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STRATIGRAPHY AND SEDIMENTOLOGY OF THE MSIKABA FORMATION IN KWAZULU NATAL SOUTH COAST, SOUTH AFRICA

By

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Dissertation submitted in fulfilment of the requirements for the Degree Of Master of Science in Geology

FACULTY OF SCIENCE AND AGRICULTURE

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NOVEMBER, 2015

DECLARATION

I, Sinovuyo Nolukholo Busakwe, declare that this dissertation to be my own unaided work. Where other sources of information have been used, they have been acknowledged and properly referenced. It is being submitted for the Degree of Master of Science (Geology) at the University of Fort Hare. It has not been submitted previously for any degree or examination in any other university or institution.

-- 2015-11-20

Signed by Sinovuyo Busakwe

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Alice

ABSTRACT

The Msikaba Formation is a Late Devonian fluvial and marine succession which outcrops from Hibberdene to Port Edward along the south coast of KwaZulu-Natal Province, South Africa.

The Formation is composed of brownish conglomerate at the bottom and white-greyish quartz arenite sequence in the middle and mixed quartz-arenite with feldspathic sandstone in the upper sequence. Previous studies put more emphasis on the correlation of Msikaba Formation with the Natal Group and Cape Supergroup, whereas this study revised the stratigraphy, and also put new insight on the petrography, sedimentary facies, depositional environments and diagenesis of the Formation.

The total stratigraphic section attains a thickness of 184 m at Margate area and 186 m at Port Edward area. The stratigraphy of Msikaba Formation is well exposed on the outcrops along the KwaZulu-Natal coastline. The stratigraphy is subdivided into 4 new members along Margate to Shelly beach section; namely Manaba Member, Uvongo Member, Mhlangeni Member and Shelly Beach Member from bottom upward.

Twelve sedimentary facies were identified and the sedimentary facies were integrated into 4 facies association: Facies association 1 (Gmm+Sm) represents braided fluvial deposits, Facies association 2 (Gcm+St+Sp+Sl+Shb) represents tidal channel and tidal flat deposit, Facies association 3 (St+Sp+Sr+Sl) is result of shallow marine deposit and Facies association 4 (Sp+Sl+St+Sm) is a mixed marine and fluvial deposit. Each facies association represents a specific stratigraphic unit and were deposited in a specific sedimentary environment.

Grain size analysis was conducted on seventeen thin sections and 500 grains were counted from each thin section. The sandstone grain size parameters of mean, sorting, skewness and kurtosis fell under the average of 0.75, 0.78, 0.4 and 1.2φ respectively. The results show that

most of the grain size are coarse to medium grained throughout the study areas and sorting of the sandstones are moderate to poorly sorted. The cumulative frequency diagrams and bivariate plots show positive skewness and negative kurtosis, which indicate a high hydrodynamic environment.

Modal composition analysis and petrography studies show that detrital components of the Msikaba Formation are dominated by monocrystalline quartz, feldspar (mostly K-feldspar) and lithic fragments of igneous and metamorphic rocks. The sandstones could be classified as quartz arenite, sub-arkosic sandstone and feldspathic litharenite; and the provenance analysis indicates that the sandstones were derived from craton interior, recycled or quartzose recycled sources which may derived from weathering and erosion of igneous and metamorphic rocks.

Diagenetic processes of the Msikaba Formation have been passed through early, mid- and late diagenetic stages. Cementation, mineral conversion and compaction affect early diagenetic stage; authigenic minerals, quartz and feldspar overgrowth are presented in mid-diagenetic stage, whereas recrystallization, replacement, deformation and dissolution have been strongly affected late diagenetic stage. Microscopy, XRD and SEM-EDX studies have identified five types of cements including smectite clay, kaolinite, hematite, quartz and feldspar cements. Quartz cement, pore-filling and pore-lining clay are the major type of cements in the Msikaba Formation.

Based on the lithology, sedimentary structure and facies variations, the Manaba Member was most probably deposited in a braided fluvial environment, the Uvongo Member was deposited in a tidal channel environment, the Mhlangeni Member was formed in shallow marine storm-influenced environment, whereas the Shelly Beach Member was represented mixed marine and fluvial environment.

The sequence stratigraphy of Msikaba Formation constitutes a transgressive sequence from Manaba Member to Uvongo Member, whereas it ended as a regressive sequence from Mhlangeni Member to Shelly beach Member.

The Msikaba Formation shows major differences with the Natal Group and Table Mountain Group (Cape Supergroup) in the lithology, stratigraphic sequence, sedimentary structures, facies system, palaeocurrent styles, fossil contents and depositional environments, which demonstrate that they are not the equivalent stratigraphic unit. Therefore, the Msikaba Formation is a separate, younger stratigraphic unit, and cannot correlate with the Natal Group and Table Mountain Group as suggested by previous researchers.

ACKNOWLEDGEMENTS

I would like to thank God for giving me courage, perseverance and diligence to finish this daunting project. My utmost sincere gratitude goes to my supervisor, Professor Ken Liu for his guidance, support and advice. His supervision and vast knowledge was invaluable in completing this dissertation and Dr Kakaba Madi for proof reading and his contribution has greatly improved the final version.

I, also wish to extend my appreciation to the Department of Geology, University of Fort Hare for providing the instrumentation for the analysis and Botany Department for assistance with SEM and EDX analysis. I would like to thank the NRF for MSc bursary support and the Govan Mbeki Research and Development Centre (GMRDC) of the University of Fort Hare for their academic workshops which were very helpful in constructing my dissertation.

My deepest appreciation goes to my parents Zolile and Mildred Busakwe and my five siblings Malwande, Linamandla, Lukhona, Sikelelwa and Yanelisa Busakwe for their unconditional love, support and prayers.

Lastly, to the staff of the Department of Geology Prof Ostwald Gwavava, Machel Katwire, Mrs Vuyokazi Mazomba and postgraduate colleagues (Kinshasa Pharoe, Xoliswa Maliwa and Zusakhe Ngxantsiya, Akinyemi Babatope) and Dr Ntokozo Malaza; your contribution to the completion of this dissertation is much appreciated.

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CHAPTER 1: INTRODUCTION

1.1 Background of the study

Msikaba Formation is distributed along the south coast of the KwaZulu-Natal Province from Hibberdene to Port St. Johns, and is dominantly a quartz-arenite sedimentary sequence. Msikaba Formation is a non-metamorphosed and non-tectonically disrupted sedimentary sequence. Previous researchers correlated it with the Palaeozoic Cape Supergroup as well as the Natal Group (Kingsley, 1975; Kinsley and Marshall, 2009), which means that it was considered to be a Palaeozoic stratigraphic succession. It is obvious that the sediments were not been metamorphosed, thus it should be younger than the Cape Supergroup which is strongly metamorphosed. It contains Lycopsid plant and trace fossils that were never found in the Natal Group (Lock, 1973); these facts indicate the Msikaba Formation is not equal to the Natal Group. Therefore, correlation of the Msikaba Formation with Cape Supergroup and the Natal Group has not been accepted to date (Marshall, 1994; Liu, 2002).

Kingsley and Marshall (2009) summarised the Msikaba Formation stratigraphy to consist a thickness of 450 m in the Port Shepstone area and with increasing thickness of over 900 metres in the extreme south. The formation is dominated by pale grey quartz arenite sandstone, quartz gritstone and conglomerates while the Natal Group comprises of red-brownish arkose sandstone, siltstone and mudstone (Marshall, 1994; Shone and Booth, 2005), which indicate the difference in lithology between the Msikaba Formation and the Natal Group. Although several studies have been carried out on various aspects of Msikaba Formation, Kingsley (1975) for instance, worked on the stratigraphy of Msikaba Formation with emphasis on its palaeocurrent analysis. Kingsley and Marshall (2009) also investigated the lithostratigraphy of Msikaba Formation. Nevertheless, previous studies remain yet with many unclosed gaps on stratigraphy and sedimentology of the Msikaba Formation, which challenge further geological research on this formation to fill these gaps. Thus, the purpose of this study is to do stratigraphic section measurement and redefine subdivisions of Msikaba Formation further into members, conduct a lithofacies investigation, interpretation, and carry out a depositional environmental study and a diagenetic process study on the succession.

1.2 Location of the study areas

The Msikaba Formations is geographically distributed along the south coast of KwaZulu-Natal Province and north coast of Eastern Cape Province. It appears as sedimentary bodies of light coloured quartz arenite rocks at its upper part and pale-brownish conglomerate and sandstone at its lower part. It is different from the red-bed deposits of the Natal Group, which are dominated by fluviatile deposits. Dweshula Basement high formed as a boundary for these two successions, the Natal Group occurs on the north of the Dweshula Basement high while the Msikaba Formation is distributed on the south of the Basement high(Figure 1.1). This palaeo-topographic high boundary was initiated by terrain accretion, granitiod emplacement, crustal thickening and isostatic rebound during the Middle to Late Proterozoic tectogenesis at ~1000 Ma (De Wit and Ransome, 1992; Hicks, 2010).

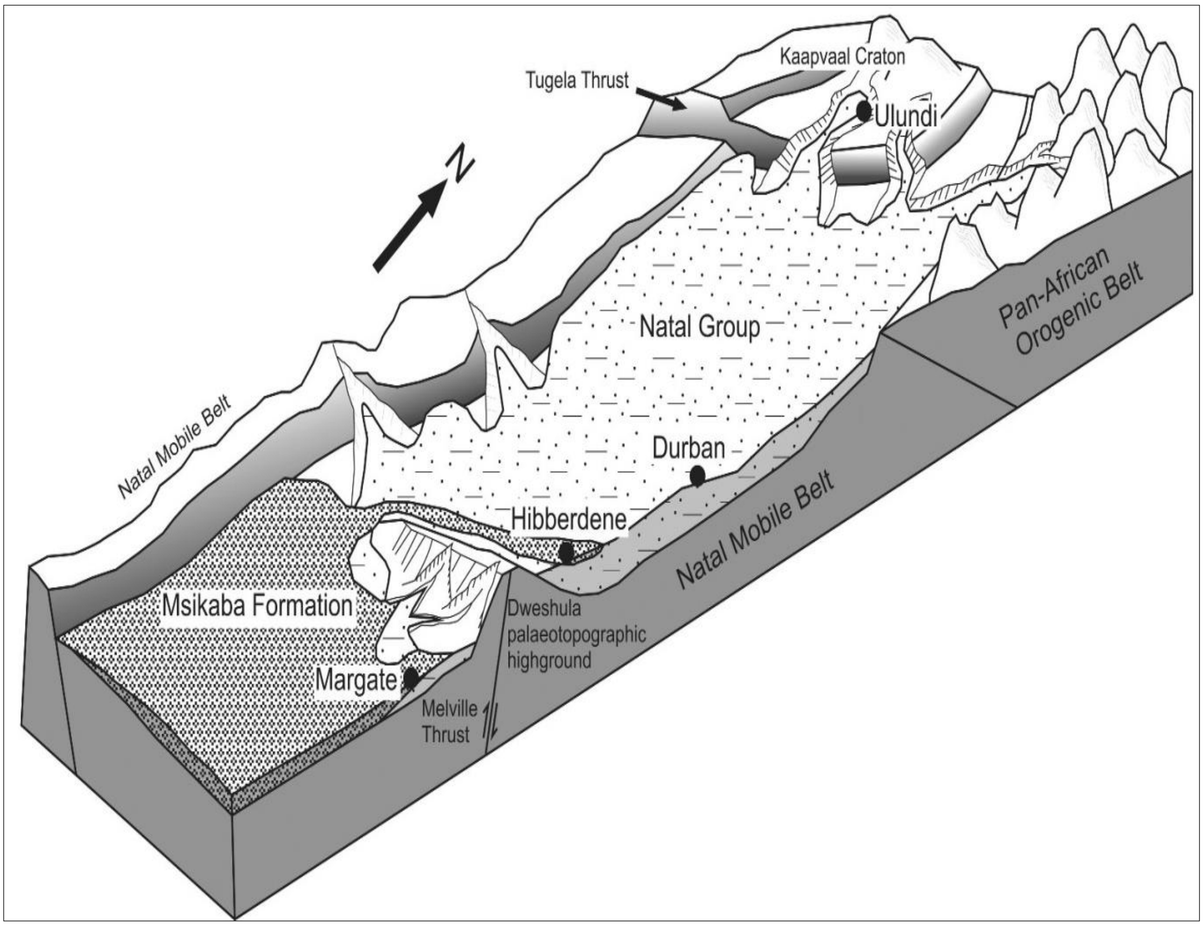


Figure 1.1: Depositional model of the Natal Group showing the distribution of Msikaba Formation at the south of Dweshula Palaeotopographic High (Hicks, 2010).

Stratigraphic sections were measured at Margate, Shelly beach and Port Edward along the south coast of KwaZulu-Natal Province, along the eastern seaboard of South Africa, which is marked as a remnant boundary where continental plates might have sheared away during the breakup of Gondwana (Cloete, 2004). In the Margate area, the Msikaba Formation crops out northwards several kilometres to Uvongo beach and Shelly beach. The lithology exposure is fairly good even though some of the lithologies are concealed by the sea water and sand. The formation in the Port Edward area is well exposed along the beach area and it runs for several kilometres southwards (Figure 1.2) into Eastern Cape Province.

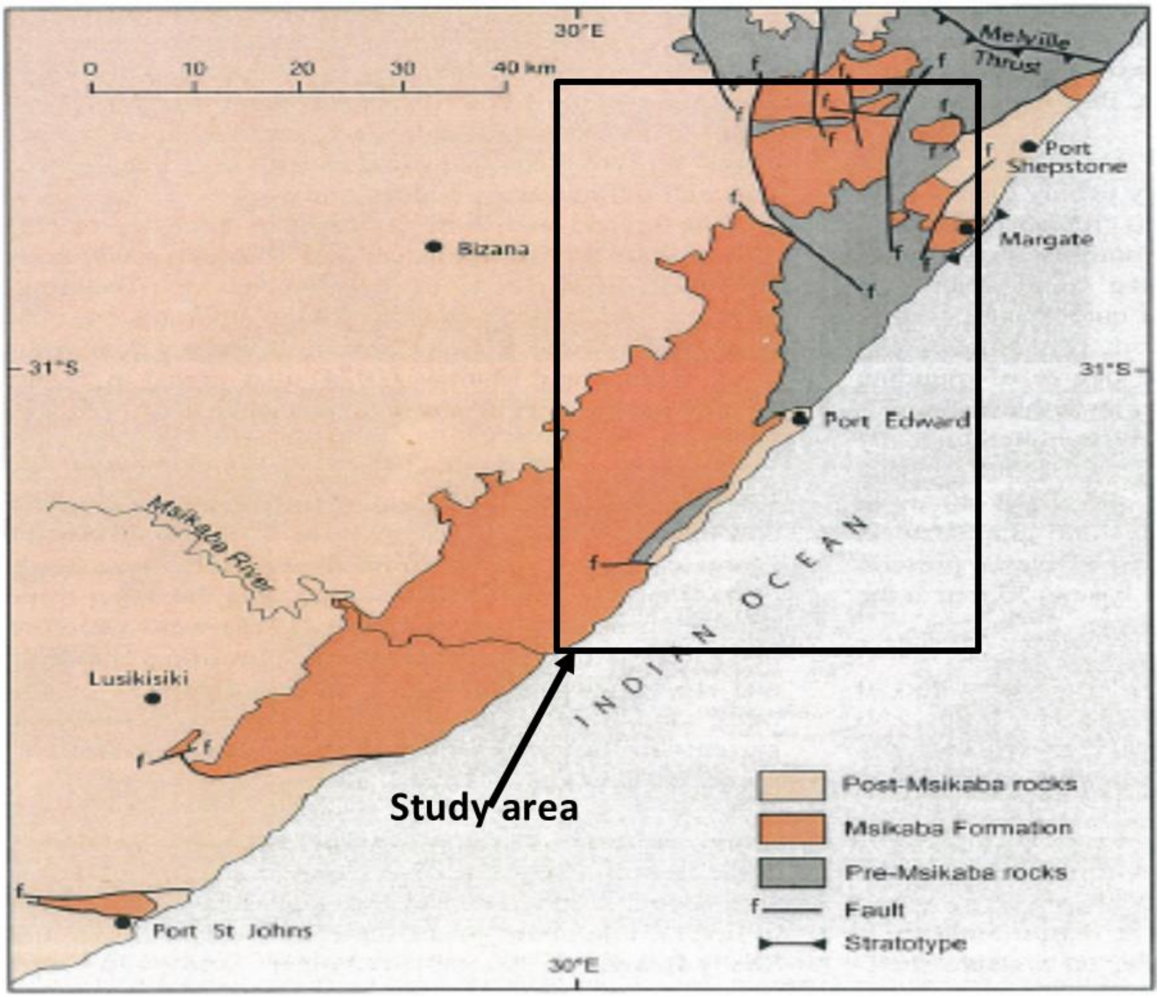


Figure 1.2: Location map of study area of the Msikaba Formation along the south-eastern part of South Africa (back ground map was based on Kingsley and Marshall, 2009).

1.3 Research problem statement

It has been documented in the literature that the biological and lithological features of the Msikaba Formation exhibit major differences with Natal Group (Marshall, 1994, 1999; Liu, 2002; Shone, 2005). However, previous research work and publications relating to Msikaba Formation, particularly on the research based on Msikaba Formation stratigraphy, sedimentary facies and diagenesis are scanty. Publications on digenesis of the formation have not been previously carried out. Thus, this research is aimed at providing new insight on stratigraphy, sedimentary facies, diagenesis and depositional environments of the Msikaba

Formation, and also to divide the Msikaba Formation further into detailed stratigraphic members.

1.4 Aim and Objectives

The aim of the research project is to study the stratigraphy, sedimentology and diagenesis of the Msikaba Formation. The study will focus on the stratigraphic subdivision, sedimentary petrology, facies variation, depositional environment and diagenetic processes of the sediments. It will also make a comparison between the Msikaba Formation and the Natal Group in order to demonstrate the similarity and difference between these two groups. Consequently, the specific objectives of this study are:

- to measure the field outcrops of the Msikaba Formation and to establish a detailed stratigraphic sequence for the Msikaba Formation;
- to subdivide the Msikaba Formation into members and to establish detailed stratigraphic subdivisions;
- to study the sedimentary facies by using petrological and palaeontological features, as well as sedimentary structures within the formation;
- to restore the depositional environment and the origin of the sediments by integrating all the information of lithological characteristics, sedimentary structures and facies, palaeocurrent direction, and palaeontological data; And,
- to conduct a detailed diagenetic study of the Msikaba Formation, including cementation, authigenic minerals, recrystallization, replacement, and diagenetic environment and diagenetic sequence of the sediments.

CHAPTER 2: LITERATURE REVIEW

2.1 General introduction

The Msikaba Formation was initially grouped along with the Natal Group and the Table Mountain Group of the Cape Supergroup by Kingsley (1975), who identified them as two different facies i.e. Hibberdene Facies now called Natal Group. They consist of red, micaceous arkoses, feldspathic sandstone and red mudstone which are located at north of the Hibberdene, and was deposited in fluvial environment. The Margate facies which is now known as Msikaba Formation is located in the south of Hibberdene and consisted of conglomerates, white quartzarenite sandstones and minor gritstone, and were deposited in the shallow high-energy environment. Kingsley (1975) further divided the Msikaba Formation into four lithostratigraphic facies namely: Manaba Conglomerate facies, Uvongo Sandstone facies, Mhlangeni Grit facies and Shelly Beach Feldspathic Sandstone facies.

Visser (1974) referred to these facies as red-bed “Natal” Facies and the quartz arenite sandstone as “Pondoland” Facies. Hobday and Matthew (1974) also identified three facies in the Msikaba Formation: sheet sandstone, lenticular trough cross-bedded sandstone and channel-sandstone facies. These facies showed unimodal south-westerly palaeocurrent patterns and trace fossils of *Scolicia and Planolites* were also found within these sandstones (Thamm and Johnson, 2006).

The Devonian Msikaba Formation unconformably overlies the Ordovician Natal Group (Figure 2.1), the unconformable contact between them represents approximately 140 Ma of an erosional regime that separated the groups, and is preserved in some of the outcrops proving that the Msikaba Formation is younger than the Natal Group (Hicks, 2010). During the assumed erosional regime, there is no evidence of sedimentation from the Ordovician to the Devonian and the upper portions of the Natal Group, and the basement rocks of the

Msikaba Formation, were eroded. Subsequently, the quartz-arenites of the Msikaba Formation were deposited in the basin situated where southern KwaZulu-Natal and Eastern Cape (Pondoland) are now located (Figure 2.2). The rocks of the Msikaba Formation are unconformably overlain by Dwyka Group of the Karoo Supergroup (Marshall, 1994).

Figure 2.1: Photograph showing Msikaba Formation conglomerates (left) laying unconformable above the Natal Metamorphic Basement (right).

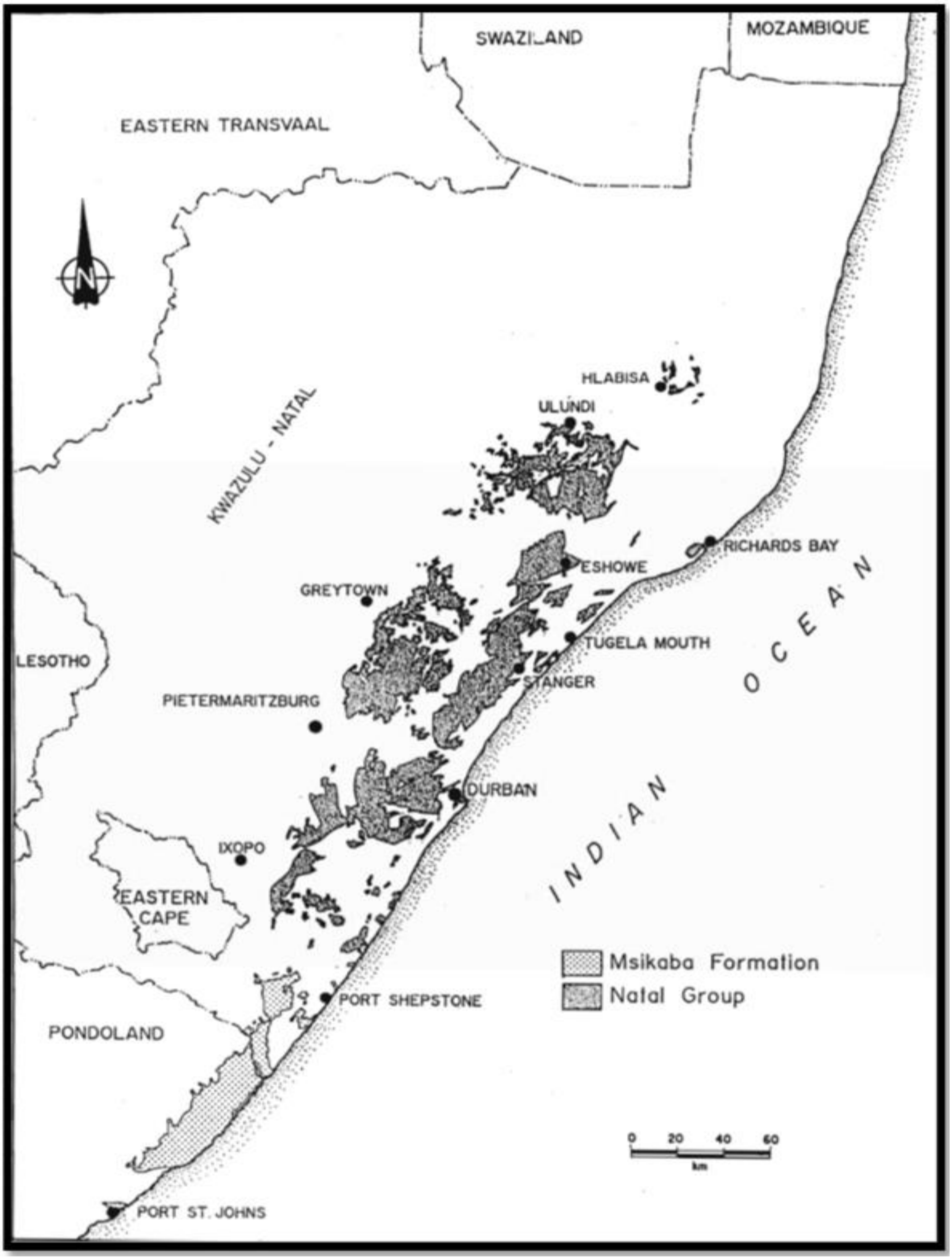


Figure 2.2: Distribution map of the Msikaba Formation along the south-coast of KwaZulu-Natal Province, South Africa (Marshall, 1994).

The correlation of Msikaba Formation with Natal Group as a time equivalent became improbable due to the discovery of a *Lycopsid* plant fossil (Lock, 1973) in the Msikaba Formation, and it was not found in the Natal Group. This inferred a Devonian 365 Ma age for Msikaba Formation and was deposited at Late Devonian period in the southernmost part of the KwaZulu-Natal, i.e. the south of the Dweshula Basement high. An Ar-Ar isotopic dating was carried out using authigenic muscovite and revealed an Ordovician 490 Ma age for the Natal Group (Thomas et al., 1992) which implied and confirmed that the Msikaba Formation is younger than the Natal Group.

Moreover, the discovery of Devonian *Lycopsid* fossils led to correlation of Msikaba Formation with the Witteberg Group in the Cape Supergroup based on age similarity (Marshall and Kingsley, 2009). However, Liu and Cooper (2002) pointed out that Msikaba Formation could even be younger than the Witteberg Group. Thus, the inferred correlation would be possible if the hiatus between the Witteberg Group and the Msikaba Formation would have been short lived because Dwyka Group unconformably overlies both groups of rocks. The glacial ice sheets of the Dwyka Group would have stripped off more than 1000 m of Msikaba Formation overburden in Pondoland, whilst simultaneously bringing about soft sediment deformation in Witteberg sandstones along the main Cape Fold Belt (Shone and Booth, 2005).

SACS (1980) recognised Natal Group and Msikaba Formation as independent Groups. However, Marshall (1994) proposed that the name of Natal Group must be restricted to the red-beds of northern KwaZulu-Natal, for which an Ordovician age has been obtained and can no longer be correlated with the Devonian Msikaba Formation in the southern KwaZulu-Natal. Marshall and Kingsley (2009) acknowledged this proposal.

Schwarz (1916) who pioneered the study on Msikaba Formation established that it was inconceivable that the nature of the lithologies could change so drastically over just ~8 km from north of Port Shepstone of KwaZulu-Natal Province to the south of Port St John's in the Eastern Cape Province.

Thomas et al. (1990) also noted that there was neither Natal Group nor Msikaba Formation rocks in Dweshula Basement High where the Dwyka Group rests directly on these Kibaran Basement rocks. To the contrary, Hicks (2010) discovered that there are six newly discovered localities of the Natal Group. He documented that these rocks actually extended to south and of the Dweshula palaeo-topographic high. The successions attained an average thickness of ~50 m and crop out as mineralogically immature, maroon, fine- to medium-grained arkosic sandstone, siltstone and shale which lie with a non-conformable, planar contact upon Natal Metamorphic Province granites and gneisses. He also discovered that Msikaba Formation overlies the Natal Group with an unconformable contact that is preserved in four outcrops near Margate Airport, which clearly shows that the Msikaba Formation is younger than the Natal Group (Hicks, 2010). According to Kingsley and Marshall (2009), Msikaba Formation is still regarded as part of the Cape Supergroup rather than the Natal Group. The Palaeozoic Msikaba Formation and Natal Group were not metamorphosed and they remained unaffected by the Cape Deformation Event which caused the strong deformation of the Cape Supergroup. A possible explanation for this was proposed by Booth et al. (2004) who suggested a collision of a microcontinent hypothesis (Figure 2.3) in the region of the present southern and southeastern part of the southern arm of the Cape Fold Belt (Shone and Booth, 2005).

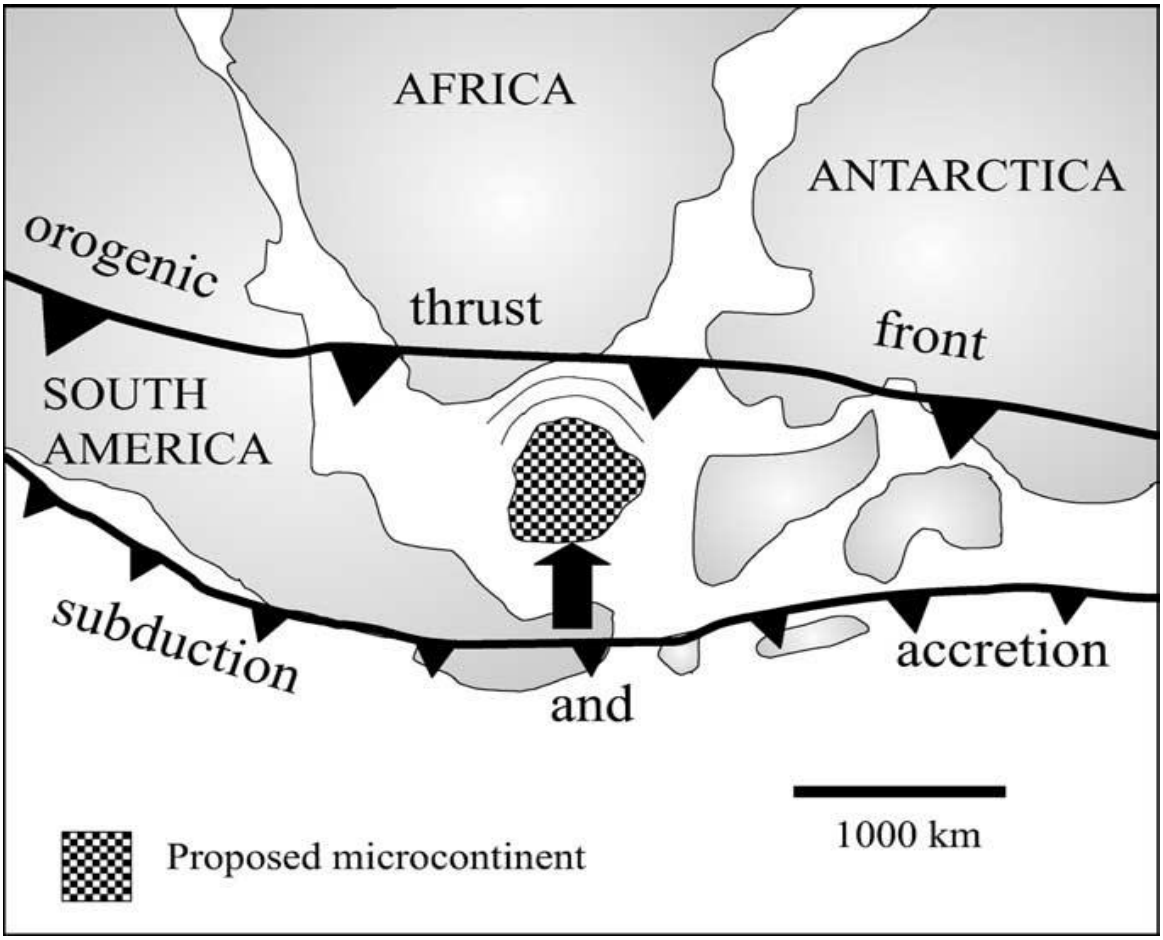


Figure 2.3: Plate tectonic model for the Cape Fold Belt. Showing the position of the proposed microplate south of the southern African coastline presumed to have collided with the African continent (Booth and Shone, 2005).

2.2 Lithostratigraphy Msikaba Formation

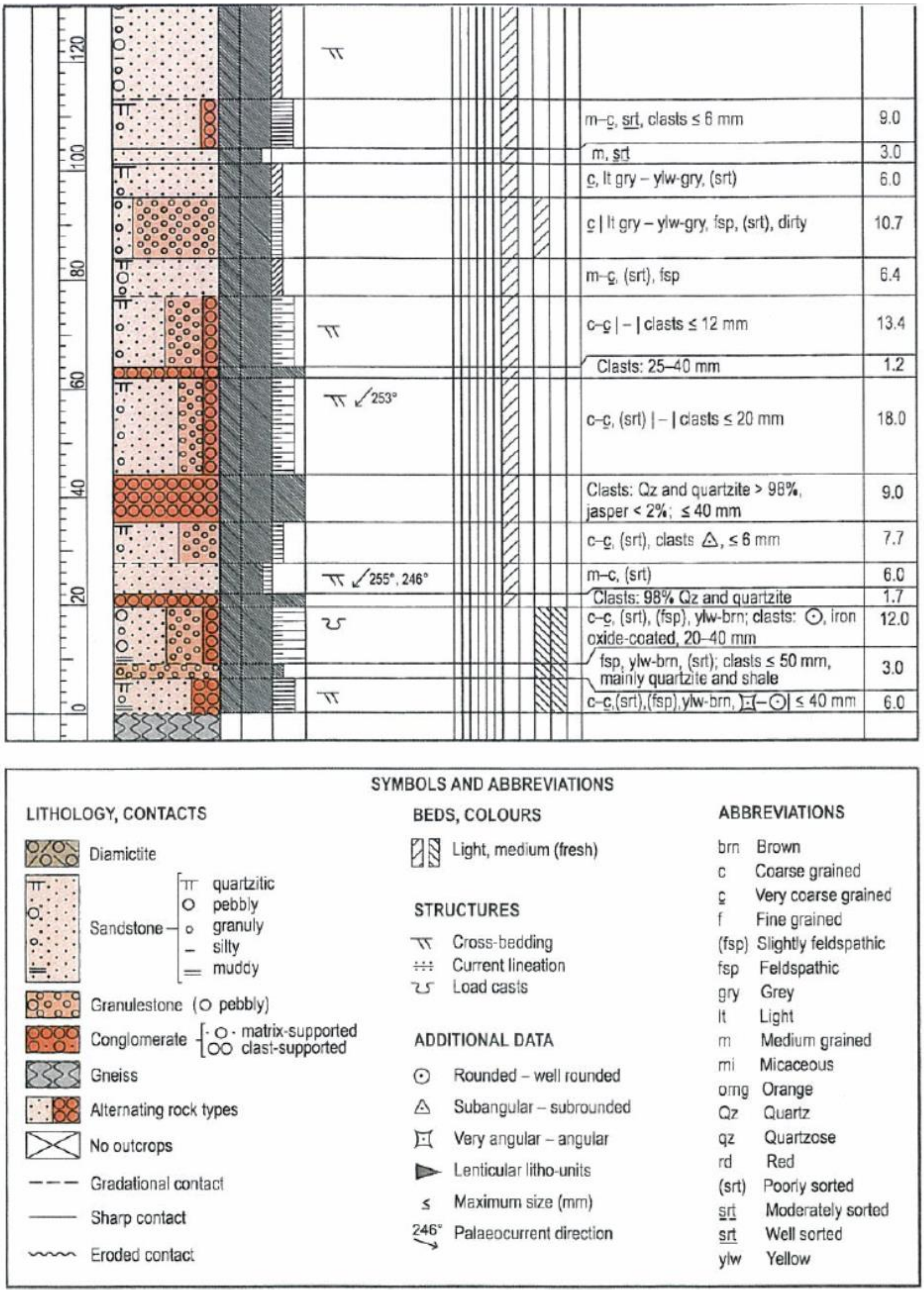
Kingsley (1975) worked on the Table Mountain Group and mapped the Margate area in a well exposed section located on north of Margate beach. He subdivided the Margate facies (Figure 2.4) into four formations namely: The Manaba Conglomerate Formation– found along the Manaba beach where the basal 20 m consist of impure grit with interbedded conglomeratic stringers. Upwards the grits become pure to very pure with fewer conglomeratic intercalations. The pebbles are composed nearly exclusively of quartz and quartzite. Their average size decreases upwards in the formation from about 3cm to about

1cm in diameter. The upper 15 m of sandstone and gritstone contain a larger amount of granular material and clay fragments than the lower part.

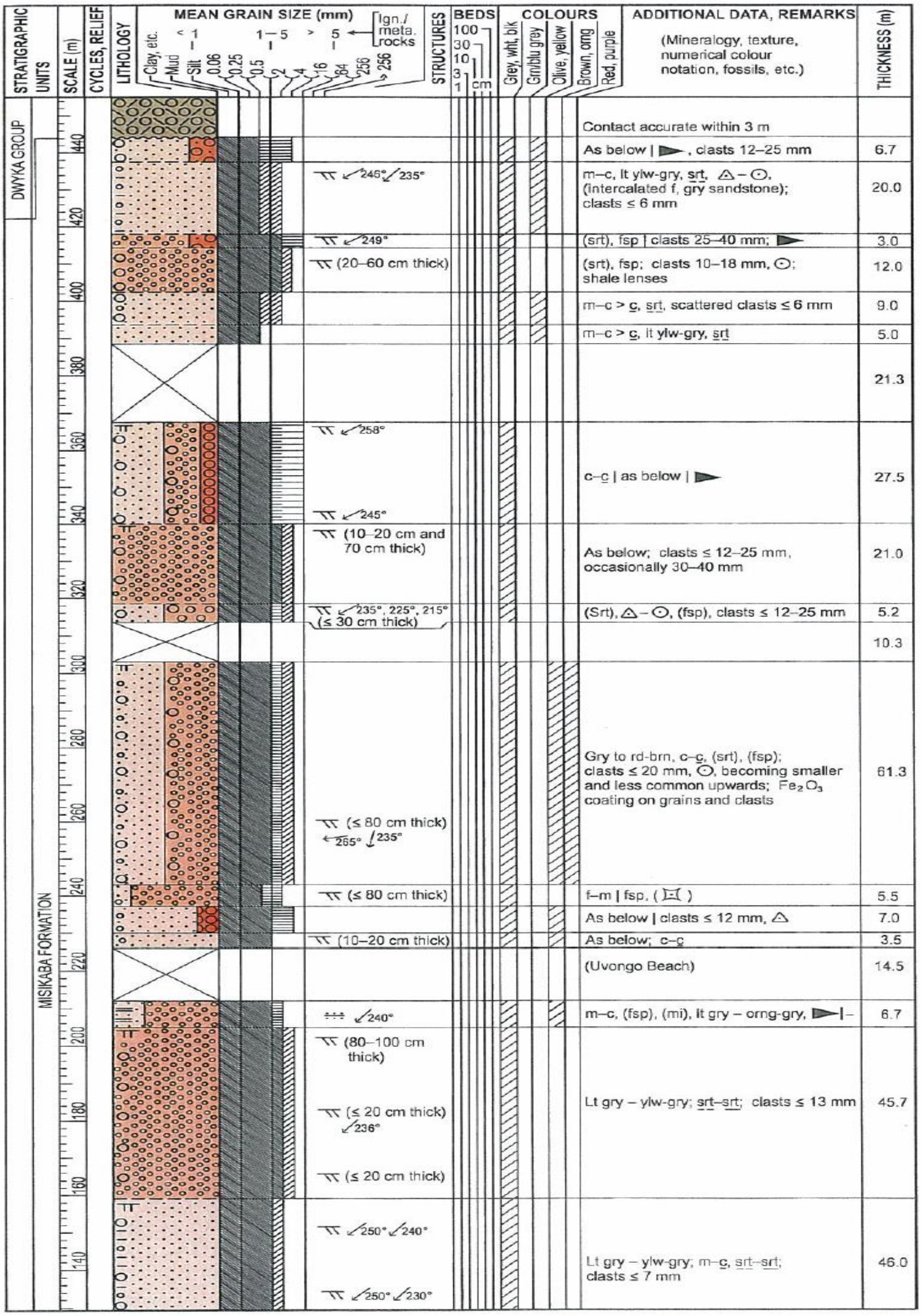
The Uvongo Sandstone Formation-the type section stretches from about 1300 m south of Uvongo beach to pure quartzose sandstone and gritstone with occasional thin conglomeratic stringers. In the lower part the pebbles rarely exceed 1cm diameter. The upper 50 m contain virtually no pebbles while the proportion of intergranular material increases. Furthermore, this upper part contains thin lenses of medium to coarse-grained sandstone.

The Mhlangeni Grit Formation–this member crops between Uvongo and Mhlangeni River mouths. Conglomeratic stringers are present in the lower and middle horizons, but diminish upwards 30 m. Pebble sizes seldom exceed 2 cm diameter. Angular grains of feldspar are associated with poorly sorted grits in some horizons. The cross-bedded units are generally thinner than 40 cm.

The Shelly Beach Arkosic sandstone Formation–outcrops of this member lies north of Mhlangeni river mouth at Shelly beach and consists of slightly feldspathic sandstone and grit. Although the contacts between the different members are transitional, the members can be identified fairly easily.



0
20
40
60
80
100
120
m–c̲, s̲r̲t̲, clasts ≤ 6 mm 9.0
m, s̲r̲t̲ 3.0
c̲, lt gry – ylw-gry, (srt) 6.0
c̲ | lt gry – ylw-gry, fsp, (srt), dirty 10.7
m–c̲, (srt), fsp 6.4
c–c̲ | – | clasts ≤ 12 mm 13.4
Clasts: 25–40 mm 1.2
253°
c–c̲, (srt) | – | clasts ≤ 20 mm 18.0
Clasts: Qz and quartzite > 98%, jasper < 2%; ≤ 40 mm 9.0
c–c̲, (srt), clasts △, ≤ 6 mm 7.7
255°, 246°
m–c, (srt) 6.0
Clasts: 98% Qz and quartzite 1.7
c–c̲, (srt), (fsp), ylw-brn; clasts: ⊙, iron oxide-coated, 20–40 mm 12.0
fsp, ylw-brn, (srt); clasts ≤ 50 mm, mainly quartzite and shale 3.0
c–c̲,(srt),(fsp),ylw-brn, ⌶–⊙ ≤ 40 mm 6.0
SYMBOLS AND ABBREVIATIONS
LITHOLOGY, CONTACTS
Diamictite
Sandstone
quartzitic
pebbly
granuly
silty
muddy
Granulestone (○ pebbly)
Conglomerate
matrix-supported
clast-supported
Gneiss
Alternating rock types
No outcrops
Gradational contact
Sharp contact
Eroded contact
BEDS, COLOURS
Light, medium (fresh)
STRUCTURES
Cross-bedding
Current lineation
Load casts
ADDITIONAL DATA
Rounded – well rounded
Subangular – subrounded
Very angular – angular
Lenticular litho-units
Maximum size (mm)
246°
Palaeocurrent direction
ABBREVIATIONS
brn Brown
c Coarse grained
c̲ Very coarse grained
f Fine grained
(fsp) Slightly feldspathic
fsp Feldspathic
gry Grey
lt Light
m Medium grained
mi Micaceous
orng Orange
Qz Quartz
qz Quartzose
rd Red
(srt) Poorly sorted
s̲r̲t Moderately sorted
s̲r̲t̲ Well sorted
ylw Yellow


STRATIGRAPHIC UNITS
SCALE (m)
CYCLES, RELIEF
LITHOLOGY
MEAN GRAIN SIZE (mm)
Ign./ meta. rocks
Clay, etc.
Mud
Silt
0.06
0.25
0.5
2
4
16
64
256
STRUCTURES
BEDS
100
30
10
3
1
cm
COLOURS
Grey, wht, blk
Grn/blu grey
Olive, yellow
Brown, orng
Red, purple
ADDITIONAL DATA, REMARKS
(Mineralogy, texture, numerical colour notation, fossils, etc.)
THICKNESS (m)
DWYKA GROUP
MISIKABA FORMATION
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
140
Contact accurate within 3 m
As below | , clasts 12–25 mm
6.7
246°/235°
m–c, lt ylw-gry, srt, △–⊙, (intercalated f, gry sandstone); clasts ≤ 6 mm
20.0
249°
(srt), fsp | clasts 25–40 mm;
3.0
(20–60 cm thick)
(srt), fsp; clasts 10–18 mm, ⊙; shale lenses
12.0
m–c > c, srt, scattered clasts ≤ 6 mm
9.0
m–c > c, lt ylw-gry, srt
5.0
21.3
258°
c–c | as below |
27.5
245°
(10–20 cm and 70 cm thick)
As below; clasts ≤ 12–25 mm, occasionally 30–40 mm
21.0
235°, 225°, 215° (≤ 30 cm thick)
(Srt), △–⊙, (fsp), clasts ≤ 12–25 mm
5.2
10.3
Gry to rd-brn, c–c, (srt), (fsp); clasts ≤ 20 mm, ⊙, becoming smaller and less common upwards; Fe2O3 coating on grains and clasts
61.3
(≤ 80 cm thick)
265° 235°
(≤ 80 cm thick)
f–m | fsp, ( )
5.5
As below | clasts ≤ 12 mm, △
7.0
(10–20 cm thick)
As below; c–c
3.5
(Uvongo Beach)
14.5
240°
m–c, (fsp), (mi), lt gry – orng-gry,
6.7
(80–100 cm thick)
(≤ 20 cm thick)
236°
(≤ 20 cm thick)
Lt gry – ylw-gry; srt–srt; clasts ≤ 13 mm
45.7
250° 240°
250° 230°
Lt gry – ylw-gry; m–c, srt–srt; clasts ≤ 7 mm
46.0

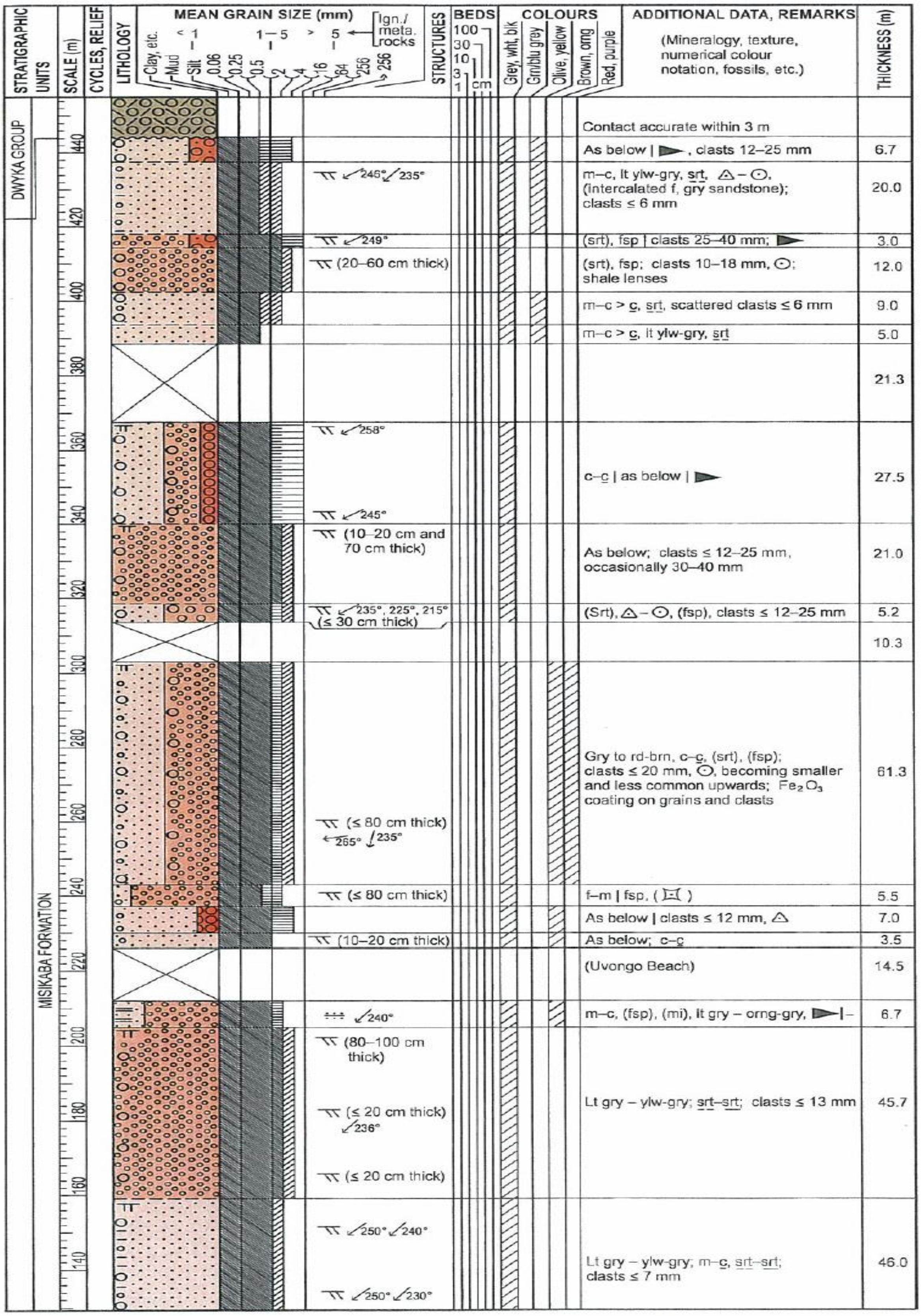


Figure 2.4: Stratigraphy of Msikaba Formation (Kingsley and Marshall, 2009).

2.3 The palaeocurrent direction of the Msikaba Formation

Palaeocurrent direction of the Msikaba Formation shows predominantly south trending flow direction throughout the outcrop areas. Planar and trough cross-bedding exhibit unimodal, southwest-trending palaeocurrent direction in the Msikaba Formation where the source area would have been located north and north easterly (Kingsley and Marshall, 2009). Bimodal herringbone cross-bedding is present amongst other unimodal sedimentary structures resulting from bi-directional flow and current reversals (reactivation surfaces) which indicate tidal sedimentation with ebb and flow currents. Bi-directional flow is not common in Msikaba Formation.

2.4 Depositional history of Msikaba Formation

Kingsley (1975) inferred good exposures of epeiric and shore-sand deposits present near Mhlangakulu River mouth and Margate. The littoral deposits are characterised by very coarse grits, conglomerate stringers, large pebble size, and well defined cross-bedded units. He resolved that the amount of conglomeratic material decreased as the Msikaba Formation sandstone sequence become homogeneous in the south. He also suggested that there is a decrease in grain size of shallow marine shelf facies took place south westward. Hobday and Matthew (1974) also concluded that Msikaba Formation sandstone is a marine shelf deposit due to the sheet sandstone facies and estuarine deposits that were attributed to presence of lenticular sandstone facies.

2.5 Palaeontology of Msikaba Formation

The Msikaba Formation contains of Devonian *lycopsid* plant fossils that occur in the Port St Johns area (Lock, 1973). *Planolite* and *Scolithos* trace fossils (Figure 2.5) were also found at various localities within the Msikaba Formation sandstone. Lack of age diagnostic fossils, in the Natal Group was identified as equivalent to the Palaeozoic Table Mountain Group on basis of similar lithofacies and ichnofacies (Kingsley and Marshall, 2009).

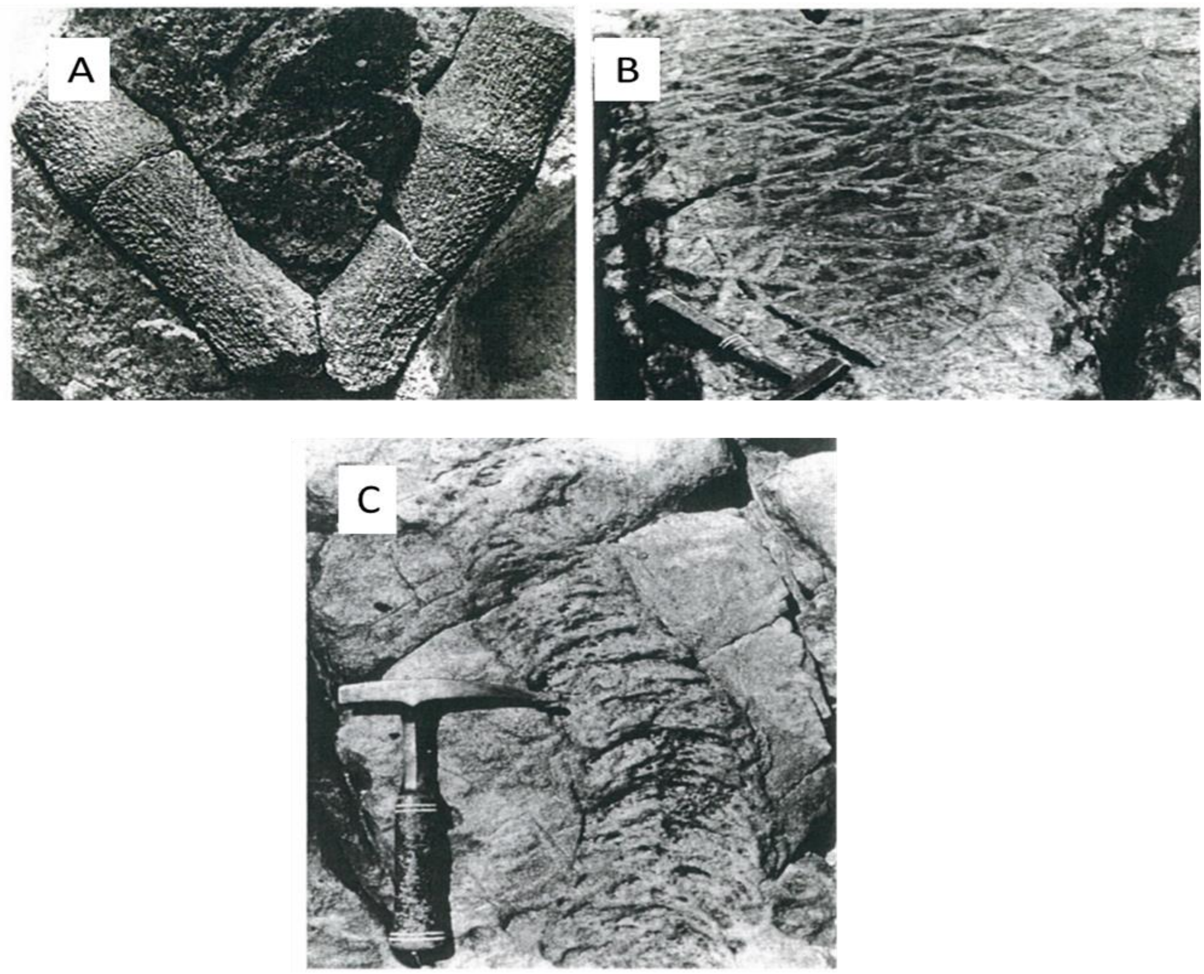


Figure 2.5: Photographs showing (A) a branching *lycopsid* stem from the Port St Johns area; (B) probable *planolites* at the Msikaba River mouth; and (C) *Scolicia* trace fossil preserved at the Lupatana northwest of Port St Johns (Kingsley and Marshall, 2009).

Although, Msikaba Formation occupies a narrow strip along the Hebberdene in the north to Port St Johns in the south (~125 km in length and about 25 km in width), the mappability of this Formation on regional scale has not been establised yet (Kingsley and Marshall, 2009). The stratigraphic subdivision for Msikaba Formation does not follow the nomination rules for stratigarphic subdivisions or nomenclature rules. The Formation can be subdivided into members and the stratigraphic thickness of the Msikaba formation also needs to be revised further.

CHAPTER 3: METHODOLOGIES

3.1 Introduction

This chapter describes different methods employed to fulfil the aims and objectives of this research project. The methodologies adopted in this work include: a comprehensive literature review, field works and laboratory analysis to characterise the sedimentary rocks in the study areas in Margate and Port Edward. Laboratory work consisted of petrographic and mineralogical analysis, scanning electronic microscopy (SEM) and energy disperse X-ray analysis (EDX), X-ray diffraction analysis (XRD), grain-size analysis, and modal compositional analysis.

3.2 Field work and sample collection

The fieldwork on Msikaba Formation was carried out along Margate and Port Edward beach areas. The two outcrops were examined in details for identification of different lithologies, determination of grain size, grain sorting and roundness variations, identification of rock colour changes and sedimentary structures, establishment of sedimentary facies and facies associations, measurement of the stratigraphic succession and establishment of the depositional environment related to the changes of hydrodynamic conditions.

The equipment used during field work included measuring tape to measure the stratigraphic columns. A geological hammer was used to collect rock samples, and was also used as photograph scale. A compass was used to measure the dip and strike of bedding occurrence, and a Global Positioning System (GPS) was used to navigate the study locality. A digital camera was used for photograph. Rock samples were collected systematically from the bottom to the top of the succession encompassing conglomerates, sandstones and mudstones. All the samples were numbered and stored in a plastic bag. The difficulties in mapping the areas were due to concealment of the strata by the seawater, beach sand and occasional rise in sea tide.

3.3 Stratigraphy measurement

The stratigraphic study encompasses lithostratigraphy and sequence stratigraphy. Lithostratigraphy is a component of stratigraphy that deals with lithological characteristics of strata and their relative sedimentary structures, mineral composition and texture in a rock unit and establishes unconformities due to facies change (Nichols, 2009). It also determines the stratigraphic nomenclature whenever there is new detailed study that has been undertaken and bears no inferences to age of the lithostratigraphic units. Sequence stratigraphy is very important in sedimentology, and is a type of stratigraphy that uses facies analysis to study cyclic changes due to sea-level shifts. It also gives clues to depositional processes to reconstruct environments.

The measurements of vertical succession were observed and recorded to construct a detailed stratigraphic succession of Msikaba Formation based on all fieldwork geological investigations. Stratigraphic measurements were taken from two representative localities on well exposed field outcrops, i.e. the 3 km long Margate section and the 2.5 km long Port Edward section. The stratigraphic column was drawn by using Microsoft Word and the scale of the stratigraphic section was deduced from the thickness of the measured beds.

3.4 Sedimentary facies analysis

Recording of lithological features and sedimentary structures is an essential part of facies analysis. A combination of lithology and sedimentary structure and other rock characteristics give rise to a facies. The appearance of a facies reflects the sedimentary processes present at a particular depositional environment. Therefore sedimentary facies aids to predict depositional process and sedimentary environment (Catuneanu, 2006).

A vast spectrum of sedimentary structures found within the Msikaba Formations along the south coast of KwaZulu-Natal Province, which were recorded as primary data from the bottom of the succession to the top of the sequence for identification of sedimentary facies, facies associations and stratigraphy correlation. Photographs of sedimentary structures that were observed in the stratigraphic sections were taken using an Olympus digital camera. For detailed facies analysis, lithofacies classification was done using a modified version of Miall (1977, 1983, 2000) lithofacies classification scheme. The lithofacies were grouped into associations which represented different kinds of depositional environments of the Msikaba Formation.

3.5 Laboratory analysis

3.5.1 Sample preparation

From the collected rock samples, eighty thin sections were made for the petrological studies of the Msikaba Formation. Thin-sections were used for mineral identification, grain size analysis, cement type investigation and diagenetic texture studies. Thin-sections were cut perpendicular to the obvious bedding planes using Struers cutting and trimming machines (Secotom-10 and Accutom-50). Where bedding planes are unclear, two different oriented sections perpendicular each other were employed.

Rock samples for Scanning Electron Microscope (SEM) analysis were broken into rock chips that have natural flat surfaces with a hammer and were mounted with Canadian slide glue on glass slides. The samples were then carbon coated in a Cressington 108 carbon/A carbon coater and kept in an air tight container to prevent moisture from the air. Subsequently the carbon coated samples were analysed with a Jeol: JSM-6390 LV Scanning Electron Microscope for identification of rock textures. Clay minerals and cement types were analysed coupled with EDX for qualitative and semi-quantitative analysis in the Botany Department, University of Fort Hare.

The rock milling machine was used to grind samples into powder that were intended for X-Ray Diffraction (XRD) mineral analysis. A minute portion of each sample was transferred into a mortar and pestle for further disintegration into powder form, after which the mortar and pestle were cleaned to prevent cross contamination from sample to sample with methylated spirit cleaning method. The sample preparation was conducted at the Geology Department, University of Fort Hare. The resultant powder was then used for XRD analysis, conducted in Chemistry Department, University of Fort Hare.

3.5.2 Modal composition analysis

Quantitative mineral composition analysis of Msikaba Formation was done through a petrographic microscope studies using the prepared thin sections. Thin sections for fine to coarse grained sandstone were chosen for variation in texture. The Gazzi–Dickinson's (1985) Method for point counting was used to accurately quantify several detrital mineral constituents of rock samples. Seventeen thin sections were selected and 500 points were counted for each thin section by using a spacing of 0.5 mm to 1mm during point counting. For this method, the matrix, cement, micas and other accessory minerals were counted but were excluded for modal analysis. However, total quartz (Qt) constituting monocrystalline quartz (Qm), polycrystalline quartz (Qp), plagioclase (P), K-feldspar (K), and lithic fragments(L) constituting sedimentary and metasedimentary clast (Ls) grains were counted and grouped to represent the sandstone detrital modes of the Msikaba Formation.

The modal composition analysis result of the detrital minerals were then normalised to 100% (Ingersoll, 1984). The result values were plotted on standard triangular diagrams (QFL) showing compositional fields associated with different provenances such as continental block provenances, recycled orogen, magmatic arc provenances (Dickinson, 1983; Dickinson and suczek, 1979). The obtained values were also plotted on QFL ternary diagrams (Pettijohn, 1980), which show different sandstone types.

3.5.3 Grain-size analysis and grain size distribution

Grain size analysis is a useful tool for understanding grain-size distribution and for studying hydrodynamic environment. It also used for prediction of sediment provenance, transport history and current condition because grain size closely linked to current energy of depositional environment (Folk, 1956). Grain size analysis was carried out with 17 thin sections of fine to coarse grained rock samples which were also used for modal composition analysis. Individual mineral grain diameters measurements taken under a petrographic microscope equipped with a calibrated eye-piece. A total of 400 grains measurements per thin section were taken by measurement of the conventional long (a) diameter method (Friedman, 1958, 1992; Adams, 1977; Johnson, 1994). The apparent dimensions of thin-section grain sizes were converted to normal sieve grain sizes using the method proposed by Friedman (1958, 1962).

Diameter measurements are monotonous, time consuming but a cheap and useful method and caution must be taken to ensure that there was no duplication of grains being measured and that the original grain diameter was recorded. Where there was a perceptible overgrowth of minerals, overgrowth part should not be taken account to the grain size. Lastly, the Udden-Wentworth grade scale was used to classify the grain size found in the Msikaba Formation sandstones (Tucker, 2005).

3.4.4 Scanning Electronic Microscope (SEM)

Sample analysis was performed using the Scanning Electron Microscope (SEM) in the Botany Department of the University of Fort Hare. The SEM model is Joel JSM-6390LV uses 15KV to running the analysis. SEM was used to identify grain morphology, rock texture, cement types, detrital and authigenic minerals, pore filling and pore-lining clays and other diagenetic changes such as replacement and recrystallization for the rock samples. The SEM analysis was coupled with the Energy Dispersive X-Ray (EDX) to determine the mineral types and mineral chemical compositions.

3.4.5 X-Ray Diffraction analysis (XRD)

X-Ray Diffraction (XRD) analysis was used to determine mineral types and compositions by measurement to the two theta degree of crystalline minerals present in the sandstone and mudstone of the Msikaba Formation. Rock samples were gridded into fine powder, and mounted into sample holder and then determined by using a Model D8 powder diffractometer with scanning speed of 30 points/min. The samples were analysed over the range of 2 to 85 degrees of two theta and a Diffrac Suite software package was used to give out the XRD pattern picture and mineral compositions.

CHAPTER 4: STRATIGRAPHY

4.1 Introduction

Field outcrops of the Msikaba Formation were measured along the Margate and Port Edward coastline areas in the Kwa-Zulu Natal and Eastern Cape Provinces. The stratigraphic sequence was constructed from the measured sections. The stratigraphy is essentially based on lithological features or properties such as colour, rock type, mineral composition and grain size of the strata of study areas, plus few exposures of body and trace fossils. Lithostratigraphy is based on the law of superposition of the strata, it is easily discernible in the layered sedimentary rocks. Msikaba Formation itself is a lithostratigraphic unit because it can be distinguished by its lithological character and by its stratigraphic position relative to other rock bodies (Nichol, 2009). The lithostratigraphic unit and observable sedimentary facies of the Msikaba Formation were documented in the field. In this study the subdivisions of Msikaba Formation have been changed into members not formations to remove the confusion. However, the subdivisions still maintain their original names in Kingsley, 1975. The new members are namely: Manaba Conglomerate Member, Uvongo Sandstone Member, Mhlangeni Grit Member, and the Shelly Beach Feldspathic Member.

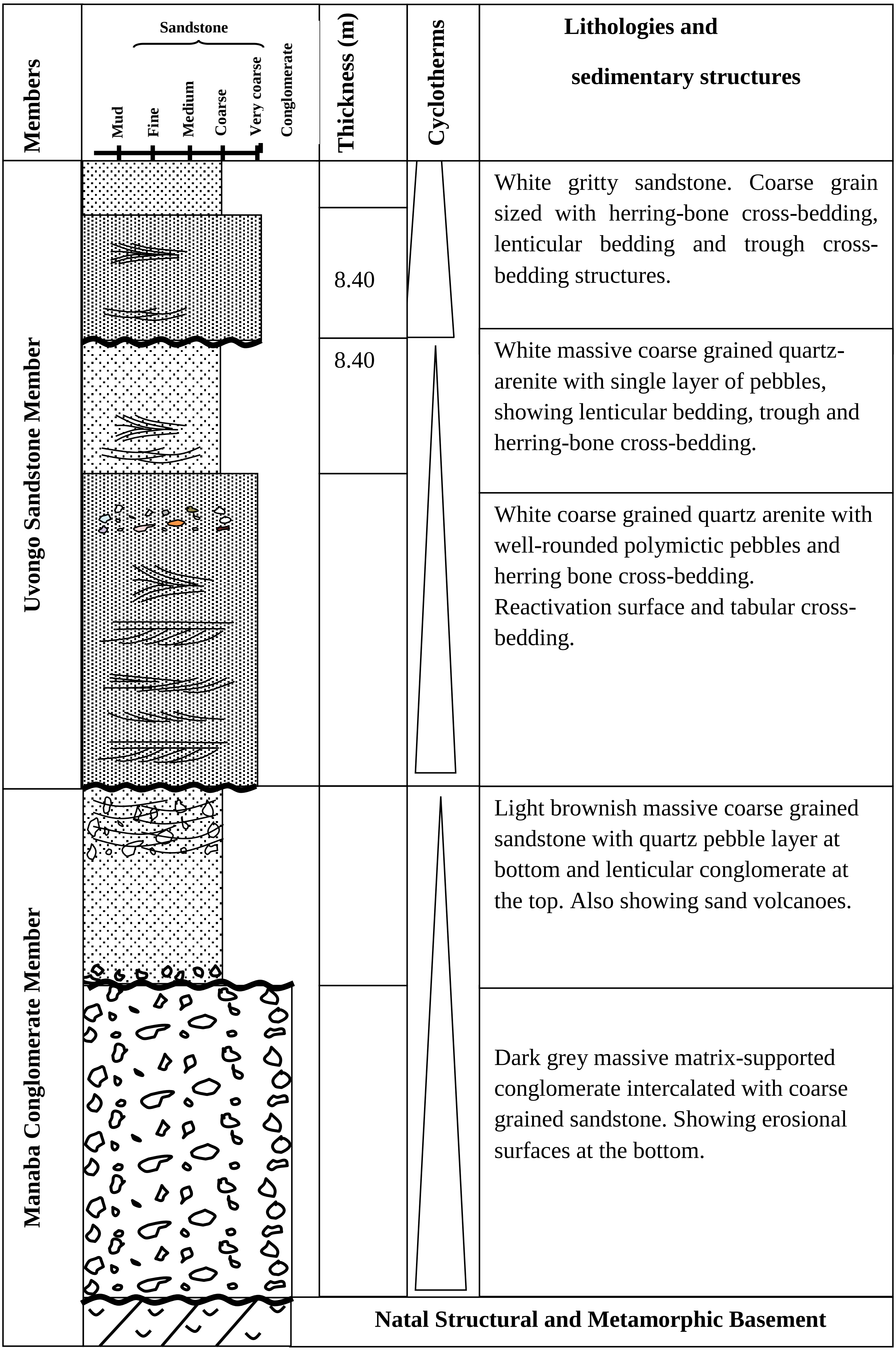
Sequence stratigraphy plays a fundamental role in linking sea-level changes to cyclicity of deposition, and it adds stratigraphic subdivisions and reflecting the linkage between sedimentary successions and tectonic movement events based on disconformity and unconformity-bounded stratigraphic units (Boggs, 2010).

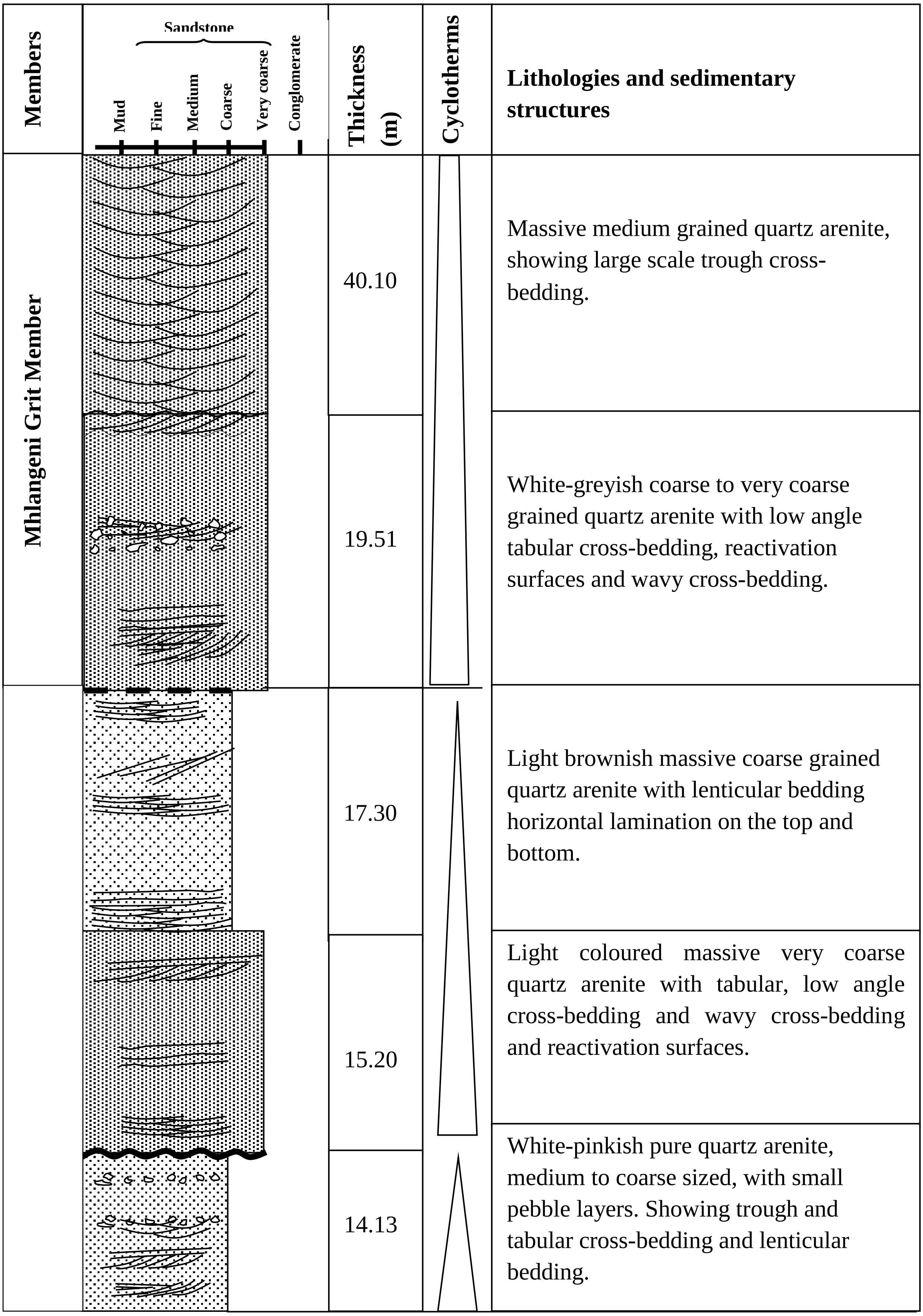
4.2 Stratigraphic section in the Margate area

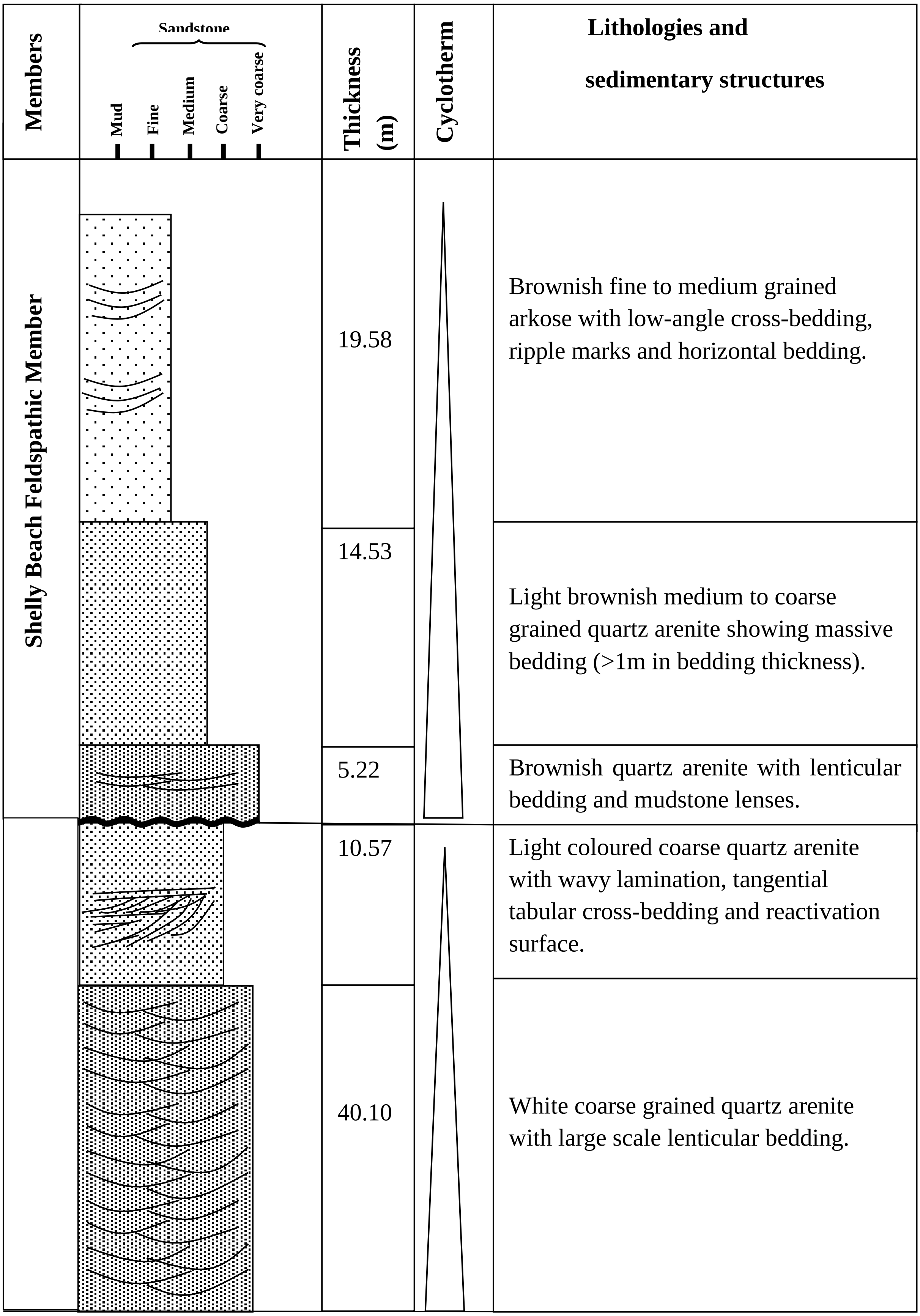
Msikaba Formation is well exposed on the Margate north beach, and is overlying directly on the rocks of the Natal Structural and Metamorphic Belt. The total thickness of the Margate succession is 184 metres, measured at latitude S30^{o}.51'14.5", and longitude E30^{o}.22'59.8". It can be subdivided into 4 Members, i.e. Manaba Conglomerate Member, Uvongo Sandstone Member, Mhlangeni Grit Member, and the Shelly Beach Feldspathic Member from bottom upward. The entire member names were given by Kingsley (1975) came from the type localities where the members are best exposed on.

The contact between the Manaba Conglomerate Member and the Natal Structural and Metamorphic Belt is an unconformity (nonconformity), thick brownish conglomerate of the Manaba Conglomerate Member deposited directly on the weathered and erosional surface of the Natal Structural and Metamorphic Belt, which constitutes the basement of the Msikaba Formation. From the outcrop of the Margate area, the sequence is essentially brownish conglomerate at the bottom, changing to white pure quartz-arenite in the middle and greyish quartz-arenite intercalated with thin mudstone at the top.

The measured section in the Margate area is illustrated below (Figure 4.1):

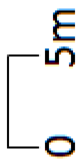

Members
Sandstone
Mud
Fine
Medium
Coarse
Very coarse
Conglomerate
Thickness (m)
Cyclotherms
Lithologies and
sedimentary structures
Uvongo Sandstone Member
Manaba Conglomerate Member
8.40
8.40
White gritty sandstone. Coarse grain sized with herring-bone cross-bedding, lenticular bedding and trough cross-bedding structures.
White massive coarse grained quartz-arenite with single layer of pebbles, showing lenticular bedding, trough and herring-bone cross-bedding.
White coarse grained quartz arenite with well-rounded polymictic pebbles and herring bone cross-bedding.
Reactivation surface and tabular cross-bedding.
Light brownish massive coarse grained sandstone with quartz pebble layer at bottom and lenticular conglomerate at the top. Also showing sand volcanoes.
Dark grey massive matrix-supported conglomerate intercalated with coarse grained sandstone. Showing erosional surfaces at the bottom.
Natal Structural and Metamorphic Basement


Members
Sandstone
Mud
Fine
Medium
Coarse
Very coarse
Conglomerate
Thickness (m)
Cyclotherms
Lithologies and sedimentary structures
Mhlangeni Grit Member
40.10
Massive medium grained quartz arenite, showing large scale trough cross-bedding.
19.51
White-greyish coarse to very coarse grained quartz arenite with low angle tabular cross-bedding, reactivation surfaces and wavy cross-bedding.
17.30
Light brownish massive coarse grained quartz arenite with lenticular bedding horizontal lamination on the top and bottom.
15.20
Light coloured massive very coarse quartz arenite with tabular, low angle cross-bedding and wavy cross-bedding and reactivation surfaces.
14.13
White-pinkish pure quartz arenite, medium to coarse sized, with small pebble layers. Showing trough and tabular cross-bedding and lenticular bedding.


Members
Sandstone
Mud
Fine
Medium
Coarse
Very coarse
Thickness (m)
Cyclotherm
Lithologies and sedimentary structures
Shelly Beach Feldspathic Member
19.58
Brownish fine to medium grained arkose with low-angle cross-bedding, ripple marks and horizontal bedding.
14.53
Light brownish medium to coarse grained quartz arenite showing massive bedding (>1m in bedding thickness).
5.22
Brownish quartz arenite with lenticular bedding and mudstone lenses.
10.57
Light coloured coarse quartz arenite with wavy lamination, tangential tabular cross-bedding and reactivation surface.
40.10
White coarse grained quartz arenite with large scale lenticular bedding.

Legend

Vertical thickness scale:



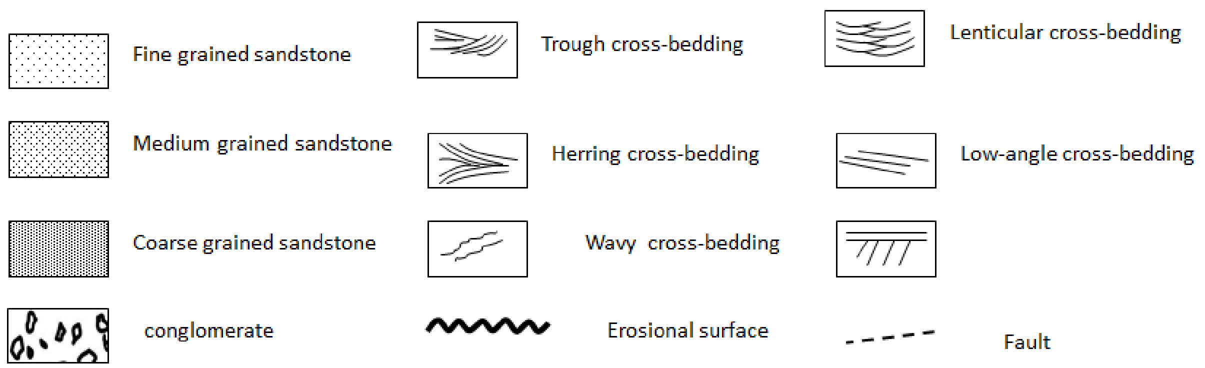


Figure 4.1 Stratigraphic section measured along the Margate beach.

Manaba Conglomerate Member

This is the lowermost member in the Msikaba Formation, and is best developed on the coastline area of Manaba beach where the name comes from. There are two recognisable lithological units in the Manaba Conglomerate Member: (1) Brownish matrix-supported base conglomerate and (2) Brown-greyish coarse sandstone further upward.

The conglomerate is matrix-supported and polymictic, consisting of milky quartz, chert, quartzite, banded iron formation, and metamorphic gneiss pebbles with a sandy/mud matrix. The pebbles are mostly rounded to well rounded, with few sub-angular. The pebble size within the conglomerate gradually become smaller or finer towards the top of the member. The pebble size in the bottom of the member ranges from 1-8.6 cm, whereas at the top pebble size ranges from 0.5-4 cm. Interbedded medium-coarse grained sandstone beds also present in the conglomerate. The conglomerate exhibits thick to massive bedding structure, intercalated sandstone exhibits lenticular bedding with tabular cross-bedding in some of the sandstone beds. Some of the conglomerate and sandstone are reddish-brown in colour due to weathering and exposed to surface. The individual bed of the conglomerate may reach to 3.8 metres thick, and each bed has erosional surface on the bottom. This is distinguished by lag of gravel and pebbles causing an uneven erosional bottom boundary. The thickness of the conglomerate is 20.50 m and has seven upward fining cycles of conglomerate-sandstone lithological change.

Overlying the conglomerate is brownish massive medium-coarse grained arkosic sandstone. The bed attains a thickness of 13.20m and shows graded bedding structure. Approximately 5.2 m at the bottom represents massive coarse grained sandstone and 8m at top is medium grained. Thin small-pebble lenticular conglomerates layers present in the whole sandstone succession with erosional surface occur at the bottom of some sandstone beds. Eight distinct upward fining cycles have been accounted in the sandstone unit, which shows typical characteristics of fluvial sediments and fluvial cyclicity styles. High content of feldspar in the rock is also consistent with the fluvial origin.

Uvongo Sandstone Member

This member is well exposed on the Uvongo beach area at north Margate, where the member name was obtained from. It marks the first appearance of marine deposits in the Msikaba Formation, it composes of white coloured coarse grained pure quartz-arenite and intercalated with thin pebble beds. The pebbles are well rounded and spherical in shape, and mainly milky quartz in composition. The sandstone shows high degree of chemical and textural maturity, indicating long distance of transportation and deposition in a high energy shallow marine environment. The sandstone exhibits fining upward cycles which begin with an erosional surface with the underlying fluviatile Manaba Conglomerate Member. There are three fining upward cycles having been accounted with an average of 8-20 metres thickness for each cycle.

The first cycle of quartz-arenite beds is characterised by trough, tabular cross-bedding with reactivation surfaces at the base which grades upwards to low angle cross-bedded quartz-arenite (6 m). Then the sandstone changes to thick bedded medium grained sandstone (15.2 m) with herring-bone and tabular cross-bedding structures. Thin layers of pebble beds are frequently occur in the quartz-arenite with quartz, chert, granite and gneiss pebble composition. Towards the top of the succession, pebble beds become more often.

The first cycle is overlain by the second cycle with coarse to medium grained quartz arenite. The sandstone beds have lenticular bedding at the base and herring-bone cross-bedding sandstone (5 m thick) grading to thick and massive bedded quartz arenite. The contact between the first cycle and second cycle is an erosional surface.

The third cycle shows an overlap of white coarse grained quartz-arenite in a pinkish hue or shade with medium grained pure quartz arenite. Small gritty sandstone layers are often present in the coarse quartz-arenite. Large scale lenticular bedding occurs at the base, and minor trough cross bedding and low angle tabular cross beddings occur at the top. There are also occasional small lenticular pebble layers towards the top of the cycle.

Mhlangeni Grit Member

Mhlangeni Grit Member is the third member of the Msikaba Formation, and it is distributed along Mhlangeni beach at the north of Margate. The member consists thick successions of six upward fining cycles that are inclined 11^{o} with a dip direction of 335^{o}. The first cycle is truncated by a linear fault running through the member, but the fault has not shortened much of the sequence. It is characterised by white and pale grey, medium to coarse grained pure quartz arenite sandstone. The cycle ranges from a thickness of 14 to 40 m, the bed is dominated by lenticular bedding at the base and overlain by a massive sandstone with low angle cross-bedding dipping approximately 3 degrees. Tangential tabular cross-bedding is well developed in the succession with minor parallel tabular cross-beddings. Towards the top of the member, reactivation surfaces and wavy cross-bedding become more persistent in the lower succession.

Tangential tabular cross-bedding and lower angle cross-bedding (dip angle $<10^{o}$) is an indicator of shallow marine environment, which are often developed in beach and tidal flat areas.

Shelly Beach Feldspathic Member

This member represents a mixed deposit of both marine and fluvial sediments. The type locality is in Shelly Beach area where it is best developed. It is composed of quartz arenite and arkosic sandstone, and is intercalated with very thin bedded mudstone lenses (each less than 10 mm thick). The quartz arenite is medium to coarse grained and becomes fine grained texture upward. The arkosic sandstone is actually sub-arkose in nature, feldspar contents are between 5-25% which is less than normal arkose of feldspar content of >25%. In the field, white quartz-arenite alternated with red-brownish sub-arkose, indicating alternation of marine water incursion and retraction, or fluvial streams incursion and retraction. The environmental shift from marine to fluvial or from fluvial to marine indicates an interaction zone of marine and fluvial environment.

Sedimentary structures present in this member are trough cross-bedding, lenticular bedding, ripple marks and tabular cross-bedding, reflecting a shallow water environment, probably a river mouth or coastline tidal flat environment. Pervasive small grit clasts are also randomly present in the sequence, indicating active water/current of higher energy hydrodynamic condition. On the top of succession, the red-brownish arkosic sandstone gradually increased, indicating depositional environment gradually shift from dominated marine environment to dominated fluvial environment.

4.3 Stratigraphic section in the Port Edward Area

The Msikaba Formation (Figure 4.2) is well exposed in outcrops along the Port Edward beach area and is characterised by an inclined strata with a dip direction of 240 degrees and dip angle of 7-15 degrees. The measured section is approximately 186 metres in thickness which consists of eight upward fining cycles that range from thickness of 20-40 metres. This succession is made up of 90 percent quartz arenite sandstone.

Manaba Conglomerate Member

The bottom of the Msikaba Formation in Port Edward area is composed of dark brownish matrix supported pebble conglomerate, which was probably deposited by a braided river system flowing from north of Margate to the south of Port Edward, and attains a thickness of approximate 20 cm. Unlike the Margate section, the bottom conglomerate in the Port Edward area is much thin and is overlies on a charnockite igneous rock and not overlies on the Natal Structural and Metamorphic Belt.

Uvongo Sandstone Member

The conglomerate is overlain by massive and thick bedded pale grey quartz arenite, which is texturally very coarse to medium grained. The sandstone shows characteristic tangential-tabular cross-bedding with reactivation surfaces and grading to a low-angle cross-bedding, lenticular bedding, tabular cross-bedding and massive bedded medium to coarse grained quartz arenite. Quartz pebble layers occur at the bottom and top of the succession. The coarse grain size and the sedimentary structures indicate that the sediments were deposited in a high energy upper flow regime in a shallow marine depositional environment and forms the first sandstone upward fining cycle in the Port Edward area.

Mhlangeni Grit Member

Overlying beds are characterised by three upward fining cycles of small quartz conglomerate units with a thickness ranging from 0.7 m to 1.3 m that are interbedded with medium to coarse grained quartz arenite sandstone. The quartz conglomerate beds are poorly sorted and some pebbles are angular in shape, which indicate the pebbles were not transported for long distance. All the cycles represent a channel fill deposits, probably formed in a tidal channel or tidal influenced tidal flat depositional environment.

The uppermost intervals are dominated by shallow marine deposits of pure quartz-arenite and show eight upward finning cycles. Each cycle thickness ranges from 5 to 30 m, and is composed of very coarse grained pure quartz arenite with large scale lenticular cross-bedding at the base and medium to course quartz-arenite at the top with tangential tabular cross-bedding and trough cross-bedding structures.

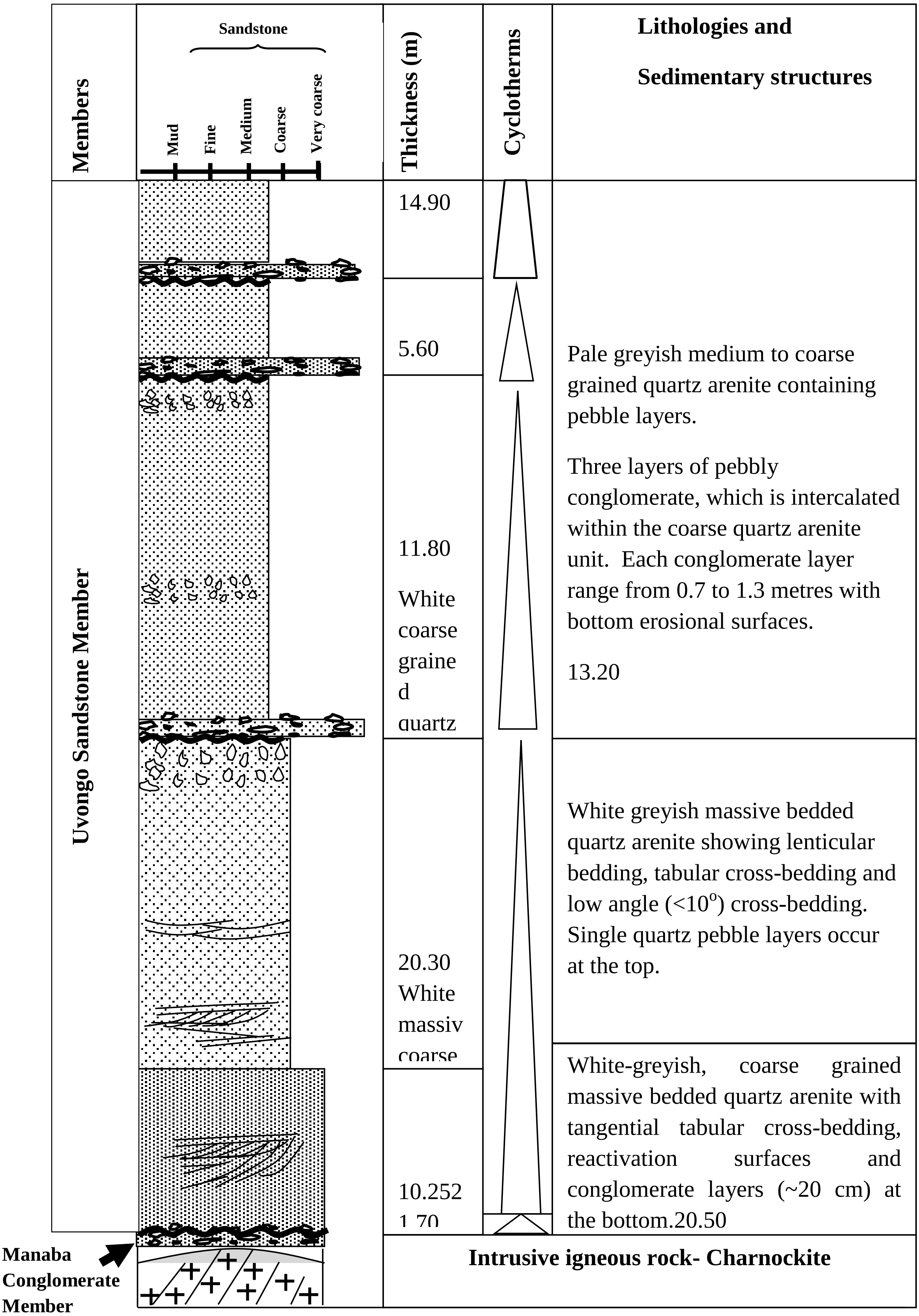
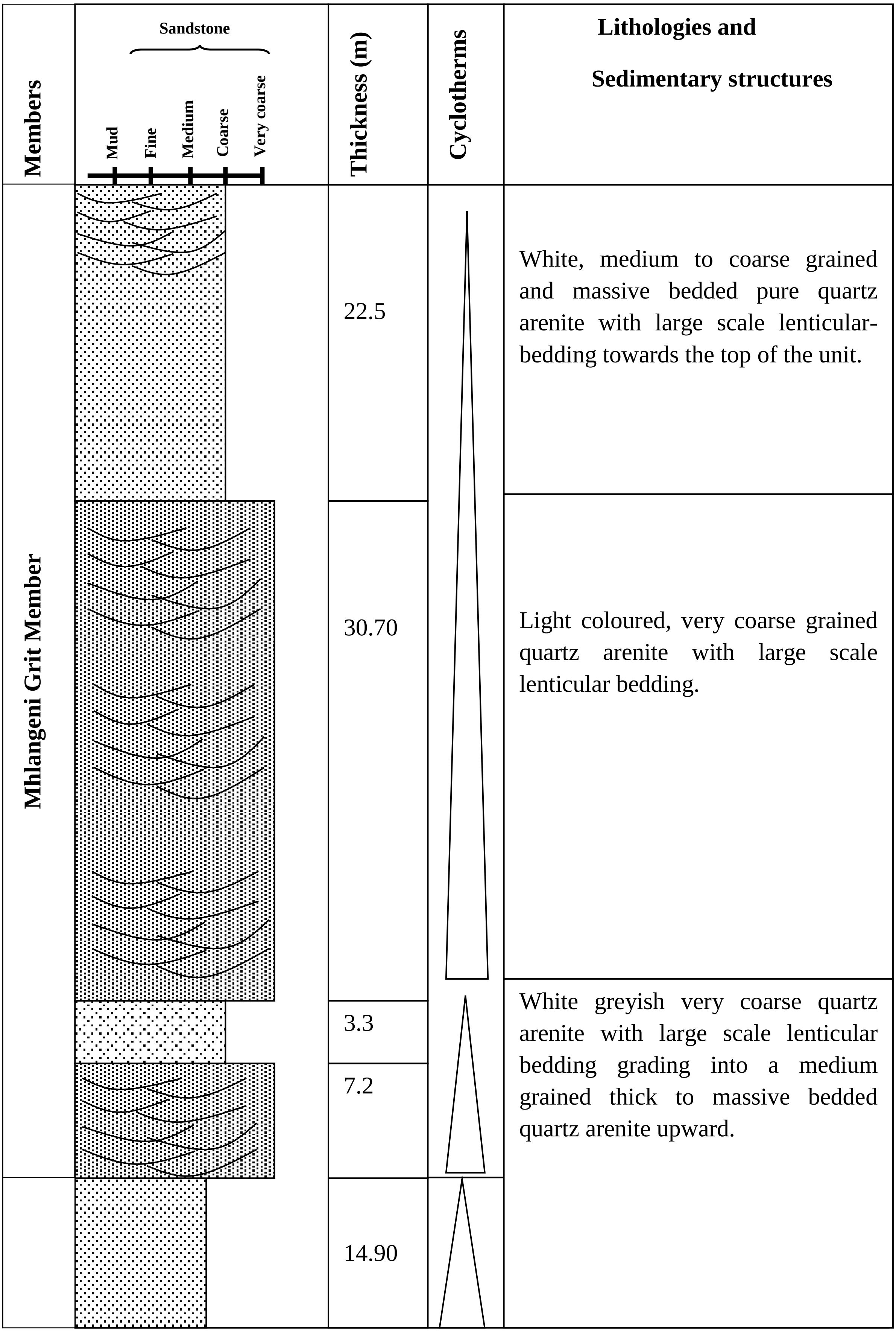

Members
Sandstone
Mud
Fine
Medium
Coarse
Very coarse
Thickness (m)
Cyclotherms
Lithologies and
Sedimentary structures
Uvongo Sandstone Member
14.90
5.60
11.80
White
coarse
graine
d
quartz
20.30
White
massiv
coarse
10.252
1.70
Pale greyish medium to coarse grained quartz arenite containing pebble layers.
Three layers of pebbly conglomerate, which is intercalated within the coarse quartz arenite unit. Each conglomerate layer range from 0.7 to 1.3 metres with bottom erosional surfaces.
13.20
White greyish massive bedded quartz arenite showing lenticular bedding, tabular cross-bedding and low angle (<10°) cross-bedding. Single quartz pebble layers occur at the top.
White-greyish, coarse grained massive bedded quartz arenite with tangential tabular cross-bedding, reactivation surfaces and conglomerate layers (~20 cm) at the bottom.20.50
Manaba
Conglomerate
Member
Intrusive igneous rock- Charnockite

Figure 4.2 Stratigraphic section measured along the Port Edward beach.


Members
Sandstone
Mud
Fine
Medium
Coarse
Very coarse
Thickness (m)
Cyclotherms
Lithologies and
Sedimentary structures
Mhlangeni Grit Member
22.5
White, medium to coarse grained and massive bedded pure quartz arenite with large scale lenticular-bedding towards the top of the unit.
30.70
Light coloured, very coarse grained quartz arenite with large scale lenticular bedding.
3.3
7.2
White greyish very coarse quartz arenite with large scale lenticular bedding grading into a medium grained thick to massive bedded quartz arenite upward.
14.90

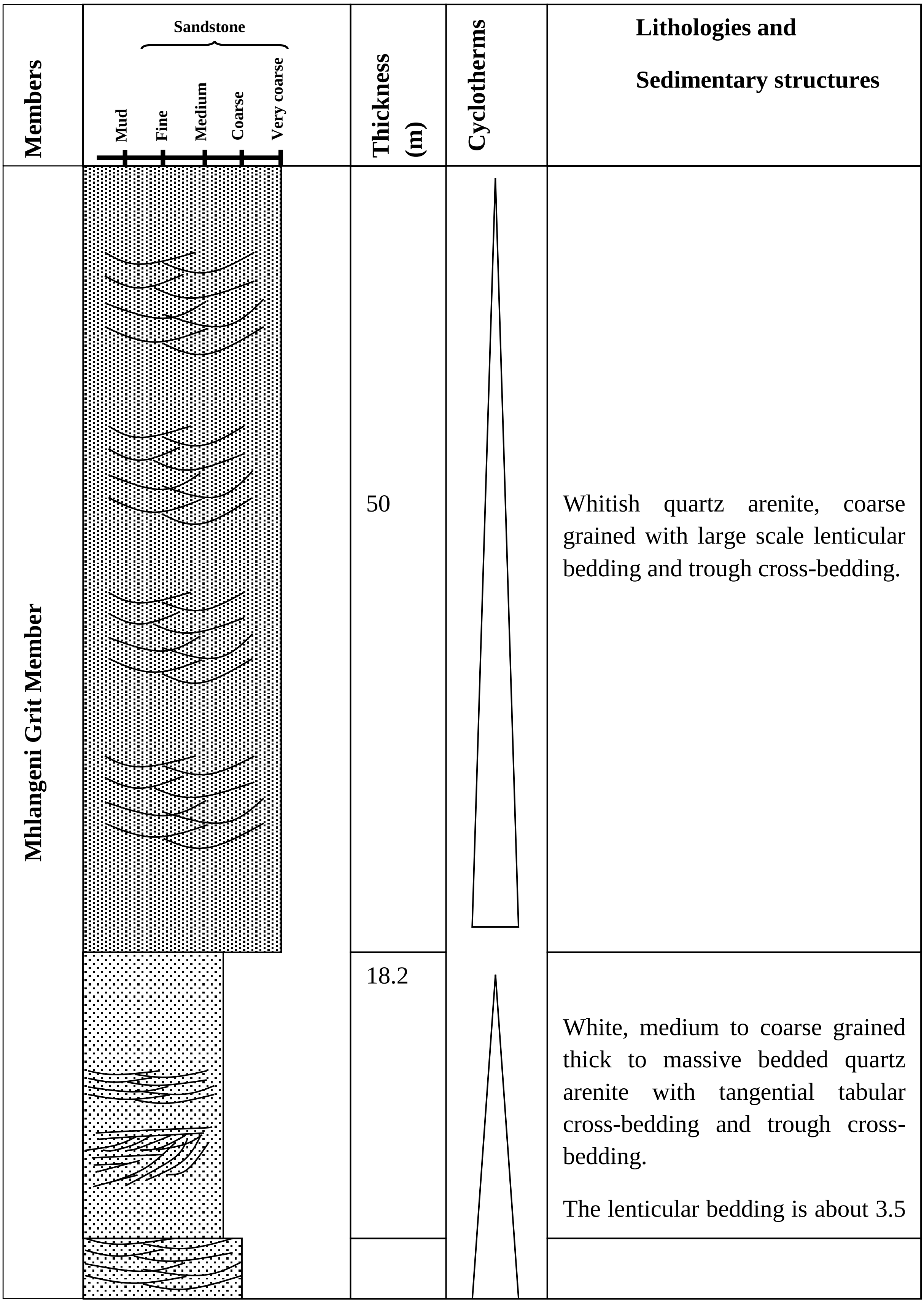


Figure 4.2 Stratigraphic section measured along the Port Edward beach.

4.4 Cyclicity of Msikaba Formation

Individual lithologies and lithological associations of the Msikaba Formation have cyclic relationships throughout the formation. The cycles vary in thickness from a few metres to several tens of metres. Cycles within the study area comprise conglomerates and quartz arenite sandstone and are varied in small scale and large scales as well.

Margate study area

The Margate stratigraphic column has smallest scale cycles that are represented by fluvial deposits in the Manaba Conglomerate Member. These small scale cycles exhibit an upward fining trend and each cycle is approximately 3 to 5m thick. Observations show eight small scale cycles of alternating conglomerate and arkosic sandstone with tabular and trough cross-bedding sedimentary structures. However on the stratigraphic column above cycles are represented by one big cycle.

Uvongo Sandstone Member, the quartz arenite sandstone exhibits fining upward cycles which begin at an erosional surface with the underlying fluviatile Manaba Conglomerate Member, and marks the first appearance of marine deposits in the Msikaba Formation. There are three fining upward cycles having an average of 8-20 metres thickness for each cycle.

The first cycle of quartz-arenite beds is characterised by trough, tabular cross-bedding with reactivation surfaces at the base which changes upwards to low angle cross-bedded quartz-arenite. It is composed of white coloured very coarse grain-sized pure quartz-arenite and intercalated with thin pebble beds.

The second cycle is coarse to medium grained quartz arenite. The sandstone beds have lenticular bedding at the base and herring-bone cross-bedding sandstone (5m thick) grading to thick and massive bedded quartz arenite. The contact between the first cycle and second cycle is an erosional surface.

The third cycle shows an overlap of white coarse grained quartz arenite in a pinkish hue or shade with medium grained pure quartz arenite with small gritty quartz layers, which are frequently present in the coarse quartz-arenite. High energy shallow marine environment.

Mhlangeni Grit Member is the third member, it consists of thick successions of six upward fining cycles that are inclined 11^{o} with a dip direction of 335^{o}. It is characterised by white and pale grey, coarse to medium grained pure quartz arenite sandstone. All the cycles range from a thickness of 14 to 40 m on each cycle, and the cycles are represented by one cycle on the stratigraphic column, the beds are dominated by lenticular bedding, low angle cross-bedding and dipping tangential tabular cross-bedding.

Shelly Beach Feldspathic Member consists of one cycle of quartz arenite and arkosic sandstone, is intercalated with very thin bedded mudstone lenses. The quartz arenite is medium to coarse grained and becomes fine grained at the top of the cycle. The environmental shift from marine to fluvial or from fluvial to marine indicates an interaction zone of marine and fluvial environment.

Port Edward area

Manaba Conglomerate Member in the Port Edward area is composed of dark brownish matrix supported pebble conglomerate and attains a thickness of approximate 20 cm that overlies on a charnockite igneous rock. It is represented by one fluvial cycle. The conglomerate forms an erosional surface with overlying quartz arenite beds.

Uvongo Sandstone Member consists of massive and thick bedded pale grey quartz arenite, which is very coarse to medium grained. The sandstone is characterised by three upward fining cycles of small quartz conglomerate units with a thickness ranging from 0.7 m to 1.3 m that are interbedded with medium to coarse grained quartz arenite sandstone. All the cycles represent a channel fill deposits, probably formed in a tidal channel or tidal influenced tidal flat depositional environment.

Mhlangeni Grit Member cycles are dominated by shallow marine deposits of pure quartz-arenite and show eight upward finning cycles and represented by one cycle on the stratigraphic column. Each cycle thickness ranges from 5-30m and is composed of very coarse grained pure quartz arenite with large scale lenticular cross-bedding at the base and medium to course quartz-arenite at the top with tangential tabular cross-bedding and trough cross-bedding structures.

4.5 Correlation between Margate and Port Edward sections

Msikaba Formation in Margate area shows a complete stratigraphic sequence overlying Natal Structural and Metamorphic Basement till to the uppermost section in the Shelly beach area. The Port Edward section was not a complete stratigraphic sequence, the basal conglomerate is not well developed, attaining a thickness of 30 cm, and overlies the charnockite igneous rock. The upper portion of the formation in the area is relatively uniform and lack of lithological changes. It is dominated by quartz arenite, with some thin layers of gritstone and siltstone/mudstone, the latter is very thin layered or absent from cycle to cycle in the succession. The contacts between the sandstone sections are mostly erosional than transitional between different lithological units and beds on both stratigraphic columns. Msikaba Formation in the Margate area is easily correlated with Port Edward stratigraphic column (Figure 4.3 below) due to resemble of strata and similar depositional environment.

Concerning the thickness of strata, Port Edward section has much thin bottom conglomerate unit, and has much thick quartz arenite unit, which show high energy upper flow regime deposition, indicating shallow depth of marine deposits. Whereas the Margate section has a thick bottom conglomerate unit and a thinner pure quartz arenite unit, indicating there was a period of fluvial dominant stage before marine water transgression and the formation of pure quartz-arenite rock units.

In conclusion, examination of previous stratigraphic columns indicates no subdivisions of the formations by Kingsley (1975) and kingsley and Marshall (2009). Kingsley's (1975) Margate facies were formally named Msikaba Formation by P.E Matthews through personal communication with SACS (Marshall, 1994). However,the subdivisions by Kingsley (1975) were not redefined and still remain as formations. This does not follow the nomenclature rules. Generally a formation can further be divided into smaller stratigraphic units called members). The established members of Msikaba Formation in the Margate area in the north were correlated with the Port Edward stratigraphic column in the south from fluvial conglomerate postulated deposition by braided river system to the beach or intertidal deposits and then shallow marine deposition of very mature pure quartz arenite sandstone.

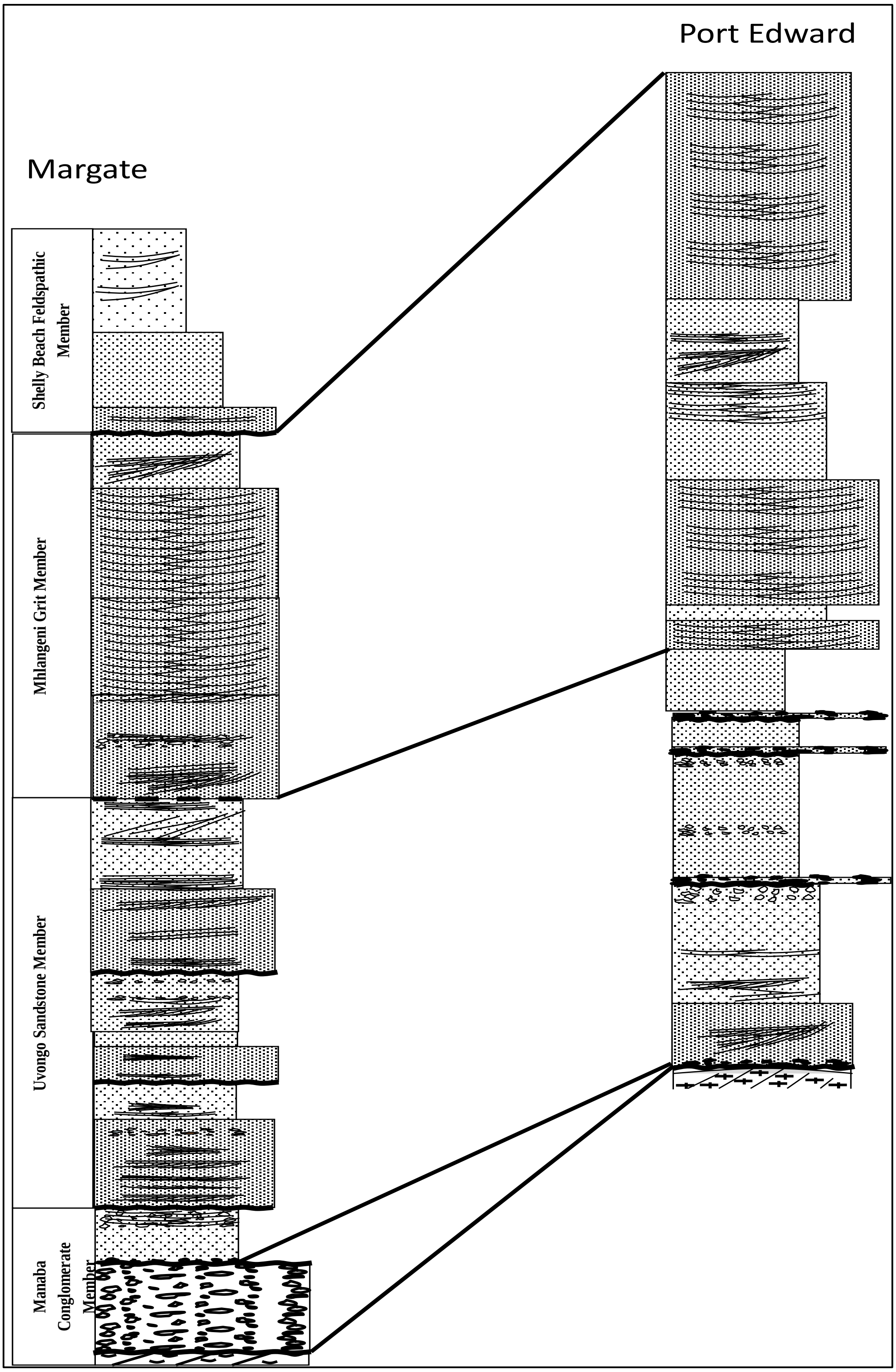


Figure 4.3: Stratigraphic correlation of Msikaba Formation between the Margate and Port Edward stratigraphic successions.

CHAPTER 5: SEDIMENTARY FACIES AND FACIES ASSOCIATIONS

5.1 Introduction

This chapter presents a description of lithofacies of Msikaba Formation that were identified in the Margate and Port Edward study areas. Descriptions of lithofacies was done on the outcrops along the coastline. The observations helped to determine and interpret the depositional environments based on the lithologies, sedimentary structures and their contact relationship. These serve as diagnostic features of depositional processes, hydrodynamic conditions and depositional environments. The major rock types that were identified in the Msikaba Formation comprise of matrix-supported conglomerates, grain-supported pebbly conglomerate, subarkose, quartz arenite, siltstone and mudstone.

Sedimentary facies is a concept that is used in a descriptive and interpretative manner so as to delineate the formation processes and depositional environments from which a specific sedimentary rock body is derived from. The term “facies” is defined as a body of sedimentary rock with specific characteristics such as combination of lithological, physical and biological aspects to distinguish it from neighbouring rock bodies, and it is defined on basis of lithology, colour, bedding, mineral composition, texture, grain size, sedimentary structures, palaeocurrent pattern and fossil content. There are two different sedimentary facies, i.e. lithofacies and biofacies. Lithofacies deals with the lithological characteristics, such as colour, mineral composition, rock texture and sedimentary structures; while biofacies deals with the biological features, such as fossil types, burial and proportion of a specific fossil, fossil assemblage and etc.

However, isolated facies is not good enough to indicate depositional history and sedimentary environment. Interpretation of depositional environment is dependent on various factors, including lithological characteristics, biological characteristics, and the vertical and lateral profile of the facies in the field outcrop. Accordingly, a collaboration of related facies that are influenced by different processes give a true and more reliable representation of a unique depositional environment. Therefore, it is safe to group the facies that are likely to occur in the same depositional environment to create a facies association (Reading, 2006; Miall, 1997).

5.2 Facies analysis of sedimentary rocks

Msikaba Formation is well exposed succession in the field, and is composed of various sedimentary rocks including matrix-supported conglomerate, massive quartz arenite sandstones, and fine grained siltstone and mudstone laminations. The thickness of a single rock unit ranges from a few centimetres to more than ten metres depending on how shallow and deep the depositional environment was. Existing also are well developed sedimentary structures found in the succession, such as lenticular bedding, trough and tabular cross-bedding, herring bone cross bedding and reactivation surface, which also indicate depositional environment. Based on the lithologies, sedimentary structures, and grain-size variations, different sedimentary facies can thus be defined in the Msikaba Formation. A modified version of sedimentary facies codes proposed by Miall (1977, 1983, 2000) is used to define the sedimentary facies which found in the Msikaba Formation (Table 4.1).

Table 4.1: Sedimentary lithofacies code used in the Msikaba Formation (modified from Miall 1977, 1983 and 2000).

Facies code		**Description**
Gmm	Conglomerates (G)	Matrix supported, massive conglomerate
Gcm		Clast-supported , massive conglomerate
Sm	Sandstone (S)	Medium bedded arkosic sandstone
St		Trough cross-bedded sandstone
Slc		Low angle cross- bedded sandstone
Sh		Horizontally laminated sandstone
Sr		Ripple mark sandstone
Sp		Tabular cross-bedded sandstone
Sl		Lenticular bedded sandstone
Shb		Herring-bone cross-bedded sandstone
Fslt	Siltstone	Fine grained siltstone
Fl	Mudstone	Laminated mudstone

5.3 Lithofacies of the Msikaba Formation

5.3.1 Brownish massive matrix supported conglomerate facies (Gmm)

The lithofacies Gmm is recorded in both Margate and Port Edward sections, and comprises of dark grey to brownish massive conglomerates with subordinate intercalated brownish arkosic sandstones. The bedding thickness varies from 0.5 m to 1.5 m, and shows very thick to massive bedding structure. This facies is typically appeared in the bottom of the Margate section, and also appeared in the bottom of the Port Edward section. The maximum thickness in the Margate section can reach to approximately 20.5m, whereas the thickness in the Port Edward area is much thinner exhibiting approximately 20cm. The conglomerate beds are characterised by poor sorting and polymictic pebble compositions such as quartz, chert, mudstone, granite, bended iron formation (BIF) pebbles, and metamorphic rock fragments. The matrix is composited of clay, silt and fine sand material and takes more than 50% of the rock volume, which means a matrix-supported texture (Figure 5.1). The pebble size is variable from 2-5 cm in diameter, indicating a poorly to moderate sorted clastic texture. Some of pebbles are elongated, but more sub-spherical (Figure 5.2) and the roundness is variable from sub-rounded and sub-angular in shape with pebble size decreases upward in the rock sequence. The interbedded arkosic sandstones are generally medium to coarse grained with a thickness ranges between 0.5-1.5m. Sandstone bed predominantly shows planar cross-bedding, lenticular bedding and convoluted beds. There are approximately seven fining upward units beginning with conglomerate at the bottom and sandstone at the top with erosional bounding surface or uneven erosional bases were observed in the Msikaba Formation. Cycles show a variation in thickness, each cycle ranges between 2.5-3.8 m.

Interpretation

Facies Gm is represented by matrix-supported conglomerate that is intercalated with coarse grained arkosic sandstone. Each unit has an erosional surface that is marked as a lag deposit of gravels and pebbles and interpreted have been deposited as a fluvial channel deposit. The matrix supported texture indicates the hydrodynamic energy was not very strong compared to the grain-supported texture, and the massive bedding structure implies the depositional rate was higher (Tucker, 1991) and the environment was relatively stable during the time of deposition. The grey-brownish colour of the deposition indicates the sediments were deposited in an oxidic environment, not in a reducing environment. The polymictic pebble compositions reflects the source came from a wide areas and the sediments were not been transported for long distance. These characteristics reflect that the conglomerate was probably deposited in a fluvial channel environment, rather than a shallow marine environment where the sediments will be more pure and the texture more mature. Considering also some pebbles are elongate or disc shaped (Figure 5.2), the depositional environment could be near the lower reaches of a river system, where marine water incursion could have occurred from time to time in the environment, thus leaving some pebbles with characteristics of shallow marine/beach sediments. According to Plint (1995), fluvial conglomerate deposits tend to be poorly sorted than shoreline and beach facies because sand and gravel is likely to segregate and be better sorted in beach environment, which are consistent with and supported our conclusions.

Figure 5.1: Photograph showing conglomerates with polymictic clasts and rounded to subrounded pebbles setting in the fine grain-sized matrix in the bottom of the Margate section.

Figure 5.2 Photograph of elongated clasts that have been eroded out in the Manaba Member.

5.3.2 White clast-supported pebble conglomerate facies (Gcm)

The lithofacies is mostly found in Uvongo Member of the Msikaba Formation in both Margate and Port Edward study areas. It is composed of quartz or quartzite pebbles that are similar in size. The pebbles in this facies are moderately to well-sorted, and moderate to well-rounded with pebble size varies from 1-4 cm (Figure 5.3). These conglomeratic beds are intercalated within thick-bedded, white quartz arenite sandstone. The pebbles are densely packed and have taken more than 50% of the rock volume, hence it shows a typical clast-supported texture, rather than a matrix-supported texture. It also shows many cyclicity of pebble bed-sandstone bed changing in the vertical stratigraphic profile in the field, and each cyclicity thickness of the conglomerate-sandstone beds ranges up to 2-5 metres. Individual pebbly conglomerate bed ranges from 10-30cm thick, and then grades to quartz arenite sandstone upwards. The quartz arenite sandstone itself is medium to coarse grained and contains scattered quartz pebbles in its internal structure. The grain-size of the pebble conglomerate decreases upward along the Margate succession and represents a large upward fining sequence due to the reduction on pebble size and sandstone grain size. Various sedimentary structures are well developed in this facies, trough cross bedding, tabular cross bedding, lower angle cross bedding, herring bone cross bedding and reactivation surface structures are very common in the outcrops.

<u>Interpretation</u>

Facies Gcm in the Msikaba Formation indicates a rapid quartz-rich sedimentation, it composes of pure quartzous pebbles or pure quartz arenite sandstone, and shows remarkable difference with the bottom Manaba Member, which is polymictic and feldspathic in lithology and of fluvial in depositional environment. The pebbles within the conglomerate and sandstone show no imbrications and the sedimentary structures of tabular cross-bedding, trough cross-bedding, low angle cross-bedding attributed to high energy hydrodynamic conditions. Considering the class-supported texture, well rounded and high spherical pebble shapes, as well as high maturity of mineral composition and high degree of rock texture and sorting, this pebbly conglomerate facies was most probably formed in a marine depositional environment influenced by storm wave and current actions. Upward in the succession, the hydrodynamic condition became weak, leading to the formation of the sandstone and pebbly sandstone rock units at the top. It is obviously that the facies was deposited in an upper flow regime high hydrodynamic environment such as a tidal channel or tidal influenced foreshore environment where intense washing and reworking by wave and tide current resulting high spherical and densely packed pebble beds.

According to Kingsley (1975) the major conglomerate zones in Msikaba Formation may also mark a renewed tectonic movement in the source areas.

Figure 5.3: Clast supported quartz pebble conglomerate from Msikaba Formation (Uvongo Member) in the Margate area.

5.3.3 Medium bedded arkosic sandstone facies (Sm)

This lithofacies occurs in the top of the Manaba Member and overlies on the matrix-supported conglomerate facies (Gmm) in the Manaba beach, north Margate. It also found in the Shelly Beach Member. The facies consists of medium bedded, medium to coarse-grained and moderately to poor sorted arkosic sandstone with individual bed thickness varying from 15-75 cm. The contact between arkosic sandstones facies with the bottom conglomerate facies is erosional (Figure 5.4). The sandstone facies contains quartz and feldspar sand grains and is cemented by fine silts and clay mineral. The sandstone shows little or no apparent internal structure or may reveal weak stratification after intense weathering. However, in Shelly Beach Member the arkosic sandstone facies exhibits identification of primary structures such as tabular and lenticular beddings. The colour of the sandstone varies from brown to reddish brown.

Interpretation

The medium bedded sandstone facies indicates a relative shallow water environment, which was less than the bedding thickness of 10-50 cm. The brownish and red-brownish colour indicates an oxidic environment, rather than a reducing environment. The mineral composition in the rock is rich of feldspar, which implies the sediments had not been transported for long distance, hence the unstable mineral of feldspar can still survive and remain in the rock. Therefore, all the characteristics of the lithofacies reflect a fluvial deposit and is lack of the features of marine sediments. Considering the arkosic sandstone facies occurs just above the matrix-supported conglomerate facies (Gmm), it was most probably deposited in a fluvial stream, and not in a marine environment. The medium to coarse grained nature and unidirectional flow also indicate the facies were produced by fluvial process than a marine process. More specifically, it may be interpreted as a fluvial-fan or fluvial plain deposit in a medium to high energy environment.

Figure 5.4: Photograph showing medium bedded arkosic sandstone with no internal structure in Manaba Conglomerate Member and uneven erosional surface in the bottom.

5.3.4 White thick bedded quartz arenite facies (Sm)

This lithofacies is thick bedded or massive and is a widely distributed and most common facies in the Msikaba Formation in the study areas (Figure 5.5). The sandstones are white or light grey in colour, and may have a yellowish hue after weathering in some localities. The rock unit thickness of the facies ranges from 2-40 m and they commonly have sedimentary structure within the beddings such as lenticular bedding, tabular and trough cross-beddings, low angle cross-bedding and reactivation surfaces. Another prominent feature is the grittiness of the quartz grain sizes and rounded to sub-angular quartz pebble clasts within the thick beds. Sometimes the pebbles occur as single pebble layer within the sandstone beds. The grain-size of the quartz arenite is coarse to very coarse grained and the dominant mineral is quartz with little feldspar and lithic fragments, thus it shows high degree of mineral composition maturity and also high degree of texture maturity with little matrix as the grain cement. Graded bedding structure may present within the beds, and the facies contacts with underlying and overlying beds with a sharp and erosional contact boundaries.

Interpretation

The lithofacies shows high degree of mineral and texture maturity with quartz content is commonly more than 85%, feldspar and clay matrix is less than 15%, which are the typical characteristics of marine sediments rather than fluvial sediments. Considering the coarse to very course grain size and sedimentary structures such as erosional surface and cross-beddings in the strata, this sedimentary facies should be formed in a higher energy hydrodynamic environment. The sediments could be recycled and could be linked to a quartz rich source rocks, thus resulting in a pure quartz arenite facies (Figure 5.6). The single pebble layers present within the sandstone beds reflect the high hydrodynamic energy was due to sudden increased probable storm event. Well-developed quartz arenite facies in the area indicates that the dominant depositional environment for the formation of Msikaba Formation was a shallow sandy beach, it could also be a shallow marine platform, or a shallow tidal flat environment where storm weather could be happened from time to time.

Figure 5.5: Photograph showing thick bedded gritty quartz arenite sandstone with weathered horizontal bedding and low angle tabular cross-bedding inside.

Figure 5.6: Photograph showing very coarse quartz arenite facies. Note the trough cross-bedding structure inside the bed.

5.3.5 Horizontal laminated (Sh) and low angle cross-bedded sandstone facies (Slc)

This lithofacies is common in the study areas. It occurs in medium to thick bedded, medium to coarse grained quartz arenite lithology. It is greyish to pale white coloured, and shows horizontal lamination or low angle (<10^o) cross bedding structures within the beds (Figures 5.7 and 5.8). After weathering in beach area, it could be changed to pinkish in colour on surface. The mineral composition of the rock is dominated by quartz with very little feldspar could be found, thus it belongs to quartz arenite group. Well-developed lamination structure varies in thickness from few millimeters to few centimetres in thickness, and aligned parallel to each other. The individual bed varies from 30 cm-80 cm and the whole facies could be reached up to 5.0 m thick. In vertical profile, it could constitute a fining-upward cycle in the succession with sand grain size gradually decreases upward from bottom to top rock unit.

Interpretation

The quartz rich lithology and the mature rock texture of the lithofacies reflects that the sediments were transported for long distance. The dip angle of the low-angle cross-bedding varies from 3^o to 10^o. According to Reineck and Singh (1980), the horizontal lamination and low angle cross-bedding are commonly found in shallow marine, particularly in the tidal flat or beach area. The quartz arenite rock unit has a fining upward nature with coarse to very coarse grain size in the bottom and gradually changes to medium and fine grained at the top. The horizontal lamination represents upper plane lamination phase which formed through subaqueous deposition at high flow velocities in the upper flow regime. The laminae is visible because of subtle grain size changes and by parting lineations on lamina surfaces (Tucker, 1982).

Figure 5.7: Photograph showing inclined horizontal-laminated sandstone from Port Edward area.

Figure 5.8: Photograph showing low angle tabular cross-bedding sandstone in Margate area.

5.3.6 Tabular cross-bedded medium to thick sandstone facies (Sp)

Tabular cross bedded quartz arenite facies is one of the major facies within the Msikaba Formation. The sandstones of this facies are white or light coloured, and are quartz rich with quartz content >90%. Feldspar and lithic fragments occur as accessory minerals (<10%). Tabular cross bedding structures are well preserved in the strata (Figure 5.9). The sandstones are medium to coarse grained, and each sandstone bed ranges from a thickness of 30 to 90 cm (Figures 5.10). In some of the areas the tabular bed sets are bound by erosional surfaces at the bottom because of erosion of the overlying beds. In some places, the tabular beds are tangential with bottom surface with an angle less than 20^o and continually have reactivation surfaces that separate the adjacent cross-bedding foresets.

The dip directions of the tabular cross bedding in the Msikaba Formation reflect the palaeocurrent direction flowed from south-east to north-west, which is remarkably different to the palaeocurrent direction of the Natal Group of north-east to south-west (Marshall, 1994). Quartz arenite sandstone facies is a mature lithofacies and is present in the Uvongo and Mhlangeni Members of the Margate area.

Interpretation

The tabular cross-bedded sandstone facies is a prominent facies in the study areas, it occurs as planar and tangential sets. Moreover, the rocks have variable grain-sizes from medium to very coarse. The thickness of tabular sets is also medium to thick bedded. All these characteristics represents sand waves deposition and may be interpreted as a product of high energy shallow marine deposit. The current energy would be variable from time to time, thus the sediment grain-size and the bedding thickness are also variable from bed to bed. The tabular beds are good current direction indicator, and represent inclined laminations with unidirectional current flow direction from southeast to northwest in the study areas. The quartz rich nature further indicates that it is a mature sediment and could be deposited in the beach zone or shallow marine foreshore environment (Walker and Plint, 1992). The tabular cross-bedding sets differ in their dip angle in the vertical profile because of different sandwave slip faces reflect weaker current results in parallel foresets and stronger flows results in tangential foresets (Collinson and Thompson, 1982).

Figure 5.9: Photograph showing parallel tabular cross-bedded quartz-arenite facies in the Margate area.

Figure 5.10: Photograph showing trough cross-bedding (middle) in quartz arenite sandstone in the Margate area.

5.3.7 Herringbone cross-bedded quartz arenite facies (Shb)

Herringbone cross-bedding structure in the study area is frequently associated with medium to thick bedded quartz-arenite lithofacies. The facies is commonly present in Uvongo Sandstone and Mhlangeni Grit Members, and is white to light grey in colour and medium to coarse in grain size (Figure 5.11 and 5.12). It is prominent in Margate area, and also occurs in Port Edward section. Herringbone cross bedding indicates bidirectional palaeocurrent flows from northwest to southeast, and vice versa. In an adjacent two beds, the cross-bedding dip direction is opposed each other, which reflects there were two opposed palaeocurrent directions during the deposition of the sediments. This facies is associated with tidal influenced environment where there are flow current and ebb current, both of the current directions are against each other (Reineck and Singh, 1980). Erosional surfaces, reactivation surfaces, trough and tabular cross-beddings are commonly found with herringbone cross-bedding in the quartz arenite facies.

Interpretation

The bidirectional tendency of herring-bone cross-bedding is a good indicator of tide influenced environment. It reflects tidal flow and ebb current direction which is opposed each other. In modern environment, herringbone cross-bedding is usually found in intertidal and subtidal zones and closely linked to tidal channel deposits, thus herring bone sandstone facies in the Msikaba Formation was also formed in a shallow marine tidal channel setting (Reading, 1996). The abundance of herring-bone cross-strata in Msikaba Formation shows a constant reversal of palaeocurrent, causing the sand dunes and sand waves to change their direction of movement of tidal current (Tucker, 1982).

Figure 5.11: Photograph illustrating herring-bone cross-bedding in the Margate area.

Figure 5.12: Photograph illustrating herring-bone cross-bedded unit in the Port Edward area.

5.3.8 Lenticular bedded quartz arenite facies (Sl)

Lenticular bedded quartz arenite sandstone is very common within the study areas. This facies is present in medium to coarse grained pale greyish quartz arenite sandstones. The bed thickness ranges from 10-70 cm, and the whole rock unit can be up to 40 m. This facies is well preserved in Uvongo and Mhlangeni Members in the Margate and Port Edward sections and width of the lenticular bed can reach to 35 m (Figure 5.13). The base of lenticular bed is usually erosional, therefore has an erosional surface with the underlying beds. Dominant mineral compositions of the sandstone are quartz and feldspar with average quartz content >80% and feldspar between 5-10% and clay matrix less than 10%. Therefore, the mineral compositions of the facies are not as pure as medium to thick bedded quart-arenite facies and contains relatively less quartz and more feldspar minerals.

This is a common facies in the Msikaba Formation and is overlain by medium to thick bedded quartz arenite sandstone facies and associated with ripple cross-laminated beds.

Interpretation

The dominant quartz mineral composition and less than 10% of feldspar content of the sandstone implies that the sediments were still marine deposits, but probably more near inland side in the coastline area. Lenticular bedding structure reflects the original shallow water channelized depositional environment, where it was influenced by shallow tidal-channels in a tidal flat environment. Vertical accretion of the tidal channel deposition results the formation of superimposed lenticular bedded sandstone bodies. Large scale lenticular sets represent wide and large channels whereas small scale lenticular sets represent shallow and small channels.

Figure 5.13: Photograph showing lenticular bedding structures in quartz arenite facies in the Margate area.

5.3.9 Trough cross-bedded quartz arenite facies (St)

This lithofacies is one of common facies in the study areas and usually occurs as thick bedded or massive bedded quartz arenite sandstone. The thickness of individual trough set ranges from 10-50 cm, and the grain-size ranges from medium to very coarse grained. The mineral compositions of the sandstone are composed of quartz (>80%) and feldspar (5-10%) with little matrix (<10%) (Figure 5.14 and 5.15). Most of the trough sets are <3 m in width, but there are large scale trough sets >5 m wide in some localities. The trough beds are usually show truncated reactivation surfaces (Figure 5.16) and are associated with low angle cross-bedding. The grit grains are common found within the sandstone, indicating upper flow regime and high energy deposit.

<u>Interpretation</u>

Trough cross-bedded facies occur as small and large scale sets throughout the formation, which are accompanied with low angle cross-bedding facies and reactivation surfaces in some localities. Trough cross bedded facies is often linked to channel erosion and deposition, such as braided fluvial channels and marine tidal channel deposits. In the case of Msikaba Formation, the trough cross-bedded sandstone is quartz-arenite in lithology, and is accompanied by other tidal sandstone facies laterally and vertically, therefore, it is interpreted as a tidal channel deposit and not a braided fluvial channel deposit.

The reactivation surfaces appear as erosional line that disturbed the cross-bedding structure and is present on the lee side of the advancing sand dunes due to decrease in water depth or partial change in flow direction (McCabe and Jones, 1977). They are not restricted to a particular environment. Reactivation surfaces can be produced by a faster-moving megaripple migrating over a moving erosional bottom of a megaripple by a subordinate current common in tidal deposits (Reineck and Singh, 1980).

Figure 5.14: Photograph showing trough cross-bedding in the Port Edward area.

Figure 5.15: Photograph showing a trough cross-bedding that is capped with low angle cross-bedding in the Margate area.

Figure 5.17: Photograph showing reactivation surface (hammer area) in Margate area.

5.3.10 Ripple mark sandstone facies (Sr)

Ripple mark structure is not common within the outcrops in the study area and occurs only locally. This lithofacies appears in medium to coarse grained light grey to whitish quartz arenite sandstone and occurs at the upper part of the Msikaba sandstone sequence. Ripples in the sandstone facies occurs as asymmetrical ripples, and the stoss side is longer than the lee side (Figure 5.18), thus it can be used to indicate the palaeocurrent direction from stoss side to lee side. The ripple mark sandstone facies are associated with lithofacies SL, St, Sm, Slt.

Interpretation

The ripple mark sandstone facies occurs predominantly as current ripples and they are asymmetric (Figure 5.18). These current ripples are produced by unidirectional current, not by oscillatory wave. Ripples within quartz arenite beds in the Msikaba Formation indicates current direction was from southeast to northwest, which is consist with the palaeocurrent direction derived from tabular cross-bedding. Considering that the sandstone is quartz rich with little feldspar content, the ripple mark sandstone of the Msikaba Formation were probably formed by tidal current rather than fluvial current. The facies is mainly occurred in the middle part of the sequence, and is associated with tabular and trough cross-bedded quartz arenite facies which were deposited in tidal influenced environment, therefore the ripple mark sandstone facies is interpreted as lower shoreface or subtidal deposits where tidal current is prevailed in the area (Duke, 1985; Duke at el., 1991).

Figure 5.18: Photograph showing ripple mark sandstone in the Margate area.

5.3.11 Laminated mudstone (Fl) and silt lithofacies (Fslt)

These facies are commonly found in the Shelly Beach Feldspathic Member. They are fine grained, brownish in colour and they occur among the quartz arenite and arkosic sandstone.

Thickness of the mudstone facies beds area less than 1cm and are not easy discernible, but are present along the vertical profile in shelly beach area.

Interpretation

The fine grained mudstone and siltstone facies are associated with fluvial deposits and not marine deposits. Deposition of these facies in the shelly beach area may indicate river mouth deposition and were interrupted by incursion of current waves and eroded some of mudstone deposits hence the thickness of the mudstone.

5.4 Facies Associations (FAs)

Facies association is a group of facies, which occur together and is considered to be genetically or environmentally related to each other. Based on the lithologies, sedimentary structures and vertical and lateral superimposed relationship of the different facies in the Msikaba Formation, four facies associations are identified in the Msikaba formation, which are Facies association 1 (Gmm+Sm)-braided fluvial deposits, Facies association 2 (Gcm+St+Sp+Shb)-tidal channel deposits, Facies association 3 (Sl+Sh+Sr+Slc)-tidal flat deposits and Facies association 4 (Sm+Sp+Sl)-mixed marine and fluvial deposits.

5.4.1 Facies Association 1 (FA 1): Braided fluvial deposits

Facies Association 1 was observed at the lowermost section of Manaba Conglomerate Member consisting of Gmm and Sm lithofacies (Figure 5.19). The conglomerate is made of pebbles ranging from 0.5cm to more than 10 cm in diameter and granule set in clayey sandy matrix. Polymictic pebbles, consisting of quartz, chert, and sorts of lithic fragments are poorly sorted showing no imbrications, and is regularly interbedded with medium to coarse grained arkosic sandstone. The sandstone beds show faint tabular, trough cross-stratification due to poor preservation associated with weathering. Individual beds range from a thickness of 1.3-2.5 m and the rock unit is 20.5 m thick showing repetitive upward fining trends with erosional surfaces on individual beds. Overlying the conglomerate unit is a medium bedded arkosic sandstone facies (Sm) that is medium to coarse grained attains a thickness of 13.20 m. Comparing with the Margate section, the Facies Association 1 in Port Edward attain a minimum thickness of 20 cm conglomerate facies (Gmm) and lacks of arkosic facies (Sm) in the section (Figure 5.20). Texturally, the facies association is composed of rock units which are immature indicating low energy braided river channel and has no characteristics of marine deposits.

Figure 5.19: Photograph showing matrix supported conglomerate (bottom) overlain by medium to coarse grained arkosic sandstone (top) showing an uneven erosional surface (middle hammer area) in the Manaba Member of Margate section.

Figure 5.20: Photograph showing matrix supported conglomerate (~20cm) at the bottom overlain by quartz arenite sandstone with tabular cross-bedding.

5.4.2 Facies Association 2 (FA2): Tidal channel deposits

This Facies Association 2 overlies Facies Association 1 is characterised by quartz arenite sandstone facies Gcm, St, Sp, Shb and Slc. The base of this facies associations is erosional. Facies association 2 is also characterised by texturally medium to coarse grained, however most the sandstone is gritty. Frequently, there is gradation from clast supported quartz conglomerate layers to medium bedded quartz arenite sandstone. White greyish, medium to thick bedded quartz arenite beds ranges from a thickness of 1m to 8.2 m with contact surfaces either transitional or sharp. These rock units show a fining upward trend. The dominant grains include major quartz, potassium feldspar, lithic fragment grains which are poorly to moderately sorted. Clast supported quartz conglomerate layers range from 10 cm to 20 cm in thickness. Quartz pebbles are poorly consolidated with little quartz arenite matrix and shows no imbrication and stratification (Figure 5.21). This facies is common in Facies association 2.

FA2 is also present in the port Edward area, overlying the matrix supported conglomerate with three upward fining sequence of very coarse (gritty) to medium grained quartz arenite. . This facies association is predominately has poorly sorted white quartz arenite sandstone with granule stone and pebble layers are present at some locations.

Figure 5.21: Quartz arenite sandstone interbedded with quartz pebble conglomerate in the Margate area (Uvongo Sandstone Member).

Figure 5.22: Photograph showing tabular and trough cross-bedding sets in the Margate area.

5.4.3 Facies association 3 (FA 3): Tidal flat deposits

FA3 is observed in Margate and south in the in Port Edward, contains thick to massive bedded, pale grey quartz arenite various facies such as Sl, Sh, Sr and Slc. This FA 3 is associated with shallow marine deposition of Msikaba formation. The thickness of the beds ranges from 2.2 to 8 m and can extent to 40 m rock units. Contains coarse to medium grained quartz arenite sandstone (Figure 5.23). It naturally, follows an upward fining trend with sharp, transitional and mostly erosional surfaces. Pebble conglomerate layers are also present. This is a common facies association, and is evident in Mhlangeni Conglomerate Member in Margate and Port Edward stratigraphy.

The thick bedded sandstone with large scale trough cross-bedding is interpreted being deposited in response to migration of dunes (Maill, 1992) along multi-directional longshore and onshore currents. It is also interpreted as high energy marine deposits (Clifton at el, 1971). Lenticular beds always form the base of each unit for almost all the facies and beds are interpreted to represent intertidal flat deposits (Reineck & Singh, 1980).

Figure 5.23: Photograph with large scale massive quartz arenite sandstone in the Port Edward area.

Figure 5.24: Photograph showing sharp contact boundary between coarse and fine grained quartz arenite sandstone in the Margate area.

5.4.4 Facies Association 4 (FA 4): Mixed marine and fluvial deposits

Facies association 4 is found in the Shelly Beach Feldspathic Member in the Margate section. it is composed of Sm, Sp and Sl facies of quartz arenite and arkosic sandstone. The unique intermixture or interbedding of mudstone/ siltstone lenses and quartz arenite and arkosic sandstone may be due to incursion of shallow marine current and braided river deposition. Thickness of individual beds ranges from 5 to 7.5 m composed of medium to very coarse pure quartz grains located at the top is a medium to fine grained brownish arkosic sandstone, Sm, Sp, St facies with bed thickness ranging from 30 cm to 19.5 m .Nevertheless, there is an interchange between marine and fluvial deposits.

Figure 5.6: Photograph showing red-brownish medium bedded arkosic sandstone facies (bottom) with tabular cross-bedded sandstone facies (middle) in the Shelly Beach Member.

Table 2: Summary of sedimentary facies and depositional environments.

Sedimentary facies	**Facies Associations (FAs)**	**Depositional environments**
Gmm, Sm Upward fining succession with erosional bases. Composed of poorly sorted conglomerate and medium bedded arkosic sandstone.	**FA 1**	Braided fluvial deposits
Gcm, St, Sp, Shb, Slc Super-mature white quartz arenite sandstone with upward fining cycles (Upward fining cycle).	**FA 2**	Tidal channel deposits
Sl, Sh, Sr and Slc. Upward fining cross-stratified very coarse to medium grained quartz arenite with large scale lenticular and trough and lag pebble conglomerate layers.	**FA 3**	Tidal flat deposits
Sm, Sp and Sl Quartz arenite is overlain by lenses of mudstone facies arenite and arkosic sandstone (Upward fining cycle).	**FA 4 (Not present in Port Edward section)**	Mixed marine and fluvial deposits

CHAPTER 6: GRAIN SIZE ANALYSIS AND PETROLOGY

6.1 Introduction

Grain size analysis is used in order to texturally characterise the sediment properties and further to the depositional environments of hydrodynamic energy (Edwards, 2001). Grain size distribution is one of the properties of sedimentary rocks, and it serves as a starting point for classification and naming of terrigeneous clastic sediments and sedimentary rocks (Blott and Pye, 2001). There are three features of particle size which sedimentologists focus on: 1) the technique for measuring grain size and expressing it in grade scale terms, 2) methods of quantifying grain size data and presenting them in a graphical or statistical form and 3) the genetic significance of the data (Boggs, 1995). Grain size analysis is different from modal mineral composition analysis and it is dependent on statistical parameters such as mean, mode, sorting, skewness and kurtosis to consider grain size distribution**.** For this study grain size analysis was conducted on quartz arenite and arkosic sandstone to determine the distribution tendency of the Msikaba Formation strata on the Margate and Port Edward areas.
Grain size measurements were conducted on thin sections under petrographic microscope with a calibrated eye piece. A total of 400 grains were measured per thin section by using the conventional method of grain's longest axis measurement (Friedman, 1958, 1992; Adams, 1977; Johnson, 1994; Liu and Greyling, 1996). The apparent dimensions of grain sizes were converted to normal sieve grain sizes using the methods proposed by Friedman (1958, 1962). Subsequently, statistical parameters of grain size distribution were calculated using Folk and Ward (1957) proposed equations.

The Udden-Wentworth grade scale (Table 3) was used to determine grain size classes because it expresses a wide range of particle size found in the natural sediments and sedimentary rock. It is sub-divided into four major categories, i.e. clay, silt, sand and gravel (Boggs, 2009).

Table 6.1: Grain size scale used by Udden (1914) and Friedman and Sanders (1978) modified from Blott and Pye (2001).

Grain size		Descriptive terminology		
phi	mm/µm	Udden (1914) and Wentworth (1922)	Friedman and Sanders (1978)	
			Very large boulders	
−11	2048 mm			
			Large boulders	Boulders
−10	1024			
			Medium boulders	Boulders
−9	512	Cobbles		
			Small boulders	Boulders
−8	256			
			Large cobbles	Boulders
−7	128			
			Small cobbles	Boulders
−6	64			
			Very coarse pebbles	Gravel
−5	32			
			Coarse pebbles	Gravel
−4	16	Pebbles		
			Medium pebbles	Gravel
−3	8			
			Fine pebbles	Gravel
−2	4			
		Granules	Very fine pebbles	Gravel
−1	2			
		Very coarse sand	Very coarse sand	Sand
0	1			
		Coarse sand	Coarse sand	Sand
1	500 µm			
		Medium sand	Medium sand	Sand
2	250			
		Fine sand	Fine sand	Sand
3	125			
		Very fine sand	Very fine sand	Sand
4	63			
			Very coarse silt	Silt
5	31			
			Coarse silt	Silt
6	16	Silt		
			Medium silt	Silt
7	8			
			Fine silt	Silt
8	4			
			Very fine silt	Silt
9	2	Clay		
			Clay	

6.2 Results and interpretation for grain size data

6.2.1 Frequency histograms and cumulative frequency curves

Grain size data was plotted on frequency histograms and cumulative frequency curve diagrams as below, where grain size frequency was plotted on the y-axis against grain size class (from -1 phi down to 5 phi) on the x-axis. In this study, grain size analysis was done to determine the grain size distribution of quartz arenite and arkosic sandstones on the study areas. The frequency diagrams portrays that the majority of grain size diameters range from -1 to 5 phi class on the Udden-Wentworth grade scale which indicates a coarse to fine grained distribution. In the Margate area, the sandstone samples from M1 – M21 frequency histograms (Figure 6.1 to Figure 6.11) shows a distribution with more medium to fine grain size. Samples P1 – P21(Figure 6.12 to Figure 6.17) from Port Edward area are very coarse indicating that majority of grain diameters fall between -1 to 2 (phi) class. The cumulative frequency distribution contributes to interpretation of hydrodynamic depositional environment and there were three types of sediment transport that were ascribed by Inman (1949), such as rolling and sliding, saltation and suspension. The Msikaba Formation samples shows three segments of cumulative frequency curves that grain size population of Msikaba Formation was in the suspension, saltation and traction states which are prevalent in shallow marine high energy depositional environment.

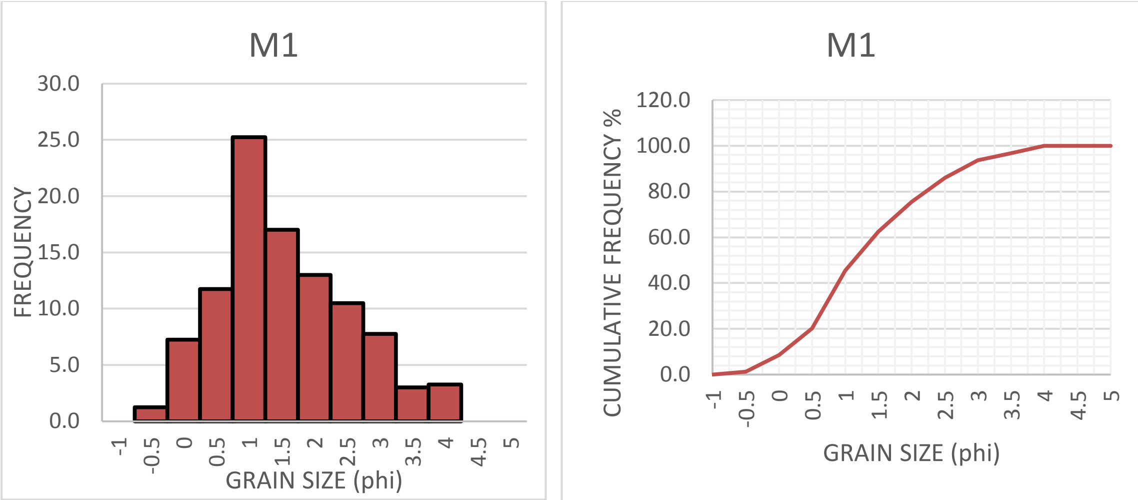


Figure 6.1: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M1.

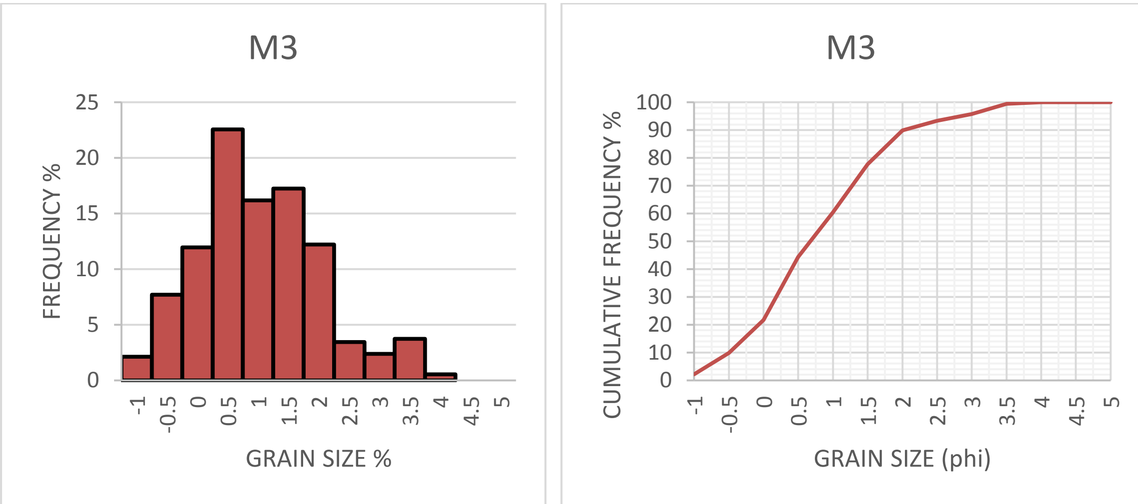


Figure 6.2: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M3.

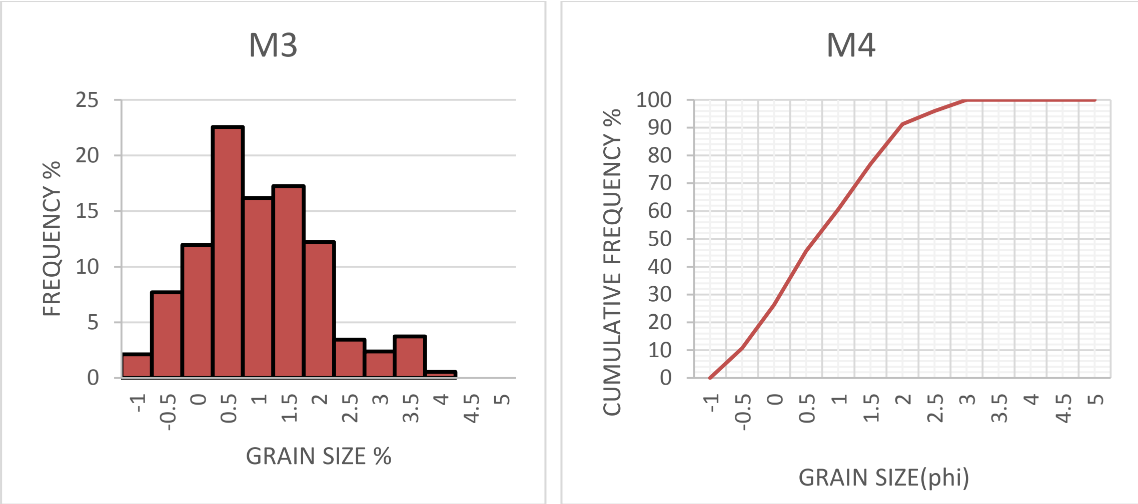


Figure 6.3: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M4.

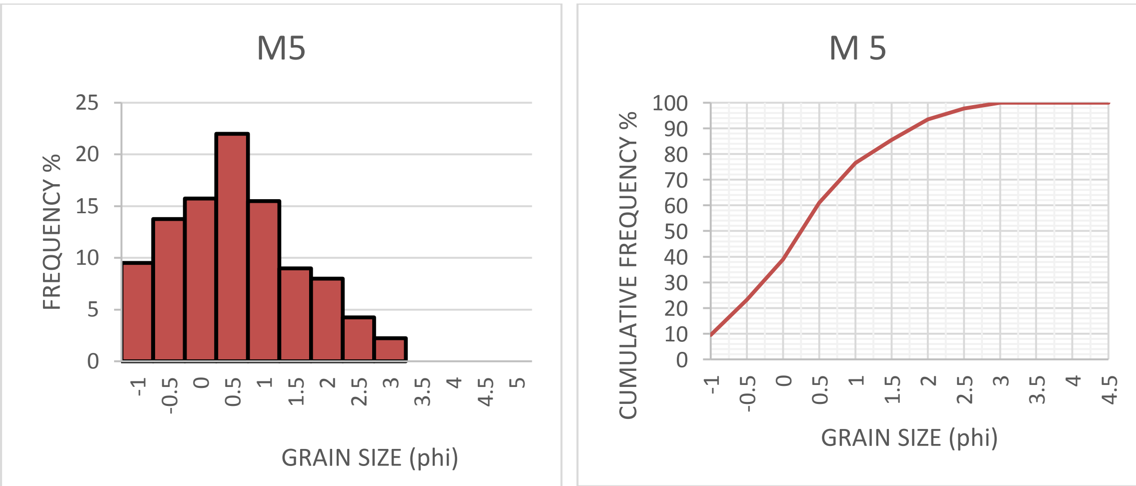


Figure 6.4: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M5.

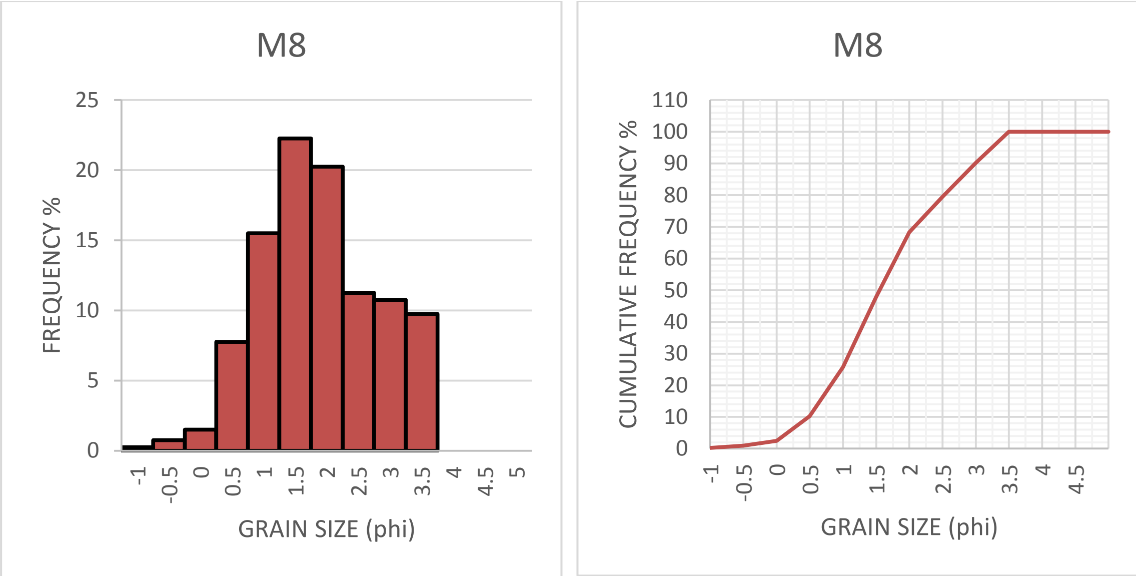


Figure 6.5: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M8.

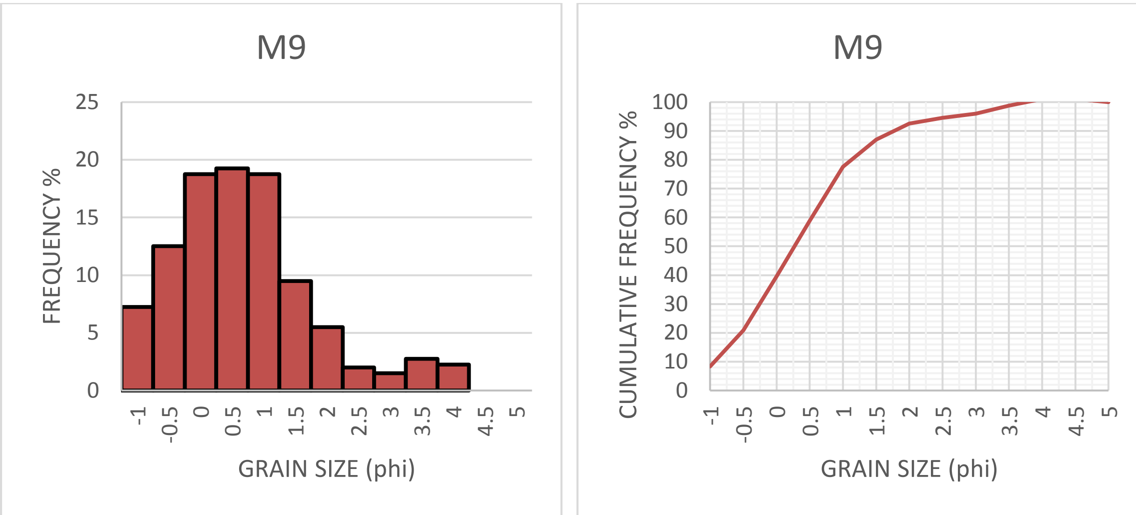


Figure 6.6: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M9.

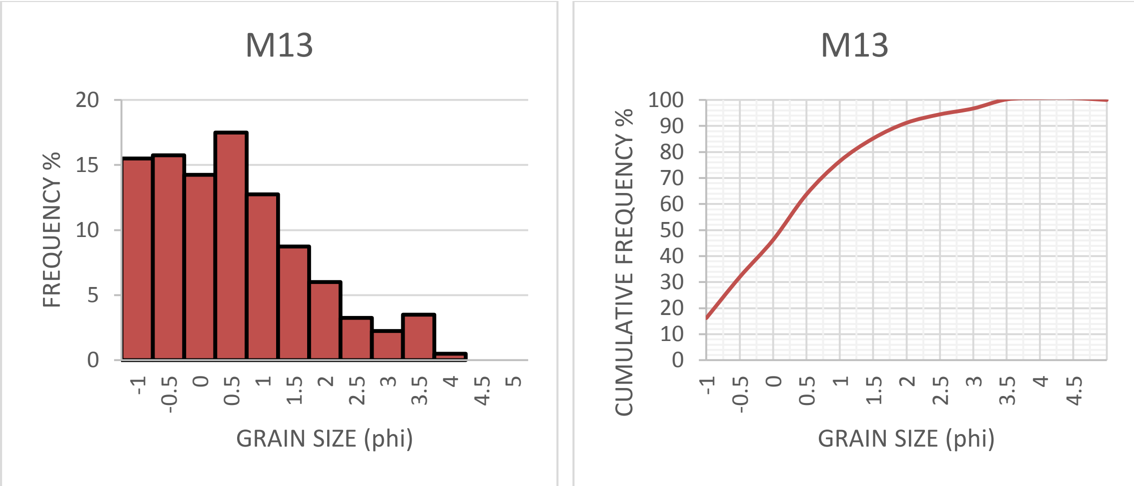


Figure 6.7: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M13.

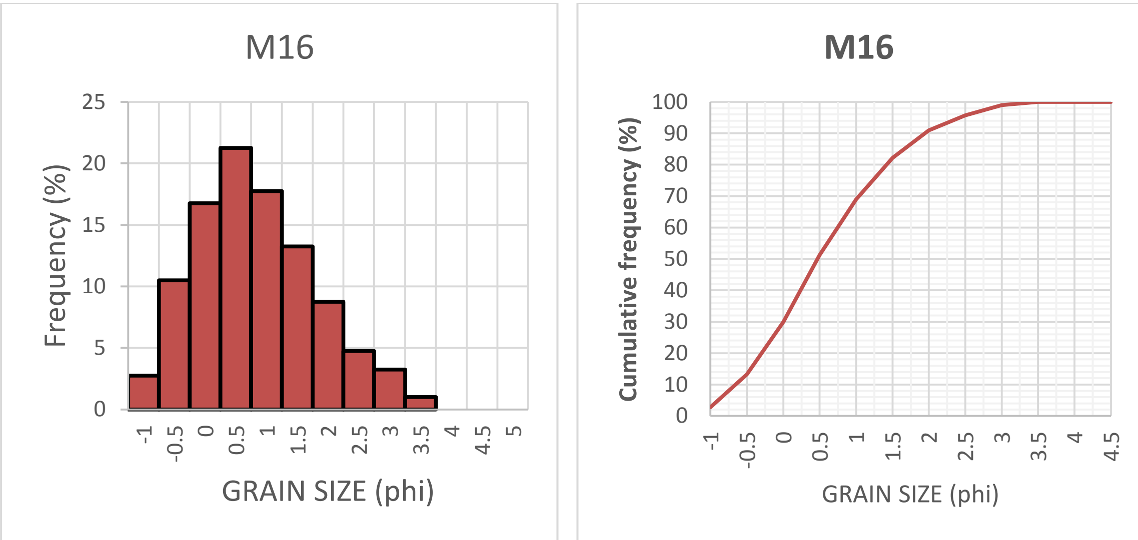


Figure 6.8: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M16.

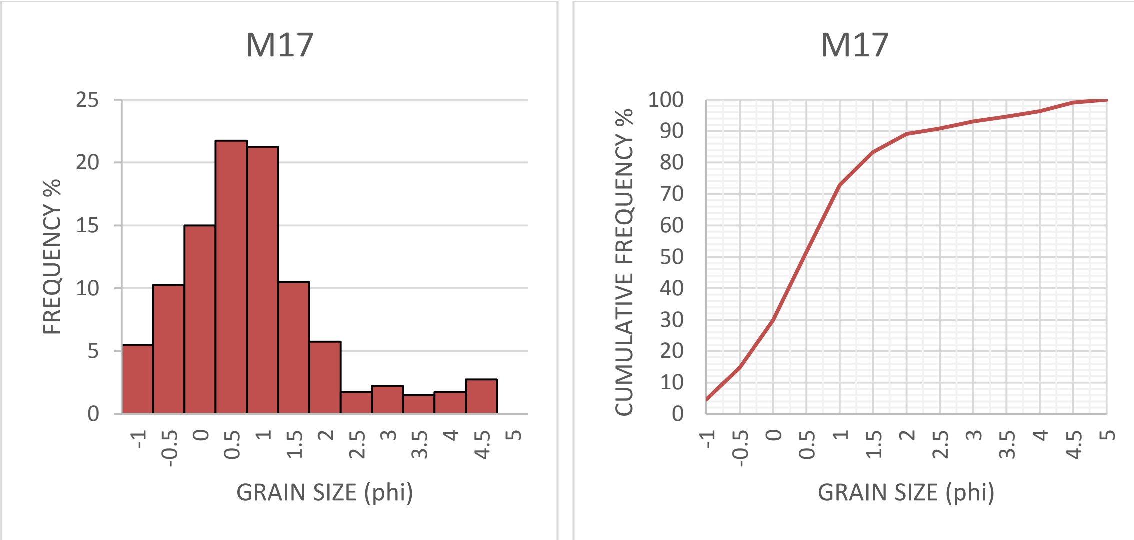


Figure 6.9: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M 17.

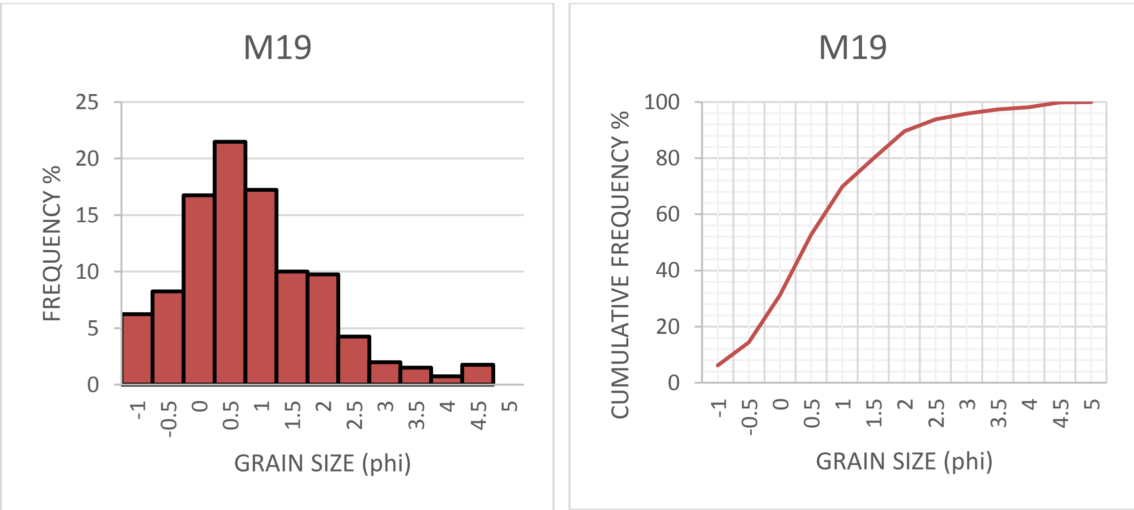


Figure 6.10: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M19.

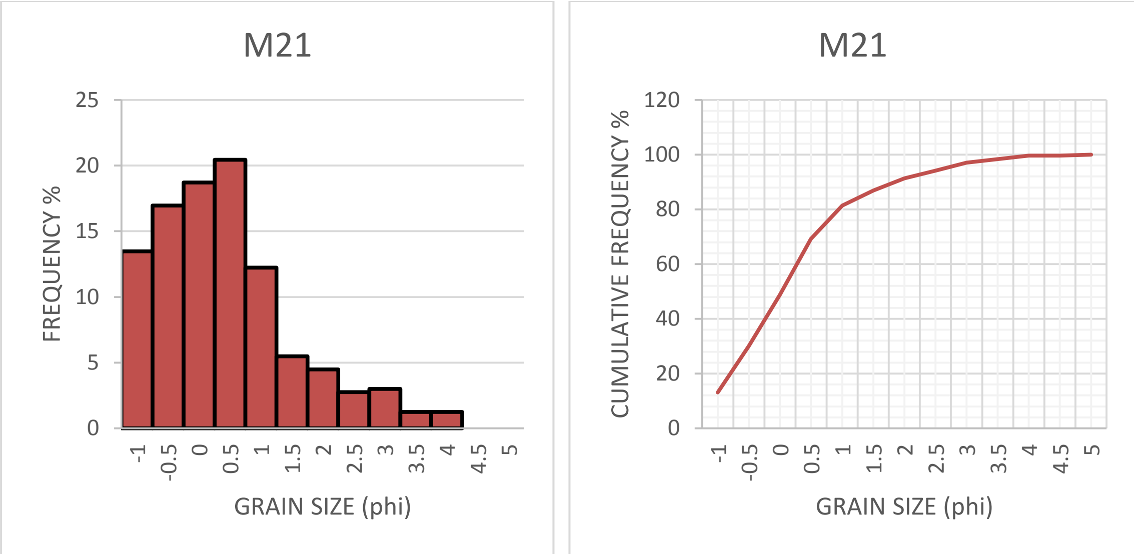


Figure 6.11: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample M21.

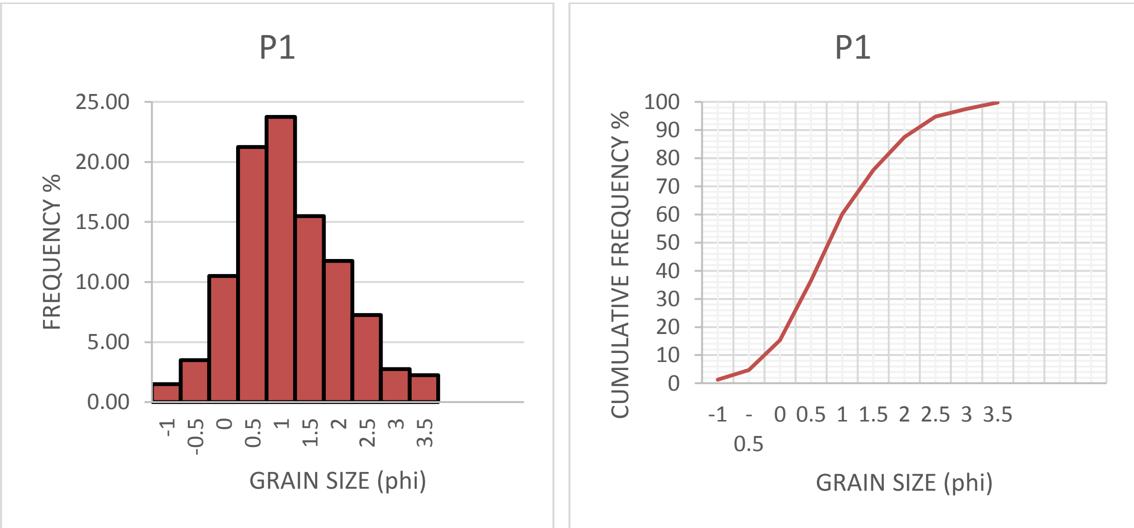


Figure 6.12: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample P1.

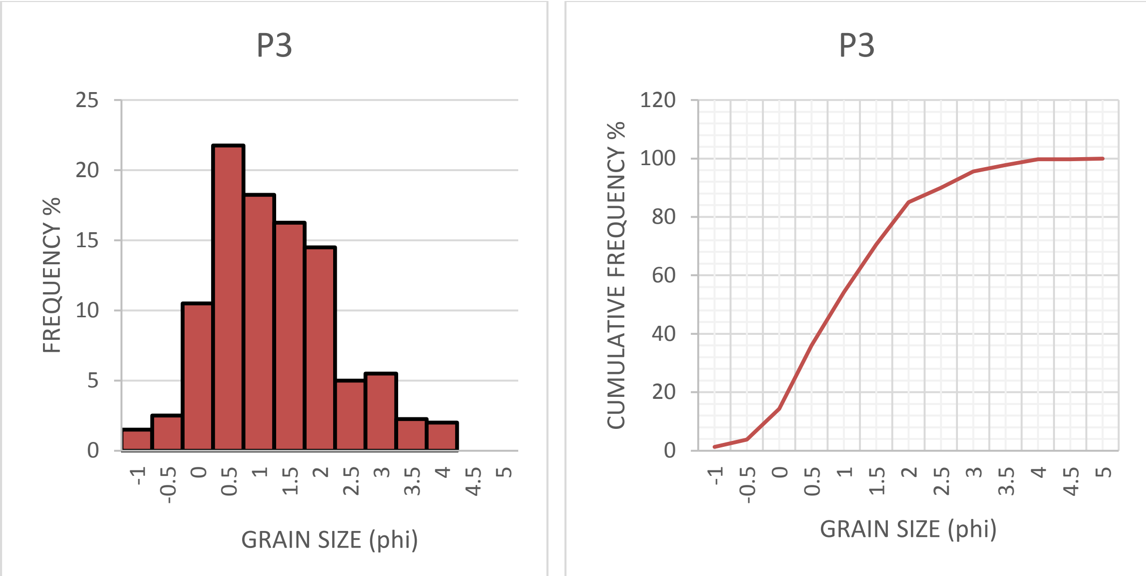


Figure 6.13: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample P3.

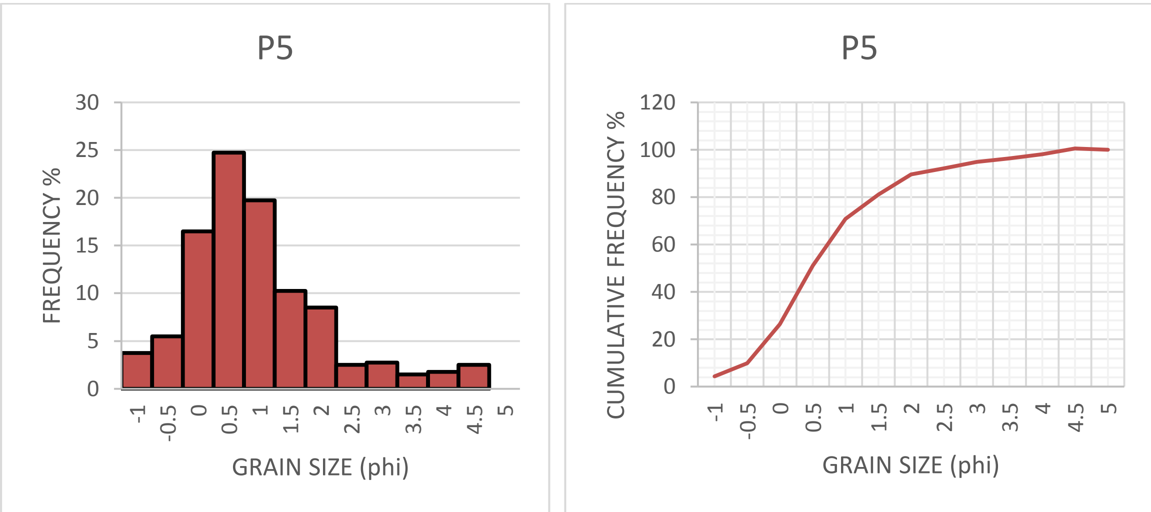


Figure 6.14: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample P5.

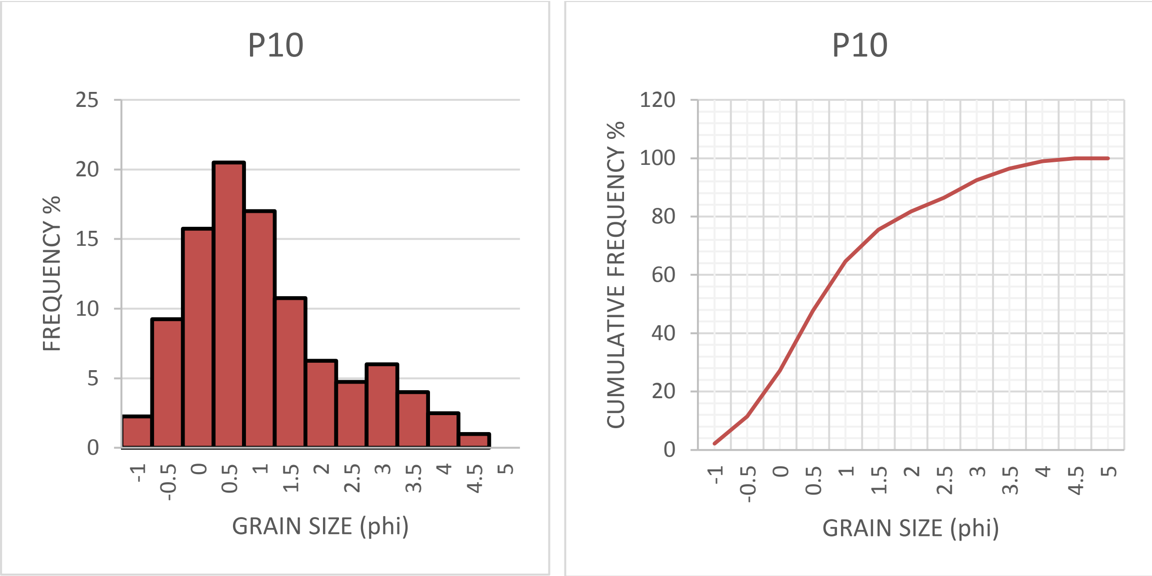


Figure 6.15: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample P10.

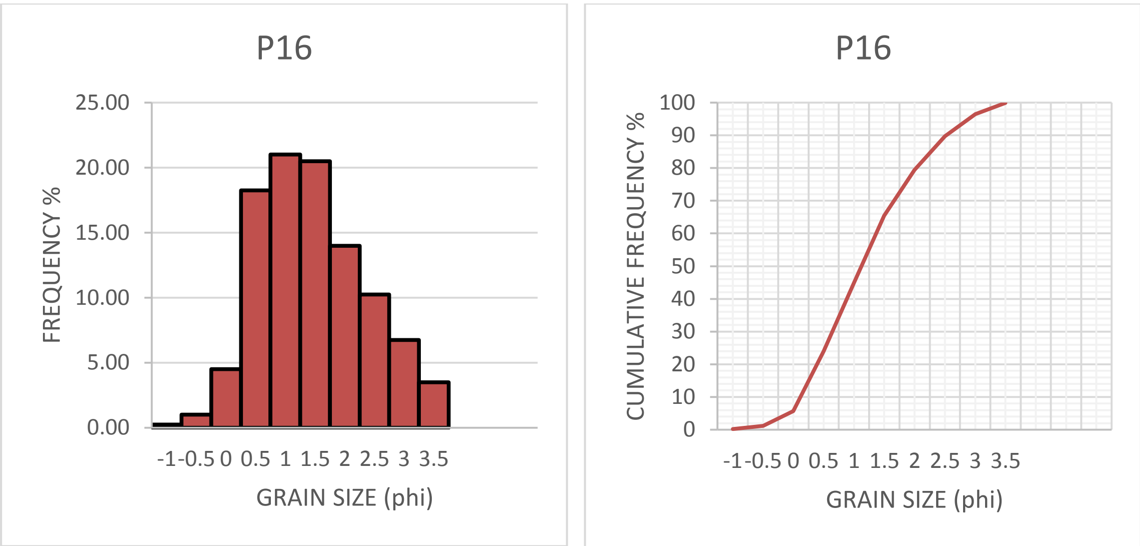
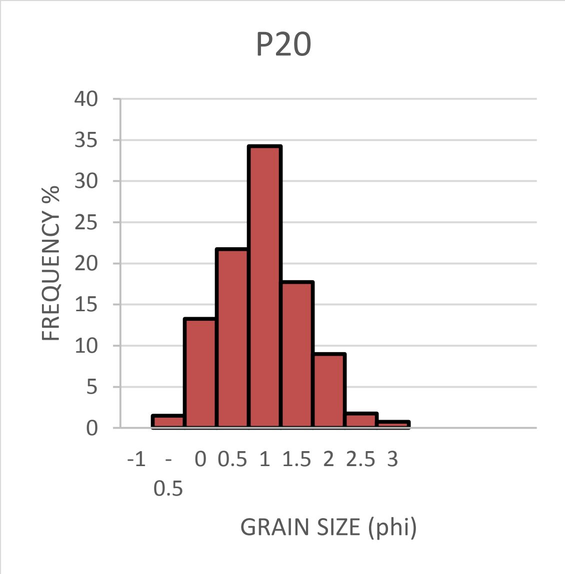


Figure 6.16: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample P16.



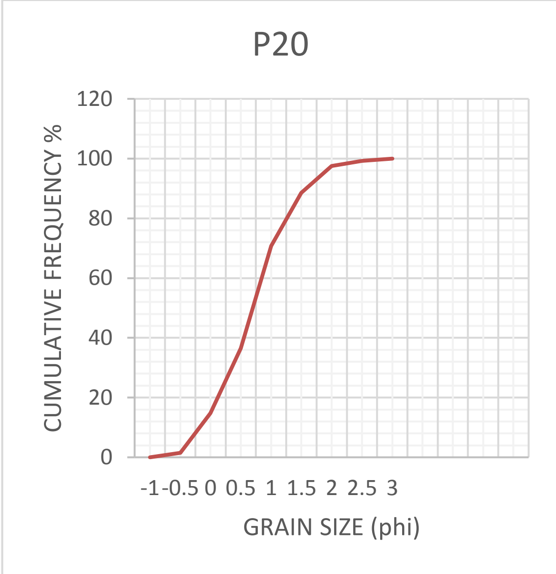


Figure 6.17: Grain size frequency histogram and cumulative frequency curve medium grained arkosic sandstone for sample P20.

6.2. Interpretation of statistical parameters on Msikaba Formation

The grain size analysis results were calculated based on the formulas using cumulative percentile values taken from the cumulative percentage frequency curves using linear interpolation and are based on a log-normal distribution of data in phi (Φ) unit. The Phi unit stands as $\Phi = -\log_2 d$, where d is the grain diameter.

Table 6.2: Grain size parameters (Φ) of the Msikaba Formation in Margate area.

Sample	**Mean (Mz)**	**Sorting** (σ_I)	**Skewness (SKi)**	**Kurtosis(** K_G**)**
M1	1.58 Φ	0.73 Φ	0.3 Φ	2.04 Φ
M3	0.75 Φ	0.83 Φ	0.06 Φ	0.95 Φ
M4	0.30 Φ	0.55 Φ	0.43 Φ	0.83 Φ
M5	0.30 Φ	0.74 Φ	0.18 Φ	0.82 Φ
M8	1.85 Φ	0.86 Φ	0.26 Φ	1.10 Φ
M9	1.20 Φ	1.53 Φ	0.52 Φ	1.35 Φ
M13	0.58 Φ	1.13 Φ	0.078	1.24 Φ
M16	1.77 Φ	1.59 Φ	0.53 Φ	1.21 Φ
M17	0.53 Φ	0.76 Φ	0.24 Φ	1.33 Φ
M19	0.60 Φ	0.79 Φ	0.24 Φ	1.03 Φ
M21	0.20 Φ	0.72 Φ	0.36 Φ	1.43 Φ
Average	0.88 Φ	0.93 Φ	0.29 Φ	1.21 Φ
Standard Deviation	0.58 Φ	0.33 Φ	0.15 Φ	0.33 Φ

Table 6.3: Grain size parameter (Φ) of the Msikaba Formation in Port Edward area.

Sample	**Mean (Mz)**	**Sorting** (σ_I)	**Skewness (SKi)**	**Kurtosis(** K_G**)**
P1	0.83 Φ	0.63 Φ	0.22 Φ	1.18 Φ
P3	1.50 Φ	1.26 Φ	0.32 Φ	1.03 Φ
P6	1.16 Φ	1.29 Φ	0.69 Φ	1.20 Φ
P10	0.87 Φ	0.91 Φ	0.36 Φ	1.57 Φ
P16	1.23 Φ	1.67 Φ	0.09 Φ	1.1 8 Φ
P20	1.84 Φ	1.41 Φ	0.65 Φ	1.80 Φ
Average	1.24 Φ	1.20 Φ	0.39 Φ	1.33 Φ
Standard Deviation	0.35 Φ	0.34 Φ	0.22 Φ	0.27 Φ

A) Mean size (Mz)

A mean is a descriptive parameter of grain size that measure average size of sediments; a mean indicates the central tendency of a grain size distribution. This parameter is calculated by the following equation:

Mean grain size: $M_{Z=}\ \frac{\varphi_{16}+\varphi_{50}+\varphi_{84}}{3}$ (Folk and Ward, 1957)

The mean values range from 0.20 to 1.85 phi in the Margate area (Table 6.2) and range from 0.83-1.84 phi in the Port Edward area (Table 6.3). The Msikaba Formation is dominated by medium to very coarse grained sediments. The dominance of medium to coarse grained beach sediments especially in the Port Edward area indicates a high energy current condition during transportation of sediments to the environment of deposition. The medium grained of arkosic sandstone indicate moderate sorting of grains and interpreted as incursions by river/fluvial sediments and deposition in a high energy marine environment in the Margate area.

B) Sorting (σ_I)

Sorting (σ_I) is a grain size parameter that calculates graphic standard deviation or dispersion. It determines the uniformity of grain size distributions of a sample and is calculated as follows:

Sorting (σ_I)= $\frac{\varphi_{84}-\varphi_{16}}{4} + \frac{\varphi_{95}-\varphi_{5}}{16}$ (Folk and Ward, 1957)

From the table 6.2 and 6.3 the obtained values of sorting in the Margate area range from 0.55-1.59 phi and in Port Edward area ranges from 0.67 to 1.67 phi. The classification of sorting proposed by Folk and Ward (1957) is as follows:

Sorting (σ_{1}): < 0.35, very well sorted

0.35 to 0.50, well sorted

0.50 to 1.00, moderately sorted

1.00 to 2.00, poorly sorted

2.00 to 4.00, very poorly sorted and

>4.00, extremely poorly sorted.

The classification indicates that the values are predominantly moderate sorted for the Margate samples whereas they are moderate to poorly sorted for Port Edward samples. More than 85% of the Margate and Port Edward samples fall under moderately sorted category. These moderately sorted values indicate a storm condition during deposition and this implies a high energy marine environment.

C) Skewness (SKi)

Skewness is a measurement of the degree of symmetry of grain-size distribution, it is a descriptive parameter that determines the majority of the grain-size measurement inclusive graphic skewness. It is defined as:-

Skewness (SK_I) = $\frac{\varphi_{16}+\varphi_{84}-\varphi_{50}}{2(\varphi_{84}-\varphi_{16})} + \frac{\varphi_5+\varphi_{95}-2\varphi_{50}}{2(\varphi_{95}-\varphi_5)}$ (Folk and Ward, 1957)

Folk (1968) suggested the following verbal scale for skewness (Ski) classification:

+1.00 to +0.30, fine and very fine skewed

+ 0.30 to +0.10, fine skewed

+ 0.10 to -0.10, near symmetrical

-0.10 to -0.30, coarse skewed; and

-0.30 to -1.00, strongly coarse skewed

The positive skewness values dominate in the two study areas, and this conveys that there is finer material in the tails of the distribution. Skewness in the Margate area ranges from 0.06 to 0.53 phi and 0.09 to 0.69 phi in the Port Edward area. Most of the samples dominate the very positive classification, followed by positive classification then the minor symmetric skewness classification.

D) Kurtosis (K_G)

Kurtosis or peakedness of the grain-size distribution is calculated by comparing the spread or the sorting off the tails in the central part of the distribution to the spread in the tails. The graphic kurtosis using this formula:

Kurtosis (K_G) = $\frac{\varphi_{95}-\varphi_5}{2.44(\varphi_{75}-\varphi_{25})}$ (Folk and Ward, 1957)

The samples were grouped or categorised according to the following kurtosis limits:

Kurtosis (K_G): 0.67 to 0.90, wide

0.90 to 1.11, medium

1.11 to 1.50, narrow;

1.50-3.00, very narrow

over 3, extremely narrow

The kurtosis in the Margate area ranges from 0.83 up to 2.04 phi, and the Port Edward samples range from 1.18 to 1.80 phi. Most of the samples fall into the narrow category, followed by medium kurtosis category. There are few samples on the wide kurtosis limit. In this area there are positive value of kurtosis and no negative values with a flat distribution. The peaks are unimodal with better sorted tail because they carry less fine grain size material.

6.3 Bivariate scatter plots of grain size parameters

The bivariate scatter plots have been used by many sedimentologists to discriminate between depositional settings based on their textural variation because they can use different combinations of statistical parameters, such as the grain sorting versus mean size. They are used based on their reliability to reflect differences in the hydrodynamic flow conditions of sediment transportation and deposition (Sutherland and Lee, 1994).

The unimodal nature of the sandstone grain size makes it possible to compare the statistical parameters. Mean versus sorting parameters (Figure 6.18) are hydraulically controlled, there is clustering in moderately to poorly sorted positions in the plot. Thus, the sedimentary environments have mostly moderately sorting co-efficiency and have a mean grain size concentrated in the medium to coarse size categories in both study areas. The dominance of medium grains and moderate sorting in the Margate area is due moderate to higher energy sedimentary environment.

In the skewness versus sorting scatter plot (Figure 6.19), the skewness increases leads to more poorly sorted sediments. So as the skewness becomes positive, it leads more poorly sorted of sediments.

Skewness versus kurtosis plot is a powerful tool for interpreting the genesis of the sediment by quantifying the degree of normality of its size distribution (Folk, 1966). Figure 6.20 shows that Msikaba Formation sediments lie within the positively skewed and leptokurtic range. This suggests that the dominance of coarse population with subordinate medium to fine sized population; which gives a positive skewness. According to Friedman (1962), extreme high or low values of kurtosis imply that part of the sediment achieved their sorting elsewhere in a high energy environment.

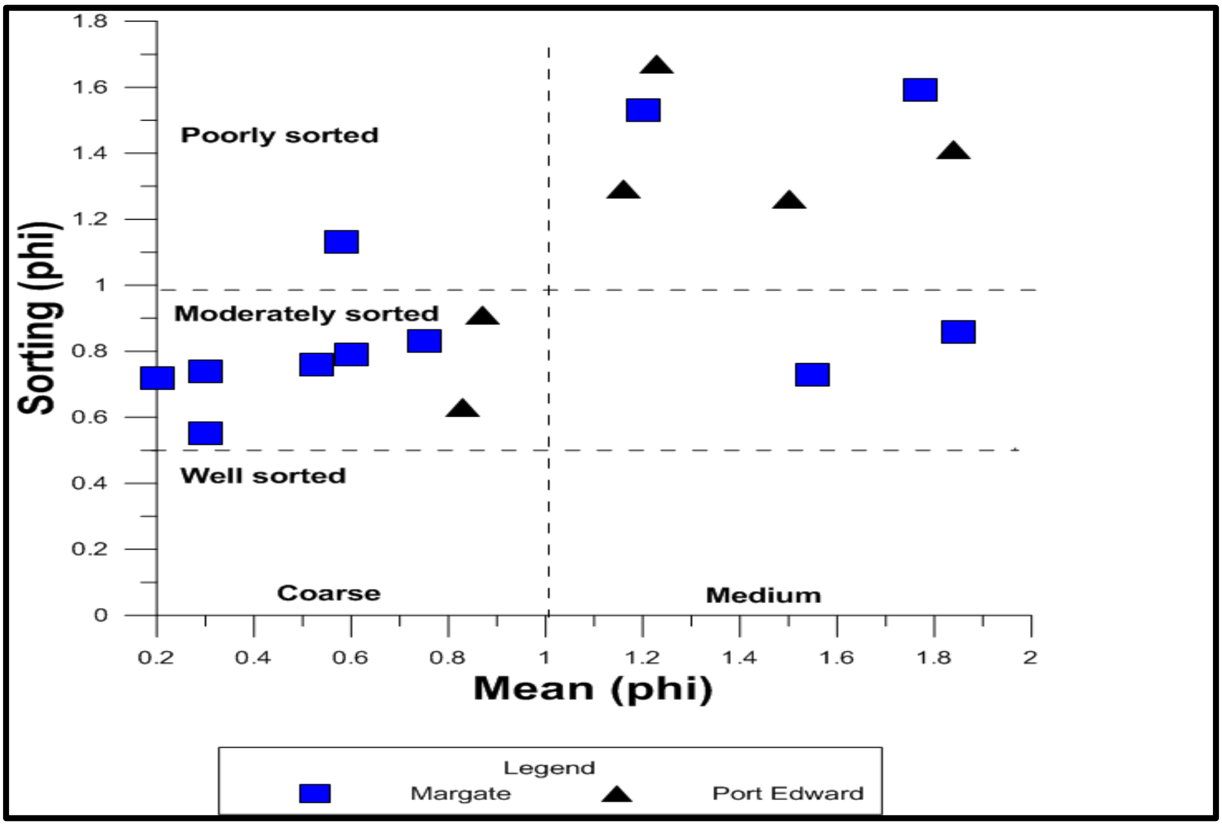


Figure 6.18: Plot of Mean (phi) versus Sorting (phi) of Margate and Port Edward area.

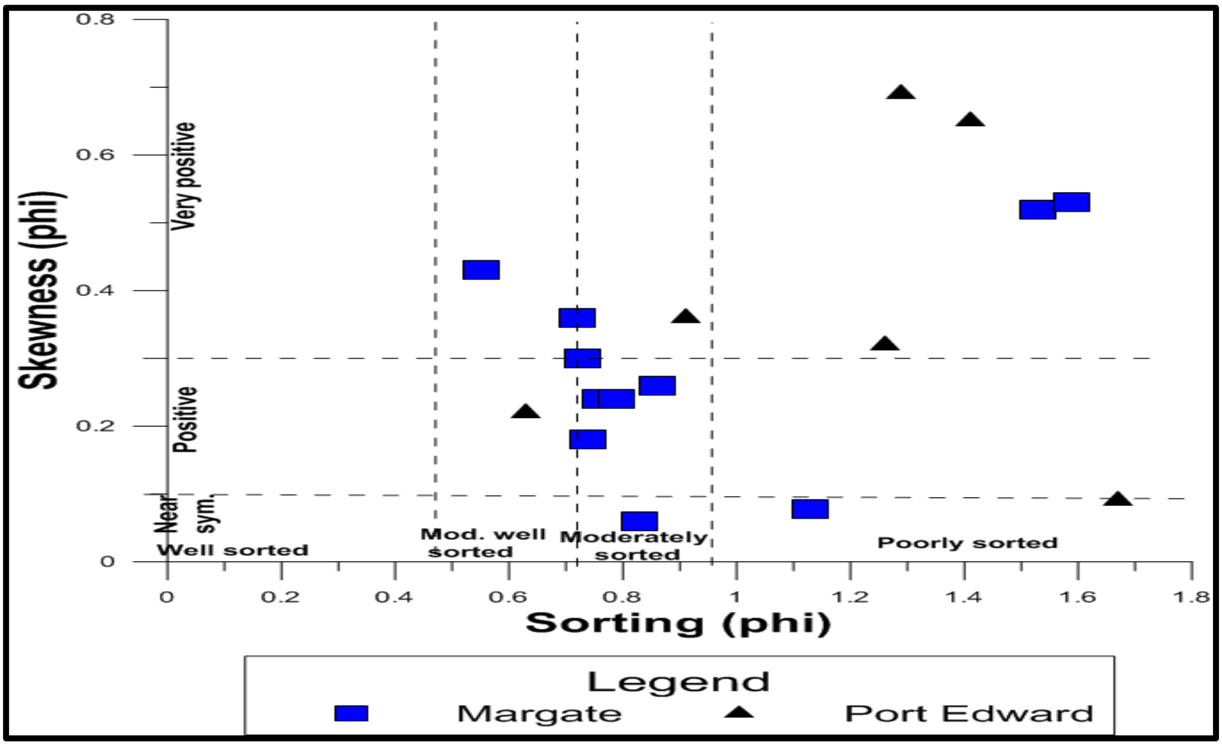


Figure 6.19: Plot of Sorting (phi) versus Skewness (phi) of Margate and Port Edward area.

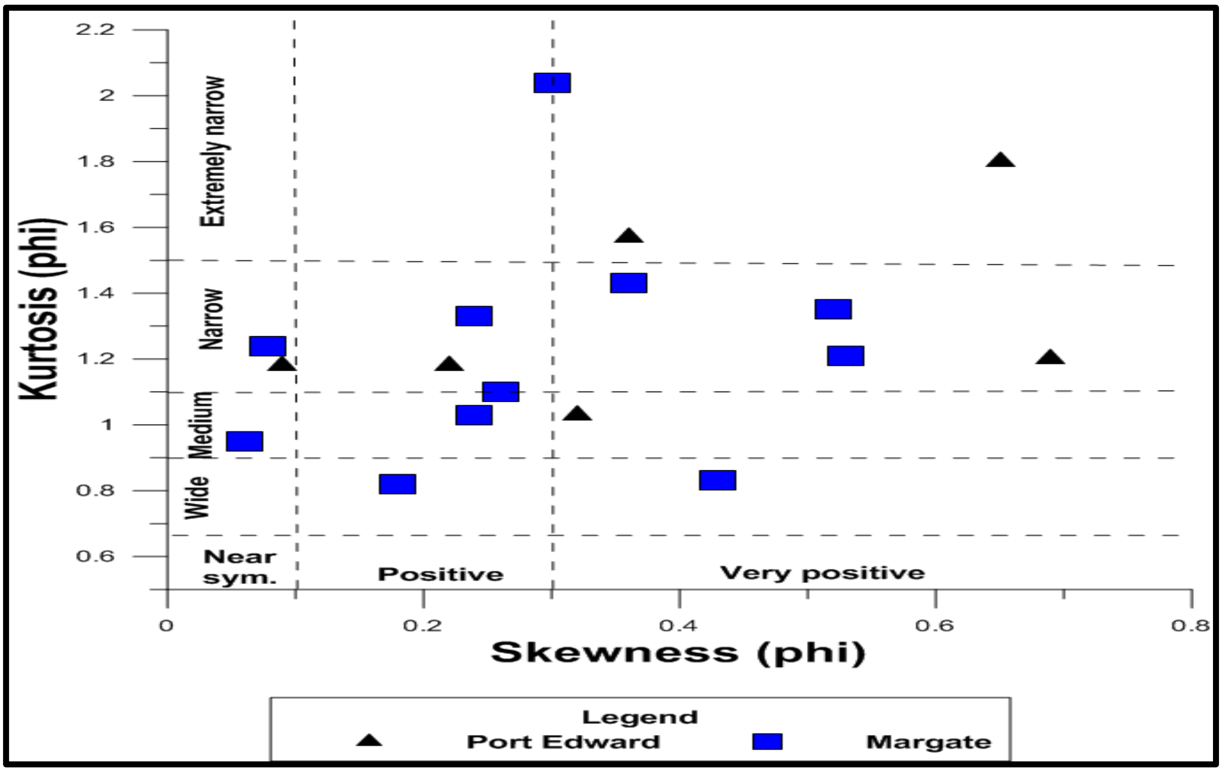


Figure 6.20: Plot of Skewness (phi) versus Kurtosis (phi) of Margate and Port Edward area.

The majority of frequency histograms for both study areas show a unimodal distribution. This suggest the sandstones are not diverse in nature and are sourced from the same provenance. However, the cumulative frequency curves show mixed features in Margate area as compared to the Port Edward area that has fixed curve segments. The statistical grain size parameters of Margate area show an average of Mz = 0.2-1.85, So = 0.55-1.59, SKi = 0.06-0.53 and K_G = 0.82-2.04, which suggesting that the Msikaba Formation sandstones are mainly coarse to medium grained, moderately sorted, positive to very positive skewness and medium and narrow kurtosis; whereas the Port Edward area shows Mz = 0.83-1.84, So = 0.63-1.67, SKi = 0.09-0.69 and K_G = 1.03-1.8, which represent coarse grained sandstone that is mostly moderate sorted than poorly sorted, showing positive and very positive skewness and narrow or extremely narrow kurtosis. The similar grain size parameters imply similar hydrodynamic environment and shows the textural maturity of source rock sediments.

CHAPTER 7: MODAL COMPOSITION ANALYSIS AND PETROLOGY

7.1 Introduction

Modal mineral composition analysis is a useful tool to study the mineral types and abundance of a rock, and it is based on the thin-section analysis under microscope. The results of modal mineral composition analysis can be further used as a tool for sandstone classification. Since it is a statistical method thus the more counted points are analysed, the results are more accurate. Thus it is usually required to account for more than 400 points for any specific thin-section. In our analysis, 500 points were counted for the sake of enhancing the datum accuracy of each sample, i.e. each thin-section. Samples with prefix M were those taken from Margate area and those with prefix P were taken from the Port Edward area in the study

Monocrystalline (Qm), polycrystalline (Qp), potassium feldspar (K) and plagioclase (P) and lithic fragments (L) (Table 7.1 below) form the framework grains for the sandstone in the Msikaba Formation. Since modal mineralogical composition of sandstones is determined on the basis of both main grains and binding material types of matrix and cements. Analysis of percentage contents of different types of grains and cements were used for the classification of the sandstone (Pettijohn, 1975; Folk, 1980). The comparative abundance of main mineral components was determined by counting 500 points in each thin section by the Gazzi-Dickinson method and the nomenclature advocated by Ingersoll at el. (1984) and Dickinson and Suczeck (1979). For the purpose of sandstone classification, ternary diagrams of quartz-feldspar-lithics (Q-F-L) were plotted and the components were recalculated to 100% for the QFL diagrams. The modal analysis results are presented in Table 7.2 and the QFL plots followed the method proposed by Pettijohn (1975) and Folk (1980).

Table 7.1: Framework parameters of detrital modes (after Ingersoll et al, 1984 and tucker, 2001)

Parameter	Recalculated parameters
Q = Quartz	Q = Qm + Qp
Qp = Polycrystalline quartz (+chert)	
Qm = Monocrystalline quartz	
Qt = Total quartzose grains	Qt = Qm + Qp
P = Plagioclase feldspar	
K = Potassium feldspar	
F = Total feldspar grains	F = P + K
Lv	Volcanic–metavolcanic rock fragments
Ls	Sedimentary rock fragments
Lsm=	Metasedimentary lithic fragments
L = Unstable Siliclastic Lithic fragments	L = Lv + Ls + Lsm
Lt = Total siliclastic lithic fragments	Lt = L+ Qp

7.2 Modal mineral composition analysis of Margate area

The Q-F-L plots (Figure 7.1) show that the sandstone ranges from sub-arkose to quartz arenite categories. The proportion of monocrystalline quartz is much higher than the polycrystalline quartz. The non-undulatory monocrystalline quartz is more abundant than undulatory variety due to less strain in detrital quartz. The Qt-F-L ternary plot shows a higher percentage of quartz mineral with deficiency in feldspar giving an average Qt=86%, F=7%, L=7.2%. Qm-F-Lt plot (Figure 7.2) emphasises total lithic fragments (Lt) present within the formation including polycrystalline quartz, chert, sandstone, metamorphic rock and muscovite grains to define the source area (Qm =74%, F=7%, Lt=19%). The k-feldspar grains and plagioclase of the account for a small percentage of bulk sandstone and this shows the maturity of Msikaba Formation sandstone with high quartz ratio as compared to feldspar. Lithic fragments show more rounded than quartz and feldspar grains with modal percentage average between (7-19%). 90% of the lithic fragment are represented by metamorphic rock fragments depicting a metamorphic source area. The cement ranges from 0.6 to 15.0% of rock volume and is composed of quartz, iron oxide and clay matrix. Muscovite flakes are abundant throughout the Margate Formation, it occurs as lithic fragments and authigenic mineral. Another mica mineral is biotite, which occurs as an accessory mineral and is less abundant than muscovite.

7.3 Modal mineral composition analysis of the Port Edward area

Quartz grains are sub-angular to sub-rounded in the thin-sections. The amount of quartz grains is higher than that of Margate area. The Q-F-L ternary diagrams (Figure 7.1) reflects a high percentage of quartz grains and low amounts of feldspar grains, (Qt=91%, F=7.4%, L=1.3%) and (Qm =85.4%, F=7.4% Lt=9.6%). This area constitutes average of 91.1% of quartz in arenite sandstone in the Port Edward area. The sandstone has a high percentage of monocrystalline quartz than polycrystalline quartz and there is abundant untwined k-feldspar than microcline. Plagioclase feldspar however is very rare in the studied thin-sections. The polycrystalline quartz is also more than the metamorphic and sedimentary lithic fragments in the formation. Lithic fragments 1.3-9.6% of the sandstone and it includes metamorphic rock fragments, sandstone, muscovite and chert in decreasing order of abundance. The texture of the sandstone is heterogeneous, varying from medium to coarse in grain size, with minor fine grained quartzite. Quartz arenite and feldspathic sandstones are cemented with silica, clay minerals and iron oxides.

Table 7.2: Percentages of detrital modes of Msikaba Formation.

Samples	Q	F	L	Qm	Qp	Lt
M1	54.8	27.2	17.9	45.5	9.3	27.2
M2	94.3	4.5	1.4	44.5	27.5	28.9
M3	98.3	1.6	0.0	65.1	8.7	8.7
M5	98.0	2.0	0.0	72.3	25.7	25.7
M8	96.9	5.1	0.0	85.8	6.1	6.1
M9	92.5	5.7	1.9	72.2	20.3	22.2
M13	79.9	7.4	12.9	49.8	0.0	12.9
M16	75.9	10.0	13.7	30.5	15.4	29.1
M17	85.3	7.4	8.2	46	9.3	17.5
M18	92.4	3.7	4.0	50.3	1.9	6.0
M21	77.1	3.4	19.4	43.7	3.4	22.9
P1	86.1	12.9	0.97	80.0	6.1	7.1
P3	84.9	12.0	2.2	80.2	4.6	6.8
P5	92.4	6.3	1.4	82.0	10.4	11.7
P10	93.6	2.9	3.5	85.6	7.9	11.5
P16	94.3	5.7	0.0	92.4	1.9	1.9
P20	95.1	4.9	0.0	92.7	2.4	2.4
Average	87.8	7.22	5.15	65.8	9.46	14.6

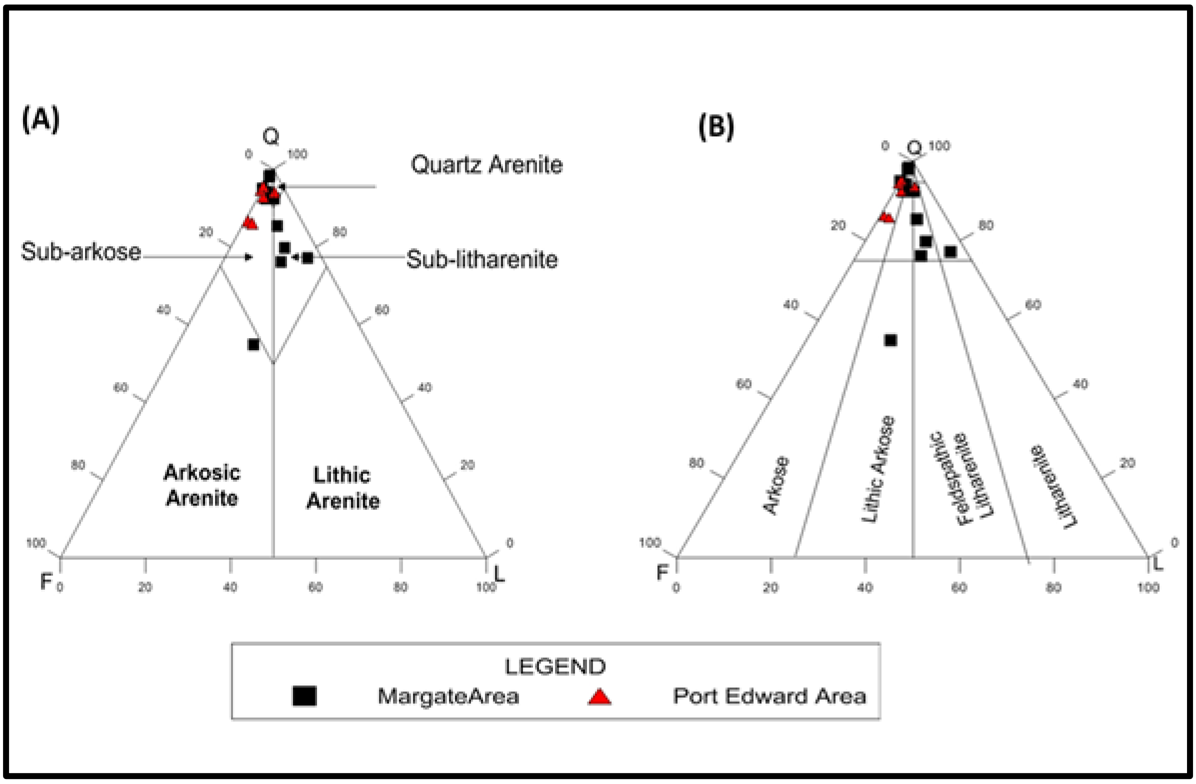


Figure 7.1 Q-F-L schemes proposed by (A) Pettijohn (1975) and (B) Folk (1980) showing composition of Msikaba Formation sandstone in Margate and Port Edward successions.

The plotted Qt-F-L ternary diagram display the calculated results with the majority of the samples are quartz arenite, sub-arkosic, sub-litharenite and feldspathic litharenite field, implying that there is high content of quartz which is approximately more than 90% in the quartz arenite samples.

7.4 Provenance

The purpose of this provenance study is to reconstruct the pre-depositional history from detrital sediments of Msikaba Formation and ultimately deducing the source area and parent-rock for the succession. Pre-depositional history is considered from the initial erosion of parent rocks to the final burial of the detritus, i.e. it is effected by transportation, deposition and diagenesis of the sediments. The provenance of sediment includes all aspects of the source area, such as source rock, climate and topographic relief (Weljie and Von Eynatten, 2004). Detrital quartz, feldspars and lithic fragments are often used as indicators of provenance. Majority of mature quartz arenite represents the transgressive sequence in the Msikaba Formation and the high quartz content is associated with the nearby Natal Metamorphic Belt as a source area. The transgressive sequence also coexists with regressive sequences hence there is inter-mixing of arkosic sandstone and quartz arenite sandstone.

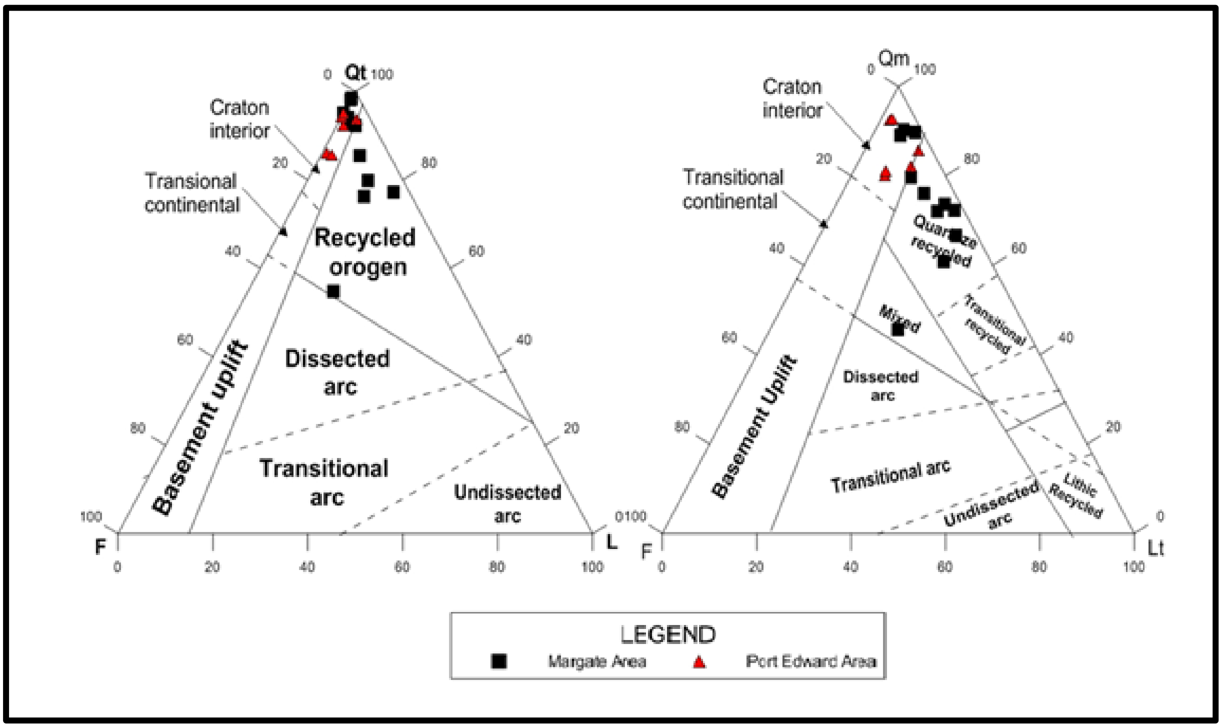


Figure 7.2 Qt-F-L and Qm-F-Lt schemes proposed by (A) Pettijohn (1975) and (B) Folk (1980) showing provenance of Msikaba Formation sandstone in Margate and Port Edward successions.

The interpretation of sandstone provenance from petrography of the Msikaba Formation on Margate and Port Edward locations is based on the schemes proposed by Pettijohn (1975) and Folk (1980). It is, therefore specifically established on the modal composition analysis for clast grains (Dickinson and suczeck, 1979) to determine the source area and tectonic province (Dickinson, 1983).

The bulk detritus of Msikaba Formation is composed of abundant quartz with minor feldspar and lithic fragments. Results from Qt-F-Lt and Qm-F-Lt plots indicate that the sandstone is likely to be derived from a mixed provenance of craton interior and quartzose recycled orogen continental blocks or provinces. The plotted samples were concentrated towards the Qt-L and Qm-L lines. Source area distribution is also deciphered through sedimentological and petrographic characteristics to determining the type source terrain of Msikaba Formation.

The most abundant monocrystalline quartz grains are coarse grained to medium grained and are sub-angular to sub-rounded in texture. Most quartz detrital grains in thin sections show non-undulatory extinction, however a small percentage of detrital quartz has undulatory extinction that is due to plastic deformation, high pressure and high temperature. The latter suggests a granitic igneous rock source and a metamorphic rock source that are represented by metamorphic fragments such as polycrystalline quartz and chert grains. The polycrystalline detrital grains demonstrate elongated or flat, sutured grain contacts with other framework grains. Compared to lithic fragments (5.15%), the polycrystalline quartz has a higher percentage of 9.46%.

Potassium feldspar grains (average 7.22 %) form a small fraction of the sandstone, unlike the quartz grains, feldspar grains are susceptible to weathering and alteration; thus most of feldspar grains are cloudy, cleaved and weathered under optical microscope. A small fraction of the orthoclase feldspar is altered to kaolinite or sericite due to alteration and weathering and also show feldspar perthite intergrowth with plagioclase inclusions hence the banded-lamellar texture (Barker, 1998). Possibly, orthoclase and microcline were derived from acidic igneous rocks or from granite and gneiss or pegmatite sources. The rare plagioclase feldspar might have been derived from low grade mica schist of Natal Metamorphic Belt. Therefore igneous and metamorphic sourced minerals are prevalent within the formation.

Other detrital components such as muscovite grains are common than biotite within the Msikaba Formation sandstone and they exhibit small to large flakes in shape. According to Carrozzi (1993), this type of muscovite is more prevalent in feldspathic arenite sandstones. They are typically found as flakes in the matrix also along the iron oxide stylolites, and they are bent and fractured due to compaction. Derived from metamorphic rock like quartzite, gneiss, plutonic igneous rocks. The presence of minor amounts of sedimentary lithic fragments such as chert, sandstone, and mudstone lithics suggest or indicate sedimentary provenance.

7.5 Petrography

Petrography study is a part of petrology, which provides detailed descriptions of thin sections of rock samples. Sixty five samples were used for petrographic analysis and they were collected from sandstones consisting of various grain sizes. The thin sections were examined by optical microscopy and counted by modal mineral composition analysis using the Gazzi-Dickinson point count method (Dickinson, 1985). The major detrital components of the Msikaba Formation are composed of quartz, feldspar, rock fragments and clay matrix, and the main cements are quartz, hematite and calcite.

7.3.1 Mineral compositions

Quartz

Quartz is the most common mineral in the Msikaba Formation, which constitutes the dominant detrital grains. Quartz mineral exists in three forms: polycrystalline and monocrystalline grains, as well as quartz cement (Figure 7.3). The quartz content of Msikaba Formation in the Margate and Port Edward areas ranges between 54.8-98 %, 84.9-95 % respectively with monocrystalline average 65.8% and the polycrystalline grains average 9.46%. The size of the majority quartz grains from 0.1 mm to 1.6 mm, which falls under medium to coarse grained. It is moderate to moderately sorted, sub-rounded to sub-angular and sometimes angular in shapes. Sometimes quartz grain also contains muscovite inclusion within the grains (Figure 7.4). The polycrystalline quartz is characterised by composition of multiple crystalline grains, whereas the chert grains are distinguished by having very fine and uniform crystalline size. The monocrystalline quartz composed of single crystalline quartz. Blatt and Christie (1963) concluded that quartz grains with non-undulatory extinction probable came from non-metamorphic rocks, whereas the grains with undulatory extinction (Figure 7.5) came from metamorphic rock source. Quartz grains also have secondary overgrowths that were precipitated around the original detrital grain boundary as a new overgrowth part (Figure 7.6). Most of the quartz grains could be the recycled quartz which is regarded as being deposited more than one time thus the rock becomes more pure in the quartz composition (Basu at el, 2013).

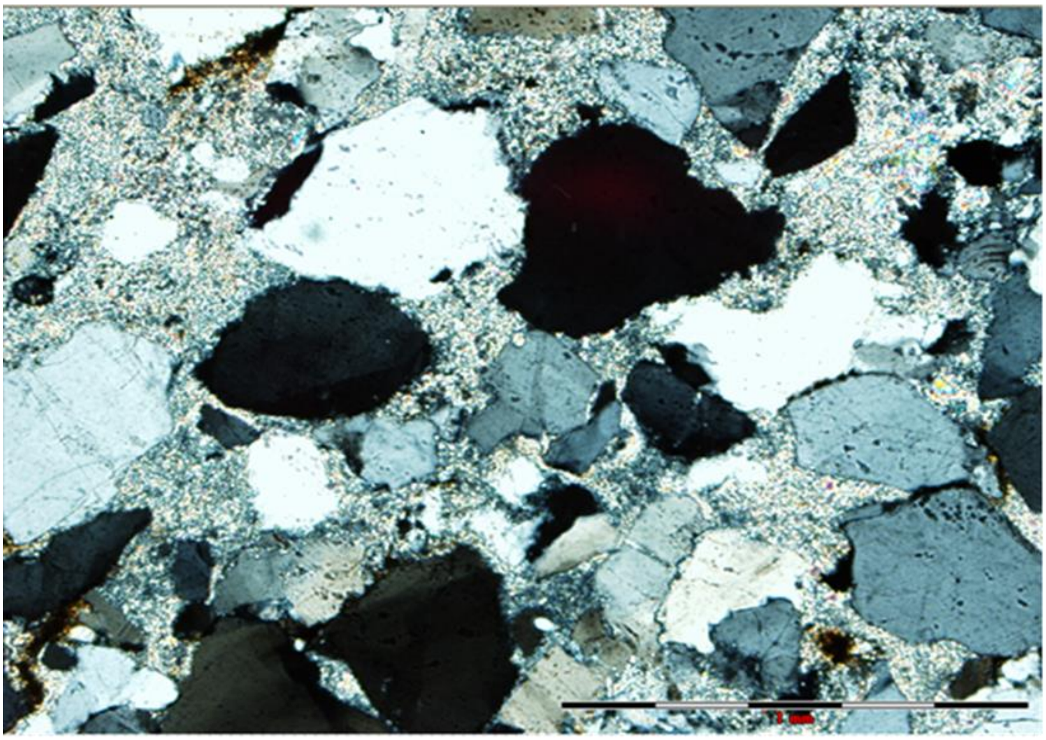


Figure 7.3: Photomicrograph showing coarse grained sandstone that is poorly sorted and with bimodal framework.

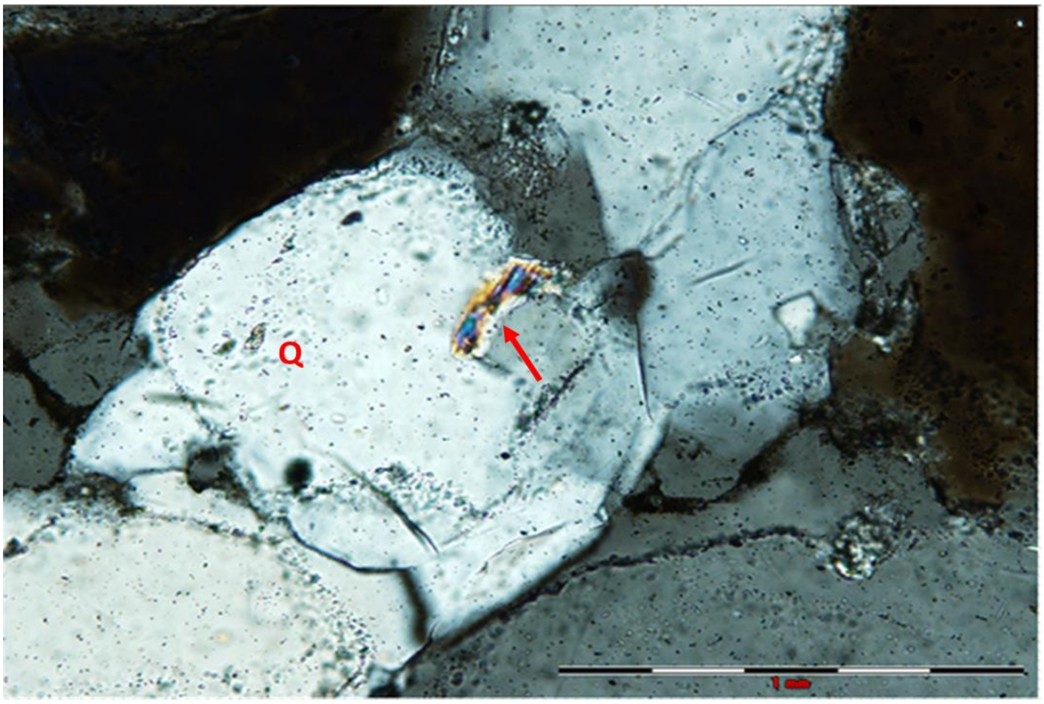


Figure 7.4: Photomicrograph of muscovite inclusion (red arrow) in a quartz grain (Q) in Margate.

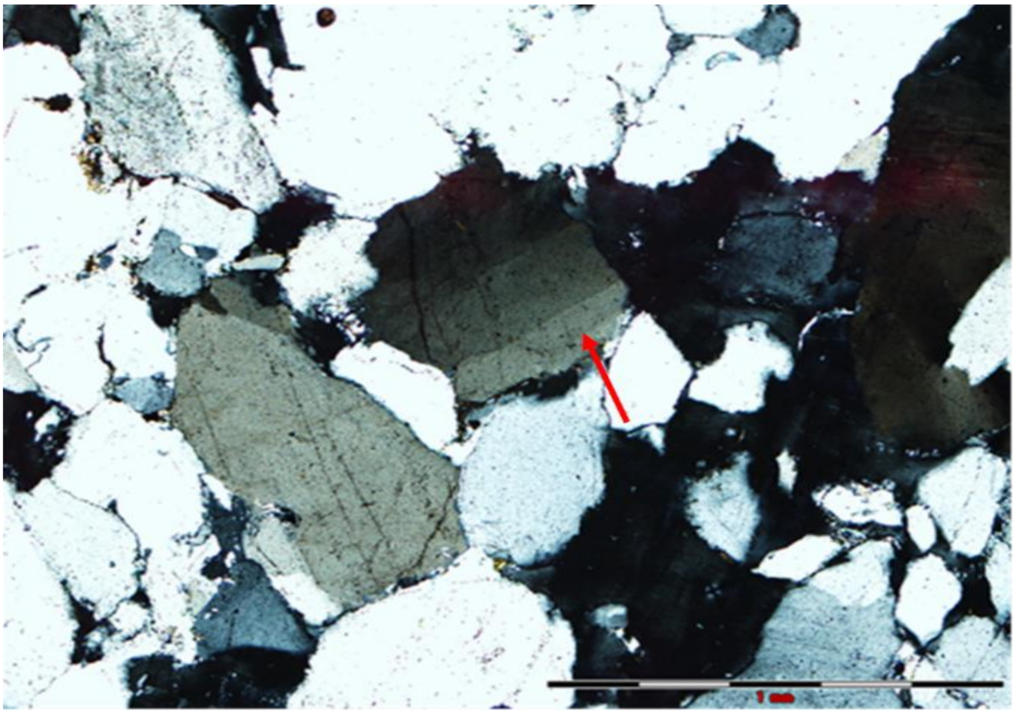


Figure 7.5: Photomicrograph showing quartz grain with undulose extinction (red arrow) from the margate area.

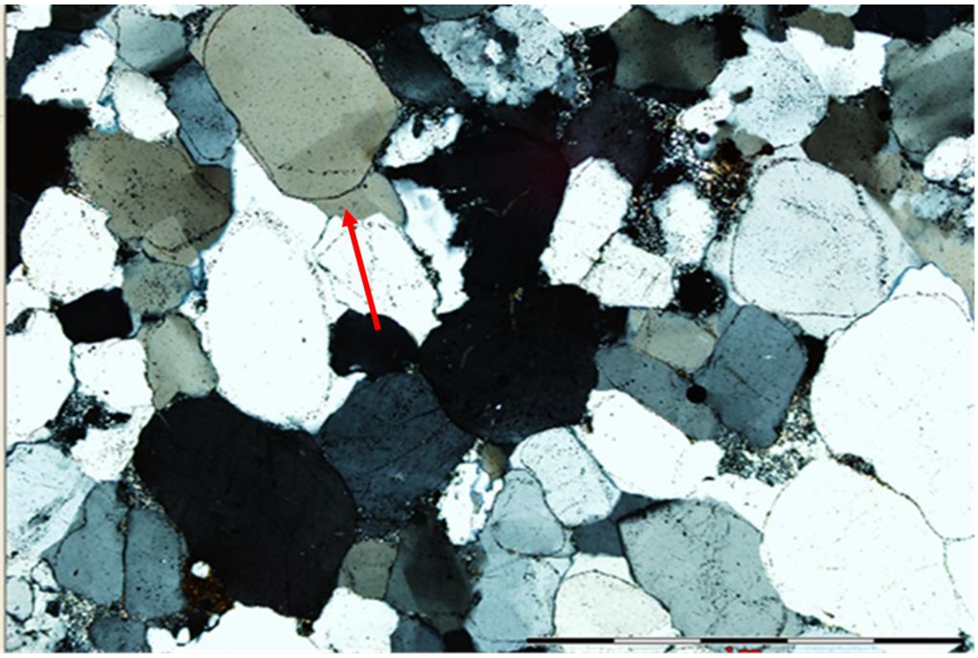


Figure 7.6: Photomicrograph of an abraded quartz overgrowth (red arrow) from Port Edward area. And intergranular overgrowths.

Feldspar

Majority of the sandstones contain average 7-7.5% of feldspar mineral in the Msikaba Formation. Feldspars grains are texturally sub-rounded to sub-angular and medium to coarse grained in size. They do not exhibit any inclusions within the grains. The K-feldspar is dominant over plagioclase. Observations from the thin sections show cloudy optical property of the feldspar due to weathering, some samples show euhedral shaped feldspar overgrowths (Figure 7.7), no twinning was found but there is a pervasive feldspar perthitic texture present in the sandstone (Figure 7.8). There are sporadic plagioclase. Replacement of feldspar is common, it is partially replaced by sericite or illite and kaolinite after weathering.

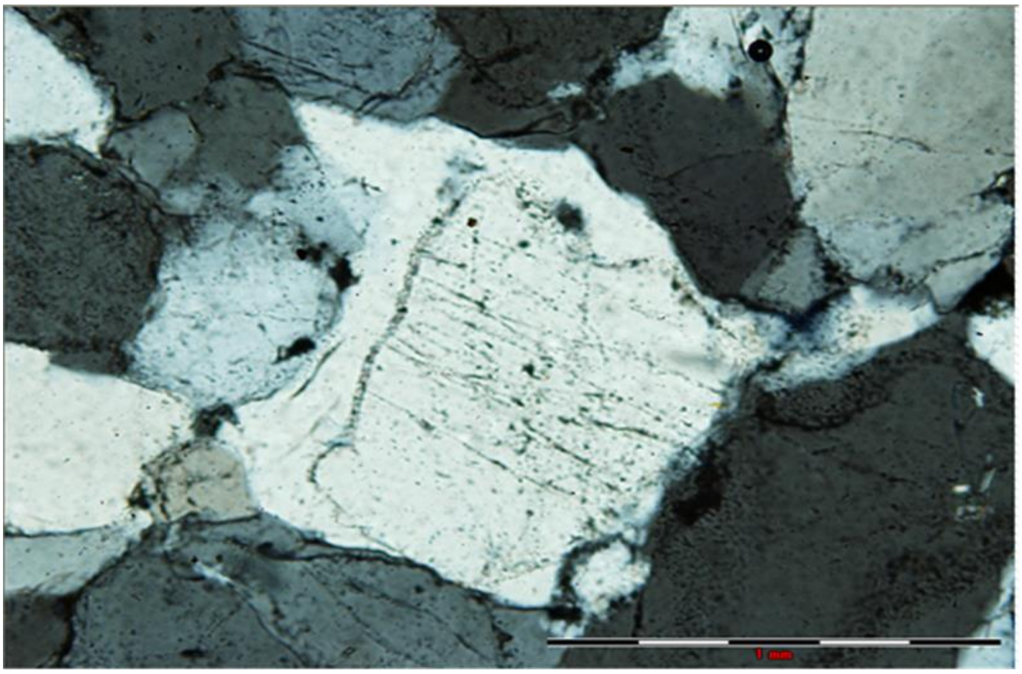


Figure 7.7: Photomicrograph of k-feldspar with overgrowth in Margate area.

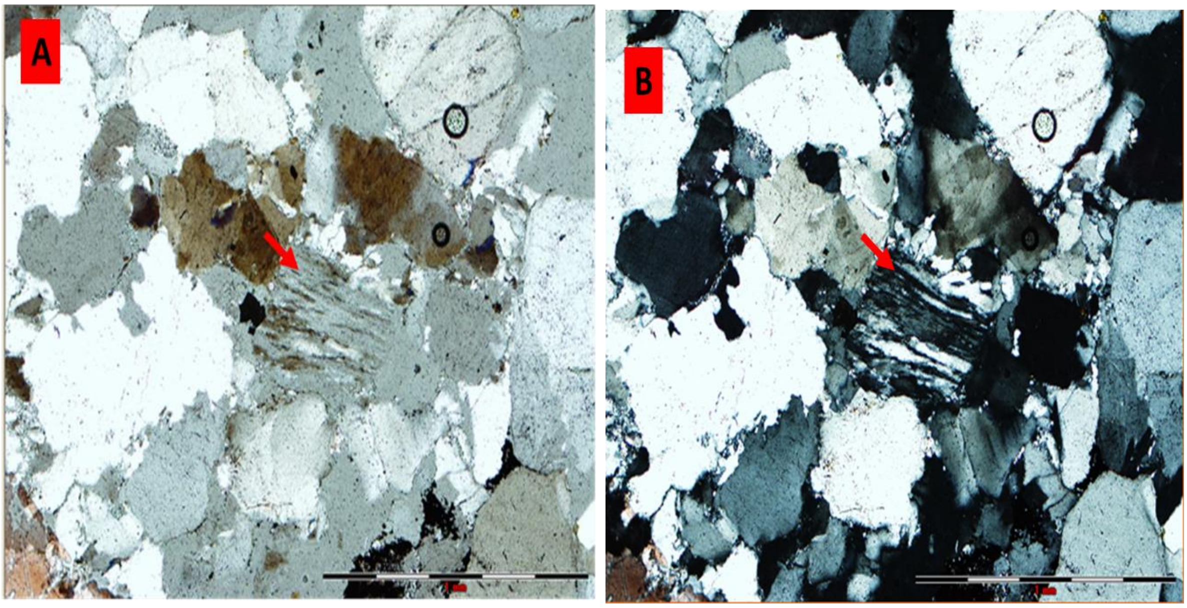


Figure 7.8: Photomicrograph showing feldspar with a perthite intergrowth (Red arrow). A- Plain polarized light (PL) and cross-polarised light.

Lithic fragments

As compared to quartz and feldspar, lithic fragments form only a small fraction of the rock volume. Fragments are made up of metamorphic, sedimentary and igneous rock clasts and they range between 1.3-7.2% in volume. Metamorphic lithics (Figure 7.9) are the most dominant in the Msikaba Formation and the fragments are sub-rounded to round in shape and fine to coarse grained in texture. Presence of sedimentary lithic fragments persists mostly in the lower members of Margate strata and there is a lesser content in the Port Edward strata. There are also rare muscovite fragments and recycled quartzite grains.

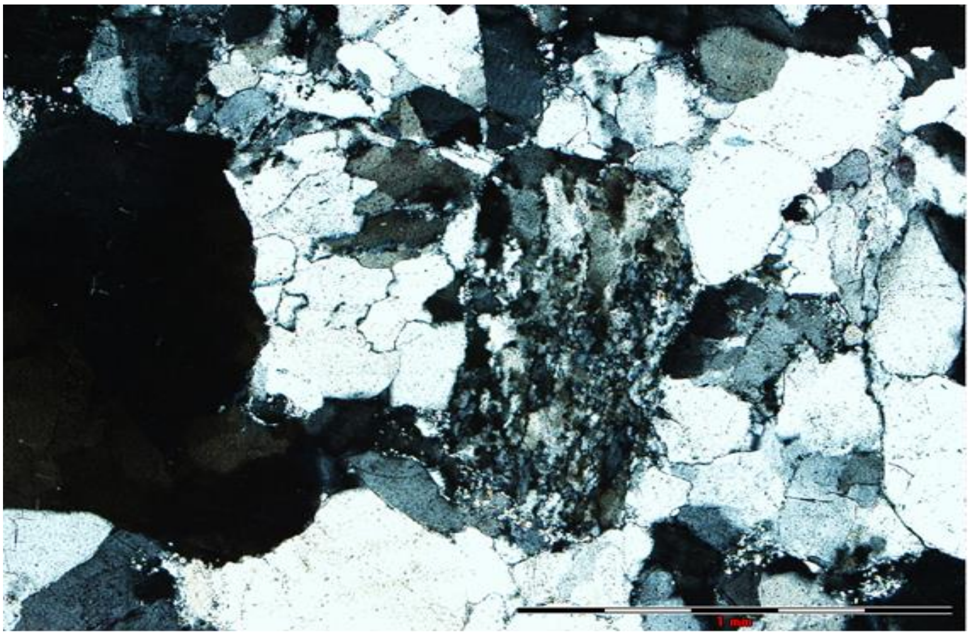


Figure 7.9: Photomicrograph showing subrounded metamorphic and sedimentary lithic fragments.

Matrix and cement

The detrital sandstone framework grains in the Msikaba Formation are bound by matrix of silts and clay mineral, quartz, hematite and calcite. Clay matrix in the Msikaba Formation has been recrystallized (Figure 7.10), and is common in fluvial and marine sandstone facies of the Margate and Port Edward strata. Quartz cement is in the form of fine quartz or quartz overgrowths that precipitated out in the pore-space between the original detrital grains (Figure 7.11). Quartz and hematite cements are also present in the mudstone in the Shelly Beach Member (Figure 7.12).

Clay minerals include smectite, kaolinite, sericite and illite. These clay minerals are best identified by Scanning Electron Microscope (SEM) and X-Ray Diffraction (XRD) analysis. Smectite and illite are the most abundant clay minerals with minor kaolinite and sericite clay minerals. Hematite cement is also common in the formation which fills the pore spaces within the sandstone grains.

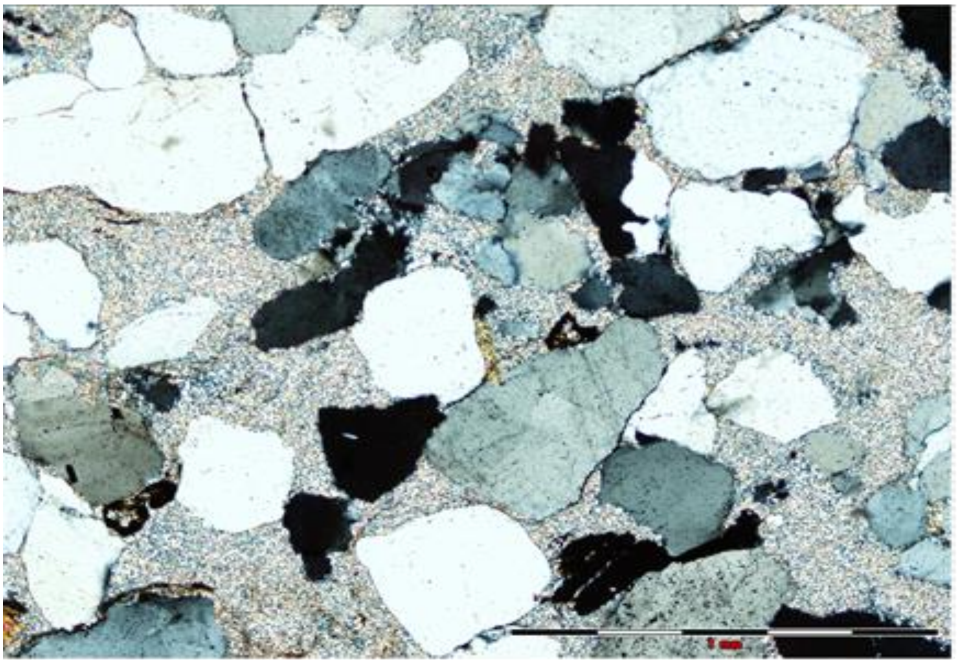


Figure 7.10: Photomicrograph of a matrix supported coarse grained sandstone frame work.

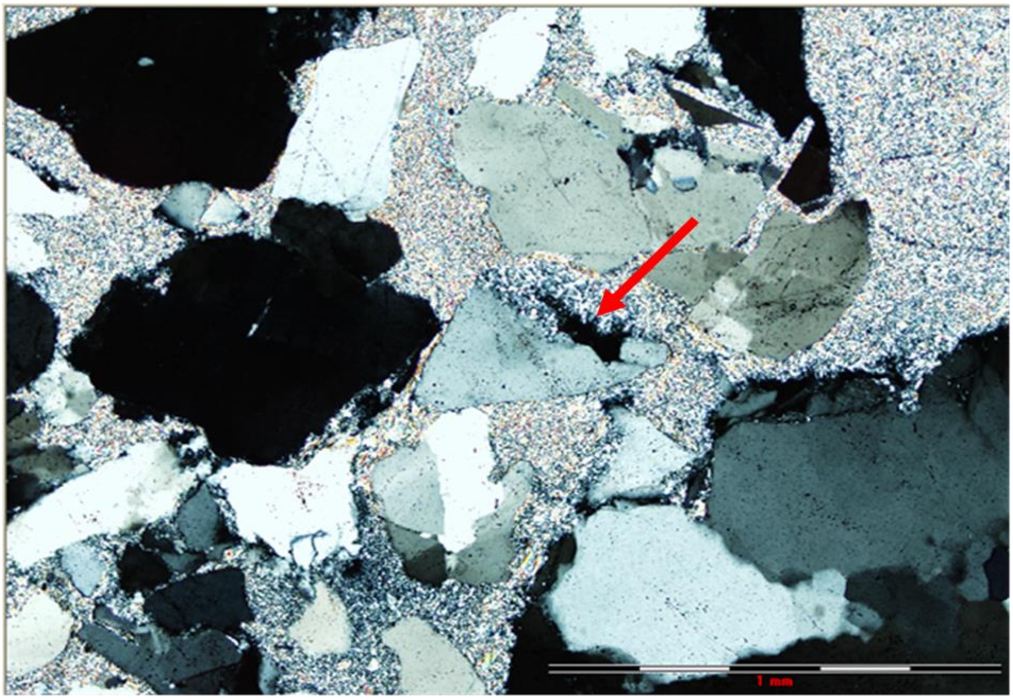


Figure 7.11: Photomicrograph showing micro pores in the sandstone and authigenic clay lining and growing vertically to the pore boundary.

Figure 7.12: Photomicrograph showing mudstone with microfractures and pores in the Margate area.

Muscovite

Muscovite occurs as a fine to coarse grained detrital flakes (accessory mineral) that are found throughout the Msikaba Formation (Figure 7.13 A and B) particularly on the Port Edward succession. Evidently, muscovite flakes appears parallel or squeezed flat amongst other grains or concentration along bedding planes and matrix. The muscovite is sometimes deformed, fractured and most of muscovite present is authigenetically formed through recrystallization of clay matrix during diagenesis and has a euhedral shape.

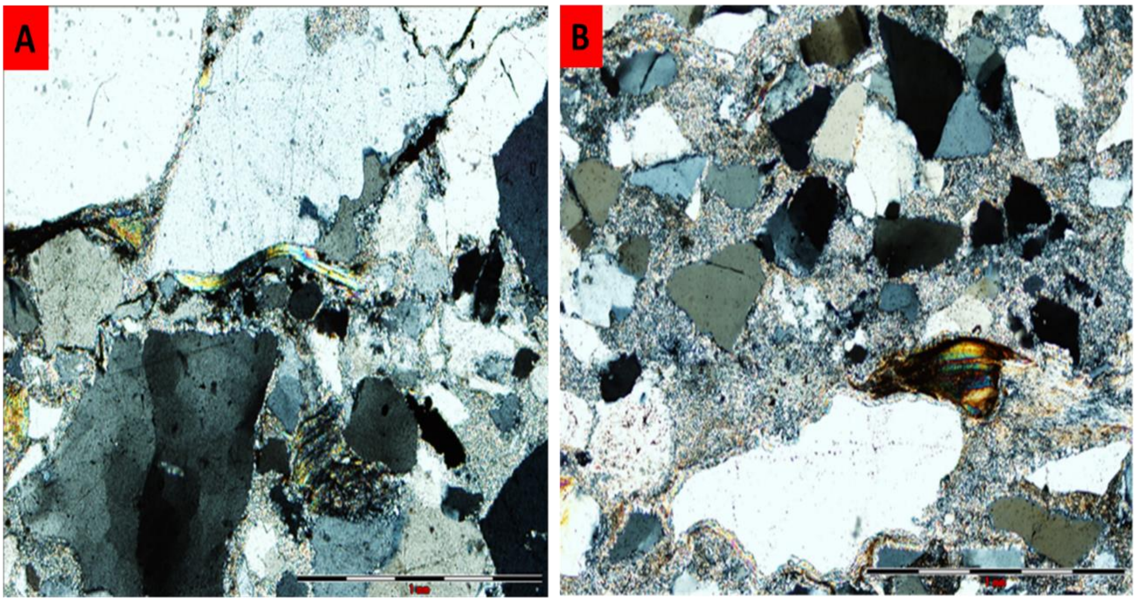


Figure 7.13: Photomicrograph A: showing bent muscovite flakes and Photomicrograph B: showing angular to subangular quartz grains and a detrital muscovite grain.

Heavy minerals

Heavy minerals in Msikaba Formation occur as accessory minerals of garnet, zircon (Figure 7.14 A), rutile (Figure 7.14 B) and detrital hematite. These heavy minerals constitute less than 1% of the whole rock volume. The detrital hematite (Figure 7.15) is predominant in the formation and is distinguished by the red brown colour in the rock samples. Moreover, hematite is also a pore filling cement filling the granular pore spaces.

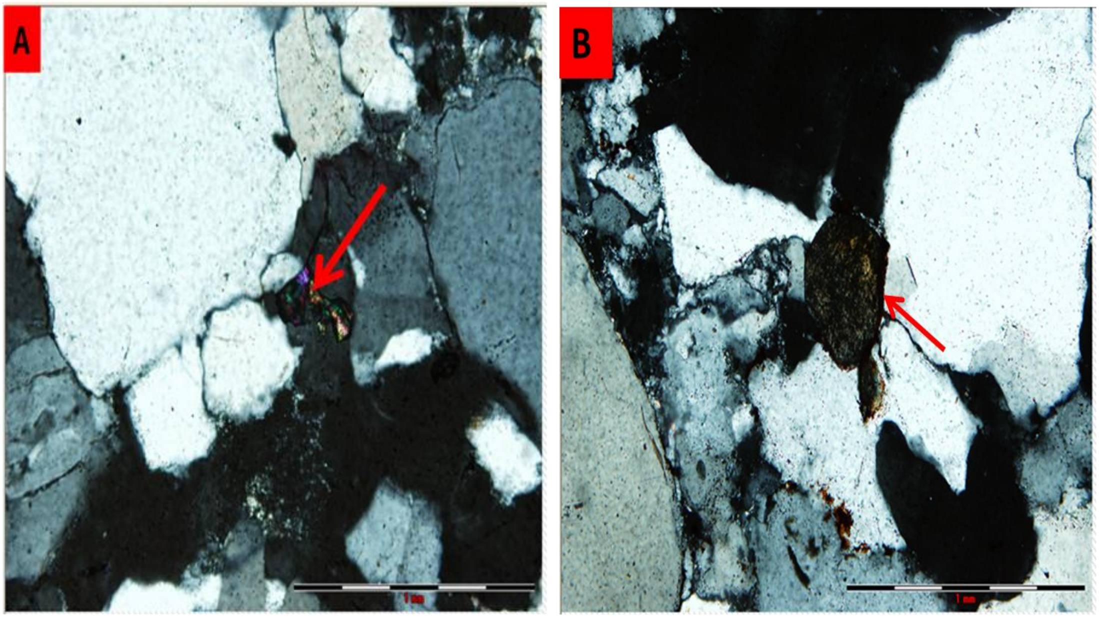


Figure 7.14: Photomicrograph showing A: zircon mineral grain (Middle, red arrow) in XPL (Left) and B: Photomicrograph showing rutile mineral grain (Middle, red arrow) in XPL (Right).

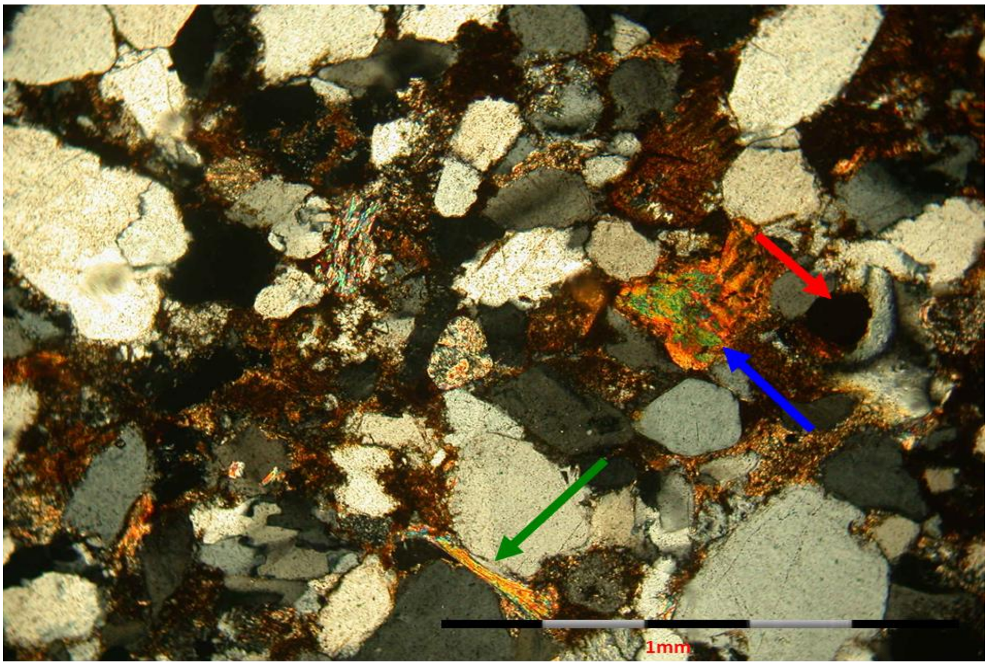


Figure 7.15: Photomicrograph showing detrital hematite grain in Margate sandstone in Manaba Member and also showing authigenic mica (Blue arrow) and detrital mica (Green arrow).

In summary, reconstruction of Msikaba Formation provenance with Qm-F-Lt and Qt-F-L ternary diagrams inferred both of the study areas to be represented by a craton interior to quartzose recycled origin. Abundance of quartz in the formation might due to intense beach recycling of the detritus leading to the depletion of feldspar. The maturity of quartz arenite is attributed to high percentage of monocrystalline quartz grains within the sandstone. Since provenance is dependent on the effects of transportation, weathering, recycling, depositional environment and diagenesis sediments factors have to be considered. The underlying Proterozoic Natal Basement, the heavy mineral, quartz and feldspar grains in the Msikaba Formation are likely to have been derived from erosion and recycling of the Natal Metamorphic Belt of the crystalline igneous and metamorphic rocks. The sedimentary lithic fragments in the sandstone may have been derived from intra-formation rock fragments.

CHAPTER 8: DEPOSITIONAL ENVIRONMENT

8.1 Introduction

A depositional environment is described as part of the earth's surface, which is physically, chemically and biologically distinct from adjacent terrains, and it is a concept of geography. Specific environments where sediments could be deposited are deserts, river valleys, lakes, deltas, and marine basins. These geomorphic units are affected by hydrodynamic conditions and tectonic movements, such as basin uplift and subsidence.

Depositional environments can be deduced by use of lithological features, sedimentary structures, palaeocurrent patterns, sedimentary facies and tectonic characteristics. They can be sites of deposition, non-deposition or even erosion during the basin development processes in the different stages.

Interpretation of depositional environments is dependent primarily on sediments and space of accommodation within a basin. Fundamental diagnostic features are the recognition of lateral, vertical profile and facies relationship. A stratigraphic sequence is a result of depositional environment that is fixed in time and space. It influenced by resultant processes that are acting on the coastal area as the depositional environment migrates laterally and vertically (Davis, 1985). Sequence stratigraphic surfaces or contacts are identified by observing the geometric relationship between strata and the surfaces against which they terminate. Another important aspect in sequence stratigraphy is the shoreline stability, and if stability is not achieved shoreline shifts may result. Transgression and regression shoreline shifts are highly controlled by the sea level changes hence stratigraphic sequences resulting from either transgression or regression are completely different (Davis, 1985; Maill, 1977 and Catuneanu, 2006). Moreover , each rise in relative sea level allows deposition of a sediment thickness approximately equal to the rise of sea level and a stratum or group of strata is formed that is separated from the units below by the surface of the former base level of deposition on which the later deposits were laid down. The surfaces represent a break in deposition that might have been very long or short (Twenhofel, 1950).

Observations of sedimentary facies changes in Msikaba Formation indicate transgression and regression systems due to their distinctive sequence of stratification which they exhibit. However, these sedimentary rocks produced could be affected by neighboring different depositional environments present.

8.2 Lithological changes and palaeocurrent directions

Detailed sedimentological study of the Msikaba Formation sandstones along the Kwa-Zulu Natal coastline yields important clues to the depositional environments. The representative different sedimentary facies changes found within the formation reflect the depositional processes. Significant depositional environments are depicted by fluvial and marine deposits unconformably lain over the Proterozoic Natal structural and metamorphic Belt. From this study, the Msikaba Formation is divided into four members in the Margate section, the lower unit-Manaba Member has two sub-units of brown-greyish pebble conglomerate at the base and a brownish sub-arkose sandstone at the top, and is overlain by whitish grey quartz arenite unit of Uvongo Member, which is composed of high maturated quartz arenite, and is capped by Mhlangeni Member of another rock unit of mature quartz arenite. The Shelly Beach Member is the top rock unit, which consists of feldspathic sandstone intercalated with red and thin bedded mudstone in the Shelly beach area. Each member has specific lithologies, sedimentary structures and is representative for a specific depositional environment.

The Port Edward section can also be subdivided into different rock units based on the lithological changes. The section can be subdivided into three members, the bottom rock unit is a conglomerate unit of Manaba Member, which is much thin comparing to the Margate section and overlies on an intrusive igneous rock of Charnockite. Upward there is a mature white coloured quartz arenite rock unit of the Uvongo Member, which is similar to the Margate section, and it is covered by the third rock unit of Mhlangeni Member of white greyish coarse grained quartz arenite, which is also identical to the Margate section. There is no Shelly Beach Member in the Port Edward section and thus there is no feldspathic sandstone of the fourth member in the Port Edward area.

The conglomerate and sandstone within the formation are characterized by ten lithofacies (Gmm, Gcm, Sm, St, Sp, Sr, Sh, Sl, Shb and Fm), which represent different formation processes and link to different formation environments.

The sedimentary structures, rock textures, lithological variations and the stratigraphic cyclicities in vertical sequence of the Msikaba Formation indicate that the bottom rock unit, the Manaba Member is a fluvial deposit, the conglomerate represents a braided channel deposit, while the top of arkosic sandstone represents fluvial plain or fluvial fan deposit. The pure quartz arenite rock unit of the Uvongo Member reflects a high energy shallow marine deposit and probably affected by tidal channel and tidal flat processes, where intense reworking and recycling processes were prevalent. Whereas the third rock unit, i.e. the Mhlangeni Member which has similar lithology and similar sedimentary structures with the Uvongo Member, is probably also deposited in a similar shallow marine environment. The fourth rock unit, i.e. the Shelly Beach Member, has mixed lithologies of white quartz arenite sandstone and red-brownish feldspathic sandstone and probably deposited by mixed fluvial and marine waters in the area near coastline where marine incursion intruded into fluvial system from time to time.

Palaeocurrent direction is an important aspect of depositional environment analysis concerned with the orientation of stratification. The consequential palaeocurrent direction of Msikaba Formation shows bimodal current directions that either southeasterly or mostly southwesterly on both Margate and Port Edward sequences.

8.3 Depositional systems

There are two depositional sequences that are recognized in the Msikaba Formation: (1) A transgressive sequence from fluvial deposits of the Manaba Member to marine deposits of the Uvongo Member; and (2) A regressive sequence from marine deposits of the Mhlangeni Member to mixed marine and fluvial deposits of the Shelly Beach Member. The whole Msikaba Formation thus represents a full complete sequence from transgression to regression process.

8.3.1 Transgressive system

Msikaba formation sandstone has experienced two depositional systems with respect to relative sea level changes recorded by different sediment compositions. The first depositional system is a transgressive system, which was a fluvial stream deposit after prolongable uplift, erosion and weathering of the Natal structural and metamorphic belt, seawater incursion further intruded the area when sea-level was risen and shifted sedimentary facies from fluvial to marine, which constitutes a transgression sequence.

Braided fluvial system

This system is represented by the Manaba Member, the bottom rock unit of the Msikaba Formation. The lowest member of Msikaba Formation in the Margate area is interpreted to represent initial transgression of a braided fluvial river system or breaded channel deposit. This system is represented by fluvial Manaba Member which strongly suggests progradation of braided river sediments. It is characterized by multiple channels as compared to a meandering river system which has one single sinusoidal channel. The braided fluvial channel deposits are commonly found in higher topographic gradient area, they have rapid discharge rate, coarse sediment loads are prevalent and have easily erodible banks than meandering rivers (Rust, 1978). However, the conglomerate and sandstone deposits (~20 m) of the Manaba Member indicate that they were deposited near the shallow end of a braided channel because there is an upward fining cyclicity due to changes from pebble beds to arkosic sandstone beds as the sequence progresses upwards. Twenty centimeters of conglomerate that is poorly exposed in the Port Edward area which is also included in the transgression phase of the formation. In the Margate area, it is well exposed and consists of small scale trough and tabular-planar cross-bedding of sedimentary structures in some of the sandstone beds which indicates braided fluvial depositional environment.

Beach and tidal channel system

This system is represented by Uvongo Member which shows four upward fining cycles in Margate area and three cycles in Port Edward area with erosional surfaces at the bottom. Sediments are deposited in a tide dominated shallow marine environment where the sands are intensely reworked by beach currents. The sandstone is pure, highly mature and quartz rich; and shows trough and herring bone cross-bedding structures which indicate a near-shore high energy tidal environment. Sedimentary facies linking this system are trough cross bedded sandstone, ripple mark sandstone, herring-bone cross-bedding sandstone and lenticular bedding sandstone that indicates a bidirectional ebb and flow palaeocurrent environment. Mature sandstones are prevalent in coastline and shallow marine environment (Reading, 1996).

8.4 Regressive system

Following the transgressive depositional system, the sandstones of the Msikaba Formation in Margate and Port Edward areas are deposited during a regressive depositional system. It is the system that is consists of marine quartz arenite of the Mhlangeni Member changes to the mixed marine quartz arenite and fluvial arkosic deposit of the Shelly Beach Member, indicating a sea level retread and fluvial stream forward process. This system is deposited from upper north topography to downward south topography, which fully filled the depositional basin and ended the depositional process of the Msikaba Formation.

8.4.1 Shallow marine system

The shallow marine system is represented by Mhlangeni Member and regarded as a high energy environment deposit. It consists of thick beds of clean, mature quartz arenite sandstone. After deposition of the braided fluvial deposits of the Manaba Member, marine transgression invaded the area from north to south, which results the Mhlangeni Member depositing a thick quartz arenite sandstone of approximately 50 m. A deeper scours surface separates the Mhlangeni Member from the Manaba Member at the base of quartz arenite and lag conglomerate pebble deposits at the bottom of the Mhlangeni Member due to marine water floods the deposition area. The shallow marine deposits in both Margate and Port Edward areas are very pure and highly mature quartz arenites, and the strata are dominated by trough and tabular cross-bedding, erosional surface, ripple mark and large scale lenticular bedding. These characteristics imply that the marine transgression was large and the Msikaba Formation represents an overall deepening from fluvial deposition to marine foreshore deposits. The sandstones could have been partially derived from the underlying sediments as a result of reworking by wave and current actions.

8.4.2 Alternated marine-fluvial system

This depositional system is represented by Shelly Beach Member, and is characterized by mixed deposits of marine quartz arenite and fluvial arkosic sandstone and red mudstone, which constitutes a regression sequence from marine changes to fluvial as sea level dropped. As the sand deposits are created and advancing landward, on the seaward side the mature sand is accumulating over a wide marine environment forming a sand blanket (Davis, 1985). The interbedded sandstone and mudstone that have shifted landward shows inter-tonguing or inter-fingering occurrence relationship during the end of slow regression during the deposition of the Margate Member.

In summary, the overall depositional environment of the Msikaba Formation is interpreted to be a braided fluvial channel (Gmm) and fluvial plain (Sm) deposits for the Manaba Member, which is located in the bottom of the Msikaba Formation. The depositional process shifted to beach and tidal environment as a result of marine transgression, and left the pure, high mature quartz arenite deposits of the Uvongo Member, which shows typical clast supported conglomerate (Gcm), trough and planar cross-bedded sandstone (St and Sp), herring bone cross-bedding sandstone (Shb) and lenticular bedded sandstone (Sl). The marine incursion was continuous to the deposition of the Mhlangeni Member, which still kept the marine environment and probably became slightly deeper from beach and tide environment changed to shallow marine environment, where large scale lenticular bedded quartz arenite (Sl), horizontal bedded sandstone (Sh) and ripple mark sandstone (Sr) were produced. The shallow marine continental shelf is believed to have been in passive margin or stable platform (Kingsley, 1975; Hicks, 2005). According to Perry and Taylor (2007) and Parker and Sellwood (1981) a continental shelf is a shallow sea floor which is less than or ranges between 10-200m deep with the outer margin marked by a continental slope. With the time passed to Shelly Beach Member of the top sequence of the Msikaba Formation, sea level gradually dropped, and thus produce a regressive sequence of mixed marine and fluvial deposits. Some fluvial red arkosic sandstone and mudstone inter-finger with marine quartz arenite as a result of marine water incursion and retreating.

The Msikaba Formation depositional environment was delineated through facies associations that were observed during the investigation. Results demonstrate that facies association 1 (FA1) represents a braided channel yielding conglomerate and fluvial plain of arkosic sandstone deposits with a fining upward signature. FA2, FA3 and FA4 represented transgression of tidal-dominated marine deposits and continental shallow marine deposits respectively. The coarse grained, moderately sorted mature quartz arenite sandstone reflects deposition in a high energy environment where the sand deposits were recycled and reworked by wave and tide currents. Additionally, there are numerous small pebble conglomerates layers (Gcm) which are pervasive throughout the formation and representing storm influenced bad-weather deposits (Kingsley, 1975). The quartz conglomerate layer also occur as lag deposits along erosive surfaces and they are also deposited by high energy current.

The thick to massive bedding facies which are prominent within the sandstones show lack of periodic tidal flow and might represent rapid deposition in high-energy settings (Boggs, 1987). Planar and horizontal laminated sandstones indicate deposition from rapid flows under upper (high) flow regime conditions (Reineck and Singh, 1973). Trough cross-bedding is a dominant sedimentary structure and might have been produced by migration of three-dimensional dunes in high-energy channelized environments (Reading, 1996).

The provenance of the sandstones of the Msikaba Formation suggests influence of granitic and metamorphic terrains as the main source rock with a subordinate quartzose sedimentary rocks. Textural features of the formation suggest long-distance transport of the sediments from the source region and indicates a cratonic or a recycled source (Dickinson et al, 1983) which is typical deposition in a passive margin basin. The compositional maturity of the

Msikaba Formation sandstone increases upwards stratigraphically. This can be attributed to a shift from braided stream to marine conditions of the depositional environments (Figure 8.1).

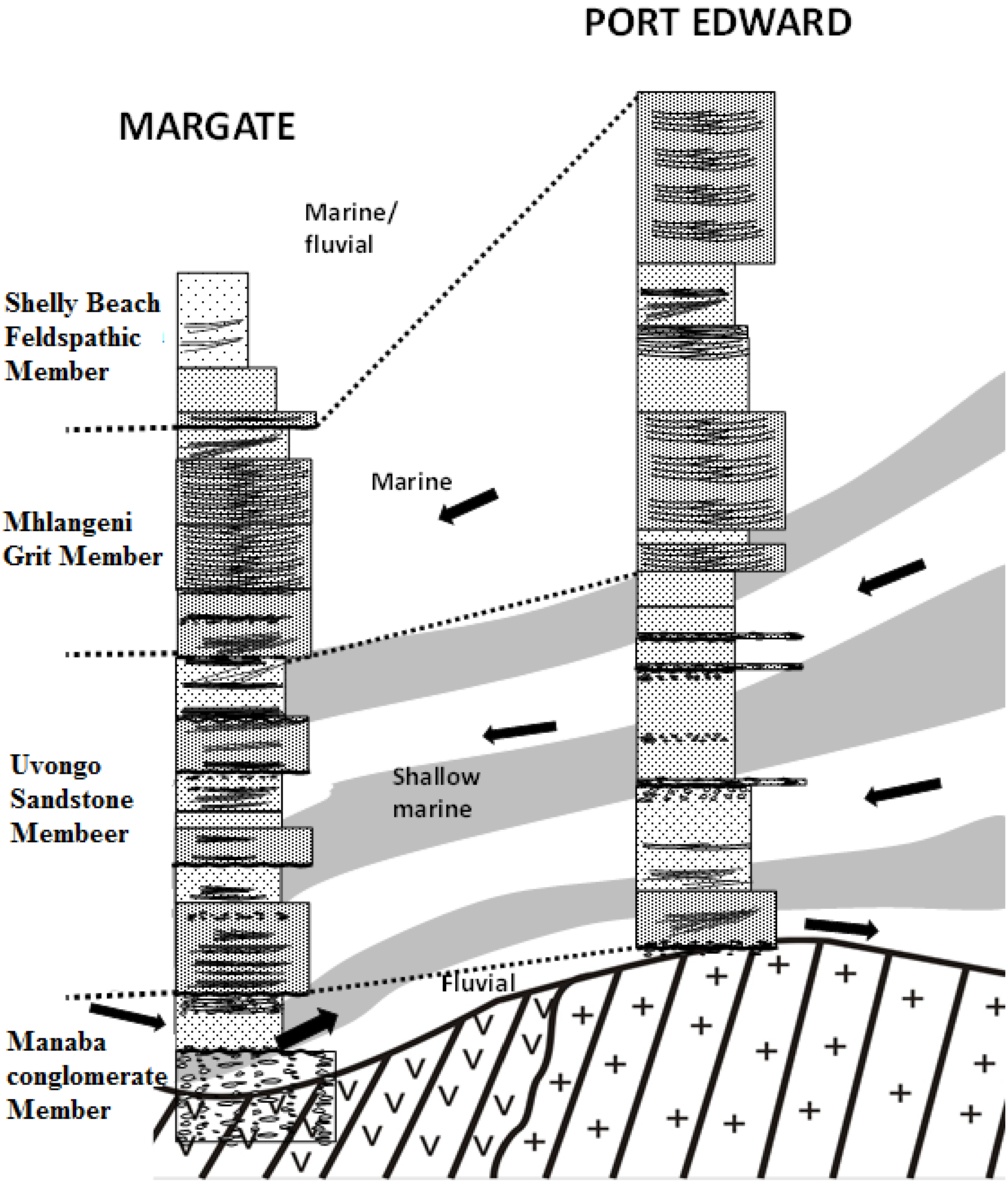


Figure 8.1: Proposed depositional model for the Msikaba Formation in the Margate and Port Edward areas. Arrows indicate palaeocurrent directions.

CHAPTER 9: DIAGENESIS

9.1 Introduction

Diagenesis is a post-depositional process where sedimentary deposits are altered between the time after deposition and before metamorphism. This process involves changes in compaction of interstitial pores, cementation, mineral convection, recrystallization, authigenesis and replacement and dissolution processes that affect physical, geochemical and biological character of the original sediment and mineral assemblage. Diagenesis plays an important role in sediment transformation from the onset of deposition and brings textural and thermodynamic stability to the environment, thus forming a sedimentary rock (Worden and Burley, 2003). According to Collinson and Thompson (1982), this concept can be comprehended from the appearance of sedimentary beds in a stratigraphic column where there are distinct beds due to different diagenetic processes rather than changes during deposition.

This chapter focuses on the processes and products of diagenesis such as authigenetic minerals of quartz, feldspars, different newly formed cements and clay minerals. Petrographic microscope and scanning electronic microscope (SEM) were used to detect diagenetic textures and minerals, including different clay minerals and their morphology changes.

For this study five samples were carbon coated with a Cressing Carbon coater 108 carbon/A machine and were analyzed with the SEM equipment modeled as Jeol JSM-6390LV, in the working condition of 15KV, which was equipped with an Energy Dispersive X-Ray (EDX) detector. This analysis helps to discover diagenetic textures and minerals that might have taken place in the Msikaba Formation.

9.2 Diagenetic Processes

The major diagenetic characteristics that were observed in the Msikaba Formation in Margate and Port Edward areas were compaction, silica cementation, feldspar overgrowth, grain replacement/alteration, pressure dissolution, kaolinite cementation and albitization. These processes are influenced by depositional environments especially during early diagenesis. A series of diagenetic changes in the Msikaba Formation are associated each other and can constitute a diagenetic pathway and diagenetic sequence.

9.2.1 Mechanical and chemical Compaction

Mechanical compaction occurs during the initial stages of rock formation. After sediment was deposited, the inter-granular pore spaces among the loose detrital grains are reduced due to weight of the overburden. This occurs through change in packing by rotation, translation, fracturing and plastic deformation, thus reducing porosity and permeability of the strata (Pettijohn, 1987). The grain contact patterns gradually change from non-contact (floating packing) to point contacts to long contact, then to concavo-convex contact and finally to sutured contact (Figure 9.1).

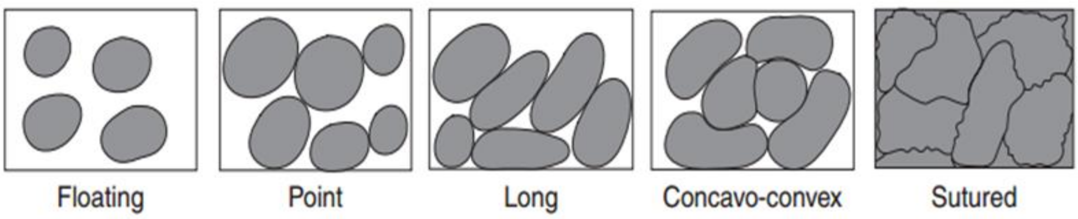


Figure 9.1: The variables of grain to grain contact patterns due to increasing burial depth (Boggs, 2009).

The Msikaba Formation sandstone in the Margate and port Edward areas displays a range of grain contacts from point to sutured contacts due progressive burial. Long contacts are common in sandstone rocks and their presence signifies intermediate burial depth (Figure

9.2). Other dominant grain contacts are concavo-convex and sutured contacts in sandstone as a result of strong compaction and pressure dissolution processes due to compression structural events in the Msikaba Formation (Figure 9.3). The presence of sutured and concavo-convex are also attributed to deep burial and in diagenetic stage. The compaction events cause a decrease in porosity and permeability in the Msikaba Formation sandstone. Fracturing is generally uncommon but observed as minor fractures present on detrital quartz grains and the mineral deformation observed on muscovite grains that are aligned with other detrital grains in the sandstones and mudstones (Figure 9.4). Quartz, chert, muscovite are the deformed grains due to pressure dissolution.

The results also show that these sandstones have undergone chemical compaction which encompasses dissolution, recrystallization and precipitation because points of contact between grains are susceptible to dissolution which is an obvious response to overburden weight and higher stress.

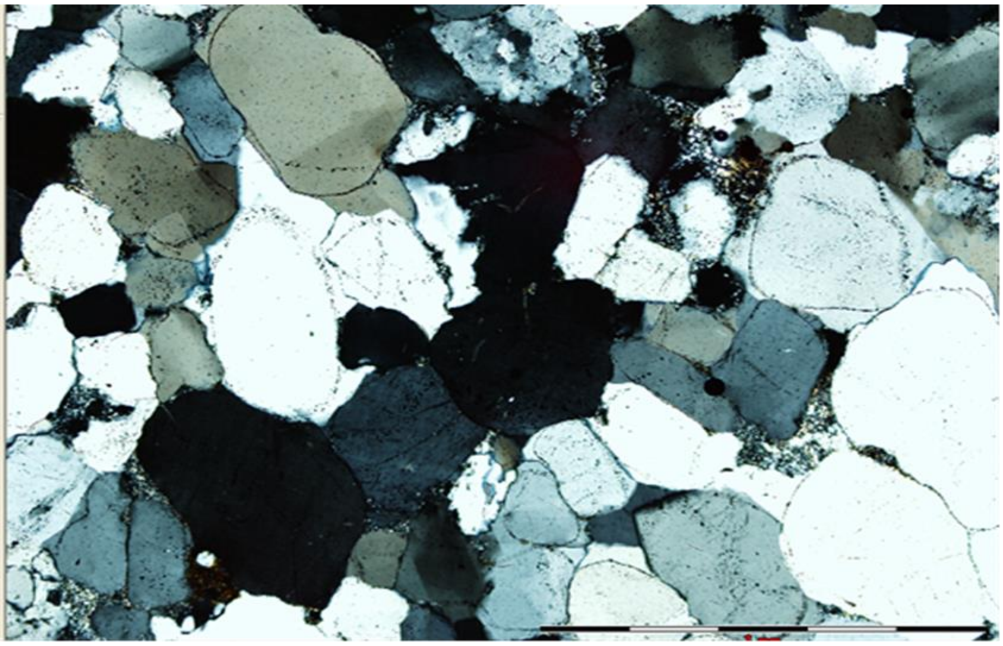


Figure 9.2: Photomicrograph of sandstone showing point, long contacts between detrital grains and also showing quartz overgrowths of the Msikaba Formation sandstone.

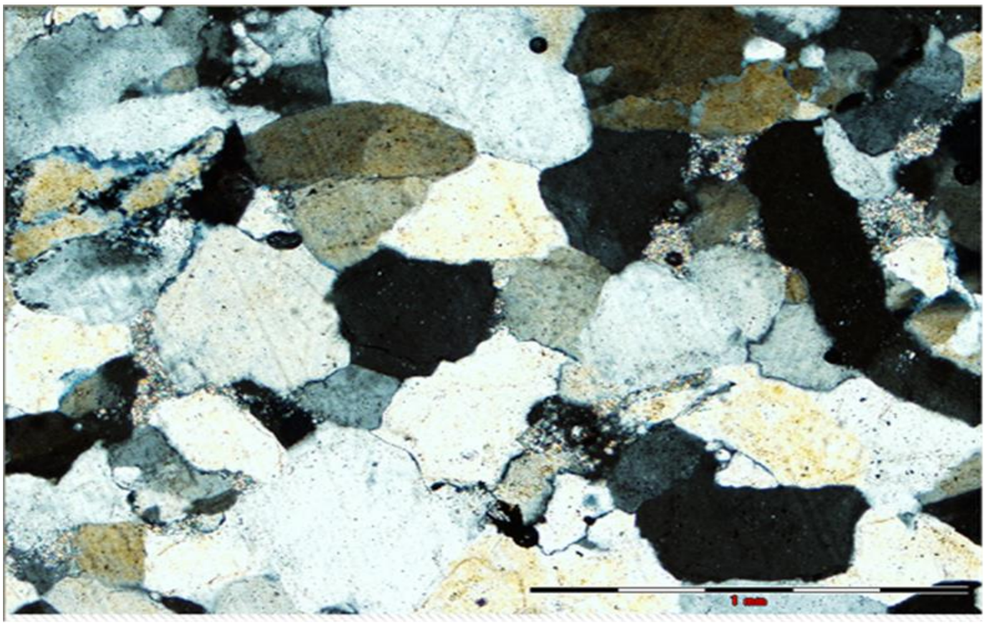


Figure 9.3: Photomicrograph showing concavo-convex grain contacts and sutured grain contacts.

8.2.2 Cementation

Cementation process is a diagenetic process, which leads soft sediments becoming a hard rock. Through optical microscopy and SEM studies, four types of cements have been observed in the Msikaba Formation, i.e. clay minerals (clay matrix), quartz, feldspar and hematite cements. For clay minerals, it can be further classified into kaolinite, smectite and illite of three subtypes.

Pore lining and pore-filling clays

Pore lining and pore-filling clays that are abundant in the Msikaba Formation, and can be recognized as kaolinite and smectite. These clays occur as matrix and are probably derived from fine detrital materials and diagenetic processes such as authigenesis and alteration. SEM analysis provides good results particularly for clay minerals. Kaolinite clay, smectite and illite clay types are common, forming clay matrix and coats between grains before the compaction and dissolution took place.

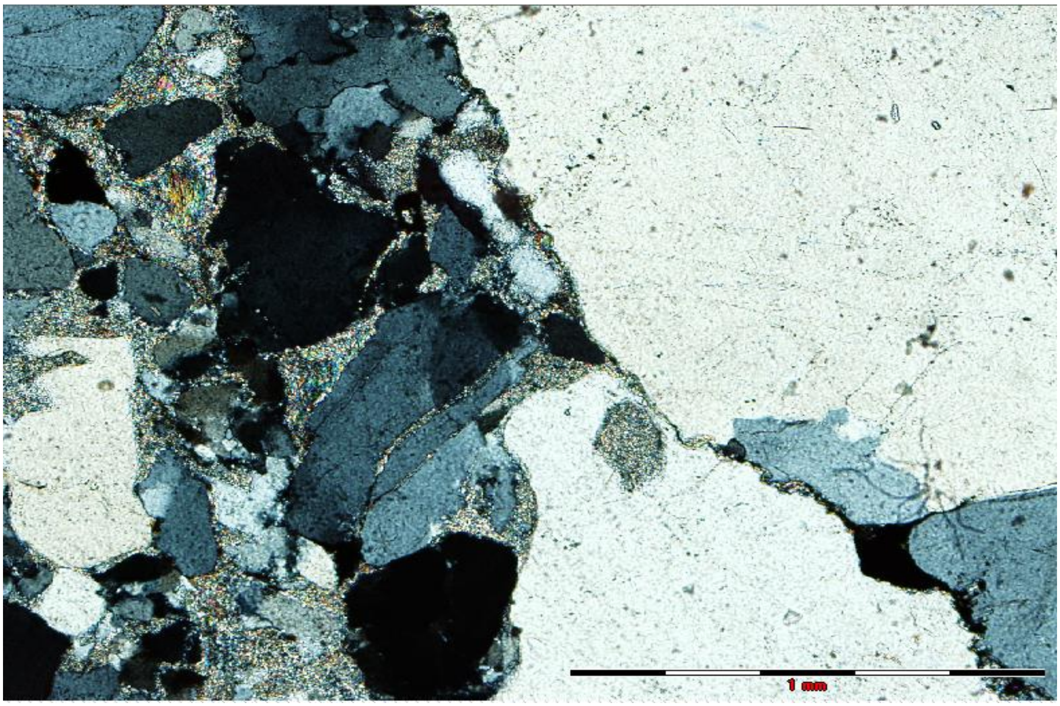


Figure 9.4: Photomicrograph showing pore filling and pore lining clay matrix.

Kaolinite

Kaolinite occurs as pore filling and lining clay mineral and also occurs as a common replacement mineral (Figure 9.5). Microscope observations of kaolinite show as white or white-greyish crystallite filling the pore spaces among the grains. SEM observations show that kaolinite occurs as pore filling aggregates which appear as booklet in crystalline shape and also known as stacked pseudo-hexagonal crystallites or plates (Figure 9.6). This kaolinite clay is formed mainly during early diagenesis and its formation is linked to continental felsic igneous rock source and is dependent on availability of acidic medium. Thus, the presence of altered K-feldspar, muscovite act as sources of silica and aluminum to form kaolinite.

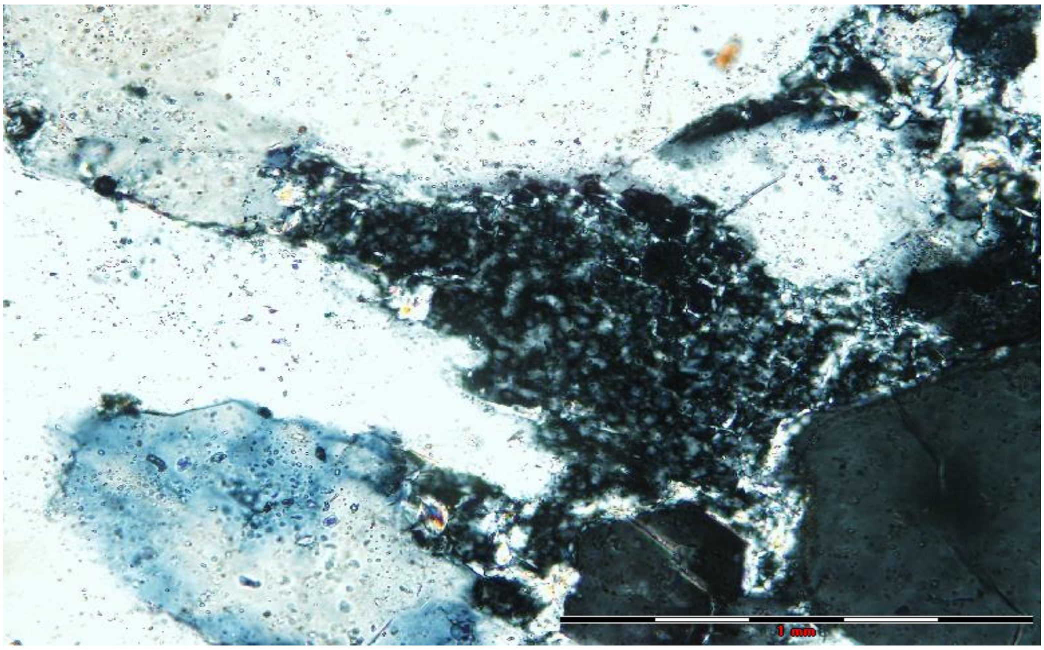


Figure 9.5: Photomicrograph showing the fine crystalline texture of kaolinite in between quartz grains. First grade of black and white interference colour and fine flakes in shape characterize the kaolinite clay.

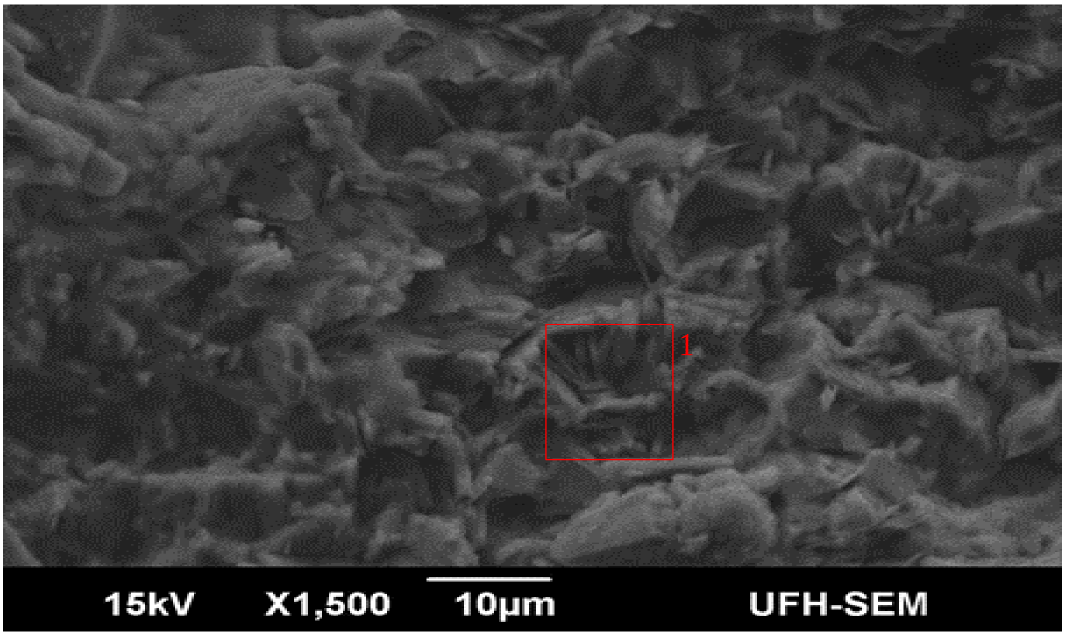


Figure 9.6: SEM photomicrograph showing booklet-like morphology of kaolinite (red area) and smectite clays (sample M15).

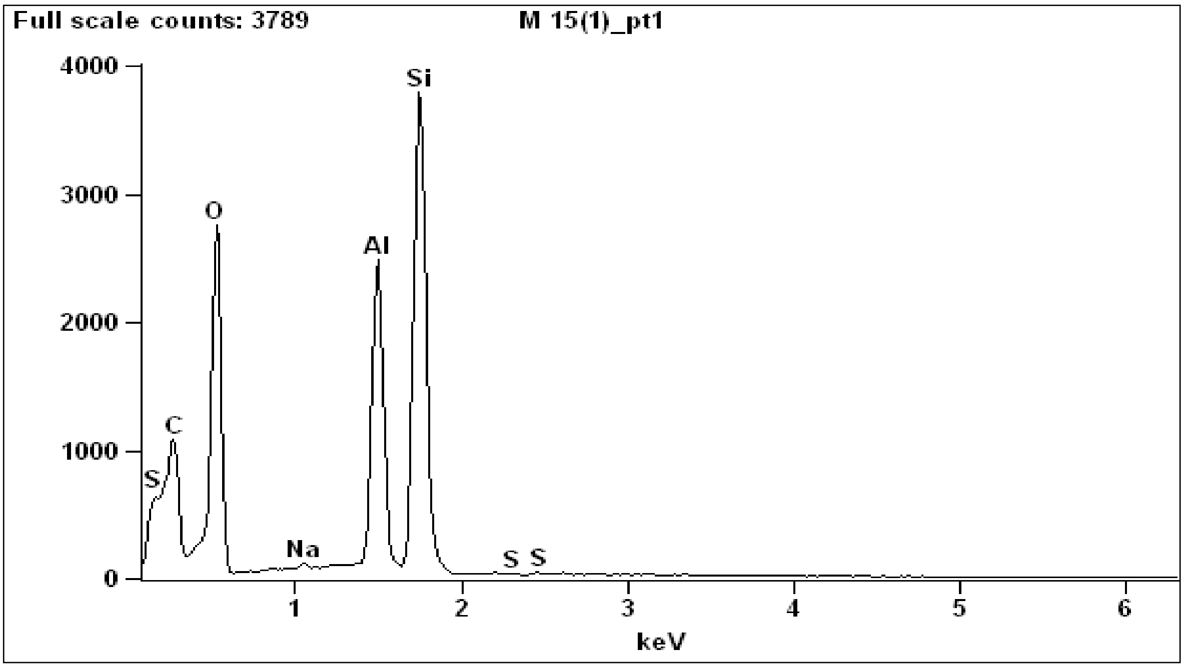


Figure 9.7: Scanning Electronic Microscope (SEM) and Energy-Dispersive X-ray (EDX) analysis of kaolinite (sample M15).

Smectite clay

On SEM analysis, smectite clay appears to have a cornflake-shaped texture and sometimes appears to have ragged-platy morphology (Figure 9.8). Smectite is the only mineral that can be transformed to illite through the process of illitization. According to Pollastro (1985) for smectite to be converted to illite, it is necessary that K^+ must be added in the interlayer space and the amount of tetrahedral Al^{3+} must be increased. Thus the reaction is expressed as follows:

$$\text{Smectite} + Al^{3+} + K^{+} = \text{Illite} + Si^{4+}$$

Thus the released silica is believed to form at least in part of quartz cement for the Msikaba Formation, and the Fe and Mg (Figure 9.8) are believed to form as part of reaction products that are more stable under the increased burial temperature conditions.

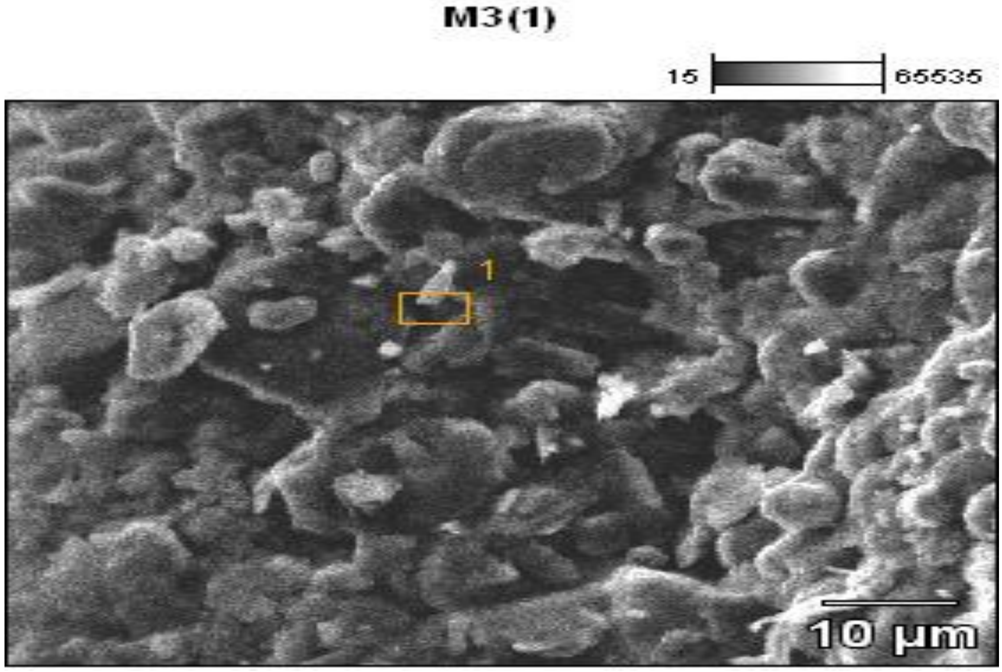


Figure 9.8: SEM photomicrograph showing smectite clay in the Margate area (Sample M3).

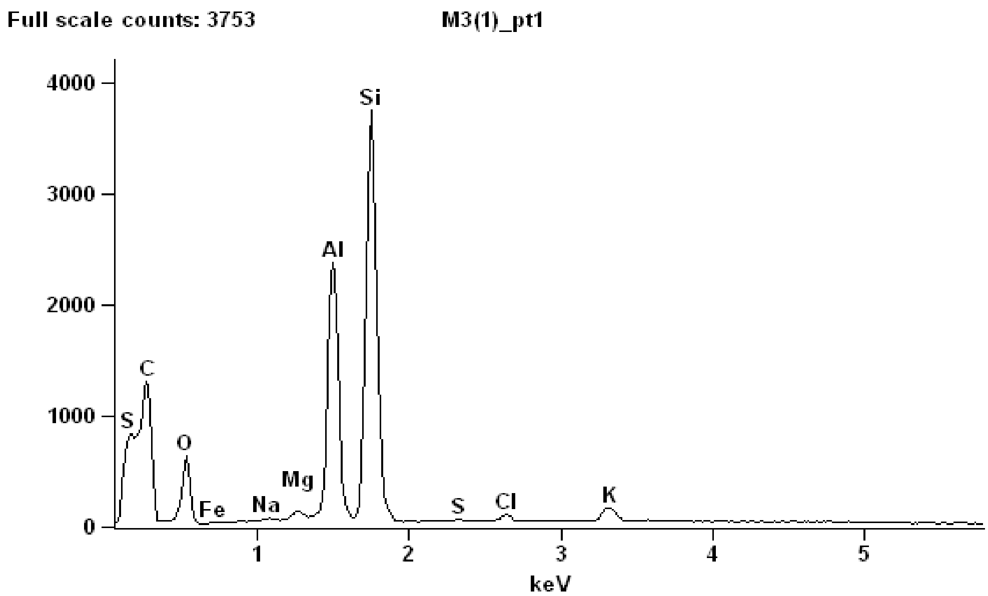


Figure 9.9: SEM and Energy-Dispersive X-ray (EDX) analysis of sample M3 from the Margate area.

Illite clay

Illite is an authigenetic pore-filling clay mineral that is represented by platelets and are arranged vertically onto the grain surfaces by SEM analysis (Figure 9.10). Illite is usually formed in the shallow burial diagenetic stage under increased temperature and requires a growth medium (pores space) with high potassium (K), silica (Si) and aluminum (Al) compositions.

Illite/smectite mixed layer is a common pore lining and pore-filling clay that occurs frequently in the Msikaba Formation sandstone and is formed later than silica cementation. It occurs during shallow burial diagenesis. Authigenesis of illite and kaolinite clays depend on the alteration of feldspars and other labile detrital minerals that easily weathered and require alkaline (illite) and acidic (kaolinite) pore fluid.

The requirement of potassium element for illitization could be supplied by weathered or dissolved feldspars and kaolinite. The SEM in combination with the Energy Dispersive X-ray (EDX) analyses not only provide the morphology of the clay minerals but also provide the chemical composition of the clay minerals. The EDX graph shows that silica and aluminum are the main chemical compositions with small amounts of potassium, iron and magnesium elements in the mineral (Figure 9.9), which is matched the chemical formula of illite of $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$. Thus, the occurrence of illite or illite/smectite mixed layers lies solely on the transformation/conversion of smectite clay mineral during shallow burial diagenetic process at increased temperatures between 90 and 130 degree Celsius (Pallandro, 1985).

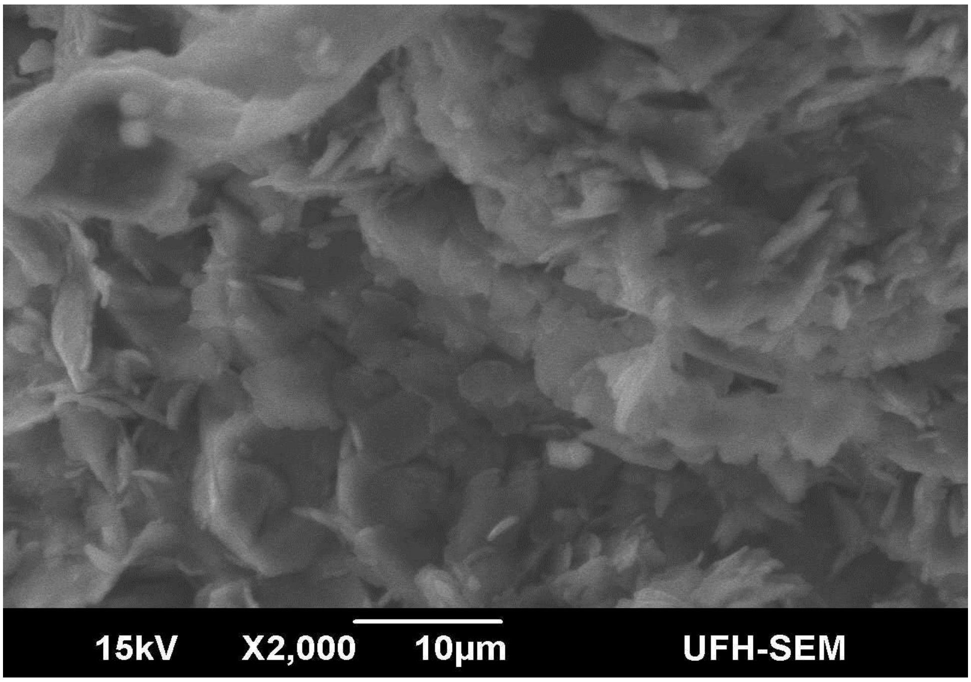


Figure 9.10: SEM photomicrograph showing fabric shaped illite and honeybox shaped smectite of mixed layer in the Port Edward area (Sample P6).

Quartz cement

Diagenetic quartz cement occurs through precipitation of silica into the pore spaces between grains. It occurs as pore-filling cement and as overgrowth. The pore filling cement is formed authigenetically in situ from pore-fluids and not from detrital grains. This type of cement was formed early in shallow marine depositional environment and represents early diagenetic process. The quartz overgrowths are also called syntaxial overgrowth that surrounds or partially surrounds the original detrital grain growing outwardly from detrital grain surface, i.e. forms an optically continuous crystal (Nichol, 2009). Separating the overgrowth and the detrital grain is a brownish hematite rim and are commonly lined with an iron coating. Quartz overgrowths are common in the Msikaba Formation and they have the same optical character as the original detrital quartz grains. The pore filling silica cement is prevalent throughout the quartz arenite sandstone, filling pore spaces was observed in the grain supported quarts arenite and not in the matrix supported wacke sandstones which is matrix rich (Figure 9.11).

The abundance of these overgrowths shows textural maturity of the quartz arenite sandstones. The dominant quartz mineral in the rock can be identified by microscopy and X-Ray Diffraction as shown in the Figure 9.12.

Occasionally isopachous quartz cement is seen as a non- syntaxial quartz rim cement, but it is rare and is found around monocrystalline quartz grains. Thin section observations show a uniform overgrowth fringe around the monocrystalline grains. It is bright and fibrous shaped and likely to have precipitated directly from silica-rich pore fluid.

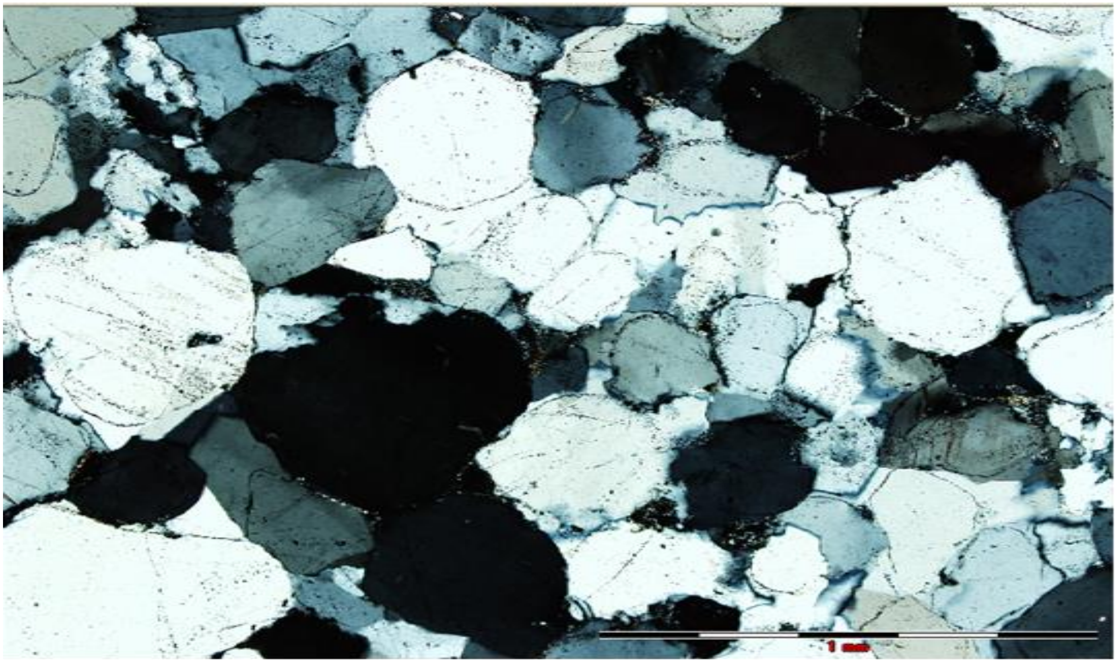


Figure 9.11: Photomicrograph of quartz arenite sandstone showing quartz cement.

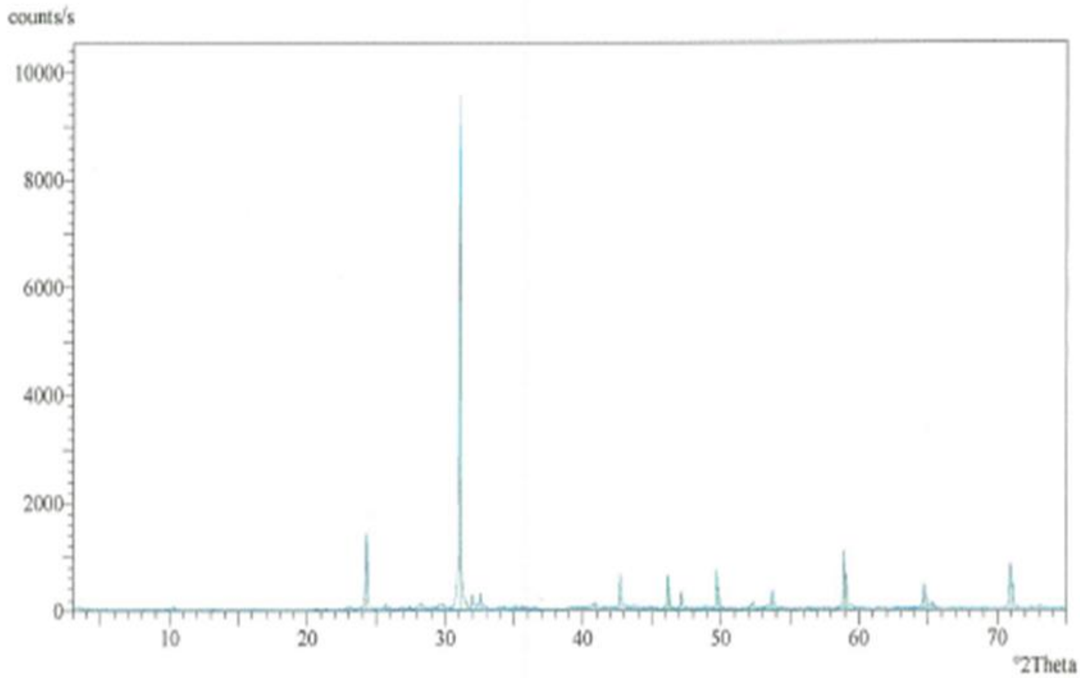


Figure 9.12: XRD photomicrograph showing dominant quartz mineral by the peak at 31^{o}.

Feldspar cement

Feldspar cement is not as common as quartz cement in the study areas and occurs as pore-filling feldspar or as feldspar overgrowths around detrital potassium feldspar grains. It had been seen in the fluvial arkosic arenite and rare in the marine quartz arenite sandstones in the Msikaba Formation. The feldspar overgrowth show hematite rims (dust rim) (Figure 9.13) around the original detrital grain. Feldspar overgrowths acts as an authigenic feldspar pore-filling cement and represents an early diagenetic mineral. Most of feldspar syntaxial overgrowths are accompanied by quartz overgrowths, but they were formed in different diagenetic stages. This diagenetic cement is formed prior to the quartz cement hence it is surrounded by quartz cement, but it is formed later than the hematite cement.

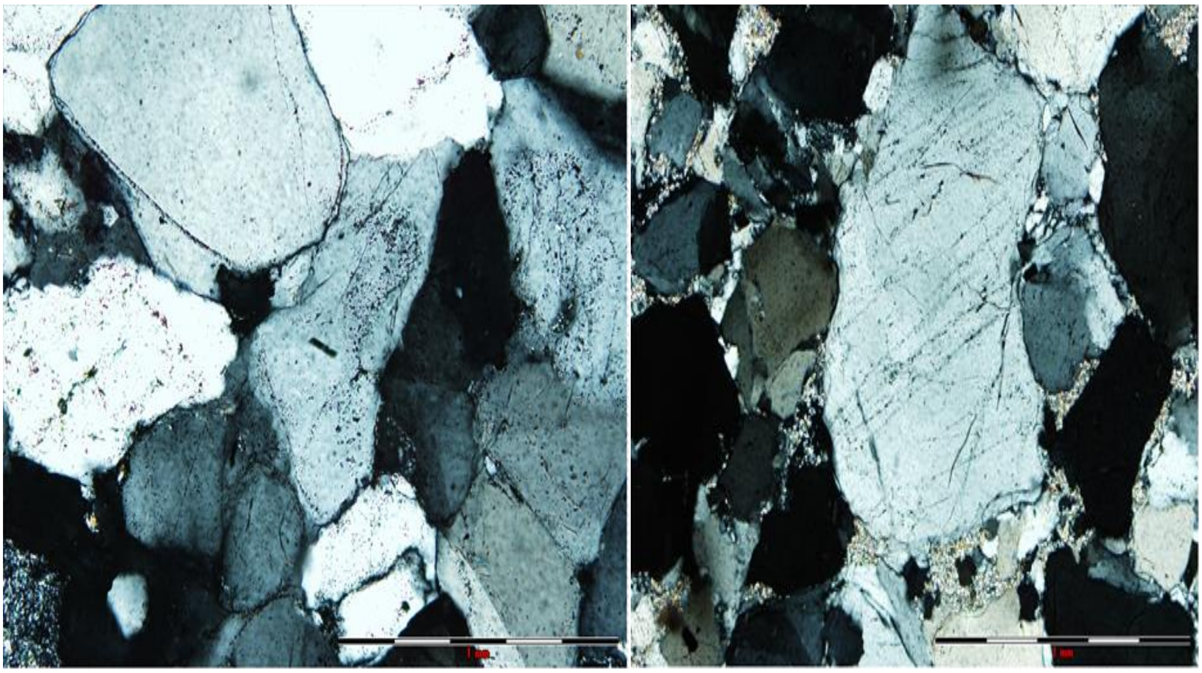


Figure 9.13: Photomicrograph shows feldspar overgrowths and the feldspar was partially altered to cloudy grain (left) with perthitic texture (right). The overgrowth part has optically continuity with the original detrital feldspar grain.

Hematite cement

Hematite is an iron oxide of authigenic mineral that is abundant in the Msikaba formation. It is recognized for its red-brownish staining colour, and it stains the detrital grains and clay minerals with a red brownish colour. This iron oxide appears as pore-filling material or as rims around detrital grains and acts as a grain coating and pore-filling cement in the pore spaces (Figure 9.14). Furthermore, the hematite cement distributes along stylolites (Figure 9.15) which was developed by pressure solution process during burial diagenesis. Hematite cement is formed much earlier than feldspar and quartz overgrowth in the Msikaba Formation, abundant biotite and other iron-bearing minerals might be the source of iron for the formation of hematite cement in the Msikaba Formation. To some extent, hematite cement is much prevalent in the Manaba Member and Shelly Beach Member which are rich of arkosic sandstone and mudstone and originated from fluvial depositional environment.

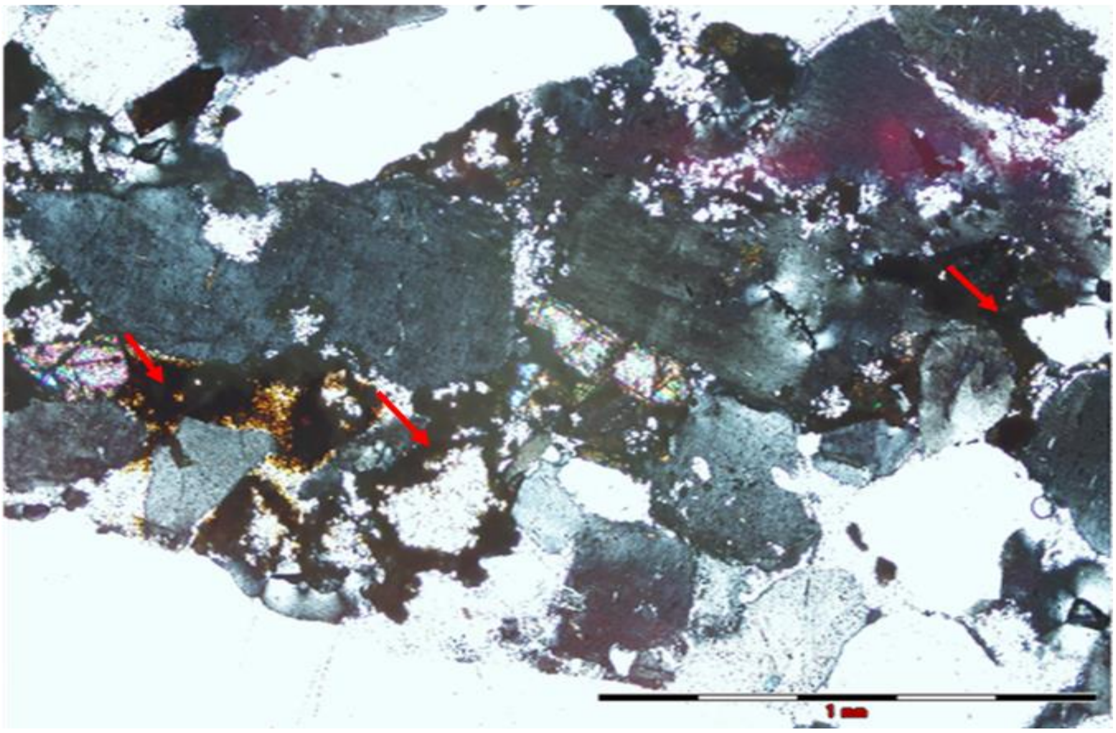


Figure 9.14: Photomicrographs of sandstone with pore filling hematite cement (red arrows).

Figure 9.15: Photomicrographs showing mudstone with hematite pellets (dark area) and hematite also fills secondary stylolite fracture (middle).

8.2.3 Dissolution

Dissolution is a very common diagenetic process in Msikaba Formation. Dissolution serves as a precursor for recrystallization and replacement and provide silica source for quartz cement and quartz overgrowths (Figure 9.16) which have been observed in the sandstone. The overgrowths are separated from the original grain by brownish iron rims or dust seams. Pettijohn (1987) indicated that dissolution process during compaction contributes to alteration of smectite to illite under conditions of deep burial as water is removed from the intergranular spaces.

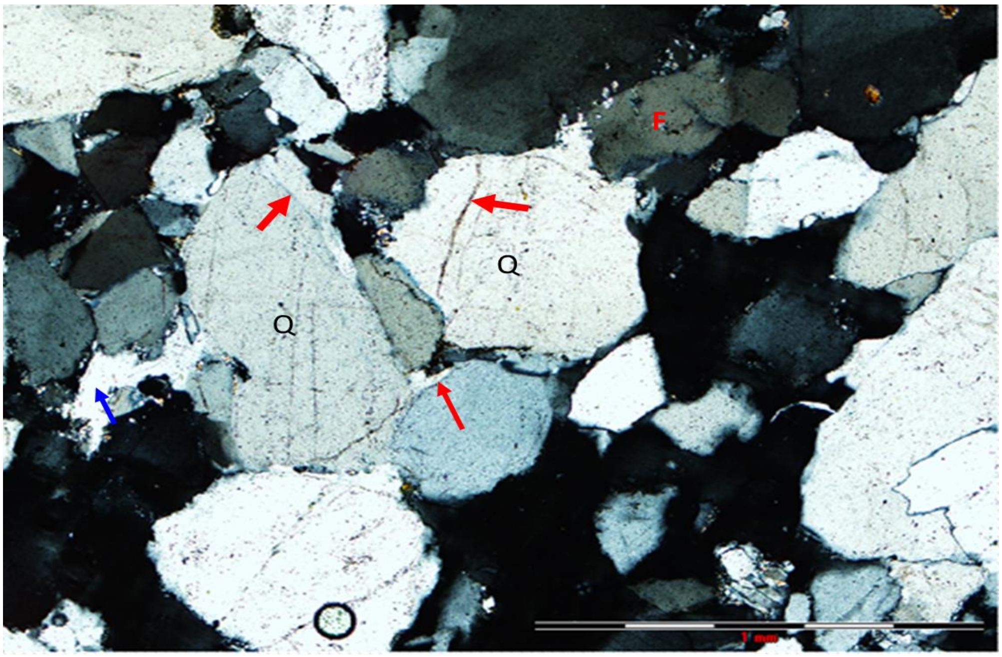


Figure 9.16: Photomicrograph of sandstone showing quartz overgrowths (red arrows) and silica cement (blue arrow).

8.2.4 Replacement

Replacement is a fairly common diagenetic process that is usually happened in the late diagenetic stage and change the unstable minerals to a more stable minerals in diagenetic processes. Replacement is a term used when a mineral or a group of minerals have been replaced by a new mineral with different chemical composition. The replacement texture observed in the Msikaba Formation is plagioclase feldspar grains that have gone through albitization (Figure 9.17). Calcium feldspar albitization is commonly associated with dissolution pores and along cleavage and twins. It also involves replacement of potassium feldspars with albite (sodium feldspar). Albitization process usually occurs during late diagenesis at deeper burial environment. K-feldspar grains are also commonly altered by sericite (Figure 9.18). The sericite grains appear as scattered fine flakes along cleavage planes or on the entire feldspar grain. Another common replacement signature of feldspars is replacement by clay minerals such as kaolinite and illite, which changes the granular feldspar into fibrous kaolinite and illite.

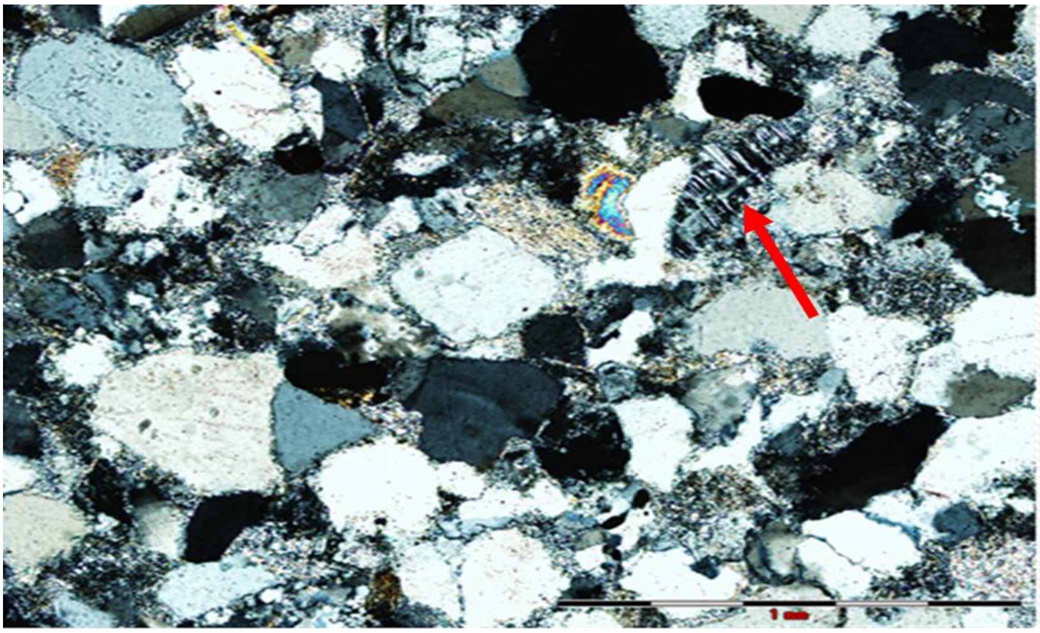


Figure 9.17: Photomicrograph of sandstone showing albitization of feldspar grain (red arrow).

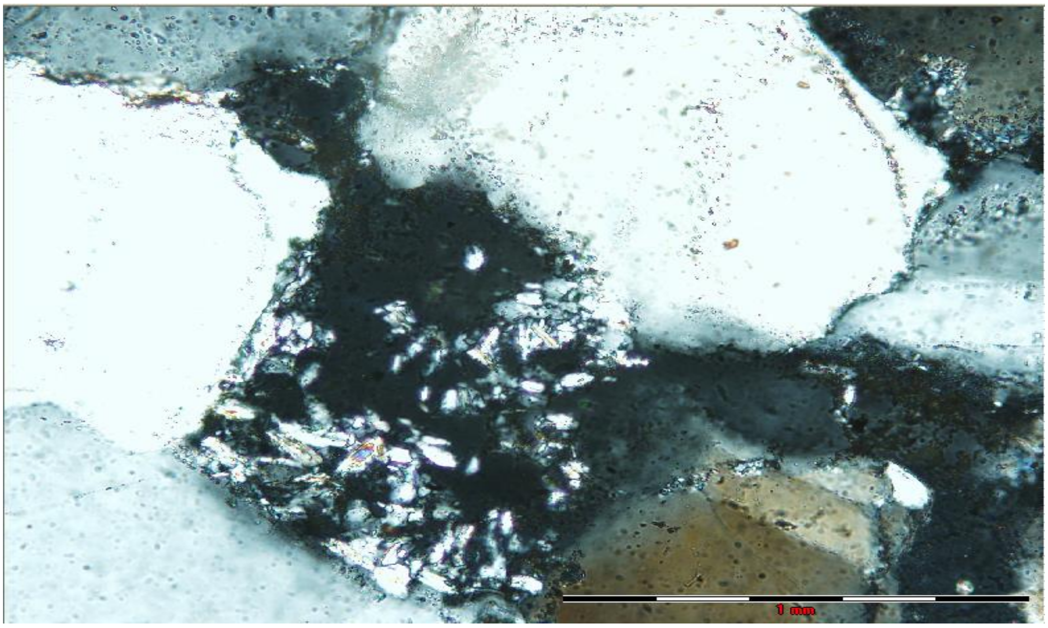


Figure 9.18: Photomicrograph of sandstone showing replacement of feldspar grain by sericite in XPL.

9.2.5 Mineral overgrowth

The quartz and feldspar overgrowths in Msikaba Formation are products of both recrystallization and cementation. The mineral has not been changed but there are changes in the shape and size of a mineral. After overgrowth, the anhedral shaped quartz and feldspar grains become more euhedral shaped. Comparing feldspar overgrowth (Figure 9.19), quartz overgrowth is more common and much developed (Figures 9.20). Quartz and feldspar overgrowths are due to burial diagenesis, and it was a result of temperature increase after sediments were buried into deep underground.

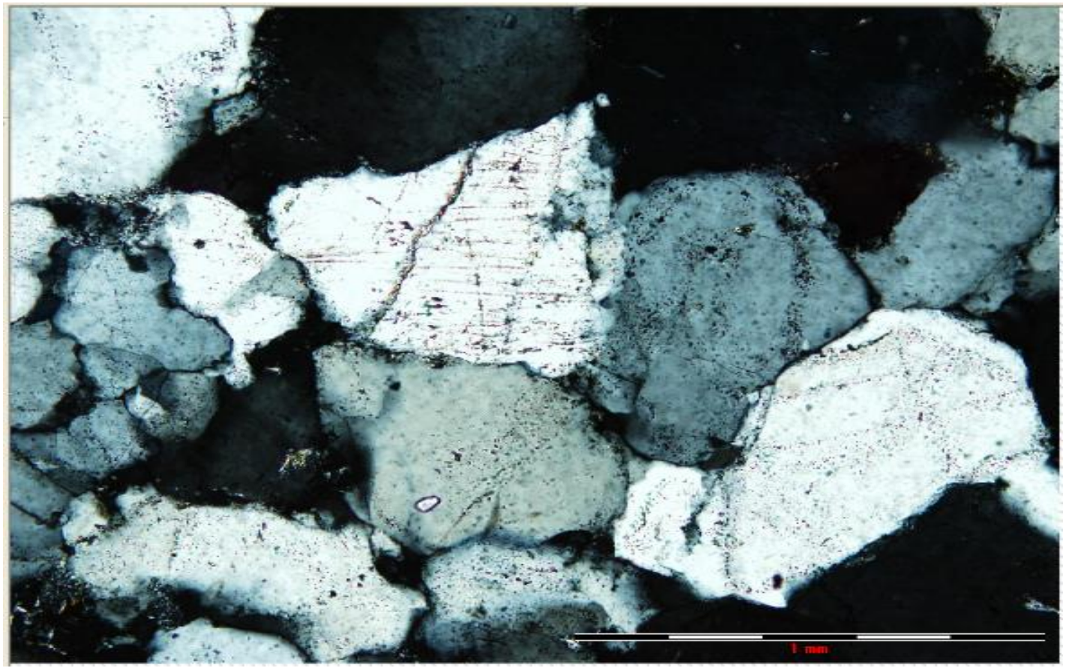


Figure 9.19: Photomicrograph of sandstone showing feldspar overgrowth from the Margate section.

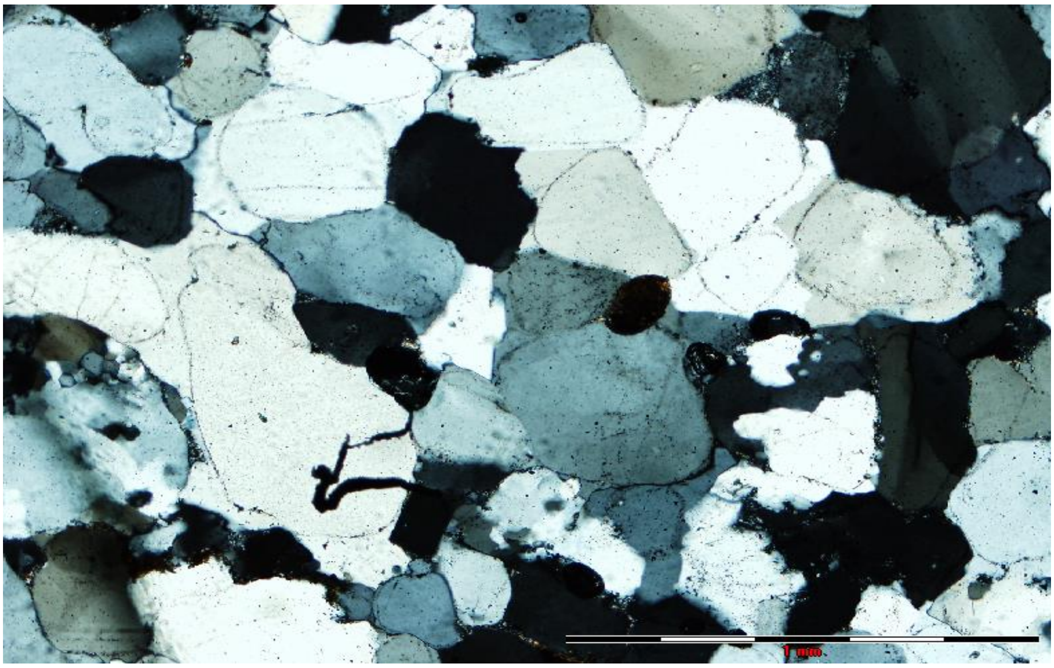


Figure 9.20: Photomicrograph of sandstone showing quartz overgrowth from the Margate section.

9.2.5 Recrystallization

Mineral recrystallization is a common phenomenon in the Msikaba Formation, which is shown by smectite clay minerals gradually change from fine flakes to medium and coarse flakes, and also shown by gradually change from smectite to illite, sericite (Figure 9.20) and finally to muscovite (Figure 9.21) with gradually increase of temperature and pressure due to increase burial depth. The clay matrix gradually changes from smectite to illite through a process of illitization. Further, detrital grains, such as quartz and feldspar have also been observed gradually recrystallized and increase their crystalline size. Through progressive recrystallization, the crystalline grain size is increased, which will reduce the pore space between grains and reduce both porosity and permeability of a rock.

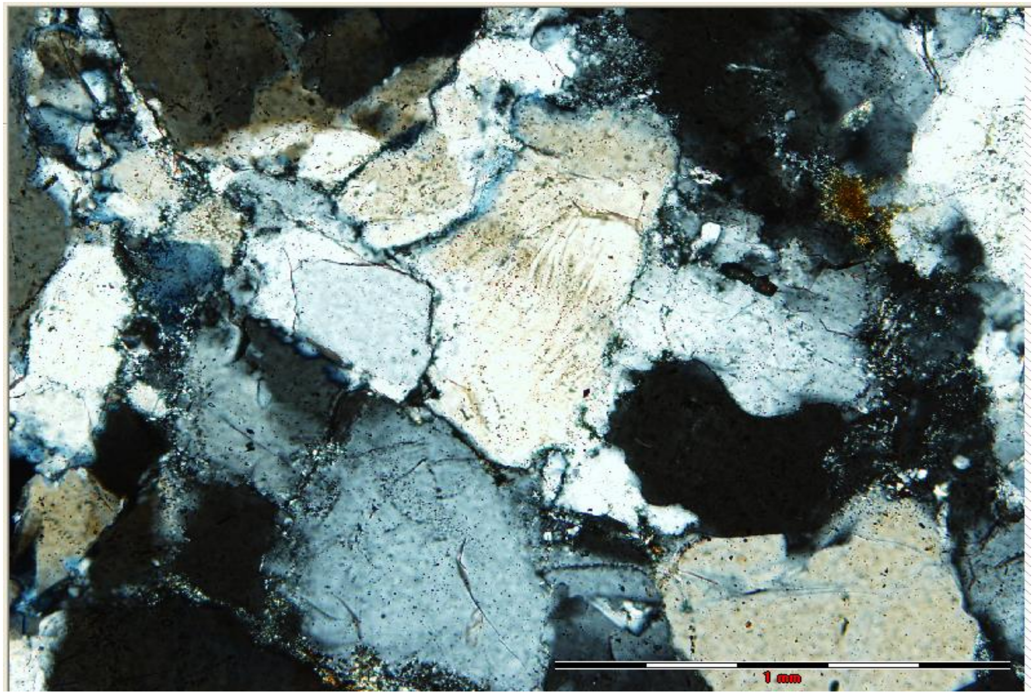


Figure 9.21: Photomicrograph showing recrystallization of clay to sericite (yellow crystals).

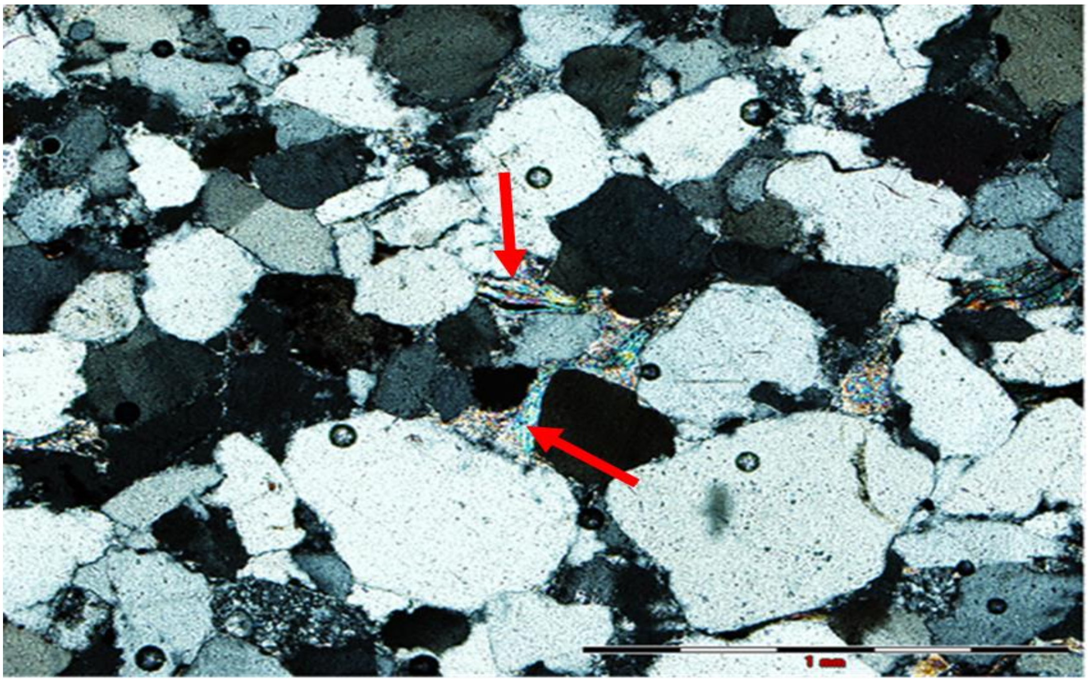
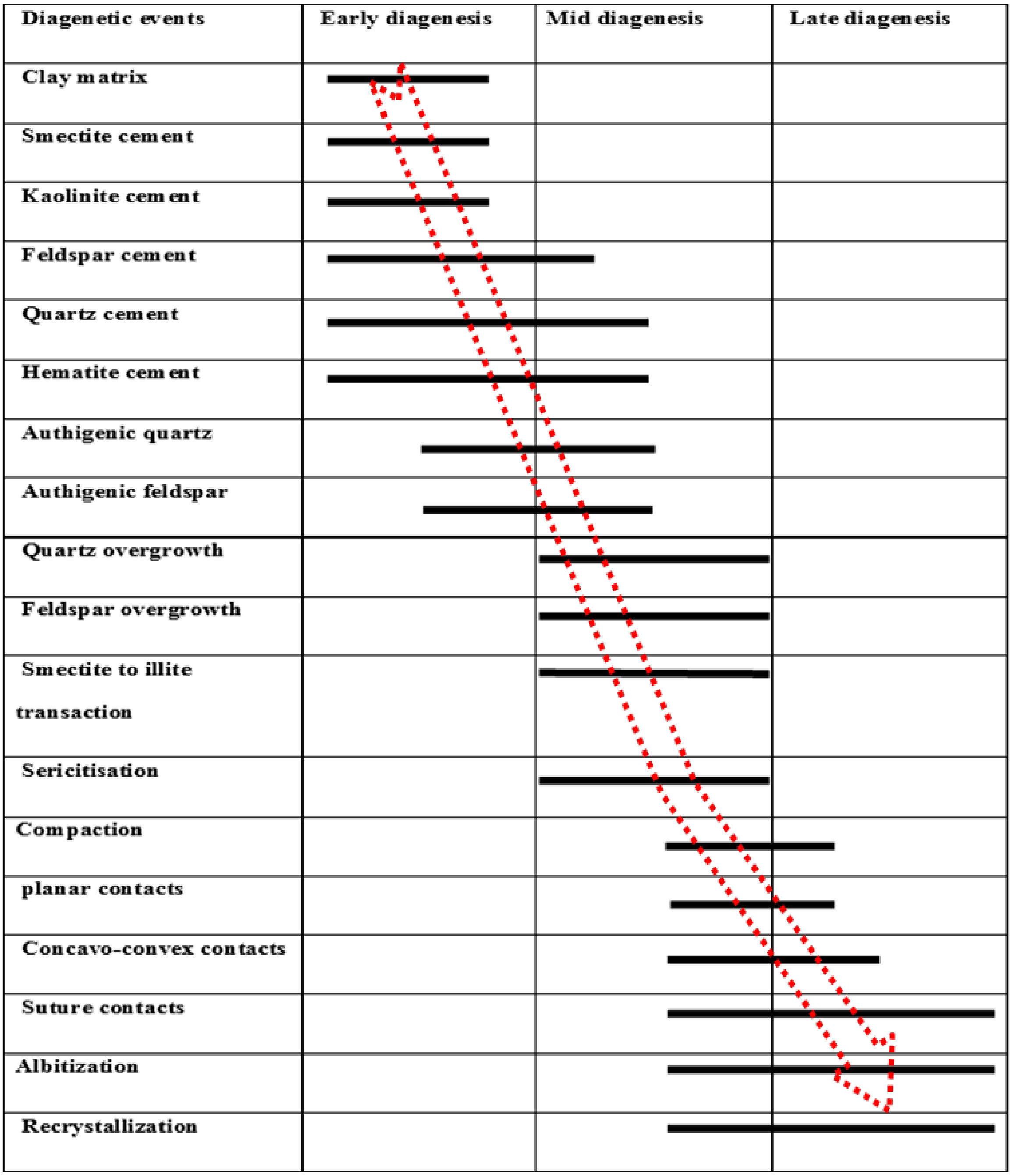


Figure 9.22: Photomicrograph showing recrystallized clay matrix into muscovite (muscovitisation) (red arrows).

9.3 Diagenetic sequence

Diagenetic sequence or pathway is the continuous processes of diagenetic changes which were happened in sediments during the geological time. It is deduced from all the diagenetic events and arranged these events on the basis of the formation time. Thus, the table/diagram of diagenetic sequence can show all the activities of diagenesis of a specific sedimentary sequence and their relative formation time and the relationship among the different events.

Table 9.1: Diagenetic events and pathway of the Msikaba Formation.



Early diagenesis

Early diagenesis is the stage of soft sediments becomes a hard rock after sediments were deposited. Mechanical compaction starts to influence the soft sediments when it was buried by overloading deposits and results in reduction of pore spaces. Cementation is almost immediately begun and precipitation of different type of cement initiated. The clay matrix was the first precipitated minerals in the pore-spaces between framework detrital grains; cements such as authigenic kaolinite and smectite are the second group of cement which were formed in the Msikaba Formation. Hematite, quartz and feldspar cement or overgrowth then precipitated as the third group of cements. Coating of quartz and feldspar grains with reddish brown hematite rims also formed in the early diagenetic stage through iron oxide rich pore-water. In summary, the early diagenetic processes were characterised by matrix and cement precipitation and the soft sediments became hard rocks through compaction and cementation.

Mid diagenesis

Mid diagenesis was started when the sediments were become shallow buried. The sediments were in a transection process from soft sediments became hard rocks, but it was still not in a fully hard state. Subsequently, quartz overgrowth, feldspar overgrowth, smectite to illite transaction, and sericitisation were the dominant diagenetic changes in the mid-diagenetic stage. Meantime, authigenic minerals, such as authigenic illite, quartz and feldspar could be occurred during the mid-diagenetic stage. Detrital grains started to pack more tightly, the contact styles changed from point contact to long plane contact and to convex-concave contact. Mineral recrystallization also started and fine crystals recrystallized to medium or coarse crystalline grains. Following the progressive burial, porosity and permeability of the rocks reduced drastically.

Late diagenesis

Late diagenetic stage is controlled by recrystallization, dissolution, replacement and over-compaction processes in deep burial environment. According to Liu (2002), the deep burial diagenetic environment poses higher temperature and pressure, thus mineral chemical and thermodynamic changes become prevalent. Consequently, recrystallization increased crystalline size of grains and cements from medium to course grained. Replacement of feldspar by calcite is common, and muscovite flakes became bent and deformed due to over compaction. Well-developed quartz overgrowths continue from mid diagenetic stage to late diagenetic stage, and fractured quartz grains and other detrital lithic grains appeared in the strata. After deep buried, grain contact patterns changed from convex-concave contact to suture contact due to pressure dissolution, and over compaction easily caused grain fracturing especially of quartz grains and grain deformation of detrital muscovite flakes.

Albitization of K- or Ca-feldspar was observed in the Msikaba, which was controlled by the stability of different types of feldspar grains and the pore water composition with higher sodium ions (Na^+) present within a deep reducing environment. Na-feldspar (albite) is more stable compared to Ca- or K-feldspar in a higher temperature deep burial environment.

The sericitisation of clay could be further recrystallized to muscovite flakes in a deep burial environment, this may have accompanied with the conversion of K-feldspar to Na-feldspar (albitization) (Que and Allen, 1996).

Petrography and diagenesis research of the Msikaba Formation indicates that most of the lithology and diagenetic processes in the Margate area are similar to the Port Edward area. But there are also some differences probably due to sedimentary facies change. The comparison of diagenetic events between Margate and Port Edward areas are list in the Table 9.2.

Table 9.2: Comparison of diagenetic events between Margate and Port Edward areas.

	Margate Area	**Port Edward Area**
Sandstone classification	Sub-arkose, feldspathic litharenite and quartz arenite	Quartz arenite
Diagenetic processes		
Compaction	Intense	Intense
Feldspar cementation	Minor	Minor
Quartz cementation	Moderate to major overgrowths	Major overgrowths
Smectite cement	common	common
Kaolinite cement	Very common	minor
Hematite cement	Major	minor
Pressure solution grain contacts	Abundant long, concavo-convex and sutured contact	Abundant concavo-convex and sutured contact
Albitization	Minor	Minor
Sericitization	From clay and feldspar minerals	From clay and feldspar minerals
Muscovite content	Minor (fine)	Major (coarse)
Recrystallization	Major	Major

CHAPTER 10: DISCUSSION AND CONCLUSIONS

The Msikaba Formation shows major differences with the Natal Group and Cape Supergroup in the lithology, stratigraphic sequence, sedimentary structures, facies system, palaeocurrent styles, fossil contents and depositional environments.

The Natal Group consists mainly of immature clastic sediments, dominantly red-brownish arkosic sandstone and mudstone which represent fluvial deposition (Marshall, 1994, Kingsley, 1975). The facies of this group include Massive pebble conglomerate, reddish coarse arkose-subarkose sandstone, red-brownish siltstone and mudstone and intercalated minor white quartz-arenite facies. Whereas the Msikaba Formation is dominantly consists of white or light coloured mature quartz arenite, with minor red-brownish sub-arkose and very rare red mudstone. The Cape Supergroup has been strongly metamorphosed and dominated by quartz arenite without arkosic sandstone in the strata. These characteristics show remarkable differences among the Msikaba Formation, Natal Group and the Cape Supergroup. A northeast to southwest palaeocurrent trend of the Natal Group confirmed by Marshall (1994), Liu and Cooper (1998) and Marshall and von Brunn (1999) shows unimodal palaeocurrent direction, whereas the Msikaba Formation shows bimodal palaeocurrent directions of tidal environment with ebb and flow currents. Bimodal palaeocurrent direction is usually not presented in fluvial sedimentation.

Up to date, there was no fossil had been found in the Natal Group, whereas branching lycopsid stem, Planolites, and Scolicia (trace fossil) had been found in the Msikaba Formation (Kingsley and Marshall, 2009). Furthermore, body and trace fossils have also been found in the upper stratigraphic section of the Cape Supergroup, including marine fossils of Skolithos, fresh-water fish and plant fossils in the Witteberg Formation (Shone and Booth et al., 2004), which are different with the fossils found in the Msikaba Formation.

From the lithological features, sedimentary structures and facies, clearly show that the Natal Group was deposited in a braided fluvial environment, whereas the Msikaba Formation was deposited in a higher energy tidal environment and the Cape Supergroup was mainly deposited in a shallow marine continental shelf environment (Tankard et al., 1982 and Broquet, 1992).

The age of the Natal Group was estimated as 490 Ma (Thomas at al., 1992), which is Early Ordovician deposits; whereas the Msikaba Formation has been found overlying on the Natal Group (Hicks, 2010) and considered as Late Devonian in age (Kinsley, 1975; Kingsley and Marshall, 2009; SACS, 1980). Thus, the Msikaba Formation is correlated with the Witteberg Group of the Cape Supergroup which is composed of quarzitic sandstone and shale and was deposited during the Devonian Period (Rust, 1973; SACS, 1980; Shone and Booth, 2005). Therefore, cannot be correlated with the Natal Group, Thus, Msikaba Formation forms a separate, younger stratigraphic unit, and but could be correlated to the Witteberg Group, the top of the Cape Supergroup.

The main aim of this project was to put much emphasis to the stratigraphy and sedimentology aspects of the Msikaba Formation. The study has provided new insight and some detailed information for the study of the Msikaba Formation. Through this study, the following conclusions are drawn:-

The Msikaba Formation is a later Devonian deposit and is composed of brownish conglomerate in the bottom and white-greyish quartz arenite sequence in the middle and mixed quartz-arenite with feldspathic sandstone in the upper sequence. The total stratigraphic section attains a thickness of 184 m at Margate area and 185 m at Port Edward area. The stratigraphy of Msikaba Formation can be divided into 4 members, i.e. the Manaba Conglomerate Member, Uvongo Sandstone Member, Mhlangeni Grit Member and Shelly Feldspathic Beach Member from bottom upward. The Manaba Member is dominant by braided fluvial sediments, the Uvongo Member represents high energy tidal channel and tidal flat deposits; whereas the Mhlangeni Member represents shallow marine continental shelf deposits and the Shelly Beach Member represents mixed marine and fluvial deposits.

Twelve sedimentary facies were identified: Eleven sedimentary facies were identified, i.e. the Matrix supported conglomerate facies (Gmm), Clast supported conglomerate (Gcm), Medium bedded sandstone facies (Sm), Trough cross-bedded quartz-arenite facies (St), Tabular cross-bedded quartz arenite facies (Sp), Herring-bone cross-bedded quartz arenite facies (Shb), Ripple marks sandstone facies (Sr), Lenticular bedded quartz arenite facies (Sl), Horizontal bedded quartz arenite facies (Sh), Low-angle cross-bedded quartz arenite facies (Sl), Siltstone lithofacies (Fslt) and Laminated mudstone facies (Fl). These sedimentary facies can be integrated into 4 facies associations: Facies Association 1 consists of (Gmm+Sm) facies representing braided fluvial deposits; Facies Association 2 consists of (Gcm+St+Sp+Shb) facies represents tidal channel and tidal flat deposits; Facies Association 3 consists of (Sl+Sh+Sr+Slc) facies represents shallow marine continental shelf deposits and the Facies Association 4 consists of (Sm+Sp+Sl+Fslt) facies and represents mixed marine and fluvial deposits. Each facies association constitutes a specific stratigraphic unit and was deposited in a specific depositional environment.

Grain size analysis shows that the sandstone grain size parameters of mean, sorting, skewness and kurtosis fall under the average of 0.75, 0.78, 0.4 and 1.2φ respectively. The results show that most of the grain size are medium to coarse grained and the sorting of the sandstones is mostly moderate to poorly sorted. The cumulative frequency diagrams and bivariate plots show positive skewness and negative kurtosis, which indicate a high energy depositional environment.

Petrography study and modal composition analysis show that detrital components of the Msikaba Formation are dominated by monocrystalline quartz, feldspar (mostly K-feldspar) and lithic fragments. The sandstones could be classified as quartz arenite, sub-arkosic sandstone (Pettijohn, 1975) and feldspathic litharenite (Folk, 1980).; and the provenance analysis indicates that the sandstones were derived from craton interior, recycled or quartzose recycled sources (Dickinson at el., 1983) which may derived from weathering and erosion of igneous and metamorphic rocks. K-feldspar grains are more abundant than plagioclase also indicates from felsic granitic source and recycled sedimentary rocks (Dickinson, 1988, Basu at el., 1975). Lithic fragments include chert, shale, schist and quartzite grains had been found in the sequence. Muscovite is pervasive throughout the formation, especially in the Port Edward area.

Diagenetic processes of the Msikaba Formation have passed through early, mid- and late diagenetic stages. Cementation, mineral conversion and compaction affect early diagenetic stage; authigenic minerals, quartz and feldspar overgrowth are presented in mid-diagenetic stage, whereas recrystallization, replacement, deformation and dissolution have been strongly affected late diagenetic stage. Microscopy, XRD and SEM-EDX studies have identified five types of cements including smectite clay, kaolinite, hematite, quartz and feldspar cements. Quartz cement, pore-filling and pore-lining clay are the major types of cements in the Msikaba Formation.

The sequence stratigraphy of Msikaba Formation constitutes a transgressive sequence from Manaba Member to Uvongo Member, whereas it ended as a regressive sequence from Mhlangeni Member to Shelly beach Member.

There are two stratigraphic sequences that are recognized in the Msikaba Formation: (1) A transgressive sequence from fluvial deposits of the Manaba Member to marine deposits of the Uvongo Member; and (2) A regressive sequence from marine deposits of the Mhlangeni Member to mixed marine and fluvial deposits of the Shelly Beach Member. The whole Msikaba Formation thus constitutes a full complete sequence from transgression to regression process.

The overall depositional environment of the Msikaba Formation is interpreted to be a braided fluvial deposits with immature FA 1 deposits for the Manaba Member, which is located in the bottom of the Msikaba Formation. The depositional process shifted to beach and tidal environment as a result of marine transgression, and left the pure, high mature quartz arenite in FA 2 deposits of the Uvongo Member. The marine incursion was continuous to the deposition of the Mhlangeni Member, which still kept the marine environment and probably became slightly deeper from beach and tide environment changed to continental shelf environment represented by FA 3 deposits. The Shelly Beach Member consisting of FA 4 shows an intermixture of shallow marine and fluvial deposits, and represents marine water started to retreat.

The Msikaba Formation shows major differences with the Natal Group and the Cape Supergroup in the lithology, stratigraphic sequence, sedimentary structures, facies system, palaeocurrent styles, fossil contents and depositional environments, which demonstrate that they are not the equivalent stratigraphic unit, and the Msikaba Formation is a separate, younger stratigraphic unit, and can’t correlate with the Natal Group, but could be correlated to the Witteberg Group, the top of the Cape Supergroup.

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