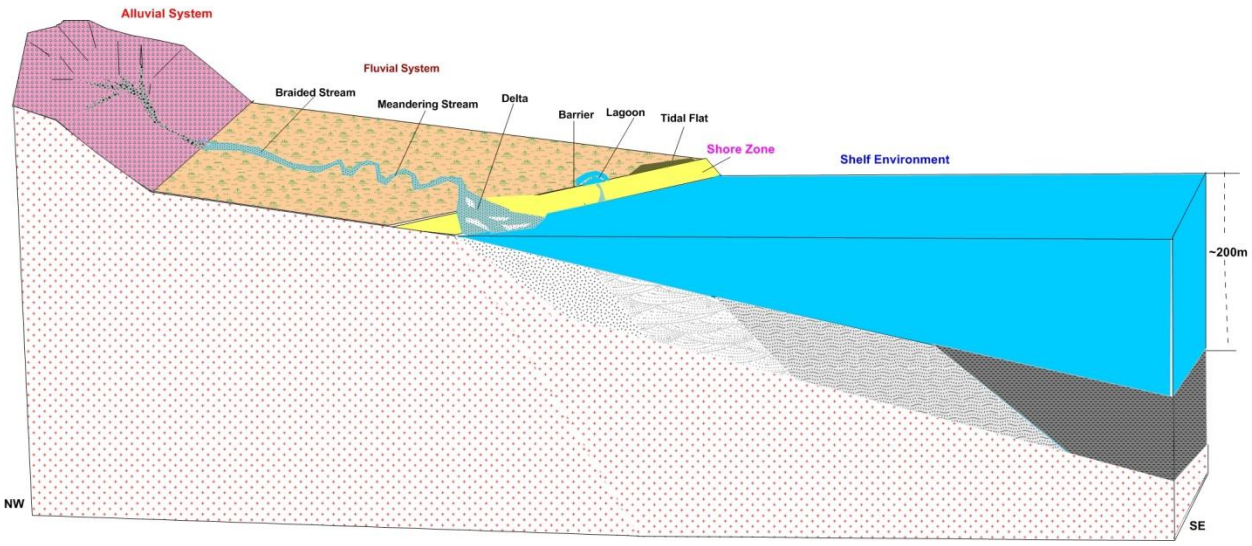
ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL SCIENCES

SCHOOL OF EARTH SCIENCES

PALEOENVIRONMENTAL RECONSTRUCTION OF THE ADIGRAT SANDSTONE FORMATION AROUND DIRE DAWA AREA, SOUTHEAST ETHIOPIA

By: DAMENU ADEFRIS NEGESSU



"A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIEES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF EARTH SCIENCE IN STRATIGRAPHY & SEDIMENTOLOGY"

Jun-2014

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THIS THESIS IS MY ORIGINAL WORK AND HAS NOT BEEN PRESENTED FOR A DEGREE IN ANY OTHER UNIVERSITY AND ALL SOURCES OF MATERIAL USED FOR THE THESIS HAVE BEEN DULY ACKNOWLEDED

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ABSTRACT

The Adigrat Sandstone Formation of southeastern Ethiopia was not previously studied independently from the other Mesozoic sedimentary units. Its environment of deposition has been inferred as braided stream from regional studies with limited data. The present research work has tried to study this unit in more detail to reconstruct paleoenvironment (depositional processes and environments) that led for the formation of this sandstone unit. The data used in this study are mainly field data such as lithology, color, sedimentary structures, textures, composition and trace fossils together with petrographic analysis of thin-sections. Using these field data and laboratory results thirteen facies types have been identified and interpreted. These facies types are: poorly sorted massive pebbly sandstone facies, poorly sorted medium grained massive sandstone, trough cross-bedded fine sandstone facies, greenish color massive mudstone facies, brownish yellow shale-dolomite-gypsum unit, herringbone cross-stratified fine sandstone facies, hummocky cross-stratified fine sandstone, slightly bioturbated normal graded sandstone, intensively bioturbated fine-medium grained sandstone, horizontally laminated fine grained sandstone, massive and well sorted quartz rich sandstone, calcareous sandstone and sandy limestone. From these, related facies types have been grouped together by which four facies associations are established and interpreted in terms of depositional environments. These are: meandering stream, shore zone clastic, lagoonal-tidal flat and shallow marine mixed carbonate & clastic facies associations from bottom to top respectively. The depositional environment and the subsequent sediment accumulation for the Adigrat Sandstone Unit of southeastern Ethiopia could have a close relationship with the Late Triassic-Early Jurassic paleogeography of Eastern Africa and to the sea level fluctuation related to the Gondwana breakup. Based on datings on the Adigrat Sandstone in more northern locations of Ethiopia and by considering the age of the top part of the presently studied unit, the sea level fluctuation responsible could be that of Norian-Callovian time. Accordingly, southeast facing and gradually subsiding marginal environment is the probable depositional site for this unit.

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ACRONYMS

Sm= Sandstone, massive

Sl= Sandstone, laminated

Sr= Sandstone, ripples

St= Sandstone, trough cross-bedded

Sp= Sandstone, planar cross-bedded

Fm= Mud- fine sandstone, massive

Gm= Gravel, massive

Shu= Sandstone, hummocky

Sbt= Sandstone, bioturbated

Pc= Gypsum, very thin-stratified

CH= Cannel

F= Facies

C= Cement

Qm= Quartz, monocrystalline

Qp= Quartz, polycrystalline

Plc= Plagioclase

M= Matrix

Mc= Microcline

Ms= Muscovite

Zr= Zircon

Ls= Lithic, sedimentary

HST= Highstand System Tract

LST= Lowstand System Tract

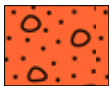
TST= Transgressive System Tract

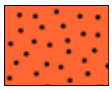
FM=Forset Microform

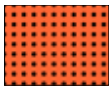
SB=Sand Bedform

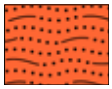
LS=Laminated Sand sheet

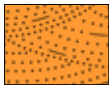
LITHOLOGICAL SYMBOLS

 Pebbly Sandstone

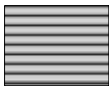
 Massive Sandstone

 Laminated Sandstone

 Sandstone, Hummocky

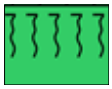
 Sandstone, trough-herringbone

 Sandstone, planar-trough

 Shale

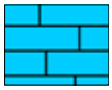
 Gypsum-Shale

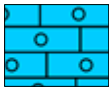
 Mudstone, massive

 Mudstone, burrowed

 Dolomite

 Calcareous Sandstone/Sandy limestone

 Limestone

 Oolitic-Peloidal limestone

1. INTRODUCTION

1.1 LOCATION, ACCESSIBILITY AND GEOGRAPHY OF THE STUDY AREA

The study area is located within the Oromia regional state specifically within the East Hararge Zone (Figure: 1 below). Geographically, the study area is part of the southeastern plateau of Ethiopia which comprises both lowland and highland areas dominated by various geographic features such as mountains, ridges, valleys, gorges and flatland areas. Elevation is variable within the study area caused by the irregularity of the local topography which reaches up to 1300 meter above sea level around Dire Dawa city whereas the highest elevation is about 2300 meter above sea level around Dengego, Kersa and Lange areas within which the studied sections are found. The mountains and highest ridges are mostly outcrops of limestone and sandstone units occasionally covered by Tertiary volcanic rocks. Exposure of the basement rocks is commonly encountered along incised valleys and mountain bottoms. On the other hand most of the lowland areas are covered by Quaternary deposits used as farmland by the local community. The settlement style of the community is following these lowland areas and their farmland is covered by 'Chat' plantation which is considered as the most important part of their income. Widespread ephemeral streams are available and their route is developed following local valleys and gorges. The study area has also variable rainfall distributions and temperature ranges throughout the year with two common rainfall seasons (i.e. Belg and Kiremt). Around Diredawa area the rainfall in the Belg season is about 253.3 mm whereas that of the Kiremt is 310.2 mm with 636.0 mm annual rainfall and the temperature range is in between 21.8 C° and 28.7 C° throughout the year with mean annual temperature of 25.3 C° (Ethiopian Meteorological Agency, 2013) .

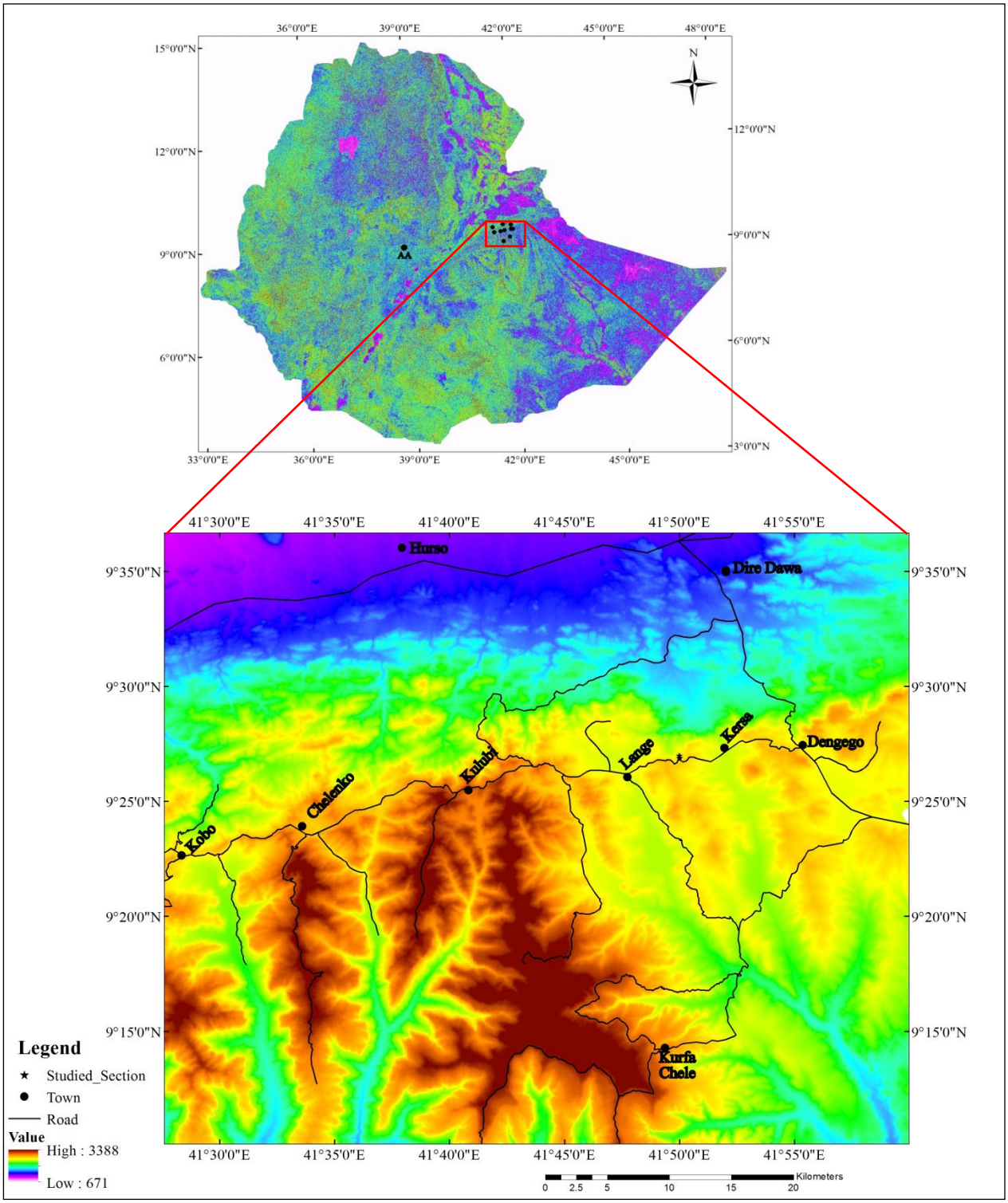


Figure 1: DEM extracted from SRTM showing the physiography and location of the study area and its surroundings

1.1 PROBLEM STATEMENT

Sedimentary rocks are archives of Earth history as they record various physical, chemical and biological processes operating on the surface of the Earth. Therefore, a close examination and analysis of these rocks and their characteristics reflects the past historical evolution of the Earth and they serve as fundamental tools for paleoenvironmental reconstructions. However, many of the published works that have been done on Ethiopian sedimentary succession are more general and focused on the general stratigraphy of a particular basin. More specifically, Adigrat Sandstone Formation of Ethiopia is not studied independently in terms of depositional environment except few studies done particularly in Abay and Mekele basins (e.g Wolela, 2008, Dawit and Busert, 2009 and Dawit, 2010). The Mesozoic succession of southeastern part of Ethiopia is also little known especially the lower sandstone unit/Adigrat Sandstone has not been studied independently in that its depositional environment has been interpreted from regional studies. In recent years, Bosellini et al. (2001) conducted investigation on the Mesozoic succession of Dire Dawa area and came up with a generalized stratigraphy. More detailed study is required and has to be done to address the scarcity of paleoenvironmental researches which have enormous applications in broad areas of sciences and disciplines thereby the present research study is intended to reconstruct paleoenvironments for the Early Jurassic Adigrat Sandstone Formation of Dire Dawa area in terms of depositional conditions and environments.

1.3 PREVIOUS WORKS

Some researchers have made study and description on the Adigrat Sandstone of Ethiopia at different localities (Ogaden, Blue Nile and Mekele basins including Dire Dawa and Harar areas) at different times and put their generous contribution for the present and future researchers. Among these, the works of Worku and Astin (1992), Bosellini et al. (2001), Tadesse and Hailemariam (2006), Gani et al. (2008), Wolela (2008), Dawit and Bussert (2009) and Dawit (2010) are the most recent works some of which contain new findings and interpretations relative to previous studies conducted by other researchers (e.g. Dawit, 2010).

According to Worku and Astin (1992), the Adigrat Sandstone Formation of the Ogaden basin has been studied in detail and subdivided into six facies types. These are massive to poorly stratified pebble conglomerate, tabular cross-bedded conglomerate, cross bedded sandstone, massive to

parallel laminated sandstone, finely laminated sandstone and massive-thinly laminated siltstone and this rock unit is interpreted as braided to meandering river deposit.

Gani et al. (2008) tried to study the stratigraphic and structural evolution of the Blue Nile basin in which they identified a repetitive fining upward facies changes overlain by a grayish green glauconitic sandy mudstone within the lower sandstone unit. Each individual fining upward cycle starts with erosional surface at the base overlain by very coarse sediments (lags). They also identified horizontal stratification, ripple cross lamination, large scale trough cross beddings, lateral accretion surfaces, mudcracks and vertebrate tracks. Therefore, based on the above facies characteristics, this rock unit is interpreted as fluvial channel deposit.

In the same year, Wolela (2008) carried out much more detailed study by which the Adigrat Sandstone Formation in the Blue Nile basin has been subdivided into six major facies based on sedimentary structures, grain size and lithofacies association as mudstone, finely laminated siltstone, very fine-grained cross-bedded sandstone, coarse to medium-grained sandstone, massive to crudely cross-bedded gravely sandstone and massive to crudely-bedded Conglomerate. Then, by considering the overall characteristics of this rock unit, its environment of deposition is interpreted as being a mixture of alluvial fan, meandering river and lacustrine deposits. The poorly-sorted massive to crudely-bedded conglomerates and gravely sandstone are interpreted as alluvial fan deposits, the coarse to medium-grained sandstone bodies were deposited by high bed-load meandering fluviatile systems and the presence of carbonaceous sediments (carbonaceous mudstones, carbonaceous claystones, carbonaceous shales and coal seams) suggests reducing environment, possibly a lacustrine depositional environment.

On the other hand a more recent and detailed study also conducted by Dawit and Bussert (2009) and the unit has been subdivided into a number of different lithofacies types together with the interpretations of their specific depositional environments. After the analysis of different facies and their association, these authors generalized their interpretation into two broad depositional environments for the Adigrat Sandstone Formation of the Blue Nile basin based on facies stacking patterns, presence of tidal influence indicators and ichnofacies distributions. These are: Incised-Valley-Estuarine System and Barrier-Beach-Strand Plain System. Finally, they concluded differently from the previous researchers in that Adigrat Sandstone Formation of the Blue Nile basin is the result of deposition in estuarine and shallow marine environments as a

result of Jurassic transgression over northeast facing passive continental margin during the onset of seafloor spreading and regional subsidence. They also identified onlap relationship of the Adigrat Sandstone with the underlying pre-Adigrat clastic deposit which serves as evidence for the prevailing transgression event. In the same year these authors interpreted the depositional environments of the Adigrat Sandstone of the Northern Ethiopia as it includes both continental and shallow marine environments within intracontinental basin forming passive continental margin flanking southeast towards Neotethys. Therefore, this rock is assumed to be formed by transgression event related to basin subsidence.

The most recent study on the Adigrat Sandstone of the Blue Nile and Mekele basins is that of Dawit (2010) in which more emphasis has been given for the stratigraphy, facies, depositional environments and palynological studies. According to this author, six broad classes of depositional systems are identified within the Adigrat Sandstone Unit of the Mekelle basin. These are: fluvial system, fluvio-estuarine system, deltaic system, strandplain system, barrier island–lagoon system, and open-coast tidal flat system. On the other hand, three depositional systems (fluvio-estuarine, barrier-lagoon and strand plain systems) are also identified within the Adigrat Sandstone succession in the Blue Nile basin.

Adigrat Sandstone Unit of the Harar area is also studied by Geological Survey of Ethiopia. Accordingly, Tadesse and Hailemariam (2006) tried to describe this unit and interpret its depositional environment. Their description shows that this rock unit has a fining upward trend of grain size in which very coarse grains are dominant at the base and finer grains at the top which again overlain by mudstone unit. Finally, using the pattern of this succession in combination with sedimentary structures, they have interpreted the depositional environment of the Adigrat Sandstone Unit to be braided stream.

On the other hand, the most recent work around Dire Dawa area is that of Bosellini et al. (2001) which focused on the general Mesozoic stratigraphy and their result shows the following rock units from bottom to top: Adigrat Sandstone, Antalo Limestone, Dire Dawa Formation, Daghani Shale, Gildessa Limestone and Amba Aradam Formation respectively. This study shows that the Adigrat Sandstone Formation of the Dire Dawa area has variable thickness with a maximum thickness of about 100 meter and has a variable extent even entirely absent in some places. The

composition of this rock unit has also been reported as being arkosic and little interpretation has been made about the source of sediment, processes and environments of deposition. According to these authors, this rock unit is considered to be braided deposit and interpreted as fluviatile origin.

1.4 SCOPE OF THE PRESENT STUDY

The primary objective of this research study is to reconstruct paleoenvironments that led the deposition of the Adigrat Sandstone Formation in terms of depositional conditions and environments while the specific objectives are to assess sandstone composition, texture and sedimentary structures, identifying sediment paleoflow directions, construct representative sedimentary logs, interpret different processes and depositional environments based on facies analysis and finally to build a facies model.

1.5 METHODOLOGY

In this study, paleoenvironmental reconstruction for the proposed rock unit has been carried out mainly from field data supported by thin section analysis. The methods that are employed for this research study are: field observation and detailed description of the unit at the outcrop scale, construction of representative sedimentary logs, sample collection and preparation for laboratory analysis, petrographic analysis of major framework constituents of sandstone using point-counting of thin sections and analysis and interpretation of facies and facies associations. Finally, using these data obtained from field such as lithology, textures, sedimentary structures, fossils and geometry (lateral and vertical changes) of the unit in combination with laboratory results, a number of facies have been identified and the unit is subdivided into different facies types. The facies present within the succession were first identified to deduce the depositional processes and environments. After identifying different facies types using these sediment attributes, interpretation of the results have been made in terms of depositional conditions and environments for each facies type or for the combination of facies (facies associations) by comparing with other related works and models proposed by different workers.

1.5.1 FIELD WORK

The fieldwork was conducted by selecting three well exposed outcrop sections named as Section-1, Section-2 and Section-3 which are suitable to clearly observe vertical and lateral facies changes. Preliminary investigation was conducted for searching full sections. Accordingly, the areas along both sides of Dengego-Dire Dawa, Dengego-Adele-Kurfa Chele and Dengego-Kulubi-Kobo main roads were covered as much as possible. However, due to the presence of somewhat clear exposure as well as its convenience and ease of access from major roads to properly collect the required data with the available time and resource, these sections are selected around Kersa town along Kersa-Lange main road and they are also characterized by well exposed cliff forming sandstone at the side of the road-cut. All of these sections were described and logged very well in the field with appropriate descriptions in terms of lithology, composition, thickness, textures, colors and sedimentary structures. 15 representative samples were collected depending on vertical facies changes and sketches were prepared to show the general geometry of the unit and its vertical and horizontal relationship with other units. Photographs were also taken to show the details of the unit even in a centimeter scale.

1.5.2 LABORATORY WORKS

Laboratory work is an essential part of most geological studies so as to confirm field results. Thus, for this study, twelve thin-sections have been prepared from representative samples. The aim of preparing these thin-sections is to make detailed analysis of composition and texture which are important data giving vital information for paleoenvironmental reconstruction in combination with field data recorded at outcrop scale. Different components and textural features have been studied under petrographic microscope for each thin-section. Major framework grains have also been identified and counted from observation of thin-sections and their relative proportions have been determined by using point counting technique.

Then, the relative proportions of these major framework grains (Quartz, Feldspar and Lithic) counted from each thin-section are plotted on a triangular diagram using these major components as the end members to form a ‘Q, F, L’ triangle which is commonly used to make compositional and textural analysis for sandstone classification and naming using the Folk (1980) and Pettijohn et al. (1987) classification schemes. The relative proportions of matrix and cementing materials have also been determined in that the Pettijohn et al. (1987) sandstone classification scheme has been applied using the relative percentages of matrix in addition to major framework grains.

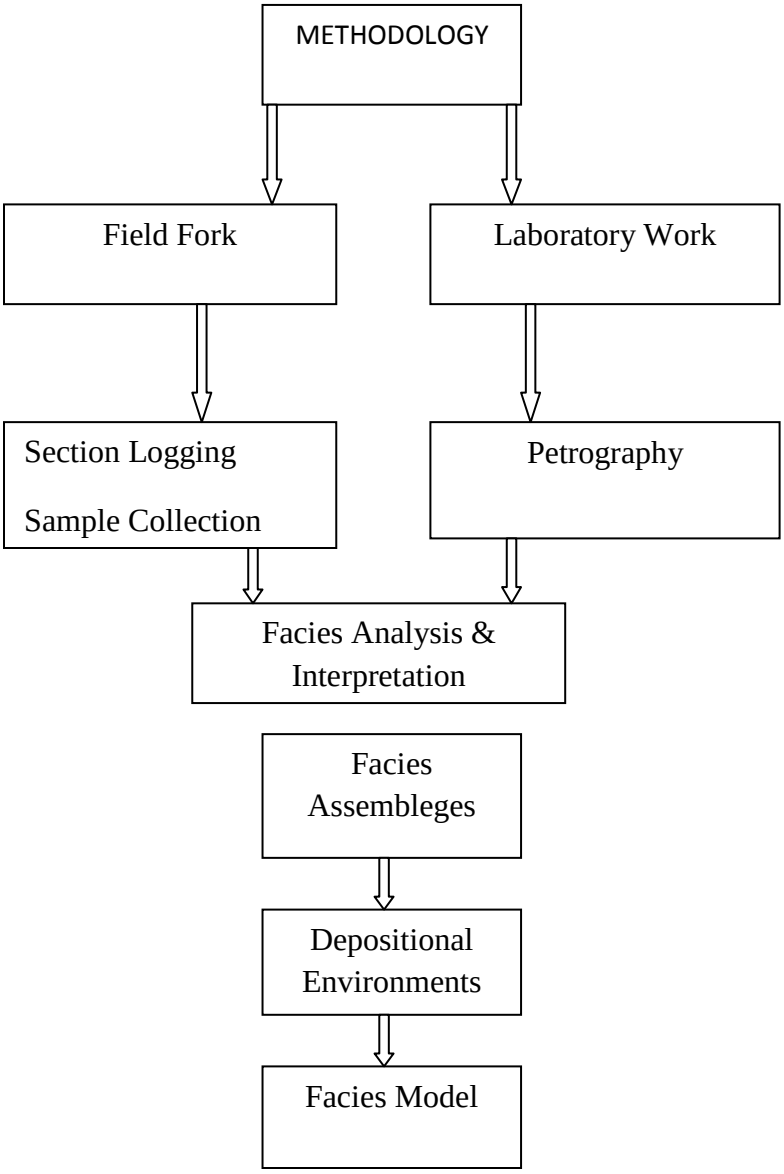


Figure 2: Flow chart summarizing the methodology of the study

1.6 LIMITATIONS OF THE STUDY

The sedimentary succession of southeastern Ethiopia (Dire Dawa & Harar areas) has wider areal coverage in that it needs large number of data from a number of well exposed complete outcrop sections to make environmental reconstruction representing the whole unit. However, because of financial and time constraints, limited number of sections were selected which are close to each other and their selection is due to the presence of somewhat clear exposure as well as its convenience and ease of access from major roads to properly collect the required data with the available time and resource. Accordingly, three well exposed sections (one complete & two incomplete sections with respect to the whole Adigrat Sandstone Unit) were identified and

studied very well to collect the necessary data as much as possible for this study. These sections are found very close to each other separated by a short distance (about 400-500 meter) and their selection was done by considering lateral variations of the unit to observe different features. However, due to the limited number of studied sections and their relative closeness, the result of this study may not be representative of the whole sedimentary unit that represents the overall depositional environment of the unit in this particular basin.

2. REGIONAL GEOLOGY

2.1 TECTONIC EVOLUTION AND SEDIMENTATION

The formation of sedimentary basins is intimately related to plate tectonic processes. In the following section hereunder, plate tectonic scenarios which give insight how the Mesozoic sedimentary basin of Ethiopia developed have been discussed. The start of the sedimentary history of Ethiopia is considered to be Ordovician-Early Mesozoic following the development of north-northeasterly and northwesterly troughs (Assefa, 1991) initiated by Gondwana breakup. As a result of increasing extension and subsidence which causes sea level to rise, marine sedimentation was prevailed in the Early Jurassic following these troughs followed by a regressive phase in Early Cretaceous caused by epeirogenic uplift. This justification given by Assefa (1991) for the development of Mesozoic rift systems and sedimentation history of Ethiopia is highly compatible with the tectonic scenarios and related sedimentation processes discussed by Kazmin (1975), Chatterjee and Scotese (1999), Fairhead (2009), Worku and Astin (1991), Binks and Fairhead (1991), Delvaux (1991), Hankel (1994), Bosellini (1988), Al-Tour (1997) and Coffin and Rabinowitz (1988).

The breakup of Gondwanaland was preceded by a significant phase of intra-continental rifting and sedimentation within the extensive Karoo basins of East and Southern Africa (Binks and Fairhead, 1991) which extends to the Ogaden basin, Ethiopia. These widespread crustal extensions (Karoo riftings) began to develop during the Permo-Triassic (Delvaux, 1991) utilizing the weak zones of the Pan-African mobile belts which surround the cratonic blocks of Southern Africa.

According to Delvaux (1991), East-Africa underwent a period of widespread crustal extension during the Permo-Triassic (Karoo rifting). The Permo-Triassic rifts refer to the development of Karoo grabens which apparently preceded the onset of Gondwana's breakup. The Karoo grabens of the ENE-WSW trend are long elongate basins filled with dominantly clastic, continental sediments. The evolution of these basins is characterized by a tectonically controlled sedimentation in progressively subsiding basins from Late Carboniferous to Middle-Late Triassic or Early Jurassic.

The Early Permian basins developed following N-S trend are coinciding with the present East-African coast and southwestern Madagascar. In coastal parts of Kenya, Tanzania, Mozambique

and also on the west-coast of Madagascar, Karoo basins developed since Early Permian along N-S trend.

According to Hankel (1994), these basins were filled by Permian-Triassic and Early-Middle Jurassic deposits known as pre-drift sediments which contain a relatively complete stratigraphic succession ranging from Late Carboniferous to Middle Triassic with a marked regional unconformity at the Permian-Triassic transition. This is a stage of clastic deposition between earlier rifting and Jurassic seafloor spreading which corresponds to the deposition of basal clastic sediments (Lower Sandstone Unit). Recent palynological studies on the karoo sediments of Madagascar (Sakoa, Sakamena and Isalo Formations) were carried out on outcrop and well sections within Morondava, Majunga and Diego basins for the sake of timing of rifting and sedimentation events. These pre-drift sediments are studied well and dated to be Early Permian-Middle Jurassic in age with major breaks in sedimentation evidenced by the recognition of unconformities. Comparison is also made with equivalent units of Mozambique, Tanzania, Kenya, Ethiopia and Somalia and the result shows correspondence of strata which is important for pre-drift reconstruction of west and east Gondwanas. Chronostratigraphic correlation of the basal clastics overlaying the peneplained basement of Gondwana is also made by Bosellini (1988) which correlates Adigrat Sandstone of Ogaden (Ethiopia) and Mandera Lugh basins (Somalia), Ngerengere beds of Tanzania, Mansa Guda Formation of northeastern Kenya, Mazeras Formation of southern Kenya, Isalo Formation of Madagascar, Kuhlan Sandstone of Yemen and Lathi Formation of western India. Their age is determined to be Triassic-Early Jurassic. The pre-drift sediments of the Ogaden basin were also identified from well data taken across the basin and have been subdivided into four formations (Worku and Astin, 1991). These are Calub Sandstone, Bokh Shale, Gumburo Sandstone and Adigrat Sandstone from the oldest to the youngest respectively. Related Karoo/pre-drift sediments also occur at outcrops in the central and northern parts of Ethiopia although Adigrat Sandstone is much more widely distributed than the other formations and it is assumed to be the product of the last phase of continental sedimentation (Worku and Astin, 1991). According to these authors, the age of this rock unit is also considered to be diachronous being older in the south (Ogaden basin) and becoming younger in the Harar area, Abay basin and Mekele basin respectively to the north.

During the break-up of Gondwana, East African province experienced several stages of extension since the beginning of separation of Madagascar from East Africa during Early

Jurassic. Seafloor spreading between East Africa and Madagascar began about 151-159 Ma (Callovian- Early Oxfordian) which is commonly known as Jurassic Magnetic Quit Zone evidenced from paleomagnetic studies of the oldest oceanic crust flanking Somalia and Madagascar (Bosellini, 1988). This separation led to the relatively N-S movement between Africa and Madagascar and formation of transform fault margin (Davie Fault Zone).

As a result of increasing extension and subsidence, syn-drift sedimentation was favored during Middle Jurassic- Early Cretaceous in which the sediments show general facies shifts from continental to mixed continental-marine during the interval between Toarciian- Early Bajocian in the marginal basins of East Africa, Madagascar and Western Australia (Hankel, 1994). During this phase of seafloor spreading and subsidence, there was sea level rise leading to Jurassic transgression and flooding of East African craton. The flooding of the African continental margin is also considered to correspond with rifting stage, subsidence and eustatic sea-level rise (Tadesse et al., 2002).

According to Kazmin (1975), northwest trending Mesozoic rift systems were formed in Ethiopia due to crustal extension and subsidence which began 225Mya and extend from Ogaden to northern, central and western parts of the country. Due to increasing subsidence, sea level raised and Indian Ocean started transgressing initially over the Ogaden and continued to the northern, central and western parts of the country with the deposition of Sandstone (Adigrat Sandstone) over the peneplained basement rocks and remnants of Paleozoic clastic rocks.

Using well data taken from Shillabo area in the Ogaden basin which show deepening upward facies changes (comprising Gumburo Sandstone, Hamanlei and Urandab Formations from bottom to top) and changes of benthic foraminifera and influx of planktonic microfacies, a linkage has been made by Brassier and Geleta (1993) between these changes and seafloor spreading, regional subsidence and flooding of the East African craton in which much of the carbonate sedimentation took place over the Late Triassic continental Sandstone (Gumburo Sandstone) formed within fracture controlled intra-continental basin.

Hamanlei and Urandab Formations of Somalia and Ogaden, Antalo Limestone of central and northern Ethiopia and Amran Group of Yemen are best examples of shallow-deep water deposits formed during this transgression event (Bosellini, 1988 and Al-Tour, 1997). On the other hand, around Dire Dawa area, Antalo supersequence (Batonian-Oxfordian) and Urandab sequence

(Oxfordian-Kimmeridgian) containing Dire Dawa Formation and Gildesa Shale are also considered to be the results of Jurassic transgression (Bosellini et al., 2001).

Following the cessation of seafloor spreading between East Africa and Madagascar during Early Cretaceous (120 Ma), tectonic deformation was intensified along the basins of rifted and transform margins of East Africa and Madagascar (Coffin and Rabinowitz, 1988). During this time the most important processes were low rate of subsidence and high rate of uplift which produced shallow water condition ultimately leading to the withdrawal of the water from the East African craton. Finally, the prevailing process was deposition of shallowing-up sequence prograding seaward such as Gildessa Limestone and Amba Aradam Formation of Dire Dawa, Gabredarre Formation of Ogaden and Somalia, Amba Aradam Formation of central and northern Ethiopia and Tawilah Group of Yemen.

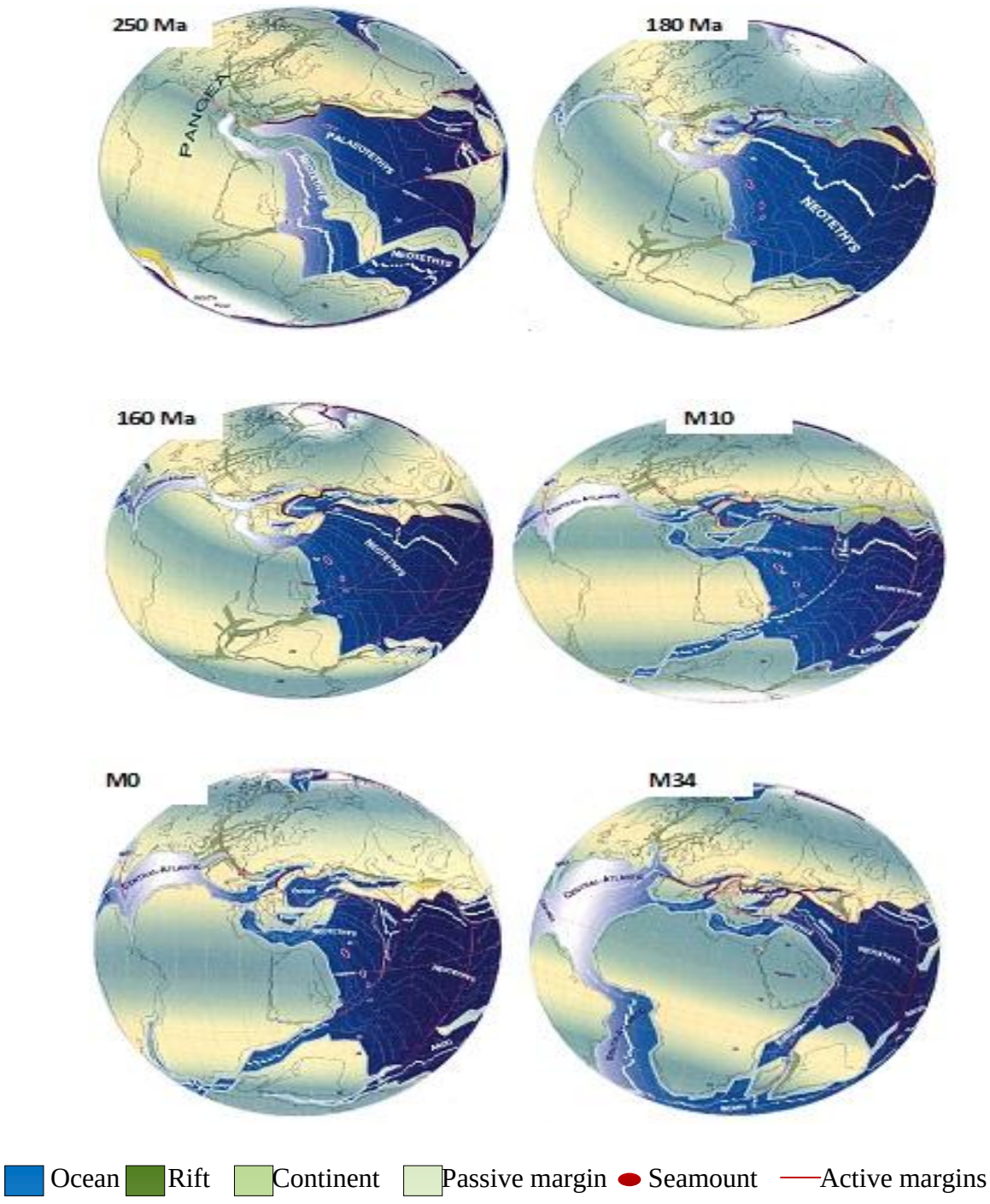


Figure 3: Global paleogeography since 250Ma (Permian-Triassic boundary) –Late Cretaceous (Santonian, M34). (After Stampfli and Borel, 2001).180Ma (Aalenian), 160Ma (Oxfordian, M25), Valanginian(M10) and Aptian(M0). Ma= Million years ago, M=Magnetic polarity chron which represents number of independent magnetic field reversals.

2.2 REGIONAL STRATIGRAPHY

The geology of Ethiopia comprises Precambrian basement rocks, Paleozoic-Mesozoic sedimentary rocks and Tertiary-Quaternary volcanic rocks and sediments (Kazmin, 1973 &1978, Merla, 1973).

The geology of southeastern Ethiopia also comprises Precambrian basement rocks, Paleozoic-Mesozoic sedimentary rocks, Tertiary sediments and volcanics and Quaternary covers (Berhe, 1985, Tadesse and Hailemariam, 2006). The most recent work on the general Mesozoic Stratigraphy of Dire Dawa area is that of Bosellini et al. (2001) which comprises the following units from bottom to top: Adigrat Sandstone, Antalo Limestone, Dire Dawa Formation, Daghani Shale, Gildessa Limestone and Amba Aradam Formation respectively.

A) PRECAMBRIAN BASEMENT ROCKS

The basement rocks of southeastern Ethiopia have been studied and classified as Lower, Middle and Upper complexes (Kazmin, 1973 &1978). The middle and upper complexes are also named as Boye Group and Soka Group respectively (Berhe, 1985). From these, highly metamorphosed Lower-Middle complexes are more common and dominant. The lower complexes comprise high grade biotite and amphibole gneisses with subordinate feldspatic gneisses, calc-silicates and amphibolites whereas the middle complexes comprise psammitic and pelitic metasediments with some subordinate marbles, calc-silicates and amphibole schists.

B) ADIGRAT SANDSTONE

The Lower Sandstone Unit is the clastic deposit unconformably overlies the basement rocks (Kazmin, 1975). This unit is also known as Adigrat Sandston Formation which is Mesozoic in age and contains interbeds of mudstone, siltstone and marl (Tadesse and Hailemariam, 2006). It has also variable thickness from place to place with a maximum thickness of 100 meter (Boselini et al., 2001 and Tadesse and Hailemariam, 2006) with dominantly arkosic in composition. According to these authors, this rock unit is considered to be braided stream deposit and interpreted as fluviatile origin. In some places Paleozoic clastic rocks named as Wauy Sandstone (Berhe, 1985) most probably of Upper Paleozoic in age are also present.

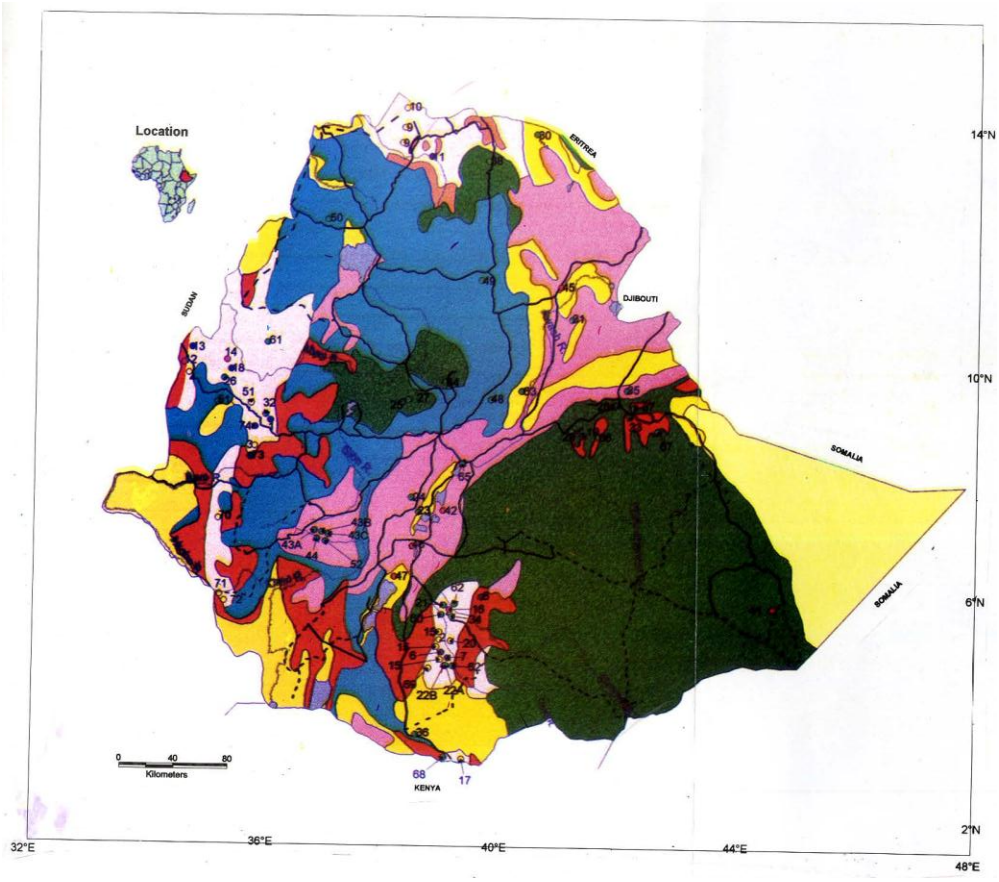




Figure 4: Generalized geological and mineral occurrence map of Ethiopia (After Mengesha et al., 1998)

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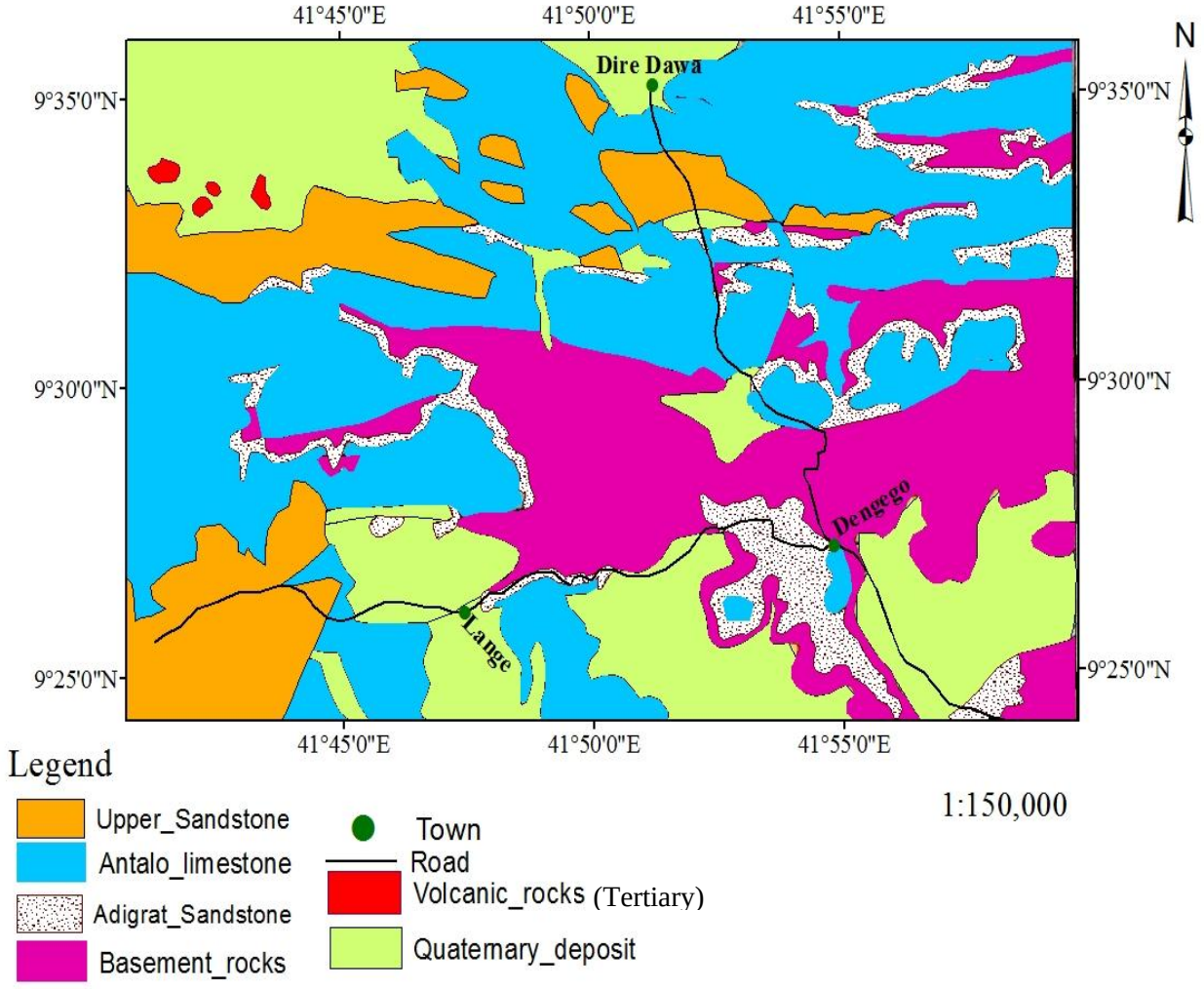


Figure 5: Geological map of Lange, Dengego and Dire Dawa areas extracted from the regional geologic map of Dire Dawa (1:250,000) prepared by Ethiopian Mapping Agency (After Berhe, 1985).

C) ANTALO LIMESTONE

This is very thick carbonate unit (150-350 meter) overlying the Lower Sandstone Unit which has been subdivided in to Lower and Upper Limestone Units/members (Boselini et al., 2001 and Tadesse and Hailemariam, 2006). Three-fold division of this unit was formerly proposed by Greitzer (1970) as Lower Limestone, Upper Limestone and Dogou Limestone. According to Boselini et al. (2001), the lower member is the cyclical portion of the unit with strongly bioturbated dark grey marl and marlstone and a cap of dark grey grainstone while the upper

member is 40-50 meter thick and comprises thick and massive limestone beds with grainstone of skeletal and nonskeletal carbonate grains, laminated in places and cross bedded at the top.

D) DIRE DAWA FORMATION

This is newly named unit by Bosellini et al. (2001) which overlies Antalo Limestone and consists of slightly nodular black-bluish mudstone at the bottom and fine grainstone beds alternate with marly wavy-bedded limestone at the top. Bioturbation is common with calcareous skeletal debris and coral fragments.

E) **DAGHANI SHALE**

Daghani Shale is the unit found overlying the Dire Dawa Formation and underlying the Amba Aradam Formation with variable thickness from place to place which consists of marly and shaley succession rich in fossils of calcareous organisms (Bosellini et al., 2001). This unit also contains a lower segment of bioturbated, dark to grey color marly limestone which alternates with thin layers of black shale interbeds.

F) **GILDESSA LIMESTONE**

The name Gildessa Limestone is also given by Bosellini et al. (2001) for the carbonate unit which disconformably overlies Daghani Shale in the type locality with a thickness of 15-20 meter.

G) AMBA ARADAM FORMATION

Amba Aradam Formation is the upper unit (Greitzer, 1970) of the Mesozoic succession of Dire Dawa and Harar areas which overlies the Limestone Unit and contains interbeds of thin limestone layers more specifically in Graua area (Gortani, 1973) of Aptian-Albian in age. Limestone intercalation within the Upper Sandstone was also identified from Hirna area (Atnafu, 1991). According to Bosellini et al. (2001), the Upper Sandstone Unit of Dire Dawa area is coarse, cross stratified and very mature with lenses of quartz conglomerate and 150-200 meter thick fining-upward pattern associated with quite thin overbank shale at the top which has been interpreted as meandering fluvial system.

H) TERTIARY VOLCANIC ROCKS

Tertiary volcanic rocks of the Harar and Dire Dawa provinces comprise basaltic and silicic rock types (Tadesse and Hailemariam, 2006 and Berhe, 1985). The basaltic rocks are different in composition and contain transitional and alkaline basalts while silicic rocks comprise rhyolites, ignimbrites, tuffs, ash and lava flows.

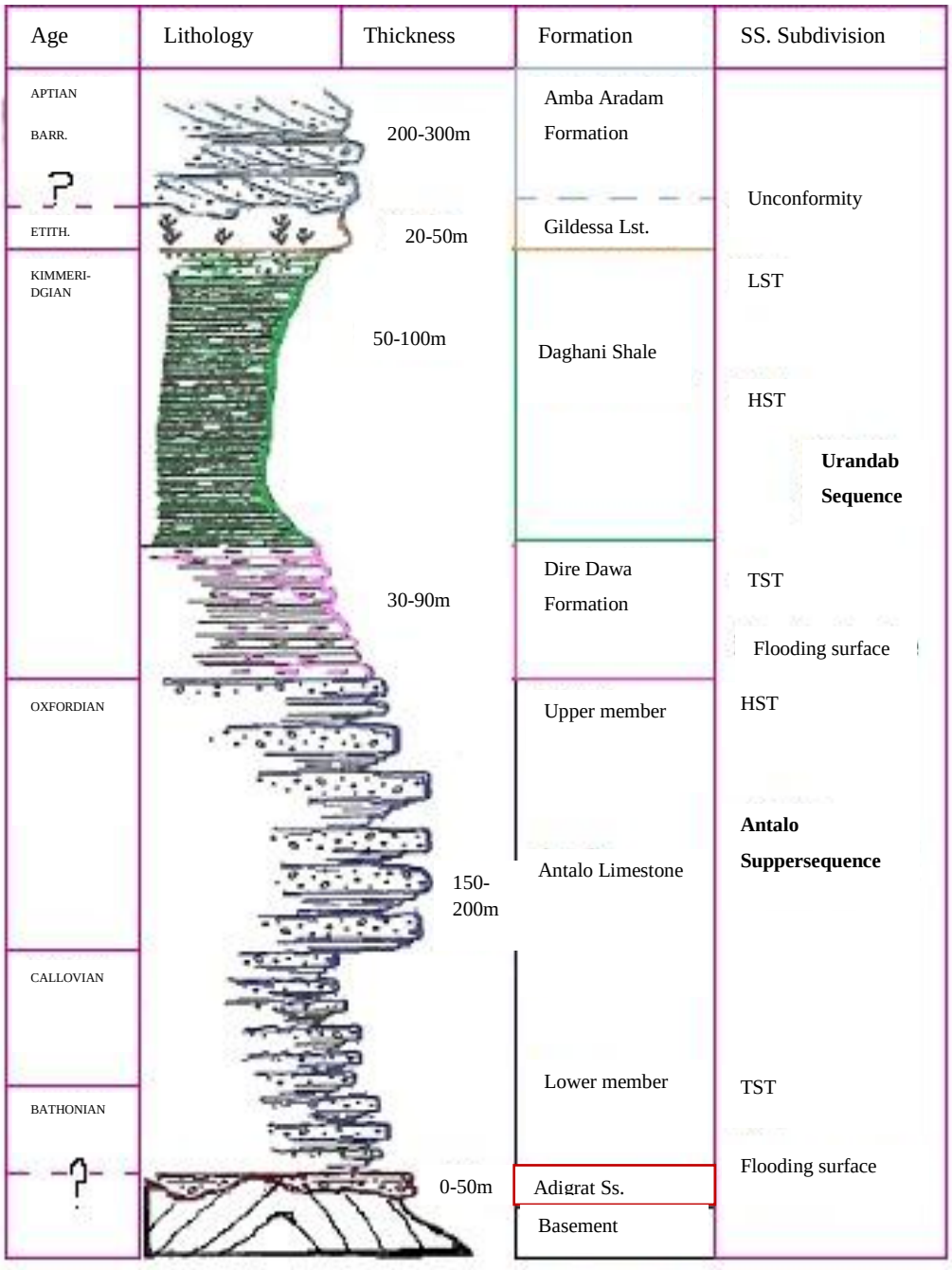


Figure 6: Regional Stratigraphy of the Mesozoic succession of Dire Dawa area (After Bosellini et al., 2001).

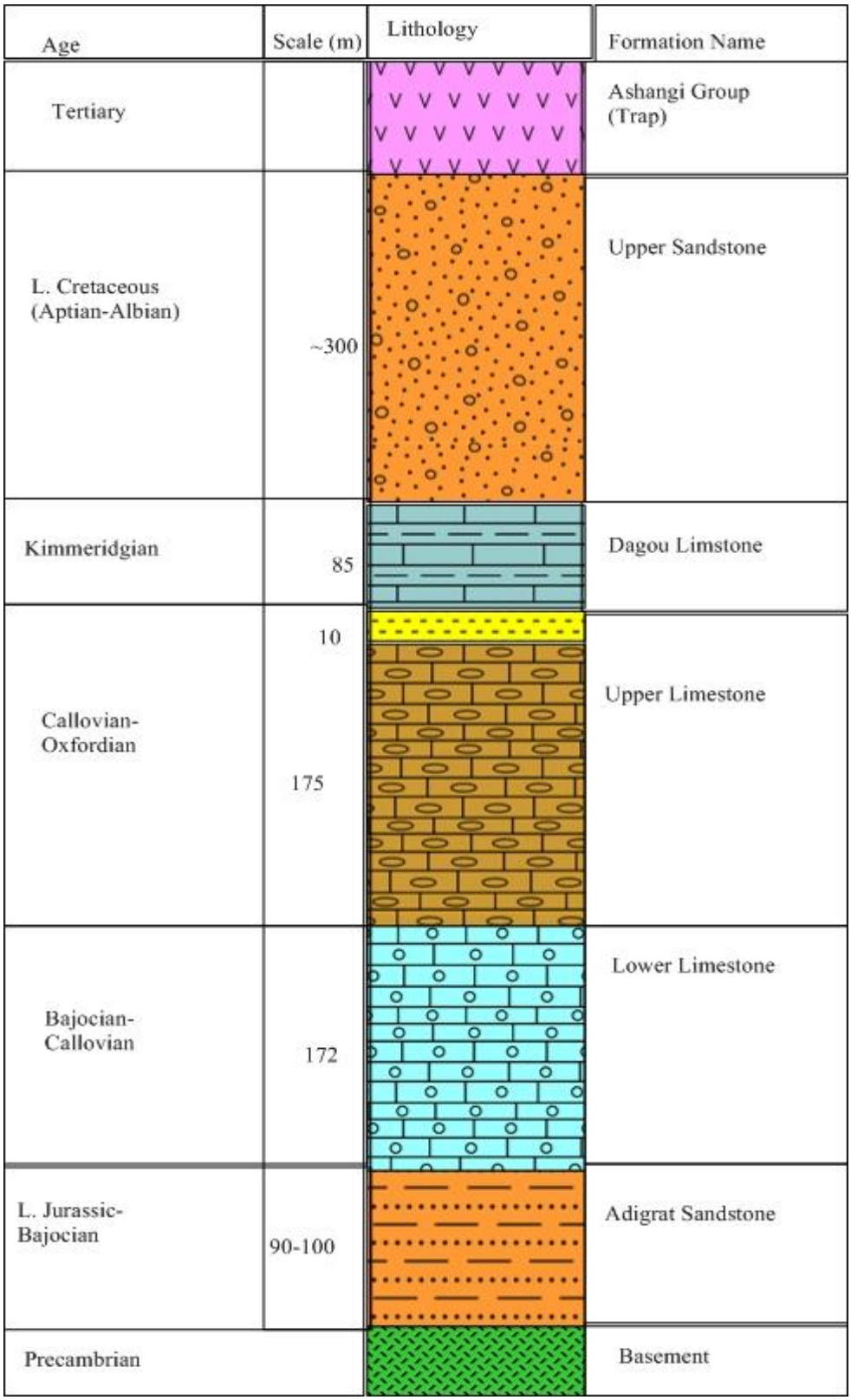


Figure 7: Regional Stratigraphy of the Mesozoic succession of Harar area (after Greitzer, 1970)

The geology of Dire Dawa area is structurally complex which is affected by fault and most of the sedimentary successions are characterized by tilted blocks of limestone and sandstone. These units are found adjacent to each other due to the effect of faulting by which it is difficult to determine their stratigraphic position in some places.

The Adigrat Sandstone Unit within the study area is laterally variable both in thickness and lithology that generally contains a fining upward sandstone, mud, shale and dolomite-mud-sandstone intercalation and calcareous sandstone that can be easily noted and logged very well.

Generally, the geology of the study area comprises Precambrian basement rocks at the bottom, Mesozoic sedimentary units (Adigrat Sandstone Unit, Limestone Unit and Amba Aradam Formation) at the middle and Tertiary volcanic rocks at the top. Trachyte intercalations sandwiched with the Lower Sandstone Unit are found outcropping over some localities (Wolde, 1986). On the other hand, exposures of basalts, tuffs and volcanic breccias are found around Kulubi area stratigraphically in between the Limestone Unit and the Upper Sandstone Unit (Canuti et al., 1972).

3. LOCAL GEOLOGY

3.1 FACIES ANALYSIS

3.1.1 INTRODUCTION

The term facies represents a unit of rock distinguished in the field by a specific combination of lithological, physical and biological structures that differentiate it from other rock units above, below or adjacent to it (Walker, 1992). Generally, the facies concept refers to the sum of characteristics of a sedimentary unit resulting from some particular set of physical, chemical and biological processes that work to produce a unit with specific textural, structural, and compositional properties. Detailed observation and description was carried out through each bed so as to recognize various sedimentary features which enable us to make facies analysis in order to subdivide the whole unit into a number of lithofacies types. Therefore, the facies types found within each studied section have been briefly discussed as follow.

3.1.2 Section-1

Section-1 is found at 0811175 Easting, 1045671Northing and 2121 meter above sea level in which the Lower Sandstone Unit overlies the basement rock separated by scoured surface at the bottom and overlain by the limestone unit at the top in which full section representing the total thickness of the unit in the type locality can easily be logged. It starts with coarse-very coarse grained sandstone bed containing randomly distributed pebbles that progressively grade into medium-fine grained sandstone together with semiconsolidated mudstone beds alternating with sandstone beds. The sandstone beds comprise crudely developed planar and trough cross-beds, bimodal/bipolar cross-beds, hummocky cross-stratification, horizontally laminated sand sheets and slightly bioturbated beds of sandstone. It also contains dolomite and calcareous sand beds making the top most part of the unit. The lower part of the unit within this section has very detailed information vital for the interpretation of depositional environments. But, in the scaled sedimentary log of the section, it has been represented in a way which an able to show these details. However, a second stratigraphic section has been projected for the sake of showing these detailed sedimentary features.

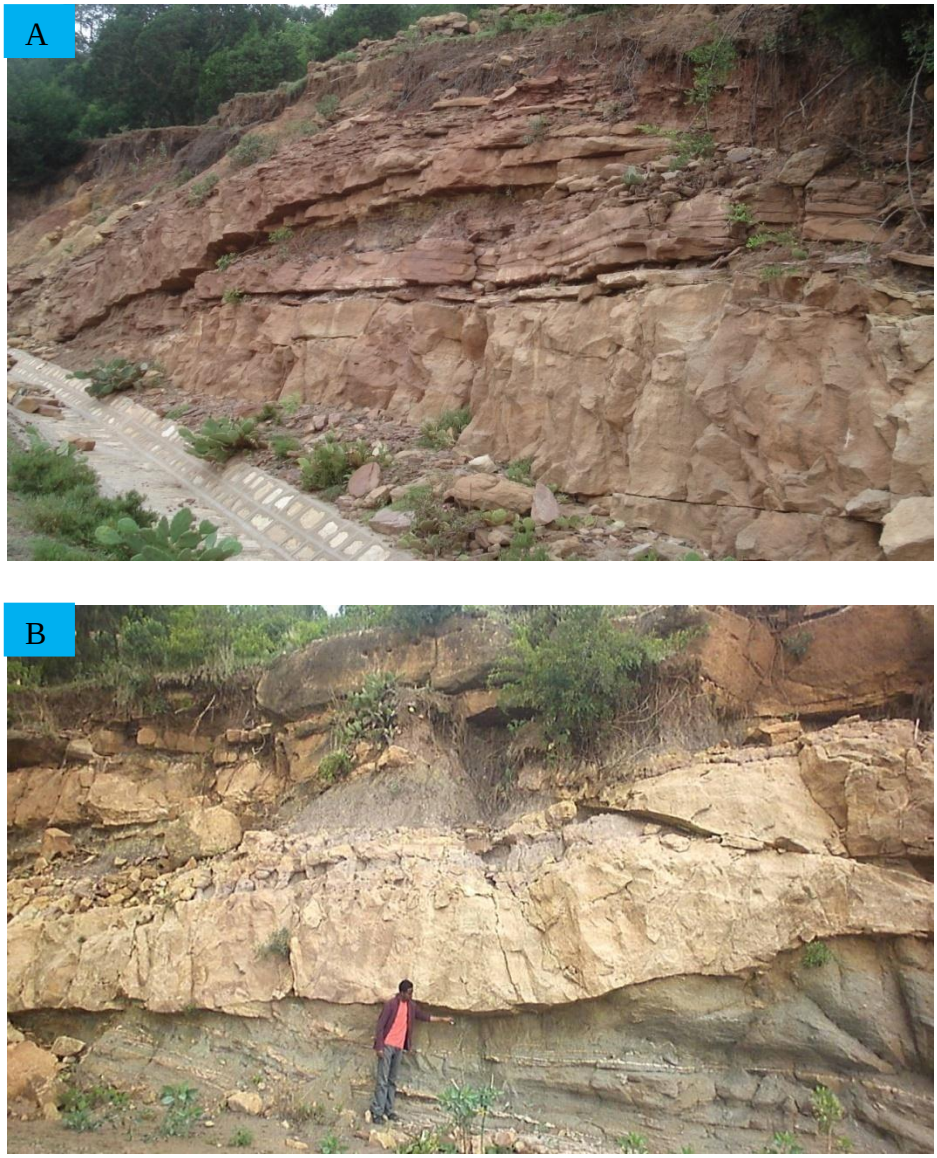


Plate-1: Field photos showing the lower most part of the Lower Sandstone Unit in Section-1. A. Fine-medium grained sandstone containing hummocky, herringbone, bioturbated and thinly laminated beds B. Pebbly sandstone progressively fining upward overlain by mudstone facies.

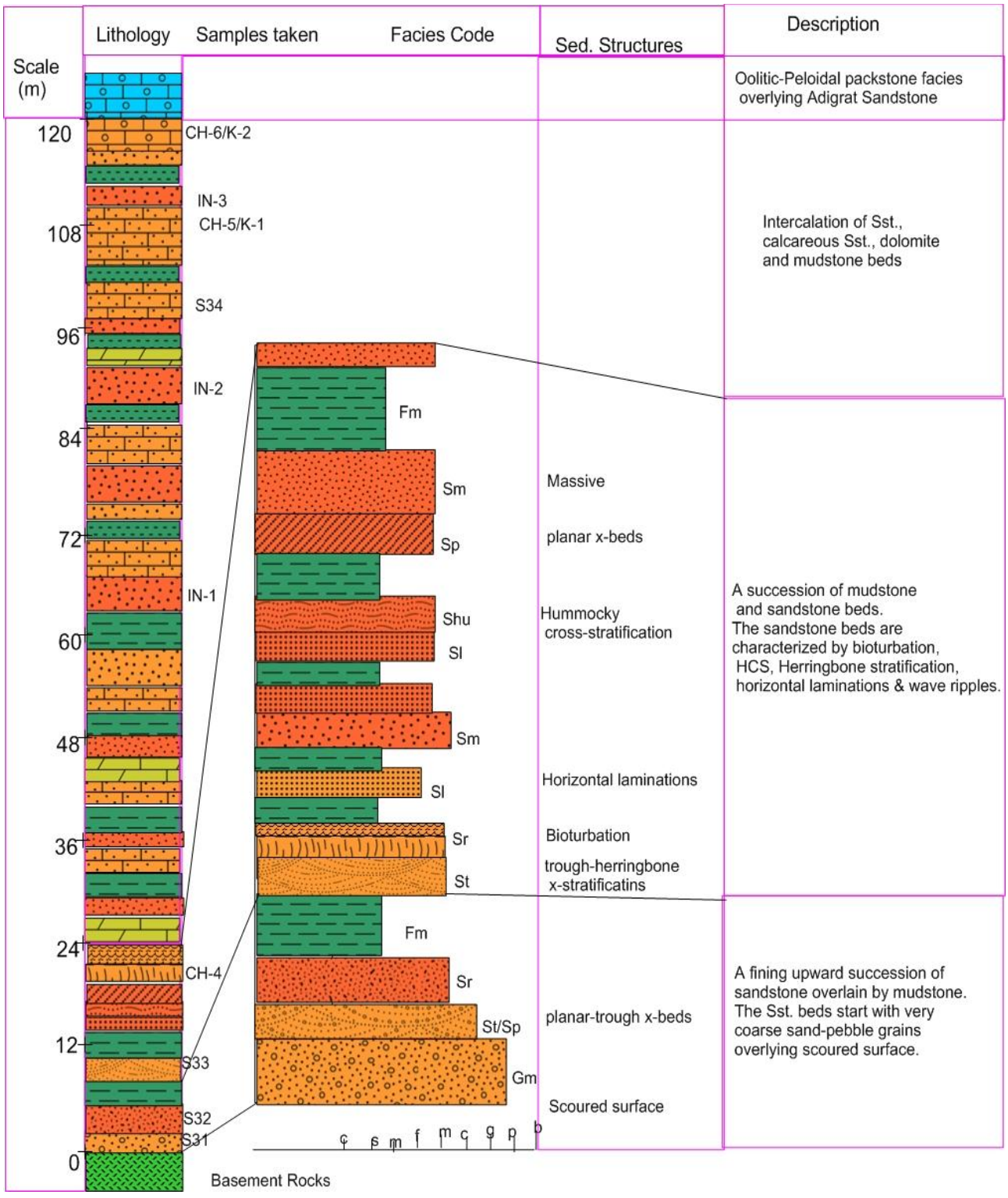


Figure 8: Sedimentary log for Section-1: The labels at the bottom show grain size (c=clay, s=silt, m=mud, f=fine sand, medium sand, c=coarse sand, g=granule, p=pebble & b=boulder respectively).

3.1.3 Section-2

Section-2 is found between Section-1 and Section-3 which is taken to see lateral variations. This section is characterized by rhythmically arranged thick beds of consolidated massive mud-fine grained sandstone and semiconsolidated greenish color mudstone beds at its lower part whereas the upper most part of this section comprises dolomite and calcareous sandstone beds in addition to mudstone and sandstone beds. The top part of this section is dominantly calcareous sandstone conformably overlain by peloidal packstone facies of the Limestone Unit by which its contact with the limestone unit could easily be traced. In this section the lower limit of the unit could not be defined due to lack of exposed basement rocks.

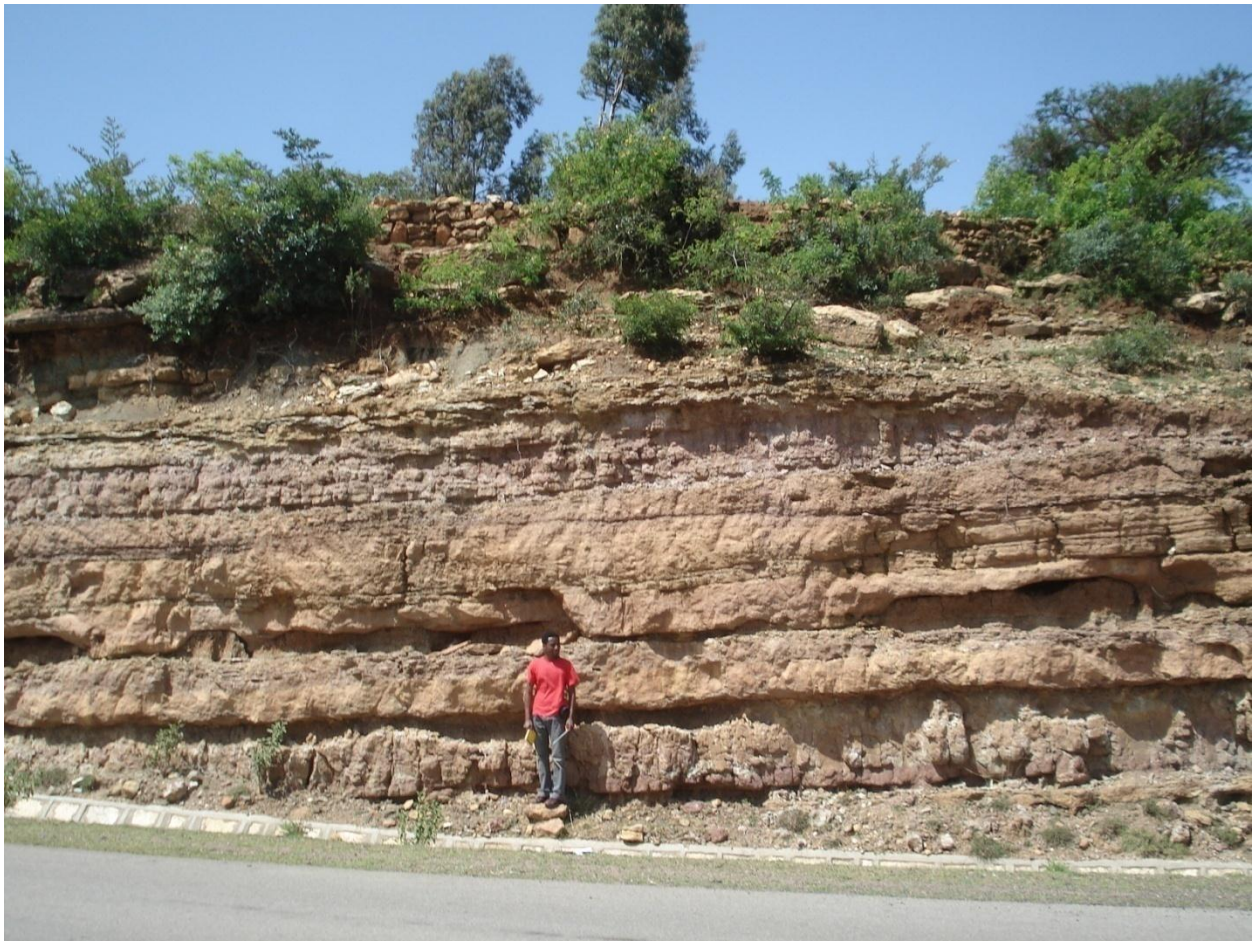


Plate-2: Field photo showing outcrops of the Lower Sandstone Unit in Section-2

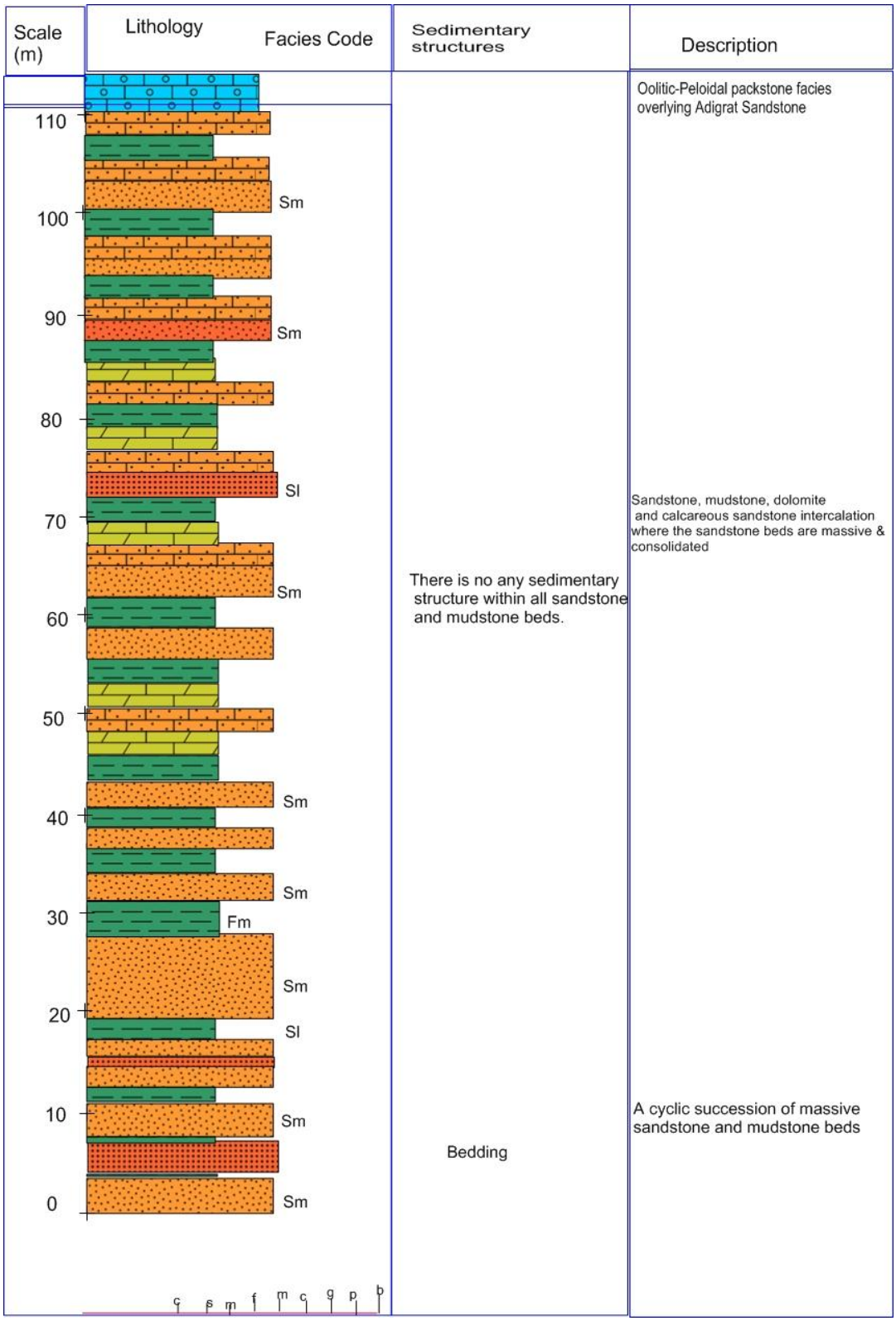


Figure 9: Sedimentary log for Section-2: The labels at the bottom show grain size (c=clay, s=silt, m=mud, f=fine sand, medium sand, c=coarse sand, g=granule, p=pebble & b=boulder respectively).

3.1.4 Section-3

Section-3 is located at 0811160 Easting, 1045877 Northing and 2084 meter above sea level. Here the Lower Sandstone Unit does not make a complete section due to the absence of the Limestone Unit overlying it. However, some part of it is exposed along quarry and road sides forming well defined cliff exposure overlying the basement and grey-greenish color intrusion.

This section contains highly consolidated quartz rich sandstone beds at the bottom part, light brown shale-marlstone, fine grained sandstone, dolomite, greenish color semiconsolidated mudstone and shale-gypsum beds at the middle and poorly exposed massive medium grained red sandstone at the top. In this section, some mudstone beds are characterized by traces of organisms such as vertical burrows identified within the bed by their contrast in sediment type relative to the host bed (mudstone).

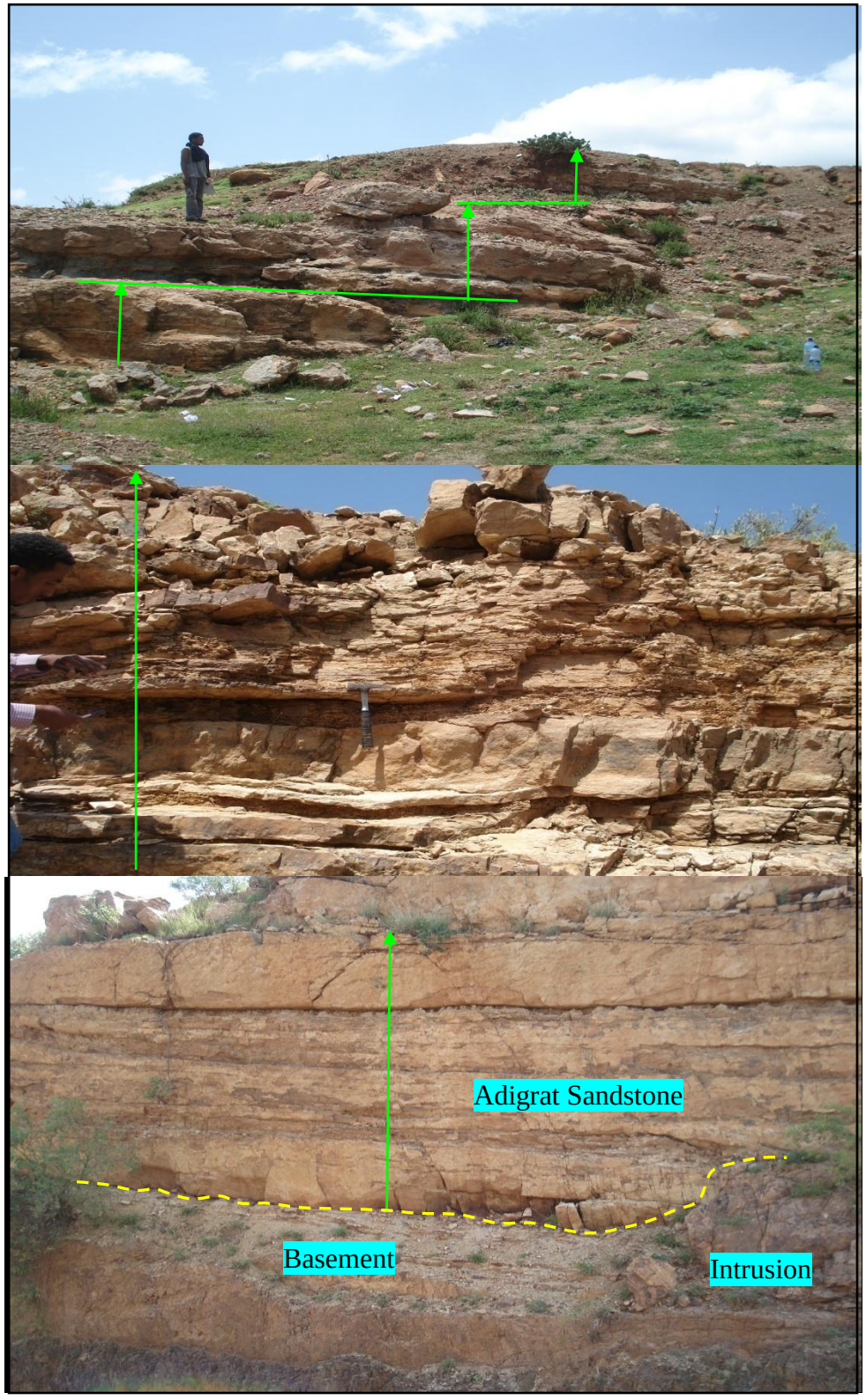


Plate-3: Photomosaic showing outcrops of the Lower Sandstone Unit in Section-3

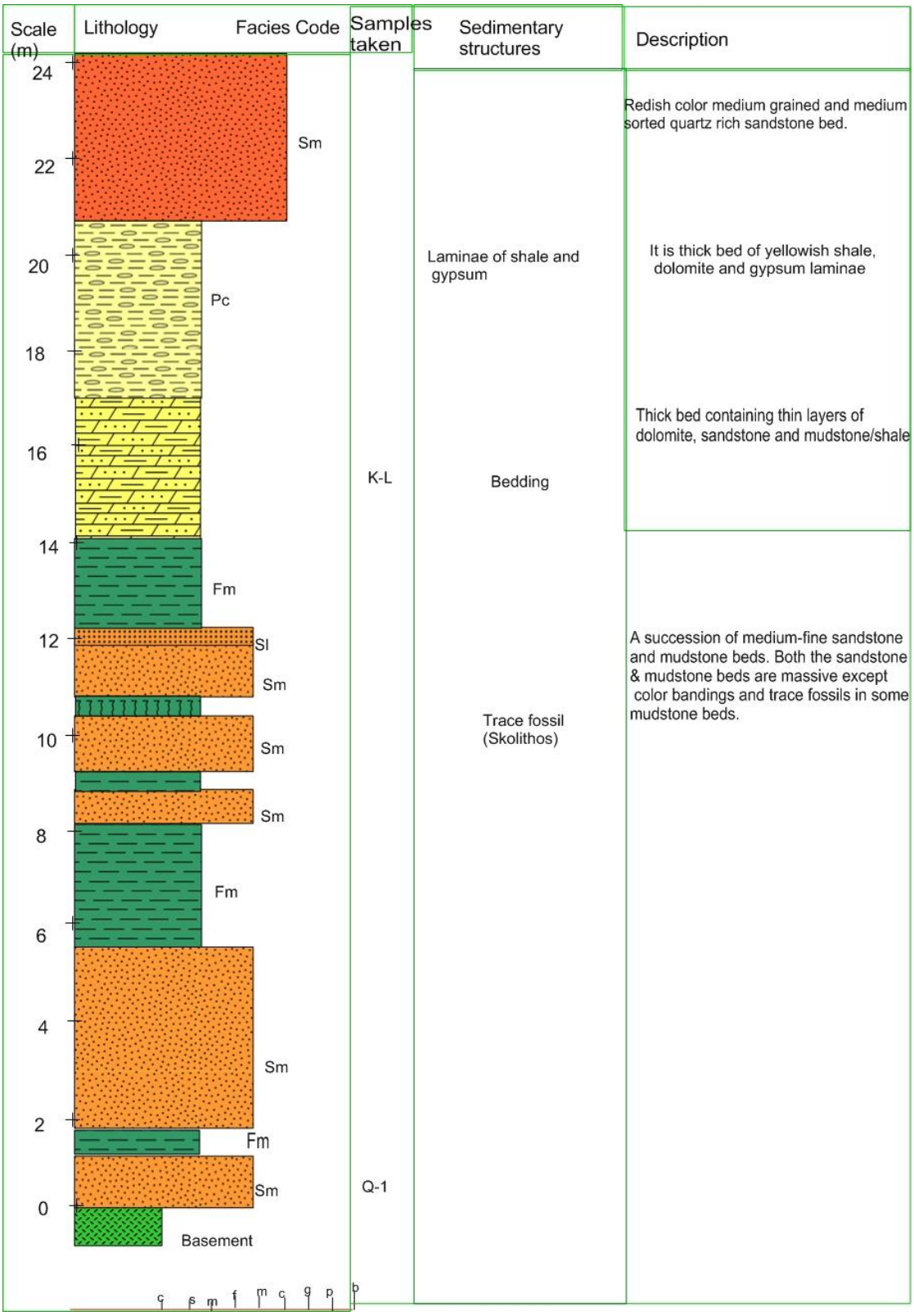


Figure 10: Sedimentary log for Section-3: The labels at the bottom show grain size (c=clay, s=silt, m=mud, f=fine sand, medium sand, c=coarse sand, g=granule, p=pebble & b=boulder respectively).

3.2 LITHOFACIES TYPES

Generally, using lithological differences and their association, it is possible to subdivide the Lower Sandstone Unit of Dire Dawa area (Kulubi- Dengego road sides) into two major subdivisions. These are the lower and upper parts of the unit. The lower part is dominantly sandstone together with associated mud and shale beds whereas the upper part is composed of dolomite, mud, sandstone, calcareous sandstone and sandy limestone beds which are poorly exposed in the type locality. The upper part of the Lower Sandstone Unit covers more than two third of the total thickness comprising sandstone, mudstone and dolomite beds. Its thickness is approximately in the range of 100-150 meter. This sandstone-dolomite-mudstone-calcareous sandstone intercalation is conformably overlain by the oolitic-peloidal packstone facies of the Limestone Unit. At the contact zone clearly exposed 30-50 cm thick sandy limestone can easily be observed and noted. Interbeds of mudstone occur within the Lower Sandstone Unit with a maximum thickness not more than 1 meter. It is well exposed in the lower part as a result of road cut forming road side cliff exposure whereas in the upper part the mudstone as well as sandstone beds are poorly exposed. Generally, Adigrat Sandstone Formation of Dire Dawa area could possibly be subdivided into a number of lithofacies types differentiated based on lithology, texture, color, sedimentary structures and trace fossils.

F_1: Poorly sorted massive pebbly sandstone facies

Description: This facies is medium to coarse grained white brown with very coarse sand grains occasionally gravely-pebbly grains at the base and medium to fine sand grains at the top and it has concave upward tabular and belt like geometry overlying scoured surface. The sediments are coarse with fine grained matrix between sandy grains, poorly sorted containing lags and pebbles (quartz and feldspars ranging in size from mm-cm). These pebbles are angular-sub-rounded, light color with yellowish stain and abundant pebbles dispersed throughout the bed together with minor amount of mud clast inclusions. The diameter of larger quartz clasts is about10 cm. It is also consolidated, immature, non calcareous with crude, small scale planar cross-beds observed in the lower, middle and upper part. The approximate dip direction of the cross-beds is west with dip amount of 12 degree.

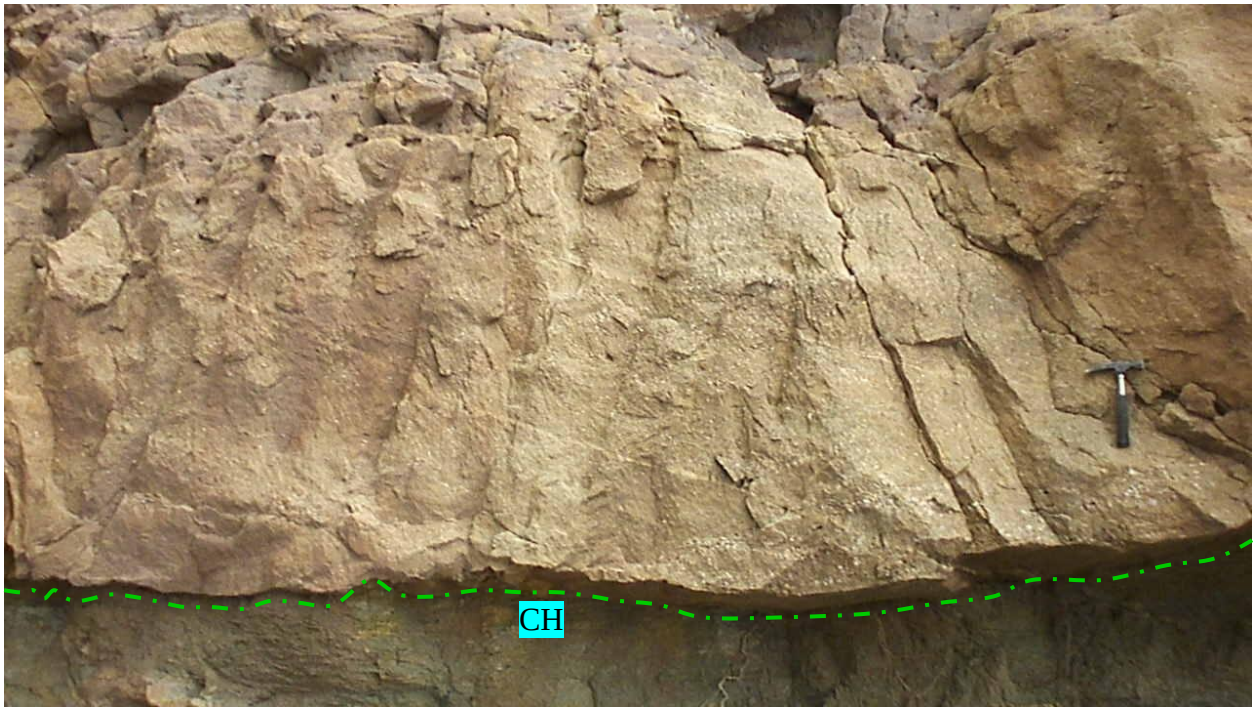


Plate-4: Pebbly sandstone overlying scoured surface progressively fining upward with crude planar-trough cross beds overlain by mudstone bed.

F_2: Poorly sorted medium grained massive sandstone

Description: This facies comprises 110 cm thick purple color, poorly sorted, medium-coarse sandstone with muddy matrix and sparsely distributed fine pebbles throughout the bed. These pebbles are concentrated at the middle of the bed but they are sparsely distributed at the bottom and upper part of the bed. The sand grains are angular to subrounded. It is consolidated with very crude planar cross-beds. The foreset of the cross-beds is dominantly of very coarse sand grains which is important to recognize these crudely developed cross-stratifications. At the top this bed is composed of fine sand grains whereas the underlying bed is very coarse sandstone showing a fining upward succession.



Plate-5: Poorly sorted massive medium grained sandstone with randomly distributed fine pebbles

F_3: Trough cross-bedded fine sandstone facies

Description: This is fine-grained reddish grey color sandstone with small scale trough cross-beddings and very thin, parallel and horizontal laminations in which the cross-beds have tangential contact with the lower bounding surface. The bottom of this bed is horizontally laminated sheet of fine sandstone and the top part is low angle trough cross-bedded relative to the middle part. These cross-bed sets have the same direction to the east and they are of the same in lithology (fine sandstone) even though they are separated by reactivation surfaces. In this case the lower bounding surface of the cross-bed set is sharp with trough shaped geometry. The shape of the cross-beds is somewhat concave upward especially at the lower part of the foresets. There is no any lithologic and grain size changes across the foresets of this sand bedform and within the cross-bed set. The middle cross-bed set has a set height of 13 cm and a set thickness of 18 cm.

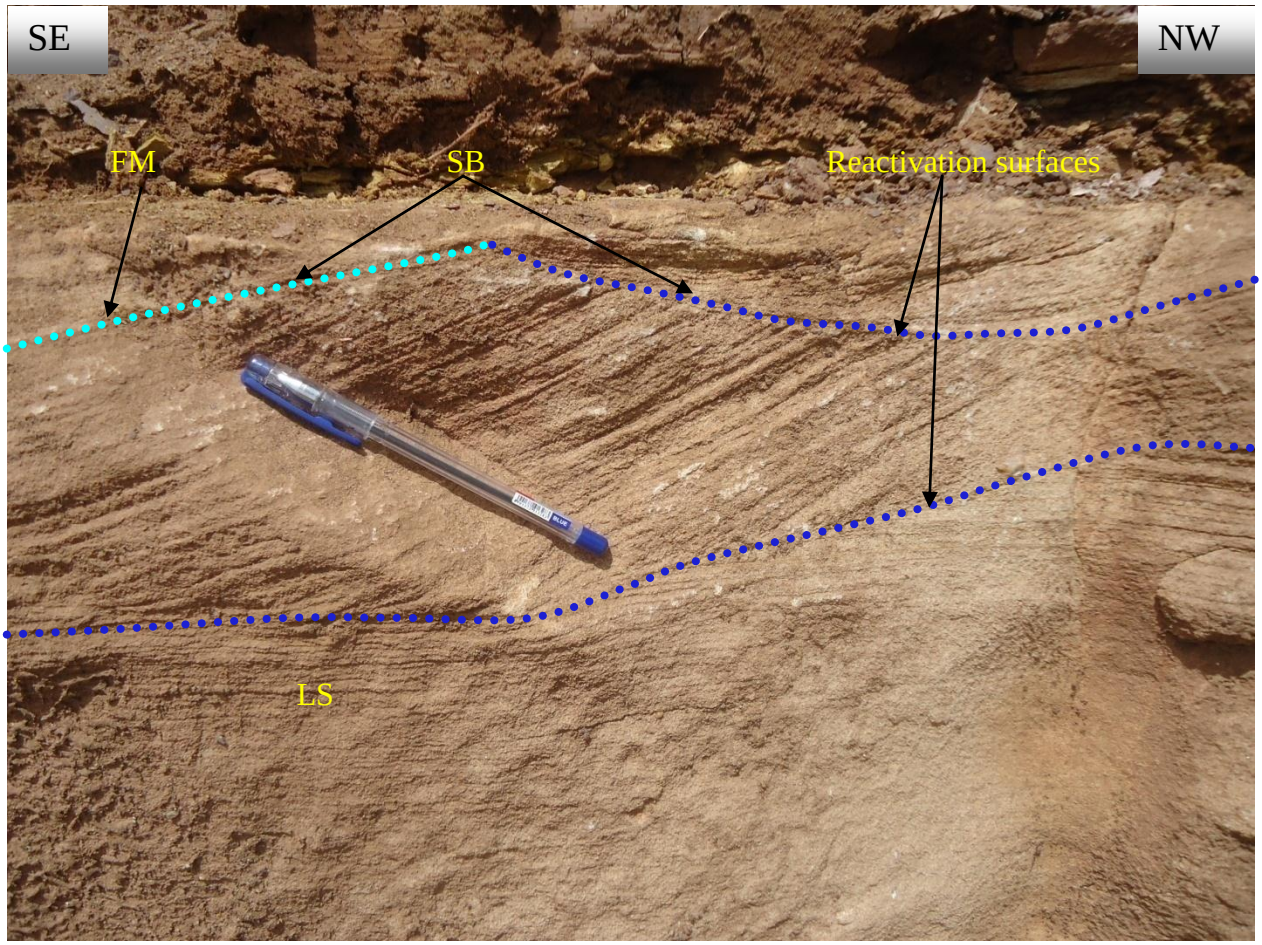


Plate-6: Fine grained sandstone with co-sets of trough cross beds bounded by reactivation surfaces and horizontal lamination at the bottom

Interpretation: Facies F_1, F_2 &F_3 together show a fining upward trend with coarser pebbles at the bottom overlying scoured surface. The association of very coarse sandstone bed with randomly distributed pebbles at the base overlying scoured surface, planar-trough cross stratified sandstone bed overlain by sandstone bed containing ripples at the middle and mudstone facies at the top in a vertical succession is interpreted as meandering stream deposit as a result of lateral migration of the channel and vertical aggradation in which the trough-planar cross stratified sandstone beds are interpreted as in channel bars/point bars with lags at the base whereas the mudstone bed is interpreted as floodplain deposit (Sultan et al., 2002, Posamentier and Walker, 2006 and Miall, 2006). The development of the cross-beds is due to the lateral migration of the bedforms. The fine-grained sandstone with small scale trough cross-bedding is linguoid sand bar of shallow channel deposit formed by the migration of dunes of sinuous crest-lines or 3-D

linguoid form sand waves (Colinson, 1978). Reactivation surfaces indicate fluctuating flow velocities causing the erosion of the underlying bedform during low water flow stage and their preservation is due to burial by deposition of sediments during high flow stage that reactivate lee side deposition (Collinson, 1970). The laminated sand sheet (Sh) with minor trough cross-bedded sandstone (St) is interpreted as flash flood deposits deposited under upper flow regime plane bed conditions (e.g. Miall, 1977, Bridge, 2006).

F_4: Greenish color massive mudstone facies

Description: It is semiconsolidated, massive fine grained unit showing color mottling without any sign of lamination. Its thickness ranges from 0.5-1.5 meter. Within this rock unit there are interbeds of thin sandstone layers. It has variegated colors with the alternations of grey, reddish and yellowish color sediments. In some places this facies contains black shale composed of fine (mud-clay) sediments with dark grey-black color. This mudstone bed occurs cyclically with the sandstone beds throughout the unit as well as with dolomite and calcareous sandstone beds at the top most part of the unit. Trace fossils (vertical burrows) are also preserved in some beds of this facies. The contact between the overlying sandstone bed and even the sandstone bed itself has wave like appearance.

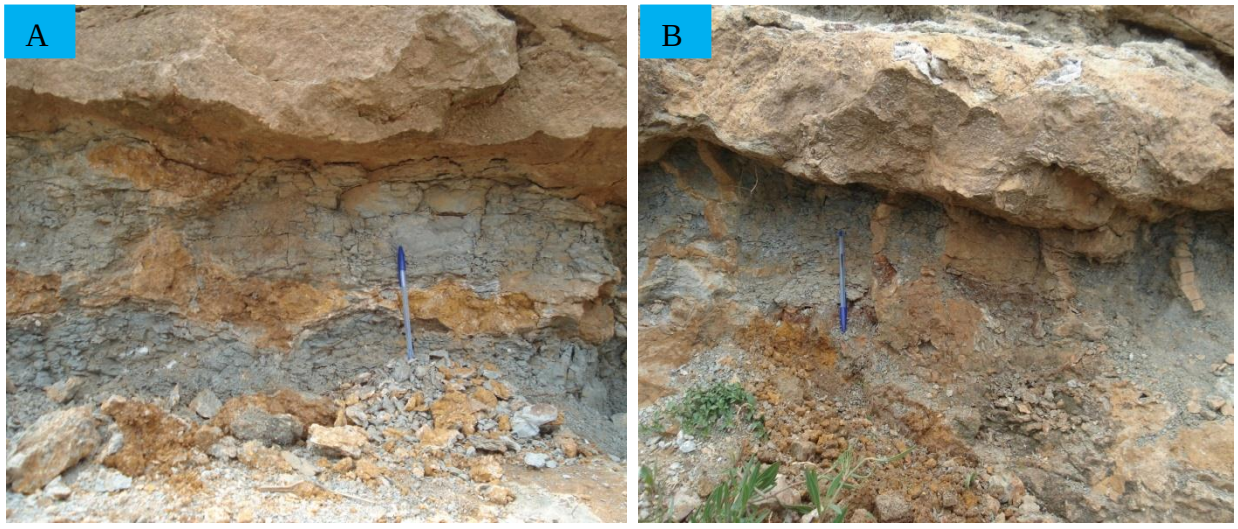


Plate-7: Greenish color mudstone with fine grained sandstone lense (A) and vertical burrows (B) overlain by fine sandstone with wavy contact

Interpretation: The greenish color mudstone facies is interpreted as offshore facies deposited from suspension whereas the overlying sandstone bed was deposited during relative sea level fall. During the initial stage of sea level fall, sandy sediments started filling tube like vertical burrows found within the mudstone bed. The presence of these vertical burrows (*Skolithos*) is evidence of shallow marine environment for this mudstone bed indicating semiconsolidated ground most probably along upper shoreface- middle shoreface environments with low tidal influence (Johnson and Baldwin, 1978, Nichols, 2009, Pemberton et al., 1992 and Clifton, 2006). According to Pemberton et al. (1992), the *Skolithos* ichnofacies is indicative of relatively high levels of wave or current energy typically developed in slightly muddy to clean, well sorted, loose or shifting particulate substrates commonly occurs on foreshore and shoreface environments. The wavy nature of the contact is indicative of oscillatory flow. Bioturbation is common on shelf mudstone facies during low sedimentation rate (Johnson and Baldwin, 1978) which does not inhibit the existence of the trace maker organisms.

F_5: Brownish yellow shale-dolomite-gypsum unit

It is 190 cm thick semiconsolidated brownish-yellowish color shale overlying quartz rich fine - medium grained massive sandstone bed and containing 1-2 cm thick lense of well consolidated grey-brown sand composed of rounded-subrounded grains.

There is also yellowish grey semi-consolidated fine grained bed which is 140 cm thick containing interbeds of dolomite and 1-3 cm thick laminae of gypsum.

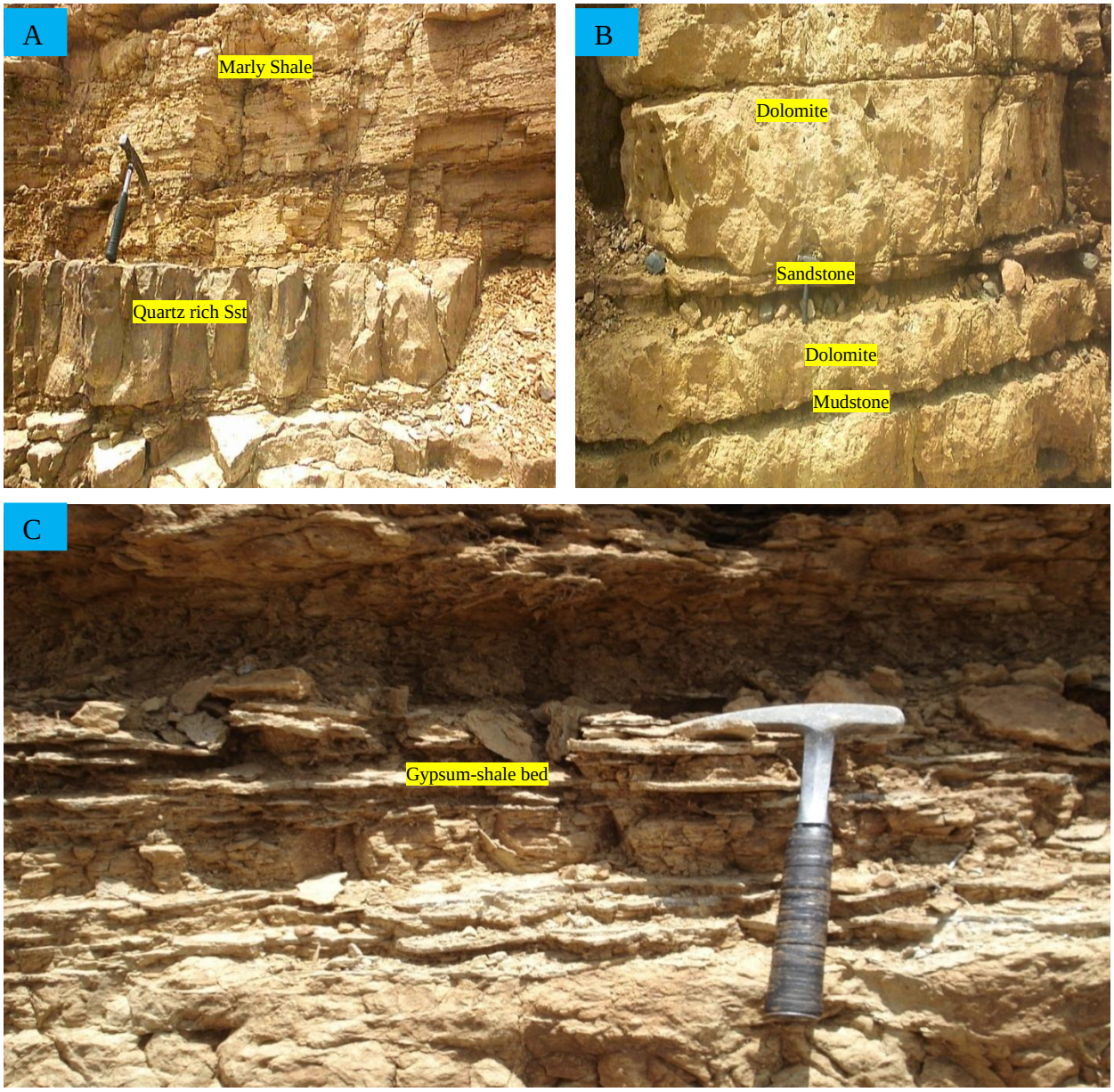


Plate-8: A. Marly shale overlying quartz rich medium grained sandstone B. Dolomite-shale bed with an interbed of red color medium sandstone C. Gypsum-shale bed

Interpretation: Marginal environments such as arid coast/sabkhas, arid lagoons, brackish ponds and high salinity shallow to deep marine water bodies are the major sedimentary basins for evaporite precipitation both in subaerial and subaqueous conditions (Schreiber, 1980, Kendall, 1989, Einsele, 1992, Harwood and Kendall, 1996 and Nichols, 2009). According to these authors, the necessary conditions for evaporite precipitation are isolation from ocean realm and high rate of evaporation relative to the influx of water from outside sources that create

hypersaline condition leading for precipitation. The rates of evaporite precipitations as well as the thickness of the resulting deposits in subaerial environments are not similar with that of subaqueous environments which can be taken as criteria for environmental interpretation. Thus, the dolomite-shale bed with the associated gypsum laminae (Plate-8: A-C above) is interpreted as the result of dolomite and gypsum precipitation together with the supply of fine terrigenous sediments in subaerial environment along sabkhas. Assefa (1991) already interpreted such dolomite and gypsum beds in Abay river basin to be the deposits of shallow lagoonal and supratidal environments.

F_6: Herringbone cross-stratified fine sandstone facies

Description: It is reddish color highly consolidated fine grained sandstone with well developed low angle planar cross-bed sets throughout the whole bed. The cross-bed sets are bipolar/ bidirectional mostly of east and west directions. The cross bed sets are composed of thin laminae of fine sand grains. This sandstone bed is underlain by mudstone bed and overlain by intensively bioturbated thick and medium grained sandstone bed.

Interpretation: Herringbone cross-stratification is the result of ebb and flood tidal currents operating along coastal areas (Nichols, 2009). These bipolar cross-stratifications are mainly used as an indication of shore wave controlled deposition (Dalrymple, 1992). Dawit and Bussert (2009) also interpreted similar bed in Abay basin as deep to shallow tidal inlet channel fill.

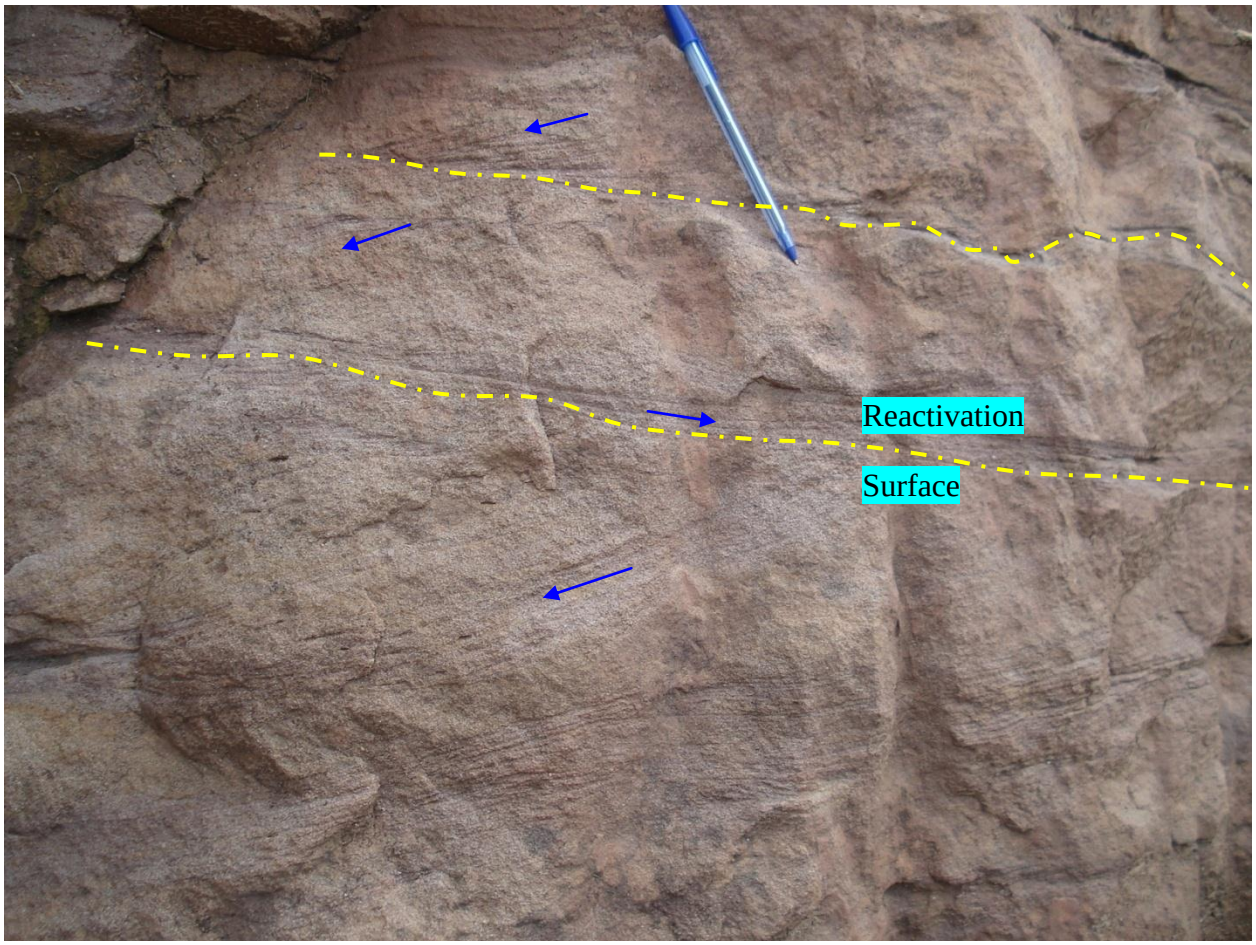


Plate-9: Herringbone cross-stratification in fine grained sandstone beds

F_7: Hummocky cross-stratified fine sandstone

Description: It is consolidated fine-grained reddish grey sandstone with low angle undulatory lamination. The laminae are wavy with indistinct orientation and different cross-bed sets stacking together.

Interpretation: Shoreface and offshore transition environments are known as oscillatory wave zones (Ellott, 1986). The sandstone beds with hummocky cross-stratification are interpreted as storm wave generated deposits in offshore-transition to shoreface depositional systems (Ellott, 1986, Johnson and Baldwin, 1978 & 1996, Nichols, 2009 and Walker & Plint, 1992). The interplay of unidirectional and oscillatory flows is considered as the important and responsible process generating hummocky cross-stratifications. According to Walker and Plint (1992), the preservation of hummocky cross-stratifications is mainly in the areas of weak tidal activity that lie below fair weather wave base (FWWB).



Plate-10: Hummocky cross-stratification in fine grained sandstone beds

F_8: Slightly bioturbated normal graded sandstone `

Description: It is thickly bedded (210 cm) reddish/purple color fine sandstone with thin lamination and low angle planar cross beds at the middle, normally graded bedding at the top in which there are slight bioturbation within the coarser sand grains at the bottom and middle of the graded bedding sandstone showing somewhat light color bands. The grains are quartz rich, well sorted and rounded medium to coarse sands.

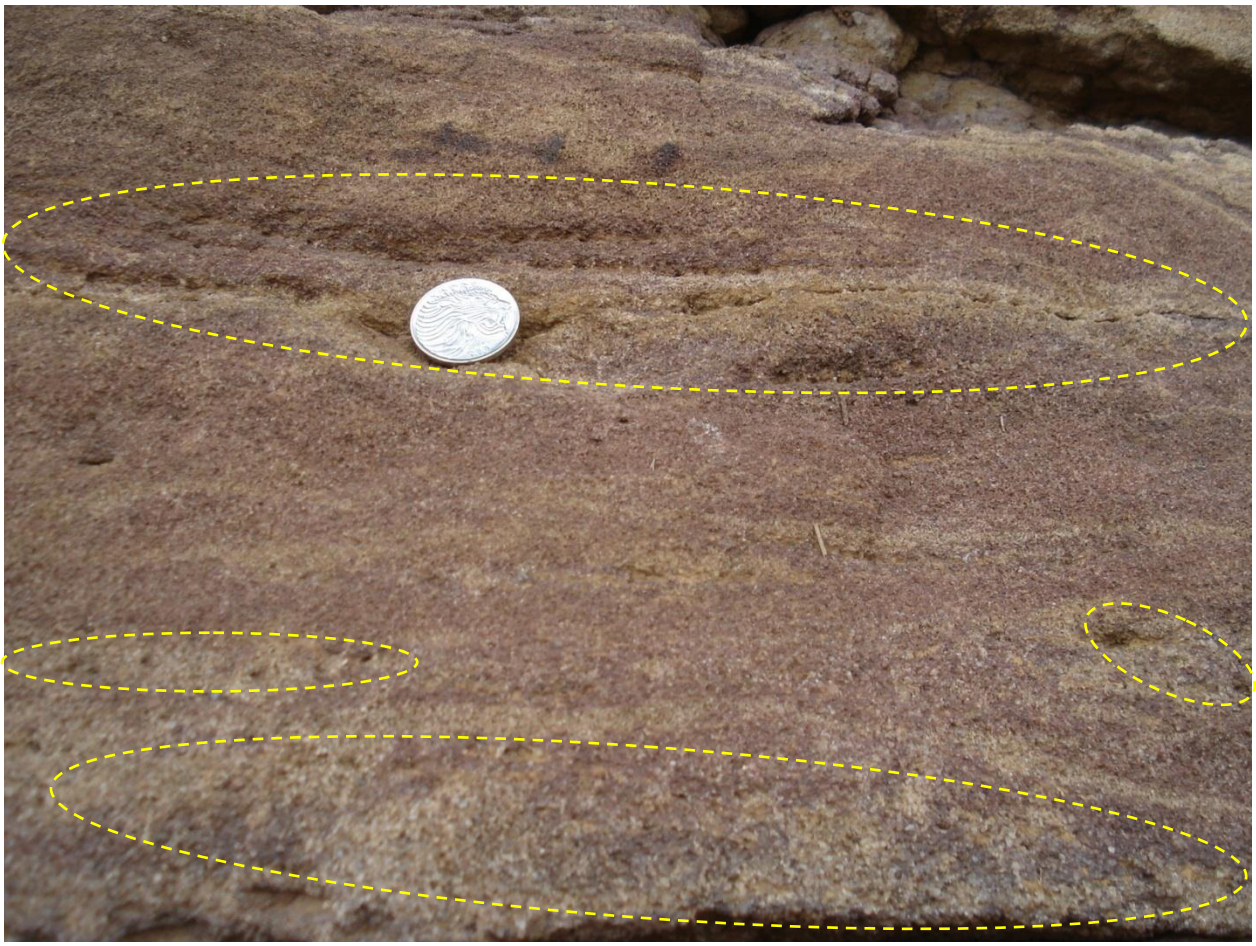


Plate-11: Normally graded, medium-coarse grained bioturbated sandstone. The dotted ellipses show intensively bioturbated zones.

F_9: Intensively bioturbated fine-medium grained sandstone

Description: It is 140 cm thick, brownish-grey color, poorly sorted, medium-coarse grained sandstone with subrounded-rounded grains and matrix. It is characterized by small scale planar-trough cross-beds. The lower 60 cm is planar cross- bedded (pebbles are common along cross-beds) and in the middle about 10 cm thick thinly bedded (average: 3 cm) bioturbated zone is its common feature along the length of the bed whereas its upper part is massive with thinly bedded to small scale trough cross-beds at the top. Laterally, there is grey-white brown, poorly sorted, fine-medium sandstone containing small scale planar-trough cross beds and intensively bioturbated zones.

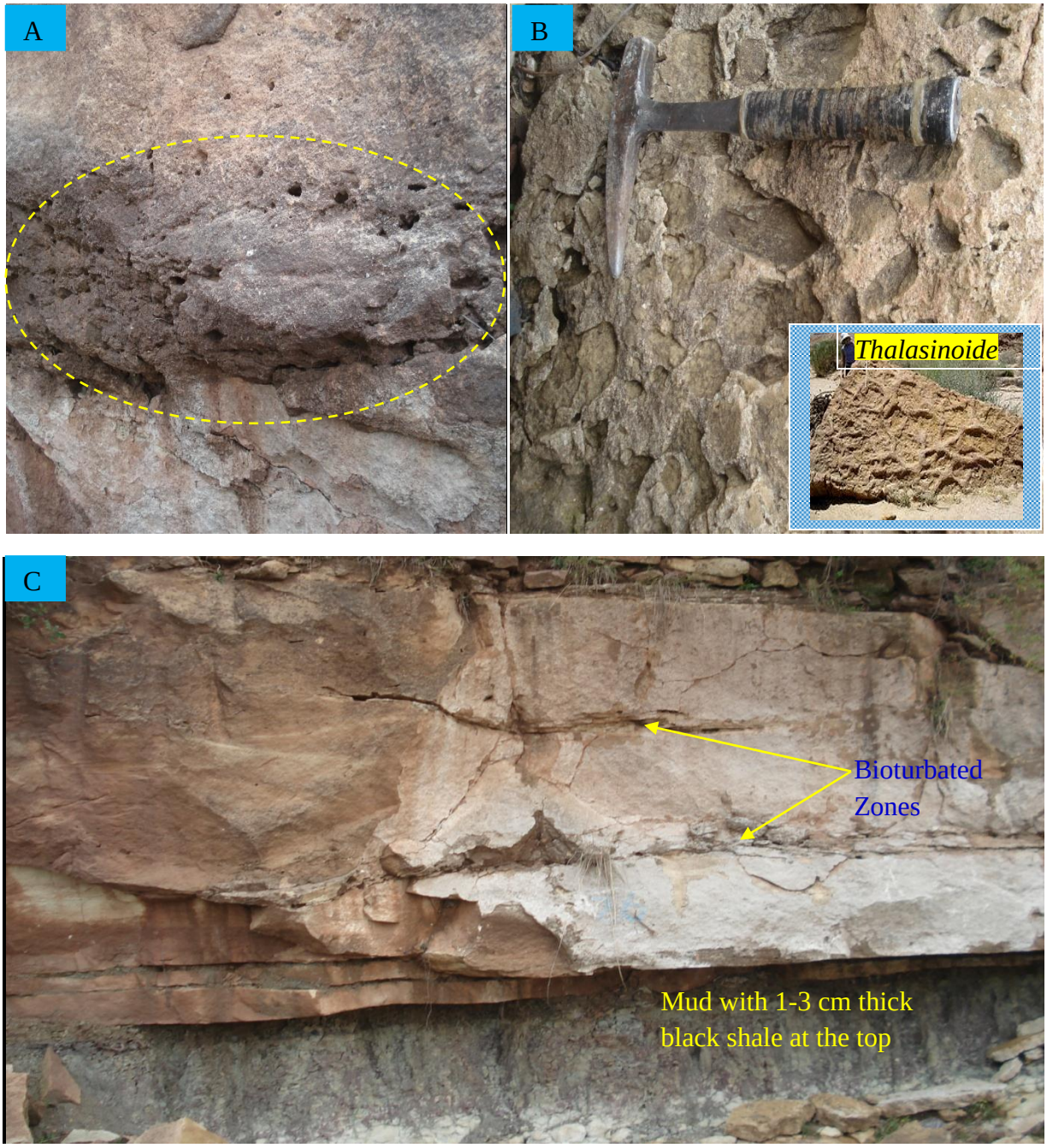


Plate-12: Biotrubated sandstone facies A. *Skolithos*, B. *Thalassinoides* ?, C. Fine sandstone with slightly undulating bioturbated zones.

Interpretation: Bioturbation is a common feature where the environment is favorable for organisms to live. Bioturbation within the coarser sediments is interpreted as deposition by high energy condition that brought nutrient for organisms to live there on this sand deposit along most probably of foreshore environment. This sandstone facies is slightly bioturbated that may show

the influence of energetic condition affecting the existence of the organisms and further reworking of the sediment grains destroying their traces (reducing their preservation potential). Well sorted and rounded sand grains also show deposition of this bed in foreshore environment. From the nature and their ordered arrangement (track pattern) of the traces shown in the above photograph of coarse sandstone, they are interpreted as walking traces (Seilacher, 2007). A transitional ichnofacies named as *Psiloichnus* ichnofacies which is found between *Skolithos* and nonmarine ichnofacies comprises surface tracks and trails of many animals wandering along backshore beach deposits, coastal sand dunes, washover fans and supratidal flats (Frey, 1975). Thus, the above trace fossil which has been interpreted as walking trace/track falls under this ichnofacies type.

The fine-medium grained sandstone (Plate-12) is intensively bioturbated relative to very coarse sandstone beds that shows the energy condition was suitable that brought nutrient and not influencing their existence. The association of symmetrical and asymmetrical ripples as well as laminated and bioturbated sandstone facies is interpreted as shoreface deposit above the fair weather wave base (Ellott, 1986). The undulatory nature of the contact separating the bioturbated zone from underlying unbioturbated bed (Plate: C above) is indicative of oscillatory wave action mainly of offshore-transition environment related to the development of hummocky cross-stratification.

F_{10}: Horizontally laminated fine grained sandstone

Description: The whole thickness of this facies (60-80 cm) is composed of thin laminae of fine consolidated sandstone sandwiched by dark grey shale. It is generally reddish grey in color being dark grey at the bottom and top at the contact zone with the shale.

Interpretation: Horizontally laminated fine grained sandstone is interpreted as upper shoreface facies (Ellott, 1986 and Johnson & Baldwin, 1978).

F_{11}: Massive and well sorted quartz rich sandstone

Description: This facies type has grey-light color with rounded medium-coarse sand grains dominantly of quartz. It is massive, consolidated and well sorted sandstone bed interbedded with mudstone and dolomite beds (Plate-14: D).

Interpretation: Well sorted quartz dominated sandstone with rounded, medium to coarse sand grains is interpreted as shallow marine sandstone deposited along foreshore environment (Baldwin & Johnson,1996 and Nichols, 2009).

F_{12}: Calcareous sandstone

Description: This facies comprises rounded-subrounded monocrystalline quartz grains with minor amounts of polycrystalline type and randomly distributed feldspar grains mainly of plagioclase. The matrix is microcrystalline calcite (carbonate mud) and the cementing material is dominantly of spary calcite with minor amount of biotite (brownish color) (Plate-14: A & B).

F_{13}: Sandy limestone

Description: This facies dominates the upper part of the lower sandstone unit at the transition to the limestone unit. It is massive highly consolidated light grey wackstone dominated by carbonate grains mainly of peloids, poorly developed ooids, micrite and shell fragments (*Bivalves*) together with randomly distributed quartz grains (Plate-14: C, E & F).

Interpretation: Both F_{12} & F_{13} are interpreted as deposited in mixed carbonate and clastic shallow marine environment. The wackestone-packstone sandy limestone facies is interpreted as deposited in low-energy shallow marine shelf or ramp environments on warm water platforms where current activity is insufficient to remove the mud (Jones and Desrochers, 1992). According to these authors, the accumulation of the mud could be either from the inorganic precipitation of calcite from sea water or from the breakdown of green calcareous algae and large skeletal particles in quit water bodies free from the influence of tidal and strong oceanic currents mainly below the wave base whereas the deposition of carbonate mud together with poorly developed peloid and ooid grains and large bioclasts could be interpreted as deposition in medium energy condition in open marine -restricted environments (none rimmed and rimmed carbonate shelves respectively). The presence of terrigenous sediment mainly of quartz grains

clearly shows deposition in carbonate shelf environment receiving terrigenous sediments from the continental landmass (Nichols, 2009). Thus, the calcareous sandstone facies which is dominated by quartz grains was deposited during high supply of clastic sediments from uplifted continental source areas that inhibited carbonate production. The clastic supply was progressively reduced which is interpreted to be due to local subsidence and sea level rise creating favorable conditions for carbonate production manifested by the formation of sandy limestone containing randomly distributed sand sized quartz grains.

3.3 PETROGRAPHY

Petrographic study has been conducted using twelve thin-sections prepared from representative samples. From the analysis of these thin-sections using petrographic microscope, different components have been identified and the percentages of major framework grains are determined by point counting technique. From the analysis of both compositional and textural characteristics under microscope, medium-well rounded and medium-well sorted quartzarenite-quartzwacke petrofacies types have been identified. Generally, this sandstone unit comprises subrounded-rounded quartz grains, minor proportions of feldspar and rock fragment, flakes of muscovite, significant amount of muddy matrix and reddish brown cementing material with carbonte mud and spary calcite cement in same of the samples . Heavy minerals are also identified mainly from calcareous sandstone and insignificant amount within other sandstone samples.

Table-1: Compositional description of Adigrat Sandstone of Dire Dawa

Composition	Description
Quartz	Quartz is the dominant mineral grain found within all thin-sections as a major component of sandstone. There are two varieties of quartz grains named as monocrystalline and polycrystalline quartz grains. Their major difference is that monocrystalline quartz is a single quartz crystal while polycrystalline quartz is an aggregate of two and more quartz crystals. Most of the quartz grains are highly fractured with small holes (vacuoles) in some of the samples.
Feldspar	One of the important components of sandstone used in compositional classification is feldspar. There are different varieties of feldspar but plagioclase feldspar and microcline are the two common types of feldspar encountered from almost all samples even though their proportion is small relative to quartz grains.
Lithic fragment	These are also the major components of sandstone composed of different mineral grains/polymineralic which can be easily recognized and identified under microscope especially under cross-polarized light observation. Rock fragments of sedimentary origin are found within some of the samples.

Cement	Reddish-reddish brown and dark brown color cementing material (Hematite) is present typically occurs as a coating around grains and partially or fully fills inter-granular pore spaces. Carbonate cement is also a major component of calcareous sandstones.
Matrix	This is very fine and dense muddy part filling the inter-granular pore spaces. Sand size quartz grains also serve as matrixes which fill the space between larger grains in some samples and carbonate mud is also found in other samples as matrix.
Other mineral grains	The presence of other minerals is rare. However, some mica group (Biotite and Muscovite) and insignificant amount of heavy minerals most probably of Zircon and Sillimanite crystals are found within some samples.

Table-2: Textural description of Adigrat Sandstone of Dire Dawa

Texture	Description
Grain size	There are different grain size distributions as noted from hand specimen observation in the field and from thin-section analysis under petrographic microscope in the laboratory. These grains range from medium sand to pebble size and their size has been determined based on the Udden-Wentworth grain size scale.
Shape	The shape of most of the grains is dicoid-bladed with some elongated, rod like grains.
Roundness	The roundness of the grains is variable with subrounded and rounded grains dominating almost all samples.
Sorting	Each rock sample contains variable grain sizes starting from very fine muddy matrix-very coarse sand grains. Thus, most of the samples are medium sorted.
Surface features	The surface of most of the quartz grains is highly fractured and striated with vacuoles observed as black lines and dots respectively under crossed polarized light.

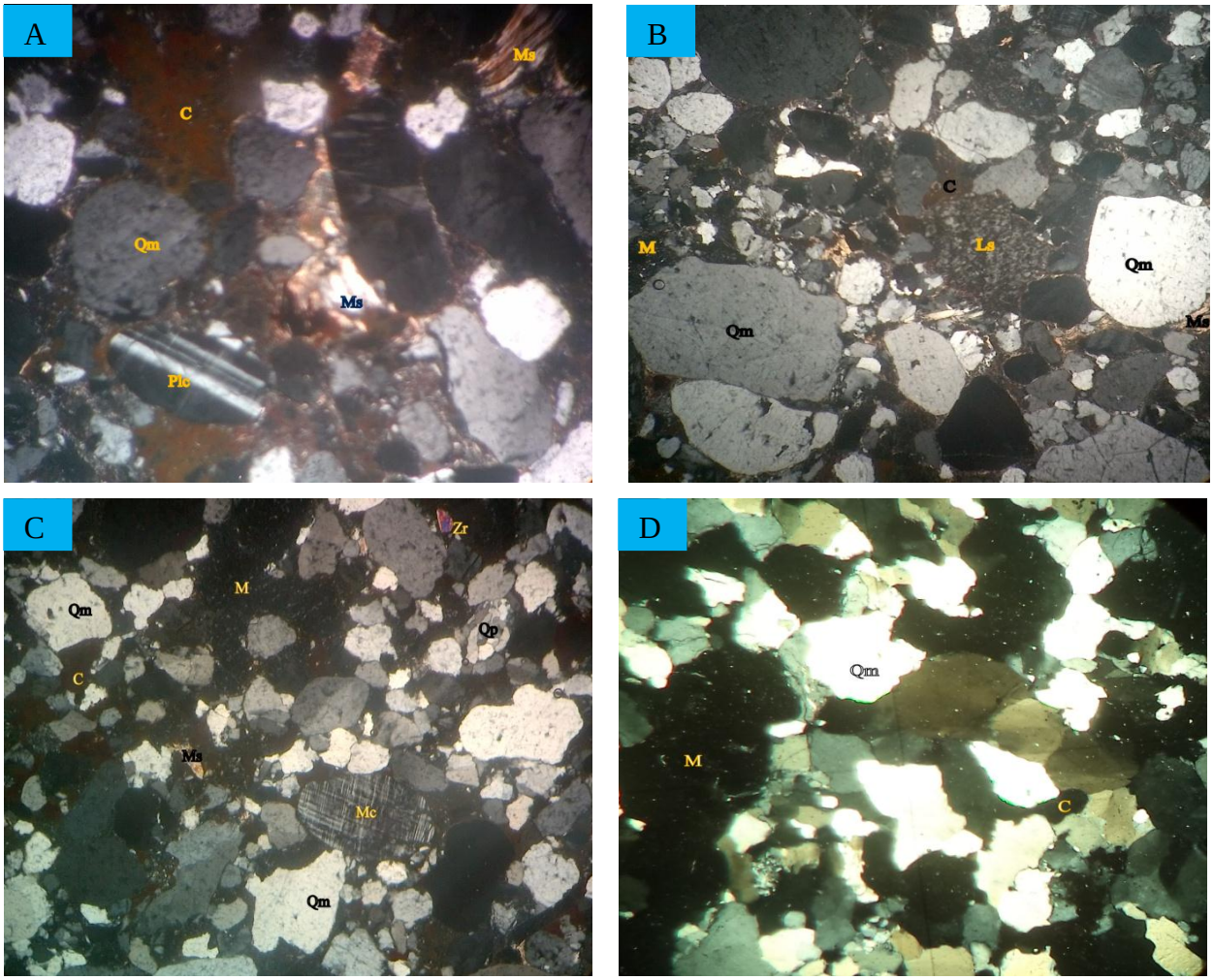


Plate-13: Photomicrographs showing plagioclase feldspar with well defined polysynthetic twinning, well rounded quartz grains and sheets of muscovite (A), subrounded- rounded quartz grains and rock fragment of sedimentary origin (Ls) with medium sorting (B), subrounded-rounded quartz grains with microcline and Zircon crystal (C). All are under crossed polarized light (XPL). A, in 100X magnification whereas B, C and D, in 40X magnification. The quartz grains appear different shades of grey under crossed polars due to different orientations of the grains.

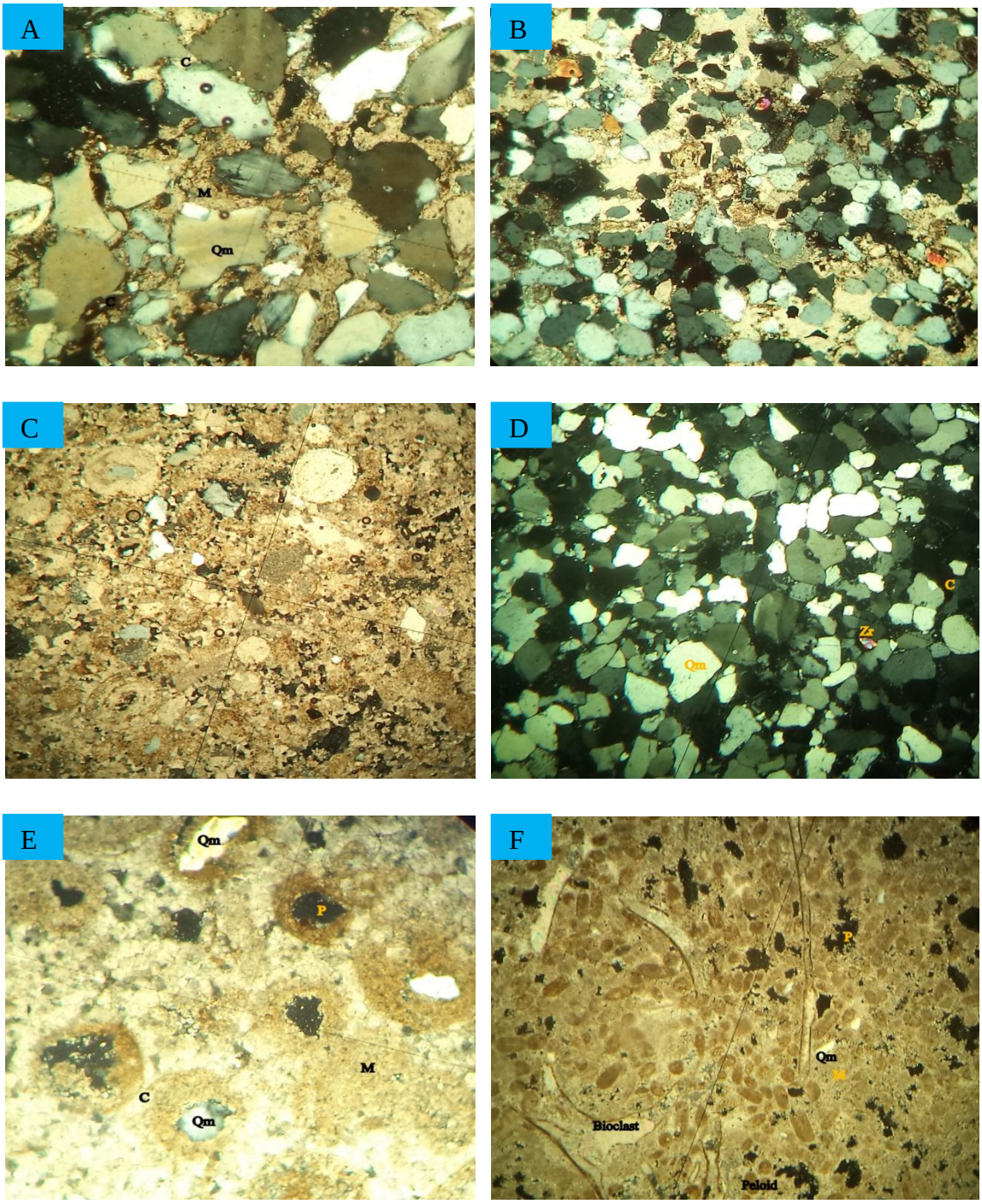


Plate-14: Thin-section photomicrographs showing 1. Calcareous sandstone dominated by subrounded-rounded quartz crystals cemented with carbonate cement containing heavy mineral grains and carbonate mud as a matrix (A & B) 2. Sandy limestone composed of carbonate grains (Ooids & peloids in C & E and peloids & bioclasts in F), mud and minor amounts of quartz grains cemented by calcite cement 3.Texturally matured quartzarenite with heavy mineral grains & dark brown cement (D). A, B & E are with 100X whereas C, D & F are with 40X magnifications. All are under crossed polarized light (XPL).

Sandstone Classification

For the classification of Adigrat Sandstone Formation in terms of composition, 350-550 major framework grains (Quartz, Feldspar and Lithics) have been counted under petrographic microscope from thin-sections and their relative proportions have been determined out of hundred. The relative proportions of cement and matrix have also been estimated.

Table-3: Point count data for sandstone samples collected from Adigrat Sandstone of Dire Dawa area

Samp.No.	% of major components of Sandstone				
	Q	F	L	Matrix	Cement
S31	96.7	2.5	0.8	25	10
S32	97	2	1	25	20
S33	96	4	0	40	15
K-L	100	0	0	30	15
Q-1	100	0	0	20	2
IN-1	99	1	0	25	5
IN-2	99.5	0.5	0	5	30
IN-3	100	0	0	2	5
CH-4	98.5	0.5	1	30	5

Sandy Limestone								
	Intraclast/ Quartz %	Bioclast %	Peloid %	Ooids %	Micrite %	Spary calcite%	Dunham' name	Folk's name
S34	2	3	15	5	10	50	Packstone	Pelsparite
CH-5/K-1	1	25	40	0	10	15	Packstone	Bio-Pelsparite
CH-6/K-2	1-2	10	50	0	13	25	Packstone	Intra-bio-pelsparite

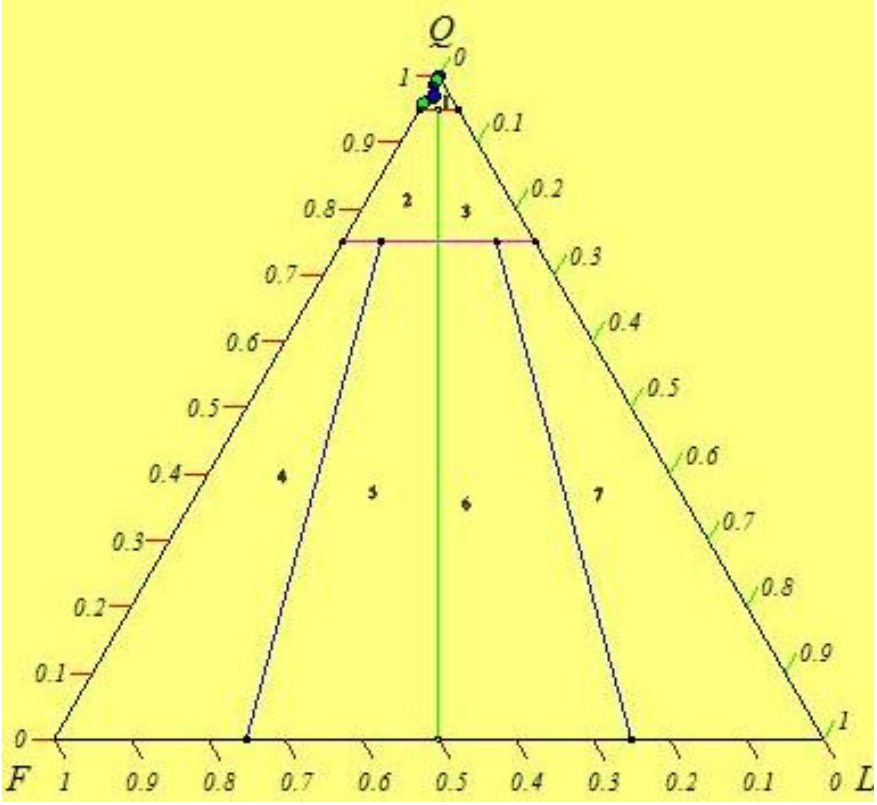


Figure 11: QFL diagram showing the composition of Adigrat Sandstone around Dire Dawa (After Folk, 1980). **1**. Quartzarenite **2**.Subarkose **3**.Sublitharenite **4**.Arkose **5**.Feldspathic Litharenite **6**.Lithic Arkose **7**.Litharenite

As noted from the above point count data (Table: 3) and QFL triangular plots, some selected sandstone samples taken from medium-coarse sandstone beds represent quartzarenite based on Folk (1980) classification scheme and according to Pettijohn et al. (1987), they represent quartzarenite-quartzwacke. On the other hand, the sandy limestone part of the Adigrat Sandstone has been given name based on Dunham's and Folk's classification systems due to the dominance of carbonate components even though it contains minor amount of siliciclastic sediment (Quartz) which is considered as intraclast.

Compositional and Textural Maturity

The mineral grains frequently occur in all samples are quartz (mono and polycrystalline quartz), feldspar (plagioclase and microcline), muscovite, rock fragment and Zircon crystal in most cases cemented with hematite and spary calcite. However, the percentage of quartz grains is very high which is in the range of 95-100%. This shows the abundance of the most stable minerals (Quartz

& Muscovite in Goldich reaction series) relative to unstable mineral grains. Therefore, this rock unit is compositionally mature. There are also well sorted samples composed of sub-rounded-rounded grains without muddy matrix which are texturally considered as matured.

Diagenetic features

Diagenesis is the combination of the overall processes that comes soon after the deposition of sediments. The most important diagenetic processes which lead to porosity reduction in sandstone are compaction, cementation, grain packing and fracturing (Hayes, 1979). The grains are close to each other with linear and convexo-concave contacts between framework grains which shows the close packing and compaction caused by the overburden pressure. The compaction of grains is also observed by the bending of muscovite grains following grain boundaries. Most of the pore spaces present are secondary porosities which are fracture controlled diagenetic products. Intra-granular porosities (vacuoles) are also present which are considered as dissolution porosities caused by silica and calcite dissolution. Due to the close packing of framework grains together with the presence of matrix and cement, the inter-granular pore spaces have been reduced to small percentages even to zero in some cases. In calcareous sandstone and sandy limestone samples significant amount of pore spaces are present in which most of them are diagenetic products due to calcite dissolution.

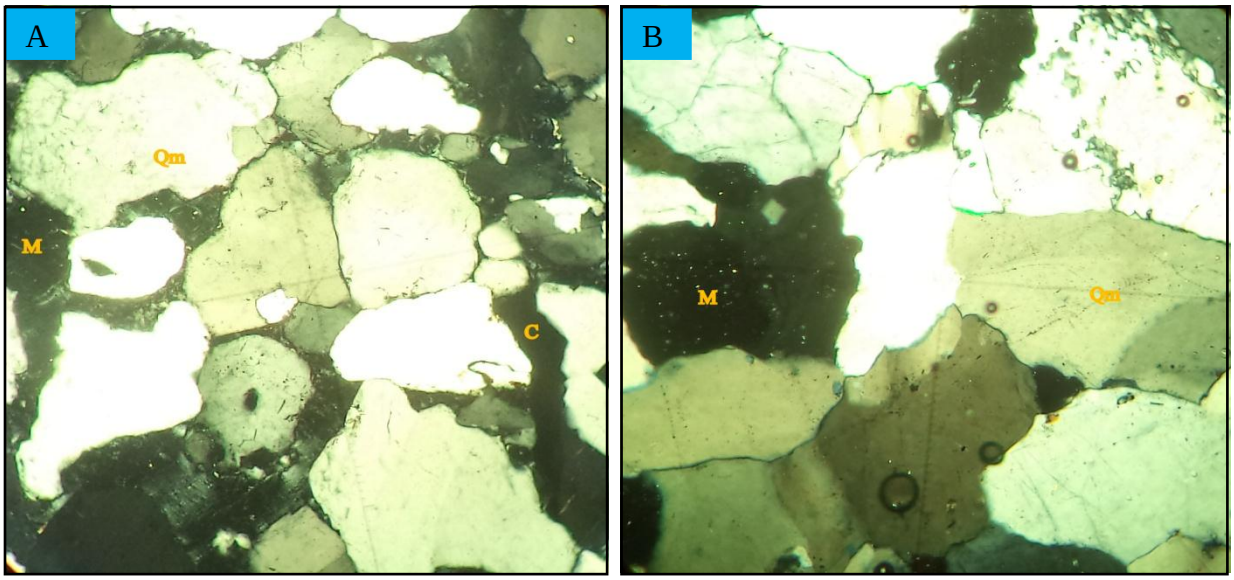


Plate-15: Photomicrographs showing diagenetic features (For additional points, see Plate-13 & 14)

Interpretation of petrographic data

The compositional maturity and the presence of lithic fragments of sedimentary origin together with quartz extinction, surface features and vacuoles show that the source of sediments was craton interior with basement rocks dominated by quartz veins and Paleozoic sedimentary rocks. Therefore, it is possible to conclude that the uplift of cratonic block containing basement rocks and Paleozoic sediments with consequent prolonged weathering and erosion processes gave rise terrigenous sediments. The rounded-subrounded siliciclastic grains are interpreted to travel far distance before being deposited in their final destination (depositional environment) by fluvial action from uplifted sediment source area and further reworking by waves along shelf environment. The grains are almost in the same size range which reflects the sorting capability of the transporting agent. The presence of heavy mineral grains particularly within calcareous sandstone is also indicator of long term transportation and reworking that leaved the most stable, abraded, rounded and well sorted grains.

The presence of carbonate wacke-packstone facies with randomly distributed quartz grains shows the cessation of clastic supply and the start and dominance of carbonate production which is considered to be the transition from clastic deposition to carbonate deposition caused by transgression event.

4. CORRELATION

Correlation has been done among the studied sections to compare local variations and similarities by which three of them contain correlatable facies associations in a vertical succession except some differences. Regional wise correlation in terms of lithology as well as depositional environments has also been made.

In the Dire Dawa & Harar area, Shillabo (Ogaden) and Berbera (Northern Somalia), clastic sedimentation had been operating and progressively ceased in the interval of Bajocian-Bathonian (175-165 Ma) (Fig.: 13). But, during this time, carbonate sedimentation was ongoing process in central Somalia, parts of Ogaden and Mandera Lugh (Kenya) basins starting from Early Toarcian (190 Ma) which is considered as the beginning of early transgression and flooding of this part of east Africa (Bosellini et. al., 2001). Clastic sedimentation in the Blue Nile basin was also started during this time in which most of its upper part is dominated by gypsum-shale unit called Gohatsion Formation (Assefa, 1980 and Russo et al., 1994) indicating the formation of transitional environment for evaporite deposition.

Braided stream depositional environment was interpreted for the Adigrat Sandstone Formation of Harar by Greitzer (1970) and Tadesse & Hailemariam (2006) and by Bosellini et al. (2001) for the Dire Dawa equivalent. However, by conducting detailed analysis of lithology, sedimentary structures and trace fossils, meandering stream, transitional (lagoonal-tidal flat) and shallow marine (foreshore-offshore) environments have been interpreted from this study.

The depositional environment for the Ogaden equivalent which is found south of the study area has also been interpreted as braided to meandering river (Worku and Astin, 1992).

In the Blue Nile basin, a range of depositional environments have been interpreted for the Adigrat Sandstone Unit by different workers at different time. These are fluvial channel deposit (Assefa, 1975, Russo et al., 1994 and Gani et al., 2008), alluvial fan, meandering river and lacustrine (Wolela, 2008), fluvio-estuarine, barrier-lagoon and strand plain systems (Dawit & Bussert, 2009 and Dawit, 2010). Dawit (2010) also interpreted fluvial system, fluvio-estuarine system, deltaic system, strandplain system, barrier island–lagoon system, and open-coast tidal flat system for the Adigrat Sandstone Formation of Mekele basin. The depositional environment

for the Mekele equivalent was also formerly interpreted as estuarine-deltaic or continental (Beyth, 1972).

According to Gani et al. (2008), a repetitive fining-upward facies succession has been identified in the Blue Nile basin and interpreted as fluvial channel deposits within the lower sandstone unit in which its top part is overlain by glauconitic sandy mudstone unit which underlies lower limestone and gypsum unit.

In Tanzania, the Middle Jurassic (Bajocian-Bathonian) was the time of transgression that changed the coastal basins of Tanzania into continental shelf in which much of the deposition took place in shallow marine-neritic depositional environments over the continental karoo sediments (Mpanda, 1997).

Equivalent unit for Adigrat Sandstone in northwest Yemen is also known as Kuhlan Formation which overlies the Lower Paleozoic Akbarah Formation and overlain by the limestone unit (Amran Group) (Al-Wosabi and Al-Mashaikie, 2006). According to these authors, Kuhlan Formation contains three lithofacies associations (distal turbidites, proximal turbidites and shallow marine represented as lower, middle and upper units respectively) and its mineralogic composition shows quartz greywacke type in the lower and middle units whereas the upper unit is dominated by quartzarenite with ferruginous and minor carbonate cements. The age of this unit is considered to be Lower-Middle Jurassic (Hadden, 2012). The depositional environment of the upper unit as well as the mineralogical composition of the whole unit is highly correlatable with that of the Adigrat Sandstone studied under this research work.

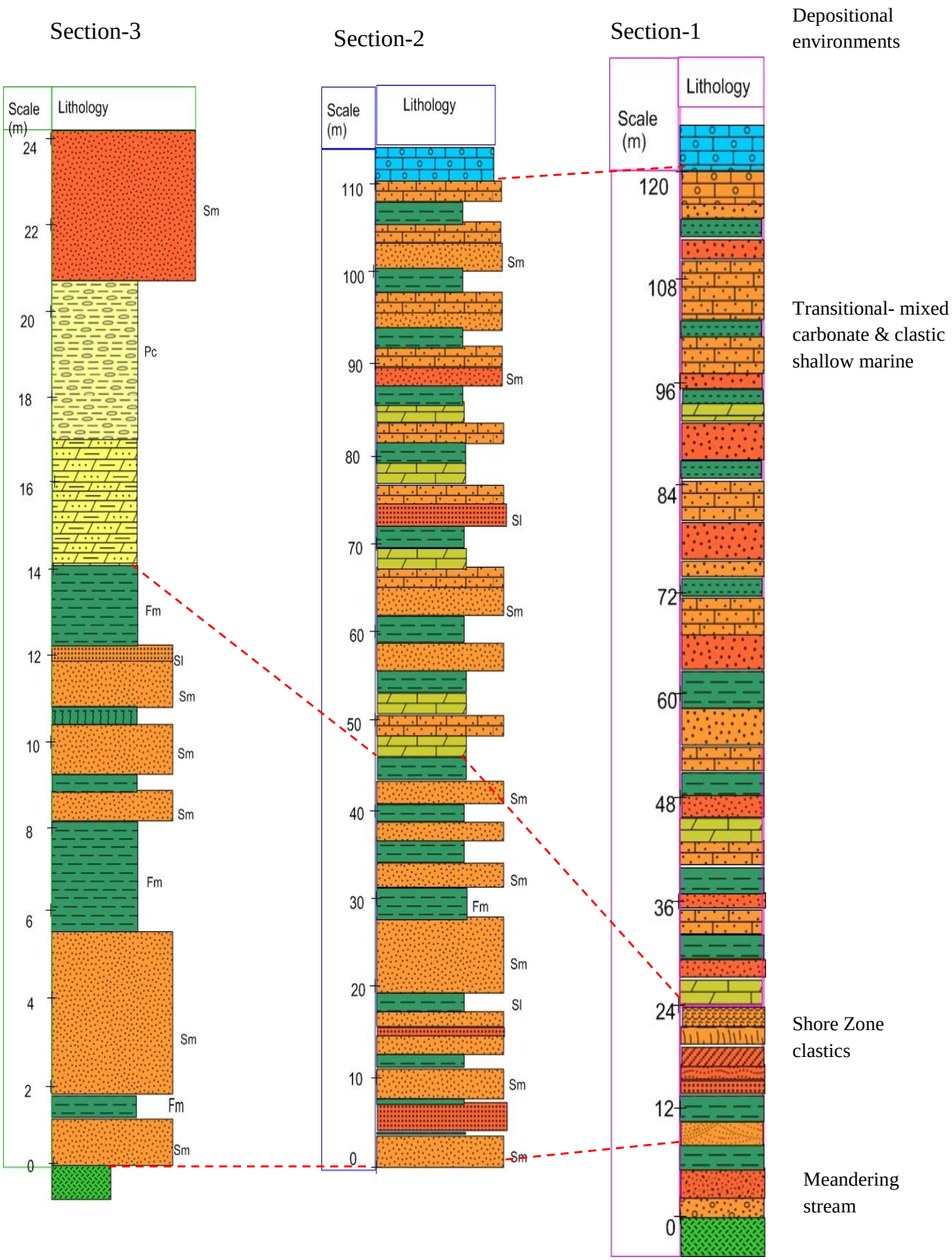


Figure 12: Lithostratigraphy & correlation of depositional environments between the studied sections

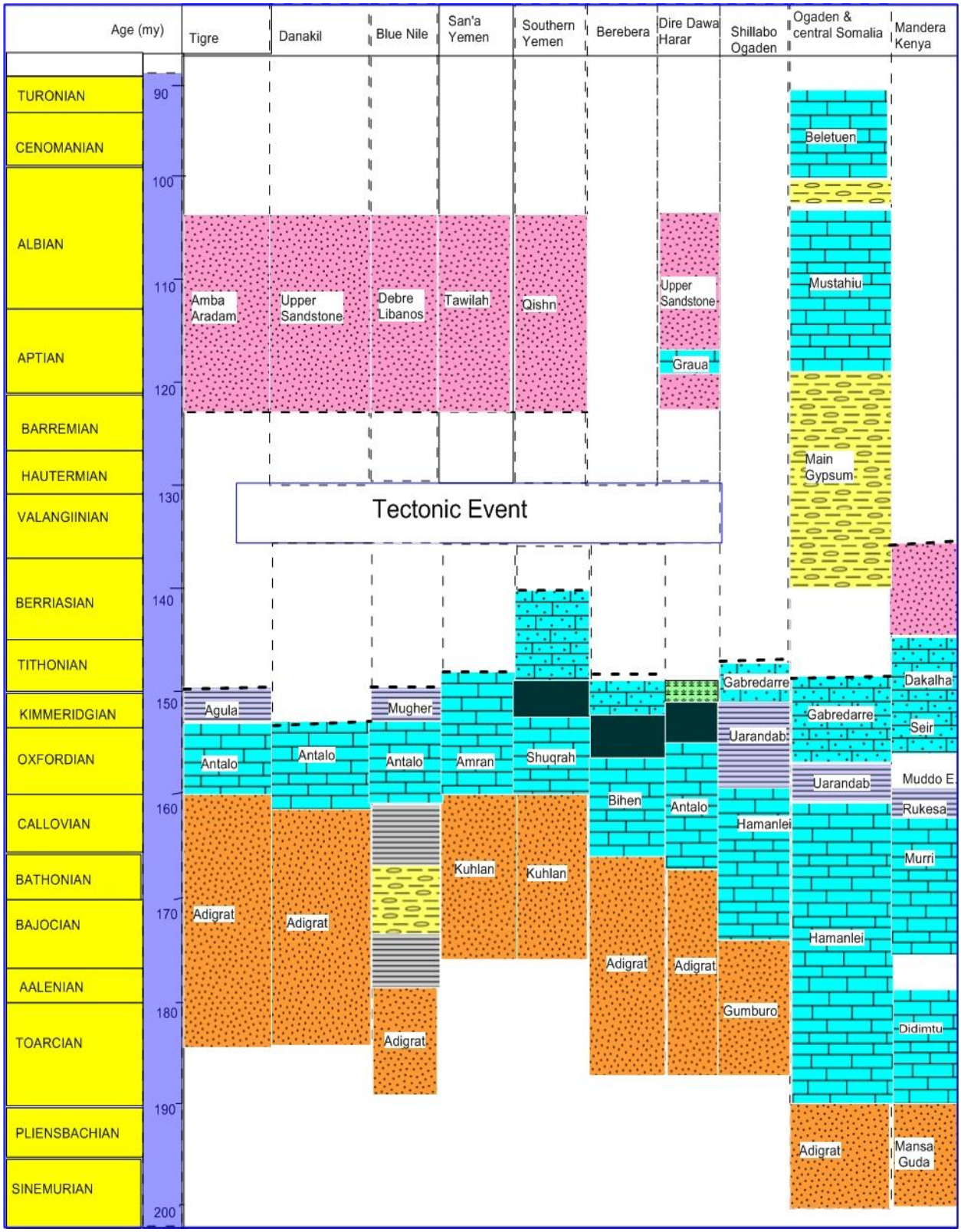


Figure 13: Regional correlation chart of the Mesozoic successions of the Horn of Africa and southern Arebia (Yemen) (After Bosellini et al., 2001and references therein).

5. DISCUSSION

5.1 FACIES ASSOCIATIONS

Facies analysis is the interpretation of strata in terms of depositional environments (or depositional systems) commonly based on a wide variety of observations. After detailed observation and description of rocks at outcrop or taken from cores, facies can be subdivided into subfacies on the basis of sedimentary structures, composition, texture, bedding, color and fossil content or it can be grouped into association of facies (H.G. Reading, 2001). Facies associations constitute several facies that occur in combination and typically represent one depositional environment. Facies successions (or facies sequences) are facies associations with a characteristic vertical order of temporally different units and their spatial relationship has been explained by Johannes Walther for the purpose of interpreting in terms of depositional environment. Walther's Law (1894) states that two different facies found superimposed on one another and not separated by an unconformity, must have been deposited adjacent to each other at a given point in time. Where there is a conformable vertical succession of facies with no major breaks, the facies are the products of environments which were originally laterally adjacent.. The vertical succession of facies is produced by the lateral migration of one environment over another.

The facies types identified from the present study have been grouped into four lithofacies associations. These are meandering stream, transitional (lagoonal-tidal flat), Shore zone clastics (foreshore-shoreface-offshore transition-offshore) and shallow marine mixed carbonate & clastic facies associations.

Meandering stream facies association

The common feature of meandering river deposits is lags at the base, point bar sandstone at the middle and mudstone facies at the top with a general fining upward succession formed by the vertical aggradation of different size clastic sediments as a result of lateral migration of spatially adjacent depositional environments through time. The same facies succession that comprises poorly sorted massive pebbly sandstone facies, poorly sorted medium grained massive sandstone, planar-trough cross-bedded fine sandstone facies with crudely developed ripples and mudstone facies at the top showing a fining upward facies succession starting with lags overlying scoured surface has been identified from the present study.

Lagoonal-tidal flat facies association

This facies association comprises dolomite, gypsum-shale, sandstone and mudstone lithofacies types generally interpreted as deposited in transitional environment.

Shore zone clastic facies association

The facies types formed within continental shelf environments are commonly controlled by the shore zone waves, the activities of organisms and depth of the water. Thus, by considering wave indicator sedimentary textures and sedimentary structures together with traces of organisms, six lithofacies types namely herringbone cross-stratified fine sandstone, hummocky cross-stratified fine sandstone, slightly bioturbated normal graded sandstone, intensively bioturbated fine-medium grained sandstone, horizontally laminated fine grained sandstone and greenish color massive mudstone facies containing traces of organisms such as vertical burrows have been identified and grouped together under this facies association.

Shallow marine mixed carbonate & clastic facies association

Shallow marine environments are areas of accumulation of substantial amounts of terrigenous clastic material brought in by rivers from the continental realm whereas shallow seas that are not supplied by much terrigenous material may be areas of carbonate sedimentation, especially if they are in lower latitudes where the climate is relatively warm (Nichols, 2009). Therefore, the facies types which contain both terrigenous and carbonate sediments (Calcareous sandstone and sandy limestone lithofacies) are grouped under this facies association.

Generally, these facies associations are found within the studied sections of Adigrat Sandstone Formation in a vertical succession starting with meandering stream facies association at the bottom overlying the basement rocks, shore zone clastic facies association overlain by lagoonal-tidal flat facies association at the middle and shallow marine mixed carbonate & clastic facies association at the top conformably underlies the limestone unit.

5.2 PALEOGEOGRAPHY & DEPOSITIONAL ENVIRONMENTS

There were two major tectonic events in Northeast Africa and Arabia during Late Permian (250 Ma) (Schandelmeier et al., 1997). These were the initiation and development of Neotethyan passive margin due to detachment of the Cimmerian blocks (Stampfli and Borel, 2001) and sever intra-plate deformations. Deposition of karoo sediments (Late Carbonifereous- Permian) in continental condition was prevailed following these intra-plate fault controlled basins whereas shallow marine condition was restricted along most part of Arabia and reaching up to Madagascar following the rift between East and West Gondwana. According to these authors, the early development of intracratonic transtensional basins was probably related to large scale strike-slip movements along transcontinental shear zones such as Trans African Lineament (TAL), Central African Shear Zone (CASZ) & Luanda-Afar Lineament (LAL).

The Late Triassic-Early Jurassic paleogeography of southeastern and eastern Ethiopia shows continental-shallow marine depositional environments (Reynolds et al., 1997). According to these authors, the onset of sea level rise and major transgression event in the interval of Toarcian and Bajocian stages created shallow marine conditions in central, southern and eastern Ethiopia, northern Kenya, Somalia and Madagascar. During the interval between Toarciian- Early Bajocian, there was general facies change from continental to mixed continental-marine which is recognized in the marginal basins of East Africa, Madagascar and Western Australia (Hankel, 1994).

The facies succession that represents the studied unit reflects changes from continental-marine facies and its top part is aged as Bajocian-Bathonian from paleontological evidences (Bosellini et al., 2001). On the other hand, in the Abay and Mekele basins, the age of this unit has been determined by using palynological dating as Late Triassic (Late Carnian–Early Rhaetian) to latest Early–Middle Jurassic (Late Toarcian–Early Callovian) (Dawit, 2010) that indicates correspondence of the age of the top part of the presently studied unit with equivalent unit of the Abay and Mekele basins. Therefore, by considering these facts, the formation of the basin as well as the subsequent sediment accumulation to form this unit could be related to the Late Triassic-Early Jurassic paleogeography of East Africa and Norian-Callovian sea level fluctuation even though the age of the lower part of the unit within the study area has not been determined. Therefore, attempts have been made to relate the results of this study with the Late Triassic-Early

Jurassic paleogeography of East Africa and the global sea level fluctuation curve starting from Norian to Callovian ages proposed by Reynolds et al. and Schandelmeier et al. (1997).

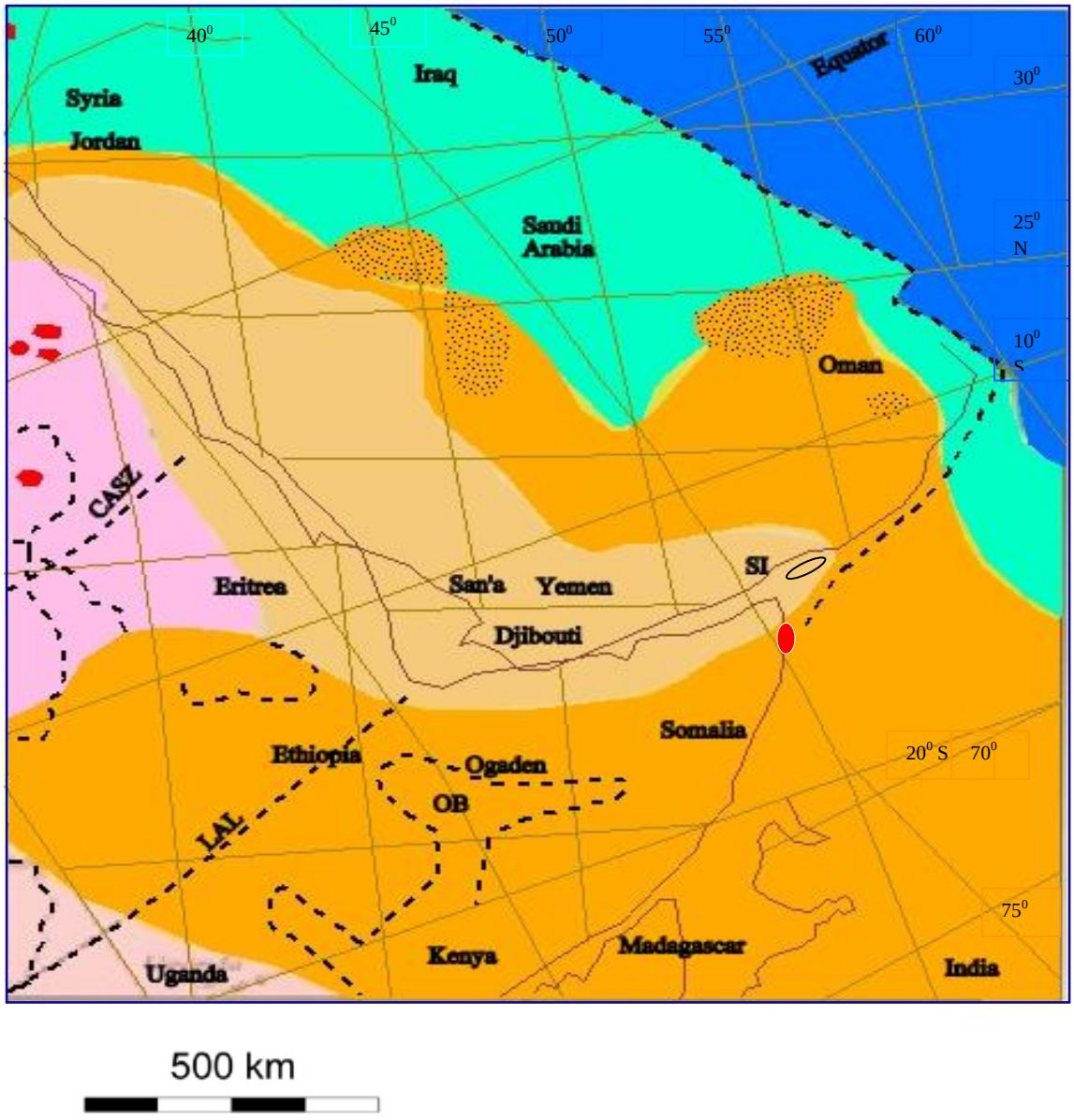
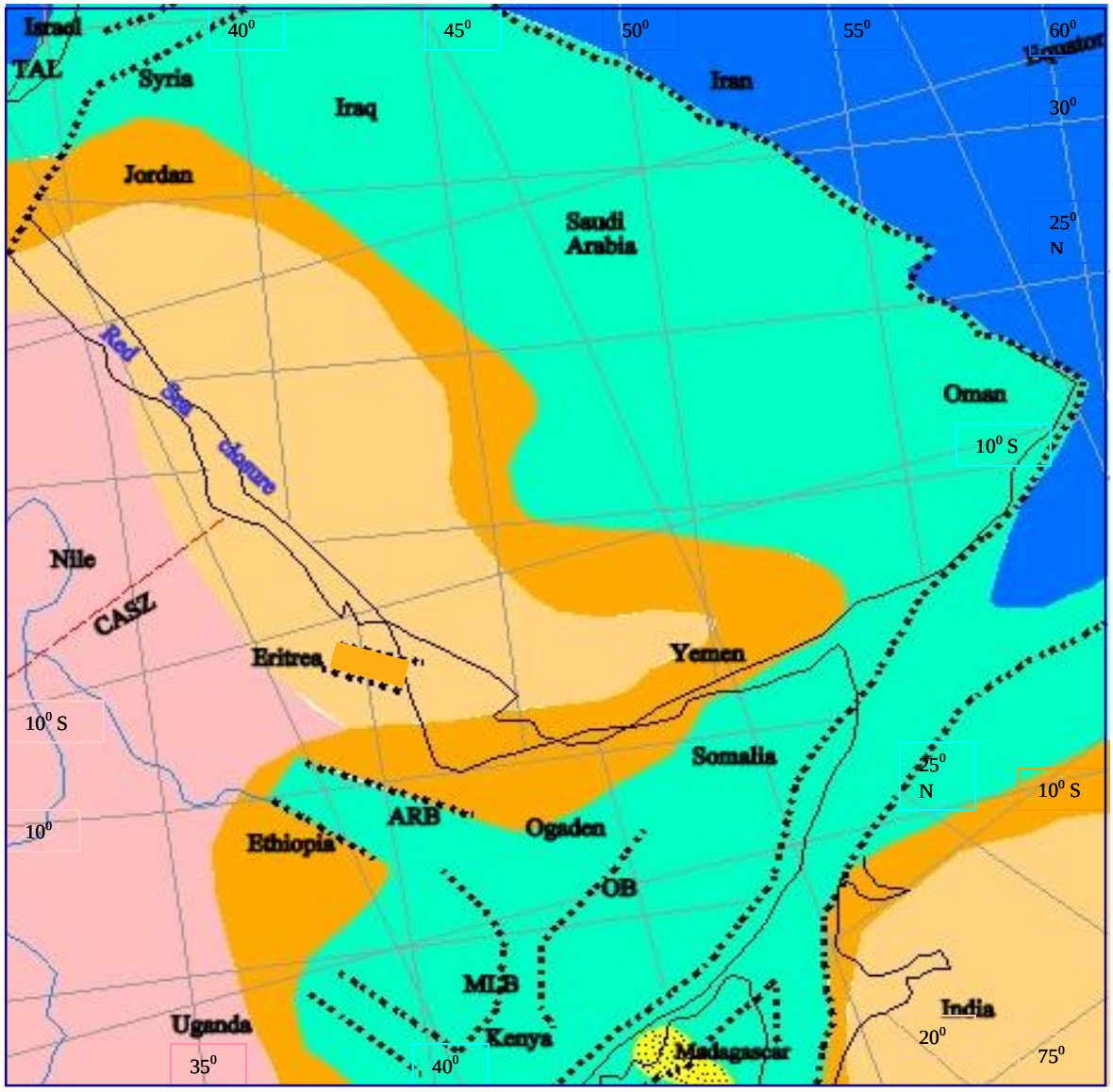


Figure 14: Late Triassic (220 Ma) palaeogeography of East Africa and most part of the Arabian platform (After Schandelmeier et al., 1997).



Legend

Exposed Basement

Area of erosion/non deposition

Continental

Shallow marine

Deep marine

Intra-plate volcanism ····· Rifts

Abbreviations

ARB=Abay River Basin

CASZ=Central African Shear Zone

LAL=Luanda-Afar Lineament

MLB=Mandera Lugh Basin

OB= Ogaden Basin **SI**= Socotra Island

TAL=Trans African Lineament

Figure 15: Early Jurassic (180 Ma) palaeogeography of East Africa and most part of the Arabian platform (After Reynolds et al., 1997). (**Scale: 1 cm = 500 km**)

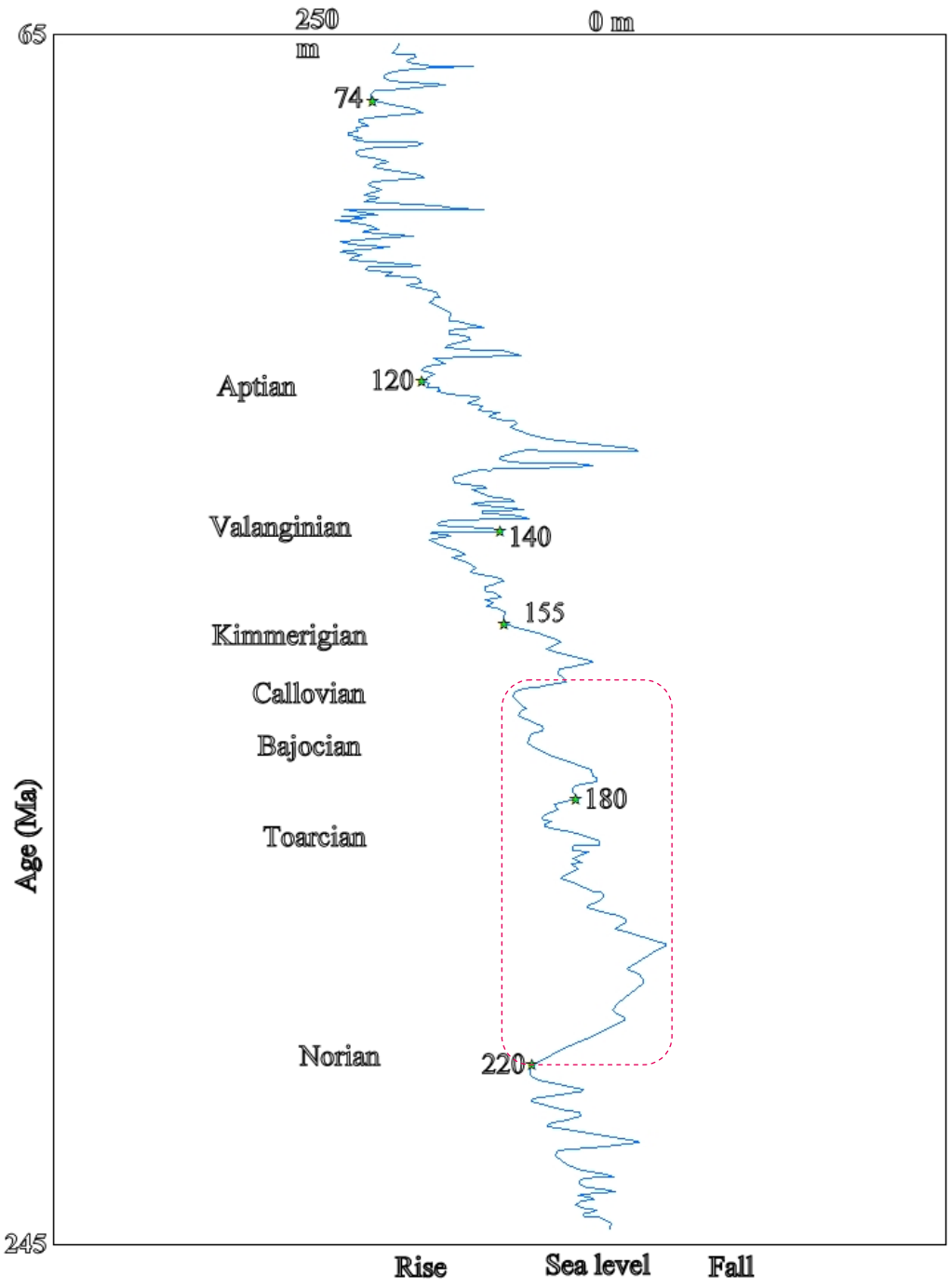


Figure 16: Mesozoic sea level fluctuation curve (After Harland et al., 1990 in Schandelmeier et al., 1997).

In the Sequence stratigraphic point of view, two sequence stratigraphic surfaces have been identified. These are subaerial unconformity and transgressive surface. The stratal stacking pattern shows fluvial (meandering stream) facies association overlying subaerial unconformity and underlies shore zone sandstone and mudstone facies overlain by shallow marine mixed clastic and carbonate facies association. The surface separating the meandering stream deposit from the overlying shore zone deposit is considered as transgressive surface (TS) and the fluvial (meandering stream) deposit is lowstand system tract (LST) (e.g. Posamentier and Allen, 1999) whereas the shore zone and shallow marine clastic & carbonate deposit is transgressive system tract (TST). This transgressive system tract has a deepening upward trend which is considered as its diagnostic retrogradational stacking pattern (Catuneanu, 2002).

The reservoir characteristic of the Adigrat Sandstone Formation has also been evaluated from the analysis of petrographic data as sandstone reservoirs are created by the accumulation of large amounts of clastic sediments which have a depositional porosity and permeability controlled by grain size, sorting, and packing of the particular sediments (Halliburton, 2001 and Morse, 1994). From thin section analysis mainly of textural features and the effect of diagenesis, it has been understood that the framework grains are packed together and the inter-granular pore spaces are filled with matrix and cement that totally reduce its potential of containing and transmitting fluid. Thus, generally, the reservoir quality of the Adigrat Sandstone of the Dire Dawa area is suggested to be poor. However, the top most part of this unit is dominated by calcareous sandstone and sandy limestone which have significant amount of dissolution porosities in that this part of the unit may serve as a good reservoir rock.

5.3 DEPOSITIONAL MODEL

Depositional models are conceptual frameworks that show paleogeography and depositional environments. In the present study, the composite stratigraphy and general facies succession show fluvial clastics (meandering stream type) at the bottom, shore zone clastic deposits at the middle and mixed carbonate and clastic shallow marine deposits at the top with the associated evaporate deposits. Therefore, from the present study, the interpreted depositional environment of Adigrat Sandstone Formation of south eastern Ethiopia comprises continental-continental shelf environments (meandering river, lagoonal-tidal flat and foreshore-offshore depositional systems) (Fig.:17 below). This shelf is described in terms of the depth to which different processes interact with the sea floor.

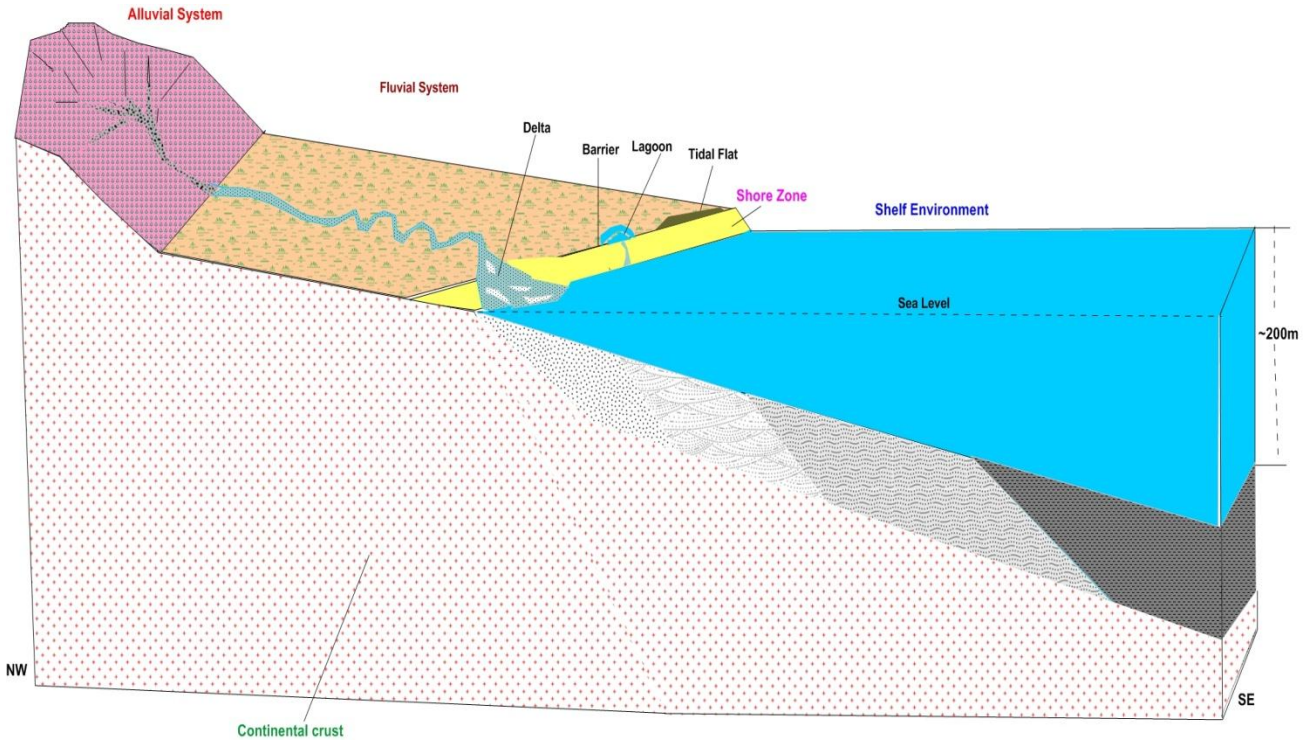


Figure 17: Faces Model showing the depositional environments for the Lower Sandstone Unit of south eastern Ethiopia interpreted from the present study.

6. CONCLUSION

This study has brought a new finding on the depositional environment of the Lower Sandstone Unit/Adigrat Sandstone of eastern Ethiopia particularly of Dire Dawa area. Three major subenvironments have been interpreted mainly from field data such as lithology, sedimentary structures and trace fossils together with thin-section analysis of sandstone composition. These depositional environments are: meandering stream, transitional (sabkhas, ponds, lagoons, tidal flats) and shallow marine (e.g. foreshore and shoreface) environments.

Most of the mudrock beds are greenish in color indicating the presence of authigenically formed mineral called glauconite which is a common component of sandstones and mud rocks formed in shallow marine environment (Nichols, 2009).

Bioturbation is observed in sand beds and vertical burrows are identified from beds of mud rocks which show the activity of organisms living in shelf environments with shallow marine conditions. Hummocky and swaley cross-stratifications preserved in fine sandstone beds also show storm dominated shore zone environment of deposition. Herringbone cross-stratification has also been identified in fine sandstone bed signifying shore wave influence along the shelf environment. The presence of thin laminae of gypsum interbedded with shale within the lower sandstone unit is also another indication of transitional environment around shelf areas. On the other hand, the top most part of the lower sandstone unit is mostly of calcareous sandstone indicating shallow marine clastic deposition together with calcite precipitation from calcareous shell of organisms lived in shallow marine environment.

Generally, the composite stratigraphy of the Adigrat Sandstone Unit of southeast Ethiopia shows a change in facies types from continental-marine in a vertical succession from bottom-top which can be interpreted as continental-shalow marine clastics and carbonate environments with the associated transitional environments.

7. RECOMMENDATION

The southeastern part of Ethiopia has an interesting geology which has not been studied very well particularly the sedimentary succession that contains much more detailed records of the Earth's history. Researchers have to turn their attention to this neglected sedimentary basin of Ethiopia so as to conduct detailed investigation as the area is potential site to carryout wide range of scientific researches.

Depositional Environment: Even though this study has brought new results with respect to the depositional environment of Adigrat Sandstone Unit of southeastern Ethiopia relative to previous works, it has its own limitations because of the number of studied sections and their relative closeness as well as the incompleteness of some sections. The results of the present study may be considered as the first ground that encourages future researchers but may not show the complete and overall depositional environment for this unit. Therefore, the overall depositional environment representing the whole unit within this particular basin has to be determined by making detailed descriptions and analysis from a number of complete sections throughout the basin.

Age: The exact age of the Adigrat Sandstone Unit of southeastern Ethiopia is unknown except its upper limit which has been considered as Bajocian-Bathonian from paleontological evidences (Bosellini et al., 2001). There are sediments (black shale) which could be productive for palynological studies in that future researchers have the opportunity to carryout palynological dating so as to determine the age of this unit.

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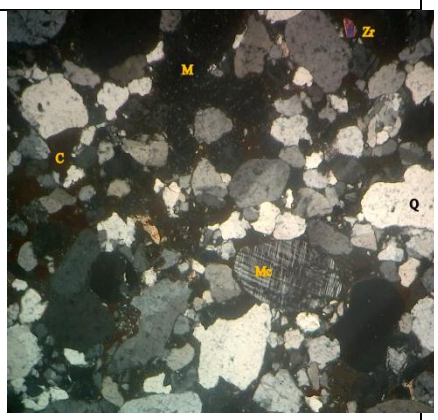
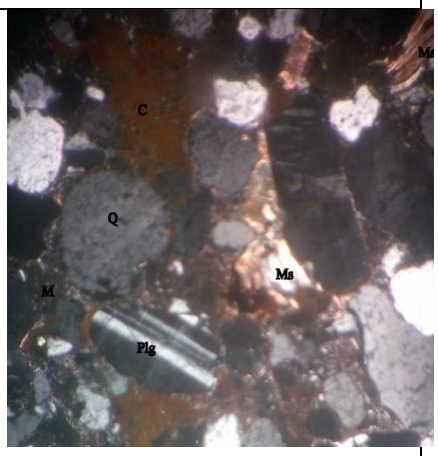
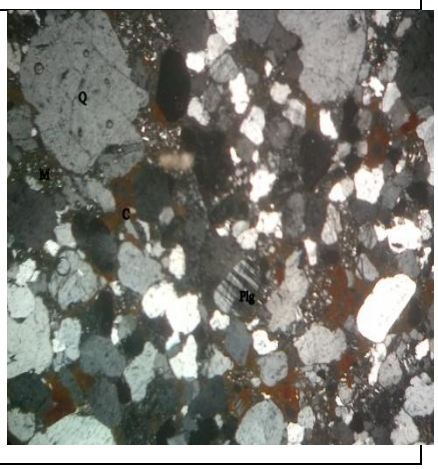
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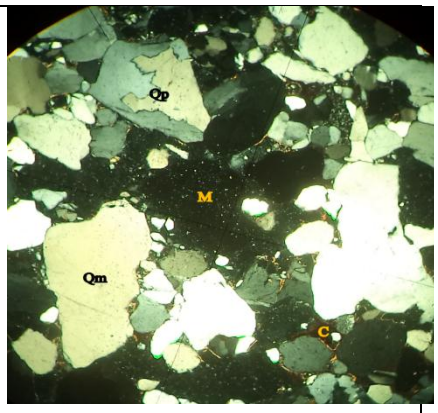
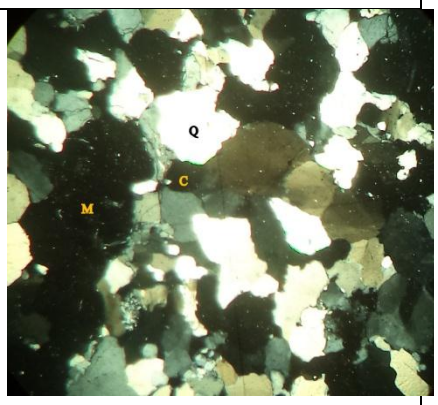
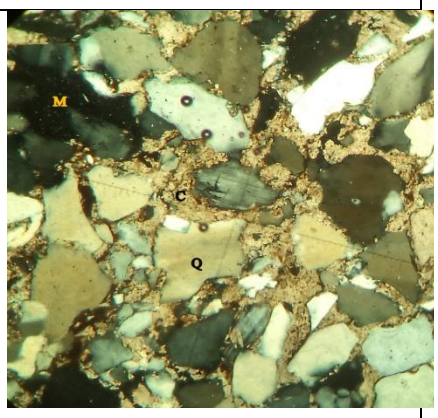
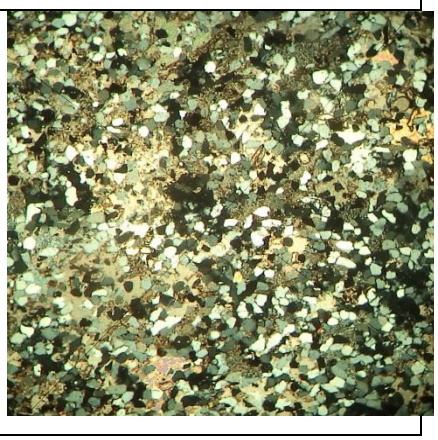
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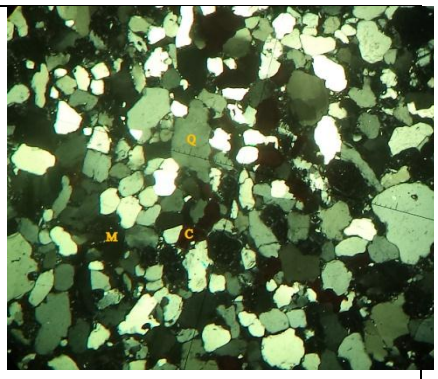
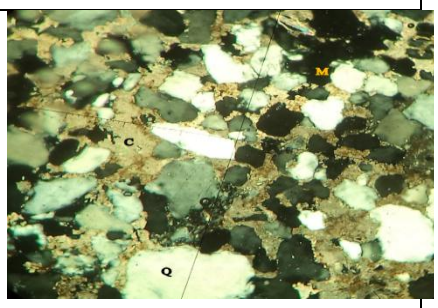
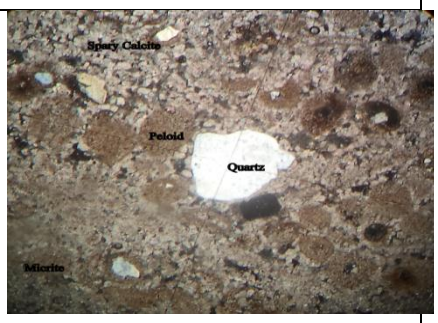
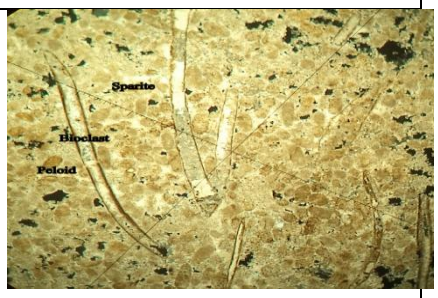
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APPENDIX

Table-1: Petrographic result of some sellected samples taken from Adigrat Sandstone Unit of Dire Dawa

S.code.	Description	Thin-section photomicrograph example
S31	This thin-section comprises large number of sub-rounded to rounded quartz grains of almost the same grain size, Feldspar grains (Plagioclase & Microcline), Flakes of Muscovite, Heavy minerals (Zircon?), Muddy matrix and Reddish color (Hematite) cement. (100X magnification under XPL)	
S32	It comprises large number of sub-rounded to rounded, Mono-polycrystalline quartz grains of almost the same grain size, Feldspar grains (Plagioclase & Microcline), Flakes of Muscovite, Polymineralic dirty grains (Rock fragments), Heavy minerals (Zircon?), Muddy matrix and Brownish color (Biotite) cement. (100X magnification under XPL)	
S33	It comprises large number of sub-rounded to rounded, Mono-polycrystalline quartz grains with variable grain sizes, Feldspar grains (Plagioclase), Heavy minerals (Zircon?), Muddy matrix and Brownish color (Biotite) cement. Fine grain quartz crystals also serve as matrix filling the inter-granular pore spaces. (100X magnification under XPL)	

K-L	It contains rounded-subrounded mono-polycrystalline quartz grains of different size, dark red cement and very dark muddy matrix. It is medium-poorly sorted. (40X magnification under XPL)	
Q-1	It contains angular, rounded-subrounded mono-polycrystalline quartz grains of almost the same size, dark red cement and very dark muddy matrix. It is medium sorted. (40X magnification under XPL)	
IN-1	It contains rounded-subrounded mono-polycrystalline quartz grains of almost the same size, spary calcite cement and very dark muddy matrix, micrite and insignificant amount of feldspar. It is medium-poorly sorted. (100X magnification under XPL)	
IN-2	It contains highly rounded medium size mono-crystalline quartz grains of the same size, large amount of spary calcite cement, micrite and insignificant amount of feldspar. It is medium sorted. (40X magnification under XPL)	

IN-3	It quartz rich with small proportions of dark brown cement and dark muddy matrix. The quartz grains are well rounded, same size, mono-crystalline with well sorting. (40X magnification under XPL)	
CH-4	It contains rounded-subrounded mono-polycrystalline quartz grains of almost the same size, spary calcite cement and micrite and insignificant amount of feldspar & lithics. It is medium-poorly sorted. (100X magnification under XPL)	
S34	It contains Peloids, Ooids, Bioclast, Quartz, Micrite and dominated by Spary calcite cement. The Ooid grains are poorly developed following quartz grains at the center as a nucleus. (100X magnification under XPL)	
CH-5/K-1	It contains high amount of Peloids together with Bioclasts, Quartz grains, Micrite and Spary calcite cement (40% Peloids, 25% Bioclast, 15% Sparite & 10% Micrite). (40X magnification under XPL)	
CH-6/K-2	It contains high amount of Peloids together with Bioclasts, Quartz grains, Micrite and Spary calcite cement (50% Peloids, 10% Bioclast, 25% Sparite & 13% Micrite). (40X magnification under XPL)	