with pebbles of chert, sandstone & siltstone, tree trunks are also present.	Conglomerate bed with pebbles that vary in size between 1-10cm.

Figure 9: Stratigraphic column of the type section at Mzamba River coast.

Figure 10: Measured section of the Mzamba Formation. Note the fining upward cycles, consisting of cross-bedded sandstone alternated with mudstone.

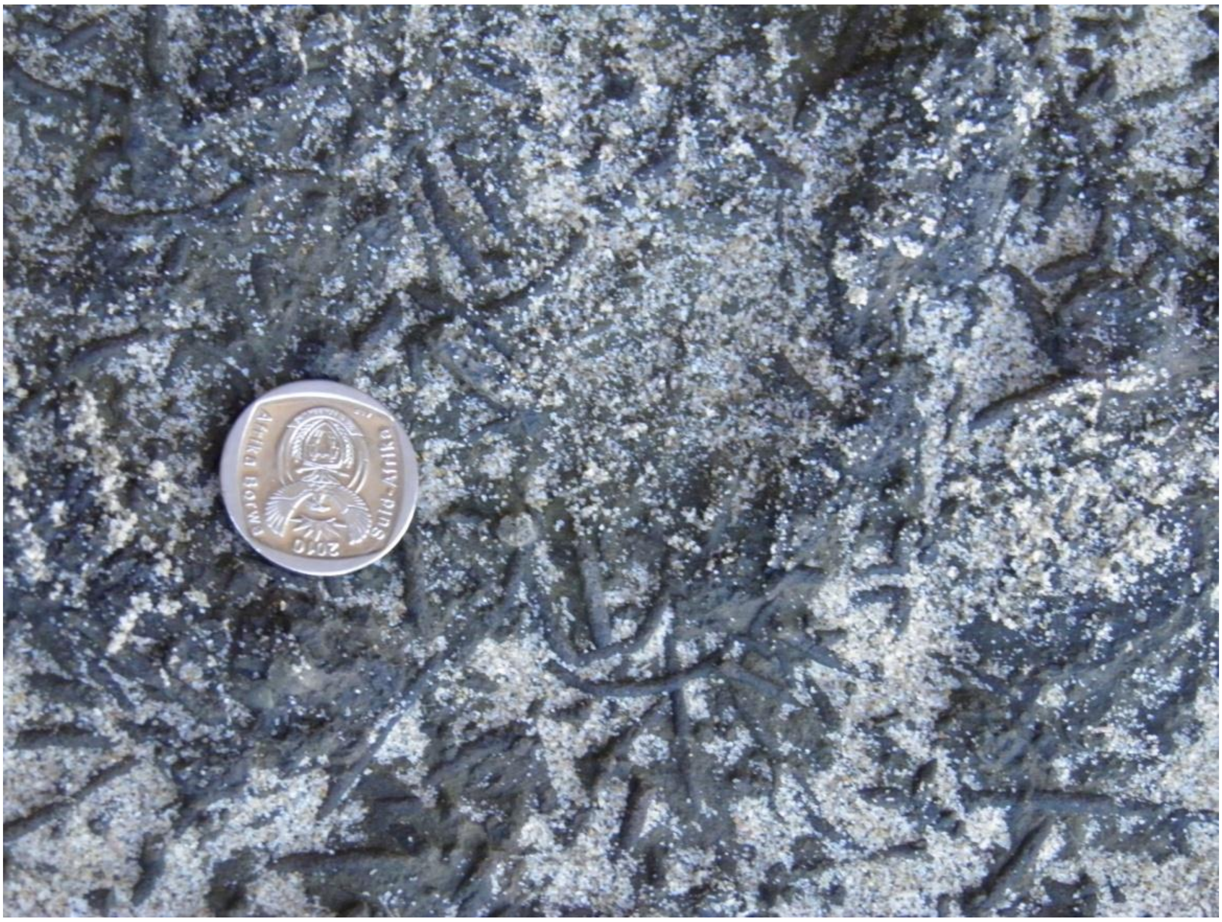


Figure 11: Burrows encountered in the grey-greenish mudstone of Unit 2. The coin is 2.3cm for scale.

4.2.2. Section 2 (paratype section)

This section was measured at elevation of 3m, with coordinates S31^{O} 06' 12.1" and E030^{O} 10' 45.7".

Unit 1

This is the bottom bed at this paratype section that attains a thickness of 45cm. It is a mudstone bed, very fined-grained, dark colored with shell fragments that are clustered horizontally. The conglomerate bed is now buried deep in the water, and does not appear as the bottom bed here.

Unit 2

This is a pecten bed; it is relatively thick with a thickness of 33cm. It is hard; buff coloured and is rich in fossils that are clustered. It is concentrated in shell fragments of differing sizes and differing orientation. This unit overlies Unit 1 with a sharp erosional bottom contact surface.

Unit 3

This is a rather thick unit of calcareous mudstone, attaining 40cm in thickness. It is fine-grained and overlies Unit 2 with a gradational bottom contact surface. It contains smaller shell fragments and some isolated chert and quartz pebbles could be found in the strata.

Unit 4

This is a 28cm thick, brown colored pecten bed. It overlies Unit 3 with a clear erosional bottom contact surface. It is very similar to the previous pecten bed in composition, with shell fragments that are clustered, aligned parallel to the bedding surface.

Unit 5

This is the thickest mudstone bed encountered, with a thickness of 2.1m, and is continuous as it is traced for a few meters in the southward direction. It is dark grey and fine-grained. It contains a layer of small clustered shells, orientated horizontally and is continuous. This unit overlies Unit 4 with a gradational contact surface, with clear different grain-size and textures.

Unit 6

This is a rather thin layer of pecten bed, with a thickness of 17cm. It is hard; light colored and is rich in shell fragments of different sizes. The shells are 1-3cm in size and they are concentrated in clusters. This unit overlies Unit 5 with an erosional bottom contact surface.

Unit 7

This is a calcareous mudstone bed that attains a thickness of 27cm. It overlies unit 6 with a gradational contact surface. This unit is medium-grained, grey-green with scattered shell fragments.

Unit 8

This is a light coloured, pecten bed of 19cmin thickness. It overlies Unit 7 with a sharp erosional contact surface, and contains a lot of shell fragments of differing sizes and thicknesses and gastropoda fragments.

Unit 9

This is a rather thick mudstone unit, with a thickness of 61cm. It is medium-grained, and contains oval shaped calcareous nodules in the size between 10-15cm. Small isolated slate pebbles are present in the strata. This unit overlies Unit 8 with a gradual bottom contact surface.

Unit 10

This is a pecten bed that attains a thickness of 34cm; it overlies Unit 9 with an erosional bottom contact surface. It is hard, light brownish and is rich in shell fragments that are well preserved and are of different sizes.

Unit 11

This is a unit of brownish coloured mudstone, with small shell fragments that are scattered throughout. The unit has a thickness of 30cm, and contacts Unit 10 with a gradational bottom surface.

Unit 12

This is a light coloured pecten bed, fully cemented, with a thickness of 33cm. It overlies Unit 11with a clear erosional bottom surface. It is rich in shell fragments that are aligned parallel to the bedding. The shell fragments are clustered and are 1-2cm in size. The unit also contains small pebbles, <0.5cm in grain size.

Unit 13

This is a unit of very fine-grained calcareous mudstone. It is 57cm thick, dark/black colored, overlying unit 12 with a gradual contact surface. It is dominated by mud material, with very fine shell fragments that are embedded in the mudstone. Iron modules are also found.

Unit 14

This pecten bed is 22cm thick, overlies unit 13 with an erosional bottom contact surface. It is concentrated in shell fragments of deferring sizes, with shells that are aligned convex-upward. Some pebbles of quartz arenite, igneous rock and slate are found. Some pebbles are big, small and plated. Lots of burrows are noted that are parallel to bedding.

Unit 15

This is a relatively thick unit of calcareous mudstone, attaining a thickness of 66cm. it is fine grained, with lenticular shell fragments that are scattered throughout the bed. It also contains small pebbles. This unit overlies Unit 14 with a gradational contact surface.

Unit 16

This is a pecten bed, with a thickness of 29cm. It has small pebbles cemented by sands and mud materials. It contains well preserved shell fragments, and gastropoda fossils. These shells are clustered together, with some being vertically orientated; some are convex-up embedded. The shell fragments are 1-3cm in size. This unit overlies Unit 15 with an erosional bottom contact surface.

Unit 17

This calcareous mudstone bed is 52cm thick and overlies unit 16 with a gradational contact surface. It is fine-grained, well cemented, grey-green in colour and has dispersed shell fragments. Lenticular calcareous nodules, with different shapes and sizes are found in this unit.

Unit 18

This is a rather thin unit of pecten bed, with a thickness of 17cm. It is very rich in shell fragments that are aligned parallel to bedding. The unit resembles graded bedding with the grain-size finning upward, and contains small pebbles of quartz and chert at the bottom. This unit overlies Unit 17 with an erosional contact surface.

Unit 19

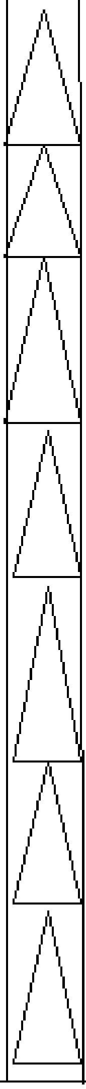
This is a very fine-grained mudstone bed, with a thickness of 25cm. It is light coloured due to weathering, appears dark colored when it is fresh which indicates that it was formed in a reducing environment. It contains articulated shell fragments and iron nodules. This unit overlies Unit 18 with a gradual contact surface.

Unit 20

This is a light colored pecten bed, attaining a thickness of 35cm and it overlies Unit 19 with a clear erosional bottom contact surface. It contains clustered, very thin shells that occur throughout the unit. The shell fragments mixed with gastropoda fragments. Some nodules are found, there are also very big broken shells (>14cm), that are aligned parallel to bedding.

Unit 21

This is the top unit, and it is accessible if one climbs up the cliff. It is a composite calcareous mudstone unit. It is about 50cm thick and is very fined-grained, and is fossiliferous. It is poorly sorted and overlies Unit 20 with a gradational contact bottom surface. Occasional pebbles occur, with shell fragments that are randomly orientated, and the top is covered with dense vegetation.

Strata No.	Stratum Column						Cyclotherm	Thickness (m)	Sedimentary Structure	Lithology
	Clay	silt	Fine sands	Medium sands	Coarse sands	Conglomerate				
21								0.50	Calcareous mudstone, with scattered fine shell fragments.	Pale-brownish very fine-grained mudstone.
20								0.35	Contains thin layers of shell, gastropoda fragments & some nodules occur throughout	Light coloured pecten bed, meduim grained
19								0.25	Mudstone bed with articulated shell fragments and iron nodules.	Fine–grained mudstone, light coloured due to weathering.
18								0.17	Rich in shell fragments, and contains small pebbles of quartz, chert and sandstone lithics.	Brownish coloured, medium-grained pecten bed.
17								0.52	Contains lenticular calcareous nodules, with different shapes and sizes.	Grey-green mudstone bed and fine-grained.
16								0.29	Pecten bed with small pebbles & well preserved shell fragments, including bivalves & gastropoda.	Hard, buff coloured pecten bed.
15								0.66	Has scattered shells and small pebbles.	Fine-grained, grey mudstone bed.
14								0.22	Rich in shells, well-developed burrows and, contains pebbles of quartz arenite, slate and igneous lithics.	Dark coloured and brownish after weathering, medium-grained pecten bed.
13								0.57	Mudstone bed with fine shell fragments, contains some iron nodules	Dark/black coloured, very fine-grained mudstone bed.
12								0.33	Pecten bed rich in shell fragments that are aligned parallel to the bedding, with some nodules.	Light-brown, meduim-grained pecten bed.
11								0.30	Contains small shell fragments that are scattered throughout the bed.	Brown coloured, fine-grained mudstone bed.
10								0.34	Pecten bed rich in shell fragments and fossils.	Hard, light coloured pecten bed.
9								0.61	Mudstone bed, contains big lenticular calcareous nodules,. Small slate pebbles are presented in the bed.	Medium-grained mudstone bed.
8								0.19	Rich in shell and gastropoda fragments.	Light coloured pecten bed.

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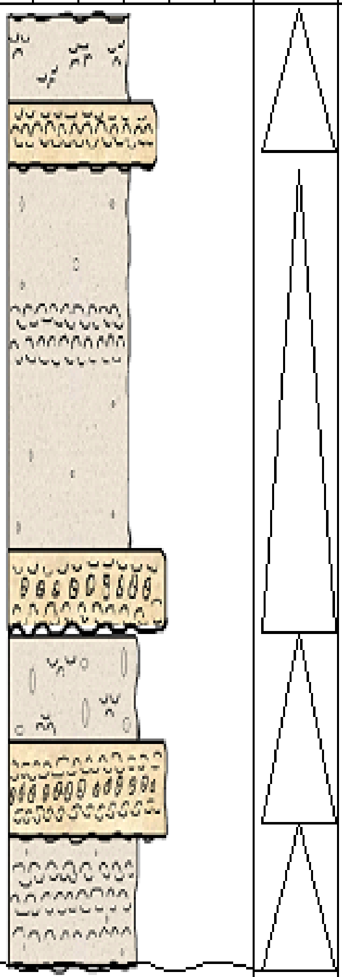


Strata No.	Stratum Column (Clay, silt, Fine sands, Medium, Coarse sands, Conglomerat)	Cyclothem	Thickness (m)	Sedimentary Structure	Lithology
7			0.27	Contains scattered shell fragments.	Medium-grained, grey-green coloured mudstone bed.
6			0.17	Pecten bed, rich in shell fragments of different sizes (1-3cm).	Pecten bed, hard; light coloured
5			2.1	It contains a layer of small clustered shells, orientated horizontally and is continuous extended.	Dark grey and fine-grained mudstone bed.
4			0.28	Rich in clustered shell fragments that are alligned parallel to bedding plane.	Brown coloured, meduim-grained pecten bed.
3			0.40	Contains smaller shell fragments and some quarts and chert pebbles.	Fine-grained mudstone bed.
2			0.33	Pecten bed rich in fossils such as oyster and gastropds that are clustered together.	Hard; buff coloured pecten bed.
1			0.45	Contains shell fragments that are clustered horizontally.	Mudstone bed, very fined-grained, dark colored .
	Not exposed				

Figure 12: 2nd stratigraphic section at the paratype location at the south of Mzamba River.

Figure 13: Pecten bed of Unit 2 in the paratype section, showing a cluster of small shell fragments, aligned parallel to bedding; also the inverse graded bedding. The pen is 13 cm for scale.

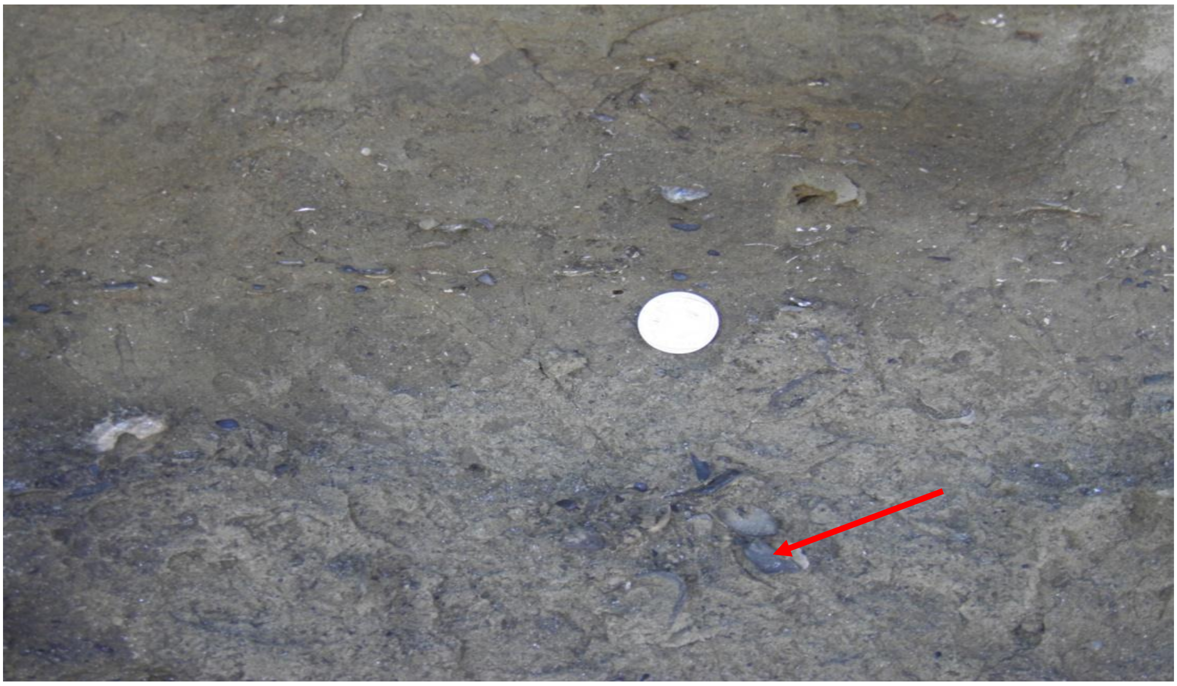


Figure 14: Paratype section mudstone bed (Unit 9), showing very fine shell fragments and some nodules. Isolated pebbles are found in the strata (arrow). A coin for scale is 2.3 cm in diameter.

Figure 15: Lenticular bedded, fine grain conglomerate and pecten bed of the rock Unit 18 (top), and oval shaped calcareous nodule (arrow) encountered in the rock Unit 17 (bottom).

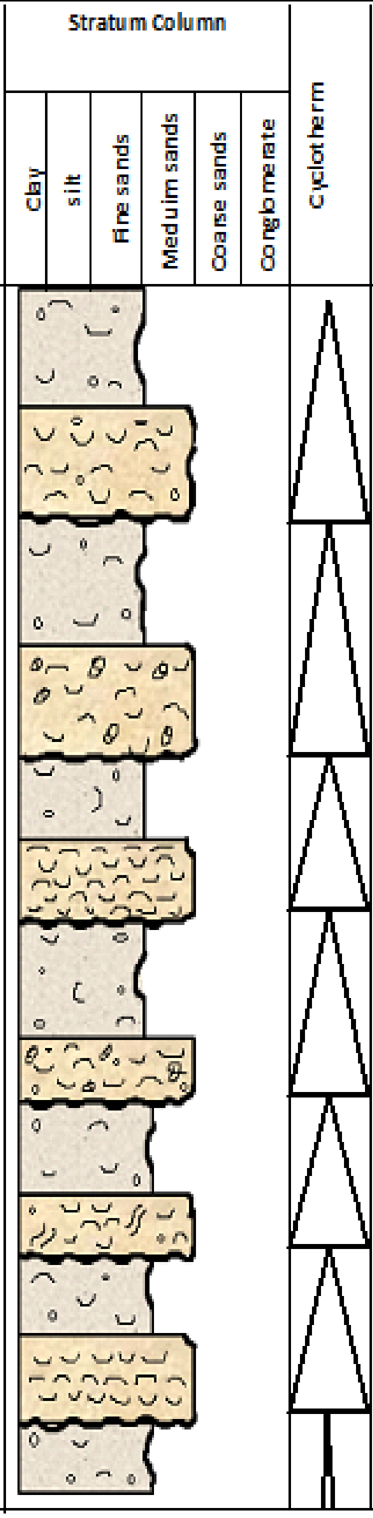
Figure 16: A large broken shell in the pecten bed in the rock Unit 21. Also showing the shell fragments occurring as cluster and are mostly concave upward in the position.

Figure 17: A large ammonite in the Mzamba Formation. The ammonite has been partially dissolved and refilled with muddy-silt material, but the original shape of the ammonite can still be seen.

4.2.3. The third paratype section

A third section was measured at elevation 5m above the sea level, at coordinates 31^{O} 06' 13.4", and 30^{O}10'39.6".

The lower part of the section was measured while the upper part of the section was observed from distance, as it was a cliff, and the accessibility was difficult. A stratigraphic column was produced as below (Figure 18), which can be divided into 45 bed units, and the lithologies, sedimentary structures, fossil contents and other characteristics are list in the figure.



Strata No.	Thickness (m)	Sedimentary Structure	Lithology
45	0.60	Contains lesser shell fragments that are randomly orientated.	Fine-grained, highly weathered mudstone bed & is blue-grey in colour.
44	0.52	Rich in shell fragments that are clustered & well preserved.	Medium-grained, brownish-coloured pecten bed.
43	0.73	Has articulated shell fragments & some nodules.	Thick-bedded, fine-grained ,greyish mudstone bed.
42	0.50	Very rich in shell fragments that are aligned parallel to bedding.	Medium- grained, light in colour, hard pecten bed.
41	0.48	Contains small pebbles & scattered shell fragments.	Fine-grained, greenish coloured soft mudstone bed.
40	0.50	Concentrated in shell fragments of different sizes.	Light coloured, medium-grained pectin bed.
39	0.70	Thin scale of shell fragments that are convex up, iron nodules are present.	Very fine-grained, dark coloured mudstone bed.
38	0.40	Full of well-preserved shell fragments, small pebbles.	Medium-grained, hard, brownish pecten bed.
37	0.60	Has fine shell fragments setting in matrix.	Dark coloured, fine-grained mudstone bed.
36	0.30	Has lots of burrows, shells are convex up, pebbles are found.	Medium-grained, buff coloured pecten bed.
35	0.45	Small to medium-sized shell fragments.	Soft, bluish coloured, fine-grained mudstone bed.
34	0.50	Rich in gastopoda, oyster & bivalve fossils.	Thin bedded, medium-grained pecten bed.
33	0.40	Dispersed shell fragments & nodules are found.	Greyish-blue, fine-grained mudstone bed.

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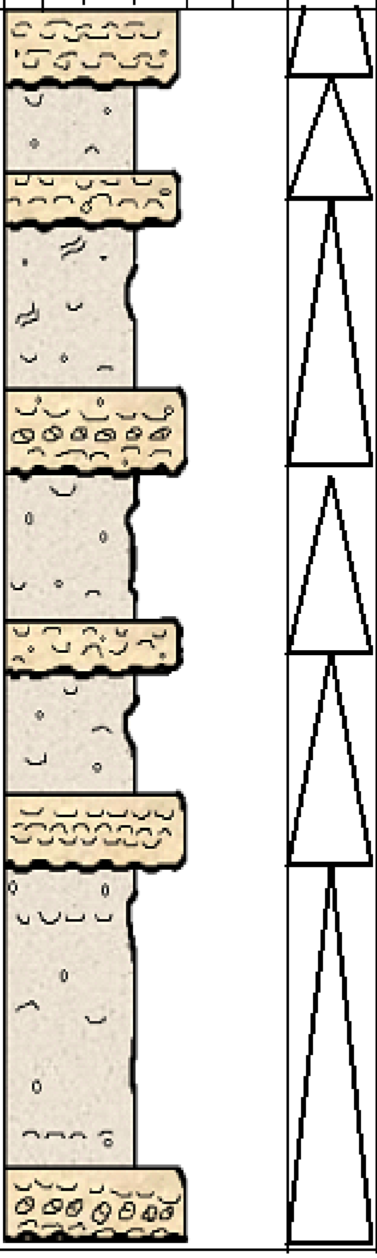
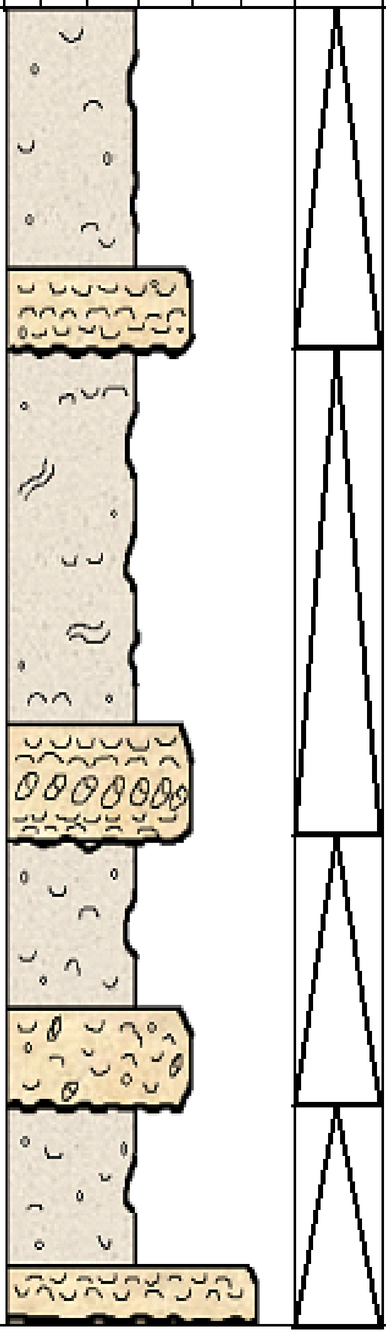


Strata No.	Stratum Column						Cyclotherm	Thickness (m)	Sedimentary Structure	Lithology
	Clay	silt	Fine sandstone	Meduim sand	Coarse sand	Conglomerate				
32								0.35	Very rich in shell fragments that are clustered.	Medium-grained, light coloured pecten bed.
31								0.41	Contains calcareous nodules, small scale shell fragments.	Fine-grained, greyish, calcareous mudstone bed.
30								0.30	Concentrated in shell fragments.	Fully cemented, medium-grained, hard pecten bed.
29								0.70	Contains some burrows that are parallel to bedding, lenticular shell fragments that are scattered unevenly.	Fine-grained, dark coloured, calcareous mudstone bed.
28								0.40	Rich in clustered bivalve, gastropoda & oyster fossils.	Brownish, hard, medium to coarse-grained pecten bed.
27								0.70	Contains dispersed shell fragments, iron nodules are present.	Greyish, fine-grained, very soft mudstone bed.
26								0.30	Concentrated in shell fragments.	Soft, medium-grained, pecten bed.
25								0.55	Has some pebbles, smaller scale shells.	Greyish-blue, fine-grained mudstone bed.
24								0.31	Full of shell fragments that are clustered.	Well cemented, hard, buff coloured pecten bed.
23								1.48	Contains dispersed shell fragments, and a layer of smaller sized shells. Small nodules are present.	Fine-grained, grey mudstone bed.
22								0.48	Rich in well preserved fossils such as bivalves & gastropods.	Hard, buff coloured pecten bed.

(Continue next page)

Strata No.	Stratum Column (Clay, silt, Fine sandstone, Meduim sand, Coarse sand, Conglomerate)	Cyclotherm	Thickness (m)	Sedimentary Structure	Lithology
21			0.72	Contains smaller sized shell fragments that are dispersed throughout the unit.	Bluish-grey, soft, fine-grained mudstone bed.
20			0.49	Rich in shell fragments that are convex up.	Light-brown, medium-grained pecten bed.
19			1.48	It contains dispersed shell fragments, iron nodules and horizontal burrows.	Dark/black coloured, very fine-grained mudstone bed.
18			0.52	Rich in clustered shell fragments that are aligned parallel to bedding.	Hard, light-coloured, medium grained pecten bed.
17			0.55	Contains shell fragments that are unevenly distributed.	Grey-green, fine-grained mudstone bed.
16			0.31	Has fossils such as oyster, gastropoda & bivalves.	Brownish coloured pecten bed.
15			0.56	Contains scattered shell fragments & some chert pebbles.	Fine-grained mudstone bed, light coloured due to weathering.
14			0.11	Thin layer of clustered shell fragments.	Hard, buff coloured pecten bed.

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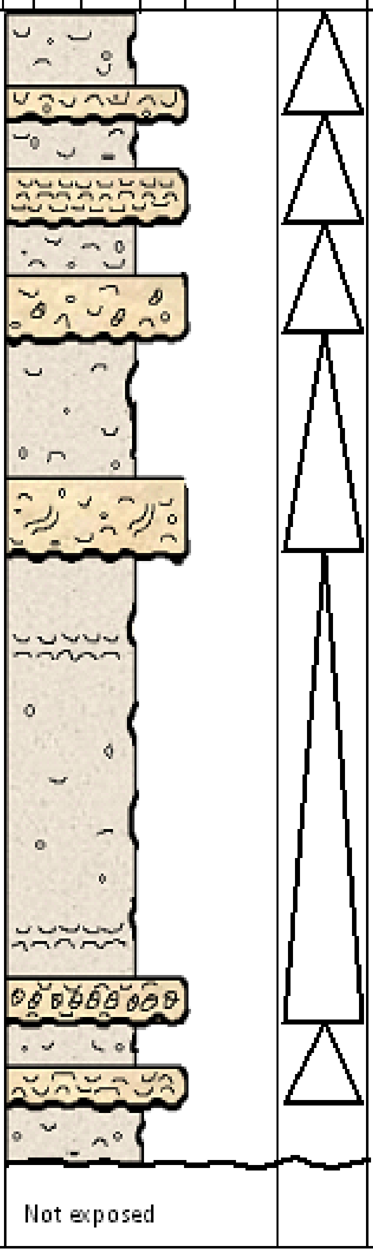


Strata No.	Stratum Column (Clay, Silt, Fine sandstone, Meduim sand, Coarse sand, Conglomerate)	Cyclothem	Thickness (m)	Sedimentary Structure	Lithology
13			0.45	Contains lesser shells, has small iron nodules.	Greyish, soft, fine-grained mudstone bed.
12			0.10	Rich in shell fragments.	Thin bedded pecten unit.
11			0.25	Contains unevenly distributed shell fragments.	Fine-grained, light coloured mudstone bed.
10			0.27	Concentrated in shell well preserved fragments.	Hard, medium-grained pecten bed.
9			0.20	Contains shells & small pebbles.	Dark coloured, fine-grained mudstone bed.
8			0.25	Rich in convex-up shells & small sized nodules.	Light, hard, pecten bed.
7			0.59	Dispersed shell fragments throughout the unit, with some nodules.	Grey-greenish, very fine-grained, soft mudstone bed.
6			0.26	Vertical burrows, fossiliferous, with small sized iron nodules.	Well cemented, hard, brownish pecten bed.
5			2.1	Contains smaller sized shell fragments, which are concentrated horizontally at the top of the unit & at the bottom of the unit. Pebbles are also present.	Dark coloured, fine to medium-grained mudstone bed.
4			0.13	Full of gastropods, & bivalves.	Light, hard, pecten bed.
3			0.10	Has preserved shell fragments.	Fine, dark mudstone bed.
2			0.10	Rich in shell fragments.	Medium-grained, light pecten bed.
1			0.18		Dark/black, fine mudstone bed.

Figure 18: The 3rd stratigraphic paratype section of the Mzamba Formation at the south of the Mzamba River.

Figure 19: Longest measured section of the Mzamba Formation, the cliff is about 12m in height. Note the vegetation covering the top exposure.

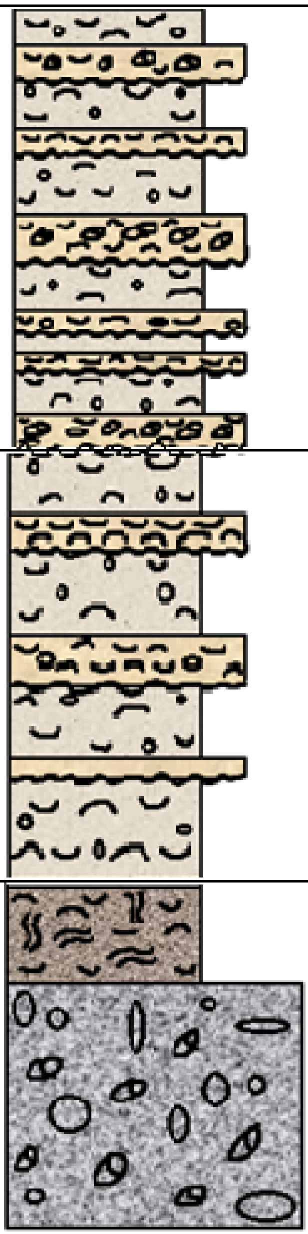
Formation	Member	Bed No	Stratigraphic column	Cycles	Thickness (m)	Sedimentary Structure and Lithology	Depositional Environment
MZAMBA	UPPER	48 TO 22			17.9	Mudstone bed articulated with pecten bed. The mudstone bed with the underlying rock forms an upward fining-up sequence. The contact between the units is erosional bottom contacts. Some iron nodules are found	Low-energy quiet environments. Continental shelf.
	MIDDLE	21 TO 3			9.5	Mudstone bed articulated with pecten bed. The mudstone is very fine-grained, has vertical and horizontal burrows, and contains smaller sized shell fragments. The pecten bed is hard, medium to coarse-grained, rich in fossils such as bivalve, sponge, gastropods and oysters.	Low-energy quiet water environments. Deep waters, continental shelf.
	LOWER	2			0.10	Sandstone bed, soft, fine-grained. Heavily bioturbated, with well-developed burrows. Parallel bedding & fossiliferous.	Shallow marine environment.
		1			2.55	Pebbly conglomerate bed, with randomly orientated pebbles. The pebbles vary in size between 1-10cm. Has well-preserved fossils of gastopoda, bivalve ,oyster & silicified wood.	High-energy shallow waters.

Figure 20: Integrated stratigraphy of the Mzamba Formation, which can be divided into three members, and each member constitutes a fining upward cycle.

Key for Stratigraphy Columns

EROSIONAL SURFACE

BIOTURBATION

FOSSILS

FINING-UPWARDS SEQUENCE

PEBBLES

PECTEN BED

CONGLOMERATE

MUDSTONE BED

SANDSTONE BED

Based on the above four stratigraphic sections (Figures 9, 12, 18 & 20), the Mzamba Formation can be divided into three members, i.e. the Lower Conglomerate Member, Middle Silt/mudstone-Shell Bed Member and Upper Mudstone-Shell Bed Member. The total thickness of the formation was measured as 31.26m in an inland borehole and 30.05m in the field outcrops. The Lower Conglomerate Member is 2.65m thick and consists of pebbly conglomerate with coarse sandstone, shell fragments and silicified wood trunks, representing shallow marine nearshore deposits. The Middle Silt/Mudstone and Shell Bed Member is 9.5 m thick and consists of black mudstone, fine-grained siltstone alternated with medium grained pecten beds, which was deposited in a storm influenced deeper marine environment. The Upper Mudstone-Shell Bed Member is 17.9m thick and is made up of fine-mudstones with articulated pecten layers which were deposited in a deep and quiet marine environment.

CHAPTER 5 SEDIMENTARY PETROLOGY

5.1. Introduction

Mzamba Formation consists of mixed deposits of both carbonate and siliciclastic rocks. Carbonate rocks are defined as containing more than 50% of carbonate minerals, among which calcite and dolomite minerals are predominated. The term limestone is used for those rocks in which the carbonate fraction is composed primarily of calcite, whereas the term dolomite is applied to both rock name and also mineral name. Considering the rock of dolomite, this is composed primarily of the mineral dolomite (Carozzi, 1960). Calcite is the stable form of calcium carbonate mineral in normal temperature environments, and may be regarded as the principal mineral of limestones. The other carbonate minerals that can be present are aragonite, siderite, and magnesite but they are minor minerals and less important than calcite and dolomite. The carbonate minerals in general include aragonite, calcite, cerussite, dolomite, magnesite, malachite, rhodochrosite, siderite, smithsonite and witherite. Limestones, which represent the final indurated product of carbonate sediments, range from the Precambrian to Present (Carozzi, 1993). Their petrographic study reveals the evolution and extinction of numerous marine organisms, which either precipitated calcium carbonate from sea water or secreted carbonate skeletons, which upon death of their respective organisms, released skeletal particles, bioclasts of greatly variable shape and sizes.

Petrographical analysis was conducted by light microscopy and SEM techniques, to study the texture, grain size, porosity and the mineralogy. The slides were stained with Alizarin Red S, which is a chemical solution and can stain calcite to red whereas dolomite has no colour change, thus can be used to distinguish dolomite from calcite. Grain size is a useful basis for subdividing clastic rocks and limestones and for their classification according to the dominating allochem. 50 thin sections were analysed and major constituent minerals were quantified for each sample.

5.2. Observations in thin-sections

5.2.1. Grain Size

Grain size is a basic descriptive measure of sediments. Grain-size distribution patterns may be characteristic of sediments deposited in certain environments and can yield information about depositional processes and hydrodynamic conditions. In turn, they are a major control factor on porosity and permeability (Flügel et al., 2010). The grain size determination was based on Folk's carbonate classification; this is because Mzamba sediments consist of allochem framework grains. The sediments also consist of a mixture of micrite and sparite cements. Carbonate grains can be broadly divided into two types, skeletal (gastropodas, molluscs) and non-skeletal grains (ooids, peloids, intraclasts).

5.2.2. Mineralogy

Limestones and dolomite, the principal calcareous rocks are composed essentially of the lime carbonates calcite and dolomite. Aragonite, siderite and magnesite are other carbonate minerals which may be present, but they are not essential minerals, they are rarely recognized where they are intimately associated with calcite or dolomite. The terrigenous sandstone and mudstone contain mainly quartz and feldspar minerals, whereas the carbonates consist of mainly calcite, with minor quartz, plagioclase, gypsum and rock fragments. Clay minerals such as glauconite, illite and smectite constitute the matrix. Cements include calcite micrite and calcite sparite (discussed in chapter 8, Diagenesis)

5.2.2.1. Quartz

Thin section analysis has revealed that quartz is the most abundant mineral, as it contributes the vast of the rock volume. Quartz appears colourless, with low relief and low interference colours when viewed under the microscope. The grains show undulatory extinction when the stage is rotated, which indicates the source of the quartz mineral was from metamorphic rocks, probably from the bottom and surrounding area of Natal Metamorphic Belt. Quartz grains vary from angular to rounded, showing various energy levels of transportation affecting the quartz grains prior to being dumped into the relatively low-energy carbonate environment.

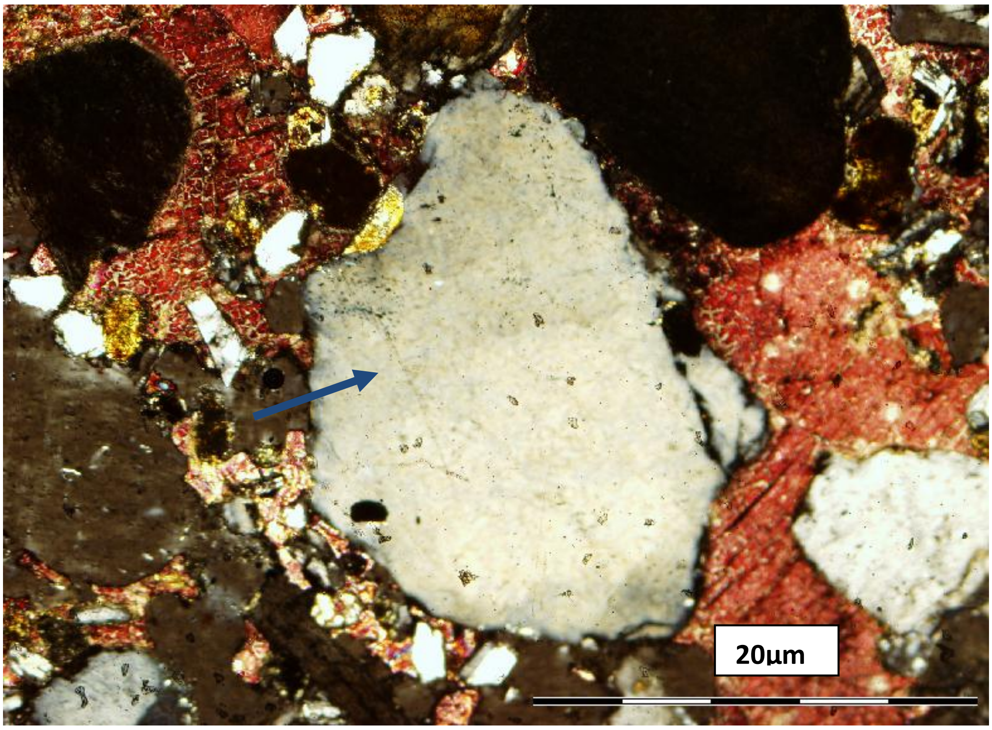


Figure 21: Photomicrograph of Unit 2 (type section). Monocrystaline quartz grain (arrow) in calcareous sandstone, with calcite as the cement (red). The whole scale (5 gradients) is 20 µm, the scale in all the other photomicrographs below is the same.

5.2.2.2. Plagioclase

Plagioclase is also an abundant mineral, but not as much as quartz. Plagioclase shows weak birefringence, exhibits twinning under the microscope. Most of the plagioclase is coarse grained and exhibit the distinct polysynthetic twinning and are sub-angular to subrounded in shape. Plagioclase occurs dominantly as detrital grains.

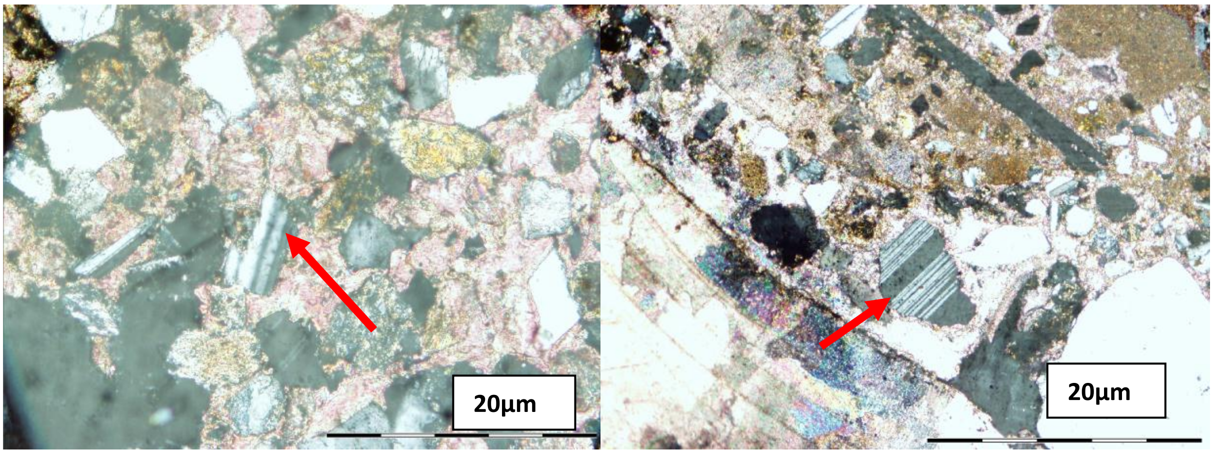


Figure 22: Photomicrograph of Unit 13 (type section). Plagioclase grains with cleavage twinning (arrows).

5.2.2.3. Gypsum

Gypsum in these sediments occurs as an authigenic mineral. It is colourless, has low birefringence, and shows weak interference colours similar to quartz. Gypsum exhibits cleavage and it still maintains its original flake shape, which is euhedral and needle-like. Gypsum occurs as a minor mineral in rock and it occurs in small sizes.

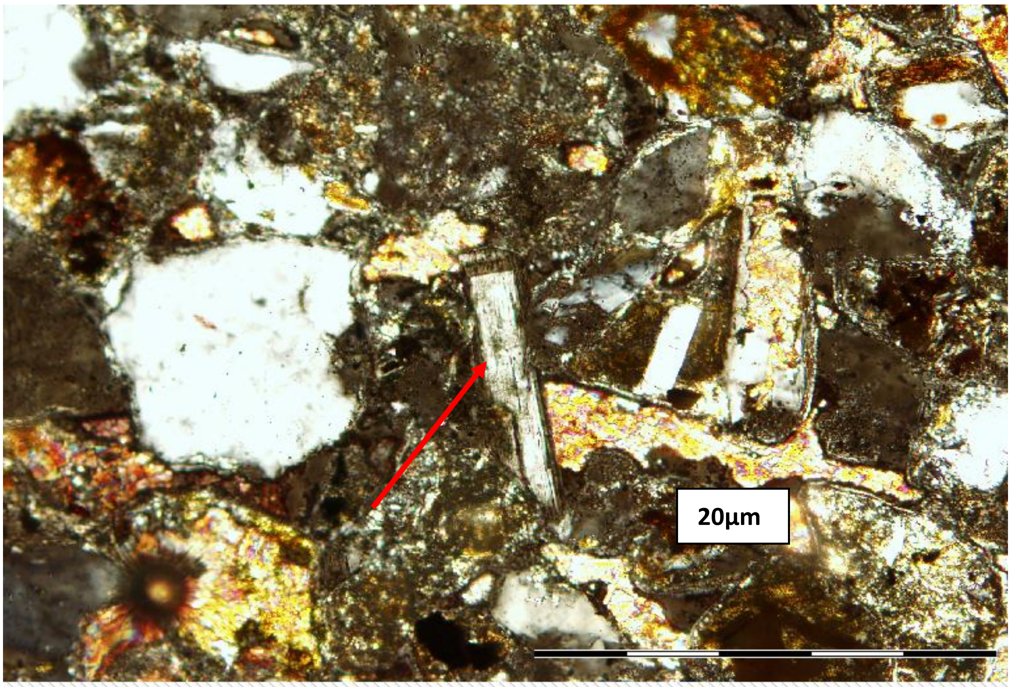


Figure 23: Photomicrograph of Unit 1 (paratype section). Gypsum showing its euhedral shape (arrow).

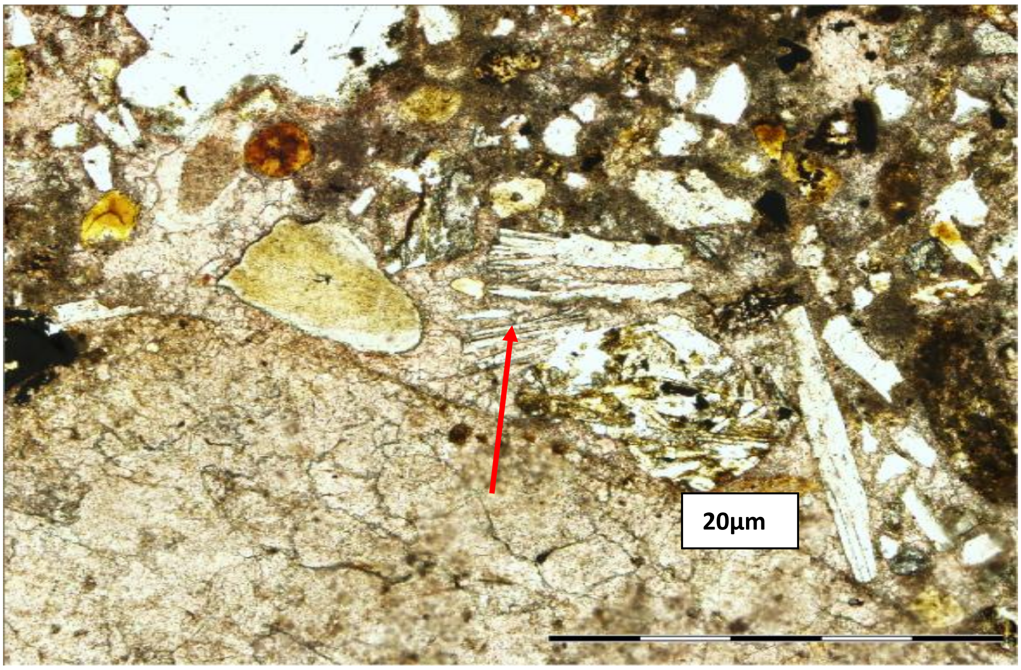


Figure 24: Photomicrograph of Unit 1 (paratype section). Gypsum showing euhedral flakes in shape (arrow).

5.2.2.4. Vitrinite

Vitrinite is one of the primary components of coals and sedimentary kerogen. It is a type of maceral, a common constituent of organic source rocks. Vitrinite forms diagenetically by thermal alteration of lignin and cellulose in plant cells. This means that it is common in sedimentary rocks that are rich in organic matters. But carbonate rocks generally contain very low vitrinite composition. In our slides, vitrinite appears as sub-rounded to well-rounded granules, bright red or pinkish pellets. It is not abundant in the Mzamba sediments, as it is found only in few slides. Vitrinite is formed during burial diagenetic process due to temperature increase with the increase burial depth.

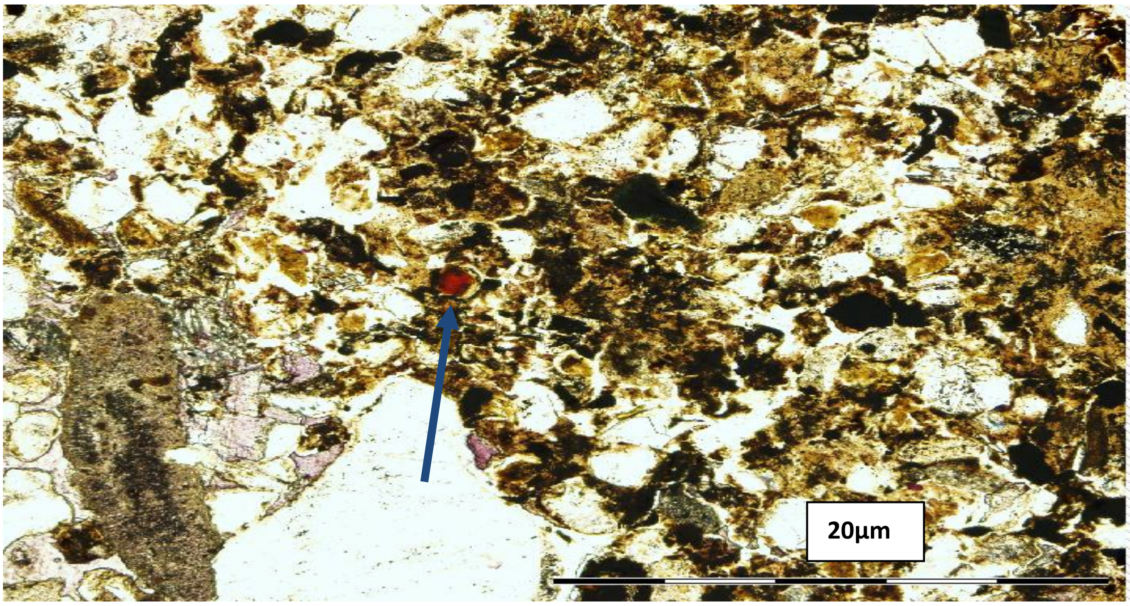


Figure 25: Photomicrograph of Unit 2 (type section), containing pinkish vitrinite pellet (middle, arrow).

5.2.2.5. Glauconite

Glauconite is a hydrous potassium aluminium silicate containing both ferrous and ferric iron and some magnesium. It is a typical sedimentary mineral, formed in shallow marine environment through authigenetic alteration. It usually occurs as green sand-size pellets, which are microcrystalline and have a generally low birefringence. This is a highly informative mineral type, it is green, round and small in size and is scattered throughout the slide. The mineral is very fine, has faint pleochroism and an outline that remains more or less ovoid.

Fresh glauconite pellets are bright green, where it is exposed to weathering it appears brownish. The green colour of the mineral is one of the most distinctive properties. It is easily observable because of its brightness. This mineral is strictly marine in origin and indicates shallow marine environment. Similar to any other authigenic mineral, glauconite may be transported from its original burial place and incorporated in sediments elsewhere. Because the mineral is readily weathered, it is unlikely to survive strong erosion and long distance transportation, and therefore glauconite usually occurs in the close areas to its original environment and thus a good palaeo-environmental indicator. Most of the glauconite observed are unstable and are easy to be weathered if exposed on the Earth's surface.

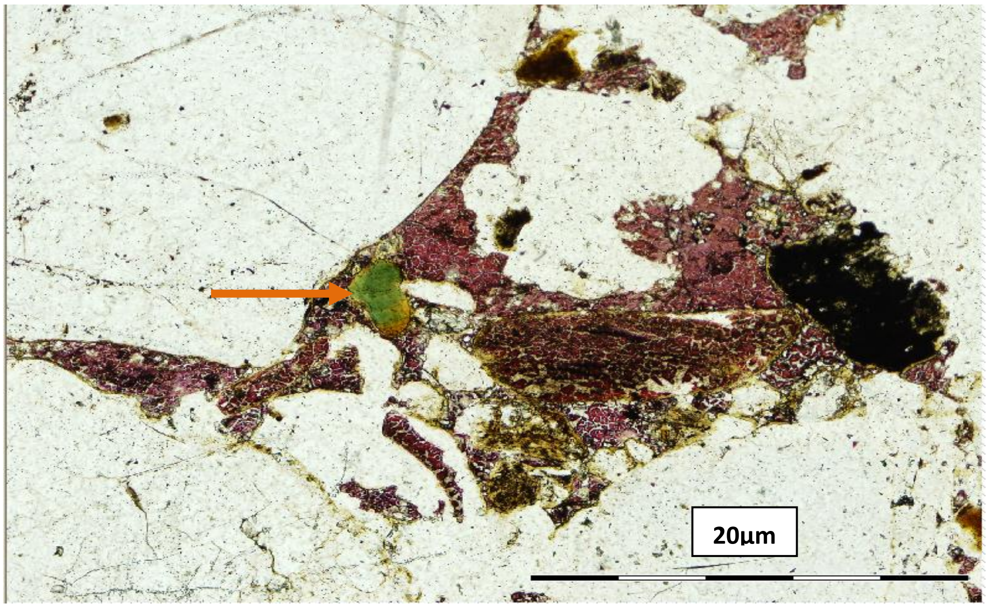


Figure 26: Photomicrograph of Unit 1 at the base, showing grey-greenish glauconite pellet (arrow).

5.2.3. Lithics

Lithic means rock fragment and all mechanically broken pieces of pre-existing rocks. Lithic fragments can be derived from sedimentary, igneous or metamorphic rocks. Rock fragments could be very useful in provenance studies, because they carry all the chemical, mineral, isotope and texture signatures of the parent rocks and can provide useful information on the provenance analysis. Some rock fragments, like the argillaceous ones are intra-basinal, therefore cautionary measures need to be taken when using them for provenance studies.

<u>Types of lithic fragments</u>

Lithics in the Mzamba Formation can be divided into two types, i.e. Igneous and Sedimentary rock types. The lithic fragments vary in size, also differs in shape, some are sub-angular to sub-rounded, and some are well-rounded due to different distance of transportation and erosion. The overall percentage of lithics in the limestone is <5%.

Siltstone rock fragment: This one appears as dark coloured, fine-grained, with small to slightly large quartz grains. They occur as varying shapes and orientations, with the majority being angular.

Mudstone rock fragment: This one occurs as bright, brownish, and very-fine-grained fragments. They contain tiny quartz grains inside, the majority of the fragments occur as sub-rounded to well-rounded in shape.

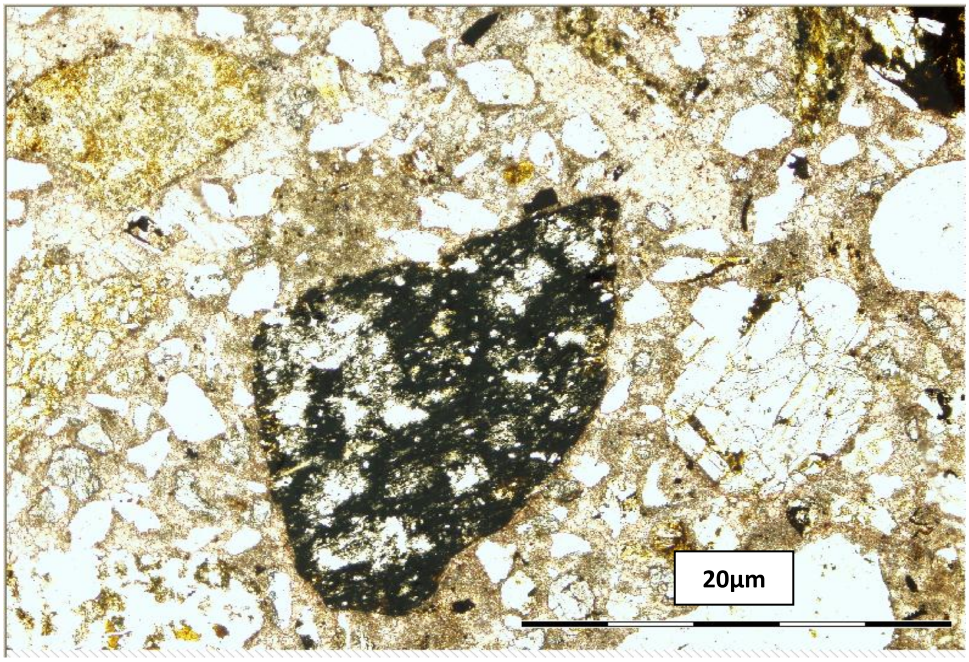


Figure 27: Photomicrograph of Unit 3 (type section). Siltstone rock fragments (dark) with quartz grains inside (white points).

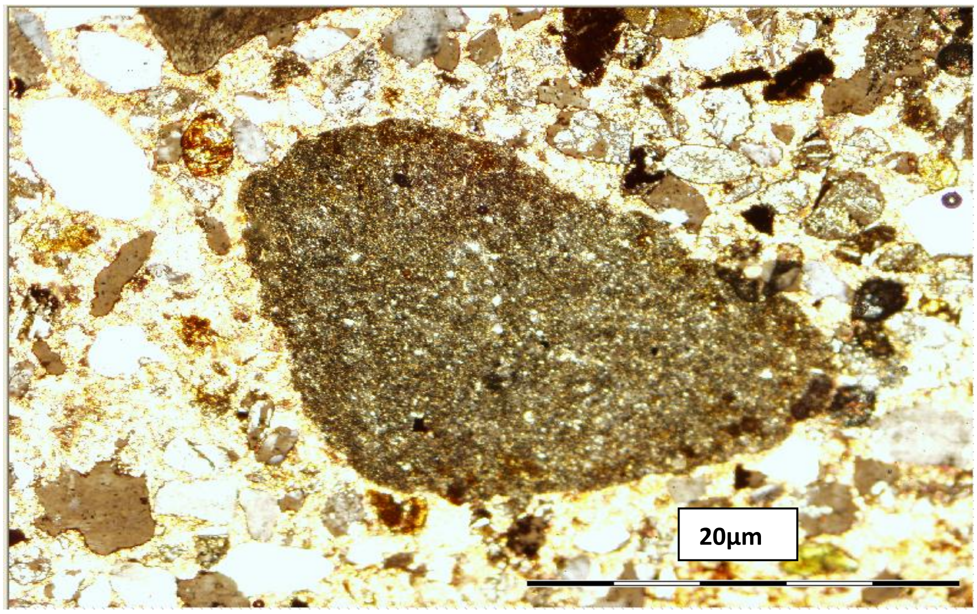


Figure 28: Photomicrograph of Unit 2 (type section). Mudstone rock fragment (middle), with small quartz grains inside (white).

5.2.4. Matrix

The matrix consists of either fine-grained carbonate mud or micrite of which the micrite results from recrystallization of mud during diagenesis. The matrix of most limestones consists of dense, fine-grained calcite crystals, known as micrite. The crystal size is usually less than 4μm, but a variety of terms have been used to describe the different crystal sizes. For most sedimentological purposes the term matrix is used to describe the component under 62μm in size, which normally corresponds to the usage of mud in descriptions of modern sediments (Tucker & Wright, 1990). The micrite is dull-looking with unclear crystals and is prone to aggrading recrystallization. If the rock consists mostly of fine-grained mud matrix, it implies deposition in a low energy environment since the fine mud material is still survived and hasn't been washed out, therefore, low-water energy environment.

Table 1: Classification of crystalline sizes for limestones and dolomite (extracted from Tucker & Wright, 1990).

Extremely Coarsely Crystalline	>4mm
Very Coarsely Crystalline	1-4mm
Coarsely Crystalline	1mm-250μm
Medium Crystalline	62-250μm
Finely Crystalline	16-62μm
Very Finely Crystalline	16-4μm
Aphanitic or Cryptocrystalline	1-4μm

5.2.5. Allochems

This refers to sediments formed by chemical or biochemical precipitation within a depositional basin; includes intraclasts, oolites, fossils and pellets. Oolites are mainly available in ancient marine limestones. They form in a wide variety of environments, from shallow marine settings to lagoons, lakes, rivers, caves and even calcareous soils. They have no direct environmental significance beyond indicating formation in a setting where calcium carbonate was available (Tucker & Wright, 1990).

The carbonates in Mzamba formation are rich in allochems, indicating marine environments in low energy. Two types of pellets are found, (1) organic pellets that are black/dark, that exhibit no internal structure with varying sizes, and (2) faecal pellets that have a clear internal structure and are sparsely distributed in the slides. Ooliths (small) exhibiting concentric / radial internal structure, some even contain quartz as a nucleus. Some ooliths encountered look broken.

5.3. Sorting

Sorting describes the distribution of grain size of sediments. The degree of sorting may indicate the energy, rate and duration of deposition, as well as the transport process. Microscopic observations show the sediments are moderately sorted to well-sorted, which show that the sediments travelled quite a distance before deposition and the environment was a quiet water depositional environment.

5.4. Porosity

Porosity of a rock is the ratio of pore volume to its total rock volume and is given in percentages (Tucker, 1990). The holes in the limestones make the rock so important in hydrocarbon exploration. Half or more of the world's petroleum is produced from carbonate reservoir rocks. The importance of a carbonate reservoir really depends more on its porosity and permeability, which is the features that controls the recovery of hydrocarbons. Some rocks are porous but have low permeability; therefore, it is the effective porosity which is important. Porosity is prone to error during estimation, especially if the point counting technique is employed.

It is said that porosity in limestones is rather different from that in sandstones. It is generally much lower than in sandstone reservoirs. Most porosity in limestone is said to be diagenetic in origin. It is important to understand which type of porosity is represented in that particular limestone, as there is a variety of porosity types. The size and the shape of pores in carbonate sediments are more influenced by skeletal materials, which can be as varied as the assemblages of organisms that create them.

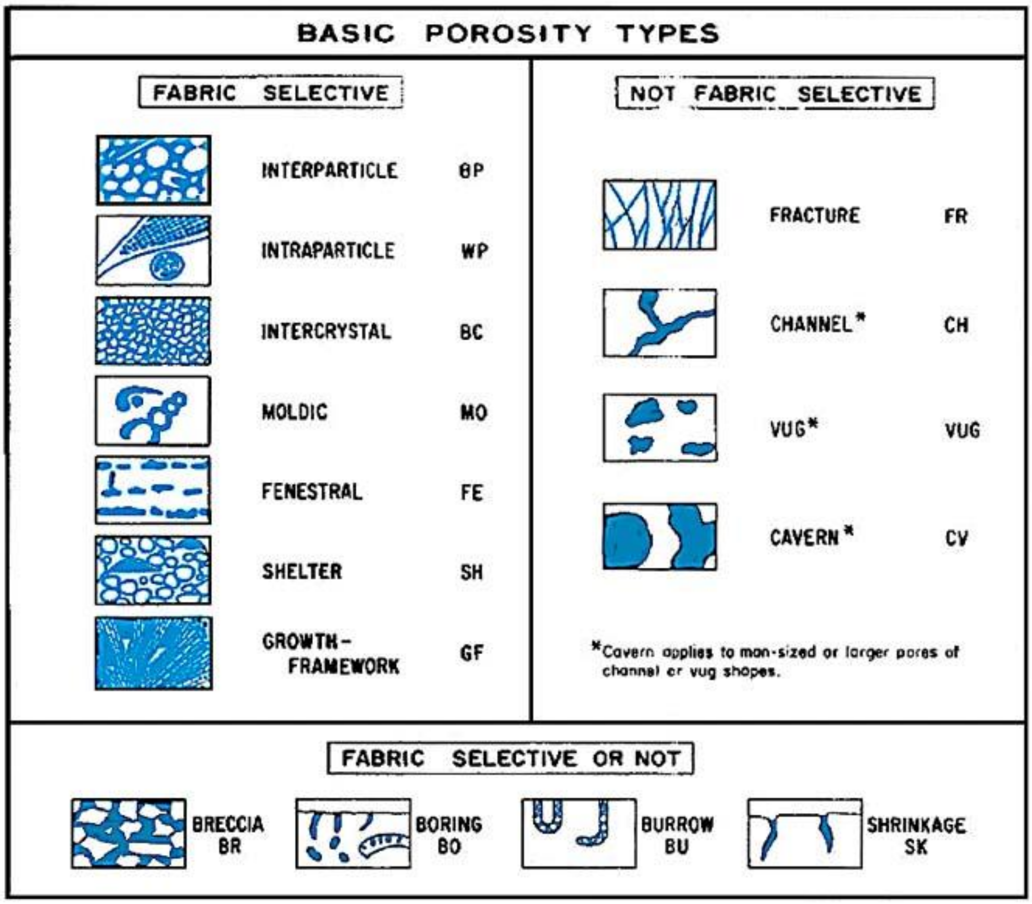


Figure 29: Porosity types based on Choquette & Pray (1970) (from SEPM Strata, 2013).

Most carbonate rocks have primary porosities of as much as 40-45%, and seawater is the first fluid to fill the pores. Filling of primary pores by internal sediments and marine carbonate cements is the first form of diagenesis to take place in this setting, and it leads to significant reductions in porosity.

5.5. Maturity

It describes the mineral composition and the texture of grains, resulting from different amounts of sediment transportation. Textural maturity is a property that relates to the amount of mechanical energy input on transported sediments through the abrasive power of currents and tides. It is observed in characteristics such as rounding and sorting of grains. The rocks of the Mzamba are generally compositionally mature, as they contain quartz, plagioclase and rock fragments.

Quartz is the most abundant and mature sediment, as it is more uniform in appearance and has similar sizes. The clay minerals are also stable because they are the same size and appearance in every thin section.

5.6. Major Rock Types

The Mzamba Formation consist of different rock types, all forming part of the Mzamba sediments.

5.6.1Terrigeneous Rocks

This refers to sand, mud and gravel weathering products formed at the Earth's surface from exposed pre-existing igneous, metamorphic and sedimentary rocks. In the study area, this refers to mudstones, sandstones and conglomerate rocks that are found. The underlying sedimentary character is the cornerstone for classifying terrigenous rocks, with the grain size of sediments being generally translated into a corresponding rock type. Claystones, siltstones, mudstone (mixed clay and silt), sandstones and conglomerates (gravels) represent the terrigenous rock group.

The classification of a particular rock is partly related to the distribution of its composite grains, therefore, conglomerates and sandstones can be further classified on the basis of mineralogical components.

The Udden-Wentworth grain-size scale used for the objective description of terrigenous sediments and this scheme is regarded as standard. The scale explains in detail the mud and sand fractions. This scheme further extends to particles coarser than boulders.

Table 2: The Udden-Wentworth grain size classification scheme (1922).

Millimeters (mm)		Micrometers (µm)	Phi (φ)	Wentworth size class		Rock type
	4096		-12.0	Boulder	Gravel	Conglomerate/ Breccia
	256		-8.0	Cobble		
	64		-6.0	Pebble		
	4		-2.0	Granule		
	2.00		-1.0	Very coarse sand	Sand	Sandstone
	1.00		0.0	Coarse sand		
1/2	0.50	500	1.0	Medium sand		
1/4	0.25	250	2.0	Fine sand		
1/8	0.125	125	3.0	Very fine sand		
1/16	0.0625	63	4.0	Coarse silt	Silt	Siltstone
1/32	0.031	31	5.0	Medium silt		
1/64	0.0156	15.6	6.0	Fine silt		
1/128	0.0078	7.8	7.0	Very fine silt		
1/256	0.0039	3.9	8.0	Clay	Mud	Claystone
	0.00006	0.06	14.0			

5.6.2Carbonate Rock

The Dunham (1962) classification was used to recognise carbonate rocks, based on the sediment fabric and the presence of any biological binding. The significance of each rock type as regards to energy levels is somehow clear.

Grainstone

This slide is very informative. It is mostly made up of grains, namely bioclasts, ooids and some pellets. The spaces in-between the grains is filled with sparite cement. There is a green grain, glauconite which is marine in origin and is an indicator of reducing environment.

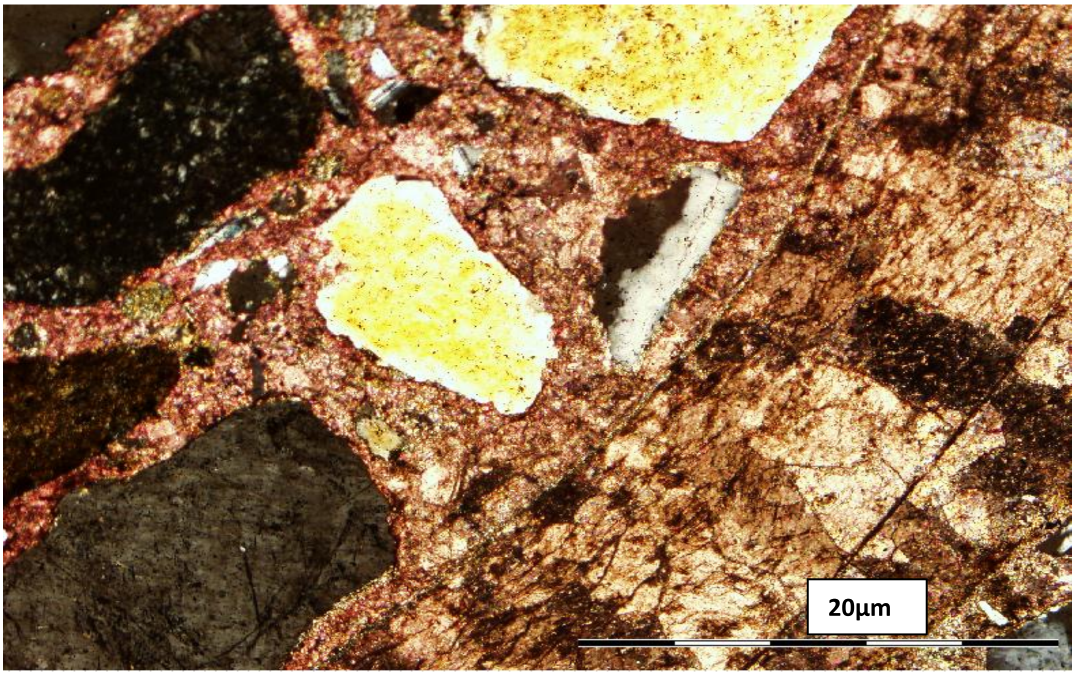


Figure 29: Photomicrograph of Unit 4 (type section). Grainstone with sparite calcite cement.

Packstone

This slide is a limestone in which sparite cement is dominant, but with some micrite found between some grains. The sparite is easily distinguished as it is coarse and has a bright crystalline character. The slide contains curved, wavy and long bioclasts, probably deposited in a relatively high energy environment, lithics (sedimentary) and peloids (organic and faecal pellets) may also present in the bed.

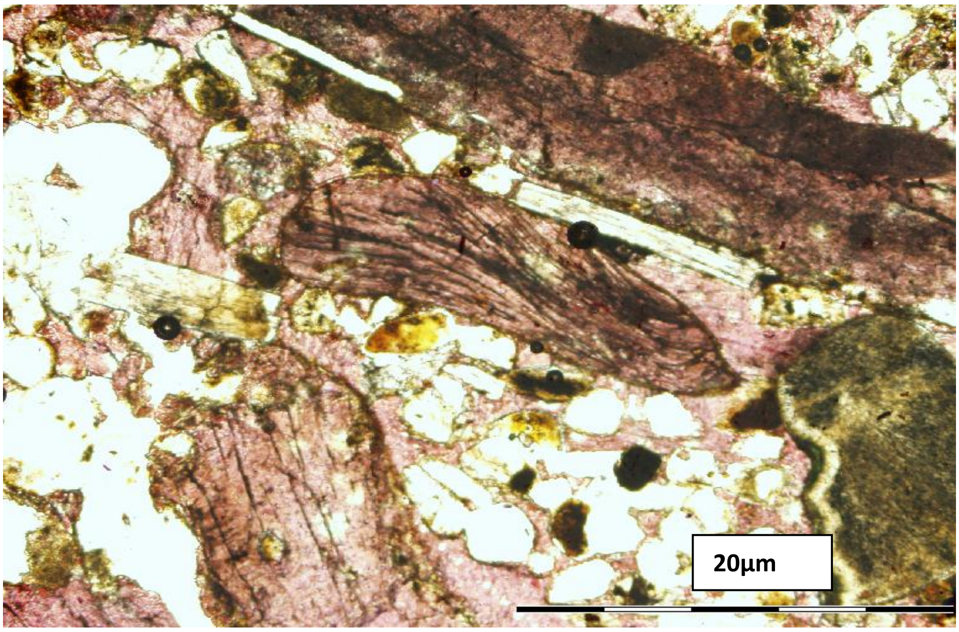


Figure 30: Photomicrograph of Unit 8 (paratype section). Packstone with bioclasts, quartz grains and pellets.

Wackestone

There is a detrital quarts and plagioclase incorporated within fine-grained limestone. The quartz varies from sub-angular to rounded grains, showing different energy levels affecting the quartz prior to it being dumped into the relatively low-energy carbonate environment. The slide contains bioclasts, pellets in micrite cement between the grains.

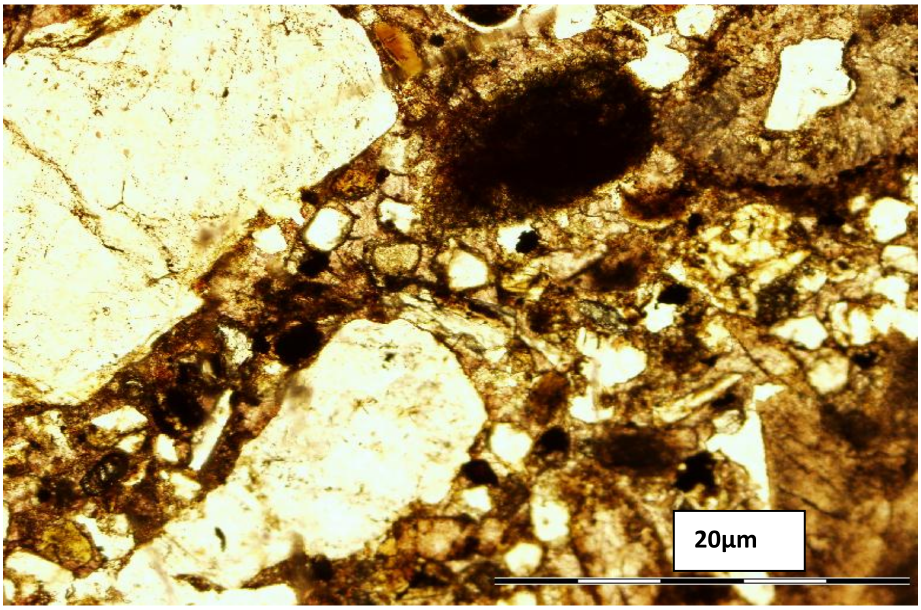


Figure 31: Photomicrograph of Unit 15 (paratype section). Wackestone with bivalve fragments, grains are cemented by micrite.

5.7. LIMESTONE CLASSIFICATION

In the early 1960's, sedimentary petrologists began to realize the necessity for an adequate, practical and relatively simple classification of limestones that will also assist in the application of oil exploration (Carozzi, 1993). Two classification schemes were widely used for carbonate rocks in the world: the Dunham (1964) classification and the Folk (1964, 1965) classification. Both these classifications describe the type of carbonate grains that make up the limestone and both these classifications give a clue to the energy levels during deposition.

5.7.1. Dunham (1962) Classification

Dunham classification is best at describing the composition of calcareous rocks and texture in hand samples. This classification emphasizes texture and it introduced the concept of mud-supported versus grain-supported limestones.

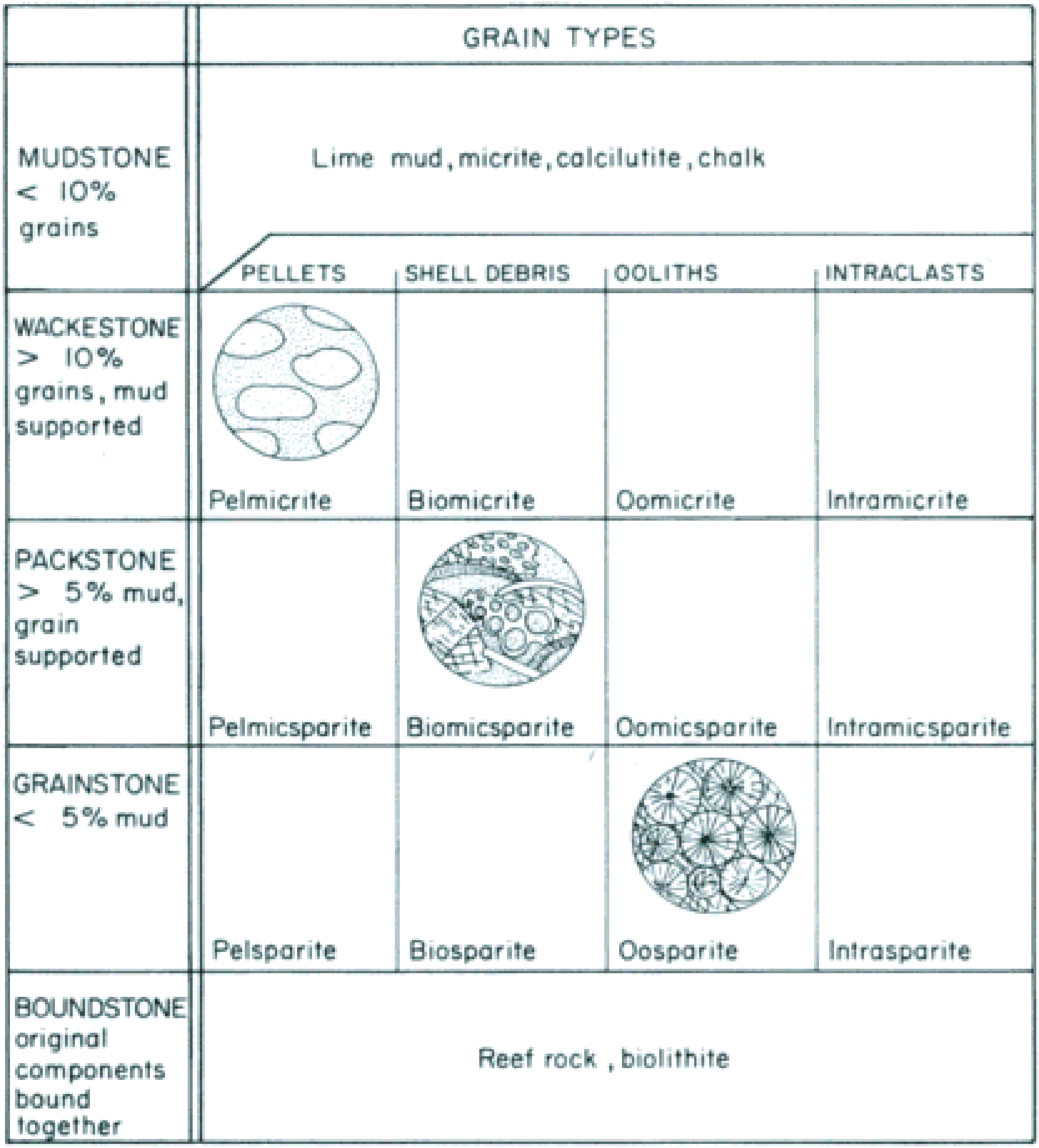


Figure 32: Nomenclature and classification of limestones (Extracted from Selly, 2000).

5.7.2. Folk (1962) Classification

Folk's classification is for thin sections, making both schemes ideal for this specific project. Folk's classification emphasizes mainly composition over texture and is based on three major constituents: allochems (skeletal and non-skeletal grains), carbonate mud matrix known as micrite, and a cement of cavity-filling sparite.

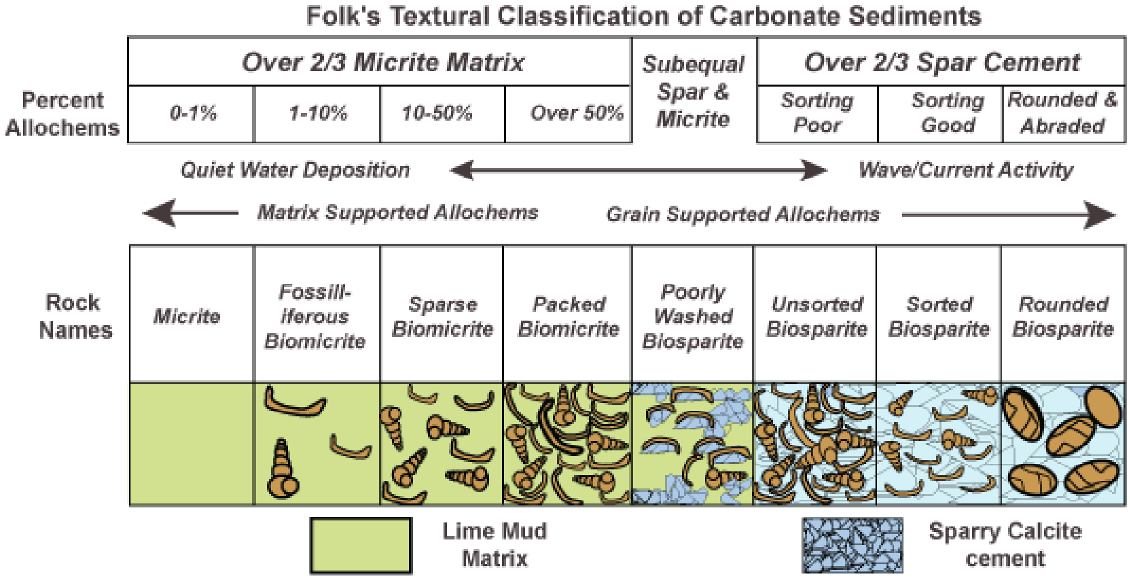


Figure 33: The Folk's Classification Scheme (from Kendall, 2005).

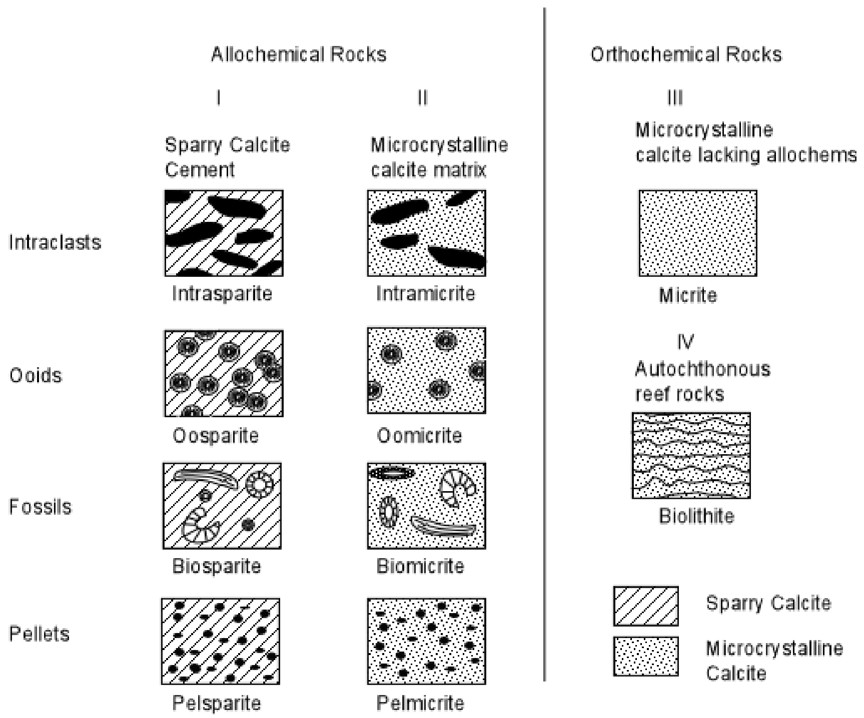


Figure 34: Types of grains and cements of limestone. Four groups of components are recognised (from SEPM Strata, 2013).

5.8. Mineralogy by XRD study

X-ray diffraction is a versatile technique for identifying most minerals, especially clay minerals. The peaks represent the positions where the X-ray beam has been diffracted by the crystal lattice. The set of d-spacing (this refers to the distance between adjacent planes of atoms), which represent the unique fingerprint of the mineral, can be easily calculated from the 2-thetha (2Ø) values shown. Four samples in powder form were sent for XRD analysis, two sandstones and two mudstones from Mzamba Formation. The results confirm the abundance of quartz and feldspar minerals, and the availability of clay minerals such as illite and kaolinite.

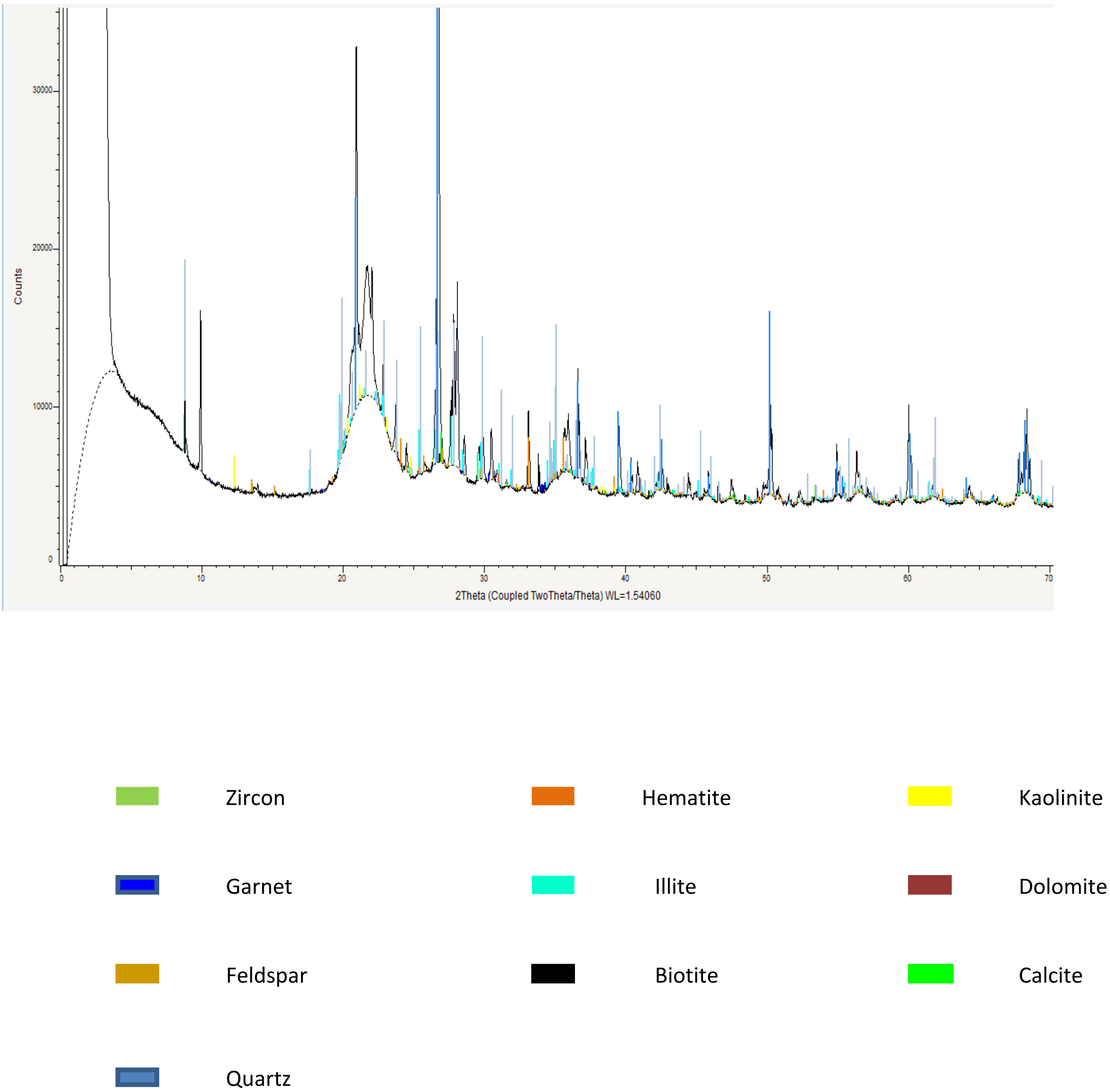


Figure 35: X-ray diffraction pattern of a fine-grained mudstone of the Mzamba Formation.

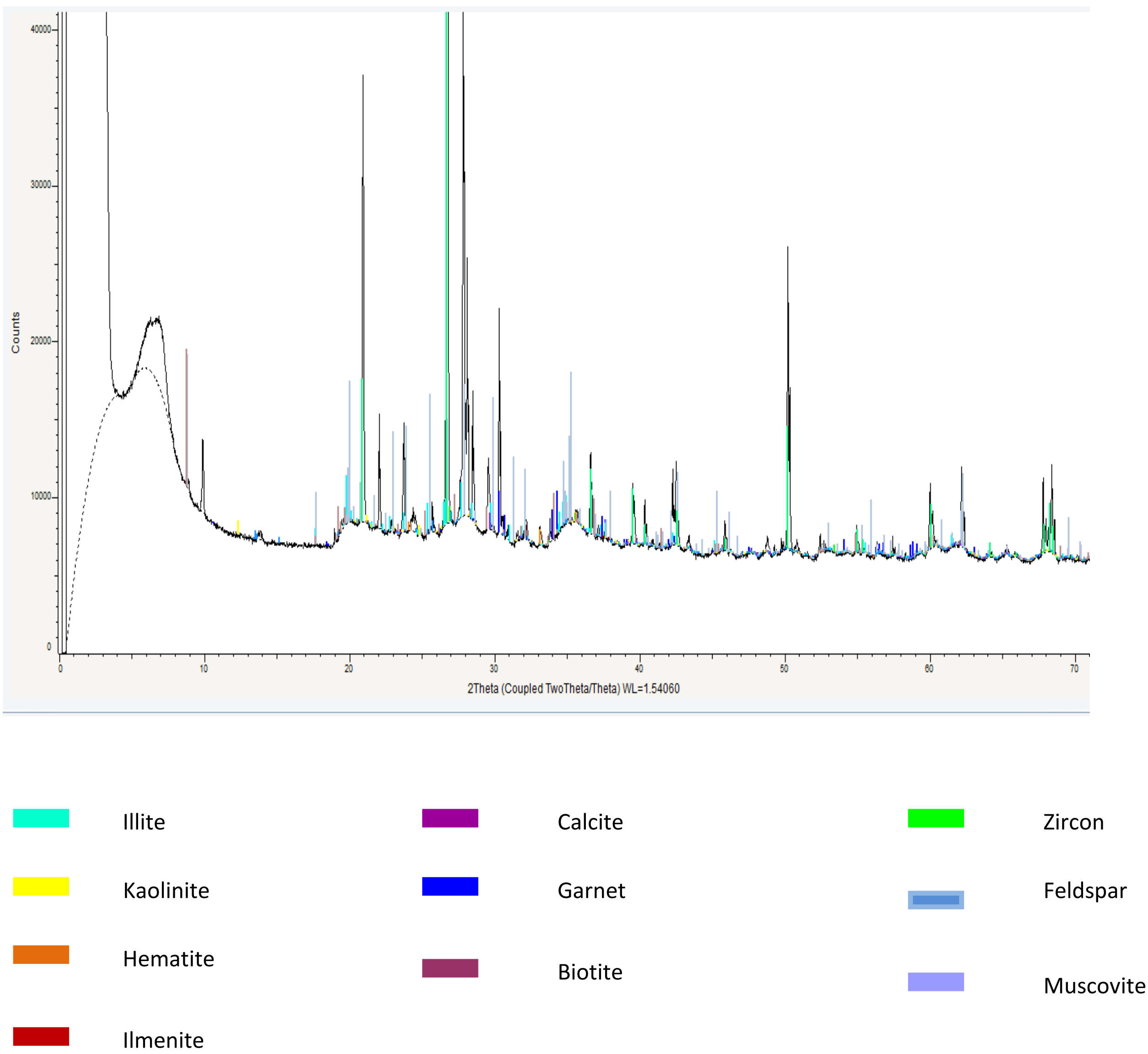
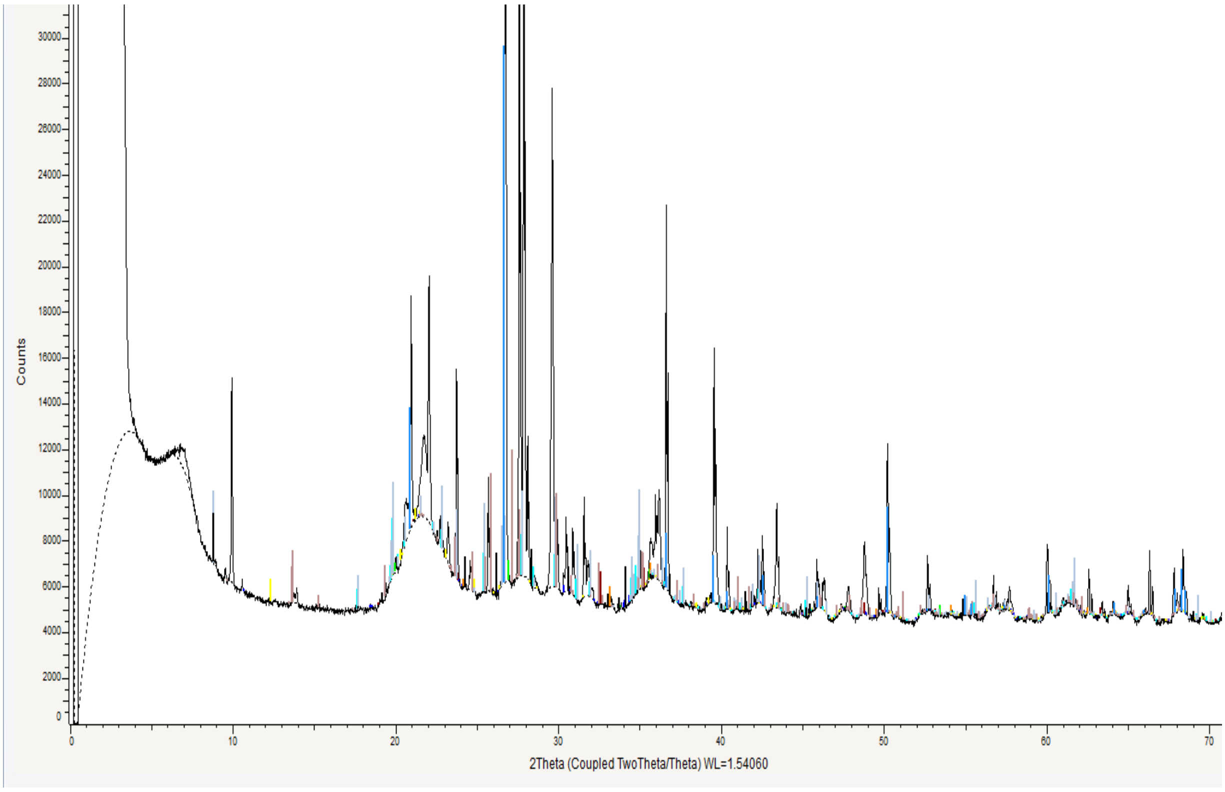


Figure 36: X-ray diffraction pattern of a coarse-grained mudstone of the Mzamba Formation.



Quartz
Kaolinite
Hematite
Illmenite
Illite
Feldspar
Calcite
Muscovite
Garnet

Figure 37: X-ray diffraction pattern of a fine-grained sandstone of the Mzamba Formation.

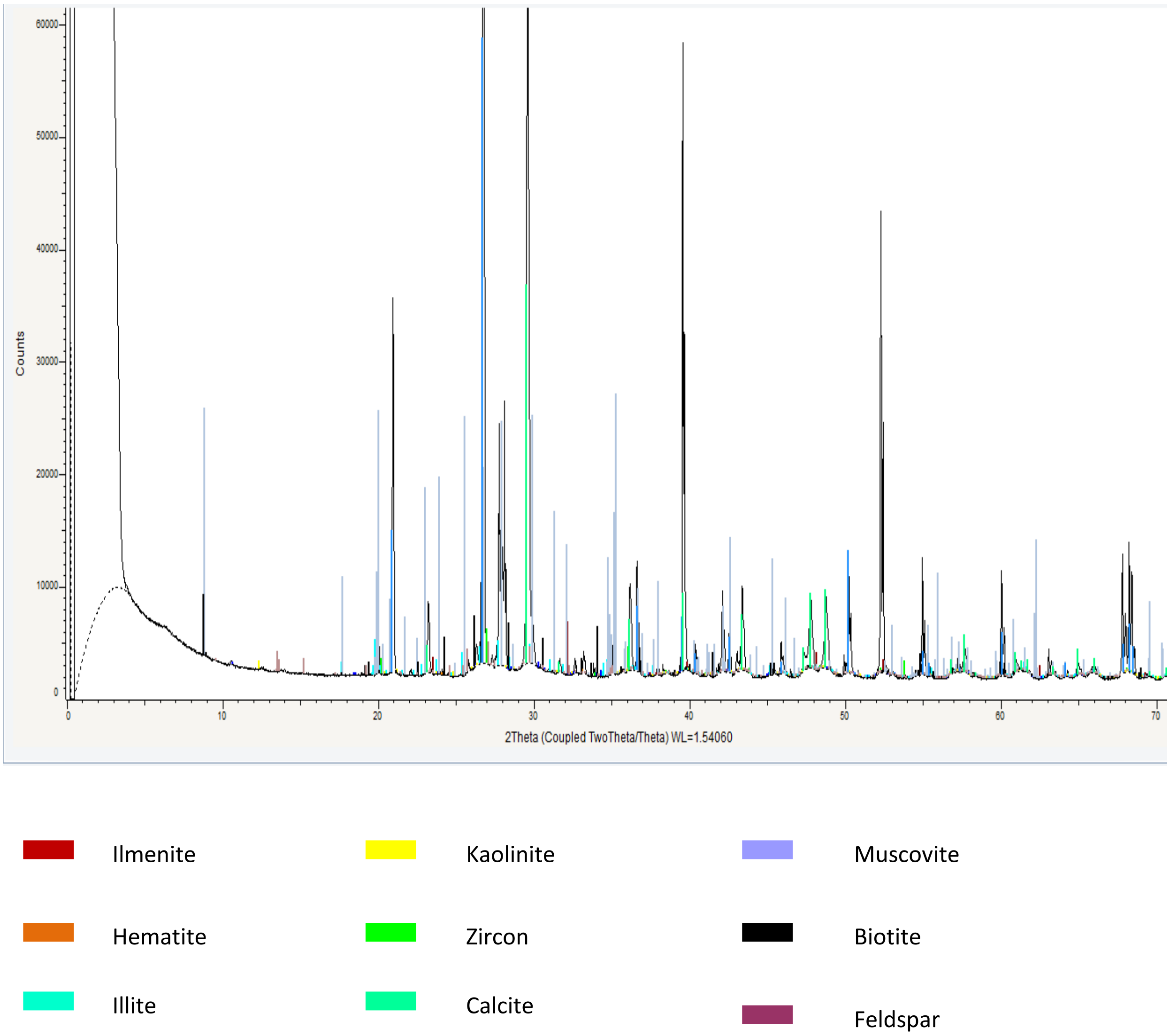


Figure 38: X-ray diffraction pattern of a coarse-grained sandstone of the Mzamba Formation.

5.9. Discussion

Figure 35 shows results of a fine-grained mudstone. The sample contains quartz (23.68%) as the most abundant mineral, making up the grains and cement. Mica, muscovite and biotite (1.27%), and smectite clay (50.26%) are found in the sample. Heavy minerals, which usually aid in provenance studies, including garnet (0.98%) and zircon (0.67%) are found in minute quantities. Other clay minerals such as illite (16.48%) and kaolinite (3.34%) are present, of which illite are the common mineral in the group of clay-minerals. The smectite-illites constitute the dominant minerals of the mudstone and were formed during the original deposition in deep marine environment. The presence of calcite cement is confirmed, which occurs as pore-filling cement.

Figure 36 is a coarse-grained mudstone and is very similar in mineral compositions to the sample of Fig. 38; the difference is in the percentages in compositions. Smectite (47.63%), occurs in large quantities. Heavy minerals of zircon and garnet still occur in very minute quantities. Calcite (28.64%) is found, which confirms it to be the pore-filling cement in the mudstone of the Mzamba Formation.

Figure 37 is fine-grained sandstone. This sample confirms that the most abundant minerals are quartz, feldspar, calcite and clay minerals of illite and kaolinite. Minor quantities of zircon (0.54%) and garnet (1.18%) are found.

Figure 38 represents a coarse-grained sandstone sample. The most abundant mineral appears to be quartz (60.43%) and it constitutes one of the cements, together with calcite. Clay minerals such as illite which occurs as matrix, as well as kaolinite are found in the sample.

CHAPTER 6 SEDIMENTARY FACIES

6.1. Introduction

Facies is a body of rock with specified characteristics. In the case of sedimentary rocks, it is defined on the basis of colour, texture, bedding, fossil content and sedimentary structures (Reading, 1978). Ideally, a facies is a distinctive rock unit that forms under certain conditions of sedimentation, reflecting a particular depositional process or environment. Facies is a term applicable to every distinguishable sedimentary record of a depositional environment. It is then important to know that the word facies covers both the lithological and the biologic features of every observed sedimentary rock, to note that facies follow one another in vertical sequence everywhere. The majority of sedimentary formations comprise several facies which occur in sequence or are interbedded (Longwell, 1948). Thus, facies can be classified as two major groups, if it based on petrological characteristics such as mineral composition and grain size is called lithofacies, whereas based on fossil content is called biofacies.

Sedimentary rocks can be formed only where sediments are deposited long enough to become compacted and cemented into hard beds or strata. Sedimentation normally occurs in areas where the sediment lies undisturbed for many years in sedimentary basins. Whereas some basins are small, others occupy thousands of square kilometres and usually have within them several different local depositional environments. Physical, chemical, and biological factors influence these environments, and the conditions that they produce largely determine the nature of the sediments that accumulate in the locality (www.britanica.com). Several different local (sedimentary) environments may exist nearby each other within a basin as conditions change laterally; the sedimentary rocks that are ultimately produced in locality can be related to these depositional environments. These different but contemporaneous sedimentary rocks are known as sedimentary facies, i.e. lithofacies, a term that was first used by the Swiss geologist Amanz Gressly in 1838. Sedimentary facies are bodies of sediments recognizably different from adjacent sediments deposited in a different depositional environment.

6.2. Facies Description

6.2.1. FACIES A: *Flat bedded Pebbly Conglomerate Facies*

Lithology and sedimentary structure

This facies is a fossiliferous rock unit which appears only at low tide and occurs at the lowermost bed of the entire succession with a thickness that varies between 20 and 40cm. Evidently, a part of the bed had been merged under seawater, therefore, the total thickness of the facies should be more than 1m thick in the stratigraphy. It appears only three to five beds above the lower tide, and is coarse grained. The bedding surfaces are relatively flat and dip at approximately three degrees and sometimes the sedimentary structures shows lenticular bedding. This facies contains differently oriented pebbles of different sizes. The pebbles in the strata are rounded to well-rounded with the common size 5-10cm in diameter, but the largest size having a diameter of 18cm and the smallest being one centimeter across. The shapes of the pebbles are mostly spherical, but roller shaped and disc shaped pebbles are also common. Oysters and other marine fossils occur in abundance and their presence testifies to the origin of the conglomerate.

Fossil content

The facies contains a population of abundant, diverse and well preserved macrofossils of bivalves and gastropods, rich in oyster and sponge fossils.

Contact relationships

Facies A is the lowermost bed, but as observations are made in the southward direction, the unit becomes buried by the sands, and does not become visible; therefore it is an uneven erosional surface at the base of pebble conglomerate facies.

Interpretation of depositional environment

The disc shaped pebbles and the well roundness characteristics of the pebbles indicate that the pebbles were deposited in a high energy shallow water environment, probably in a near shore marine environment. There are also many shell fragments and silicified wood trunks had been found in the strata, which are also consistent with the facies was formed in a shallow water marine environment. The conglomerate facies was well present in the base of the sequence, which means that it was probably laid down during transgression of the seawater over an unconformity on the top of the Palaeozoic Natal Group.

Figure 39: Pebbly conglomerate bed at the base of the measured section with well-rounded pebbles. Some pebbles are disc or roller shaped, which are common in a shallow water beach environment.

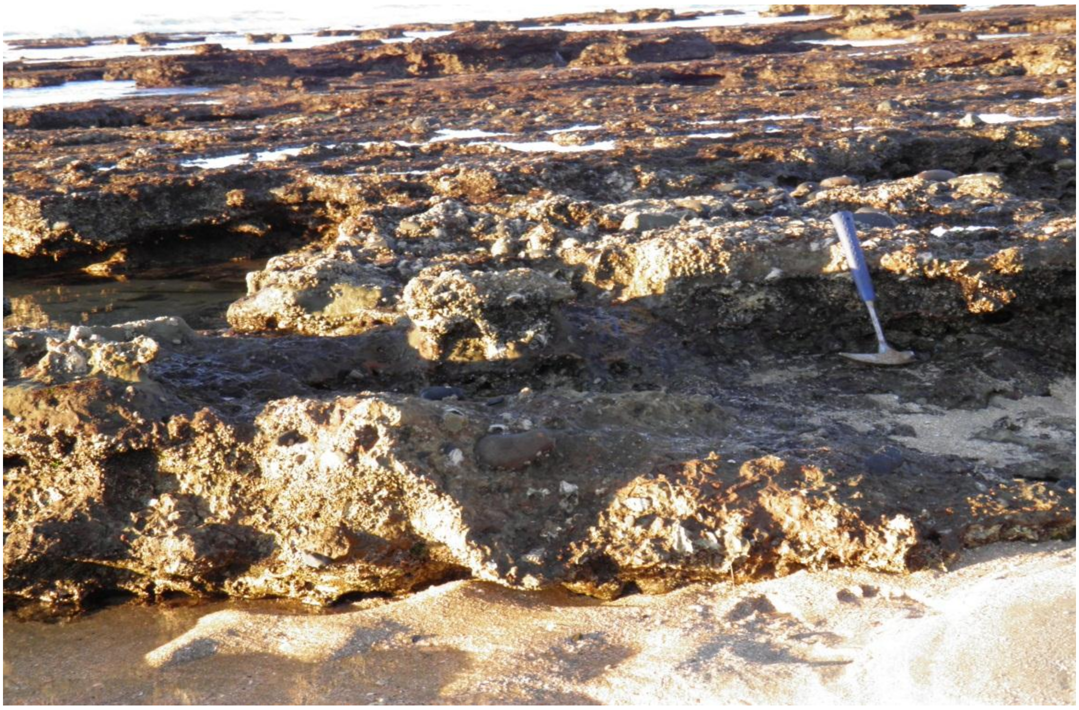


Figure 40: Pebbly conglomerate facies constitutes the lowermost bed. The bedding surface of the conglomerate is relatively flat.

6.2.2. FACIES B – *Cross-Bedded Coarse Calcareous Sandstone Facies*

Lithology and sedimentary structure

This lithofacies is best developed at the locality with co-ordinates S31° 05' 813" and E30° 11' 002" at the coast of Mzamba River, and occurs at an elevation of two meters above sea level. This unit occurs just above the conglomerate facies, with a thickness variable between 20-58cm for a single bed. It consists of fine-grained sandstone with uniform grain size which is brownish in colour.

Fossil content

Facies B is rich in well preserved shell fragments as shown in Figure 41 below. The fossils are unevenly distributed.

Contacts and relationships

This facies occurs directly above the Facies A, which overlies with a conformable contact with the bottom conglomerate facies and underlies below the fine grained mudrock facies, therefore, it constitutes a perfect fining-upward sequence.

Interpretation of depositional environment

A relatively shallow water depositional environment, near the coast, which is suggested by the presence of shell fossils. The carbonate was precipitated by marine organisms that need land derived nutrients.

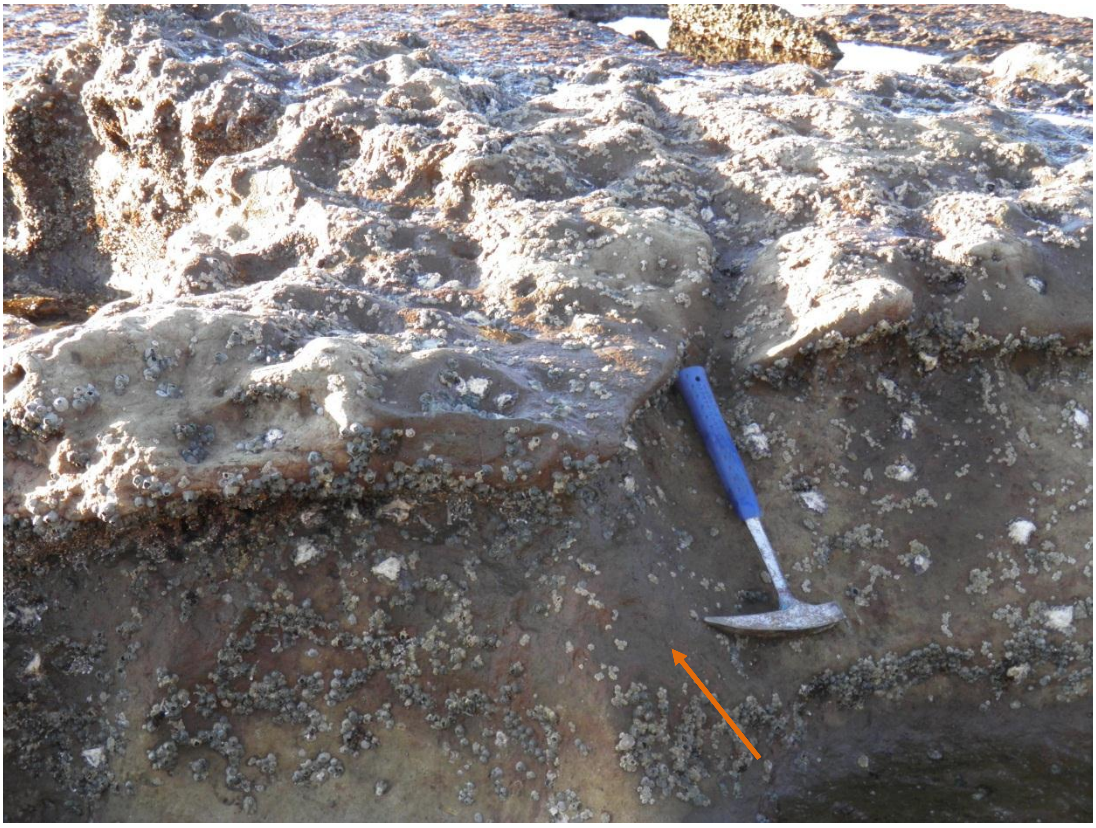


Figure 41: Brownish, fine-grained calcareous sandstone (arrow). There are lots of living oysters of about 2-5 cm in diameter on the surface of a beach rock. The oysters just attach on the rock surface, not inside the rock.

6.2.3. FACIES C- *Burrowed Sandstone Facies*

Lithology and sedimentary structure

At the locality with co-ordinates S31^{o} 05' 48.7" and E030^{o} 10 '59.0" and an elevation of two metres above sea level, Facies C occurs with the calcareous sandstone. It contains well developed and clearly visible vertical burrows. The burrows occur at the surface of the calcareous sandstone facies (Fig. 42). The burrows occur as vertical tube in the size of the 0.5-1.5cm in diameter and up to 18cm in length.

Fossil content

Silicified wood trunks with a length of up to 3m and a diameter of up to 21cm are common. The wood trunks had been bored by shells or worms therefore the wood trunk remained with lots of holes surrounding the trunk surface. After being bored, the holes were filled with mud and silts, and were also gradually silicified after being buried and thus the wood trunks had become very hard and resistant to weathering.

Interpretation of depositional environment

Burrow and bioturbation are usually produced by shells and worms, or some other micro-organisms. The origin of this facies is attributed to shallow marine environments, as evidenced by presence of the wood trunks and shells. Vertical burrows are often occurred in shallow water environment, such as intertidal and supratidal environment, whereas flat or horizontal burrows occur in relatively deep water environments. Also, big wood trunk fossils in the strata imply that the depositional environment was near the coast, not far from source locality.

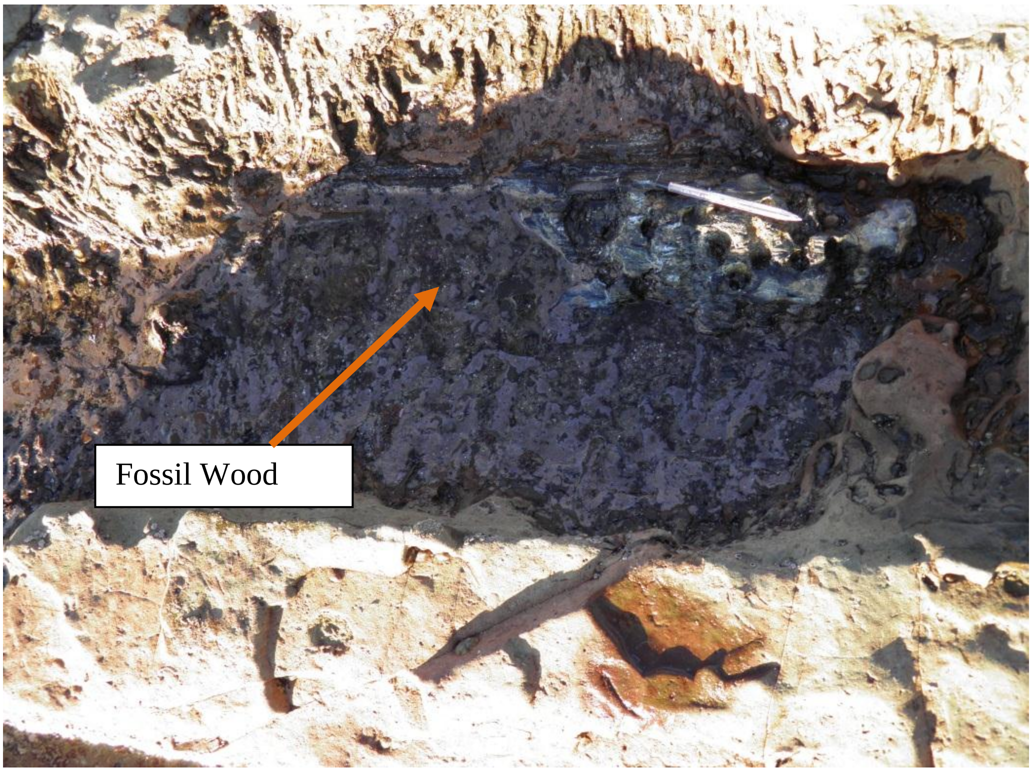


Figure 42: Burrowed facies with fossil wood (arrow).

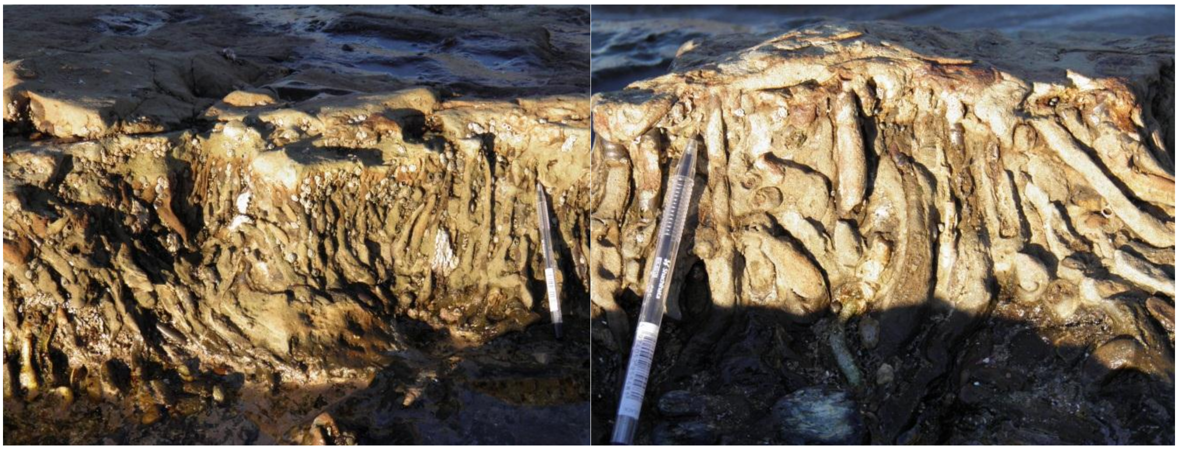


Figure 43: Cross section of the calcareous sandstone showing numerous vertical burrows.

6.2.4. FACIES D - *Shell-fragmental fine-grained calcareous sandstone facies*

Lithology and sedimentary structure

This very fine-grained facies is widely exposed and is very flat lying. The strata dip at 4° with a dip direction of 150°. The succession attains a thickness of 57cm, is well cemented, hard and consolidated. The strata have some evident cross-bedding, grey-greenish in colour and are overlain by younger sediments. This is one of the major facies in the type section.

Fossil content

The facies contains smaller shells that are dispersed in the unit and smaller gastropoda fragments that are also scatted in the strata.

Contacts and relationships

The unit occurs nearby the burrow facies, not very different to the previous calcareous sandstone facies. The difference is in the colour (this one is darker) and the grain sizes is finer. The bottom of the unit forms an erosional uneven contact surface, which may be due to erosion and changes of the water energy.

Interpretation of depositional environment

Facies D is believed to have been deposited in a sub-tidal, low energy environment, therefore, the grain-size of the sediments was decreased, and the bedding becomes more flat or horizontal without any cross-bedding or wave mark.

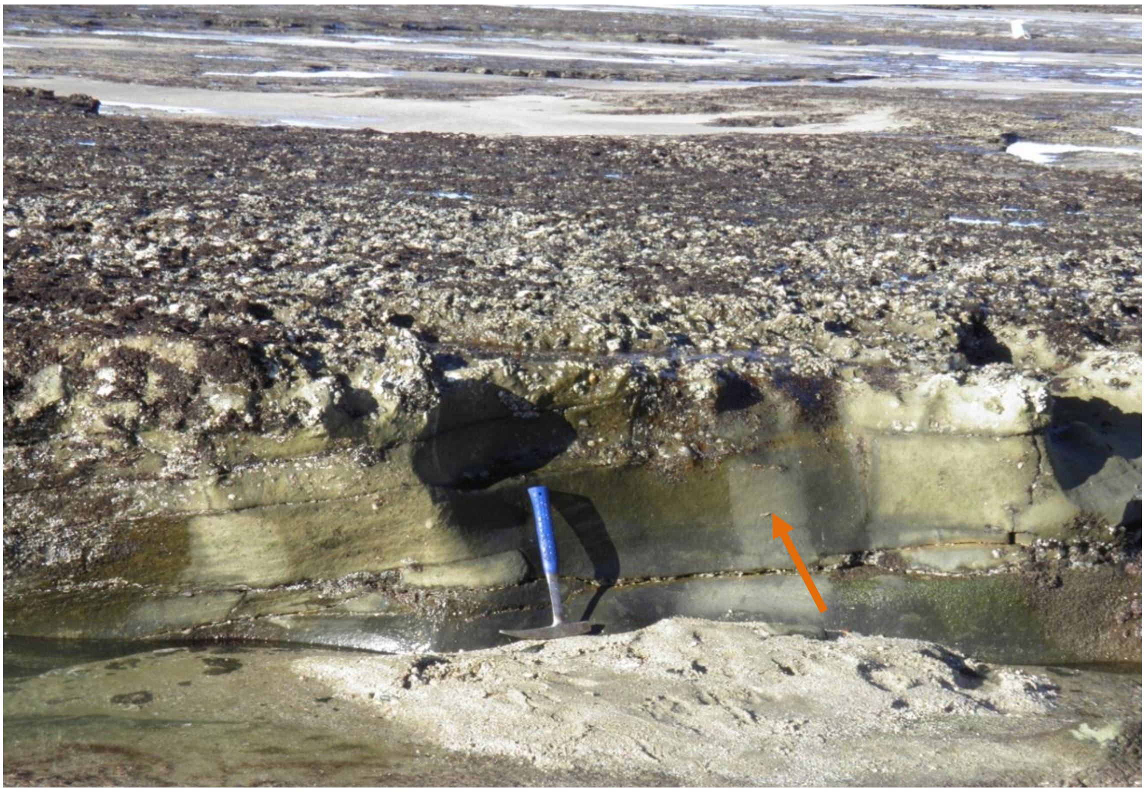


Figure 44: Widely exposed shell-fragmental sandstone facies (arrow).

6.2.5. FACIES E- *Horizontal bedded calcareous mudstone facies*

<u>Lithology and sedimentary structure</u>

This greyish-blue, very fine-grained mudstone facies attains a thickness that varies from 15-45cm, and is about 25cm in average which probably linked with low depositional rate and lack of sediment supply during deposition. The lamination structure accompanied by the dark colour and fine grain-size indicate that the sediments were deposited in a low energy reducing environment. The facies contains dispersed shell fragments.

<u>Contacts and relationships</u>

This facies is located at the top of each small fining upward cycle at the type section. This mudstone facies is in direct contact with sandstone facies at the bottom, and also contact with a small patch reef. This is a major facies. The contact with the calcareous sandstone is gradational, showing a difference in texture and grain size.

Interpretation of depositional environment

Considering that the facies is of fine-grain sized, dark coloured and shows lamination structure, it was probably deposited in relatively quiet and deep waters, low energy and low depositional rate environment. Particularly, the dispersed fine shell fragments in the strata and the shells were mostly thin-shell species, suggesting that the sediments were of marine deep water signature.

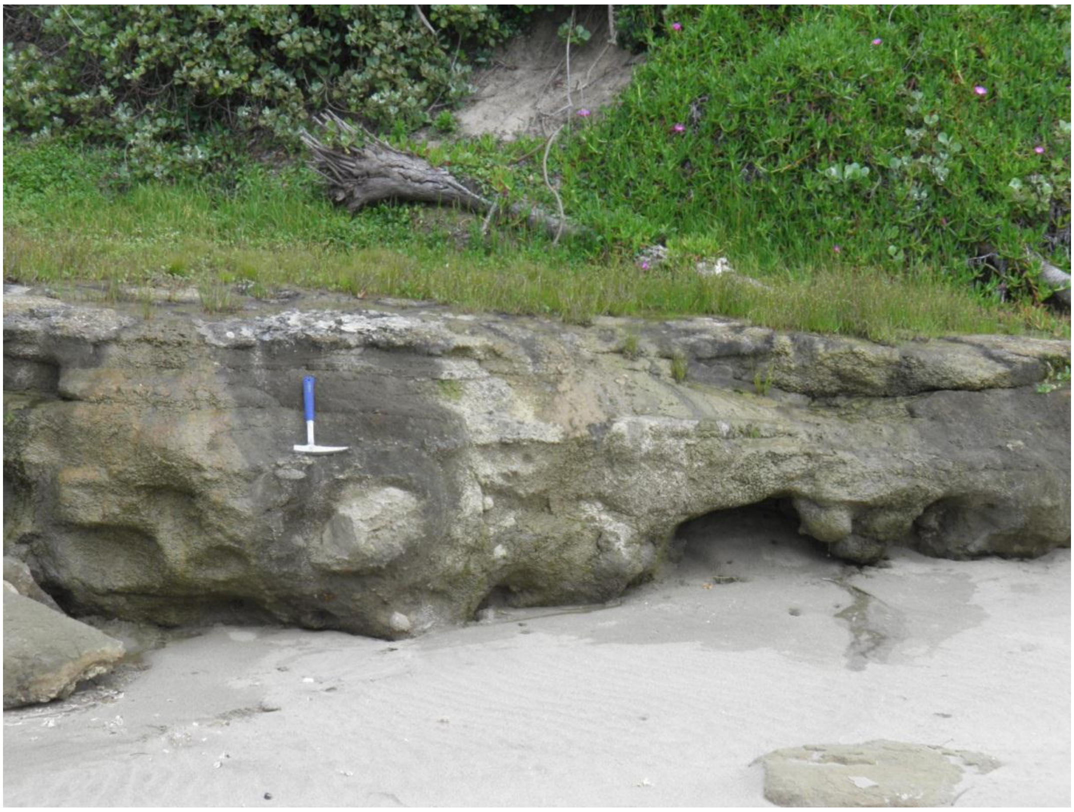


Figure 45: Fine laminated or thin bedded calcareous mudstone facies.

6.2.5 FACIES F- *Calcareous Patch Reef Facies*

Lithology and sedimentary structure

This medium-grained, greyish or light grey coloured facies attains a maximum thickness of 72cm. It consists of medium-grained carbonate or calcareous sandstone. It is not found anywhere else in such a big chunk along the coastline in the sequence and occurs only at this locality in such a large scale. It does outcrop in other areas, not so far, but in a much smaller scale of outcrops. In some areas, the carbonate reef or calcareous sandstone is embedded by a fossil bed, with medium to large-sized shell fragments. This facies is typical of boundstone rocks, whereby the reef shows signs of being bound during deposition.

Fossil content

Facies F contains a population of abundant clustered carbonate composed of sands and bio-fragments which were bounded by algae, coral and sponge, plus carbonate cements. Besides of algae and bacteria, macrofossils of oysters and bivalves may also be preserved. Burrows are also found in the bedding.

Contacts and relationships

This facies occurs inside the calcareous sandstone, truncated to the sandstone and it looks like a dome shaped patch reef which grew up from calcareous sandstone terrace.

Interpretation of depositional environment

These are unique sedimentary systems, isolated and are common in the geological record. This facies was formed from shallow waters; it developed from small reefs into larger structures. This is a typical back-reef facies and they are common in the organic carbonate strata. Boundstones generally are deposited in higher energy environments.

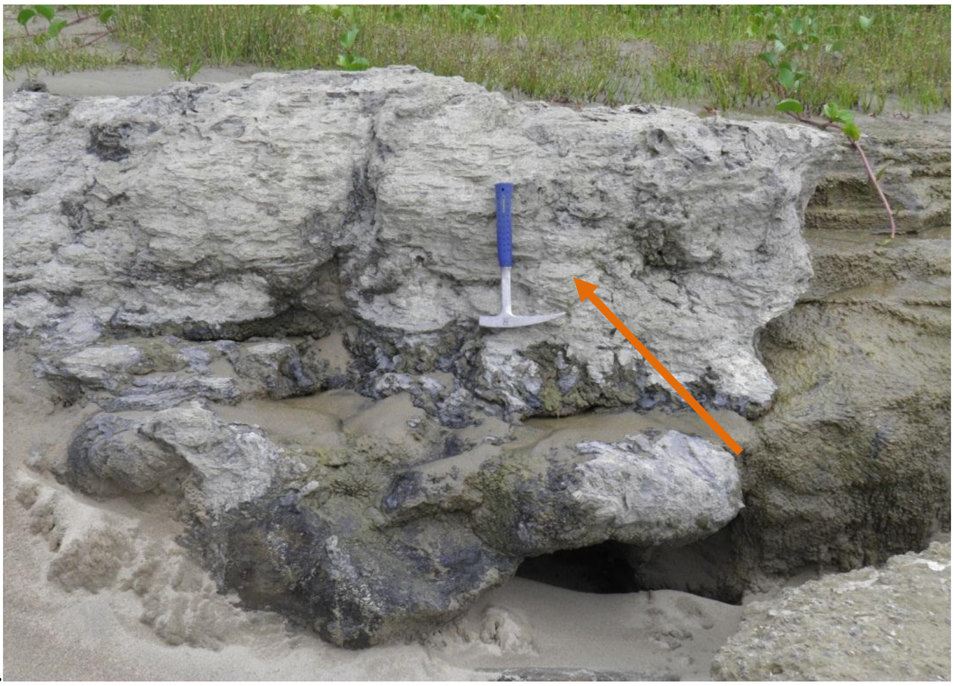


Figure 46: Patch Reef facies, showing typical laminae layers of reef structure (white part, arrow).

6.2.6. FACIES G- *Reef Facies*

<u>Lithology and sedimentary structure</u>

This facies is washed-out; it is medium-grained and is calcite cemented. It is rich in shells, coral, with small pebbles and broken oysters. The surface is smooth to undulatory with small coral growths. The facies is usually composed of skeletal debris that is derived from reef crest. Bio-erosion is extensive with some early cementation.

<u>Interpretation of depositional environment</u>

The reef facies was formed by carbonate precipitation and deposition in a relative shallow water environment, such as intertidal zone. The wave intensity decreased because waves dissipated in reef crest. The facies is typical of reef flat facies. It is usually behind and partially protected by the reef crest, in which two environments are noted: reef pavement and the sand apron. The reef pavement is the one that is immediately behind the crest and gets shelter from. The sand apron extends behind the pavement and has varying water depths, which extend in the parallel direction (Tucker, 1990).

Figure 47: Reef facies, showing flat bedded porous coral reef occurrence.

6.3. Facies Model

A facies model could be defined as a general summary of a specific sedimentary environment, written in terms that make the summary useable in at least four different ways. The basis of the summary consists of many studies in both ancient rocks and recent sediments. Facies modelling is usually the last stage in the process of facies analysis, which consists of the detailed description of exposed or cored sediments, their classification into objectively defined facies, the compilation of the characteristics of each facies, the deduction of the process of deposition of each facies, the examination of the spatial relationships between facies and the recognition of the facies association, the interpretation and modelling of individual facies (Anderton, 1985). Reliable facies models cannot be produced without careful facies analysis. The field of stratigraphy and sedimentology is one of the most active areas concerned with the formulation of facies models for various sedimentary environments.

Walker (1976) suggests that a facies model must fulfil four important functions:

a) It must act as a norm, for purposes of comparison.

b) It must act as a framework and guide for future observations.

c) It must act as a predictor in new geological situations.

d) It must act as a basis for hydrodynamic interpretation for the environment or system that it represents.

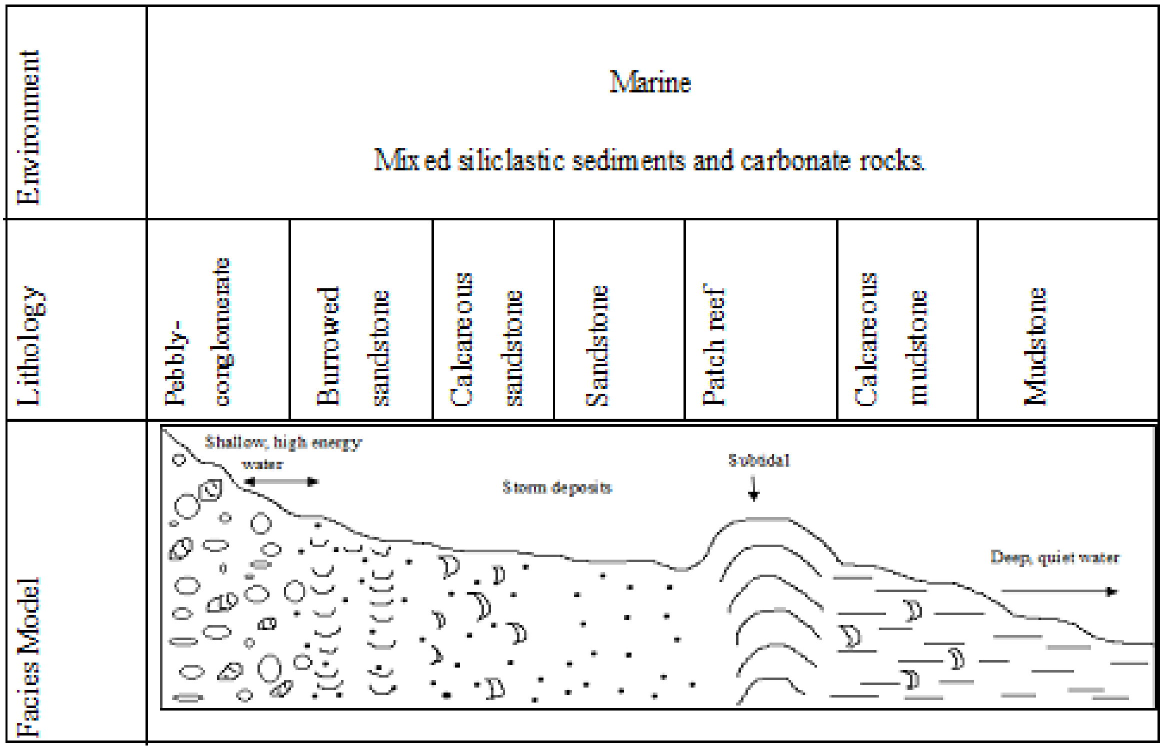


Figure 48: Generalised facies model of the Mzamba Formation.

CHAPTER 7 PALAEONTOLOGY

7.1. Introduction

Mzamba Formation is a marine succession of Cretaceous in age (Cooper, 1974; Cooper and Liu, 2006). It is a fossil-bearing sediment and contains both fauna (Chapman, 1904) and flora fossils in the strata, including diverse species of fauna of bivalve, gastropod, ammonite, brachiopoda, foraminifera, and echinoderm; and flora of silicified wood trunks. Various trace fossils had also been found in the succession, including vertical and horizontal burrows, tracks and as well as coprolites (faecal pellets). Some of these fossils are good indicators for sedimentary environments, such as bivalve, echinoderm and ammonite, which inhabited in marine environment. Some other fossils are found, such as assemblages of wood-trunks and shell fragments which are hosted together and represent shallow water, near inland environment, where high energy shallow water washed out the plants to near shore environment and mixed with broken shell fragments. Furthermore, trace fossils of burrow and tracks can be used to distinguish water depth; the horizontal burrows are normally present in deep water environment while the vertical burrows live in intertidal and supratidal zones.

There were a number of researchers that concentrated on the palaeontology of the Mzamba Formation, particularly fossils of bivalve, bryozoan, foraminifera and ammonite species had been widely reported in the literature (Cooper, 2006; Greyling, 1991; Spath, 1921, 1922).

7.2. Bioclasts

There are many bioclasts which have been found in the deposits. Bioclast is a grain (allochem) within a carbonate rock derived from the remains of the hard parts of carbonate-secreting organisms. Originally, the term bioclast was used for fossils which were transported, broken and abraded and which became part of the organic debris. Today the term is used for fossil fragments seen in thin sections of carbonate rocks (Flügel et al., 2010). Of all the components of limestones, there is a great diversity of bioclasts that is found to be rather difficult to be identified. The most common bioclasts in the Mzamba Formation are derived from molluscs, echinoids, corals, crinoids and foraminifera. Bioclasts may be whole fossils, or just a part of hard fossil body, i.e. fragmental parts of skeletal material. Bioclasts are often surrounded by thin micrite envelopes or can exhibit syntaxial overgrowth. There can be great variety in one thin section, and the bioclast content of limestones could be variable with age, such that, a bioclast grainstone of Palaeozoic age, will look very different from one of Tertiary age. In identifying bioclasts, one should keep in mind the size of the fossil, the shape of the grain, the wall structure and the age of the rock itself being examined (Adams & MacKenzie, 1998).

The nature of bioclasts differs with the type of organism and the alteration during diagenesis. Articulate brachiopods, echinoids and crinoids all are comprised of calcite that often preserves internal shell structure, but different species have different wall structures and crystalline mineral shapes. Brachiopods tend to have a two layer structures with an inner foliated layer and an outer prismatic layer of calcite. Echinoid spines are circular to elliptical and exhibit a range of radial structures. Most bivalves and gastropods have shells originally composed of aragonite, which are usually inverted to calcite or have been removed during diagenesis and are preserved as casts filled with sparry calcite due to diagenetic alterations.

7.3. Bivalve

During this study, we had made some new discoveries of fauna and flora fossils in the Mzamba Formation, which include fauna bivalve, gastropoda, echinoderms, brachiopoda; flora fossils of silicified wood trunks; and trace fossils of tracks and burrows, as well as coprolites (faecal pellets).

The bivalves are the most important contributors to the fossil species of the Mzamba Formation, which were hosted mainly in limestones and minor in mudstones of the strata. Bivalves were living in marine environments since the Cambrian and in non-marine environments since the Carboniferous. The bivalves are a very large group with species occupying most marine, brackish and freshwater environments. It is unusual to find complete shells, because the valves disarticulate easily after the death of the organism and transportation. In most cases, it is single valves or fragments of valves which are found in limestone. Bivalves can grow to large sizes, so that in a standard thin section often only a small part of the shell is seen. Bivalve shells can be wholly aragonite, wholly calcite or a mixture of the two, and the shell structures also differ from species to species (Klappenback, 2013). Bivalve shells consist of several layers of specific internal microstructure, composed of micron-sized crystalline aragonite or calcite.

7.3.1. Type 1: Pteriaceae

This type of bivalve is found in Ordovician sediments to recent sediments. Pteriaceae is a large family of ferns in the Plantae Kingdom. Members of the family have creeping tendencies and they are epipetric (grow on rock).

It is a large sized bivalve with thick shells, showing visible long prismatic shell-structures, comprising crystals aligned roughly at right angles to shell surface. Thick plate is vertical to shell wall. It is rich in organic carbon, which is the reason for the dark colour. The picture was taken here under parallel light.

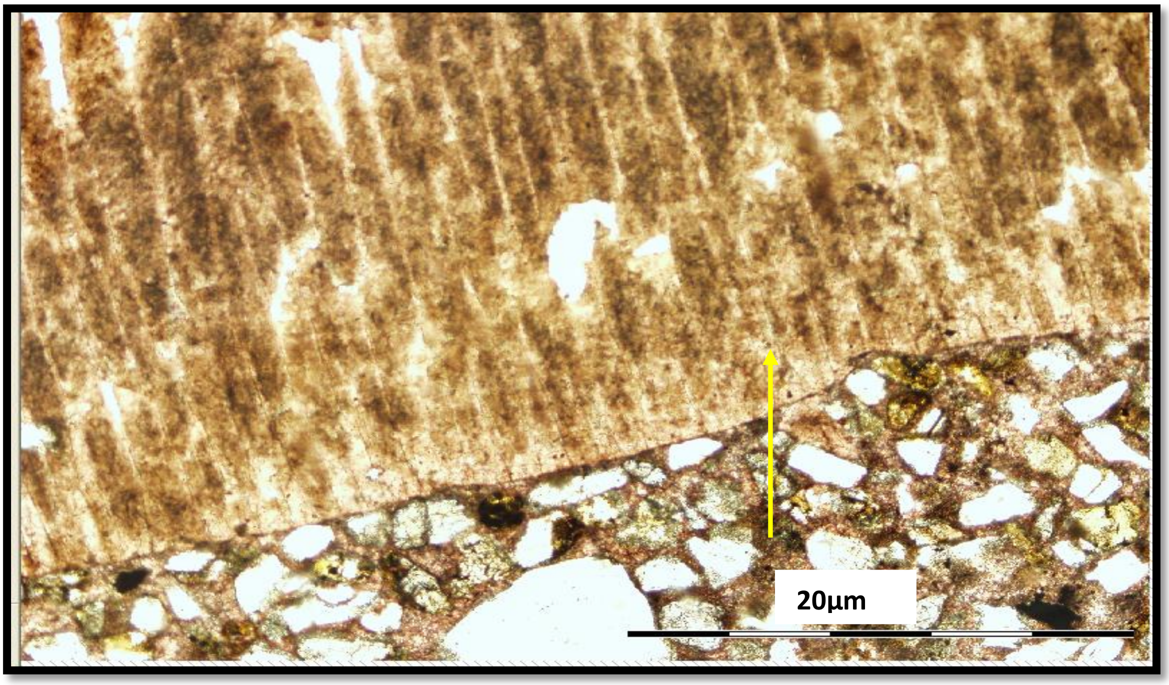


Figure 49: Photomicrograph of Unit 4 (type section). Pteriaceae (arrow).

7.3.2. Type 2: Pinnacea

This species occurs in Carboniferous period to recent sediments. It belongs to the superfamily Pinnacea Leach, the Pinndae Leach family and Pinna Linnaeus genus.

It exhibits coarse prismatic texture, elongate, occurs in calcite cement, sub-ventricular to shell wall. Their living environment is the bottom of the seafloor, and usually crawls during movement.

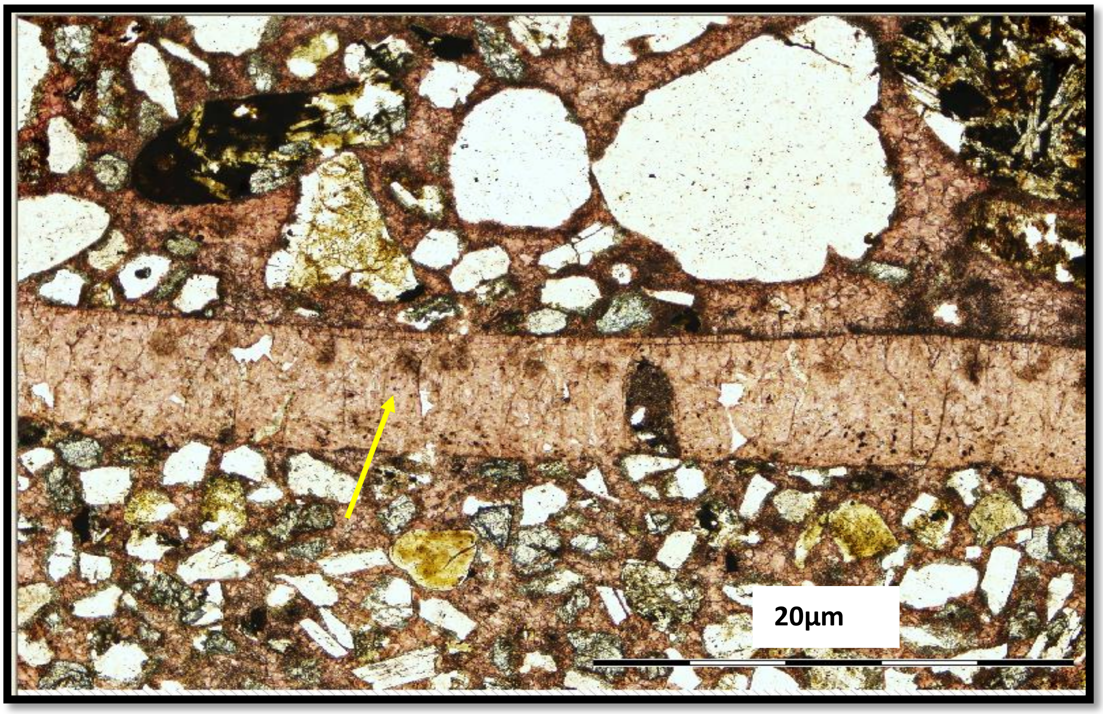


Figure 50: Photomicrograph of Unit 2 (type section).Pinnacea (arrow).

7.3.3. Type 3: Ostreacea

It belongs to the Ostrea Group, Ostreidae family, bivalve superfamily. They occur in the Permian Period till recent. These organisms have a common name of oyster and are mostly found in brackish waters and some are found in normal sea waters. This type of oyster dwells at the bottom of the sea or attaches to a rigid rocky detritus. They do not move, and they have to wait for their food to come to them.

These figures (51 &52) show part of a thick-shelled oyster, foliated, lamellar calcite structure and fine-grained at the edges .The sediment is fibrous, has uneven walls with fibrous calcite parallel to the shell wall.

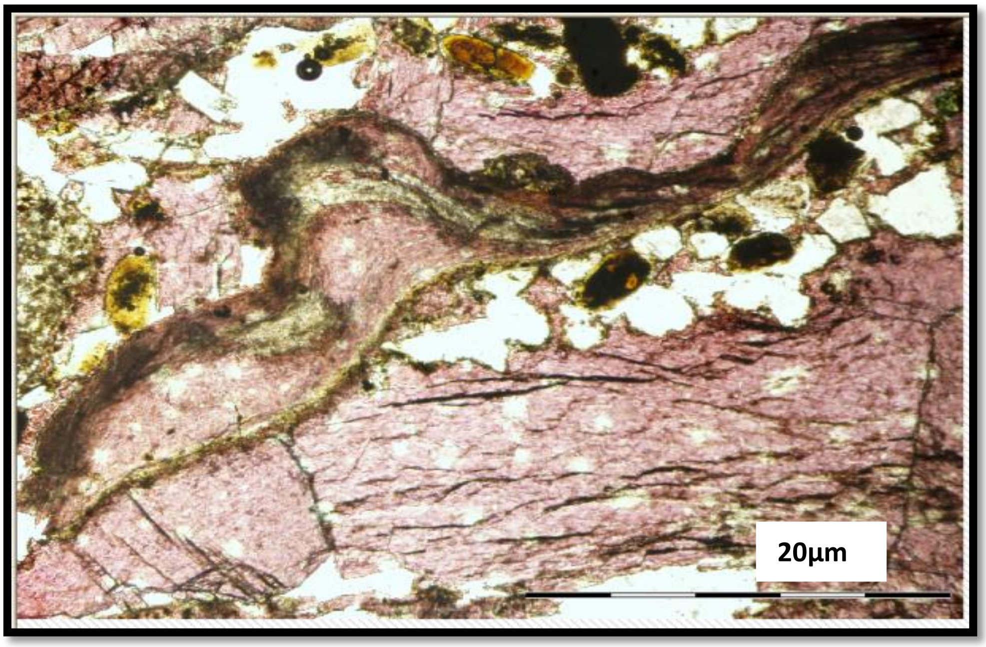


Figure 51: Photomicrograph of Unit 8 (type section). Thick shelled Ostreacea (one type of oyster).

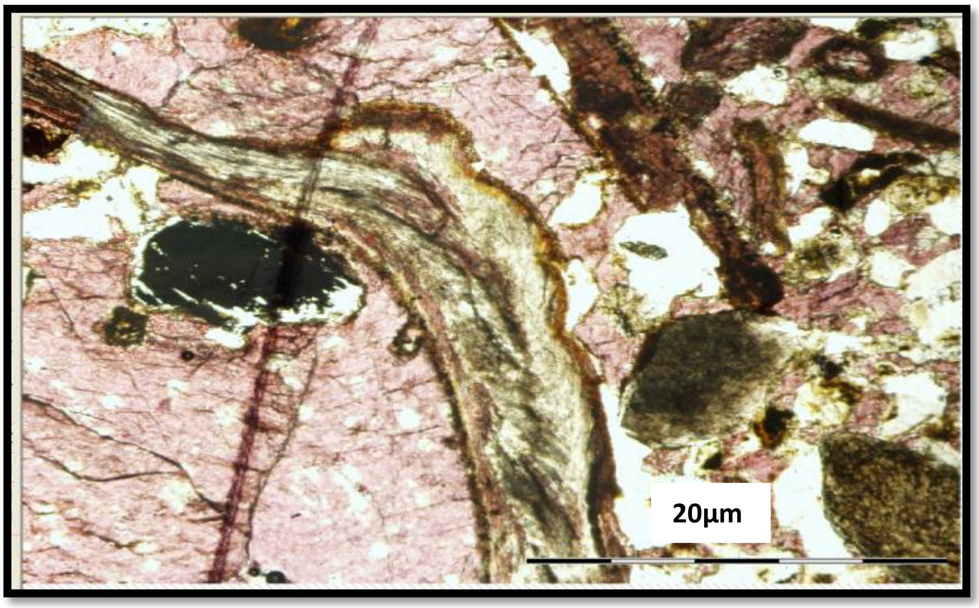


Figure 52: Photomicrograph of Unit 8 (type section). A foliated Ostreacea (one type of oyster, middle).

7.4. Gastropoda

Gastropodas are the second group fossils of major importance in the limestones of the Mzamba Formation, and a highly diverse group, not only in the number of species available, but also in their size, shape and morphology. Just like the bivalves, they also occur throughout the

Phanerozoic, but are most abundant in Mesozoic and Cenozoic sediments. Gastropod shells are nearly all made wholly of aragonite although there are a few with mixed mineralogy, comprising an outer layer of calcite and an inner layer of aragonite (Klappenback, 2013). Most gastropods are benthic, vagile creatures. The majority of gastropods have shells of aragonite with similar internal microstructures to bivalves. The internal microstructure of fossil gastropods also is rarely seen because the original aragonite is mostly dissolved out and the void filled by calcite cement. Gastropoda may resemble certain foraminiferas, but the latter are usually much smaller and composed of dark micritic calcite (Tucker, 2001).

7.4.1. Type 1: Mesogastropoda

This class is found in the Ordovician Period till recent, with the majority of them found in the Mesozoic to Cenozoic Eras. This group consists of gastropoda and snails, both sea and land species. Most of them are found in the sea, but there are numerous species in freshwater and with a few occurring on land. They move around by crawling.

Under the microscope, they attain a prismatic fibrous texture. Surface layers show prismatic fibrous calcite crystals, which are vertical to shell wall. The fibrous texture shows evidence of change to coarse crystalline granular calcite texture in the inner tube.

The photos below show a part of a large gastropod, with foliated calcite structure. It is fine-grained at the edges. Shells that are made of coarsely crystalline calcite, some remnant of the original shell structure remains. Neomorphism took place and thus destroyed some original shell structures. Some shells were partly dissolved and thus leaving a void, but it could be recrystallized in situ and changed to granular calcite. The inner chamber had been fully filled with calcite cement which was recrystallized to coarse granular calcite. Figure 56 below shows a large scale gastropoda, named as Mesogastropoda, which is found in the sediments from Mzamba Formation. It also has crystalline granular texture.

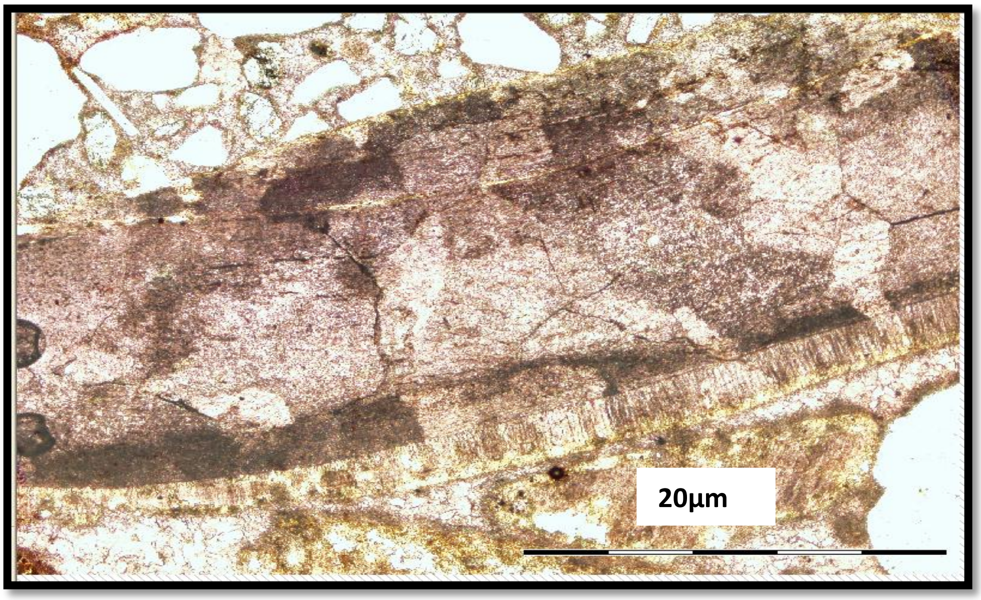


Figure 53: Photomicrograph of Unit 2 (paratype section). Part of a large Mesogastropoda.

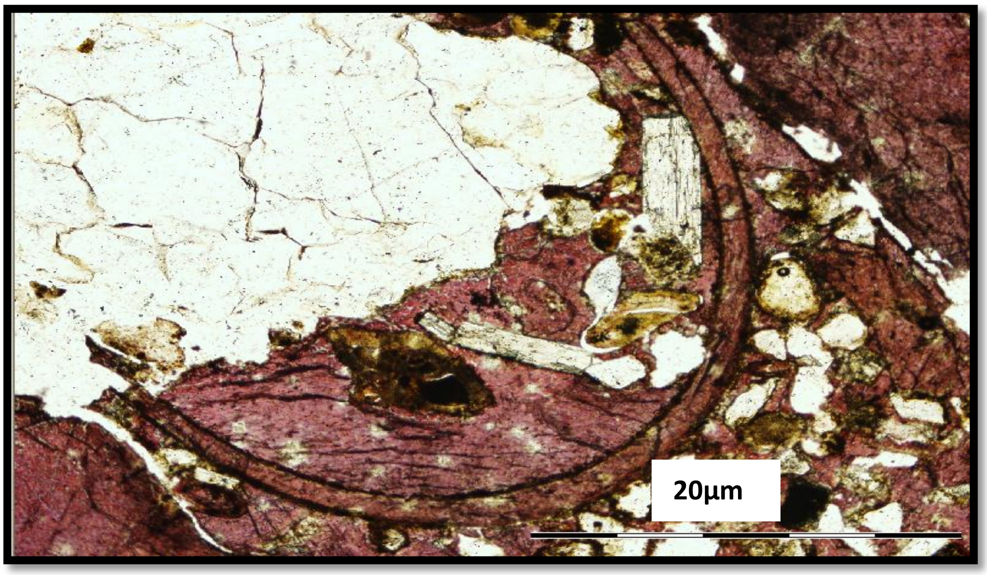


Figure 54: Photomicrograph of Unit 10 (paratype section). A Mesogastropoda (middle).

7.4.2. Type 2: Cerithiacea

Belongs to the Cerithidea Class, under Gastropoda Family. It occurred from Devonian Period till recent with different species. Cerithiacea is a minute, generally cylindrical organism, but other species could exist in marine, freshwater and in land. They mostly live in tropical and warm temperate regions. The majority of the species are sand dwellers, and they are crawling benthos.

This thin-section is occupied nearly full by the Cerithiacea fossil. A part of the gastropods is preserved as casts, with the inside of the shell being partially filled with medium sized granular calcite sediments, and outside shell-wall is thin and dense parallel layered aragonite (Fig. 55 &56). The sediment has a crystalline granular texture.

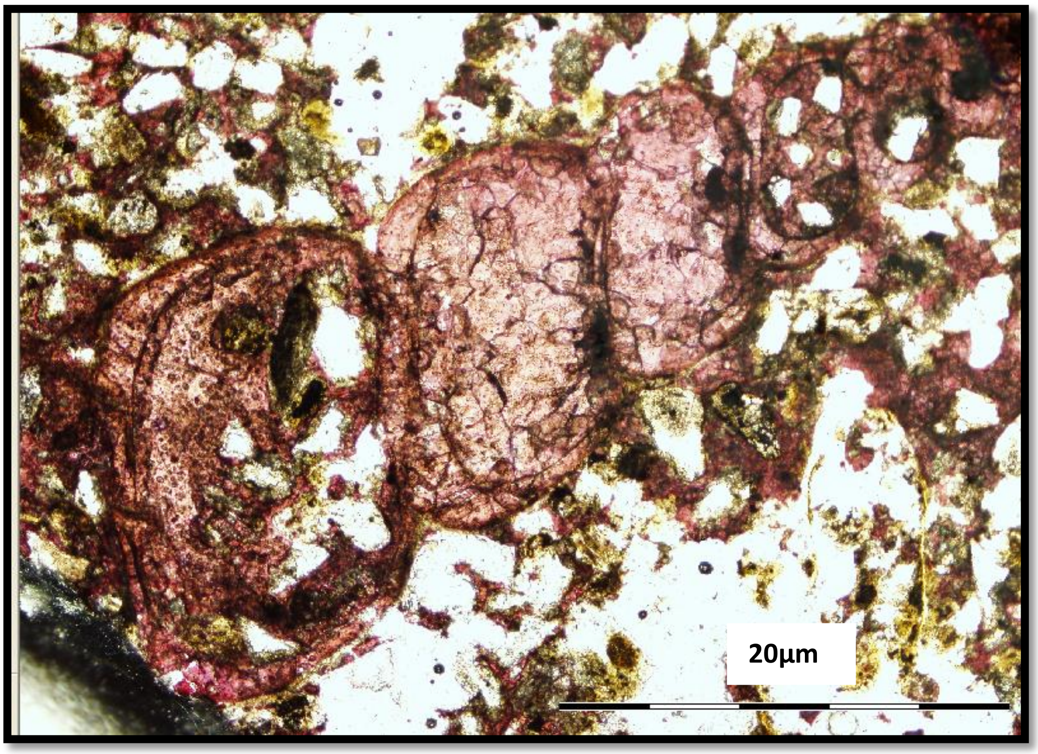


Figure 55: Photomicrograph of Unit 16 (paratype section). Longitudinal section of Cerithiacea (middle).

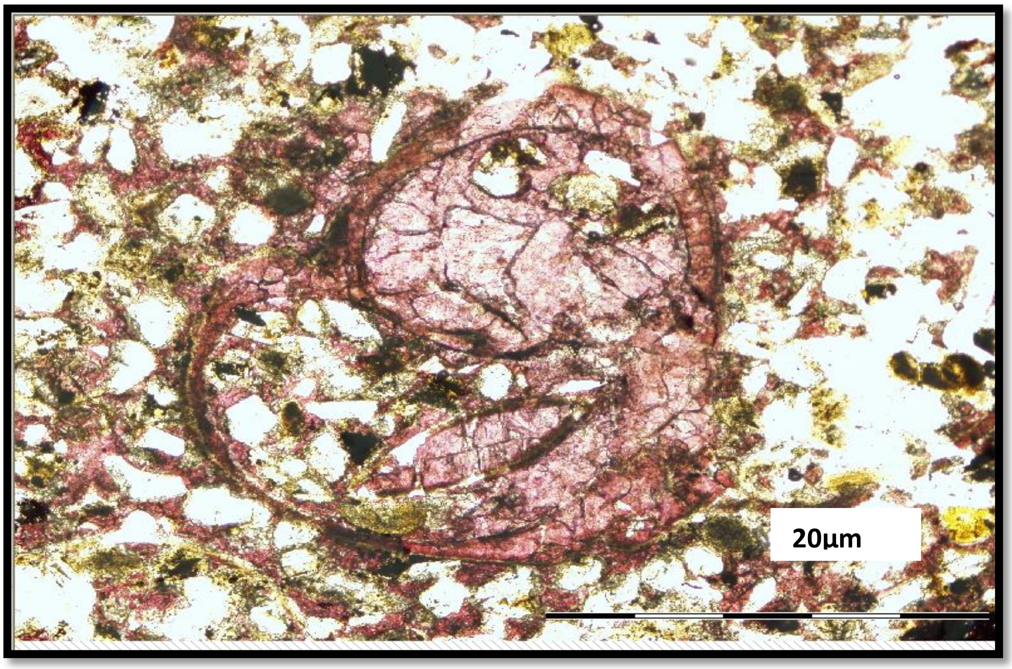


Figure 56: Photomicrograph of Unit 16 (paratype section). Transverse section of Cerithiacea (middle). There is an ostracoda inside the chamber (bottom chamber).

7.5. Brachiopoda

Brachiopodas are another major contributors to the bioclastic content of marine limestones of the Mzamba Formation. Brachiopods were living from especially in the Palaeozoic extending to Mesozoic. The dominant component of brachiopod shells is a foliated layer consisting of fine fibres or prisms arranged with their long axes at a low angle to the shell wall. Usually, a thin outer layer of granular or prismatic calcite, with prisms arranged normal to the outside of the shell, is visible; but this is often not preserved in fossil specimens (Adams & MacKenzie, 1988). In section brachiopod shells can be similar to those of bivalves in shape and size, most articulate brachiopods were composed of low Mg calcite, so the inner structure is fairly well preserved. The differences between brachiopoda and bivalve are as follows:

- The shape of brachiopoda shell is symmetrical, whereas bivalve shell is asymmetrical;
- The two shells of bivalve have the same size, while the two shells of brachiopoda show different size with one bigger than the other;
- Brachiopoda has flesh stem and stem pore structures, whereas bivalve has none of these structures.

7.5.1. Type 1: Pectinacea

It belongs to the Brachiopoda class, and occurs in the Ordovician Period till recent. It is found in nekton benthos environments, where these organisms actively swim independently in water or current. In the Figure below, the shell has been strongly crystallized and the primary structure was partially destroyed due to diagenesis (Fig. 57).

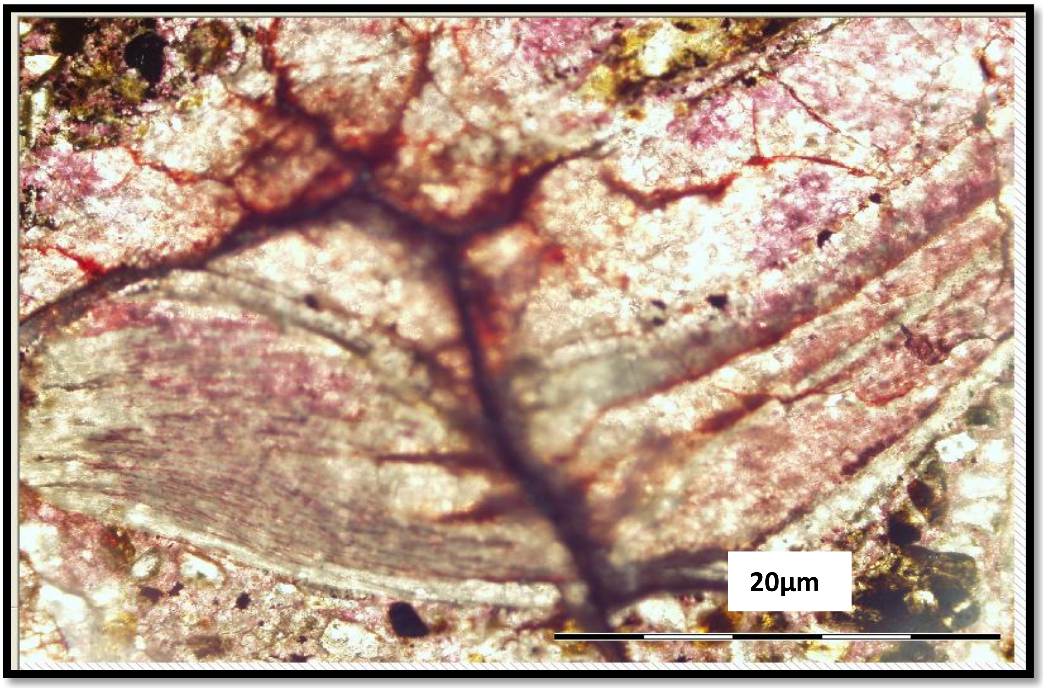


Figure 57: Photomicrograph of Unit 1 (type section). Pectinacea (middle).

7.6. Echinoderm

76.6.1. Type 1: Echinocystoidea

It belongs to the Phylum Group, under the Echinoderm Class. It is found to occur in the Jurassic period till the Cretaceous. These organisms are found living in the sea floor. Under the microscope, it shows a prismatic texture, with dense hexagonal granular calcite crystals, which mosaic tightly to constitute the shell. The hexagonal crystals in the fossil shell also show vague orientation which generally vertical to the shell wall.

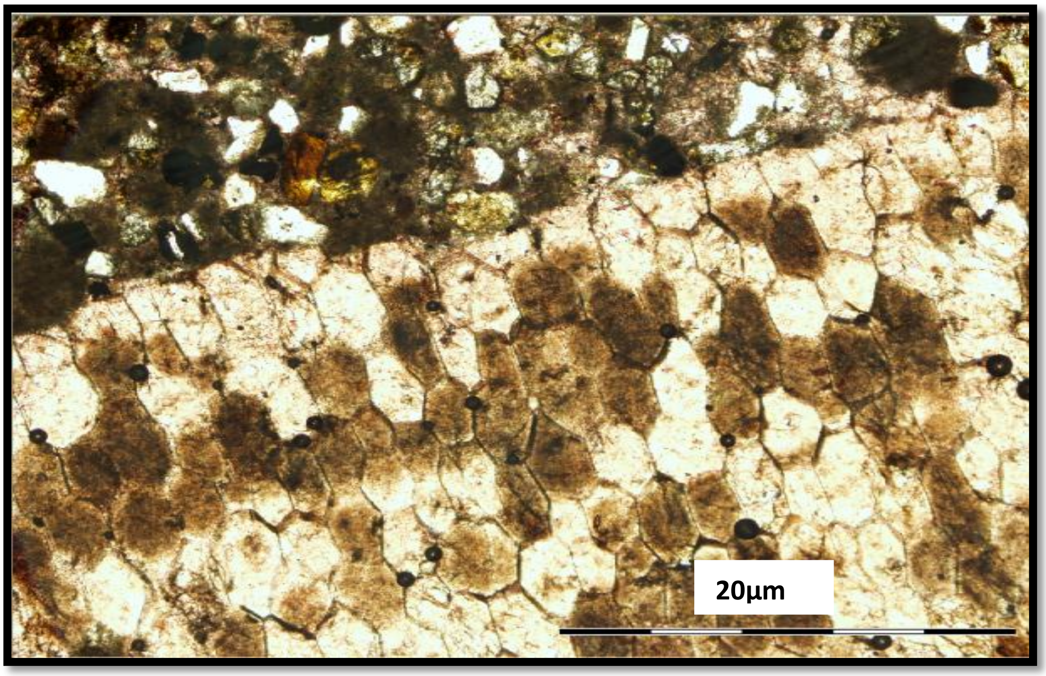


Figure 58: Photomicrograph of Unit 1 (2nd paratype section). Echinocystoidea showing a prismatic texture (middle).

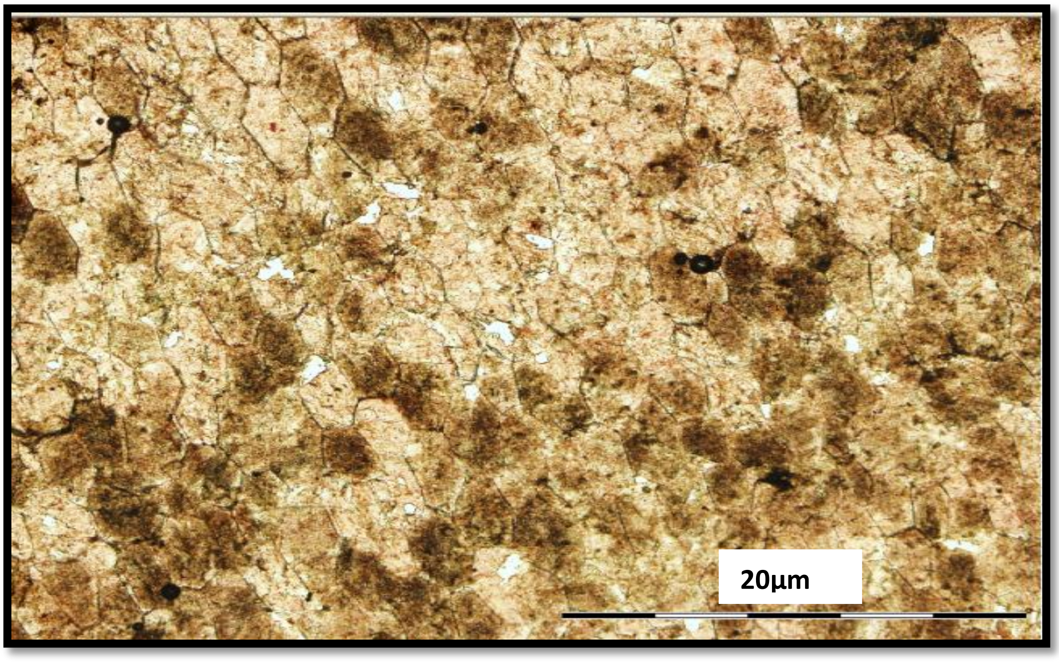


Figure 59: Photomicrograph of Unit 1 (2nd paratype section). Echinocystoidea with dense hexagonal granular calcite crystals in a mosaic pattern.

7.6.2. Type 2: Crinoidea

Crinoidea is a marine animal that make up the Class Crinoid, which belongs to the echinoderm family. They are neither abundant nor familiar to the organisms today. However, they dominated the Palaeozoic fossil record of echinoderms and shallow marine habitat until the Permo-Cretaceous extinction. Palaeozoic limestones are made up largely of crinoid skeletal fragments, while it gradually decreased in Mesozoic sediments.

Crinoidea commonly has a long round tube, and flower shaped top structure. The centre of the tube is empty, and therefore could be filled with calcite crystals (Fig. 60).

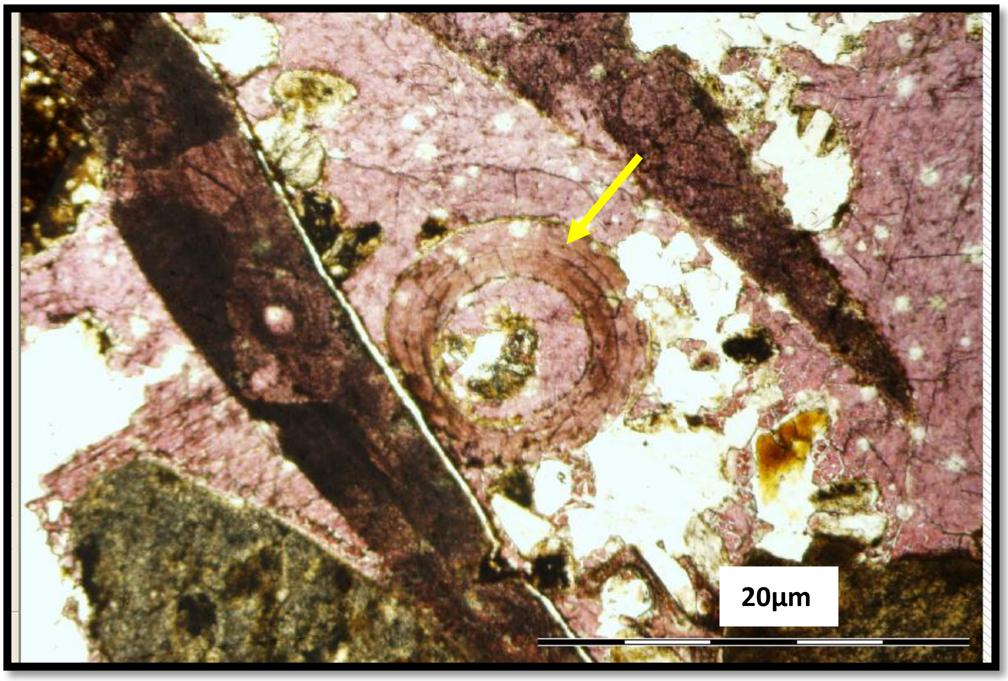


Figure 60: Photomicrograph of Unit 2 (2nd paratype section). Crinoidea (arrow).

7.7. Trace fossils

Different types of trace fossils have been found in the Mzamba Formation, which include horizontal and vertical burrows, feeding tracks and Coprolites (Faecal pellets). Trace fossils play an important role because they represent data source that is not limited to animals with easily fossilized hard parts, and they also reflect the behaviour of organisms.

7.7.1 Burrows

The most common trace fossils encountered in Mzamba Formation are the burrows, which were observed in the outcrops at the field exposures. They are two types of burrows, i.e. horizontal burrows and vertical burrows. The Fig. 61 shows horizontal burrows which developed along bedding surface or inside bedding but parallel to bedding surface. The Fig. 62 shows vertical burrows which are boring vertically to bedding surface. These burrows are encountered at both the bottom and top parts of the sequence, especially in the calcareous sandstone and some mudstone units.

Figure 61: Horizontal burrows along the bedding surface in Unit 2. Coin is 2.3 cm for scale.

Figure 62: Near-vertical burrows in the sandstone and also in silicified wood. Pen is 13cm for scale.

7.7.2 Tracks

Tracks are produced by movement of animals, particularly micro-organisms as a result of feeding, resting or crawling. The Fig. 63 shows typical crawling tracks along bedding surface, some of the tracks show forked routes due to the animal moving back and forth.

Figure 63: Track fossil along mudstone bedding surface, which are mostly 1cm in width and 5-15cm in length. Some of the tracks show forked routes. Pen for scale is 13cm.

7.7.3 Coprolites (Faecal pellets)

Coprolites are referred to as aggregates of spherical grains with which the external shape resembles microscopic clusters of grapes. Aggregate grains are composite grains consisting of ooids, skeletal material and peloids bound together by organic films and aragonite or Mg-calcite carbonate cements (Flügel et al., 2010).

There are two types of pellets, one type is produced by chemical precipitation and cohesion process; whereas the other type is produced by organism digestion, i.e. faecal pellets. Faecal pellets produced by worm or gastropod. The outside of the faecal pellets are rounded and smooth, but could be partially replaced by calcite during diagenesis, and the inside is the original pellets which is rich organic matters and therefore is dark in colour. These pellets are nearly the same size and shape since they were produced by the same organisms. Based on the origin, the late type pellets are therefore also called as faecal pellets. Typical coprolites are composed of clay minerals or mud and exhibit very little microcrystalline texture, uniformly or structureless. The space between the faecal pellets is usually occupied by carbonate cements (Fig. 64).

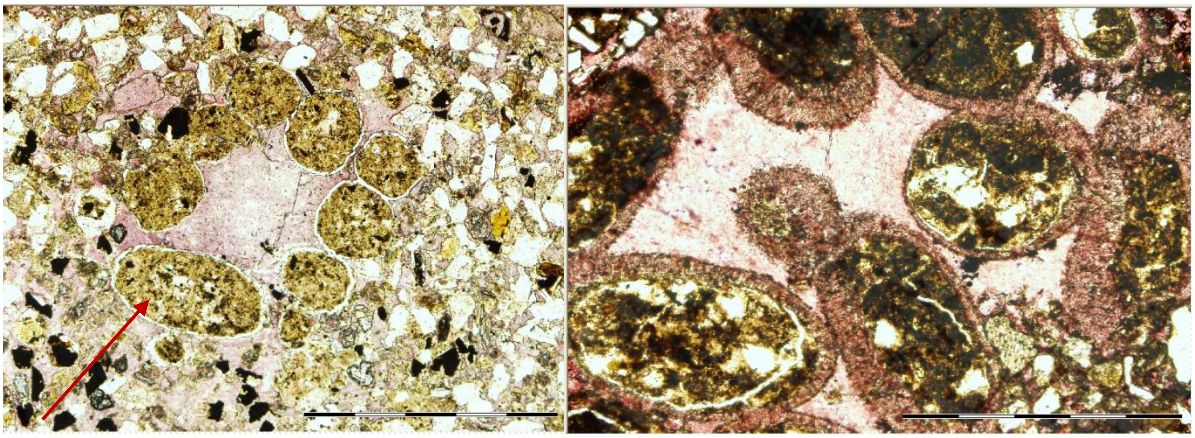


Figure 64: Coprolites (faecal pellets). The whole scale is 20µm. The left photo shows uniform and structureless faecal pellets, whereas the right photo shows replaced faecal pellets by calcite around the pellet boundary. Note the dark or brownish colour of the coprolites due to organic carbon rich.

7.8. Silicified Wood Trunks

Although silicified wood is not an original plant fossil, the original wood has been replaced by silica (SiO_2) after the plant was buried in sediments. These woods are completely preserved in situ burial, they are relatively large, with the longest being 31m in length with a diameter of 21cm, and therefore, they were obviously wood trunks. These wood trunks occur horizontally in the lower parts of the sequence, mostly in the conglomerate beds mixed with shell fragments, which represents high energy, shallow water near inland environment. The wood trunks lay down horizontally in the beds and thus parallel to bedding surface.

The host rock of this fossil is the silicified sandstone, and the wood was also burrowed, both horizontal and vertical burrows. After the burrowing, silica precipitated in the holes, thus made the wood trunks became silicified. The silicified wood appears to have various colours (black, green, cream), which represent silicified in different diagenetic stages with different mineral compositions. Since the wood trunks had been intensively burrowed and silicified, all the tissues and textures have been destroyed, thus led the recognition and classification of the plant fossil becoming difficult or even impossible (Fig. 65).

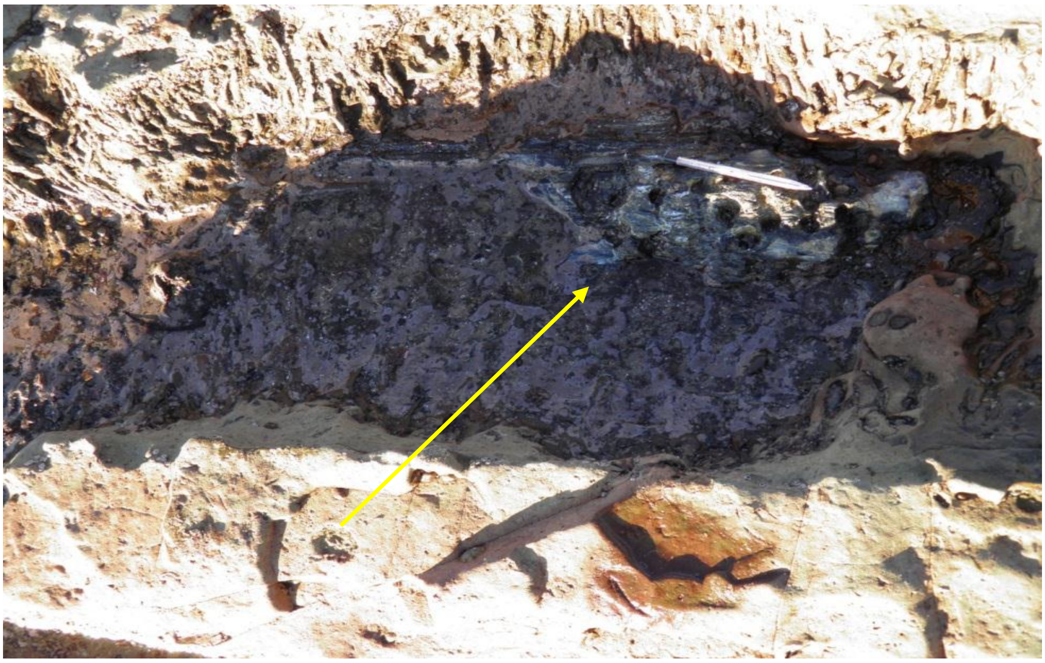


Figure 65: Extensively burrowed and silicified wood trunk (arrow). Pen is 13 cm for scale.

In conclusion, Mzamba Formation is a fossil-bearing succession of Cretaceous in age. Various fossils, including fauna and flora had been found in the sediments. We had made some new discoveries of fossils, including bivalve, gastropoda, echinoderms, brachiopoda; trace fossils of tracks, burrows and coprolites, and plant fossils of silicified wood trunks.

From evolutionary point of view of the sequence, the benthonic species predominated in the lower part in the succession, whilst the planktonic species are abundant in the upper part of the sequence, which points to increase in water depths of the depositional environment; thus the Mzamba Formation, from the bottom to top, constitutes a perfect transgression sequence.

Further work still needs to be done in the palaeontology study to identify more detailed species of these fossils. At current stage, we identified these fossils only to Family or Genus, not to Species.

CHAPTER 8 DIAGENESIS

8.1. Introduction

Diagenesis is the term used for all the alterations that a sediment undergoes after deposition and before the temperature could be regarded as metamorphism. Diagenesis encompasses all natural changes in sediments occurring from the moment of deposition, continuing through compaction, lithification and beyond—stopping shortly at the onset of metamorphism. The boundary limit between diagenesis and metamorphism is not precise in terms of pressure or temperature, nor is there a sharp boundary between diagenesis and weathering (Ali et al., 2010). Diagenesis is both complex and easily misunderstood because natural systems of water, geochemistry, climate and a variety of other factors drive these processes (Nobles, 2010). Carbonate diagenesis operates in three principal environments: the marine, near surface meteoric and burial environments, and there are features of the cementation, recrystallization, compaction fabrics and other textures which are diagnostic of a particular diagenetic environment.

Diagenesis is believed to be an active field of research in sedimentology, because of its importance in petroleum geology. After deposition, carbonate sediments are subjected to a variety of diagenetic processes. The two most important diagenetic processes are compaction and lithification. During diagenesis, carbonates may undergo changes in porosity, mineralogy and chemistry. Carbonate minerals are more susceptible to dissolution, recrystallization, and replacement than most siliciclastic minerals. Carbonate minerals may experience pervasive alteration of mineralogy, e.g. aragonite-to-calcite. These changes therefore can alter or destroy the original depositional textures. Carbonate sediments are usually not transported far from their source, so their mineral size, shape and sorting have little to do with transport energy system.

For the purpose of Scanning Electron Microscope (SEM) study, two samples of sandstones and two mudstones were analysed. The four samples were carbon coated and the analysis was made by using SEM model of Jeol JSM-6390LV, Voltage 15 kV, with Secondary Electron Detector and Energy Dispersive X-Ray (EDX) detector.

8.2. Cementation

A chemically precipitated substance that binds particles of clastic rocks is termed cement. The cement forms an integral and important part of a rock, and its precipitation affects the porosity and permeability of the rocks. Many minerals may become cements, with the most common being silica, calcite, clay minerals, but iron-oxide, phosphate and other carbonates can also act as cements, including gypsum, anhydrite, feldspar and zeolite minerals.

The slides were stained with chemicals of Alizarin Red S to distinguish dolomite from calcite since these two minerals are very similar and are difficult to distinguish from each other. In the Mzamba Formation, four types of cements are distinguished, i.e. calcite, smectite, illite, and quartz have been identified by using transmitted light microscopy and SEM techniques. Among these four types of cements, different cementation textures are recognised.

The pores between detrital grains are filled with an aggregate or mosaic of minerals, most frequently carbonate, silica or clay minerals. Pore-filling may be partial or complete, may consist of only one mineral or several minerals, and may or may not be associated with replacement of detrital grains. Sparry calcite cement is associated with this texture. This texture is particularly common in the carbonates of the Mzamba Formation.

Figure 66: Pore-filling texture in a bioclast.

8.2.1. Calcite cement ($CaCO_3$)

The calcite cement show two different textures, micrite and sparite. The micrite cement is dull-looking with unclear crystals, and it fills the spaces between the allochems and grains. In most of the slides, micrite is more than 50%, which shows that the depositional environment had low energy. The sparite cement is clear to translucent, bright, with large calcite crystals. It shows that the depositional environment has strong currents while micrite being fine crystalline sized, has been washed away by strong current. Sparite cement can never be more than 50% in volume in thin-sections; many carbonates are composed of nearly 100% micrite, which is also the norm we see with the Mzamba sediments.

Precipitation of cements in carbonate sediments is a major diagenetic process and it takes place when pore-fluids are supersaturated with respect to the cement phase and there is no kinetic factors inhibiting the precipitation (Tucker et al., 1990). Petrographic and geochemical studies of these cements enable deductions to be made of the environment and conditions of cementation. Cementation of limestones requires an enormous input of $CaCO_3$ and an efficient fluid flow mechanism for complete lithification. The source of $CaCO_3$ varies with the different diagenetic environments.

As mentioned earlier, two types of cements i.e. carbonate (calcite) and clay minerals (smectite and illite) have been identified in the Mzamba Formation. Different textures are distinguished among the cements.

8.2.1.1. Calcite Micrite

Micrite cement is composed of anhedral calcite crystals with grain size <4µm which is then equal to the micrite category of Folk (1962). This cement is found in the mudstone lithofacies, fine sandstone lithofacies and reef facies. Micrite cement is one of the major cement types in the Mzamba. The rocks that contain micrite as the dominant cement usually show a total grain content of 30%-50% and micrite cement content of about 15% - 35%. The availability of glauconite and vitrinite in the samples indicates that the micrite was formed in an early diagenetic stage in a reducing environment. Micrite cement is an unstable mineral phase in diagenetic process, therefore it has been patchily neomorphosed to microspar, and some of it has been leached out and formed secondary pores.

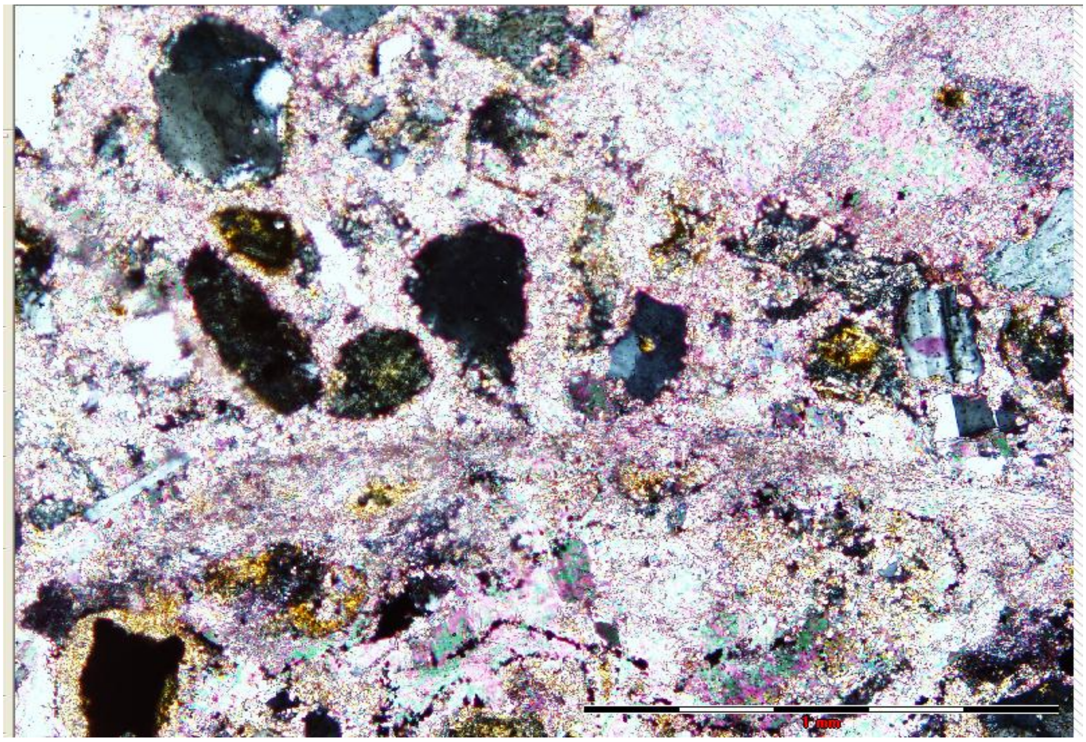


Figure 67: Pinkish calcite micrite cement. Scale is 1mm for this photo.

8.2.1.2. Calcite sparite

Sparite calcite cement type is found between grains, with grain content of about 50% - 75%. Sparite in carbonate means that its crystalline grain-size is >4 µm, and usually is about 10-20µm in grain size. Granular sparite is also a major type of cement in Mzamba Formation. This sparite cement shows clear, bright, tightly packed anhedral crystals under microscope. The coarse-grain, bright appearance of the cement point to precipitation from a low ionic concentration in a dilute phreatic environment where the crystals grow slowly, with better expulsion of impurities (Liu, 1996).

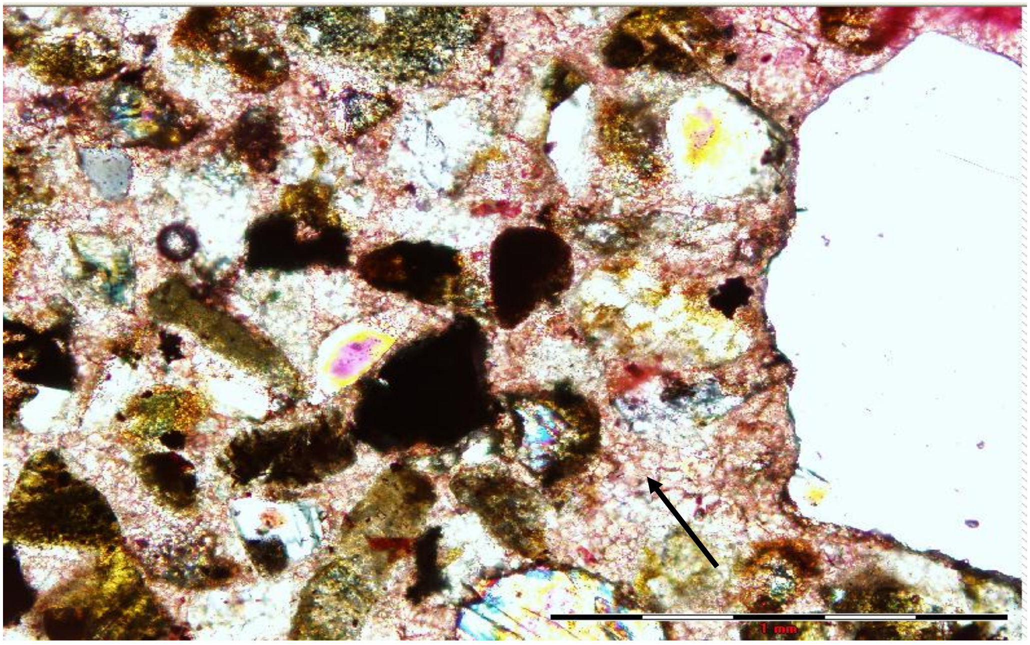


Figure 68: Calcite sparite cement (arrow). Scale is 1mm for this photo.

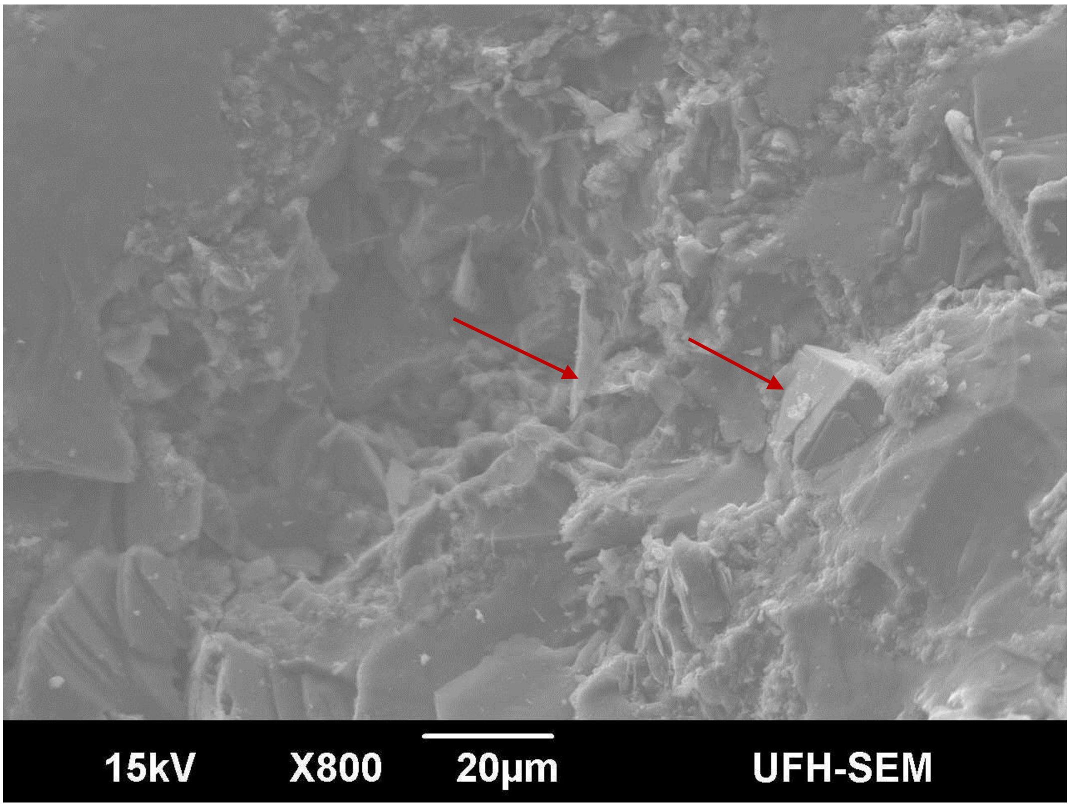


Figure 69: SEM photomicrograph showing calcite cement with clear euhedral crystals.

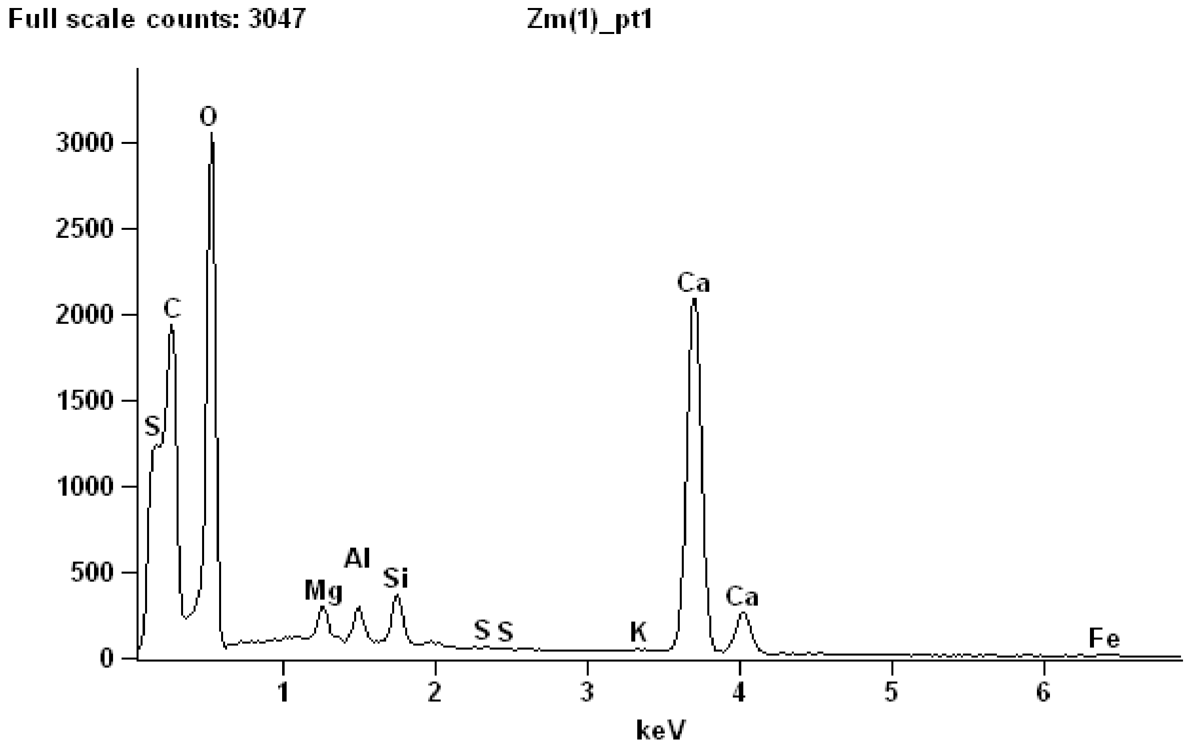


Figure 70: Calcite cement identified by SEM-EDS, also mixed with small amount of clay minerals.

8.2.1.3. Clay cement

Smectite $CaMg_2(S_{i4}O_{10})(OH)_2 \cdot nH_2O$

This is a name used for a group of phyllosilicate mineral species, the most important of which are montmorillonite, beidellite, nontronite, saponite and hectotite. It appears as a honeybox texture, because it exhibits a typical honey bee hive (Liu and Buchardt, 1993). Smectite usually changes to illite, a process termed illitization. It is a common mineralogical reaction during the burial diagenesis of clay rich sediments, such as mudstones and shales. Smectite is the original clay mineral which could be converted to illite with the temperature increase during diagenesis, and constitutes a smectite-illite co-exist mixture among the same crystallites giving rise to non-periodic structure (Lanson, et al., 2009).

Smectite clay matrix occurs in the fine-mudstone facies and sandstone facies. It resembles a honeybox texture with SEM analysis. In Mzamba sediments, the clay matrix content in thin section varies between 20% - 50% by volume, and the mineral composition is smectite and illite clays. It occurs together with quartz silts, which points to a low-energy, quiet water, reducing environment.

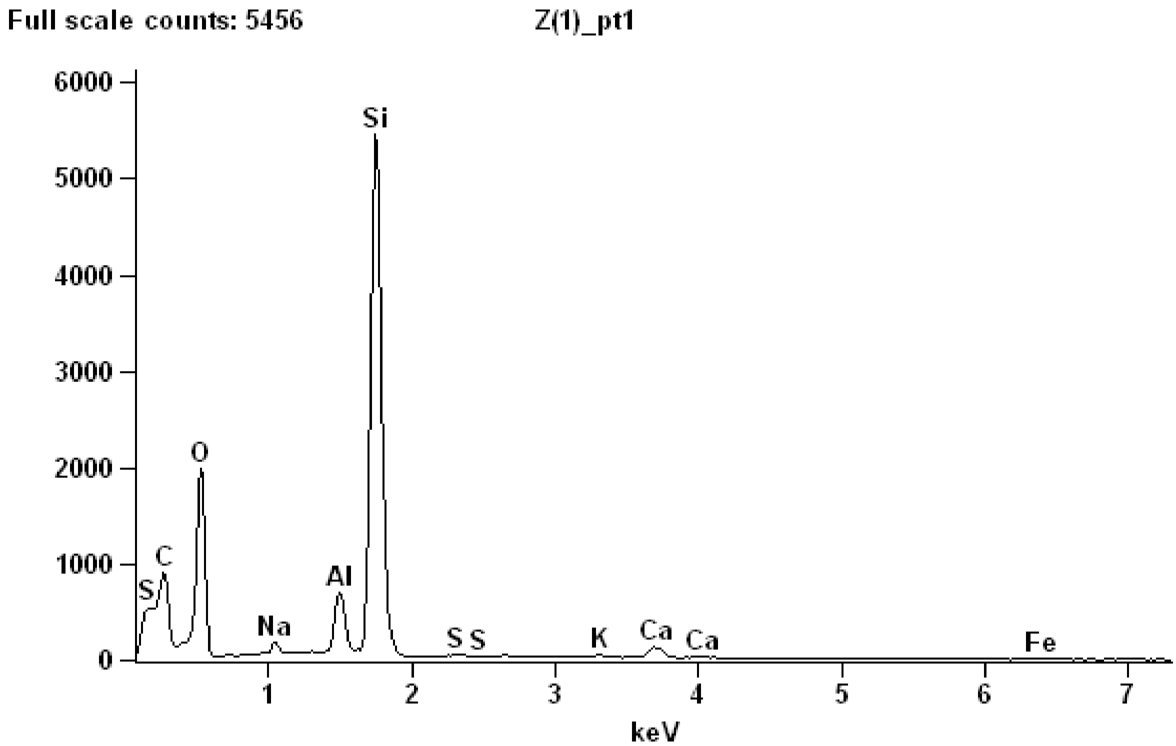


Figure 71: Silicate (clay) cement and minor calcite mineral mixture identified by SEM-EDX.

8.2.1.4. Quartz cement (SiO_2)

There is also an abundance of quartz cement found in the siltstone and sandstone, determined by microscope and SEM, but it is usually difficult to observe by using conventional petrographic method. It is one of the dominant cement types, it appears as fine micro quartz cement between the grains of the Mamba sediments. Quartz cement as syntaxial overgrowths is one of the two most abundant cements in sandstones. It shows dense fine granular quartz cement filling the pore space (Fig. 72 & 73).

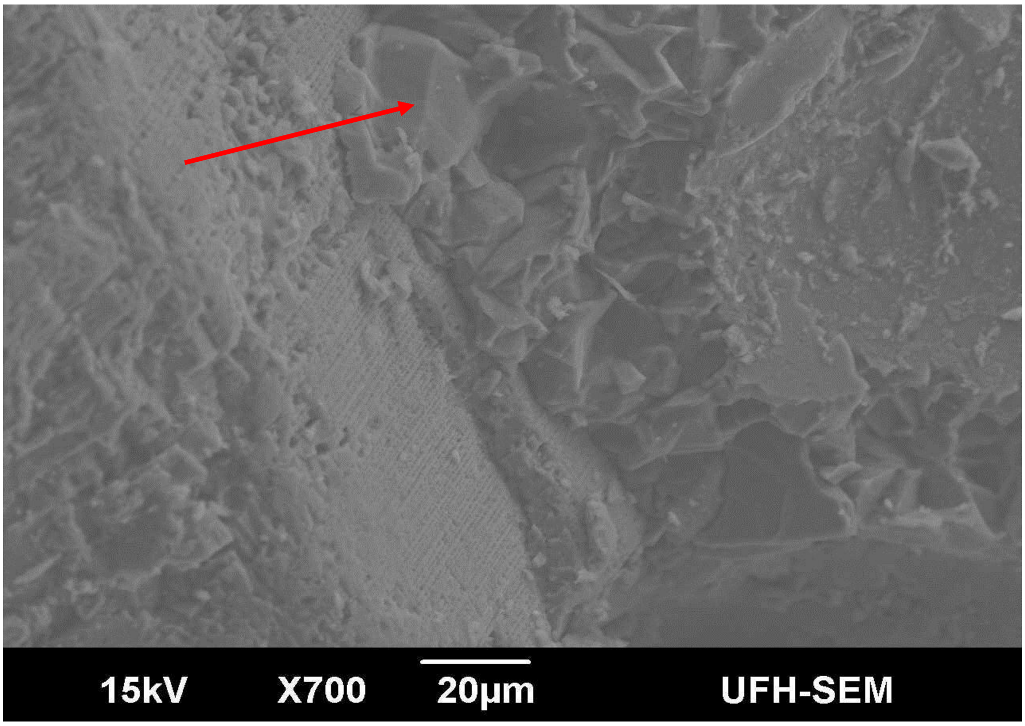


Figure 72: SEM photomicrograph showing quartz cement in sandstone (arrow).

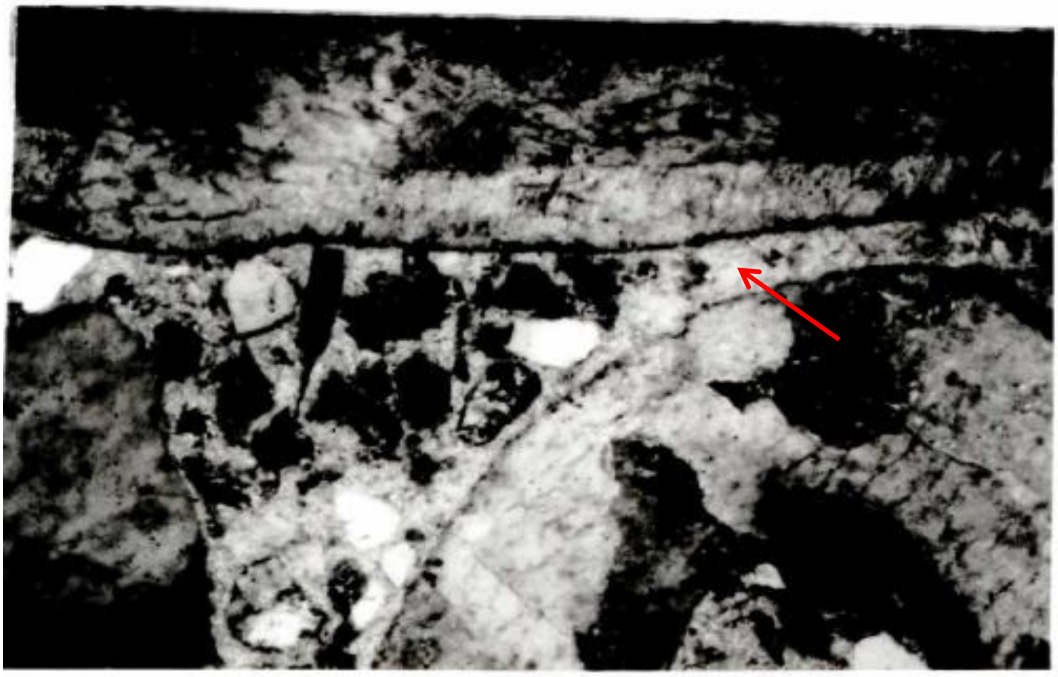


Figure 73: Microscope photomicrograph showing quartz cement (arrow).

8.2.1.5. Isopachous quartz rim cement

Syntaxial quartz rim cement is found around grains. It is bright and fibrous (Fig.74) which is likely to have precipitated directly from silica-rich pore fluids.

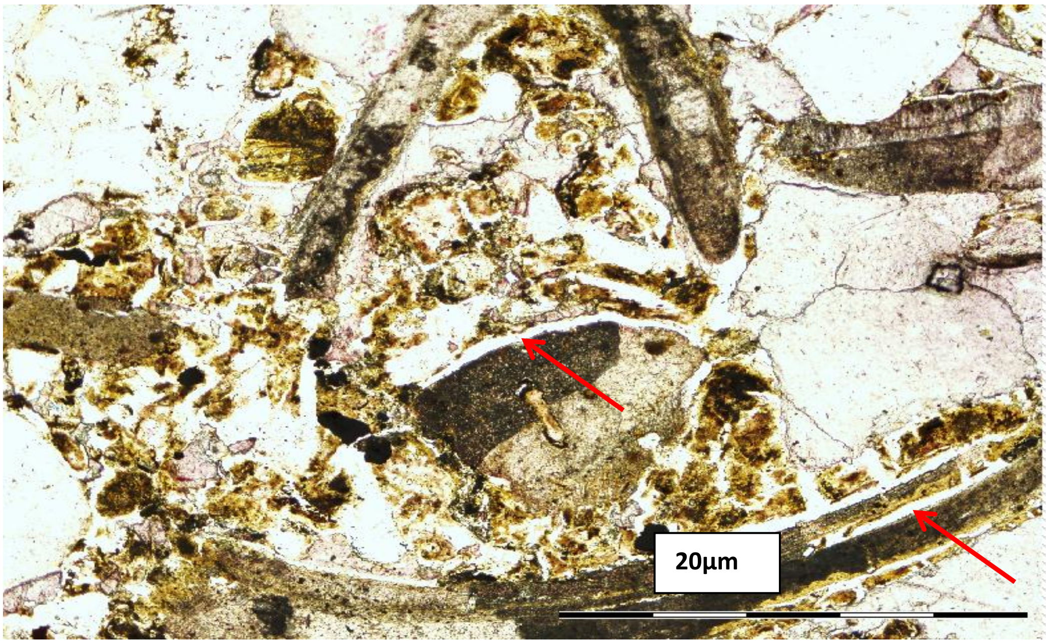


Figure 74: Pore-filling texture of isopachous rim (arrows) of quartz cement.

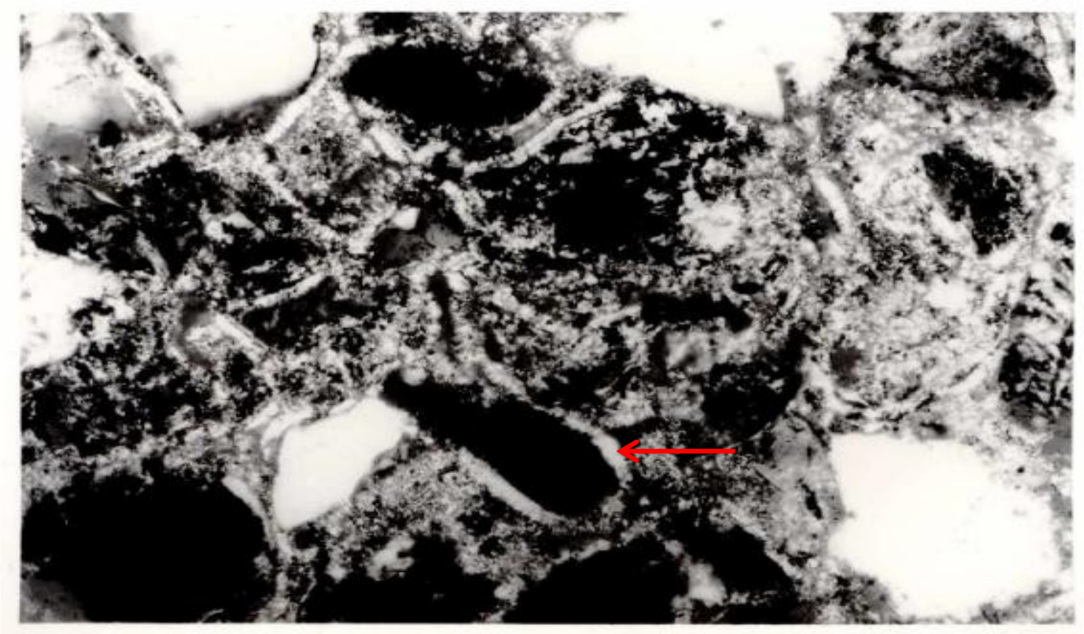


Figure 75: Isopachous quartz rim cement (arrow) around grains.

8.2.1.6. Micrite envelopes

This fine-grained calcite rim is found surrounding the grains in the rock. The thickness of the rims is only a few microns. It is mostly found surrounding bioclasts, and also some peloids. The presence of micrite envelopes cement in bioclasts may assist in preserving the shape of the bioclast when removed by dissolution process that occurs during diagenesis, so the bioclast can be filled by sparry calcite to form a cast.

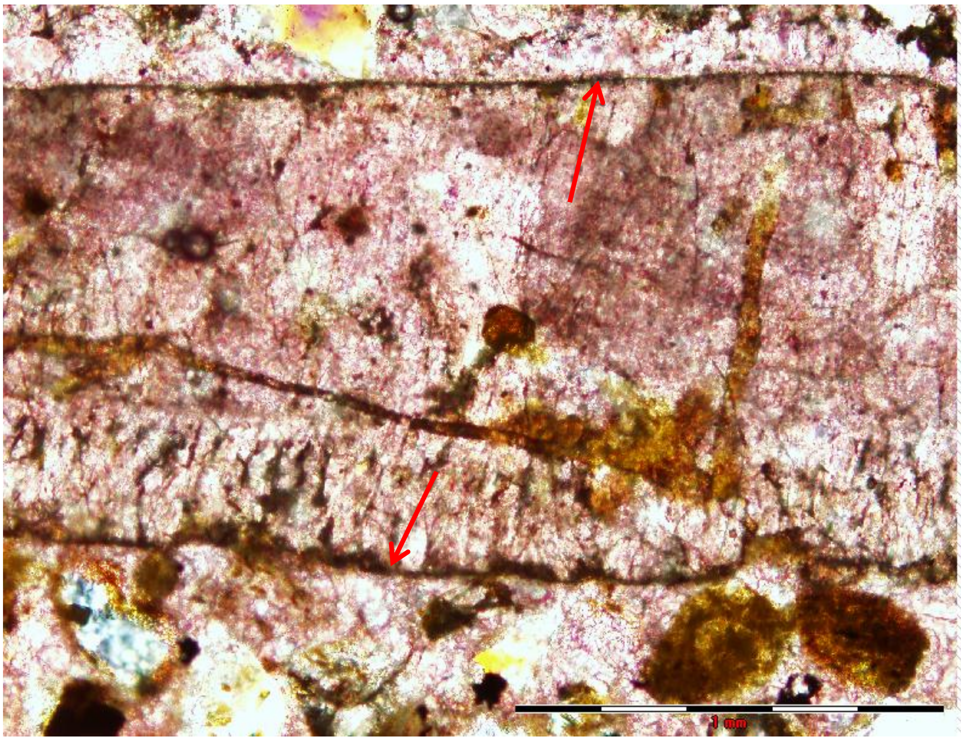


Figure 76: Micrite envelope (arrows) around a bioclast.

8.2.1.7. Isopachous rim calcite cement

Bright white to pale-yellow rims of calcite are present in the Mzamba Formation. The rims are single layered, and equal in thickness. The crystals are found surrounding grains, creating a bright rim. The rim consists of microcrystalline crystals of calcite or silica. Isopachous rim cement is a good indicator of phreatic diagenetic environment where the pore space is fully saturated with pore-fluids and therefore cement could grow up around the surface of the grains with a vertical orientation to grain surface. This cement forms only in phreatic diagenetic environment, never in the vadose environment.

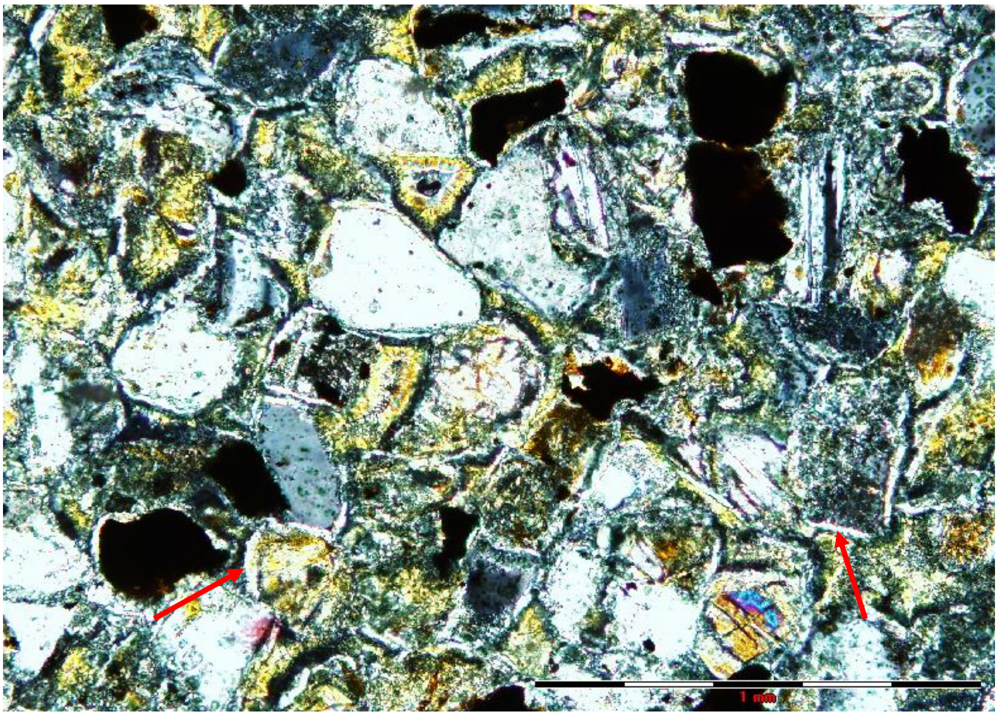


Figure 77: Bright white isopachous rims cement (arrows).

8.3. Authigenic Minerals

8.3.1. Authigenic Plagioclase $CaAl_2Si_2O_8$

Authigenic plagioclase is common and occurs in almost all the slides we made. It occurred as fine crystalline grains in shape of laths or flakes that exhibit polysynthetic twinning. It has weak birefringence and fairly low relief, with cleavage planes that are not well developed under microscope. It shows typical euhedral lath or plate shapes of plagioclase which embedded in clay matrix, indicating the plagioclase was grown up from mud matrix during diagenesis. The picture below shows euhedral, needle-like authigenetic plagioclase occurring in matrix.

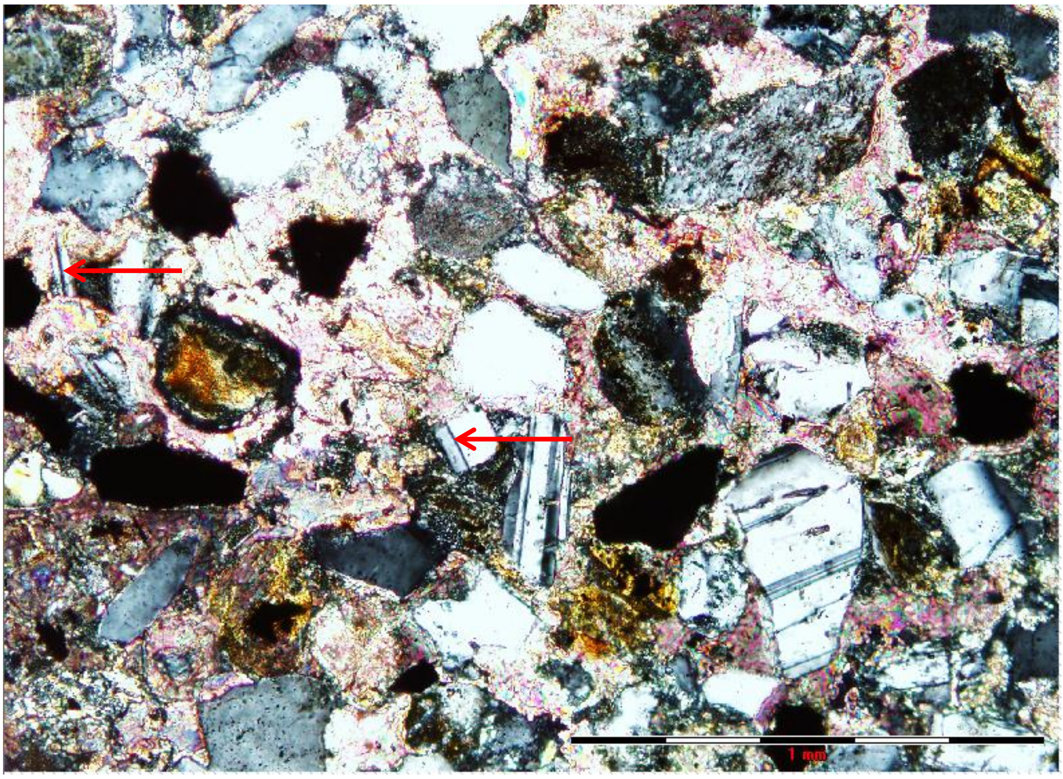


Figure 78: Authigenic plagioclase with twinning (arrows).

8.3.2. Authigenic Quartz (SiO_2)

Authigenic quartz occurs in euhedral to subhedral shapes and different crystalline sizes, and it's very common in the rocks and is present in all the slides. It appears as colourless, with low relief and no cleavage under microscope. Quartz grains are generally micro- to fine grained sized, they appear black and white when the stage is rotated. Some quartz grains are bluish in the middle, showing blue coloured interference due to the thin-section is not in a standard thickness. The euhedral shape of quartz grain indicates that they were grown in situ during diagenesis, and have not been weathered, eroded or transported, and therefore they are not terrigenous clastic grains which coming from outside of the deposition basin. The euhedral to subhedral shapes of the grains are good indicators to distinguish authigenic minerals from detrital minerals which are usually rounded or anhedral due to transportation.

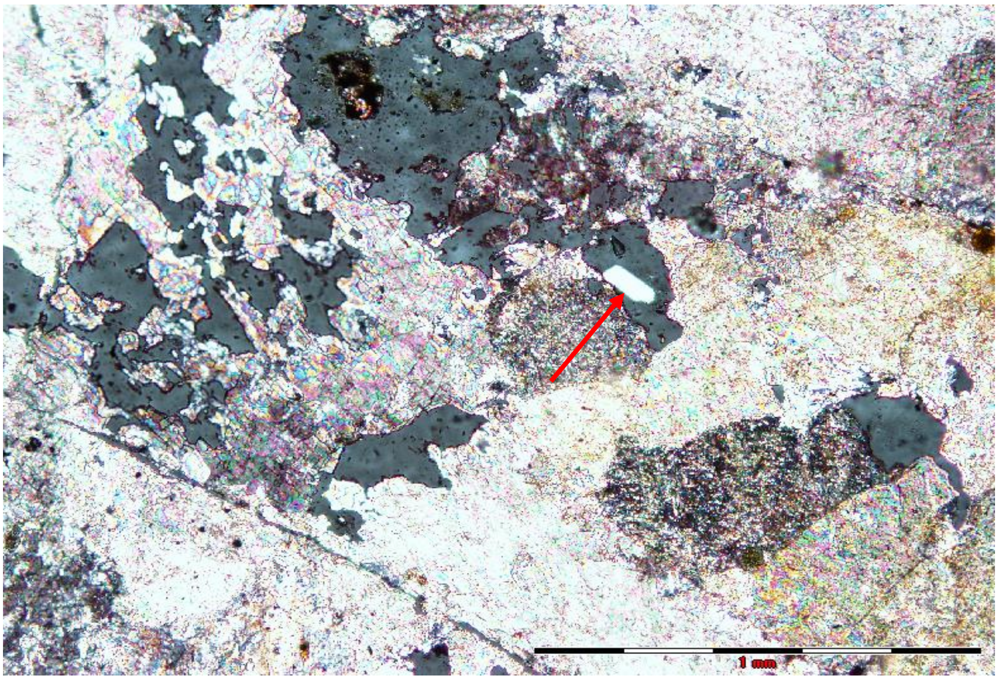


Figure 79: Clean authigenic quartz (arrow).

8.3.3. Authigenic Feldspar

Similar to authigenic quartz, authigenic feldspar has also been found in the Mzamba Formation. Feldspar can be easily confused with quartz since their optical properties are very similar to each other. It occurs as a colourless or pale brownish coloured mineral, with low optical relief and fairly fine crystalline grains under microscope. Feldspar appears not as clean as quartz under microscope because it contains more impurities and inclusions and is easily weathered if the rock exposed on the Earth's surface. It is presenting not as common as authigenic quartz, and is found only in a few layers in the Mzamba Formation. It exhibits cleavage, and unclean optical properties, which can be used to distinguish from quartz.

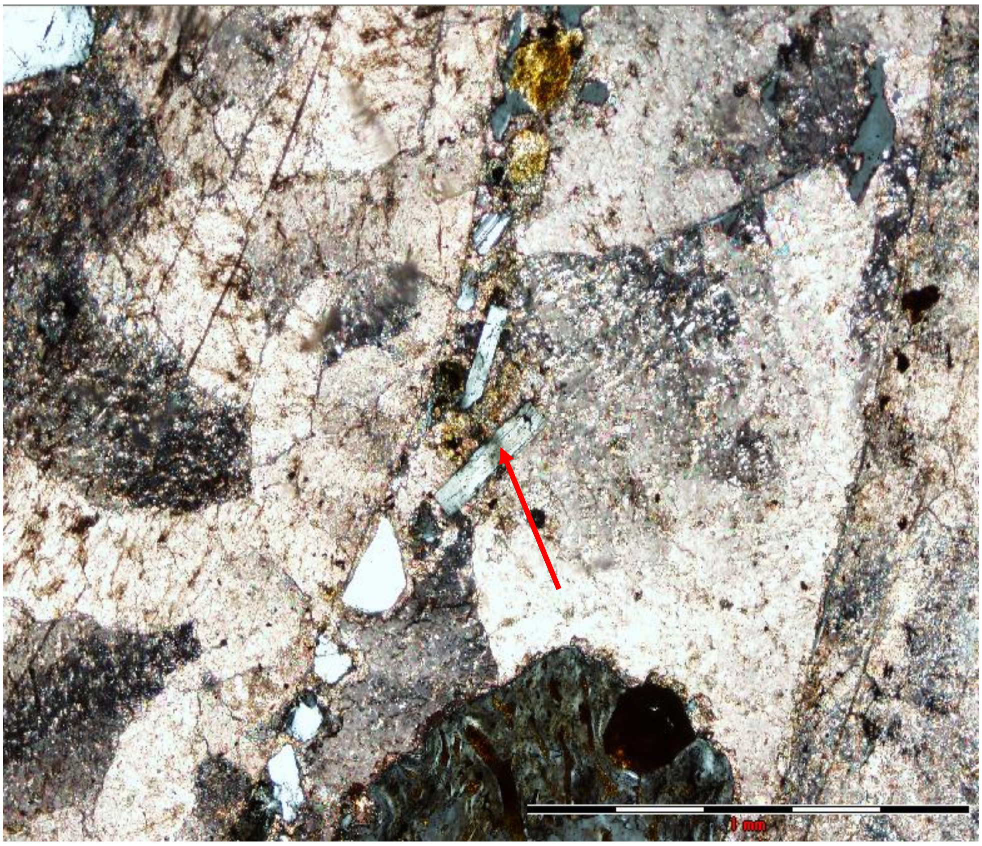


Figure 80: Authigenic feldspar, with cleavage planes (arrow).

8.3.4. Authigenic Glauconite $(K,Na)(Fe^{3+},Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$

Glauconite is a diagenetic K- and Fe-rich clay mineral, and occurs usually as pellets or nodules in the Mzamba Formation. Glauconite occurs only in reducing environment, never in oxidic environment, therefore it is a good indicator for depositional environment, and particularly it is common in organic carbon-rich marine environment, such as black shales and sandstones (Liu, 1990; Liu & Chen, 1994). This mineral is also linked to slow sedimentation rates during sediment accumulation. Fast deposition environment is unfavourable to the formation of glauconite pellets. The size of the glauconite pellets is usually 1-2mm, and the pellets are oval or spherical in shape.

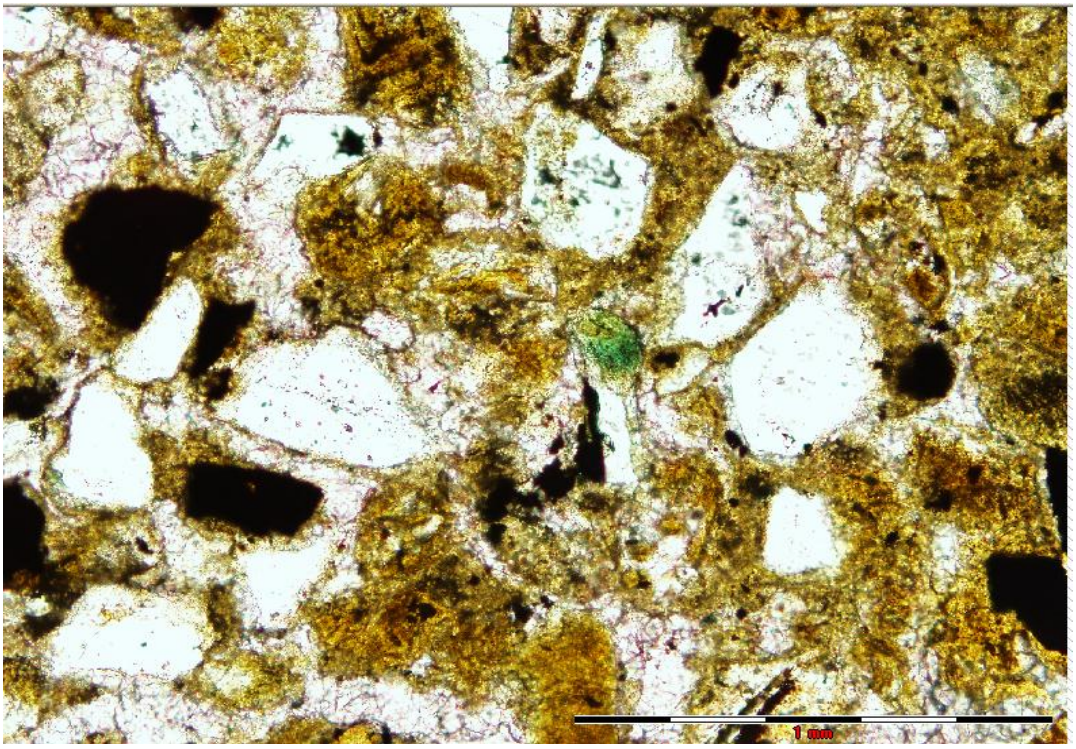


Figure 81: Bright glauconite pellet (middle greenish grain).

8.3.5. Authigenic Vitrinite (organic carbon)

Vitrinite is an organic mineral, and is rich of organic carbon. It occurs as black, reddish or pinkish in colour under microscope, and the more mature, the more darker in colour it becomes. It forms diagenetically by thermal alteration of lignin and cellulose in plant cell-walls. Vitrinite is the most common component of coals, and the study of vitrinite is key for identifying the maximum temperature of diagenesis, and the thermal evolutionary history of sediments in sedimentary basins. Since the vitrinite in the Mzamba Formation is still in red brownish in colour, therefore the sediments were not suffered high temperature diagenetic change, and probably only entered into shallow-burial diagenetic stage (Liu, 1995, 1997). This is also consistent with the younger age (Cretaceous) of the sediments.

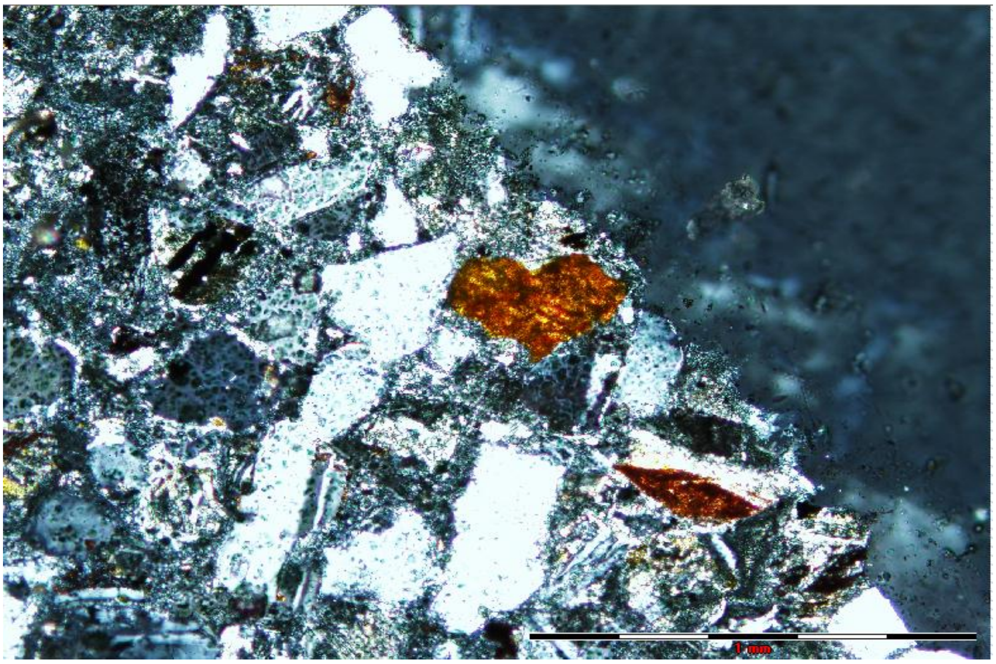


Figure 82: Pinkish, heart-shaped vitrinite pellet (pink-brownish coloured).

8.4. Mineral conversion

Clay minerals are the most important component of mudstone and sandstone in the Mzamba Formation. They are formed by the alteration of existing minerals or by the synthesis from elements when the sediments were deposited. Individual clay minerals are usually too small to be examined under the optical microscope, but they are much easy to be identified by SEM (scanning electron microscope). Clay minerals are usually platy or fibrous in shape, they are sensitive to temperature change during diagenesis. Therefore, clay minerals are good indicator for diagenetic stage, burial temperature and burial depth. The following clay minerals are found in the Mzamba Sediments:

Smectite-illite conversion

$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$

SEM images confirm that there is illite cement present in mudstone and sandstone in the Mzamba Formation. Illite has fabric-like texture, and is the cement between detrital grains. The illite fibres are rather fine and appear in sets. These fibres in the mudstone appear to have grown from the edges of detrital quartz grains. The filamentous and platy habits of illite might provide a vastly increased surface area. This fibrous illite may severely affect the porosity and permeability of sandstone, and can cause serious problems for hydrocarbon and groundwater production.

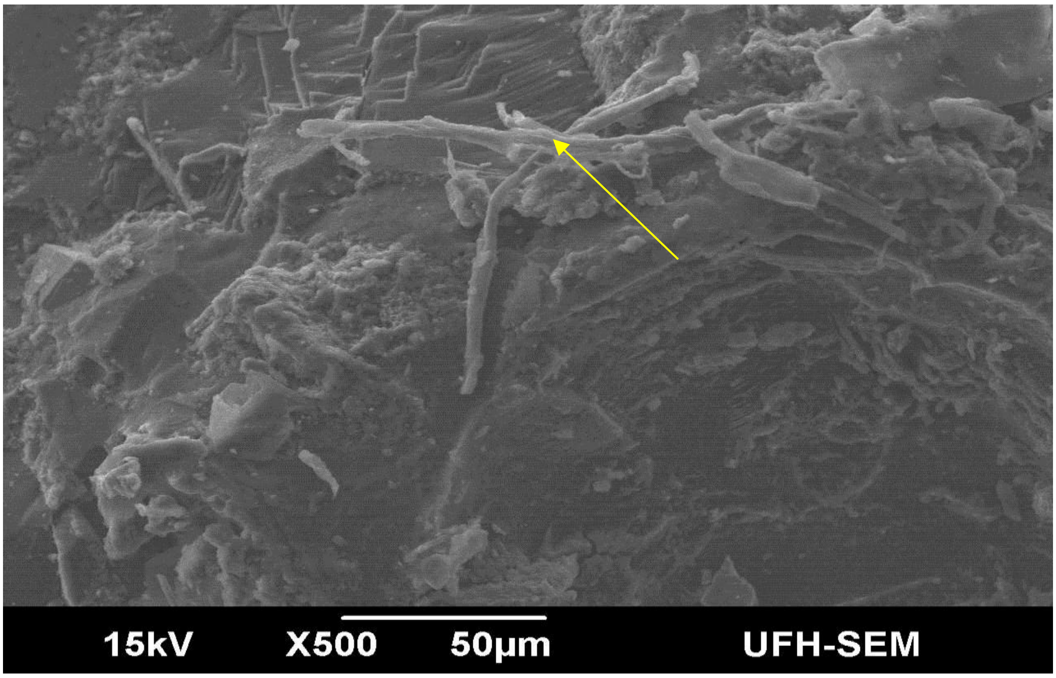


Figure 83: SEM photomicrograph showing Illite fibres (arrow).

In the sandstone sample, the illite occurs as platy and fibrous mineral, exhibiting mica structure (Fig. 84) since it is a phyllosilicate. Where it occurs in this nature, it is associated with smectite crystals and quartz grains. The platy illite is not widely distributed in the sample, but it also reduces porosity and permeability due to it stacks in pore-space.

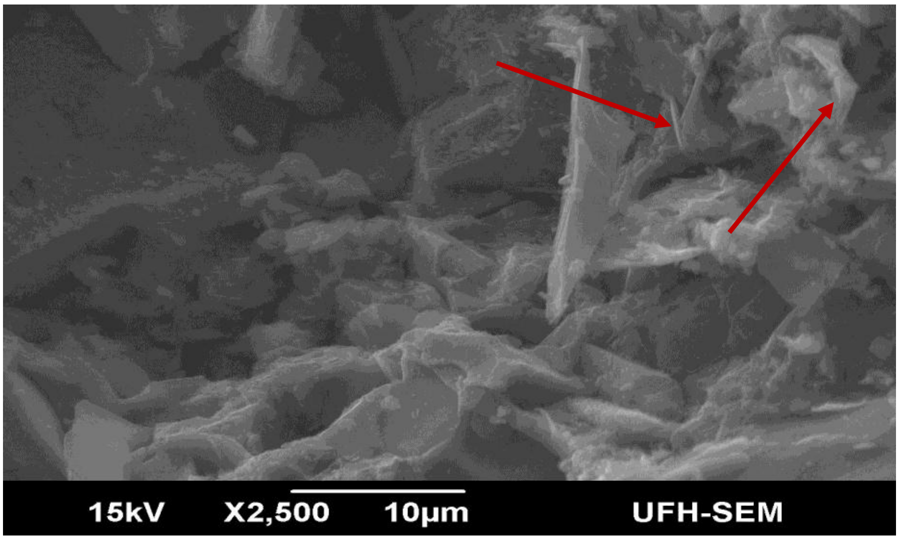


Figure 84: Platy and fibrous illite (arrows), associated with smectite and quartz.

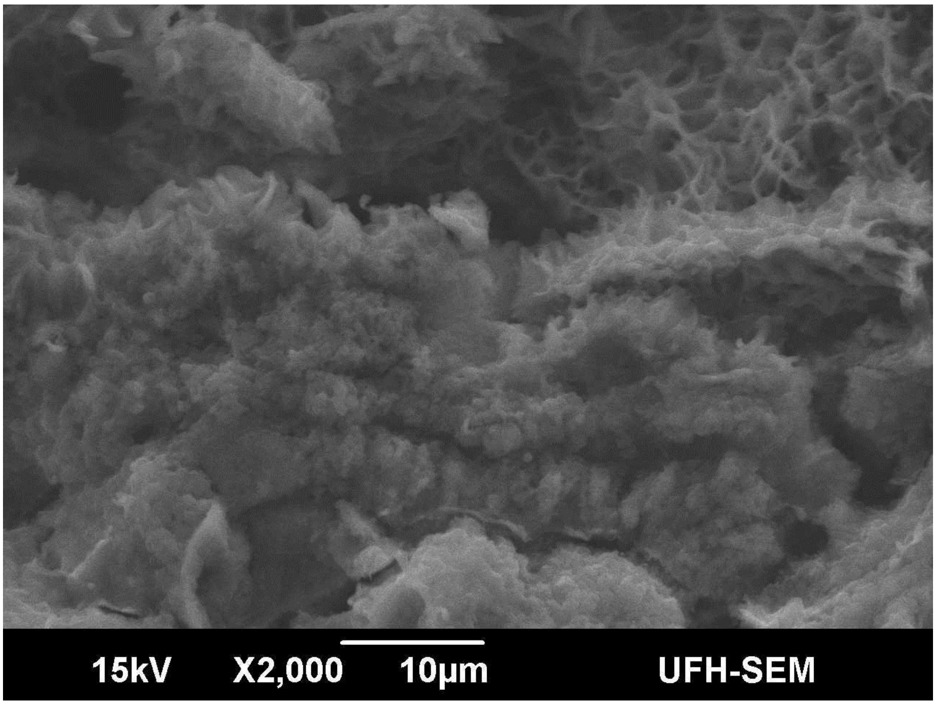


Figure 85: SEM photomicrograph showing smectite, resembling honeybox texture (upper right), and it gradually changes to typical fibrous shaped illite (middle).

The smectite illitization developed as a function of burial depth. The illitization process implies polytypic changes evolving from turbostratic staking in smectite. According to (Merriman & Peacor, 1999), the smectite-to-illite transition is complete in sequences where pelites have been subjected to sedimentary burial with associated overburden stress and temperature increase at depths in order of ~3000 metres, the illite formation indicates a burial diagenesis stage. Further temperature and burial depth increase could lead illite changing into sericite, then muscovite in a more late diagenetic stage.

8.5. Recrystallization Texture

Recrystallization is a diagenetic process, which takes place due to increased temperature and pressure. During recrystallization, the grains making up the protolith change shape and size. The density of the mineral may also change during the process if the diagenetic environment was involved in high pressure. Recrystallization occurs due to heating of the protolith. The temperature at which this process occurs can vary depending on the minerals present. In the course of recrystallization, inclusions or impurities remain behind in their same relative positions so that relict structures may still be preserved. Thin section identification showed evidence of a broken oolith showing recrystallization, which lead to formation of sparry calcite.

Some slides exhibit recrystallization texture of bioclasts, which refers to a ‘ghost” of original bioclast that has been partially or totally destroyed by recrystallization. The original fibrous calcite has been changed to coarse granular calcite after recrystallization of the bioclast, this type of recrystallization is also called neomorphism.

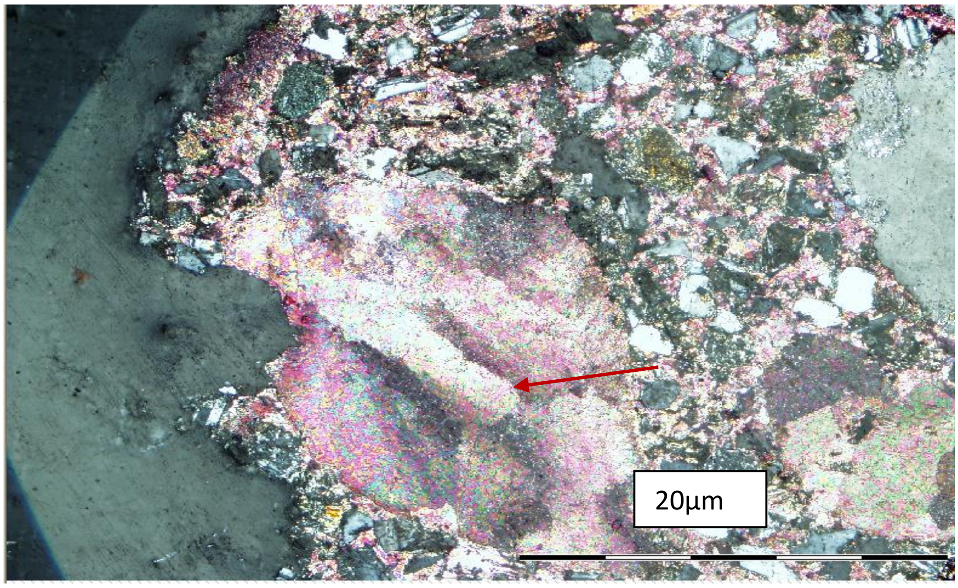


Figure 86: Recrystallization texture of calcite (arrow) in a bioclast.

Thin-section analysis reveals that quartz overgrowths are also present in the slides. The newly growth part is in optical continuity with the inside detrital grains. Under microscope of parallel light, the overgrowth outside part is usually more pure, more bright and clean than the inside detrital grains, which indicating that the overgrowth part was formed by chemical precipitation around the surface of the detrital quartz grains after the sediments were buried. Quartz overgrowth on framework quartz grains tends to develop at diagenetic temperature at about 60^{o}-$100^{o}C$, which is equal to a burial depth of about 1.3-2.7km if considering the Earth’s surface temperature is about $20^{o}C$ (Liu, 2002; Liu and Greyling, 1996).

Overgrowth texture is typical in the quartz grains, thus it is called quartz overgrowth. Actually, there was also feldspar overgrowth in slides in the Mzamba sediments. Quartz overgrowth is observable, in which the cement is in optical continuity with the detrital quartz grain in which it nucleated. The dust line which indicates the original faint boundary of the particles, shows the size and shape of the original quartz or feldspar grains.

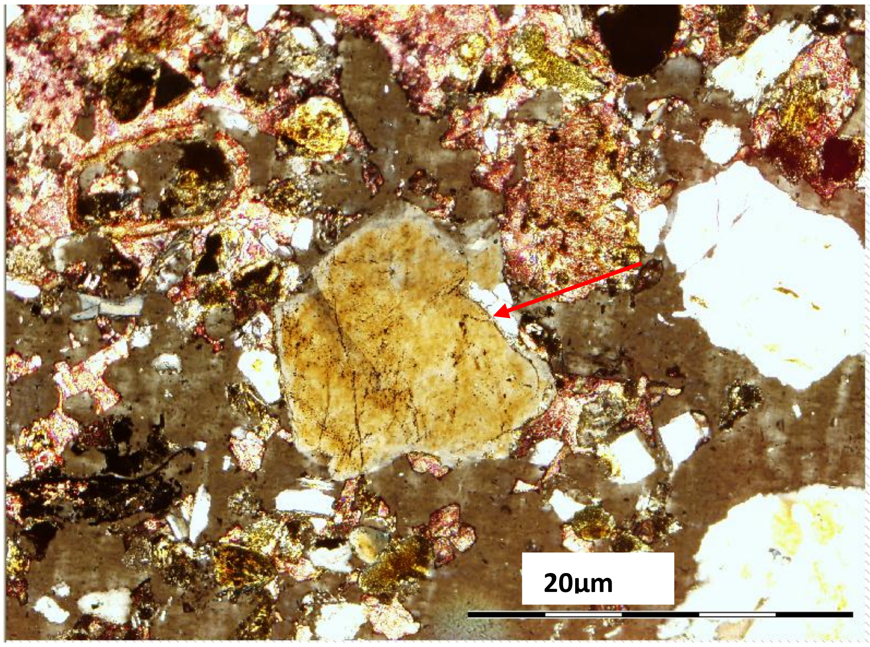


Figure 87: Quartz overgrowth texture (arrow) showing the dust line of the original boundary of the quartz grain.

8.6. Replacement Texture

Replacement occurs where a mineral or mineral aggregate has been replaced by a new mineral with different chemical composition. The mineral could keep the shape of the original mineral (Pseudomorphic shape) or totally changed to a new mineral shape. Replacement happened when the old mineral becomes unstable due to diagenetic environment change thus leading to formation of a more stable mineral which replaces the unstable mineral. The common example is quartz and calcite, quartz can replace calcite in an oxidic environment, whereas calcite can replace quartz in an alkaline environment. This texture has also been found in the Mzamba Formation, calcite replaced feldspar grain is observed. The calcite replacement taking place here is selective replacement, i.e. calcite replaces quartz and feldspar, and not replaces other minerals in the sediments.

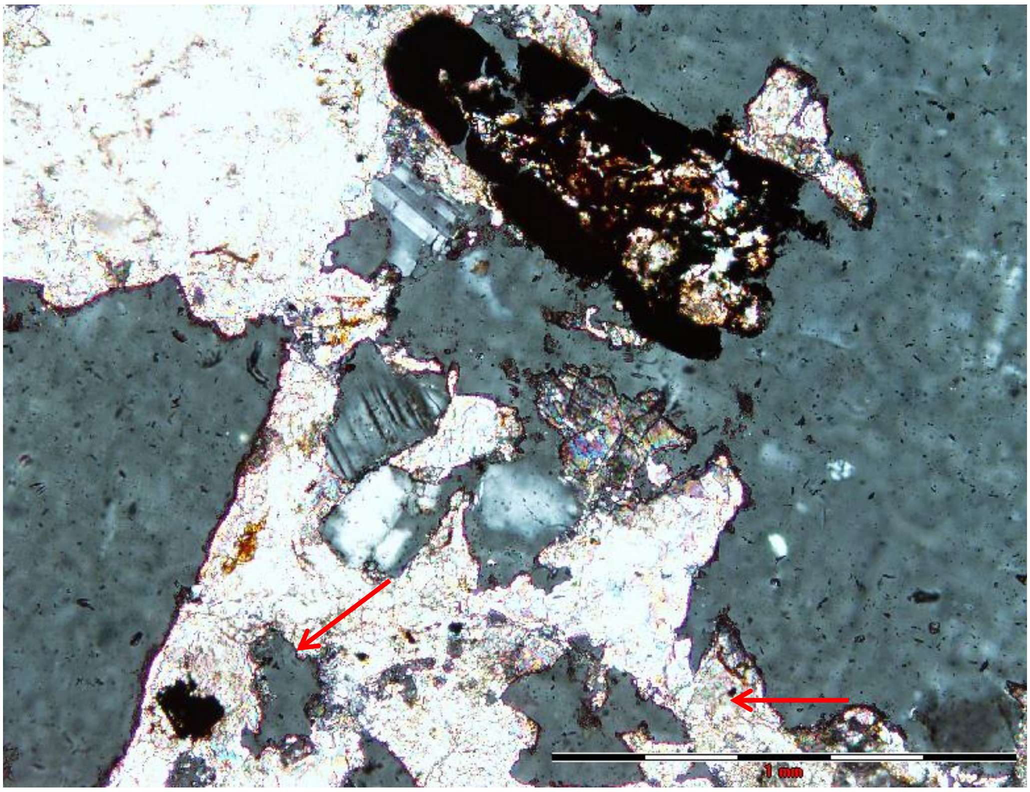


Figure 88: Calcite replacing feldspar (arrows).

8.7. Diagenetic Sequence

Table 3 Diagenetic process and pathway of the Mzamba Formation

Mineral textures	Syndiagenesis	Early diagenesis	Late diagenesis
Glauconite pellets			
Micrite envelopes			
Smectite			
Calcite micrite			
Calcite sparite			
Vitrinite			
Isophacous rim			
Quartz cement			
Smectite-illite			
Neomorphism			
Replacement			
Dissolution			
Deformation			

The three phases have thus been named by the Fairbridge (1967) as follows:

a) Syndiagenesis

b) Early diagenesis

c) Late diagenesis

This is a spatial classification designed to establish the environments of the mechanical and geochemical processes. The three phases are evolutionary and dynamic, passing from one to the next across recognizable boundaries. The following describes the diagenetic processes taking place in the Mzamba sediments, according to the three stages.

8.8.1. Syndiagenesis

The most important diagenetic processes taking place during this stage are recognised as follows:

Microbial micritization- this appears to be the first process taking place in the sediments, as micro-organisms present in the marine sediments bore into the carbonate allochems, which in turn reduces the carbonate grains to micrite. The micrite envelopes frequently observed around the detrital grains and bioclasts are a result of this process. This process usually occurs in shallow water environments.

Cementation- this is the process by which calcite cement precipitated, binding the grains together. These crystals form in the pores of the sediment, and resulting in the formation of a consolidated rock. The cement can be either micritic calcite cement or sparry calcite cement depending on the different diagenetic environments. This process continues till the middle diagenesis.

Clay mineral authigenesis- It refers to the alteration of one clay mineral converted to another. In this case, smectite changes to illite, a process known as illitization. This smectite-to-illite transition occurs in clay-rich sediments, such as the mudstone of the Mzamba Formation. This process is facilitated due to the co-existence of illite and smectite in the same crystallites.

8.8.2. Early Diagenesis

Cementation- this is a process continuing from early diagenesis. At this stage, the remaining pores in-between grains are filled with cements.

Dissolution- Understanding compaction is important for porosity prediction in sedimentary basins. This process resulted in the close packing of quartz and feldspar grains in some slides. The close packing or the squeezing of the mineral grains was as a result of mechanical loading or structural pressure.

Recrystallization- the extent of the recrystallization was determined only by microscopic observations. This process is observed clearly on the allochems (ooids) whereby the oolith looks broken and recrystallized to sparry calcite, micrite changed to granular sparite, and quartz overgrowth textures are formed.

8.8.3. Late Diagenesis

Replacement- this is the process of almost simultaneous solution and deposition by which a new mineral of partly or totally different chemical composition may grow in the body of an old mineral or mineral aggregate. According to the above explanation, replacement is accompanied by very little or no change in the volume of the rock, but the mineral types and chemical compositions could be changed. In practise, this process is accompanied by expansion or contraction. Calcite completely replacing feldspar grain is evident in this sediment. During the burial stage, the replacement taking place in the sediments is selective replacement of feldspar grains by calcite. The process usually occurs at a relatively higher temperature and deeper burial environment, and the resulting polymorphs or pseudomorphs of feldspar grains.

Dissolution- inter-cyrstalline pores are formed due to mechanical solutions, when the sediments encounter marine water in the phreatic zone. The pores formed in-between detrital grains are later filled by carbonate cement, lime mud and silica.

Table 4: Summary of the diagenetic processes taking place in the carbonate sediments of the Mzamba Formation.

Burial depth	Diagenetic Stage	Diagenetic Process	Results
Shallow	Syndiagenesis	Smectite Clay, Biogenic alteration, Micrite envelope, Grain micritization, Glauconite pellets, Faecal pellets.	Microorganisms bore into the carbonate allochems, making micrite envelopes around the grains. Micrite and sparry cements are formed.
	Early diagenesis	Cementation, Authigenetic minerals, Mineral conversion, Overgrowth.	Cementation, remaining pore spaces or secondary pores are filled. Primary porosity is created, due to the grains dissolving. Precipitation of quartz and carbonate cements. Smectite changes to illite.
Deep	Late diagenesis	Replacement, Recrystallization, Grain broken and deformation, Compaction, Dissolution.	Alteration of one clay mineral to another (smectite to illite), quartz overgrowths, Inter-crystalline pores are formed, solution of carbonate cements, selective replacement of feldspars, complete filling of pores between detrital grains.

CHAPTER 9 DISCUSSIONS & CONCLUSION

This research project is aimed at finding new insights on the stratigraphy and sedimentology of the Mzamba Formation in the Eastern Cape. Through this study, we have generated some new findings in the stratigraphic subdivision, sedimentary facies, depositional environment and petrological characteristics. We also found a number of new fossils, and provided for the first time, the diagenetic processes of the sediments of the Mzamba Formation.

9.1 Discussions

9.1.1 Stratigraphy

The stratigraphy of the Mzamba Formation consists of mainly four different rock units, i.e. the conglomerate unit, sandstone unit, mudstone unit and carbonate unit (pecten beds).The formation shows repeated cyclical patterns of change from pecten bed to mudstone, which constitute a series of fining-upward cycles.

The type locality of the Mzamba Formation is located at the coast of Mzamba River mouth, at the south of Port Edward, Eastern Cape Province. The whole sequence is 31.26m thick in an inland borehole and 30.05m measured in the field outcrops. Three new members have been established for the stratigraphy of the Mzamba Formation, i.e. the Lower Conglomerate Member, Middle Silt/Mudstone-Shell Bed Member and Upper Mudstone-Shell Bed Member. The Lower Conglomerate Member is 2.65m thick and consists of pebbly conglomerate and coarse sandstone. Silicified wood trunks and shell fragments were found in the member, representing a shallow marine (near shore) deposit. The Middle Silt/Mudstone-Shell Bed Member is 9.5 m thick and consists of fine-grained siltstone, mudstone and medium grained pecten bed. Disarticulated shells and distorted bedding occurrences of this member indicate it was deposited in a storm influenced marine environment. The Upper Mudstone-Shell Bed Member is 17.9m thick and is made up of fine mudstone with articulated pecten layers which was deposited in a deep and quiet marine environment.

9.1.2. Minerals and petrology

Mzamba sediments comprise of mixed deposits of carbonates and siliciclastic rocks. Grain size and composition were used as the parameters to differentiate the lithologies. Classification of the Mzamba sediments were based on Folk (1962) and Dunham's (1962) classification schemes. The rock types encountered in the Mzamba Formation are carbonate rocks including packstones, wackestones, grainstones and boundstone; and the siliciclastic rocks of conglomerate, sandstone and mudstone. The Mzamba sediments are moderately -well-sorted.

9.1.3. Sedimentary Facies

Based on lithology, sedimentary structures, and stratum architecture, seven different facies have been distinguished. Facies A (*flat bedded pebbly conglomerate*), which occurs at the lowermost part, in the entire succession. Facie B (*Cross-Bedded Course Calcareous Sandstone Facies*) occurs just above Facies A with a discomformable contact. It is fine-grained, with uniform grain size and is rich in well preserved shell fragments. Facies C (*Burrowed Sandstone)* which occurs nearby the Facies B, the burrows are well developed, and are vertical or slightly deflected to the bedding plane. Facies D (*Shell-fragmental fine-grained calcareous sandstone*) is hard, well cemented and consolidated. The facies contains smaller dispersed shells. It is similar to Facies C and occurs near the burrow facies. The bottom of the unit forms an erosional uneven contact, which is possibly caused by changes in the water energy.

Facies E (*Horizontal bedded* c*alcareous mudstone*) is very fine-grained. It is located at the top of each small fining-upward cycle at the type section. This facies has laminations, accompanied by a dark colour, which indicates that the sediments were deposited in a reducing environment. Facies F (*Calcareous Patch Reef*) is typical of boundstone rocks. It consists of carbonate or calcareous sandstone. Facies G (*Reef*) is washed out and calcite cemented reef facies. It is rich in algae, shells, broken oysters, coral and small pebbles.

9.1.4. Palaeontology

The Mzamba Formation is a fossiliferous sequence, and contains both fauna and flora fossils. The pecten beds host well-preserved bivalve, gastropod, brachiopoda, ammonite, and echinoderm; whereas silicified wood trunks, trace fossils of faecal pellets, burrows and tracks were found in conglomerate and mudstone. Some new fossil species were collected and studied, which include Bivalve: Pteriaceae, Pinnacea and Ostreacea; Gastropod: Cerithiacea and Mesogastopoda; Echinoderm: Echinocystoidea and Cronoidea. The benthonic species predominate in the lower part in the succession, whilst the planktonic species are abundant in the upper part of the sequence, which points to increase in water depths of the depositional environment.

9.1.5. Diagenesis

Diagenesis of carbonate rocks results in cementation, recrystallization, mineral alteration and porosity creation. Carbonate minerals are more susceptible to alteration, dissolution, recrystallization and replacement than most of silicate minerals. Four types of cements are distinguished using petrographic analysis, i.e. calcite, smectite, illite and quartz. Among these four types of cements, different cementation textures are distinguished. The calcite cement show two different textures, micrite and sparite. The clay cement consists of the smectite and illite and basically occurs as matrix. Authigenic minerals which formed in situ during early diagenetic stage including quartz, orthoclase, plagioclase, glauconite and vitrinite are evident. SEM and XRD images confirm the presence of the clay mineral smectite, illite, calcite and quartz. The smectite-illite conversion indicates early diagenesis stage. Recrystallization had partially destroyed the original textures of the bioclasts, and calcite replacement led feldspar and clay matrix changing to calcite. Three stages of diagenesis have been identified in the Mzamba Formation, i.e. syndiagenesis, early diagenesis and later diagenesis. Each stage had specific diagenetic processes, textures and diagenetic minerals.

9.2 Conclusions

The mineral compositions of the Mzamba Formation can be divided into four groups: Terrigenous group includes minerals of quartz, orthoclase, plagioclase, muscovite and various rock-lithics; the clay mineral group consists of smectite, illite and sericite; and the carbonate mineral group is composed of calcite and dolomite. Whereas, the fourth mineral group of diagenetic minerals, consist of pyrite, glauconite, hematite, gypsum, albite and organic maceral of vitrinite. Heavy minerals of garnet, zircon and rutile are also terrigenous in origin, which are accessory minerals and occur only in minor amounts in the strata.

The Mzamba Formation constitutes a perfect transgression sequence, the pebbly conglomerate at the bottom represents high energy deposits of shallow water environment , the grain-size gradually becomes finer in the middle part of the succession and finest at the top of the formation, which is laminated to thin-bedded mudstone and represents deep marine, quiet water deposits. The fossil evidences are also consistent with the water depth change, the bottom beds contain shallow marine shell fragments and wood-trunk plant fossils representing a near shore environment, then it changes to benthic bivalves and gastropod assemblage of shallow marine fossils, and end with floating and swimming type of fossil assemblage at the top, which represents deep marine water environment at the last.

Therefore, it is evident that the sediments of the Mzamba Formation were deposited in a marine environment. It started from shallow marine near shore setting, and it gradually shifted to a deeper water condition, and ended in a quiet water of deep marine environment.

Further work still needs to done in the palaeontology study to identify more detailed species of these fossils. At current stage, we identified these fossils only by Family or Genus, not by Species.

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