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Post Box No. 4007, Navarangpura, Ahmedabad-380 09. ✆ Phone : 079-26302872 ● Fax : 079-26300242

UGC Project: F. 47-1026/14 (WRO) **Depositional Environment of Himmatnagar (Ahmednagar) Sandstones of Lower Cretaceous Age, North Gujarat, India.**	**Dr. Nishith Y. Bhatt** ***Principal Investigator*** **Dr. Paras M. Solanki, *Co-P.I.***

To,
Dr. R. Manoj Kumar
The Joint Secretary
University Grants Commission
(MHRD, Govt. of India), Western Regional Office,
Ganeshkhind
Pune – 411007.

M. G. SCIENCE INST.
Ahmedabad-9.
Outward No. 7471/2020
Date : 15/07/2020
Sign. :

Subject: 1. Submission of documents for the Minor Research Project awarded to Dr. Nishith Y. Bhatt (F. 47-1026/14 (WRO) dated 20-2-2015) with reference to your letter no. F. NO. 3-10/13 (WRO/Policy-MRP dated 24/06/2020. The letter was received by us wide Inward no. 2594/20 dated 11.07/20.
2. Letter dated 05/02/2020 for file no. 47-1026/14 (WRO), received by us on 11/02/2020 inward no. is 2038..

Dear Sir,
Greetings! Actually delay has occurred as PI or Co-PI has not received the grants for second year and that is why report was not submitted. At present, we have received your letter in Feb, 20 but due to COVID-19 delay has occurred in the submission.

Please find herewith the things that were requested in the letter.

Final Project Completion Report and Executive Summary.

Regrets for delay in reply. This is to request you to settle the Minor Research Project account and SEND the **NO DUE CERTIFICATE** and oblige.

Thanking you and regards,

Dr. N.Y. Bhatt
Principal Investigator
(DR. N. Y. BHATT)
HEAD
DEPARTMENT OF GEOLOGY
M. G. SCIENCE INSTITUTE
NAVRANGPURA, AHMEDABAD-9

M. G. SCIENCE INSTITUTE
AHMEDABAD

Dr. B.K. Jain
Principal
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UGC Project: F. 47-1026/14 (WRO) Depositional Environment of Himmatnagar (Ahmednagar) Sandstones of Lower Cretaceous Age, North Gujarat, India.	Dr. Nishith Y. Bhatt *Principal Investigator* Dr. Paras M. Solanki, *Co-P.I.*

CERTIFICATE

This is to certify that the Minor Research Project titled **'Depositional Environment of Himmatnagar (Ahmednagar) Sandstones of Lower Cretaceous Age, North Gujarat, India'** awarded to P.I. Dr. N.Y. Bhatt has been completed and executive summary of the project has been uploaded on the college/university web site, the URL link is mgscience.ac.in/pdf/executive-summary-UGC-MRP-NYB.pdf. This certificate is as per the requirement under prescribed Minor Research Project guidelines.

Dr. N.Y. Bhatt
Principal Investigator

(DR. N. Y. BHATT)
HEAD
DEPARTMENT OF GEOLOGY
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PRINCIPAL,
M. G. Science Institute,
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Executive Summary Report of the UGC Minor Research Project

DEPOSITIONAL ENVIRONMENT OF HIMMATNAGAR (AHMEDNAGAR) SANDSTONES OF LOWER CRETACEOUS AGE, NORTH GUJARAT, INDIA

Submitted to the

University Grants Commission

(UGC Ref No. F. 47-1026/14 (WRO) dated 20 February, 2015)

by

DR. NISHITH YASHVANTRAY BHATT (PI)

AND

DR. PARAS MUKUNDBHAI SOLANKI (CO-PI)

DEPARTMENT OF GEOLOGY
M.G. SCIENCE INSTITUTE
AFFILIATED TO
GUJARAT UNIVERSITY
AHMEDABAD - 380009

July 2020

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UGC Project: F. 47-1026/14 (WRO) **Depositional Environment of Himmatnagar (Ahmednagar) Sandstones of Lower Cretaceous Age, North Gujarat, India.**	**Dr. Nishith Y. Bhatt** ***Principal Investigator*** **Dr. Paras M. Solanki, *Co-P.I.***

UGC Minor Research Project **(F. 47-1026/14 (WRO) dated 20-2-2015)**

Final Report

The Minor Research Project was undertaken with the objective of identification of depositional environment of Himmatnagar (Ahmednagar) Sandstones of Lower Cretaceous Age, North Gujarat, India.

The lower Cretaceous age of Himmatnagar Sandstone Formation represent wide range of conditions from low to high wave and current energy. This can be deduced by sedimentological and palaentological study of the area.

Himmatnagar Sandstone Formation is divisible into three parts: Lower Member, Middle Member and Upper Member. Lower Member is exposed along Sabarmati River and its surroundings, Middle Member is exposed along Hathmati River and surroundings while Upper Member is deposited on both of these Members.

Eight lithofacies have been identified in the Himmatnagar Sandstone Formation among which all are exposed in different parts of the study area. The lithofacies are 1. Basal Conglomerate (BC) lithofacies; 2. Horizontally-Stratified Sandstone (HSS) lithofacies; 3. Cross-Stratified Sandstone (CSS) lithofacies; 4. Silty-Shale (SS) lithofacies; 5. Intercalated Shale-Sandstone (ISS) lithofacies; 6. Planar Cross-Stratified Sandstone (PCSS) lithofacies; 7. Grey Wacke (GW) lithofacies and 8. Gritty-Pebbly Cross-Stratified Sandstone (GPCSS) lithofacies.

Based on trace fossils, geometry of the beds, sedimentary structures and absence of roots of plants (which suggests transported nature), upper shoreface to foreshore and near-shore aeolian environment of deposition can be interpreted for Lower Member, while on the same bases upper shoreface to foreshore environment of deposition for Middle Member of Himmatnagar Sandstone Formation.

While based on uneven erosional-unconformable lower contact in channel structures, south to southwest trough cross-stratification, presence of angular to sub-rounded gravely to cobbly fragments, absence of plants except wood logs, wide occurrence and limited thickness suggest deposition of Upper Member in fluvial to estuarine environment of deposition.

Total 23 ichnofossils have been identified in the study area, such as *Arenicolites, Calycraterion,Chondrites,Circulichnus, Cochlichnus, Desmograpton, Diplocraterion, Gordia, Gyrochorte, Haentzchelinia, Isopodichnus, Lobichnus, Monocraterion Ophiomorpha, Palaeophycus, Planolites, Phoebichnus, Psilonichnus, Rhizocorallium, Rosselia, Skolithos, Teichichnus* and *Thalassinoides.* Most of the trace fossils indicate marginal marine to marine environment of deposition.

Three ichnofacies have been recognized like *Psilonichnus* ichnofacies, *Skolithos* ichnofacies and *Cruziana* ichnofacies, which depicts aeolian to upper-middle shoreface environment of deposition. Upper Member repented cross-stratified sandstone, gritty pebbly beds, trough cross-stratification indicate fluvial to estuarine environment.

(DR. N. Y. BHATT)
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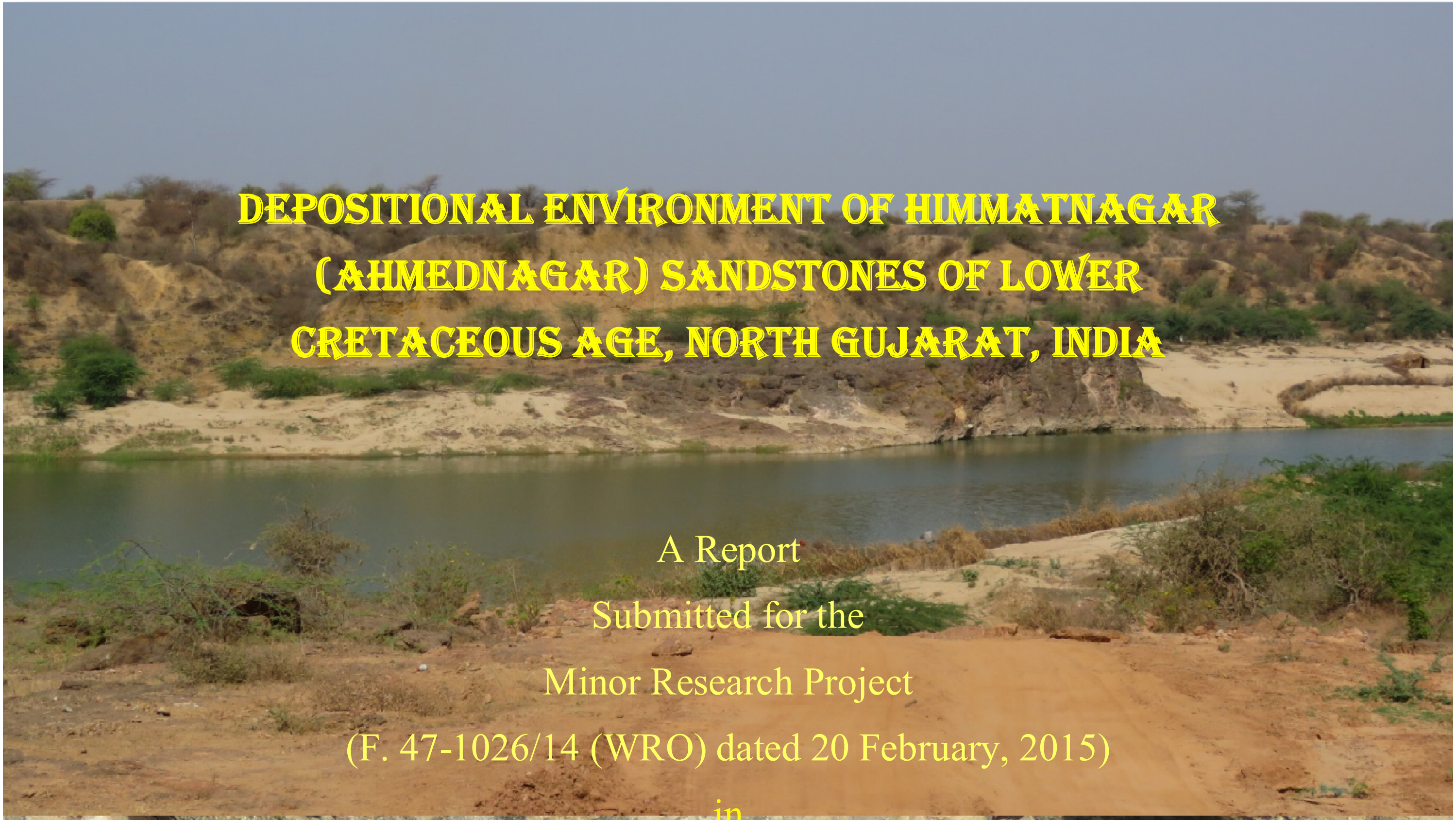

DEPOSITIONAL ENVIRONMENT OF HIMMATNAGAR (AHMEDNAGAR) SANDSTONES OF LOWER CRETACEOUS AGE, NORTH GUJARAT, INDIA

A Report

Submitted for the

Minor Research Project

(F. 47-1026/14 (WRO) dated 20 February, 2015)

in

Geology

by

DR. NISHITH YASHVANTRAY BHATT (PI)

AND

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July 2020

CONTENTS

PREFACE

Himmatnagar Sandstone was thought to be fluvial in nature. Himmatnagar Sandstone is considered to became a Formation. It is divisible in to three members - Lower, Middle and Upper. Only Upper member seems to be fluvial to estuarine, but it seems that Lower and Middle members are marine to marginal marine in nature.

Here, Himmatnager Sandstone formation is divided in to three members viz. Lower Member which is exposed in and around Sabarmati River section. Another is Middle Member. It is exposed in and around Hathmati River section. Third is Upper Member which is found exposed in the entire area of Himmatnagar Sandstone Formation, in both Sabarmati and Hathmati River sections. It is fluvial to estuarine in nature and hence found exposed in the entire area. It also indicates two phases of marine transgression and then after third phase of fluviatile to estuarine deposition.

The Himmatnagar Sandstone Formation is also divisible in to eight lithofacies Their depositional environment is also interpreted.The lithofacies are1. Basal Conglomerate (BC) lithofacies - Upper Shoreface; 2. Horizontally-Stratified Sandstone (HSS) lithofacies - Foreshore to Upper Shoreface; 3. Cross-Stratified Sandstone (CSS) lithofacies - Foreshore to Upper Shoreface; 4. Silty-Shale (SS) lithofacies - Middle Shoreface; 5. Intercalated Shale-Sandstone (ISS) lithofacies - Middle Shoreface to Foreshore;6. Planar Cross-Stratified Sandstone (PCSS) lithofacies- Near Shore Aeolian;7. Grey Wacke (GW) lithofacies- Upper Shorefaceand 8. Gritty-Pebbly Cross-Stratified Sandstone (GPCSS) lithofacies - Fluvial to Estuarine.

Based on trace fossils, geometry of the beds, sedimentary structures and absence of roots of plants (which suggests transported nature), upper shoreface to foreshore and near-shore aeolian environment of deposition can be interpreted for Lower Member, while on the same bases upper shoreface to foreshore environment of deposition for Middle Member of Himmatnagar Sandstone Formation.

While based on uneven erosional-unconformable lower contact in channel structures, south to southwest trough cross-stratification, presence of angular to sub-rounded gravely to cobbly fragments, absence of plants except wood logs, wide occurrence and limited thickness suggest deposition of Upper Member in fluvial to estuarine environment of deposition.

Total 23 ichnofossils have been identified in the study area, such as *Arenicolites, Calycraterion,Chondrites,Circulichnus,Cochlichnus, Desmograpton, Diplocraterion,Gordia,* *Gyrochorte, Haentzchelinia, Isopodichnus, Lobichnus, MonocraterionOphiomorpha, Palaeophycus, Planolites,Phoebichnus,Psilonichnus,Rhizocorallium, Rosselia, Skolithos, Teichichnus*and*Thalassinoides*. Most of the trace fossils indicate marginal marine to marine environment of deposition.

Three ichnofacies have been recognized like *Psilonichnus*ichnofacies, *Skolithos*ichnofacies and *Cruziana*ichnofacies, which depicts aeolian to upper-middle shoreface environment of deposition. Upper member represented cross-stratified sandstone, gritty to pebbly beds, trough cross-stratification indicate fluvial to estuarine environment.

ACKNOWLEDGEMENT

The authors are first of all grateful to University Grants Commission's Western Regional Office and their officers at Pune for giving an opportunity to study in details the Himmatnagar Sandstone Formation by granting this project. Particularly authors are thankful for their kind support in this noble work.

Authors are also thankful to Dr. B.K. Jain, Principal, M.G. Science Institute, Navrangpura, Ahmedabad for constant encouragement and support throughout and work and later on up till the submission of the project report.

Authors are also thankful to then HOD of Geology Department, M.G. Science Institute, Navrangpura, Ahmedabad for rendering all the possible help.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The state of Gujarat comprises an area of approximately 20,000 km^2 and is enclosed within the north latitudes 20°50’ to 24°50’ and east longitudes 68°40’ to 74°40’. It furnishes an interesting example of a terrain endowed with geological, physiographic and climate diversities. Geologically, Gujarat provides a wide spectrum of rock type of different ages. Whereas, the Aravalli in the northeast is as old as 2,500 Ma, the unconsolidated alluvial and beach material in its central and Western part is dated back to a few thousand years only. All the important lithological type, igneous, sedimentary and metamorphic occurs within the state.

The geomorphic diversity is reflection of the various combinations of geologic and climatic factors. The structural disposition and varying rock type govern the geological conditions whereas the climate factors (rainfall, temperature and wind) which vary very greatly are reflected in the surface and subsurface. The long coastline, the extensive alluvial plains, the vast saline wastelands, the rocky tablelands and the hill ranges, all have their own geographic characteristics.

The Gujarat state exposes rocks belonging to the Precambrian, Mesozoic and Cenozoic Era. The hard rocks cover about 49% of the total area of Gujarat, the rest being occupied by sediments of Quaternary period. The hard rock comprises of Precambrian metamorphosed and associated intrusives, sedimentary rocks of Mesozoic and Cenozoic Era and the traps/flows constituting Deccan volcanism of Cretaceous-Eocene age (GSI, 2001).

1.2 Physiography

Gujarat is divisible into three physiographic units:

1. Mainland Gujarat,
2. Saurashtra and
3. Kachchh.

Study area lies in the Mainland Gujarat.

1.2.1 Mainland Gujarat

The mainland Gujarat is divisible into following two well defined sub-zones:

1. The Eastern Rocky Highlands and
2. The Western Alluvial Plains.

The Eastern Rocky Highlands which show an altitude range of 300 m to 1100 m are the extensions of the major mountain of West India – the Sahyadri, Satpura and Aravalli. The Sahyadri in the southern part of Tapi River is characterized by N-S trending hill ranges; from north to south these show a progressive increase in altitude with a step-like topography is characterized by E-W and NNE-SSW trending step faults, horsts and grabens. The overall topography is moderately rugged. The hill ranges are flat-topped and the valleys are shallow and wide. Elevation-wise a major part shows an altitude variation from 150 m to 300 m, though the hill ranges in the Dang area in the South show higher altitudes. The highest hill is 793 m. The hilly terrain between the Narmada and Mahi rivers, referred to as the Vindhyan range provides an example of topography typical of Proterozoic metamorphics and granitic rocks. No specific trend is observed but the ranges around Chota-Udaipur are E-W while northward in the Lunawada and Baria regions quartzite hills show NNE-SSW trend. The altitude ranges between 150 m and 500 m, the average heights being ~350 m. The hilly areas in north Gujarat form the southwestern extremity of the Aravalli Mountains. Within the limits of Gujarat State, the Aravalli hills do not show any well-defined direction, but regionally they confirm to the NE-SW trend. A majority of these hills fall within an altitude range of 300 m to 600 m. They occur as both ridge and rounded hills.

The Western Alluvial Plains comprise a thick pile of unconsolidated sediments deposited by a combination of fluvial and aeolian agencies mainly during the Quaternary period. These from the western half of the mainland including coastal plains, and fall within the altitude range of 25 m to 75 m with a gradual seaward slope. The eastern parts rise gradually towards the hilly areas, and provide a somewhat mixed landscape; though alluvium still predominates, it gradually merges into residual deposits. These plains of north and central Gujarat in their deepest parts are very thick and could be as deep as 500 m at places. Across these plains flows the major rivers of Gujarat.

The study area forms part of Himmatnagar Tehsil of Sabarkantha District in North Gujarat which mainly comprises of Himmatnagar Sandstone. These are composed of thick massive beds of undisturbed, horizontal sandstones with intercalated shales and conglomerates. These vary in colour between white, different shades of pink, red and brown. They occur around Himmatnagar and between Kapadvanj and Dakor. These are well known building stones, and are extensively used.

1.2.2 Saurashtra

The peninsula of Saurashtra forms a rocky tableland fringed by coastal plains, a major portion shows Deccan lava flows. The central part is mainly undulating plains. To the north, the Saurashtra peninsula is flanked by the gulf of Kachchh and to its west and south, lie the Arabian Sea (Merh, 1995). The NE part of Saurashtra is covered by Uppermost Jurassic and Cretaceous Dhrangadhra and Wadhwan group of rocks. On the periphery of Saurashtra peninsula, a thin flank of Tertiary and mainly Quaternary rocks are present.

1.2.3 Kachchh

Kachchh is divided into the four geomorphic types:

I. The Rann
II. The low lying Banni plains
III. The hilly regions
IV. The southern coastal plains

The Rann forms a salt-encrusted wasteland rising few meters above sea level. It is divided by the rocky highland into the Great Rann to the north and the Little Rann to the east. The two Rann areas are inundated by knee-deep water during monsoon.

The Banni plains is in form of shrubby and grassland area which lies between the Great Rann and the rocky Mainland.

The hilly region contains three units:

a) The Island Belt
b) The Kachchh Mainland
c) The Wagad

The southern coastal plains border the Mainland against the Gulf of Kachchh in the south and the Arabian Sea in the west. All hill ranges and low ground run almost parallel and characterized by peculiar lithology, folding and faulting. The highest peak in Kachchh is Kaladungar (465 m) in the Patcham Island (Merh, 1995).

1.3The Coastline

Geologically and Geomorphologically, the coastline of Gujarat is quite distinct from the rest of the west coast. About 1600 km long and overlooking the Arabian Sea, its various segments provide evidences of the role played by eustasy and coastal process occurring during

Quaternary period. Reflecting a strong structural control, the coastline shows much variation in its trend, shoreline feature and near and off-shore conditions.

The north of Ghogha, right up to the mouth of Sabarmati the coast is highly muddy and shows extensive development of mud-flats and mud-banks. On crossing the Sabarmati River one enters the Mainland. The trend of the Mainland coast is almost N-S and exhibits much diversity in its different segments.

1.4 Climate

Gujarat being located on the Tropic of Cancer falls in the sub-tropical climatic zones and a largest of the state lies between 35° C to 45° C isotherms. The rainfall of the state is moderate.

The average climate of the study area is moderately humid.

Gujarat state experiences diverse climate conditions in terms of the standard climatic types, tropical climates viz., sub–humid, arid and semi–arid, are spread over different regions of the state. Out of total area of the state 58.60 % fall under arid and semi–arid climatic zone. The arid zone contributes 24.94 %, while the semi–arid zone forms 33.66 % of the total area of the state. The regions in the extreme north comprising the district of Kachchh and the western parts of Banaskantha and Mehsana, the northern fringe of Saurashtra (Jamnagar) and its western part have arid climate and the rest of the state has semi–arid climate. The districts of Valsad, Dang, Surat, Vadodara and Kheda have sub–humid climate. The principal weather parameters that build the climate of the state are rainfall and temperature, although others like humidity, cloudiness, dew and fog are also important from the agricultural point of view.

1.4.1Rainfall

The average rainfall of the district Sabarkantha (in which the study area lies)is between 510 mm and 760 mm in a year.

1.5 Drainage

The rivers of the mainland originate in north-eastern and eastern highlands after flowing southwesterly and westerly empty either in the Arabian Sea, Gulf of Khambhat or disappears in the Rann of Kachchh.

The study area is along the Sabarmati River which rises in the Udaipur hills and flows southwards draining into Gulf of Khambhat, its tributaries are Khari, Meshwa, Hathmati, Majhum and Watrak.

1.5.1 Mainland Gujarat

The rivers of the Mainland originate in north-eastern and eastern highlands are flowing south-westerly and westerly and empty either in the Arabian Sea, Gulf of Cambay or disappear in the Rann of Kachchh. In the north, river Banas which rises in the Sirohi hills of Rajasthan flows southwest and is lost eventually in the Rann of Kachchh; its major tributary is Sipu that joins near Deesa. Central part occupied by Sabarmati River and its tributaries. The Dhadhar river joints the sea further south of the Gulf, Narmada and Tapi rising in the hilly region of the Madhya Pradesh flow due west, draining into the Gulf of Cambay.

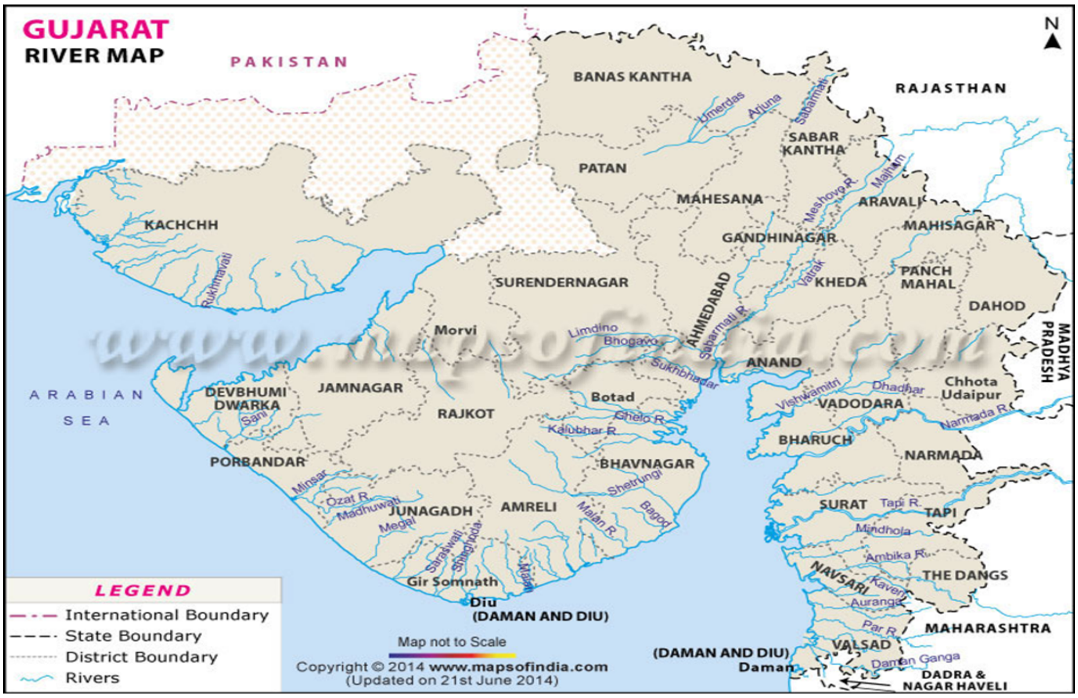
1.5.2 Saurashtra

Saurashtra has a typical radial drainage system on account of its configuration. The northerly flowing important rivers draining into the Little Rann are Aji near Rajkot, Machhu near Wankaner, Morbi and Malia, Bambhan and Phulka near Dhrangadhra. The other small rivers joining Gulf of Kachchh are Und, Dhrol, Rangmati, Sasoi, Phulzer and Ghi. The river Bhadar in the south-western parts passes near Jepur, Kutiyana and joins the sea near Navibandar. Other rivers are Bhogat, Wartu, Ozat, Maduvanti, Megal, Hiran,Saraswati and Shingoda. Amongeasterly flowing rivers, there are two Bhogawo River, Sukhbhadar near Ranpur and Dhandhuka, Kalubhar near Umrala and Shetrunji near Amreli, Palitana and Talaja join the Gulf of Cambay.

1.5.3 Kachchh

There are numerous small rivers in the Kachchh region. Those flowing north disappear in the Rann. While the remaining join either the Arabian sea or the Gulf of Kachchh. Some of the main rivers are Khari, Kaila, Niruna, Nara, Mati-weriwali, Rukmavati, Kankavati, Bhukhi, etc. There are dams across Khari, Kaila, Niruna etc. and the other rivers are also prepared to be harnessed by having storage schemes to overcome the scarcity conditions affecting this region quite frequently.

Figure 1.1: Drainage Map of Gujarat.



1.6 Soils

The soils of Gujarat show much diversity and can be broadly divided into 5 orders. The study area comprises of Inceptisols. Soils of this order are found in parts of Sabarkantha and Panchmahal districts. These have formed over basaltic, granitic and alluvial parents, occurs on gentle to moderately sloping interfluves. These are dark grey to light grey, reddish brown, yellowish red and dark reddish brown in colour and are product of weathering under tropical semi-arid to humid climate with annual precipitation of 500 to 2000 mm and mean temperature of 26° C. Inceptisols are calcareous in nature and are neutral to alkaline in reaction. The clays are rich in smectite group of clay minerals.

Depth of Soil: Vary in depth from 30-80 cm.

Texture: Silty-loam to clay. The coastal Inceptisols have sandy-clay-loam to clay texture.

Structure: Sub-angular and blocky and have A-C horizon.

The soils of Gujarat show much diversity and can broadly be classified into five orders:

(1) Entisols (2) Inceptisols (3) Vertisols (4) Aridisols (5) Alfisols.

1.6.1 Entisols

Entisols have developed over trap, granite, gneiss, quartzite and alluvium and are well distributed in mainland Gujarat. They are light grey, greyish brown and reddish brown in colour, and have formed under tropical semi-arid climate marked by annual precipitation of 55 to 950 mm and mean temperature of 25˚ to 26˚ C. These soils are calcareous and alkaline in nature.

Depth of soil: Few cm to 1 m and the profile show A-C horizons.

Texture: Sand clay, loam or clay, loam to clay.

Structures: Weak, sub-angular, blocky and at places crumb like.

1.6.2 Inceptisols

Soils of this order are found in Sabarkantha and Panchmahal districts. These have formed over basaltic, granitic, gneisses and alluvial parents; occurs on gentle to moderate and steep pediments, in sloping isolated plateaus, valley bottoms and moderately sloping interfluves. These are dark grey to light grey, reddish brown, yellowish red and dark reddish brown in colour and are product of weathering under tropical semi-arid to humid climate with annual precipitation of 500 to 2000 mm and mean temperature of 26˚ C. Inceptisols are calcareous in nature and are neutral to alkaline in reaction. The clays are rich in smectite group of clay minerals.

Depth of soil: Vary in depth from 30-80 cm.

Texture: Silty loam to clay. The coastal inceptisols have sandy-clay-loam to clay texture.

Structure: Sub-angular and blocky and have A-C horizons.

1.6.3 Vertisols

These are generally deep black in colour. It is locally known as 'Regur' or black cotton soil. Morphologically, they are confined to uplands, piedmont plain, flood plain, and intervening valley and occur mainly in semi-arid to semi-humid and humid climate with annual precipitation ranging from 500 mm to 2000 mm and mean annual temperature of 27˚ C.

These soils are neutral to alkaline in reaction and are classified as chrom-usterts and usterts.

Depth of soil: The total soil depth varies from 50 cm to as high as few meters.

Texture: This is mainly clay soil with montmorillonite mineralogy having high shrink-swell potential.

Structure: Structurally they are sub-angular, blocky with polygonal cracks on the surface.

1.6.4 Alfisols

Alfisols are found in the central Banaskantha and north-eastern part of Surendranagar district. They have developed mainly over sandstone and at place over alluvial deposits. These soils occur mainly over gently sloping pediments in warm semi-arid to semi-humid region with rain fall of 500 mm to 700 mm and mean annual temperature of 26°C. These are mostly reddish to reddish brown in colour with an argillaceous horizon and tend to form a belt between Aridisols of warm arid region and Inceptisols of warm humid region of the state. The soils represent ustalf and halp-ustalf.

Depth of soil: The soil depth varies from 50 cm to few meters with lots of free lime at the base.

Texture: Texturally, these are loamy to clayey.

Structure: Sub-angular and blocky with A-C horizons.

1.7 Ground Water

The quality and availability of groundwater in Gujarat is variable and depend on rainfall, topography and hydrogeological setting. It occurs as the following physiographic settings:

1. Hilly tracts of Mainland
2. Alluvial plains
3. Tablelands of Saurashtra and Kachchh

The study area comprises the former two settings.

On the Mainland, the hilly tracts in the northeast, east and south provide an erratic groundwater scenario. Groundwater accumulates only in secondary porosity viz. zones of weathering, joint planes, cracks and fissures. Water table in these rocky areas varies from 4 to 10 m below the ground level and the aquifers are mostly unconfined.

The alluvial plains provide better conditions for the storage of groundwater and a major portion of groundwater exploitation activity is confined to these plains. The junction between the eastern hill areas and the well demarcated alluvial plains is the principal site of recharge of groundwater. Though maximum thickness of alluvium is around 500 m, good water suitable for drinking and irrigation purposes range from 5 to 35 m below ground. Groundwater at greater depth tends to be saline. However, in some areas of North Gujarat where water occurs under artesian conditions, it has been tapped from a depth of as much as 300 m, but below this level, the water is saline and unsuitable for human consumption and agriculture.

The diverse terrain conditions have given rise to different ground water situations in the state. The rock formations ranging in age from Archaean to Recent include gneisses, schists, phyllites, intrusives, medium to coarse grained sandstones, basalts and recent alluvium. The high relief area in the eastern and north-eastern part occupied by Archaean and Deccan Trap have steep gradient allowing high run-off and therefore have little groundwater potential. The yield of wells in these formations ranges from 5-10 m3/hr. The yield in sandstones varies from 50-170 m^3/hr. The yield of wells tapping Quaternary alluvium in Cambay basin ranges between 75-150 m^3/hr.

1.8 Tectonic Framework and Stratigraphic Set-up

The rocks of Gujarat belong to formations ranging in age from the oldest Precambrian to the Recent. Stratigraphically, however, the record is incomplete as the rocks of Palaeozoic Era are totally absent. The sedimentary and volcanic rocks reset over the south-westerly extended Proterozoic rocks of Rajasthan and are post-Triassic. The major geological events of Gujarat thus are confined to Mesozoic and Cenozoic Eras. The geological evolution of Gujarat initiated sometime in Triassic with the breaking up of Gondwanaland and the subsequent geological history is related to the northward drift of the Indian sub-continent; the Mesozoic and the Cenozoic tectonics related to the breaking up of the western continental margin and subsequent drift have mainly controlled the geological evolution of Gujarat. The depositional history and Deccan volcanism are part and parcel of this major tectonic phenomenon.

The structural set-up of Gujarat is controlled by two major Precambrian orogenic trends i.e. NE-SW Aravalli trend and ENE-WSW Satpura trend. The tectonic boundary dividing the Indian shield into a southern peninsular block and northern foreland block is the Narmada Son lineation. A series of parallel extension faults opened up the Khambhat basin and the western continental shelf.

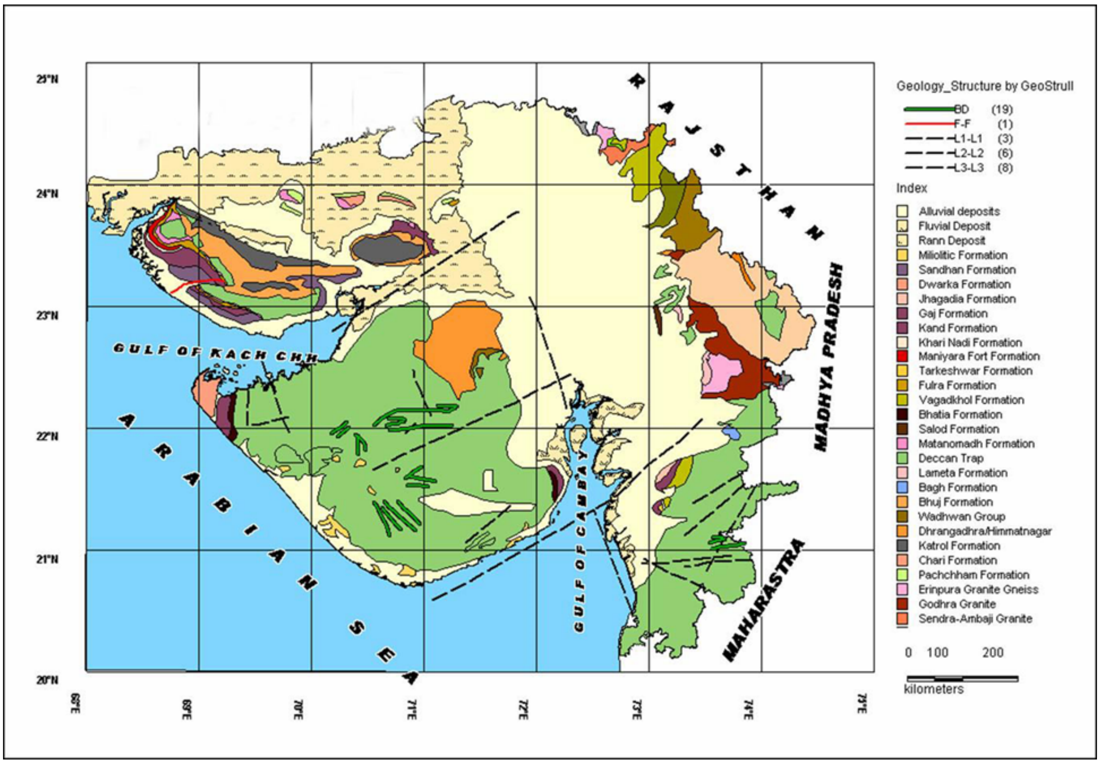
1.8.1 Structure and Stratigraphy

The geological evolution of northern and eastern parts has been controlled by the Precambrian orogeny-Aravalli and Delhi cycles, and the older crystalline rocks ideally show folds, faults and magmatism related to the two orogeny. The major portion of the mainland however, exhibits imprints of the Mesozoic and Cenozoic events, and the various rock formations reflect the uplift and subsidence along the two major lineaments - Narmada and Cambay rift systems. The Cretaceous and Tertiary sedimentary basins are fault-controlled and manifest the tectonism related to the two major fractures. Whereas the Cretaceous sedimentation and existing distribution and outcrop pattern clearly show an E-W trending fault control, the Tertiary rocks were deposited in the tectonic basins bound by N-S and E-W faults. The structure is reflected in topography which typically shows a progressive stepping down from south to north along E-W faults and from east to west along N-S faults.

The rocks of mainland show an age range from Proterozoic to Recent but a striking feature of the mainland stratigraphy is the total absence of Palaeozoic and the development of only the uppermost Mesozoic rocks. The oldest strata that rest directly over the Precambrian belong to Cretaceous age in mainland. The Deccan Trap is well represented and so are the Tertiary and Quaternary, though the sedimentary records are not complete and fully exposed.

Stratigraphy of Gujarat comprises of Precambrian to Recent with the gap of entire Palaeozoic and Triassic.

Figure 1.2: Geological Map of Gujarat.



Generalised stratigraphy of Gujarat is given in the following table.

Table 1.1: Generalised Stratigraphy of Gujarat.

Era	Period	Epoch	Super group/ Formation	Locality	Age in Million Years
CENOZOIC	QUTAERNARY	HOLOCENE	Undifferentiated sediments/Rann deposits	Alluvial plains of Gujarat, Rann, Banni& Coastal deposits	0.01
		PLEISTOCENE	Chhaya formations/ Miliolite formation	(1) Saurashtra coast from Gopnath northwards extending beyond Porbandar	1
				(2) Kachchh area	
	TERTIARY	PLIOCENE	Sandhan Formation		
		MIO-PLIOCENE	Dwarka Formation Jhagadia Formation	Dwarka OkhaJhagadia	12
		MIOCENE	GajFormatio Kand Formation Babaguru Formation	Piram Island, Saurashtra coast, Kachchh, Jhagadia, Kand near Ankaleswar	25
		OLIGOCENE	Maniara Fort Formation	Kachchh	40
		OLIGOCENE-MIOCENE	Kharinadi Formation	Kachchh	
		EOCENE-OLIGOCENE	Tarkeswar Formation	Tarkeswar (Surat dist.)	
		EOCENE	Fulra Formation Kakadinadi Formation Nummulitic Formation Vagadkhol Formation	Kachchh	60
		PALEOCENE-EOCENE	Bhatia Formation Salod Formation	Jamnagar, Bharuch, Surat,Valsad, Kheda, Sabarkantha, Kachchh, Saurashtra	
		PALEOCENE	Matanomadh Formation	Kachchh	
MESOZOIC-CENOZOIC		CRETACEO-EOCENE	Deccan Trap	Parts of Sabarkantha, Panchmahals, Vadodara, Bharuch, Surat & Major parts of Valsad and Dangs, Major parts of Saurashtra, Small parts of Kachchh	110
MESOZOIC		UPPER CRETACEOUS	Lameta Formation Bagh Formation	Kheda, Panchmahal, Narmada, Sabarkantha, Vadodara	
		LOWER-MIDDLE CRETACEOUS	Wadhavan Group	Saurashtra	
			Bhuj Formation	Kachchh	
			Dhrangadhra Group	Saurashtra	
		LOWER CRETACEOUS	Himmatnagar Formation	Sabarkantha	
		JURASSIC CRETACEOUS	Katrol (Jhuran) Formation	Kachchh	150
		UPPER JURASSIC	Chari (Jumaran) Formation		
		MIDDLE JURASSIC	Pachchham (Jhurio) Formation		
PROTERO-ZOIC		NEOPROTEROZOIC	Syn-to-Post Delhi intrusives	Palnpur, Danta, Ider, Modasa, Taranga, Dharoi, Virpur, Wanakbori, Godhara	

		PALEO-MESO-PROTEROZOIC (Delhi Super group)	Sirohi Group	Banaskantha	1500
			Kumbhalgarh Group	Danta, Ambaji, Palanpur	
			Gogunda Group	Khedbrahma, Shamalaji	
		PALAEO-PROTEROZOIC (Aravalli Super group)	Champaner Group	Chhotaudaipur, Shivrajpur, Jambughoda	
			Lunavada Group	Modasa, Shamlaji, Lunavada, Baria	
			Jharol Group	Modasa, Shamalaji	
			Udaipur Group	Northen parts of Gujarat	
ARCHAEAN PROTERO-ZOIC			Pre-Lunavada Gneissic Complex	Kanjeta-Nadatod, Chhotaudaipur	4000
			Pre-Champaner Gneissic Complex	Jetpur, Sabarkantha, Panchmahal, Banaskantha, Vadodara	

1.9 General Geology

The study area is covered by igneous, metamorphic and sedimentary rocks. The rocks are chiefly granites and gneissose granites of intrusive nature with minor dykes and veins of quartz, pegmatite intermediate to basic igneous rocks of Precambrian age; quartzites, schists and phyllites of Aravalli and Delhi supergroups; shales, sandstone and conglomerate of Himmatnagar Sandstone Formation, Deccan trap lava flows of Cretaceous-Tertiary age and soils and alluvium of Holocene age.

1.10 Flora and Fauna

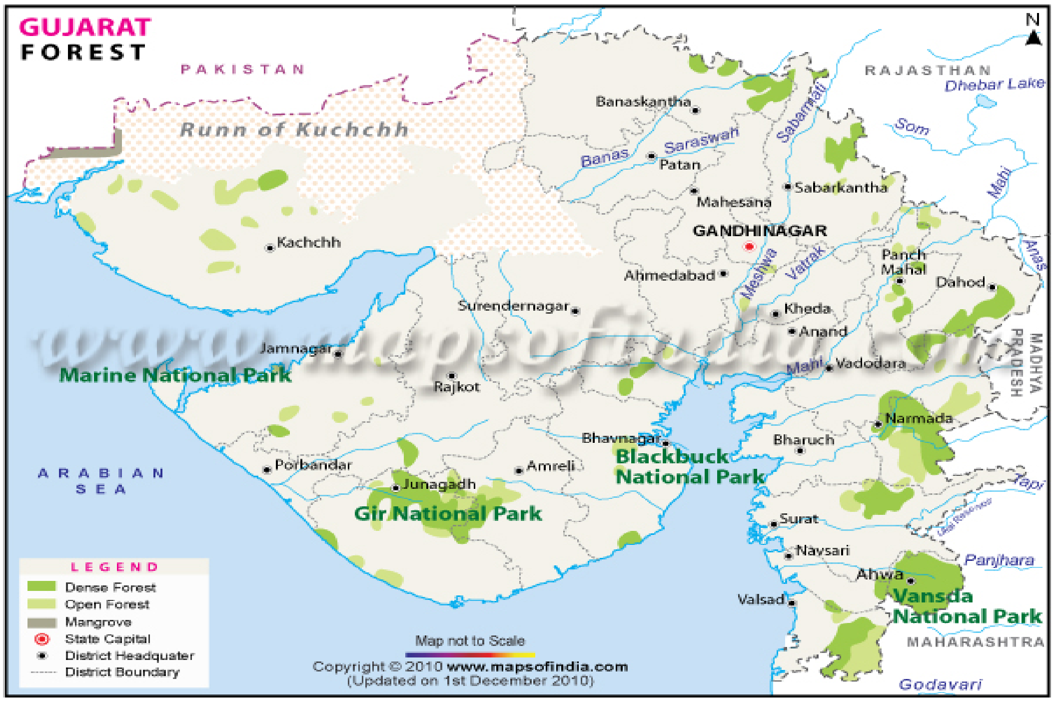
The vegetation of Gujarat varies very greatly in its different parts. The diversity is due to variations in rainfall, altitude, soil etc. The district comprises of various species of medicinal plants.

The fauna includes bears, panthers, leopards, hyenas, water fowl, raptors, passerines, and flying squirrels all living under a canopy of diverse plants and trees. During winter, all manner of migratory birds occupies the forest; during the rainy season there are wetland birds.

1.10.1 Forest Area

The recorded forest area in the state is 18,927 km^2, which is 9.66% of the geographic area. Reserved protected and unclassed forests constitute 74.61%, 2.53% and 22.86% of the total forest area respectively.

Figure 1.3: Forest Map of Gujarat.



1.11 Communication and Transport

All parts of the state of Gujarat are easily accessible as the state has a well developed communication and transport system.

Himmatnagar has a railway Station (Meter gauge line) and a Gujarat State Road Transport Corporation (GSRTC) bus depot. Himmatnagar is connected with National Highway No. 8(Mumbai to Delhi).

Gujarat's towns and cities are well connected to each other and to the rest of India by road and rail. The Road and Buildings Department (RBD) of state government are responsible for construction and maintenance of roads including state highways and Panchayat roads in Gujarat. This department is operating through 6 wings spread across the state in 26 districts. There are 17 national highways with total length of 4,032 km and more than 300 state highways with total length of 19,761 km. The state highways are arterial routes linking district headquarters and important towns within the capital and important cities. Besides, the state highways also connect the districts with national highways of the neighbouring states. The biggest network, however, is made up of Panchayat roads in rural Gujarat which cover a total length of 30,019 km and sugarcane roads (in villages) having a total length of 1,746 km. Coastal shipping routes link the state's many ports. Kandla is a major international shipping terminal.

Railways provide one of the best means to transportation in Gujarat, making it well connected with all parts of the country. There are customary trains to and from Delhi and Mumbai. The major cities of Gujarat like Vadodara, Ahmedabad and Surat connect to almost all the important cities of India via rail networks.

There is air service both within the state and to major Indian cities outside Gujarat. Transportation in Gujarat by air is quite feasible. Number of international flights to and from Ahmedabad is available for the tourists. Gujarat consists of 10 domestic airfields. Being the sixth largest city of India, Ahmedabad holds the international airstrips of the state. Recurrent international flights to countries like Europe, America and Middle East are available from Ahmedabad.

Figure 1.4: Road Map of Gujarat.

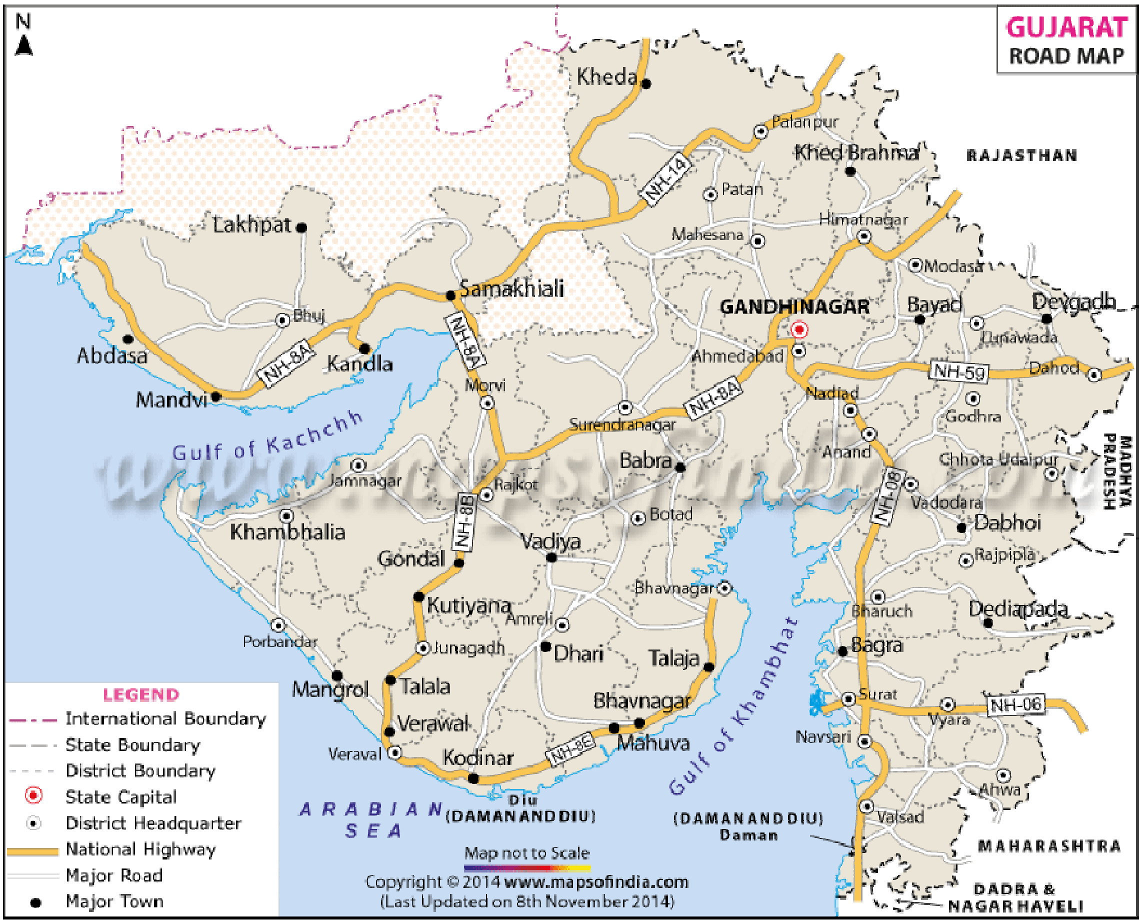
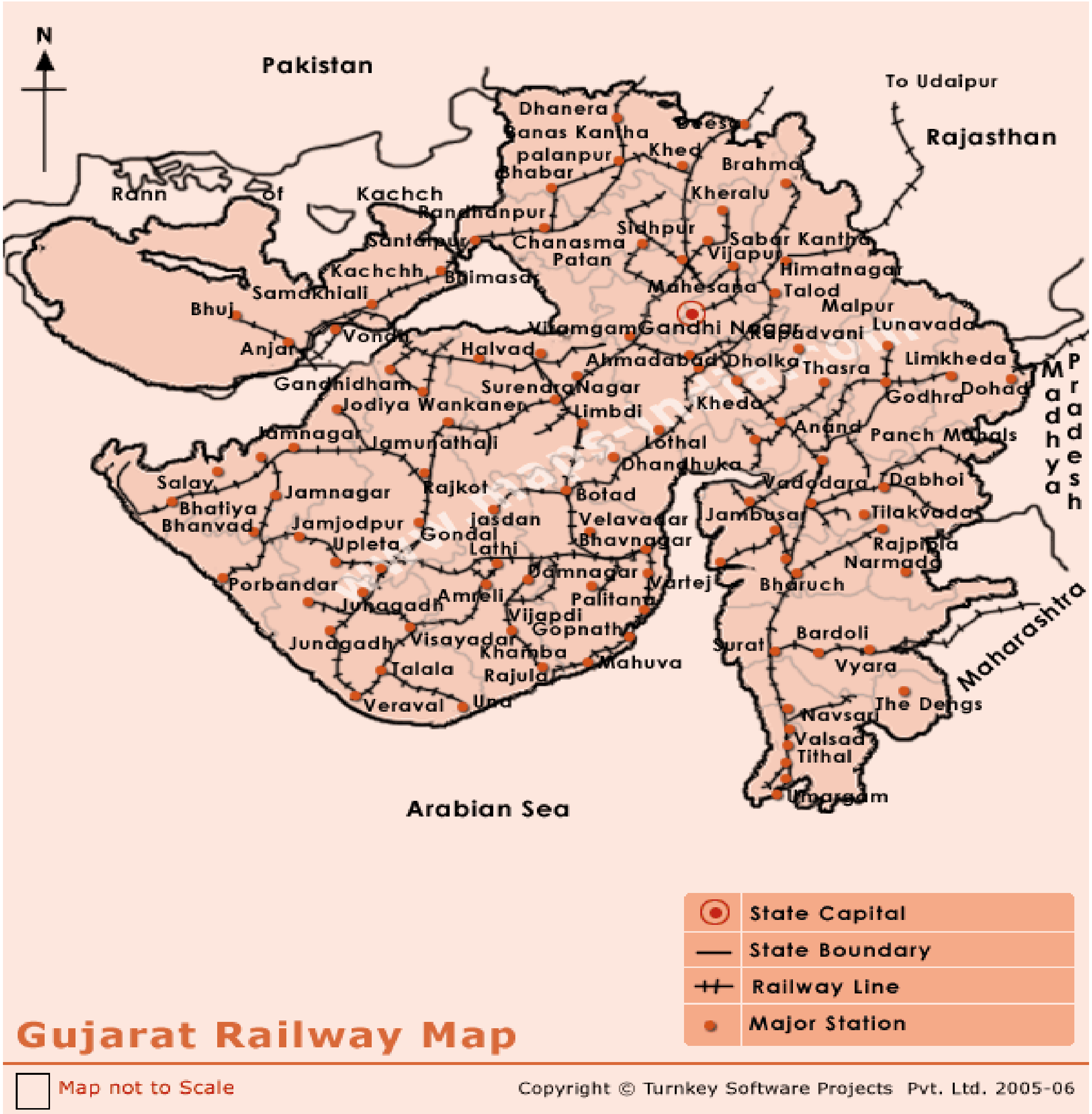


Figure 1.5: Railway Map of Gujarat.



CHAPTER 2

OVERVIEW OF SABARKANTHA DISTRICT

2.1 Introduction

The district derives its name from the Sabarmati River that separates Sabarkantha from the neighbouring districts. The district is bounded by the Rajasthan State to the north, Banaskantha and Mehsana districts to the west, Gandhinagar district to the south and Aravalli district in southeast direction. It is a border district in the eastern part of the Gujarat and is situated between 23^{o} 03’ 32” and 24^{o} 29’ 40” North latitudes and 72^{o} 43’ 34” and 73^{o} 39’ 26”. The district head quarter at Himmatnagar is well connected with road and rail with Ahmedabad and Gandhinagar.

The district consists of eight talukas namely Himmatnagar, Idar, Khedbrahma, Prantij, Talod, Vadali, Poshina and Vijaynagar. It is spread across an area of 7390 km^2.

2.2 Climate

Sabarkantha district is located in east part of Gujarat, which comes under normal rainfall areas in Gujarat, having sub-tropical climate with moderately low humidity. The main seasons prevailing in the district are (a) monsoon - mid of June to October, (b) winter - November to February, and (c) summer – March to June.

The maximum daily temperature during the year ranges from 31.0° C in January to 48.5° C in May while minimum temperature ranges from 11.5° C in January to 27.5° C in May. Maximum humidity ranges from 81.0% to 25.5%. The wind speed ranges from 88.0 to 184.9 km/day, where asevapo-transpiration ranges from 3.5 to 7.8 mm/day.

2.3 Geomorphology

2.3.1 Physiography

Physiographically, the district can be divided in to two zones i.e. the hilly regions and the plains. The hill ranges cover the northern and eastern part of the district where as the plains, showing the undulating topography, are confined towards west and south. Hilly area shown the high relief formed by the long narrow steep sloped and flat topped Aravalli ridges which are intervened by narrow longitudinal valleys. The hilly tract known as Poshina Patti area covers Khedbrahma, Vijaynagar and parts of Idar talukas. The highest elevation is about 682.75 m amsl towards west of Vijaynagar. The hill ranges are aligned roughly in NE – SW and N – S direction. Near the peripheries of the ridges, there are prominent round hills and mounds of granites near Himmatnagar and Idar. Southern and western parts of the district are mostly plain and sandy area covers the Parntij, Himmatnagar and parts of Idar talukas.

2.3.2 Drainage

Sabarmati, the major river of the district, flows from north to south, along the western border of the district originating from the hill ranges of the Rajasthan. The area is mainly drained by the south-westerly flowing river, namely the Hathmati, the Khari, the Meshwa, the Majham and the Vatrak.

2.3.3 Soils

Sandy, goradu and medium black are the three main types of soil found in almost all talukas. Sandy soil is chiefly found in the central part of the district covering mostly Himmatnagar and Idar talukas. The goradu soil covers Prantij, and Himmatnagar talukas and the medium black soil covers Khedbrahma, Vijaynagar and Idar talukas.

2.3.4 Geology

Geologically, Sabarkantha district is the manifestation of diverse geological extension from Lower Proterozoic to Holocene. The stratigraphy of Sabarkantha district is presented in table 2.1. The oldest formation in the area is Aravalli Supergroup comprises of various meta-sediments belongs to Lower Proterozoic. The rock types encountered in the area are sedimentary, meta-sedimentary, volcanic and metamorphic rocks. Among the different rock types, the rocks of Aravalli and Delhi Super group cover a large area in the northern and eastern part of the district. The regional stratigraphy, established by the Geological Survey of India is as follows.

2.3.4.1 Aravalli Supergroup

The rocks of the Aravalli Supergroup occupy by mainly the eastern part of the district and are represented by the Goran and the Samlaji Formation of the Jharol Group and KadanaFormation of the Lunavada Group. These comprises of highly folded phyllite, chlorite-mica schist, quartzite, garnetiferous mica schist, calc-amphibolite schist, feldspathic-mica schist and meta-gray-sub-wacke.

At places, serpentinite and talc-carbonate rocks of the Rakhabdev Ultramafic suite are seen. Around Vadali, Khedbrahma and Golwada many hills of calc-gneiesses trend north, north-east to south, south-west. These are generally complicated in their formation and bending.

General strike is NNE-SSW and dip is steep. At places, gneisses are intruded by aplite veins. Crystalline dolomites occur as an intercalated sequence within the meta-sediments and constitute an important lithological unit. They have restricted occurrence at Bhanmer, Kendon valley and Jesangpur. Dolomitic limestone occurs as a narrow band within mica schist around Bamanwada and Sunak.

The quartzites are fine grained to medium grained and thin bedded. The quartzites occur as scattered isolated outcrops near Meru, Bhanmer and Kheradi. Mica schists, chlorite schist and biotite gneisses are exposed east of Golwada. Phyllites are thinly foliated and hard to friable.

2.3.4.2 Delhi Supergroup

The northern part of the district is mainly occupied by the rocks belonging to the Kelwara and Antalia Formation of Gogunda group and Todgarh Formation of the Kumbhargarh Group of the Delhi Supergroup. They comprise of quartzite, biotite schist, calc-biotite schist, phyllite, calc-gneiss, calc-schist, marble and biotite gneiss/migmatite.

The rocks belonging to Aravalli and Delhi Super-groups are strongly deformed under at least three phases of deformation. The regional trend of the beds and foliation vary from NNE – SSW to NE – SW with steep dips on either side. Epidiorite, hornblende schist, amphibolites, pyroxene granulite and gabbro of the Phulad Ophiolite suites are found north of the Songarh. The area in the north is intruded by the Sendra – Ambaji granite. Godhra granite (CA 955 Ma) is exposed in the central part, granite, quartz vein and quartz porphyry, quartz vein and dolerite belonging to the Malaniigneous suite are observed around Idar.

2.3.4.3 Himmatnagar Formation

Conglomerate, variegated sandstone, shale, clay-stone, and chert belonging to the HimmatnagarFormation of Mesozoic age are found in and around Himmatnagar. They are exposed up to Arsodia, in south they occur as scattered outcrop, especially near Wantra, Viravada etc on the hill top.

The conglomerates are not always seen at the base of the HimmatnagarFormation. It is however well exposed in the river cuttings near Arsodia. The pebbles in the conglomerate are mostly of quartzites. Near Arsodia, between the basal conglomerate and Himmatnagar sandstone, there are several bands of variegated clays.

Sandstones are generally loosely aggregated, but at several places it is also compact. There are several bands of shale with in sandstones.

2.3.4.4 Lameta Formation

LametaFormation, consisting of variegated clay, banded chert and limestone of upper Cretaceous age are seen in the southern and south-eastern part of the district.

2.3.4.5 Deccan Traps

Basaltic flows with associated minor inter-trappean horizons, grouped under the Deccan traps are limited to the southern and south-western parts in the Meshwo and MazumRiver sections. These are of “aa” and “pahoe-hoe” type lava flows. Basalt flows also occupy the area east and north-east of Kapadvanj, south of Bayad and north of Dabha and it is also exposed along the VatrakRiver section north of Thalpore.

2.3.4.6 Tertiary Formations

Mata-no-madhFormation, consisting of ferruginous sandy beds, sandstone, clay laterite and conglomerate of Palaeocene age are found exposed in the western part of the district. Laterites have supposed to be originated from the weathering of coarse grained granites and Himmatnagar sandstones. Laterite has varying proportions of limonitic and aluminous ingredients.

2.3.4.7 Alluvium

Rest of the area is occupied by the wind-blown sands of the AkhajFormation, flood plain and channel fill deposits of VarahiFormation of Holocene. Alluvium mainly composed of medium to coarse sand, gravel, cobble and boulders with clay are present in the southern part of the district. Alluvium also found in patches along the Meshwo and Majhum river, north-east of Nawagam, south-west of Bheswara, west of Varngam, south of Khilori and also in patches along the VatrakRiver section.

Aeolian sands are brownish yellow, fine to medium grained, sub-rounded to rounded and unconsolidated sand occupies the area between the Meshwo and MajhumRivers.

Table 2.1: Stratigaphy of Sabarkantha District.

Geological Age	Supergroup	Group	Formation	Lithology
Holocene			Varahi Formation	Flood plain and channel fill deposits
			Katpur Formation	Flood plain and channel fill deposits
			Jantral Formation	Sand sheet and sand dune deposits
Palaeocene			Mata no madh Formation	Ferruginous sandy beds, sandstone, clay, laterite and conglomerate
Cretaceous to Eocene	Deccan Traps		Basalts	Porphyritic and amygdaloidal basalt flow with intertrappean sediments
Upper Cretaceous			Lameta Formation	Varigated clay, banded chert and limestone
Lower Cretaceous			Himmatnagar Formation	Conglomerate, variegated sandstone, shale, claystone and chert
Upper Proterozoic		Malani Igneous Suite		Olivine Dolerite
			Idar Granite	Granite, Quartz porphyry, quartzitic vein
			Godhra Granite	Granite
Middle Proterozoic			Sendra - Ambaji Granite	Granite and leucogranite with quartzo - feldspathic veins
			PhuladOphiolite Suite	Epidorite, hornblende schist, amphibolite, pyroxene granulite and gabbro
Lower to Middle Proterozoic	Delhi Supergroup	Kumbhalgarh Group	Todgarh Formation	Calc-gneiss, calc-schist, calc-gneiss, impure marble, calcitic marble, biotite schist, calc-biotite schist, biotite gneiss/migmatite
		Gogunda Group	Kelwara Formation	Biotite schist, calc-biotite schist and phyllite
			Antalia Formation	Quartzite and quartz sericite schist, biotite schist and calc-biotite schist
Lower Proterozoic	AravalliesSupergroup	Lunavada Group	Kadana Formation	Mica schist and metasubgraywacke, quartzite
		Intrusive	Rakhabdev Ultramafic suite	Serpentinite and talc-carbonate rock
		Jharol Group	Samlaji Formation	Garnetiferous mica schist, quartzite, calc-amhibolite, feldspathised mica schist
			Goran Formation	Phyllite, chlorite-mica schist, quartzite

CHAPTER 3

STRATIGRAPHIC UNITS

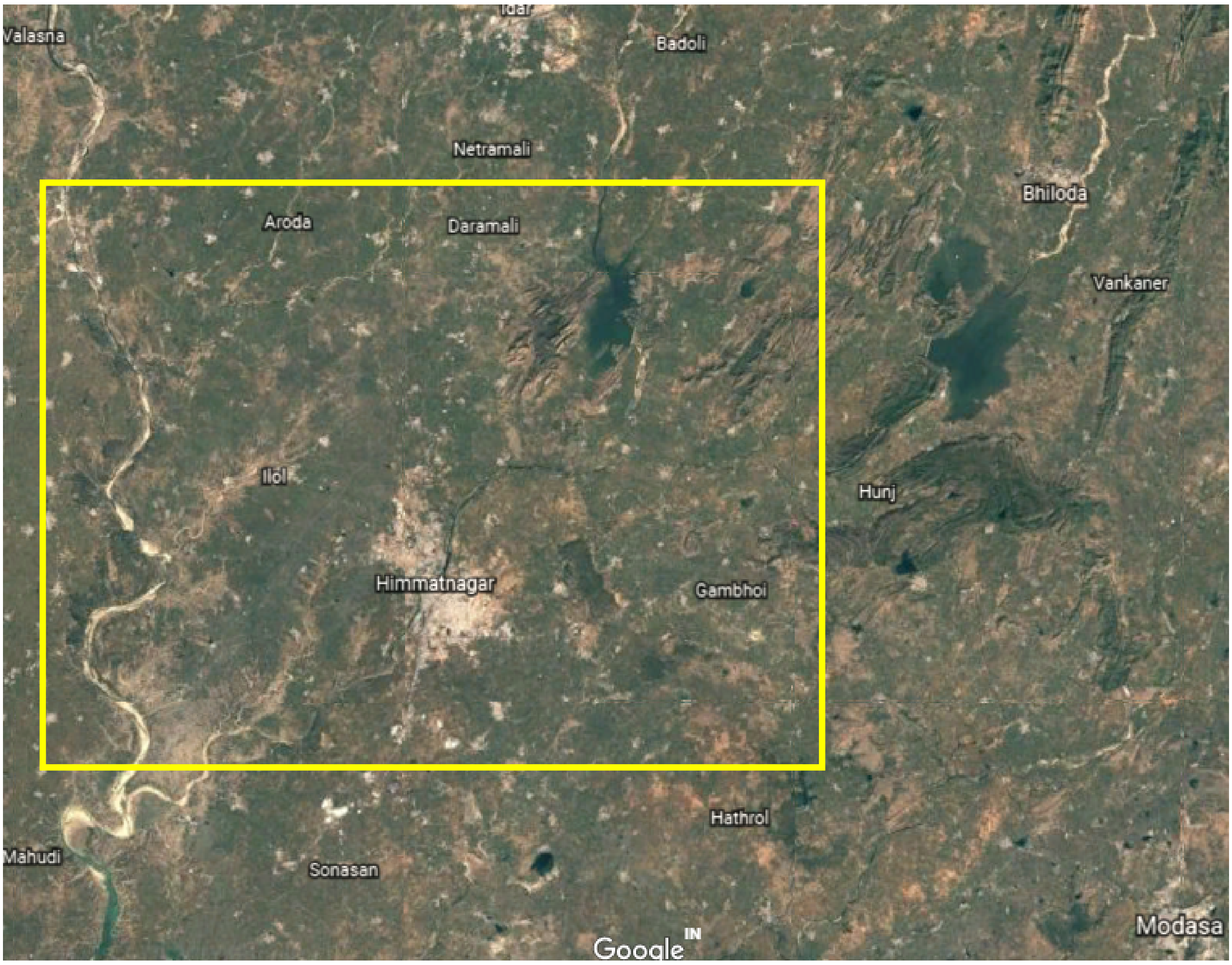
3.1 Introduction

The Himmatnagar town is situated at about 80 km NNE of Ahmedabad on banks of Hathmati River, a tributary of Sabarmati River. The latitudes and longitudes of Himmatnagar town are 23°36’16’’N and 72°57’39’’E. The Mesozoic rocks exposed in the study area range in age from Neocomian to Albian i.e. early to middle Cretaceous and are overlain by Deccan Traps. Alluvium of Quaternary age is exposed along low grounds while in river valleys and on gentle hill slopes the hard sedimentary rocks are exposed. The Himmatnagar Sandstone is name given to alternate sequence of conglomerates, sandstones and shales after Himmatnagar town. The Sandstones predominate as the rock type. Limited work has been carried out on this rock, which is classified in a single unit-Himmatnagar Sandstone Formation. In the southeast part of the study area, the formation is overlain by Deccan Traps. Exposures of the formation cover an area of approximately 700 km^2 mainly in Sabarkantha district of Gujarat state.

Present work is carried out to interpret the environment of deposition of the rocks on the basis of geology, lithology, stratigraphy, bed geometry, sedimentary structures, plant fossils and trace fossils.

The area under investigation forms part of Himmatnagar Taluka of Sabarkantha District in north Gujarat which is covered by igneous, metamorphic and sedimentary rocks. The rocks are chiefly granites and gneissose granites of intrusive nature with minor dykes and veins of quartz, pegmatites, intermediate and basic igneous rocks of Precambrian age; quartzites, schists and phyllites of Aravalli and Delhi super–groups; shales, sandstones and conglomerates of Himmatnagar Sandstone Formation, Deccan Trap lava flows of Cretaceous–Tertiary age and soils and alluvium of mainly Holocene age. The rocks of Aravalli and Delhi super–groups are oldest which are highly folded, faulted and intruded by younger intrusives. Himmatnagar Sandstone Formation is mainly horizontal to sub–horizontal and exposed in form of flat topped hillocks towards the east of Himmatnagar and in stream and river sections on west of Himmatnagar Town below thin alluvium cover up to Sabarmati River.

Figure 3.1: Image of study area based on Google Earth.



3.2 Himmatnagar Sandstone Formation

The Himmatnagar Sandstone Formation was earlier referred to as Ahmadnagar Sandstone by Middlemiss. Subsequently Gupta and Mukherjee, called them as Himmatnagar Sandstone.

In this formation, the sediments were laid down in two cycles, a Lower Cretaceous transgressive cycle followed by regression and a Mid-Cretaceous transgressive cycle again followed by regression. The two cycles include short phases of transgressive and regressive cycles. The two cycles include various alternations of silty-shales, sandstones and conglomerates. The rock formation includes various alternations of silty-shales, dominant sandstones and conglomerates patches. Overall, the sandstones are dominant in the study area with silty shales at places and pockets of conglomerates at few places. Fossil content (plant fossils) is also abundant in lower part in sandstones and silty-shales and it decreases or else absent in almost all the successions except few and abundant on the partings of the silty-shale and sandstone intercalations. Fossil content (plant fossils) is also abundant in the lower part in sandstones and silty–shales which decreases or altogether absent in the upper gritty and conglomeratic rocks. Trace fossils are present in almost all the rocks of the sequence except few and abundant in the silty–shale–sandstone intercalations. Fossil wood is preserved in various rock types.

Based on field observations, the rocks of Himmatnagar Sandstone Formation are sub–divided in three members based on different parameters such as rock types, sedimentary structures, grain size variation, types of contacts, thickness of strata, vertical and lateral extension and presence of body (plant) and trace fossils.

Up till now, Himmatnagar Sandstone Formation is considered as fluvial to deltaic in environment of deposition based on plant fossils, grain size analysis and frequent cross–stratification. Here, we put forward the view of marginal marine to marine environment of deposition for the Lower and Middle members of the formation based on sedimentary structures, grain size variation, types of contacts, thickness of strata, vertical and lateral extension and presence of body (plant) and trace fossils. The depositional environment of Upper member is estuarine to fluvial on the basis of trough cross–stratification, channel structures at base, presence of large wood fossils, presence of angular to sub–rounded pebbles to cobbles in gritty sandstones and limited thickness without delta structure.

Thickness of the beds is less towards north and northeast which increases in south and southwest. The formation seems to be continuous with the rocks of Bhuj Formation and Wadhwan groups of the same age, which later on detached due to the rifting along Cambay Basin.

The Himmatnagar Sandstone Formation is thus considered younger than Dhrangadhra sandstones group; and of the same age as the Wadhwan Sandstone Group of Saurashtra, Songir Sandstone Formation of Vadodara, Bhuj Formation of Kachchh, Nimar Sandstone Formation of the Nimarvalley (M.P.) and the Barmer Sandstone Formation of west Rajasthan.

To the east and north of Himmatnagar, the formation is seen resting over a weathered granite–gneiss basement. To the west, disseminated exposures of the rocks are found along stream valleys up to Sabarmati River. The Himmatnagar sandstones are siliceous to ferruginous in nature with subrounded to rounded sand grains.

Rocks of the formation have been studied in detail at different localities. The exposures can broadly divided into three parts (1) Around Himmatnagar town on both the banks of

Hathmati River and their tributaries and east of Himmatnagar town where it forms discrete outcrops spread over an area of about200 km^2. (2) On the banks of Hathmati River and its tributaries down-stream of Himmatnagar town. (3) On the banks of Sabarmati River and its tributaries after Valasana village up to Derol village.

At few exposures of first locality, unconformable junction between Middle and Upper members is clearly visible. Palaeosol is also present at the unconformity at Hathmati River section near Himmatnagar. While at second and third locality, unconformable junction between Middle and Lower members are clearly visible. Only at one locality near Dedhrota on Sabarmati River, contact between Lower and Middle members is visible in form of lateritic material.

Table 3.1: Lithostratigraphic / Lithofacies classification of Himmatnagar Sandstone.

Formation	**Member**	**Lithology / Lithofacies**	**Thickness**		**Age**
Himmatnagar Sandstone	Upper Member	Gritty-Pebbly Cross-Stratified Sandstone (Gritty-cobbly, trough cross-stratified Sandstone; coarser fragments are angular, sub-angular to sub-rounded.)	~25 m		Mid-Cretaceous
	Middle Member	Horizontally Stratified Sandstone	4.5 m	67.5 m	Early to Mid Cretaceous
		Silty-Shale	6 m		
		Intercalated Shale-Sandstone	3 m		
		Horizontally Stratified Sandstone	12 m		
		Cross-stratified Sandstone	12 m		
		Silty-Shale	8 m		
		Grey Wacke	22 m		
	Lower Member	Horizontally Stratified Sandstone	04 m	60 m	Early Cretaceous
		Planar Cross-stratified Sandstone	04 m		
		Silty-Shale	03 m		
		Horizontally Stratified Sandstone	04 m		
		Silty-Shale	02 m		
		Horizontally Stratified Sandstone	06 m		
		Cross-stratified Sandstone	12 m		
		Silty-Shale	08 m		
		Horizontally Stratified Sandstone	12 m		
		Basal Conglomerate	5 m		

3.2.1 Lower Member

Basal rocks of the Lower Member are well exposed along Sabarmati River section near Valasana village. The thickness of the rocks is ~60 m. Extra-formational conglomerate is the lowermost unit of this member which lies on weathered granitic-gneiss basement of the Precambrian age.

These sequence is conformably followed by rocks on the banks of Sabarmati River at Eklara, Kot, Sapteshwar, Kadoli, Pedhamali,Aglod and Dedhrota, represented by alternation of horizontally stratified sandstones, cross-stratified sandstones, thin silty-shale and planer cross-stratified sandstone (present only at Sapteshwar) are present. The horizontally stratified sandstones in Sabarmati River sections are ferruginous-pink to brown in colour. The grains are rounded to sub-rounded. The silty-shale in Sabarmati River sections are pinkish in colour and ferruginous in nature. The silty-shale consists most of the plant remains, which are found without root portions hence suggest its transported nature. The planer cross-stratified sandstone exposed near Sapteshwar on Sabarmati River section is white to yellowish-white in colour, clay rich, friable in nature with fine, rounded grains. The horizontally stratified sandstones, silty-shales, mottled sandstones and intercalated shale-siltstones are also exposed along a stream section (a tributary of Sabarmati meeting the river near Dedhrota), which contains numerous trace fossils in the sandstones like *Thalassinoides, Palaeophycus*and *Skolithos*. Near Sapteshwar typical marine trace fossils *Rhizocorallium*and*Gyrochorte* have been found in intercalated shale-siltstone immediately after Sapteshwar bridge in down-stream direction. In the same manner, many trace fossils have also been observed on left bank of Sabarmati River near KattiHanumanji temple at Kadoli showing the marine environment of deposition with symmetrical ripple marks. Here, Lower Member is directly overlain by the rocks of Upper Member.

On the top of the sequence, sandy lateritic material is present near Dedhrota village on both the banks of Sabarmati River. It is approximately 20 m in thickness, reddish to brownish in colour. Base of it is considered as unconformity between Lower and Middle Member of HimmatnagarSandstone Formation. It is uneven in nature. Uppermost part of Lower Member is represented by intercalated shale-siltstone sequence, which is unconformably present below the laterite. It is angular in nature. It is extended almost in E-W direction. So, Lower Member can be extended from Valasana to Dedhrota and towards east around Ilol and beyond it. But, in which way unconformity between Lower and Middle Member is extended is unknown except near Dedhrota and hence exact area of Lower Member can-not be demarcated due to lack of exposures.

This member shows development of various sedimentary structures such as wave ripple marks, stratification, lamination, hummocky-stratification, planer cross-stratification, trough cross-stratification and herringbone structure. Inverse grading and mud drapes are also present in horizontally stratified sandstone. The strata show wedge shaped geometry.

Burrows are common in horizontally stratified sandstones, silty-shale and planer cross-stratified sandstone. Intertidal ridge-runnel structures are observed with hummocky cross-stratification in cross-stratified sandstone.

Horizontally stratified sandstone is present near the top of the Lower Member in Sabarmati River sections. Numbers of sand/mud volcano structures are present in Sabarmati River sections indicating seismic events, which are found exposed below Sapteshwar bridge on left bank and on right river bank near Aglod.

The rocks contain few body fossils which are mainly of fragmented bivalves, trace fossils (*Arenicolite, Cochlichnus, Desmograpton,Gordia, Gyrachorte,Haentzschelinia,Ophiomorpha, Isopodichnus,Lobichnus,Monocraterion, Palaeophycus, Planolites, Rhizocorallium, Rosselia, Skolithos*, *Teichichnus,Thalassinodes,* vertebrate trace fossilsetc.) and plant fossils. The planer cross-stratified sandstone also contains large scale crustacean and vertebrate burrows.

All these characters suggest that the rock sequences of Lower Member are indicative of marginal marine-backshore-foreshore to marine-shoreface environment of deposition.

3.2.2 Middle Member

The base of the Middle Member is exposed behind Hanuman temple opposite to the way to Rajpur on Himmatnagar-Idar road and in the Vantada (Wantra) hill on eastern extremity in the study area. It is also found exposed in a small stream section near Modasa town.

Near Hanuman temple opposite to the way to Rajpur on Himmatnagar-Idar road, it is present showing extra-formational, polymictic, para-conglomerate on gneissose granitic basement rock. It is characterised by nonconformity. At Vantada village, greywacke, which is 22 m in thickness, is exposed only here. The rock is highly friable and is chiefly made of angular, sub-angular to sub-rounded grains of quartz, feldspar, hornblende and mica with more than 15% of clay content which allows grains to float. Few pebbly bands are also present. It is followed by white silty-shale at Vantada hill. The rock contains good amount of plant debris. It is wide lens shape covering east side of Vantada hill extended in north-south direction. Mottled burrows are also present at few places in the rock. The silty-shale is overlain by cross-stratified sandstones which occur only at Vantada hill. The ferruginous concretions are common in sandstones. The rocks also contain fragmented invertebrate shells in addition to plant fossils which occur at the top. The rocks are medium to fine grained with rounded to sub-rounded grains. At stream section near Modasa, the base of the Middle Member is exposed above granite in form of a pebbly wacke. It is in form of nonconformity. The rock is about 2.5 to 3 m in thickness. At no other place in between Modasa and Vantada exposures of the HimmatnagarSandstones are found. The exposures of basal part of Middle Member is also present in form of ~20 m thick lateritic band extended in E-W direction and present above intercalated shale-siltstone of Lower Member angularly and unconformably.

The Middle Member rocks are well exposed in Hathmati River section and its tributaries after Himmatnagar town and conspicuously exposed in main Himmatnagar town along both the banks of the river. The Hathmati is a tributary of Sabarmati River. The thickness of Middle Member rocks is ~67.5 m. The Middle Member is abundantly rich in plant fossils and burrows.

The lower most unit of this Middle Member in the study area is comprise of intercalation of pink to white silty shale and finely laminated sandstones, which has a thickness around 3 m. The rock is chiefly composed of sub-rounded grains of quartz, feldspar and mica. The rock is highly rich in clay content and hence highly friable. The base part is obscure.

Lower part is comprised by mottled sandstones which are 2 m thick and made up sub-rounded to rounded, medium to coarse grained quartz enclosed in ferruginous cementing matrix. It is further succeeded by cross-bedded sandstone which has a thickness about 12 m on the down streamside. Along both the banks of Hathmati River near Himmatnagar, this Middle Member strikingly shows alternate sequence of shale, siltstone and sandstone intercalating with each other along with palaeosol is found preserved.

It is followed by highly plant fossil bearing silty-shale. The colour of the rock is whitish pink to pinkish. Grain size is fine chiefly made up of clay with silty grains. The rock is highly rich in plant debris and plant fossils (*Sphenopteris*, Ferns, petrified wood, *Calamites*, etc) along with mottled burrows (e.g. *Chondrites, Skolithos, Monocraterion, Ophiomorpha, Thalassinoides, Psilonichnus, Arenicolites,* etc.). The plant fossils are mostly without root portion and hence transported. Algal parts are also enclosed within shales.

These highly fossiliferous rocks are succeeded by silty sandstone. The rocks are whitish to dull white in colour. The rock unit is ~3 m thick. These rocks are highly affected by deformational structures. The rocks contain structures like convolute bedding, seismites and flame structures. Majority of this structures indicate period of seismic events.

These silty sandstones are overlain by laminated sandstone. The rocks are highly ferruginous in nature and hence possessing reddish to dark pinkish shade. This rock unit is very less in thickness comprising only around 1.5 m. The rocks are highly laminated along with load cast preserved in underlying surface.

The top most part of Middle Member at Hathmati section near Himmatnagar-Idar road is made up of horizontally stratified sandstone. The grain size varies from fine to medium, composed of rounded to sub-rounded grains of quartz and feldspar. The rock unit is 3 m thick. It is followed by beds of horizontally stratified sandstones, cross-stratified sandstones and variegated mottled sandstones on both the banks up to Ring Road Bridge. Thickness is approximately 8 m, 12 m and 6 m respectively.

On the east side of Himmatnagar town, the sandstones are present in form of small hills and hillocks, with thin gravelly to pebbly layers. While, in Hathmati River downstream of Himmatnagar and along the tributaries of Hathmati, sandstones are horizontal to cross-stratified and with large amount of bioturbation. The rocks are exposed along Hathmati River as well as tributaries present near Hapa and Kundol villages. Thin silty-shales are present at few places. Two to three intercalated sequences of horizontal and cross-stratified sandstones are present along Hapa stream section. Here, cherty bands in form of fragments are also found, but in situ exposures have not been found.

The exposure of Middle Member is found on western bank of Hathmati River near Kundol village on downstream side. Medium grained sandstone of Middle Member is present with bioturbation. Volcanic ash was also found preserved along with it, which was unconsolidated in nature suggesting short term volcanic events.

All these characters of rock sequence are indicative of marginal marine or marine depositional environment.

3.2.3 Upper Member

The rocks of Upper Member are well exposed in Sabarmati River at Aglod and Sapteshwar. The maximum observed thickness in Upper Member is ~12 m here. The thickness varies at different places. The Upper Member comprises of gritty to cobbly sandstone. The rock shows trough cross-stratification and occurs above Lower Member, forming large scale channel structure in the underlying rocks showing the contact between the two is erosional and unconformable. The sandstones are made of sub-angular to sub-rounded gritty quartz and feldspar grains with angular to sub-rounded gravels to cobbles of quartz, granite, gneiss, quartzite and pegmatite found mainly in underlying Pre-Cambrian rocks. The cementing material is mainly siliceous which makes the rock hard and compact. Body fossils are absent, trace fossil (burrows) and plant fossils (fossil wood) are present. Along the river side contact is visible between cobbly sandstone of Upper Member.

Middle Member is not exposed anywhere in the area investigated.

The rocks of Upper Member are also well exposed in Hathmati River at Himmatnagar and downstream of it. The maximum observed thickness of the Upper Member is ~25 m. The thickness of this rock is varies at different places. The Upper Member comprises of gritty sandstones and conglomerates. The rock shows trough cross–stratification and occurs above Middle Member forming large scale channel structures. In that way, contact between the two is erosional and unconformable. The sandstones are made up of sub–angular to sub–rounded gritty quartz and feldspar grains and conglomerates are made up of angular to sub–rounded pebbles to cobbles of quartz, granite, gneiss, quartzite and pegmatite mainly in the lower part. Few boulders are also visible. On many pebbles/cobbles white siliceous encrustation is present. The cement is siliceous makes the rock much hard and compact. Body fossils are absent but, burrows are present in this rock. Graded bedding is clearly visible in conglomerates with fining upward sequence.

Hummocky Structure is also found along down streamside of Hathmati in Upper Member. Ripple marks are found preserved in sandstones. Majority of rocks are black in colour due to algae on the surface. In the river bed further downstream side contact between Middle and Upper Member is exposed. Conglomerate of Upper Member is overlying sandstone of uppermost part of Middle Member. This Middle Member sandstones are medium grained yellowish, ferruginous with glauconitic material.

All these features were leading us to conclude that the depositional environment may be fluvial to estuarine.

CHAPTER 4

LITHOFACIES

4.1 Introduction

According to Miall (1985), the word facies is used in both, a descriptive and an interpretive sense and described based on textures, sedimentary structures, fossils and lithologic-association of sedimentary rock on the scale of an outcrop. According to him, descriptive facies include certain observable attributes of sedimentary rock bodies, which can be interpreted in terms of depositional processes. Each lithofacies represents an individual depositional event, which are characteristic of particular depositional environments. These are commonly cyclic and form the basis for defining sedimentation models (Miall, 1985).

In the present study an individual lithofacies is considered to be a rock unit defined on the basis of its sedimentary physical and biologic structures. Sedimentary facies are bodies of sediment recognizably different from adjacent sediment deposited in a different but adjacent depositional environment. Sedimentary facies reflect depositional environment, each facies being a distinct kind of sediment for that area or environment. Generally, facies are distinguished by what aspect of the rock or sediment is being studied. Thus, facies based on petrological characters such as grain size and mineralogy is called lithofacies. They are the direct result of the depositional history of the basin. By ascribing modes of origin to different facies one can visualize a genetic system of facies.

The Lower Cretaceous (Himmatnagar Sandstone) sequences in the study area consist of seven principal lithofacies. This discrimination is based on area of occurrence, lithofacies features, including composition, grain sized, bedding characteristics, lateral and vertical continuity, physical and biogenic sedimentary structures and on pattern of vertical sequence.

Sedimentary facies, physical, chemical, and biological aspects of a sedimentary bed and the lateral change within sequences of beds, which are of the same geologic age can be termed as lithofacies. Sedimentary rocks can be formed only where sediments are deposited long enough to become compacted and cemented into hard beds or strata.

The characteristics of the rock unit come from the depositional environment and original composition. Sedimentary facies reflect depositional environment, each facies being a distinct kind of sediment for that area or environment.

In order to gain detailed facies information, stratigraphic sections were measured at different localities.

Following lithofacies have been identified in the study area: 1. Basal Conglomerate (BC) lithofacies; 2. Horizontally-Stratified Sandstone (HSS) lithofacies; 3. Cross-Stratified Sandstone (CSS) lithofacies; 4. Silty-Shale (SS) lithofacies; 5. Intercalated Shale-Sandstone (ISS) lithofacies 6. Planar Cross-Stratified Sandstone (PCSS) lithofacies;7. Grey Wacke (GW) lithofacies and 8. Gritty-Pebbly Cross-Stratified Sandstone (GPCSS) lithofacies.

4.2 Lithofacies

4.2.1 Basal Conglomerate (BC) lithofacies

The lithofacies occurs in Valasana and surrounding area. It is found upstream of bridge at Valasana on Sabarmati River to approximately 1.5 km downstream of Sabarmati River on right side. It has a thickness of ~5 m. It contains well-rounded to sub-angular pebbles and cobbles of various country rocks such as granite, quartzite, gneiss, gabbro, quartz porphyry, pegmatite etc. Pebbles and cobbles are in contact with each other, so the rock is ortho-conglomerate. Fragments present are of different type of rocks so, it is a polymictic conglomerate. At the same time, as the fragments are formed outside the depositional basin, rock is extra-formational conglomerate. The rock is much different than the conglomeratic rock occurring in the Upper Member of the rock at the base. The rock in the Upper Member is cross-stratified, while rock in the Lower Member is horizontally stratified.

It shows a transgressional depositional environment on a denuded surface for the first time marking a non-conformity.

4.2.2 Horizontally Stratified Sandstone (HSS) lithofacies

Horizontal Stratified Sandstone lithofacies is present in Lower Member at Kot, Arsodiya, Sabarmati River near Sapteshwar Mahadev Temple and near Katti Temple. The cumulative thickness of horizontally stratified lithofacies at Sabarmati River section near Sapteshwar is ~14 m, where repetition occurs three times. It is also found present near Sapteshwarbridge on right bank where it is ~ 5 m in thickness and ferruginous to clayey in nature.

A contact between gritty sandstone to conglomerate - cobbly cross-stratified sandstone and horizontally stratified sandstone which is of 5 m thickness is exposed near Sapteshwar. The sandstone comprises of trace fossils such as *Skolithos, Ophiomorpha*, etc. The sandstone exposed near Sapteshwar is cream, purple and red in colour. Another exposure of horizontally stratified sandstone is found near Katti temple. Here the sandstone forms the topmost part of the Lower member with a thickness of 1.5 m. Near the topmost part of the Lower member, glauconite clay (green sand) marks its presence. The sandstone is also highly ferruginous.

The sandstones of the lithofacies are also ferruginous to cherty pink, purple, red (ferruginous) and grey (siliceous) in colour, mostly fine grained to coarse gritty at few places. Grains are chiefly sub-rounded to well-rounded.

Horizontally Stratified Sandstone lithofacies is present in Middle Member at Hathmati River near Kundol village, southeast of Himmatnagar. The cumulative thickness of HSS lithofacies at Hathmati River section near Himmatnagar is ~15 m, where it repeats three times as we go towards downstream side (BorKampa road and along Bholeshwar Mandir near Post Office). It is characterized by horizontal stratification and on few places by lamination. Hummocky stratification and mud drapes are also common sedimentary structure found in the facies. Hummocky stratification is present on top at Hathmati section near the BorKampa road.

The sandstones of the lithofacies are also ferruginous to cherty, pink, red (ferruginous) and grey (siliceous) in colour, mostly fine grained to coarse to gritty. Grains are chiefly sub-rounded to well rounded.

Plant fossils (*Matonidiumindicum, Sphenopteris, Pagiophyllum, Elactocladus, Brachyphyllum*, ferns, Cycadean frond, petrified wood, etc.) and trace fossils (*Skolithos, Ophiomorpha, Psilonichnus, Monocraterion, Arenicolites, Diplocraterion, Thalassinoides, Teichichnus, Palaeophycus, Planolites*, etc.) are commonly present in the lithofacies.

It is topmost lithofacies of Middle Member, which occurs below unconformity with Upper Member (represented by gritty–cobbly sandstone lithofacies).

The lower parts of beds in Middle Member are exposed along Hathmati River section on downstream side at two places (near Jumma Mosque and along the way to Parabada road). These beds comprise the thickness of ~10 m. The sandstones are chiefly made up of sub-angular, fine to medium grained quartz with the grey colour matrix (siliceous). The lower portion of these beds is comprised of mottled sandstones. The mottled appearance is produced due to the effect of burrowing. This mottled sandstone part is about 2 m thick.

Above characters (horizontal stratification/lamination, hummocky stratification, and mud drapes and trace fossils) of the lithofacies are suggestive of environment of deposition, which must be upper foreshore to upper shoreface.

4.2.3 Cross-Stratified Sandstone (CSS) lithofacies

It contains cross-stratified sandstone of Lower Member and present at Arsodiya village. The lithofacies consist of 30 cm to 1 m thick wedge shape cross-stratified tidal bundles. Total thickness of the lithofacies is ~12 m. The lithofacies is chiefly composed of fine to very fine sand and at few places it shows fine lamination.

The sandstone is grey (siliceous), purple to red (ferruginous) in colour, hard, compact and cherty in character and arenaceous varies from sand grains to gritty on top of cross-stratified beds. In the lithofacies sub-angular to sub-rounded, moderate to poorly sorted, fine to medium grains of quartz, feldspar, muscovite flakes and opaque grains are recognized. The cementing matrix is mainly siliceous and ferruginous at few places.

It contains Cross-Stratified Sandstone of Lower Member and present in Vavdi, Vantada, Berna and adjacent hills in top part. This lithofacies consists of 30 cm to 1 m thick wedge shape cross-stratified tidal bundles. Total thickness of the lithofaciesis ~12 m. Wedge shape geometry, inverse grading, planar cross-stratification and wave ripples are common. Other structures include lamination, hummocky cross-stratification, tidal bundles, herringbone structure etc.

Intertidal ridge-runnel structure is also observed on Vantada hill top. Rarely, small scale ripple cross-lamination is visible along larger fore set cross-stratified beds. The lithofacies is composed dominantly of fine to very fine sand and at few places shows fine lamination. The sandstone is grey (siliceous), purple to red (ferruginous) in colour; hard, compact and cherty in character and varies from fine grained to gritty on top of the cross-stratified beds. Sub-angular to sub-rounded, moderately to poorly sorted, fine to medium grains of quartz, feldspar, muscovite flakes, opaque grains are recognized in the lithofacies. The cement is mainly siliceous at few places ferruginous. Coating of very fine radiating quartz crystals is common on framework grains. Herringbone structure indicates that the current periodically flows in the opposite direction as in case of intertidal environment.

Few body fossils (mainly fragmented bivalves), plant fossils (*Witchseliaraticulate, Matonidiumindicum, Ptilophyllum,* Cycadean frond and fossil wood) and trace fossils (*Monocraterion, Chondrites, Calycraterion, Thalassinoides, Psilonichnus*and *Skolithos*) are recognized in the lithofacies.

All the above characteristics are indicating foreshore to upper shoreface environment of deposition.

It also contains cross–stratified sandstone of Middle Member and present in Hathmati River section near Himmatnagar bypass road. This lithofacies consists of ~4.5 m thick wedge shape cross–stratified tidal bundles. Wedge shape geometry and wave ripples are common. Other structures include hummocky cross–stratification and herringbone structure. Small scale ripple cross–lamination is visible along larger fore–set of cross–stratified beds. The lithofacies is chiefly composed of fine to medium sand and at few places it shows fine lamination.

The sandstone is mostly grey (siliceous) and at few places red (ferruginous) in colour, hard, compact and cherty in character and arenaceous varies from sand grained to gritty on top of the cross–stratified beds. In the lithofacies sub–angular to sub–rounded, moderate to poorly sorted, fine to medium grains of quartz, feldspar, muscovite flakes and opaque grains are recognized. The cement is mainly siliceous and at few places ferruginous. Over growth coating of very fine radiating quartz crystals is common on framework grains.

Herringbone structure in the lithofacies indicates tidal action of foreshore environment. Wedge shape geometry of the rocks is characteristic of tidal bundles. Wave ripple marks indicate high energy storm or tsunami event in marine to marginal marine environment above the wave base. Hummocky stratification is found in high energy condition of foreshore to upper shoreface environment due to deposition on swells and troughs. Much sorting is depicted by the grain size of the rocks.

All the above characteristics are indicating foreshore to upper shoreface environment of deposition for the lithofacies.

4.2.4 Silty-Shale (SS) lithofacies

It occurs as Lower Member of Himmatnagar Sandstone Formation at Arsodiya village near Sapteshwar and near KattiHanumanji temple at Kadoli. Colour of the rock is white to pink with finer grain size, made up of clay with silt and fine sand.

At Katti temple, a section of hard silty-shale is exposed in contact with gaugy material which indicates faulting. The material is sandy and calcareous in nature. On the bank of Sabarmati River, contact between Lower and Upper Member is clearly visible. The Lower member is of silty-shale, which is ferruginous in nature and consists of plant material and scattered burrows. The Upper member is in contact with silty-shale is of gritty sandstone with huge - vertical *Skolithos* and *Monocraterion* like burrows. At Sabarmati River section near

Sapteshwar, silty-shale overlies horizontal stratified sandstone (HSS) of Lower Member. The lithofacies is 2 m in thickness and deposited in tidal flat environment.

It also occurs in Middle Member of Himmatnagar Sandstone Formation in Vantada and Hathmati River section. This rock is thinly laminated shale with thin siltstone intercalations at Hathmati section. Colour of the rock is white to pink and grain size is fine, made up of clay with silt and fine sand. The rock is thinly laminated shale with thin (0.5 to 1 cm thick) siltstone intercalations at places. In Hathmati River section the facies is represented by pinkish silty–shale having 3 m thickness and repeated twice. Parting lineation is observed at one place. Here fragmentary plant fossils without root portions and various trace fossils are present. Silt size particles (finer than sand – generally 0.1 mm but coarser than clay – around 0.004 mm) are chiefly made up of angular to sub–angular quartz grains. Sediments are also showing horizontal lamination and hummocky stratification. These rocks are highly affected by deformational structures. These lithofacies shows deformational structure like convolute bedding, flame structures and seismites. They are such structures that result from deformation during or shortly after sedimentation but before induration of the sediment into rock. Majority of structures indicates period of seismic events. Flame structures consist of mud and are wavy or "flame" shaped. These flames extend into an overlying ferruginous laminated sandstone layer. This deformation is caused from sand being deposited onto mud, which is less dense. Seismites are sedimentary structures disturbed by seismic waves from earthquakes. They are commonly used to interpret the seismic history of an area. Thus, flames are thin fingers of mud injected upward into the silty sandstones. These features form during soft-sediment deformation shortly after sediment burial, before the lithification of sediments. The convolute bedding is formed when complex folding and crumpling of beds or laminations occur. This type of deformation is found in fine or silty sands, and is usually confined to one rock layer mostly in the upper part of a single bed and hence preserved over here.

In Vantada section, this lithofacies is greyish white in colour and 8 m thick bed. It is highly - fossiliferous containing plant fossils. The facies is most probably deposited in marginal marine lagoon environment. In Hathmati River section the facies is represented by pinkish white silty-shale having 2 m thickness. Here also, plant fossils and various trace fossils are present. The characters of the facies are identical at Hathmati River section and Sapteshwar on Sabarmati River section.

Silt size (finer than sand - generally 0.1 mm - but coarser than clay - around 0.004 mm) particles are chiefly made up of angular to sub-angular quartz grains. Sediments are also showing horizontal lamination at places and characterized by disseminated plant debris.

It contains many plant fossils (*Calamites, Pagiophyllum, Brachyphyllum, Gleichinia, Araucarites, Circinate Vernation* of ferns, *Williamsonia*Flower, twigs, Petrified wood, Conifer and its cone etc.), body fossil (insect wing) and trace fossils (*Skolithos, Monocraterion, Psilonichnus, Thalassinoides, Chondrites, Planolites, Palaeophycus, Calycraterion, Circulichnus, Ophiomorpha, Phoebichnus*etc.).

One more exposure of silty-shale facies occurs in the stream section which is passing through Ilol meeting Sabarmati River near Dedhrota. Here, the silty-shale facies of rocks are thick having a thickness of ~14 m. It is light grey to black in colour. It shows gentle dip of 2^{o} to 5^{o} towards north direction and shows minor faulting of few meters towards north.

Based on above characters, it can be interpreted that trace fossils and sedimentary structures indicate that the lithofacies at Hathmati sections must be deposited in foreshore to upper shoreface environment.

4.2.5 Intercalated Shale-Sandstone (ISS) lithofacies

It occurs in Middle Member of Himmatnagar Sandstone Formation on Hathmati River near left side bank, below bridge near Himmatnagar. They are 3 m thick. The beds constitute alternate sequence of silty-shale and silty-sandstones, which occur in form of 5 cm to 10 cm thick intercalations.

Silty-sandstones are compact and hard, ranging from fine to medium grained with grey colour shades. While silty-shales are soft in nature and of fine grained, ranging in colour from whitish pink to pink.

Effectively, intercalation occurs when there are two distinct energy differences in depositional environments. By following intercalations laterally, we often end up in rocks dominated by one or the other type of sedimentation. The intercalation occurs as the different energy level in environments which fluctuate back and forth. Here, the depositional environment is characterized by the alternations of depositional material.

Trace fossils found in the lithofacies are *Rhizocorallium, Gyrochorte, Cochlichnus, Desmograpton, Diplocraterion, Gordia, Haentzchelinia, Isopodichnus, Lobichnus*etc.

So, based on beds, characteristics we can say that the environment was changing from middle shoreface to foreshore.

4.2.6 Planar Cross-Stratified Sandstone (PCSS) lithofacies

Planar Cross-Stratified Sandstone (PCSS) lithofacies is present at Sabarmati River section near Sapteshwar Bridge in Lower Member of Himmatnagar Sandstone Formation. This facies is yellowish white in colour, 4 m thick section with planar cross-stratified fine grained sandstone. The lithofacies is soft and friable in nature containing of sub-rounded to well-rounded fine grains of mostly quartz. Cement is clayey.

Large size crustacean and vertebrate trace fossils range in 1 m to 3 m in length and 20 cm to 30 cm in diameter are commonly present in the lithofacies with other trace fossils like *Skolithos, Thalassinoides, Ophiomorpha*etc.

The lithofacies represents coastal aeolian environment of deposition.

4.2.7 Grey Wacke (GW) lithofacies

Rock of Grey Wacke lithofacies is variety of argillaceous sandstone that is highly indurated and poorly sorted. A good section of the HimmatnagarSandstone is exposed in the hillock located near Vantada Village about 12.5 km east Himmatnagar town. It occurs in Middle Member of HimmatnagarSandstone Formation in Vavdi, Vantada (Wantra) hill, Berna hill and adjacent flat toped hill in East of Himmatnagar town.

It is chiefly made up of angular, sub-angular to sub- round grain of quartz, feldspar, hornblende and mica with much clay content. Few pebbly bands are present. Grey Wacke is mostly grey, brown, black and greenish black dull coloured sandy rock. Some of the gains are gritty to pebbly.

Grey Wacke is unfossiliferous. No-body fossil or trace fossil and plant fossil occurs in the facies. Their component particles are usually not much rounded and the rocks have often been considerably indurated by introduction of interstitial silica. Some varieties include feldspathic Grey Wacke, which is rich in feldspar and lithic Grey Wacke, which is rich in tiny rock fragments.

The grains are fine to medium sand sized, and matrix materials generally constitute more than 15% of the rock by volume. Variety of minerals, such as quartz, orthoclase, plagioclase, calcite, iron oxides and graphitic carbonaceous matters, together with fragments of gneisses, various schists, and quartzites are present as frame work grains. Few grains of biotite, chlorite, tourmaline, epidote, apatite, garnet, augite, and pyrites are also present. The cement is argillaceous/clayey.

The Grey Wacke is seen resting over a weathered granitic gneiss forming nonconformity at the base. The exposure of the nonconformity is present all around Vantada hill. The contact between granite-gneisses and Grey wacke is undulating and uneven because of the highly weathered nature of the rocks at the contact. The facies seem to be deposited and preserved in a transgressed sea in the area on much older rocks in shoreface environment.

A 15 cm thick quartz-conglomerate is present approximately 2 m above the unconformable contact of the facies. Similar 10-15 cm thick conglomerate is exposed approximately 7.5 m above the base. Both are extra-basinal, oligomictic, para-conglomerates indicating some high energy event responsible for their deposition. The matrix of the conglomerate is mainly composed of white micritic mudstones and argillaceous to silty red ferruginous pebbly claystone. Clasts of conglomerate are matrix supported - float within the matrix, which is called para-conglomerate. Para-conglomerates are commonly debris flow deposits.

4.2.8 Gritty-Pebbly Cross-Stratified Sandstone (GPCSS) lithofacies

The facies is present almost everywhere in the study area except around Ilol where it has not been represented anywhere. It is found along Sabarmati River on beds of Lower Member and also on the banks of Hathmati River on rocks of Middle Member. The rocks are not found present anywhere on eastern rocky exposures present in the hillocks. A conspicuous section is visible along Hathmati river channel near Kundol village.

This facies consists of clast-supported, massive beds. It is 25 m thick. Clasts range from 0.5 cm to 7 cm in diameter and made up of granules, pebbles and cobbles set in a matrix of ferruginous, sand material. They are sub-angular to rounded, poorly sorted and consist of quartz, granite, gneiss, quartzite and pegmatite. The long axes of the clasts are randomly arranged and there is neither an imbricated nor a horizontal fabric. The facies is poorly consolidated and has a reddish brown or brown colour. There is presence of plant fossils, e.g. branches and at few places bioturbation is visible. The base of this lithofacies is irregular and scoured. The presence of irregular base gives a channel-like appearance to this facies.

The Cobbly Sandstones are graded from cobble as basal lag deposit to pebble size clasts and granules. The upper part of the bed which is gritty, medium grained sandstones is massive, and horizontally stratified. The grain size of the sediment is identical to that of the matrix of the underlying cobbly sandstones. There is gradation from cobbly to pebbly zone, but in most cases the clear junction is abrupt. The base of this lithofacies is irregular and erosional. A thin ferruginized band marks the lower contact at some places where the facies overlies massive sandstone bed. The band is probably formed as a result of permeability barrier between the two lithologies, which traps the percolating rain, water from where iron precipitates out.

The rocks of this lithofacies are cross-stratified and gritty to cobbly sandstone present in Sabarmati River at Arsodiya village, South of Sapteshwar and Near Katti temple. It forms the overlapping sequence and belongs to the Upper member of Himmatnagar Sandstone Formation. Thickness of gritty cross-stratified sandstone lithofacies varies from 3 m to 15 m. A thickness of approximately 10-15 m is found near Sapteshwar Mahadev Temple. The rudaceous fragments in the rocks are sub-angular to angular to sub-rounded in shape. The rock depicts channel structure, trough cross-stratification and graded bedding at most of the exposures of lithofacies and shows southward (downstream) palaeocurrent direction.

Above characters of the lithofacies are suggestive of environment of deposition, which must be of fluvial to estuarine type of environment.

Plate 4.1

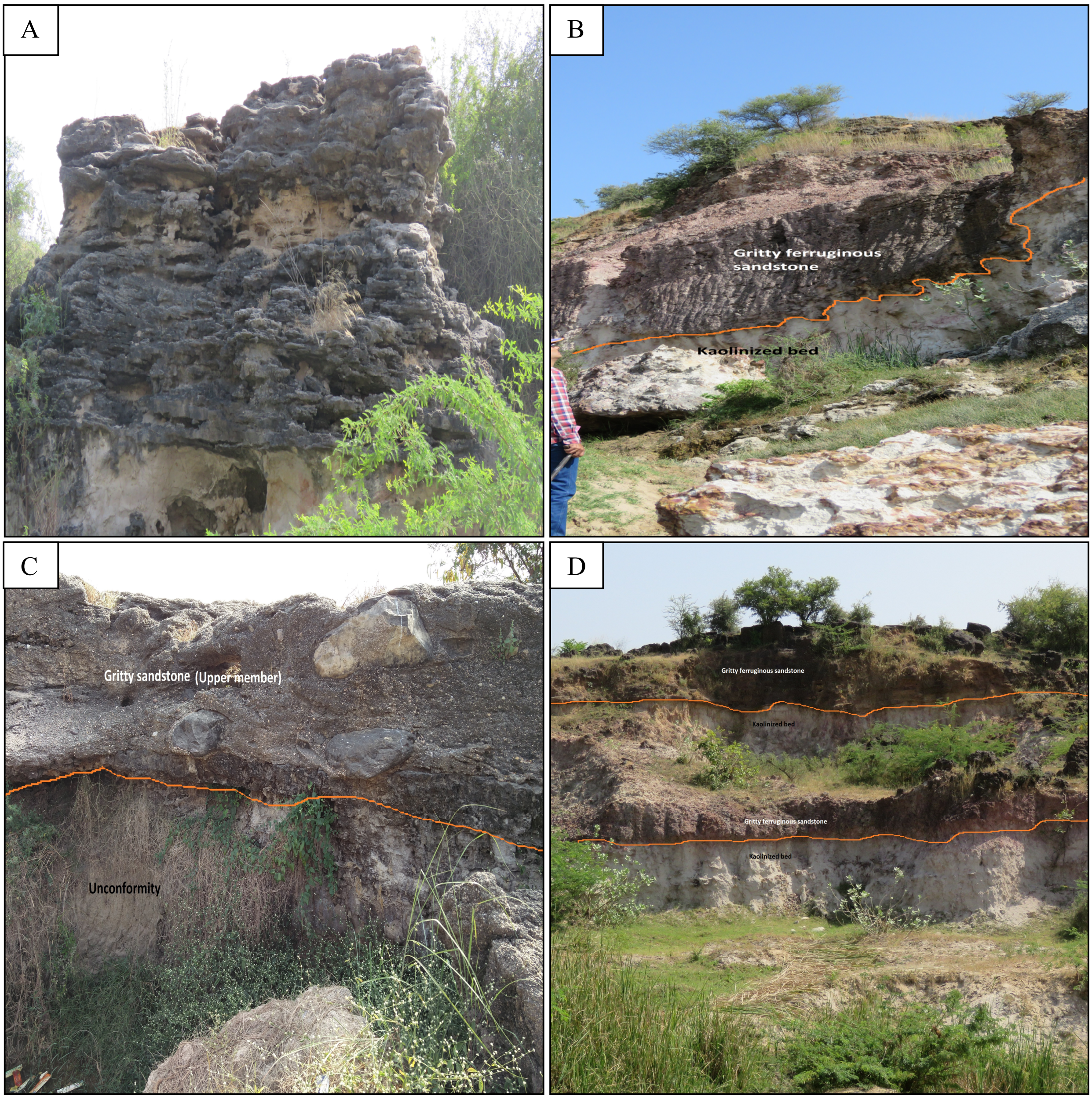


Plate 4.1: (A) Horizontally Stratified Sandstone (HSS), near Arsodiya village, (B) Contact between Kaolinized bed of HSS lithofacies and Gritty ferruginous sandstone (GPCSS) at Arsodiya village, (C) Gritty sandstone (GPCSS) in unconformable contact with HSS, near Sapteshwar, (D) Alternate beds of Kaolinized bed and ferruginous sandstone (HSS) with unconformity with Gritty ferruginous sandstone near top of the sequence at Arsodiya village.

Plate 4.2

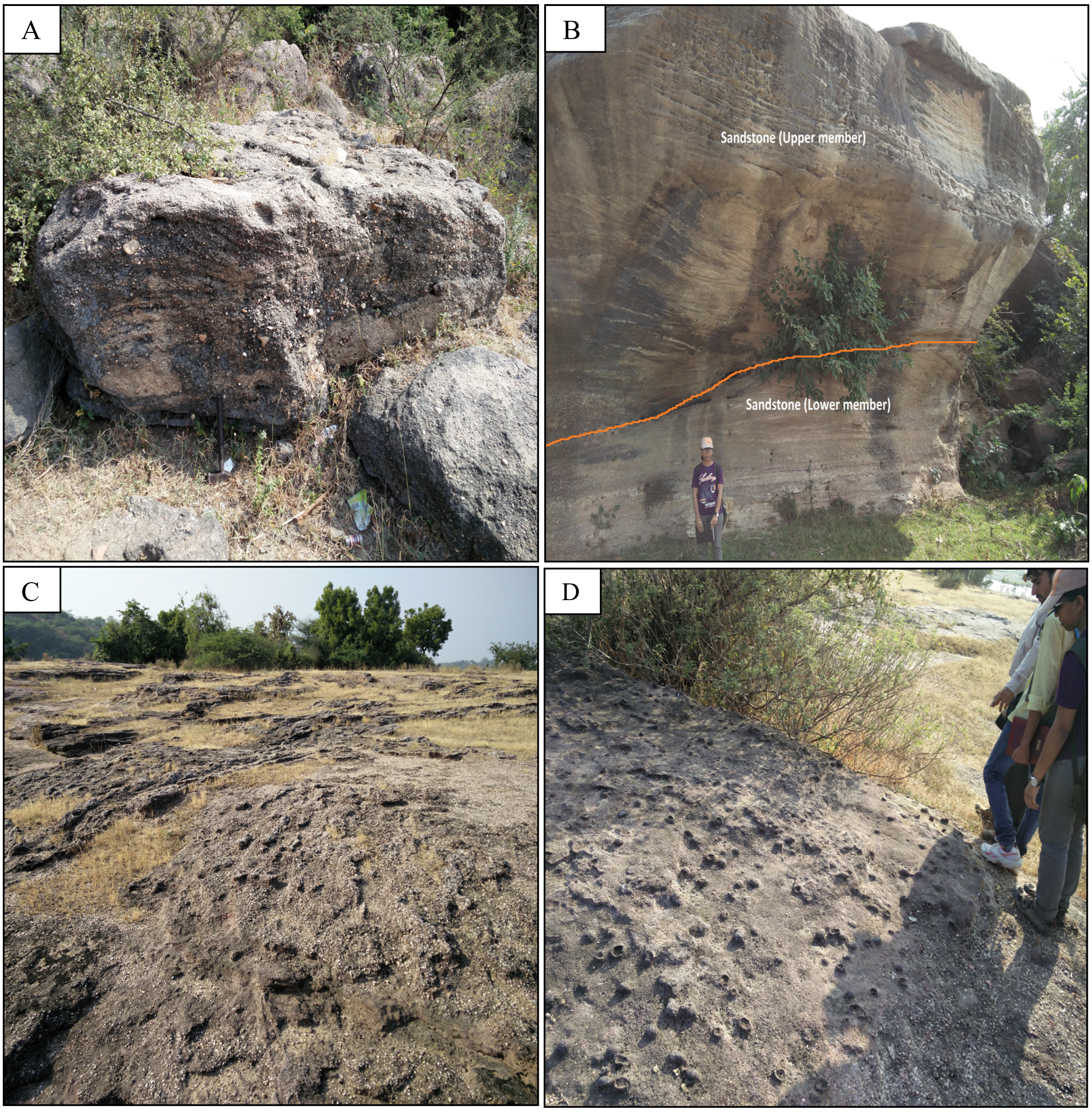


Plate 4.2: (A) Cross-stratified sandstone, near Sapteshwar, (B) Contact between the Upper Member and the Lower Member Sandstone, near Katti, (C) Gritty sandstone bed of GPCSS lithofacies, near Katti, (D) Uppermost bed of Gritty Sandstone comprising *Pholeus bifurcates* trace fossil, near Katti.

Plate 4.3

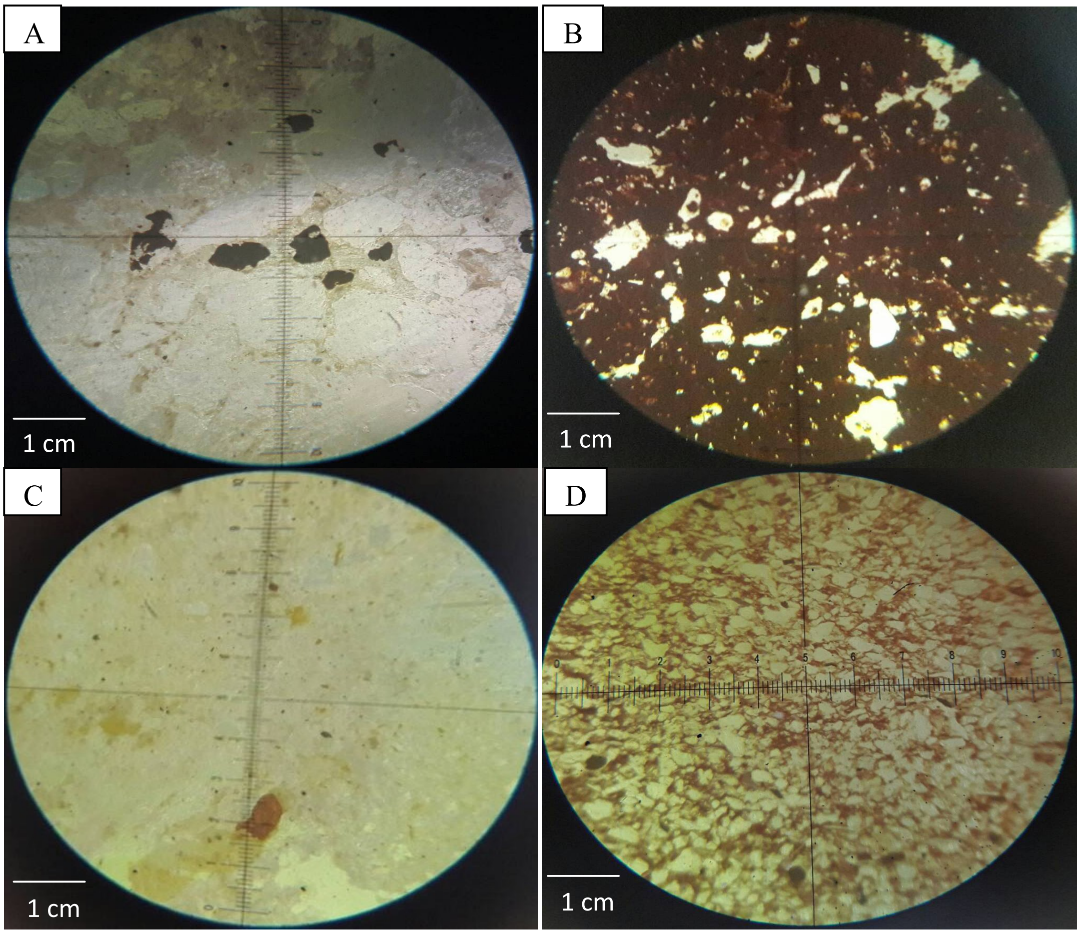


Plate 4.3: (A) and (B) are the lithosection of conglomerate. (A) shows clayey material while (B) shows higher amount of ferruginous matrix, both (A) and (B) contains unidentified plant fragments, (C) the section shows Gaugy material which contains Ankerite $Ca(Fe,Mg,Mn)(CO_3)_2$, the dark shiny material shows the presence of calcite, it also shows some amount of ferruginous matrix, (D) the section is of Silty-Shale which shows some mica flakes, the section shows a fair amount of ferruginous material along with plant fragments.

Plate 4.4

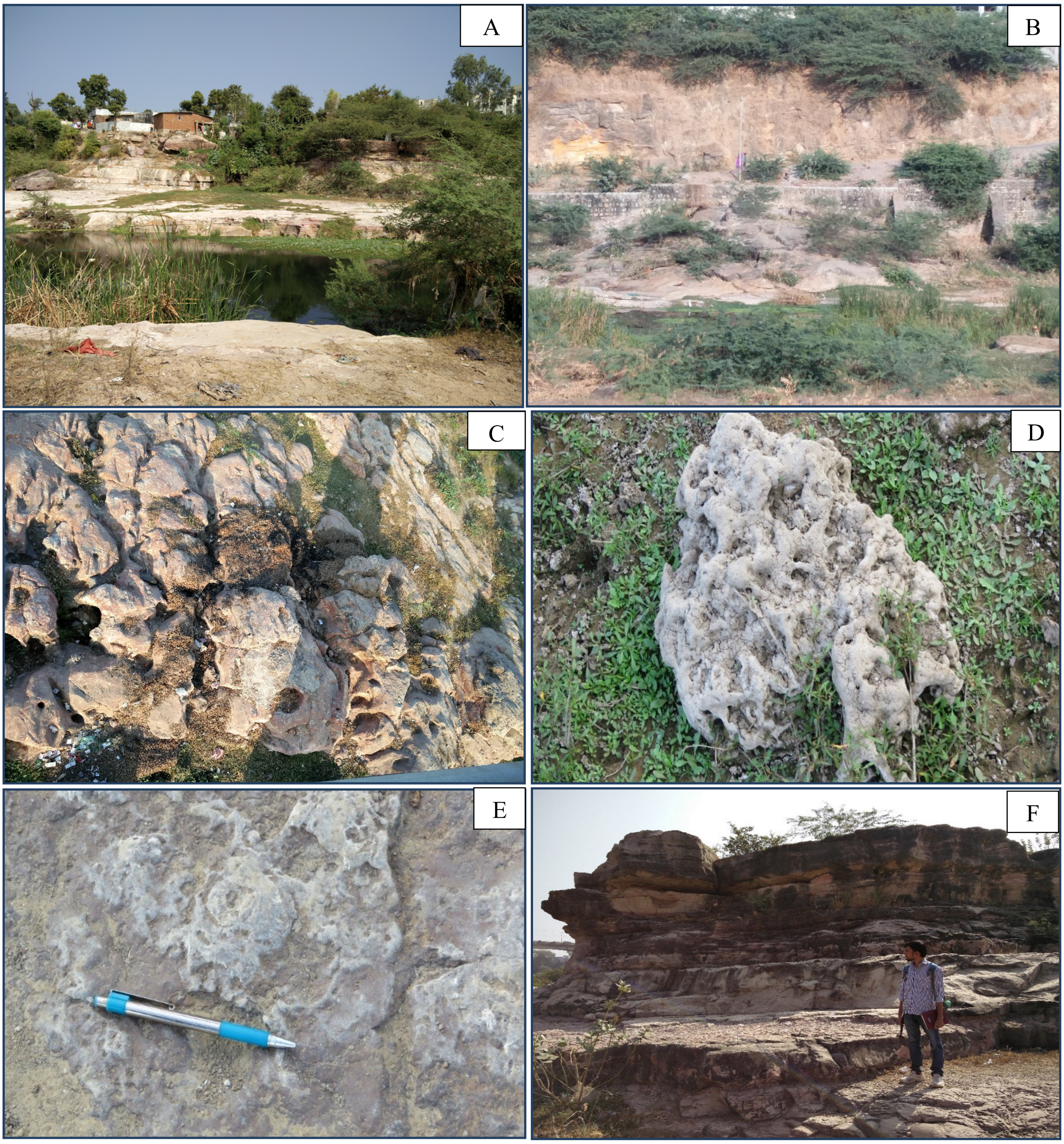


Plate 4.4: (A) Unconformity between Upper Member and Middle Member, (B) Horizontally Stratified Sandstone near Jumma Mosque, (C) Mottled Sandstone on HathmatiRiver bed below bridge on Parabada road, (D) Trace fossils *Skolithos* and *Thalassinoides*in topmost part of Middle Member along Hathmati River section near Kundol village, (E) Trace fossils: *Thalassinoides*and *Monocraterion,* (F) Horizontal stratification in Sandstones along Hathmati River section.

Plate 4.5

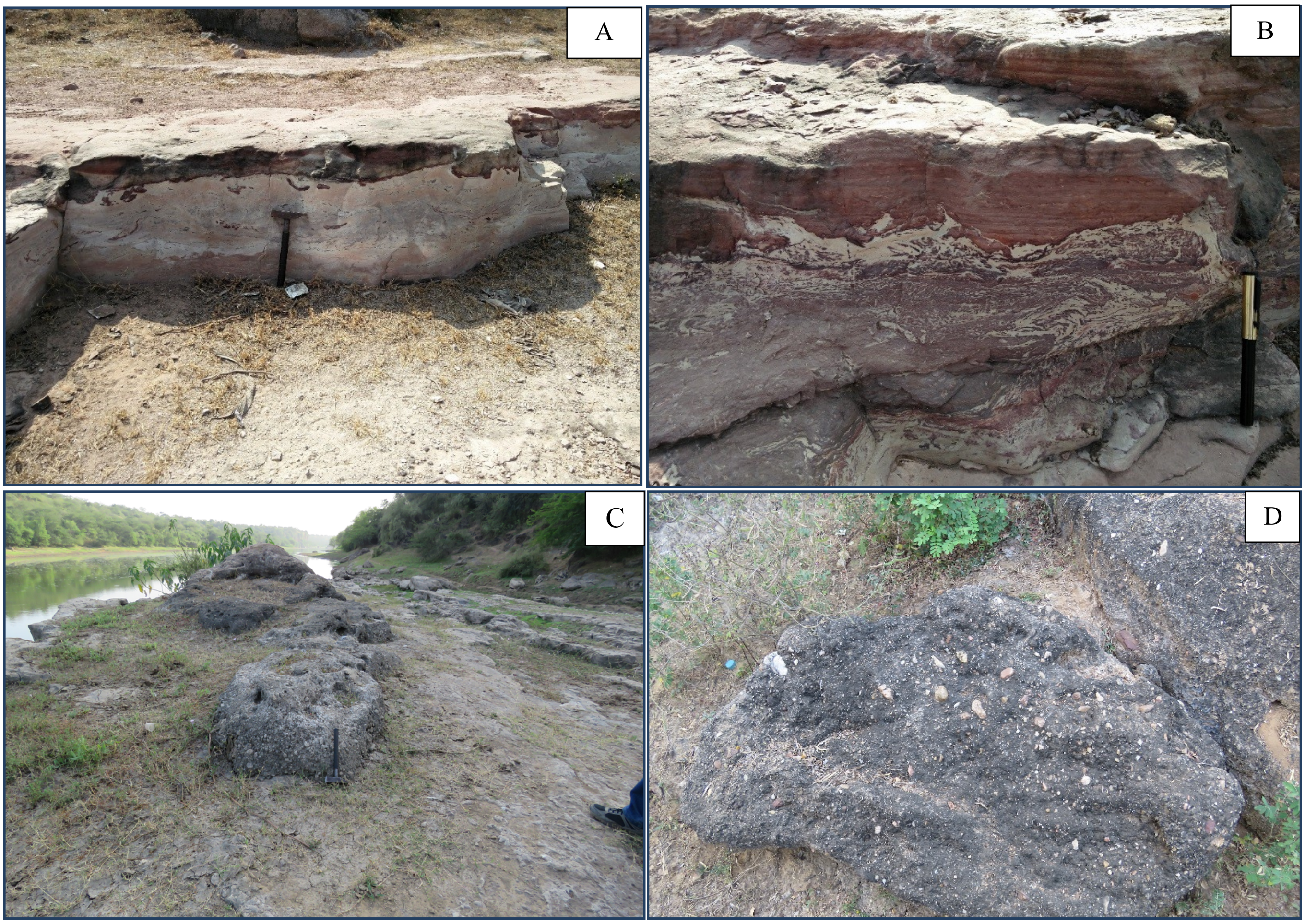


Plate 4.5: (A) Convolute bedding, (B) Flame structure in Hathmati River section at Himmatnagar in Silty-Shale and Horizontally Stratified Sandstone lithofacies respectively. (C) Cobbly Sandstone at Hathmati River section near Kundol village. (D) Fining upward sequence in Cobbly Sandstone.

Plate 4.6

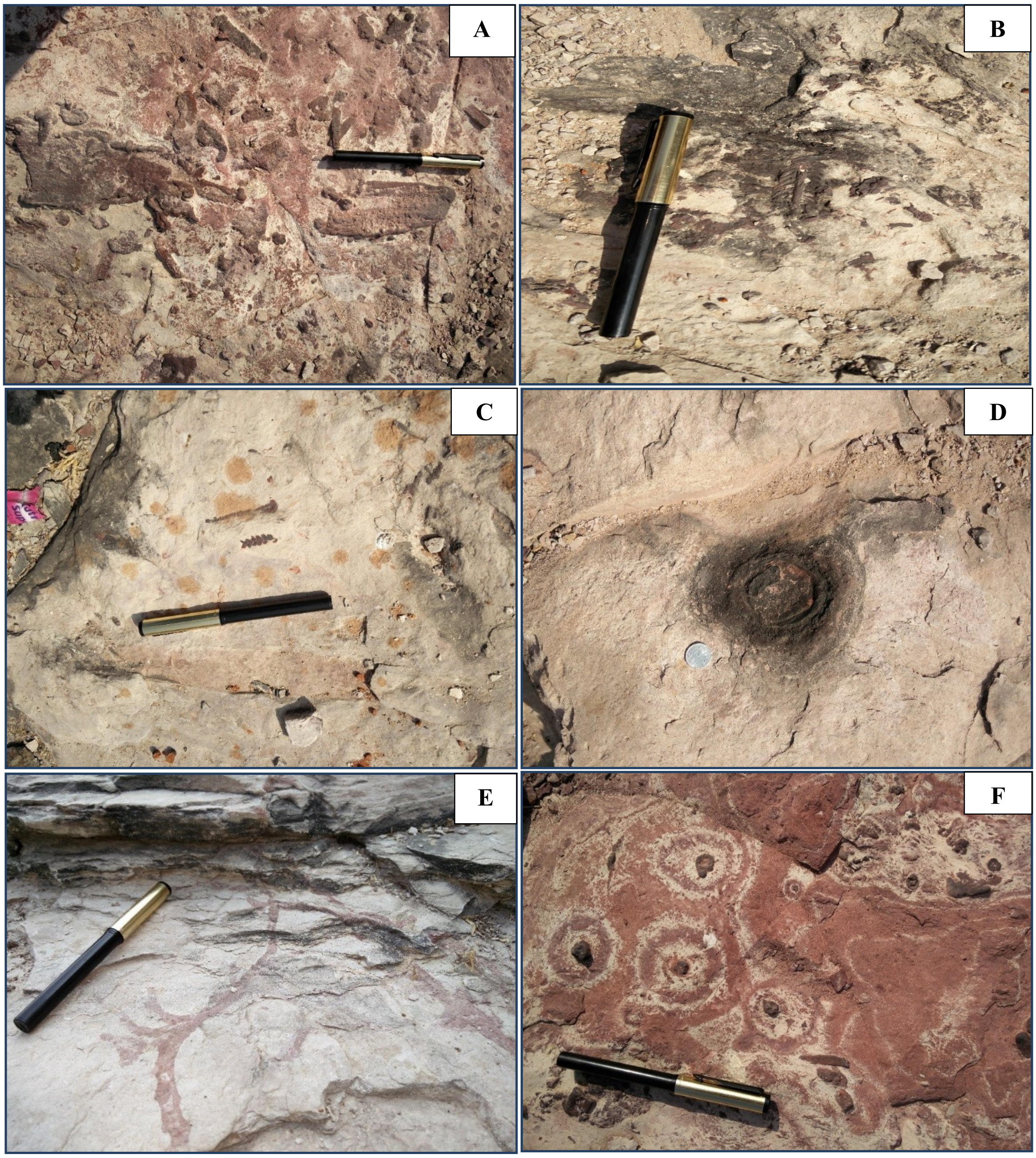


Plate 4.6: (A) Plant/wood fossils, (B) and (C) Leaf impressions, (D) *Rosselia,* (E) *Psilonichnus,* (F) *Ophiomorpha* and *Chondrites.*

Plate 4.7

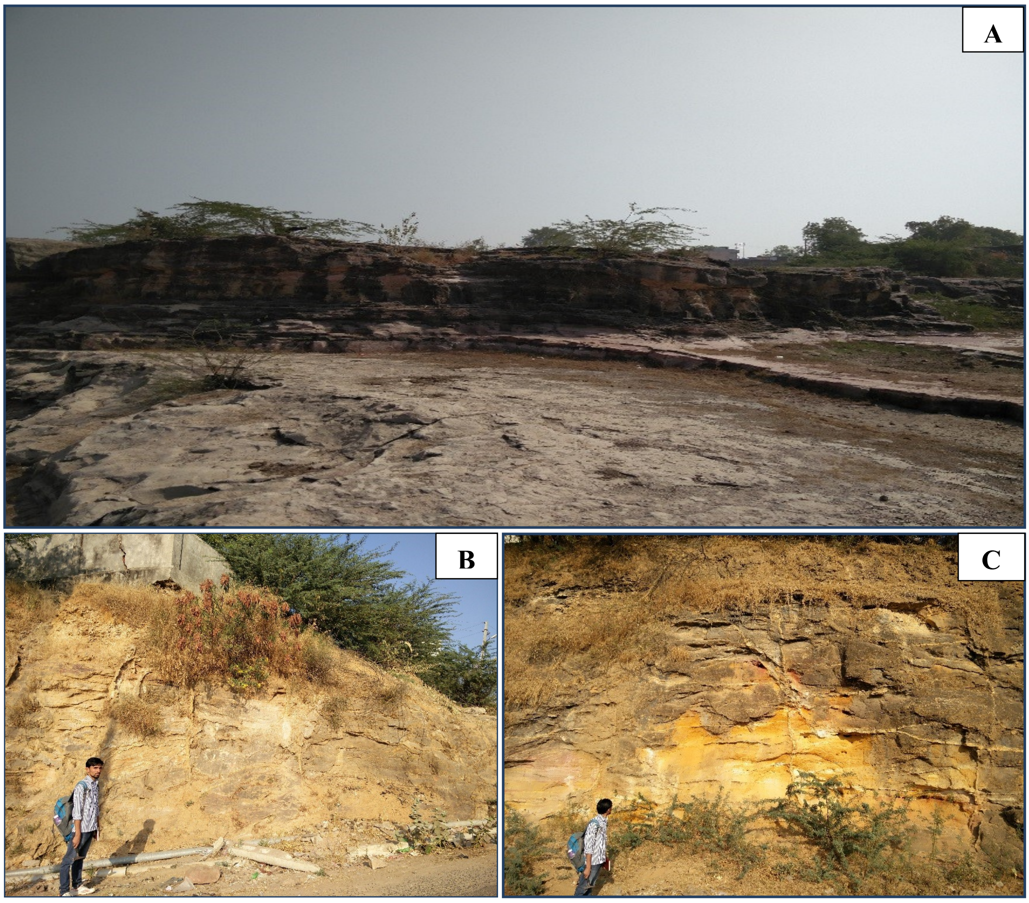


Plate 4.7: (A) Intercalation between Silty-Sandstone and Silty-Shale on Himmatnagar-Idar road in Hathmati River. (B) and (C) Cross-stratified Sandstone on Himmatnagar collector office road in Hathmati River.

Plate 4.8

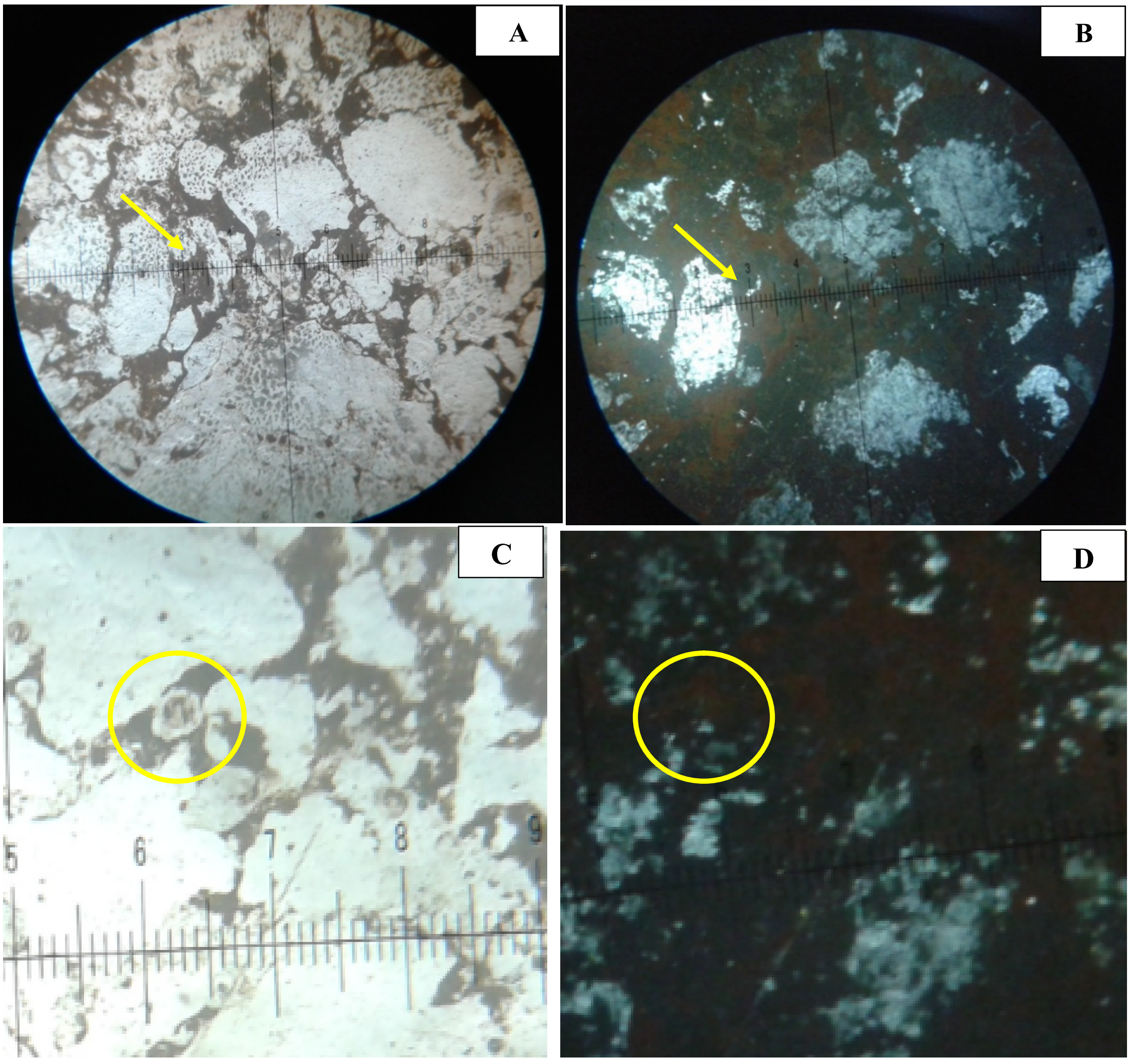


Plate 4.8: (A and B): Cobbly Sandstone of GPCSS lithofacies is showing quartz grains enclosed in grain supported ferruginous matrix with the grain size ranging from 4 to 7 mm. Corrosion along the boundary between quartz grains has indicated by arrow. Fluid inclusions are present suggesting the hypabyssal igneous origin of quartz grains. (C and D) Same rock is with plant fossils; (C) OTP and (D) BCN views. Field of view is 3.5 mm across.

Plate 4.9

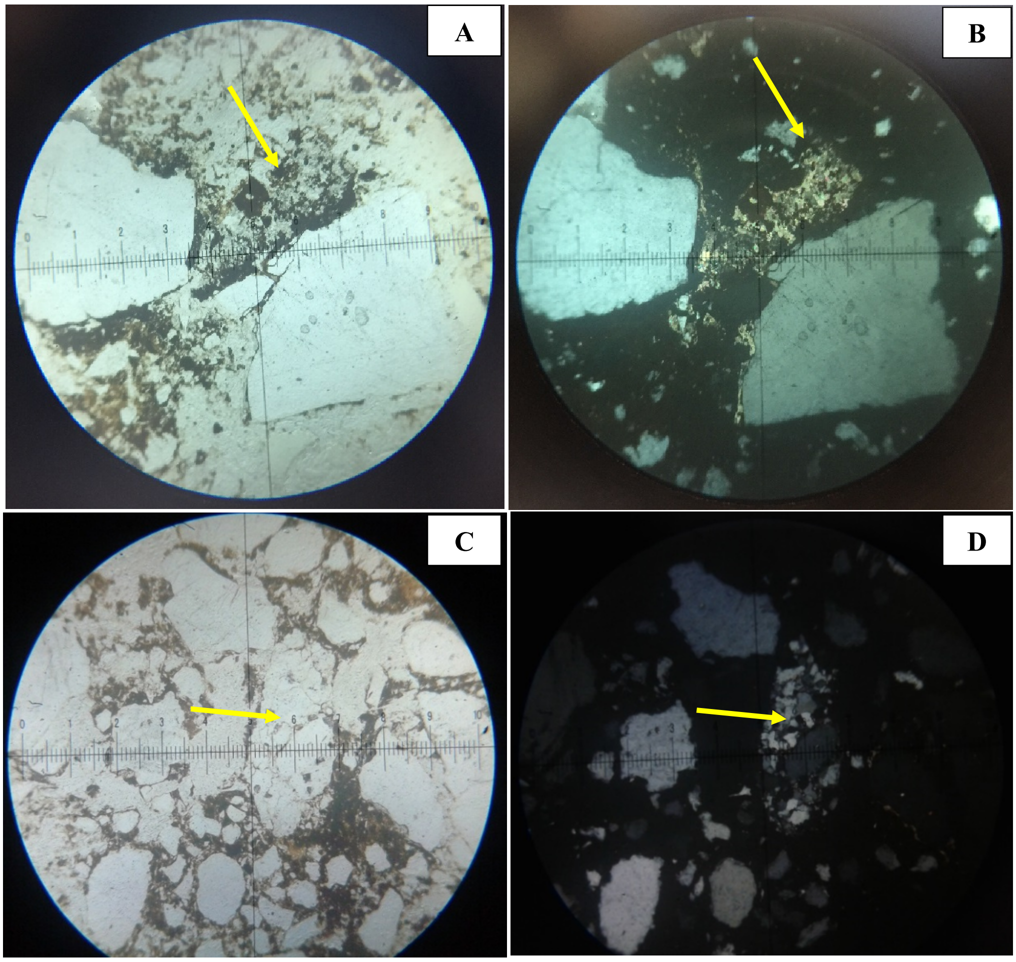


Plate 4.9: (A) and (B): Horizontally Stratified Sandstone of HSS lithofacies is showing quartz and felspar grains enclosed in grain supported ferruginous matrix with the grain size ranging from 2 to 4 mm. Remnant calcareous matrix, which was later altered by ferruginous material. (C) and (D): Fragment of Sandstone entrapped in matrix. Plane polarized light, field of view 3.5 mm across.

Plate 4.10

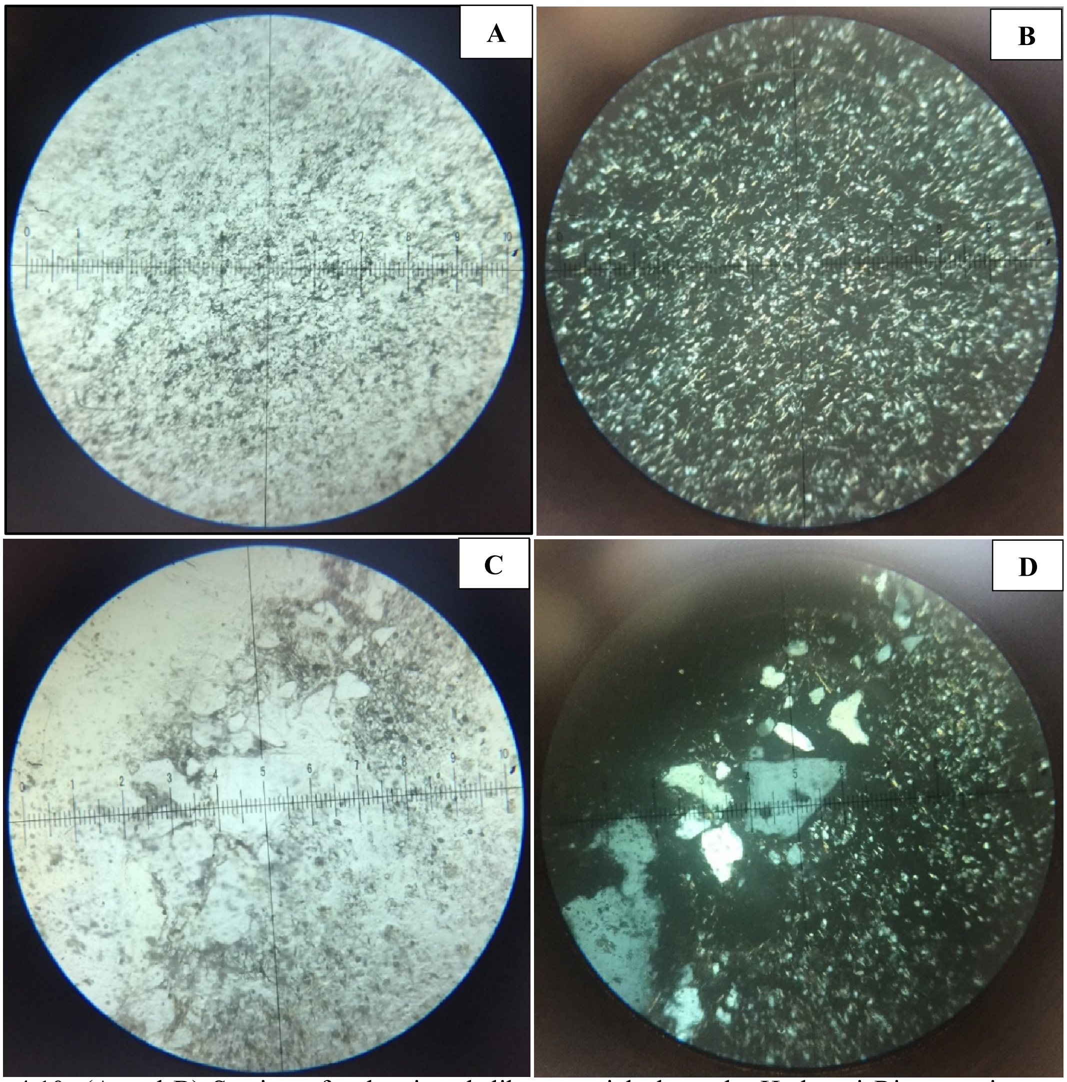
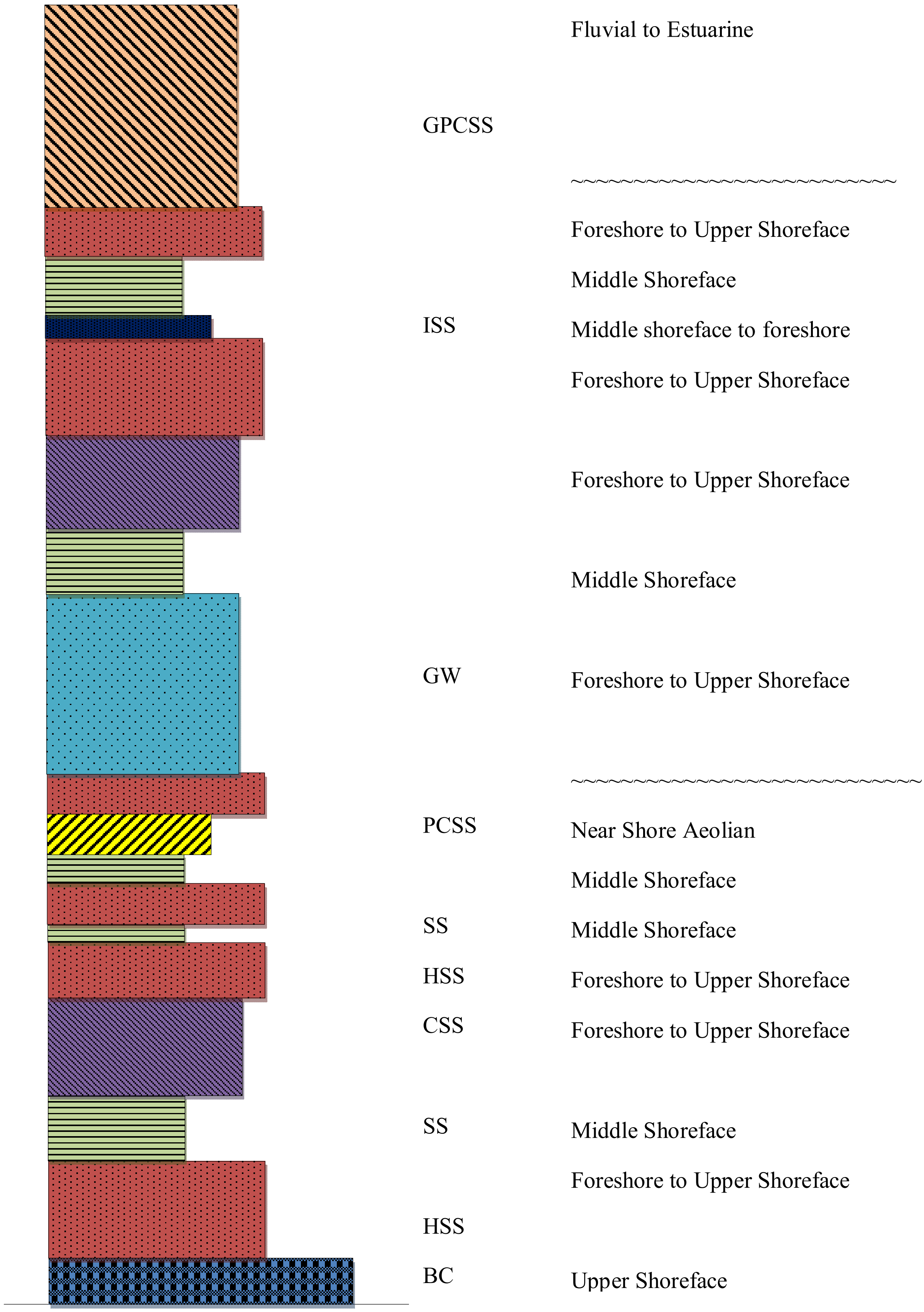


Plate 4.10: (A and B) Section of volcanic ash like material along the Hathmati River section near Kundol village showing very fine grain size. Grains of mica (muscovite) are abundantly present within the clayey material, suggesting that it might be erupted from Mud / Sand volcano. (C) and (D) Patches of quartz grain is present. Plant fossils are also sufficiently present. Both are of transported origin. Field of view is 3.5 mm across.

Table 4.1: Environmental conditions of lithofacies of Himmatnagar Sandstone formation.

No.	Lithofacies	Environment
8.	Gritty-Pebbly Cross-Stratified Sandstone (GPCSS)	Fluvial to Estuarine
7.	Grey Wacke (GW)	Upper Shoreface
6.	Planar Cross-Stratified Sandstone (PCSS)	Near Shore Aeolian
5.	Intercalated Shale-Sandstone (ISS)	Middle shoreface to foreshore
4.	Silty-Shale (SS)	Middle Shoreface
3.	Cross-Stratified Sandstone (CSS)	Foreshore to Upper Shoreface
2.	Horizontally Stratified Sandstone (HSS)	Foreshore to Upper Shoreface
1.	Basal Conglomerate (BC)	Upper Shoreface



Fluvial to Estuarine
GPCSS
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Foreshore to Upper Shoreface
Middle Shoreface
ISS
Middle shoreface to foreshore
Foreshore to Upper Shoreface
Foreshore to Upper Shoreface
Middle Shoreface
GW
Foreshore to Upper Shoreface
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
PCSS
Near Shore Aeolian
Middle Shoreface
SS
Middle Shoreface
HSS
Foreshore to Upper Shoreface
CSS
Foreshore to Upper Shoreface
SS
Middle Shoreface
Foreshore to Upper Shoreface
HSS
BC
Upper Shoreface

CHAPTER 5

ICHNOLOGY

5.1 Introduction

Ichnologist is a scientist whose area of study and research is ichnology.**Ichnology** is the study of trace fossils. Implicit to this definition is that the traces made by plants and animals reflect some sort of behavior.Ichnology is the branch of geology and biology that deals with traces of organisms' behaviour, such as burrows and footprints. Ichnology can be divided into two major subdivisions: **palaeoichnology** (the study of ancient traces) and **neoichnology** (the study of modern traces). Most ichnologists are involved in palaeoichnology but a considerable number also study neoichnology for the comparison of modern equivalents (and their trace makers) to ancient traces. This introduction emphasizes palaeoichnology, but examples from neoichnology are provided in some cases for clarification of concepts. Indeed, some fossil traces were well studied long before modern equivalents were found at all, causing a reverse form of uniformitarianism: "the past is the key to the present."Parallels relationship can often be drawn between modern traces and trace fossils, helping scientists to decode the possible behaviour and anatomy of the trace-making organisms even if no body fossils can be found.

5.2 Historical Background

The work of Linnaeus (1758) invented binomial nomenclature which, among the nomenclatures yet invented, is the excellent and most practical system for classification of organisms. However, this system was invented for the animals and not for their behaviour. This statement is therefore important while classifying and naming trace fossils with the help of ICZN. Secondly, trace fossils are reflection of behaviour; they are the sedimentary structures resulting from their behaviour. Trace fossils are made by organisms; they have morphology and for morphology we have classification scheme but it seemed to be nearly impossible to fit sedimentologic remains of behaviour into this scheme because it was not meant for this purpose. Finally after the one and the other additional smaller fights, Ichnology came under the shade of the law of the ICZN. In 1999, with the fourth edition of the ICZN, ichnology fully became integrated into the zoological system of nomenclature. Thus, although the rules of the ICZN rules, the International Code of Zoological Nomenclature defined "trace fossil" as "fossilized work of an animal" which sound convincing but was insufficient. Berting et al (2003) proposed a new definition of trace fossils but did not found general acceptance among the ichnologists and zoologists. Later the definition was emended, refined and discussed for years by several authors (Genise et al, 2004; Bertling et al, 2004) which defined trace fossils as "Morphologically recurrent structure resulting from the life activity of an individual organism modifying the substrate". Studies clearly depicted that various morphologies may be produce by one particular organism and various different animals may produce morphologically identical structures.

5.3 Occurrence

Trace fossils are best preserved in sandstones; the grain size and depositional facies both are contributing to the better preservation. They may also be found in shale and limestone.

5.4 Classification

Trace fossils are generally difficult or impossible to assign to a specific maker. Only in very rare occasions are the makers found in association with their tracks. Further, entirely different organisms may produce identical traces. Therefore conventional taxonomy is not applicable, and a comprehensive form of taxonomy has been erected. At the highest level of the classification, five behavioural modes are recognized:

5.4.1 Domichnia: dwelling structures reflecting the life position of the organism that created it.

5.4.2 Fodinichnia: three-dimensional structures left by animals which eat their way through sediment, such as deposit feeders.

5.4.3 Pascichnia: feeding traces left by grazers on the surface of a soft sediment or a mineral substrate.

5.4.4 Cubichnia: resting traces, in the form of an impression left by an organism on a soft sediment.

5.4.5 Repichnia: surface traces of creeping and crawling.

Fossils are further classified into form genera, a few of which are even subdivided to a "species" level. Classification is based on shape, form, and implied behavioural mode.

Because identical fossils can be created by a range of different organisms, trace fossils can only reliably inform us of two things: the consistency of the sediment at the time of its deposition, and the energy level of the depositional environment.

5.5 Palaeoecology

Trace fossils provide us with indirect evidence of life in the past, such as the footprints, tracks, burrows, borings, and faces left behind by animals, rather than the preserved remains of the body of the actual animal itself. Unlike, most other fossils, which are produced only after the death of the organism concerned, trace fossil provide us with a record of the activity of an organism during its lifetime.

Trace fossils are formed by organisms performing the functions of their everyday life, such as walking, crawling, burrowing, boring or feeding.

Perhaps the most spectacular trace fossils are the huge, three-toed footprints produced by dinosaurs and related archosaurs. These imprints give scientists clue as to how these animals lived. Although the skeletons of dinosaurs can be reconstructed, only their fossilized footprints can determine exactly how they stood and walked. Such tracks can tell much about the gait of the animal which made them, what its stride was, and whether or not the front limbs touched the ground.

However, most trace fossils are rather less conspicuous, such as trails made by segmented worms or nematodes. Some of these worm castings are the only fossil record we have of these soft-bodied creatures.

5.6 Palaeoenvironment

Fossil footprints made by tetrapod vertebrates are difficult to identify to a particular species of animal, but they can provide valuable information such as the speed, weight, and behaviour of the organism that made them.

Such trace fossils are formed when amphibians, reptiles, mammals or birds walked across soft (probably wet) mud or sand which later hardened sufficiently to retain the impressions before the next layer of sediment was deposited. Some fossils can even provide details of how wet the sand was when they were being produced, and hence allow estimation of paleo-wind directions.

Assemblages of trace fossils occur at certain water depths, and can also reflect the salinity and turbidity of the water column.

5.7 Trace Fossil Descriptions

In the present study, ichnofossils i.e. ichnogenera are named according to International Commission on the Zoological Nomenclature (I.C.Z.N.) rules. Here the trace fossils are

1lassified and described as per the Ksiazkiewicz (1977), modified by Uchman (1995) in combination with other classifications (Chamberlain 1971, 1977 and Seilacher 1953). Based on field observations and collected data 23 ichnogenera were identified. A list of ichnogenera is given in Table 5.1, which is followed by brief description of each.

Table 5.1: Ethology of various ichnogenera present in Himmatnagar Sandstones.

Sr. No.	Ichnogenera	Ethology	Page number
1.	*Arenicolites*	Dwelling (*Domichnia*). Suspension feeding (*Fodinichnia*)	56
2.	*Calycraterion*	Dwelling (*Domichnia*).	57
3.	*Chondrites*	Feeding (*Fodinichnia*).	58
4.	*Circulichnus*	Grazing *(Pascichnia).*	58
5.	*Cochlichnus*	Grazing *(Pascichnia).*	60
6.	*Desmograpton*	Grazing *(Pascichnia).*	61
7.	*Diplocraterion*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	60
8.	*Gordia*	Grazing (*Pascichnia*).	61, 62
9.	*Gyrochorte*	Grazing (*Pascichnia*).	62
10.	*Haentzschelinia*	Dwelling *(Domichnia).*	65
11.	*Isopodichnus*	Crawling (*Repichnia*).	64, 65
12.	*Lobichnus*	Grazing (*Pascichnia*).	65
13.	*Monocraterion*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	66
14.	*Ophiomorpha*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	69
15.	*Palaeophycus*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	68
16.	*Planolites*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	68
17.	*Phoebichnus*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	69
18.	*Psilonichnus*	Dwelling (*Domichnia*).	70
19.	*Rhizocorallium*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	72
20.	*Rosselia*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	72
21.	*Skolithos*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	67
22.	*Teichichnus*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	74
23.	*Thalassinoides*	Dwelling (*Domichnia*); Feeding (*Fodinichnia*).	75

Lower Member: (HSS) *Ophiomorpha, Palaeophycus, Phoebichnus, Planolites, Psilonichnus, Skolithos, Teichichnus, Thalassinoides*;(SS) *Calycraterion, Chondrites, Circulichnus, Monocraterion, Ophiomorpha, Palaeophycus, Phoebichnus, Planolites, Skolithos, Thalassinoides*; (CSS) *Calycraterion, Chondrites, Circulichnus, Monocraterion, Ophiomorpha, Palaeophycus, Phoebichnus, Planolites, Psilonichnus, Skolithos, Thalassinoides*;(PCSS) *Ophiomorpha, Skolithos*and *Thalassinoides*; (ISS) *Arenicolites, Cochlichnus, Desmograpton, Diplocraterion, Gordia, Gyrochorte, Haentzchelinia, Isopodichnus,Lobichnus, Rhizocorallium, Rosellia*;(HSS) *Skolithos, Ophiomorpha, Psilonichnus, Monocraterion, Arenicolites, Diplocraterion, Thalassinoides, Teichichnus, Palaeophycus, Planolites*(CSS) *Rhizocorallium, Rosselia,Monocraterion, Chondrites, Calycraterion, Thalassinoides, Psilonichnus* and *Skolithos.*

Middle Member: (ISS) *Skolithos, Monocraterion, Psilonichnus, Thalassinoides, Chondrites, Planolites, Palaeophycus, Calycraterion, Circulichnus, Ophiomorpha, Phoebichnus, Lobichnus.*

Total 23 ichnofossils have been identified in the study area, such as *Arenicolites, Calycraterion, Chondrites, Circulichnus, Cochlichnus,Desmograpton,Diplocraterion,Gordia, Gyrochorte,Haentzchelinia,Isopodichnus, Lobichnus, Monocraterion, Ophiomorpha, Palaeophycus, Phoebichnus, Planolites, Psilonichnus, Rhizocorallium, Rosellia, Skolithos, Teichichnus* and *Thalassinoides.*

5.7.1 U – Shaped form

Ichnogenus: *Arenicolites* Salter, 1857, p. 204

Diagnosis: Simple U–shaped tubes without spreite, perpendicular to bedding plane. Varying in size, tube diameter, distance of limbs and depth of burrows. Limbs rarely somewhat branched, some with funnel shaped opening; walls commonly smooth, occasionally lined or sculptured. Burrows may reach considerable depth.

Description: Vertical to slightly oblique U-shaped burrows (can be J-shaped) without spreiten. Tubes are cylindrical, smooth walled.Burrow can have flared openings or funnel-shaped apertures. Depth-width ratios vary. Distances between openings vary.

Ichnospecies: *Arenicolites* isp.
(Figure5.1A)

Diagnosis: It is a simple U–shaped form without spreite. Diameter as well as distance between tubes is less. Perpendicular to bedding plane, found on bedding plane in form of pairs and also in vertical sections.

Description: As seen in the photograph, tubes found in pair on bedding plane, which has circular aperture. Wall of the burrow is smooth with lining. Burrow is perpendicular or inclined to bedding without spreite. Both the limbs are more or less parallel and bottom is rounded. Diameter of the tube is 3 to 4 mm. Distance between the tubes varies from 2 to 20 mm. Depth observed is 15cm.

Preservation: Full relief, endichnial burrow.

Behaviour: Suspension feeding, dwelling, sound resonance (Wilson, 1971).

Environmental Settings: Eolian (Ekdale et al., 2007), marine, freshwater, lacustrine and fluvial (Eagar et al., 1985), continental beds of Carboniferous (Chisholm, 1968) or Triassic

(Bromley and Asgaard, 1979) age. Reported in eolian settings in Jurassic Navajo Sandstone (Ekdale et al, 2007).

Possible Trace Makers: Polychaete worms, vertebrates, crustaceans, wasps, may-fly larvae, beetles.

Geologic Range: Cambrian-Recent (marine), Carboniferous-Recent (continental: Eagar et al., 1985).

Facies: HSS

Stratigraphic position: Lower and Middle members.

Association: *Skolithos, Thalassinoides*.

Remarks: It is produced by worm or worm like animals. It is distinguished from the other species of *Arenicolites* by its parallel tubes with circular aperture and no spreite. It is considered as the type species of *Arenicolites* (Hantzschel, 1975). *Arenicolites* are considered as dwelling structures of suspension feeding polychaetes.

5.7.2 Circular and Elliptical Structures – Circular Structures

Ichnogenus: *Calycraterion* Karaszewski, 1971, p. 104.

Diagnosis: Simple plug shaped structures. They are regular calyx shaped depressions, usually asymmetrical.

Ichnospecies: *Calycraterion samsonowiczi* Karaszewski, 1971.
(Figure 5.1 B and C)

Diagnosis: Calyx shaped depressions with funnel shape. They are regular calyx shaped depressions. Calyx is 15 to 40 mm in diameter and 5 to 15 mm in depth. Two or three small circular depressions present on the bottom representing outlets of filled burrows, 2 to 5 mm in diameter.

Description: Curving trace on the bedding plane; Sub-median ridge; transverse rise-and-groove sculpture.Simple plug shaped structures. This is a depression with funnel shaped outermost rim. Calyx is 25 to 27 mm in diameter and 5 to 7 mm in depth. There are two small circular depressions or knobs representing outlets of filled burrows – almost 20 mm in diameter. The overall geometry, the lack of a low ring-like wall around the tubercle, and the asymmetrical nature of *Calycraterion* distinguish it from *Bergaueria*, *Mammillichnis* and *Margaritichnus* (Pemberton, Frey and Bromley, 1988). Karaszewski (1971) considered

Calycraterion as having been produced by annelids, with the smaller depressions or knobs representing burrow outlets.

Preservation: Concave epirelief.

Behaviour(s): Domichnia.

Environmental settings: Shoreface.

Possible tracemakers: Bilaterally symmetrical animal.

Geologic range: Vendian.

Facies and Stratigraphic position: CSS and SS.

Association: -

Remarks: It is considered as dwelling structures – domichnia.

Behaviour: Dwelling structure.

Ichnogenus: *Chondrites* Von Sternberg, 1833, p. 25.
(Figure5.1 D and E)

Diagnosis: Large complexes of small root-like tunnels and shafts in dendritic patterns.

Description: *Chondrites* is a branching, vertically to horizontally oriented feeding burrow; the three-dimensional character of *Chondrites* can be visualized by imagining an upside-down tree, with a main burrow "trunk" connecting to the sediment-water interface and increasingly complex branches downward into the sediment.

Chondrites is interpreted as a feeding burrow that is often associated with low-oxygen substrates, although there are exceptions to this generality. Usually, burrows never cross, except by a different *Chondrites* system. Sometimes, look like bird feet. Form along bedding planes.

Behavior(s): Fodinichnia; feeding burrows of a deposit feeding worm organism.

Environmental settings: Fully marine conditions perhaps indicative of low oxygen zones. **Possible tracemakers:** Unknown, perhaps worms.

Geologic range: Precambrian – recent.

Facies and Stratigraphic position: HSS and SS.

Association: -

Remarks: It is thought to be originated for accommodating excreta material of originating animal.

Ichnogenus: *Circulichnus* Vyalov, 1971, p. 91.
(Figure 5.1 F)

Diagnosis: Smooth circular to ellipsoidal burrow.

Description: Ring shaped trace, formed by some cylindrical object. Circular burrows with smooth wall and lining,preserved on bedding plane. Burrow is filled with the material, which is identical to the host sediments.

Behaviour(s): It is considered as a grazing trace- Pascichnia.

Environmental settings: Marine to Continental

Possible tracemakers: Circular Structures formed by some cylindrical object.

Geologic range: Ordovician-Palaeocene.

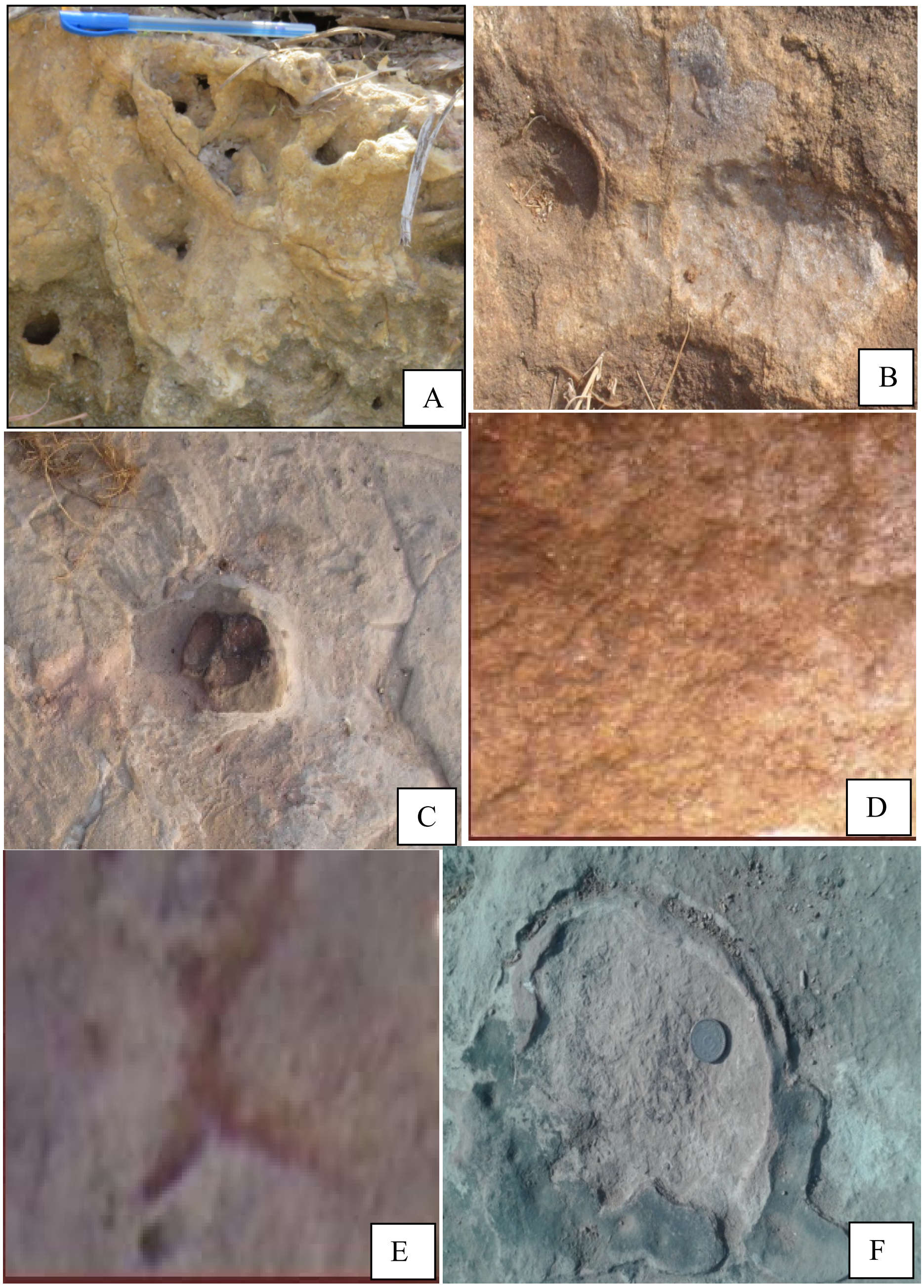


Plate 5.1: (A) *Arenicolite,* found in Sandstone suggesting foreshore to upper shoreface environment, near Katti. (B) *Calycraterion* found in Cross-stratified Sandstone (CS) lithofacies from Vantada hill. (C) *Calycraterion* found in Silty-Shale (SS) lithofacies from Hathmati river section. (D) *Chondrites* found in Cross-stratified Sandstone from Vantada hill. (E) *Chondrites* found in Silty-Shale (SS) lithofacies from Hathmati river section.(F) *Circulichnus* found in Silty-Shale (SS) lithofacies from Hathmati river section.

5.7.3 Winding and Meandering Structures

5.7.3.1 Winding structures

Ichnogenus: *Cochlichnus* Hitchcock, 1858, p. 161.

Diagnosis: *Cochlichnus* are winding structures, regularly meandering smooth trails, resembling sine curve.

Ichnospecies: *Cochlichnus kochi* Ludwig, 1869.
(Figure 5.2 A)

Diagnosis: Regular gently meandering, smooth unbranched trails with parallel ridges on both the sides.

Description: Smooth sinusoidal trails. On both the sides, the trails shows two gently raised rims, this runs in a parallel manner. Regular meanders resemble sine curves and without any ornamentation. Total length is about 42 cm with a constant diameter of 0.5 cm. Amplitude of sine curve is 14 to 16 cm and the wave length is about 20 cm.

Preservation: Convex epirelief.

Facies and Stratigraphic position: ISS. Lower member of Himmatnagar Formation.

Association: Nil.

Remarks: According to Eager et al. (1985), these are crawling traces and probably feeding structures of small worm or worm like animals. *Cochlichnus* has been recorded in sediments of supposed low salinity palaeoenvironments (Hakes, 1976).

Behaviour: Repichnia.

Environmental Setting: Tidal flat - flysch.

Possible Tracemakers: Worm.

Geologic Range: Cambrian to Recent.

5.7.4 Vertical U-shape structure with spreite

Diplocraterion Torell, 1870.
(Figure 5.3 D)

Type Species: *Diplocraterion parallelum* Richter, 1926, p. 213.

Diagnosis: U-shaped burrow with spreite, vertical to bedding plane, limbs of U - parallel, both limbs of successive U-tube confluent with limbs of preceding U-tube.

Description: *Diplocraterion* is an ichnogenus describing vertical U-shaped burrows having a spreite(weblike construction) between the two limbs of the U. The spreite of an individual Diplocraterion trace can be either protrusive (between the paired tubes) or retrusive (below the paired tubes).Opening of tubes mostly funnel shaped, bottom of burrow semicircular, rarely straight, horizontal cross section on bedding planes dumbbell shaped, diameter of tubes 5 to 15 mm; distance between limbs 1 to 7 cm, depth of burrow 2 to 15 cm.

Facies: ISS, in Lower member.

Stratigraphic Distribution: It occurs in Lower member.

Association:*Arenicolites, Skolithos, Rhizocorallium.*

Behaviour: Pascichnia.

Environmental Setting: Shallow to deep-water turbidity environments.

Possible Tracemakers: Polychaete worms.

Geologic Range: Cambrian to Recent.

5.7.5 Horizontal H shape forms

Ichnogenus: *Desmograpton* Fuchs, 1895, p. 394.
(Figure5.2 B)

Diagnosis: Trail, roughlyin form of long and very narrow letter H, single patterns usually lined up in ribbons; form variable; similar to *Paleomeandron* Peruzzi but with long appendices.

Description: Straight or undulating burrow with lateral appendages; smooth convex hyporelief; burrow diameter 0.3-1.7 mm.

Behaviour: Pascichnia.

Environmental Setting: Deep-water turbidity environments.

Possible Tracemakers: Polychaete worms.

Geologic Range: Silurian-Miocene.

5.7.6 Meandering Structures

Ichnogenus: *Gordia* Emmons, 1844, p. 24

Diagnosis: *Gordia* are winding structures. These are long, slender, smooth worm like trails of uniform thickness throughout. Mostly bent but not meandering.

Ichnospecies: *Gordia valdensis* Melichar, 1903.
(Figure5.2 C)

Diagnosis: Smooth worm like trails with uniform thickness.

Description: These are smooth worm like non-branching trails with uniform thickness. They are long, slender and bent structures. Thick thread-sized meandering ridge casts occur, in which smooth wormlike bends are developed. The most notable characteristics of the specimens are their uniform width and high length to width ratio. Length of the trail is about 5 cm long with 0.2 cm width.

Preservation: Convex epichnia.

Facies and Stratigraphic position: road section.

Association: *Ophiomorpha, Palaeophycus, Planolites.*

Remarks: It is considered as grazing trace – pascichnia. The assignment of this species to *Gordia* may be open to question since the actual shape of the meanders, never wholly developed, is unknown. It is included in the ichnogenus *Gordia* because it does not have regular sinuous curves of *Cochlichnus,* loose meanders of *Helminthopsis* (Miller and Knox, 1985) and the regular meanders of *Cosmorhaphe* (Ksiazkiewicz, 1970).It is considered as grazing trace – pascichnia.

5.7.7 Plaited structures

Ichnogenus: *Gyrochorte* Heer, 1865, p. 142

Diagnosis: *Gyrochorte* are plaited winding structures. Trace up to 5 mm wide. Plaited ridges are biserially arranged, obliquely aligned pads of sediment. Smooth biserial grooves separated by median ridge. Course strongly winding and direction change sharply. Trace may intersect itself or other traces.

Ichnospecies: *Gyrochorte comosa* Heer, 1865.
(Figure5.2D)

Diagnosis: Ridges on bedding planes with biserially arranged, obliquely aligned transverse pads, both series separated by median furrow.

Description: It includes winding ridges and tunnels, bilobate in nature. The trails usually consist of two lobes showing biserial arrangement separated by median furrow. Each lobe consist uniformly developed obliquely aligned pads. The angle between the pads and the median furrow varies from 40° to 50°. The trails are strongly winding and crossing over each other frequently in such a way that the earlier formed ridges are not destroyed. Diameter of the trail is about 3 to 6 mm. Length is variable, maximum observed length is about 15 cm.

Preservation: Convex and concave epirelief.

Facies: ISS.

Stratigraphic position: Lower member of Himmatnagar Sandstone Formation.

Association: -

Remarks: Weiss (1940, 1941) and Seilacher (1955) interpreted *Gyrochorte* as produced by a polychaete or worm like animal moving obliquely through sediment. According to Gilbert and Benner (2002) it produced by a detritus–feeding worm like animal, probably annelid that created a bilobed, vertically penetrating and sometime plaited meandering trace.

Behaviour: Grazing trace produced by a cylindrical animal moving across the sediment surface obliquely to the bedding planes.

Environmental Setting: Opportunistic thigmotactically sensitive behaviour with shallow water marine environmental setting.

Possible Tracemakers: Polychaete worm.

Geologic Range: Cambrian to Recent.

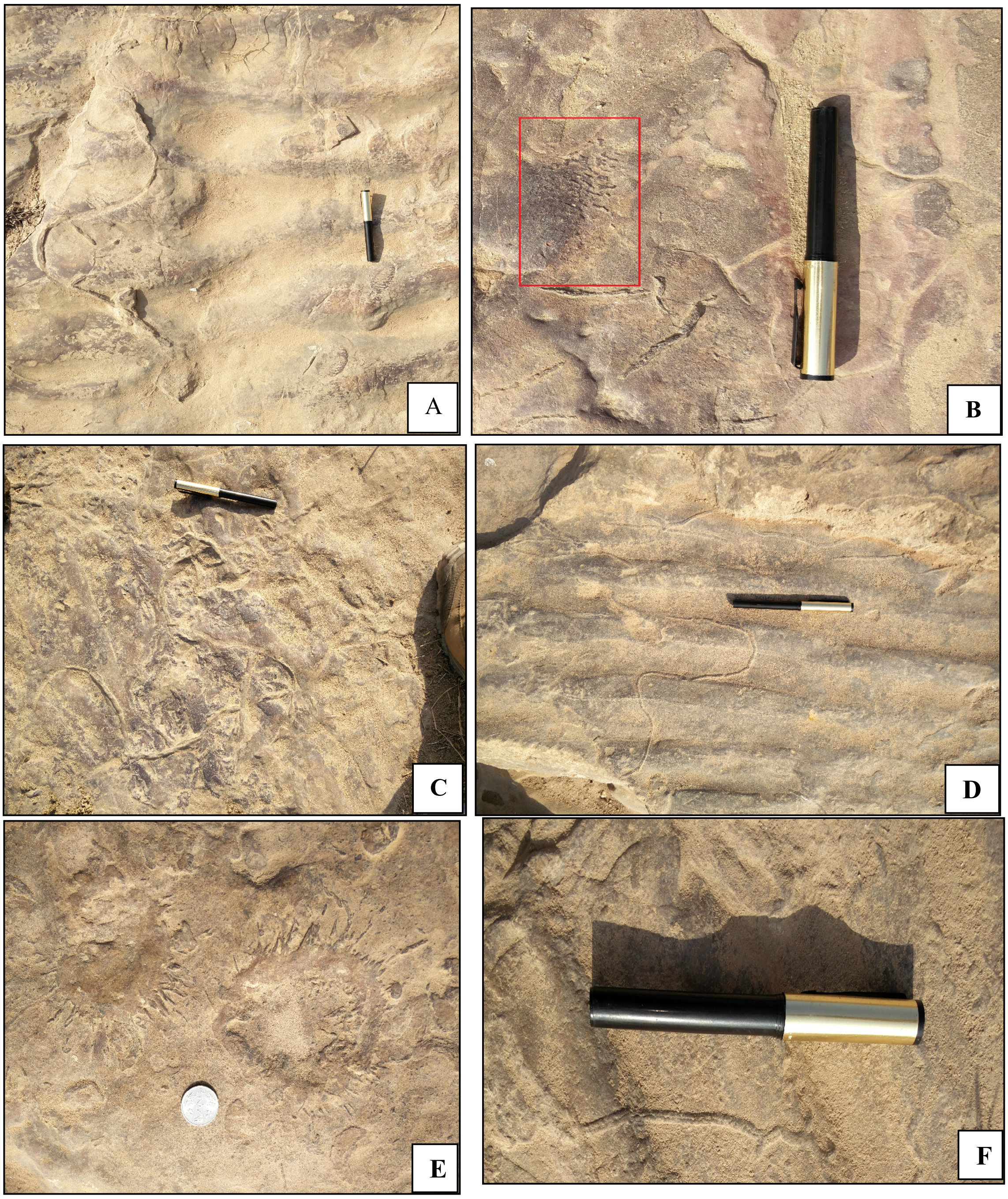


Plate 5.2: (A) *Cochlichnus* (B) *Desmograpton* (H-shaped) (C) *Gordia* (irregular meandering) (D) *Gyrochorte* (E) *Haentzschelinia* (F) *Isopodichnus*.All the above trace fossils are found in sandstone suggesting foreshore to upper shoreface environment, near Katti.

Ichnogenus: *Isopodichnus* Bornemann, 1889, p. 25.

Diagnosis: Dimorphous trace fossil consisting of small, straight or curved double ribbon trails, up to about 6 mm wide, transversely striated by fine furrows; both 'ribbons' separated by median furrow; trail may be intermittent.

Ichnospecies: *Isopodichnus problematicus* Schindewolf, 1928, p. 27.
(Figure5.2 F)

Diagnosis: They are series of double ribbon like bilobed trails separated by median furrow.

Description: The Katti form is straight to gently curved, parallel to the bedding plane and consisting of series of coffee bean shaped (double ribbon) like bilobed trails separated by median furrow (0.1 to 0.15 cm deep). Commonly, small band like structure also consists of unevenly spaced transverse ridges on the lobes. The maximum observed length is about 8 cm, width 0.6 to 0.7 cm, with coffee bean shaped parts having dimension of 0.7 to 0.8 cm.

Behaviour: Parallel to the bedding plane, a central furrow is flanked by two hypichnial ridges.

Environmental Setting: Mostly restricted to brackish water environment.

Possible Trace Makers: Crustaceans.

Geologic Range: Cambrian to Cretaceous.

Ichnogenus: *Haentzschelinia* Vyalov, 1964, p. 113.
(Figure5.2 E)

Diagnosis: Star like trail with elevated centre.

Description: Radiating grooves, rather irregularly and often only unilaterally developed. Probably a feeding or dwelling burrow.

Behaviour: Domichnia.

Environmental Setting: Marginal marine, foreshore.

Possible Trace Makers: Goby fish.

Geologic Range: Triassic to Recent.

Ichnogenus: *Lobichnus* Kemper, 1968, p. 72.
(Figure 5.3 B)

Diagnosis: Very small or scooped hollows which form irregular main stem with unilateral pectinate branches comprised of very small leaf shaped hollows also arranged unilaterally.

Description: Systems are highly variable with many transitions between forms. Limited to lobate configuration and thus resembling ammonite sutures. It is somewhat similar to *Lophoctenium.* Endogenic and preserved exclusively in trough of ripple marks. It is an indicator of shallow water.

Behaviour: Parallel to the bedding plane. It seems to be produced by an elongate animal.

Environmental Setting: Shore-face with ripple marks.

Possible Trace Makers: Unknown.

Geologic Range: Not known.

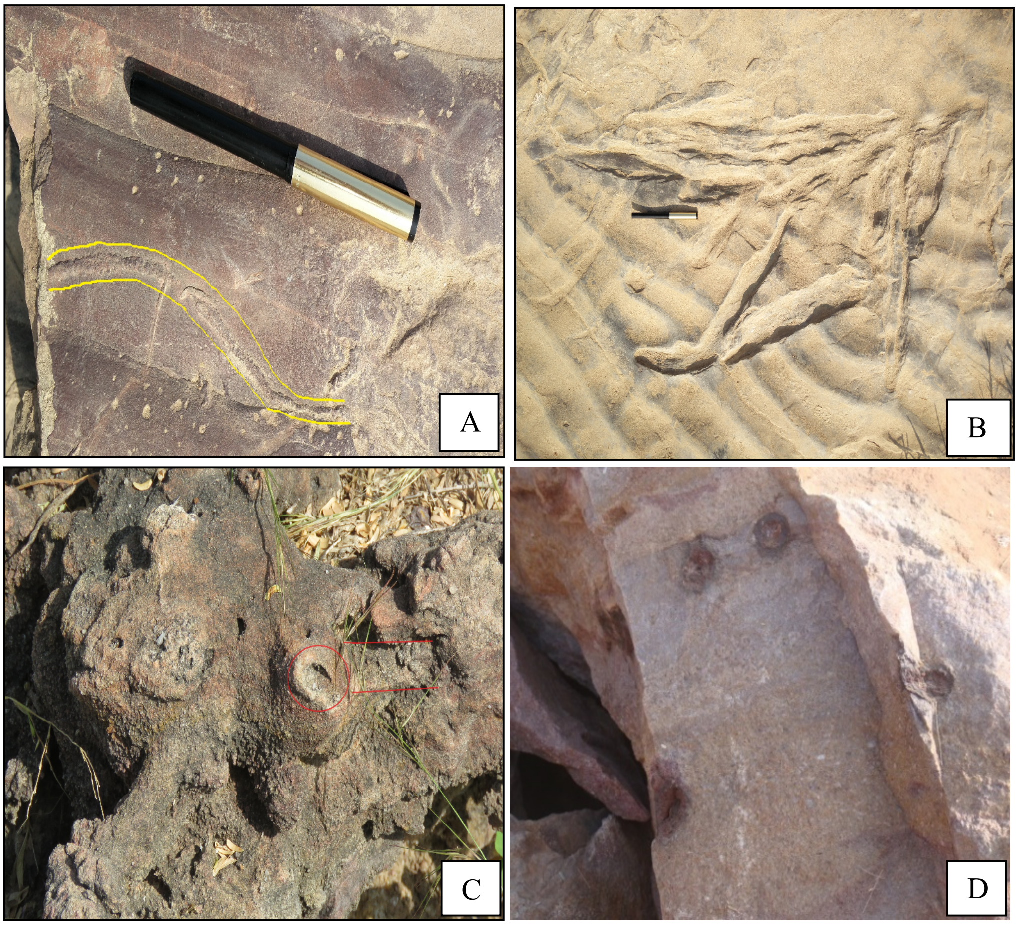


Plate 5.3: (A) Horizontal *Ophiomorpha* (B) *Lobichnus*. (C) *Monocraterion* and *Palaeophycus* in Gritty sandstone, at Arsodiya village.(D). *Diplocraterion* and *Monocraterion* found in Cross-Stratified Sandstone (CS) from Vantada hill.

5.7.8 Simple Structures – Vertical forms

Ichnogenus: *Monocraterion* Torell, 1870, p. 13; Westergard, 1931.
(Figure5.3 C and D; 5.4 A)

Diagnosis: Simple vertically oriented burrow that shows a funnel-like projection at the top.

Description: *Monocraterion* is a simple vertically oriented burrow that shows a funnel-like projection at the top of the burrow; erosion of the burrow top can make this trace fossil indentifiable as *Skolithos*. Vertical endogenic burrow with funnel shape opening - a dwelling burrow. Vertical funnel structure (simple or multiple) penetrated by a central straight or slightly curved (unbranched), plugged tube. It appears as a series of concentric rings in transverse section, usually 1-4 cm in diameter.

Behaviour(s): Dwelling, deposit feeding. As a combined dwelling and feeding burrow where the funnel probably served as a trap for prey organisms moving near the burrow opening; the probable trace maker is a polychaete worm.

Environmental settings: Fully marine; shallow water settings, and rarely deep water.

Possible tracemakers: Marine worms or worm-like organisms.

Geologic range: Cambrian-Recent.

Plate 5.4: (A).*Monocraterion* found in Silty-Shale (SS) from Hathmati river section.

Ichnogenus: *Skolithos* Haldeman, 1840.
(Figure 5.9 B; 5.10 A and B)

Diagnosis: *Skolithos* is a simple, tube-like, vertically oriented burrow.

Description: Straight, vertical to slightly inclined, cylindrical tube burrows. *Skolithos* is a simple, tube-like, vertically oriented burrow that typically shows a much greater length versus width. *Skolithos* is interpreted as a dwelling burrow made by a suspension-feeding animal.

Straight vertical to slightly inclined, cylindrical tube burrows. Burrows are parallel, do not branch, cross, nor interpenetrate. Walls of burrow are smooth with structure-less fill. It can be slightly J-shaped.

Behaviour(s): Dwelling, suspension feeding, predation.

Environmental Settings: Found in virtually every type of environment from marine to terrestrial. Present in high-energy marine conditions, especially in near shore shallow marine facies, deep marine, submarine channels and canyons; continental floodplain and dune settings.

Possible Trace Makers: Worms, phoronids, and insect larvae. Arthropods, small vertebrates.

Geologic Range: Precambrian-Recent.

5.7.9Simple Structures – Horizontal form

Ichnogenus: *Palaeophycus* Hall, 1847.
(Figure5.5 B to E; 5.7 B)

Diagnosis: Oriented horizontal or oblique to bedding, and has a distinctive burrow lining.**Description:** *Palaeophycus* is interpreted as a combined feeding and dwelling burrow made by a worm-like animal. Unbranched, cylindrical lined burrows which are predominantly horizontal, straight to sinuous, smooth walled, with variable diameter and typically structureless fill similar to host rock.

Behaviour(s): Multiple behaviour including burrowing and dwelling.

Environmental settings: Marine to continental including alluvial, lacustrine, and aeolian.

Possible trace makers: Multiple invertebrate burrowing species both marine and continental.

Geologic range: Precambrian-Present.

Ichnogenus: *Planolites* Nicholson, 1873.
(Figure 5.5 F; 5.7 C; 5.8 A)

Diagnosis: Simple, unlined, unbranched cylindrical or sub-cylindrical in filled burrows. **Description:** Simple, unlined and unbranched in filled burrows, straight to gently curved, horizontal to oblique to bedding planes. Burrows may cross-over. Lithology of fill differs from that of host rock.

It is typically distinguished from *Palaeophycus* by its lack of a burrow lining. *Planolites* is interpreted as a feeding burrow made by a worm-like animal.It is typically distinguished from *Palaeophycus* by the material from which it is formed; *Palaeophycus* is formed from the insitu bed while *Planolites* can be identified by different material from which the burrows form.

Behaviour(s): Deposit feeding, dwelling.

Environmental Settings: Shallow marine - deep marine deposits to continental. Found in alluvial, lacustrine, and eolian settings.

Possible Trace Makers: Various invertebrate burrowing organisms including worms and insects.

Geologic Range: Precambrian-Recent.

5.7.10 Branched Structures – Y– T shaped Form

Ichnogenus: *Ophiomorpha* Lundgren, 1891, p. 114.
(Figure 5.3 A; 5.5 A; 5.6 A)

Diagnosis: *Ophiomorpha* is a branching burrow with horizontal, oblique, or vertical box-like networks; the exterior of the burrow is characterized by a knobby structure formed by a pelleted lining.

Description: Three dimensional burrow systems, vertical and horizontal. Cylindrical tunnels are dichotomously branching, generally at acute angles and 0.5 to 3 cm in diameter. Tunnels internally smooth, but outer surface of burrow lining characteristically mammillate due to presence of discoid or ovoid pellets, which are several mm, rarely more in diameter. The traces are vertical and horizontal cylindrical burrows. Tunnels branch and locally swell close to or at points of branching. Smooth interior walls. Outer surface of burrow lined with ovoid pellets.

Behaviour(s): Trace is the dwelling burrows of decapod crustaceans, and as a combined dwelling and feeding burrow made by a shrimp-like animal.

Environmental settings: Marine environment, littoral, sub-littoral, or upper neritic. Prolific numbers in marine shoreface environments. Also found in brackish water, sandy substrates including estuaries and tidal shoals.

Possible trace makers: Crustaceans, shrimp, ghost shrimp.

Geologic range: Permian-Recent.

5.7.11 Radial Form with Vertical Shaft

Ichnogenus: *Phoebichnus* Bromley and Asgaard, 1972.
(Figure5.7A)

Diagnosis: *Phoebichnus* are radial structures with vertical shafts.

Description: These radial burrows have a 5 mm thick lining. Central shaft is 6 to 8 cm in diameter, nearly vertical to bedding plane, with numerous long, straight radial burrows oriented more or less parallel to bedding. Radial burrows about 1.5 cm in diameter including distinct, annulated wall lining about 5 mm thick.

Behaviour(s): Central shaft is Domichnia, radial burrows are Fodinichnia.

Environmental settings: Opportunistic shallow tier found in shallow marine siliciclastic deposits. P**ossible tracemakers:** Unknown marine organism.

Geologic range: Lower Jurassic-Middle Jurassic.

Ichnogenus: *Psilonichnus* Fürsich, 1981.
(Figure5.6 B; 5.7 D, E and F)

Diagnosis: Vertically oriented burrow, normally shows Y-branching toward the burrow top.

Description: *Psilonichnus* is a vertically oriented cylindrical, unlined burrow that normally shows J- Y- or U-shaped structures; lateral branches not necessarily the same diameter as the parent trunks.

Behaviour(s): Dwelling.

Environmental Settings: Marginal marine to terrestrial. Beach, backshore dunes and lagoonal environments.

Possible Tracemakers: Crustaceans such as crabs.

Geologic Range: Cretaceous-Recent.

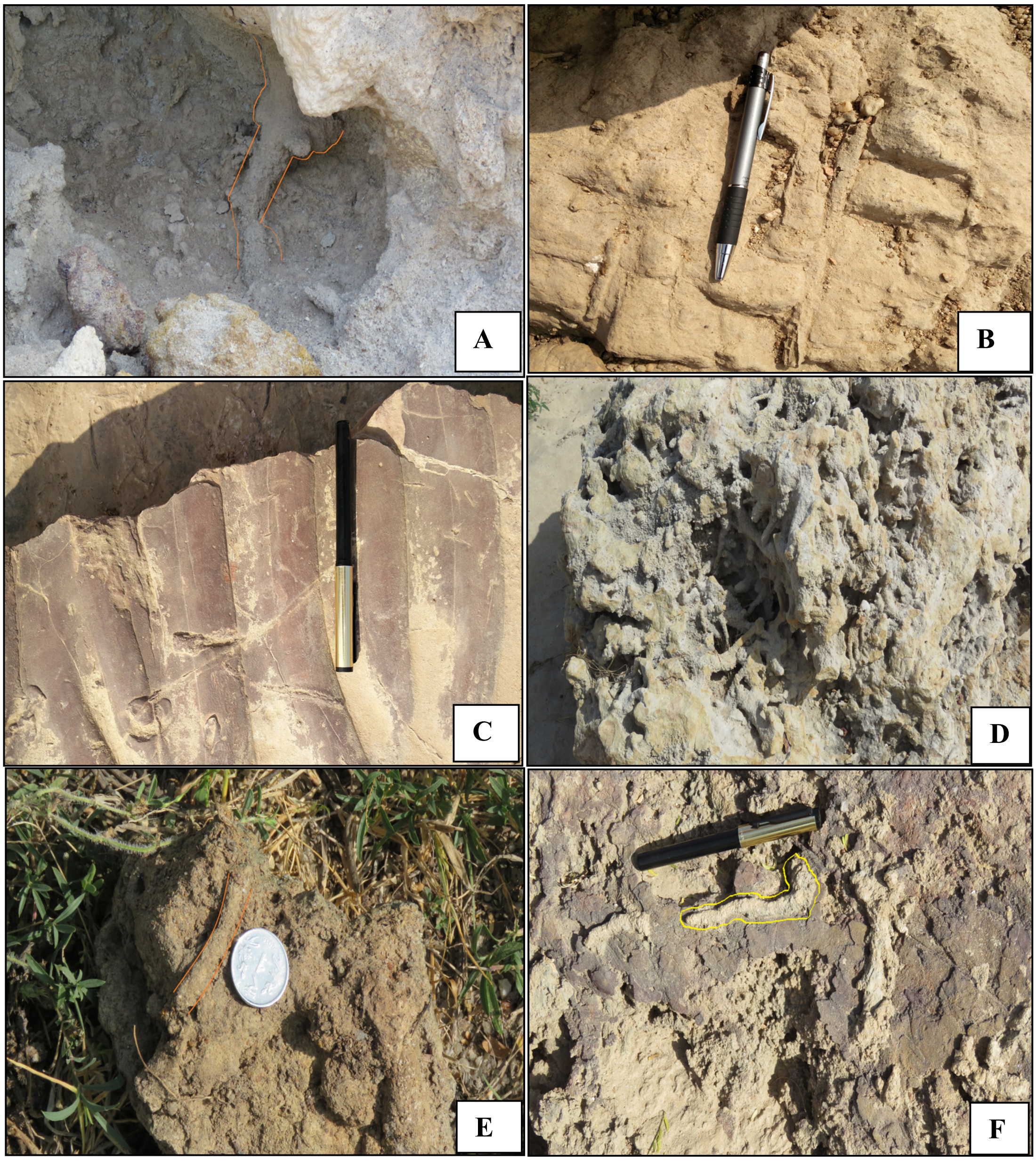


Plate 5.5: (A) *Ophiomorpha* in Kaolinized bed which is identified by pelleted lining, at Arsodiya village (B) *Palaeophycus* in Sandstone, near Sapteshwar (C) *Palaeophycus* in Sandstone of foreshore to upper shoreface environment, near Katti (D) *Palaeophycus* and *Thalassinoids* in Gritty Sandstone, at Arsodiya village(E) *Palaeophycus* in Gritty Sandstone, at Arsodiya village (F) *Planolites* in Ferruginous Sandstone, at Arsodiya village.

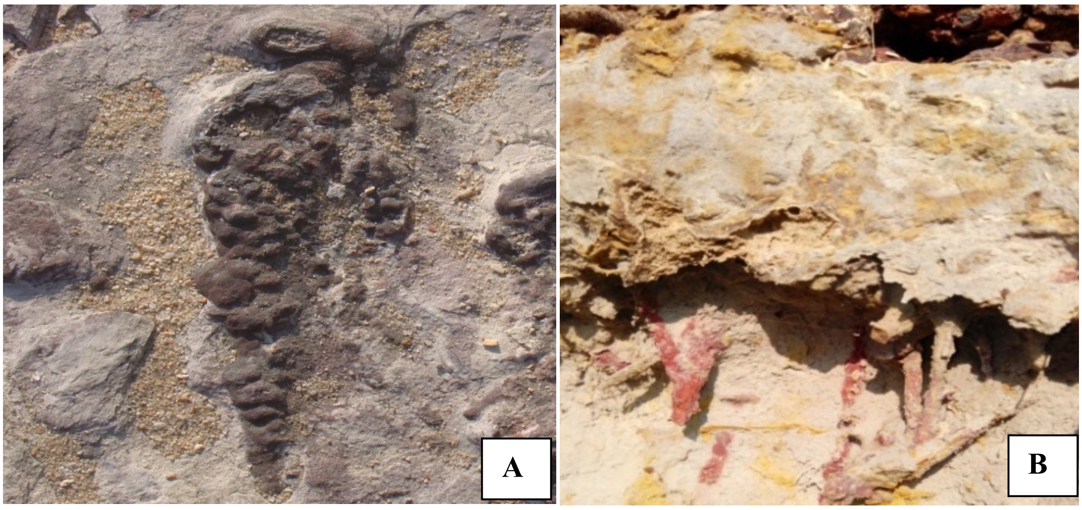


Plate 5.6: (A).*Ophiomorpha* found in HorizontallyStratified Sandstone(HSS) from Hathamti river section. (B).*Psilonichnus* found in Planer Cross-stratified Sandstone (PCS) near Sapteshwar bridge.

5.7.12 Spreiten Structures - U-Shaped

Ichnogenus: *Rhizocorallium* Zenker, 1836.
(Figure 5.8 B)

Diagnosis: U-shaped tubes with sinuous, bifurcating or planispiral spreite.

Description: Long, ~1 cm thick, U-shaped tubes with sinuous, bifurcating or planispiral spreite, usually parallel to oblique to bedding; arms are several cm apart. May show lateral flags and scratch markings on the outer side of tubes and (excrement pills) may be incorporated.

Behaviour: Domichnia and/or fodinichnia; dwelling and feeding burrow of a suspension-feeder or deposit-feeder.

Environmental Setting: Found in shallow to deep marine settings.

Possible Trace Makers: Crustacean, annelid.

Geologic Range: Cambrian-Recent.

Ichnogenus: *Rosselia* Dahmer, 1937.
(Figure5.8 C)

Diagnosis: Conical to irregular, funnel-shaped, vertical, concentric burrow.

Description: Conical to irregular, funnel-shaped, vertical, concentric burrow with a central cylindrical pencil-thick tube.

Behaviour: Domichnia, fodinichnia; Dwelling and feeding burrows of a filter- or suspension-feeding organism.

Environmental Settings: Found in shallow marine shoreface and deep-water flysch deposits.

Possible Trace Makers: Annelid worms, arthropods, sea anemones.

Geologic Range: Cambrian-Recent.

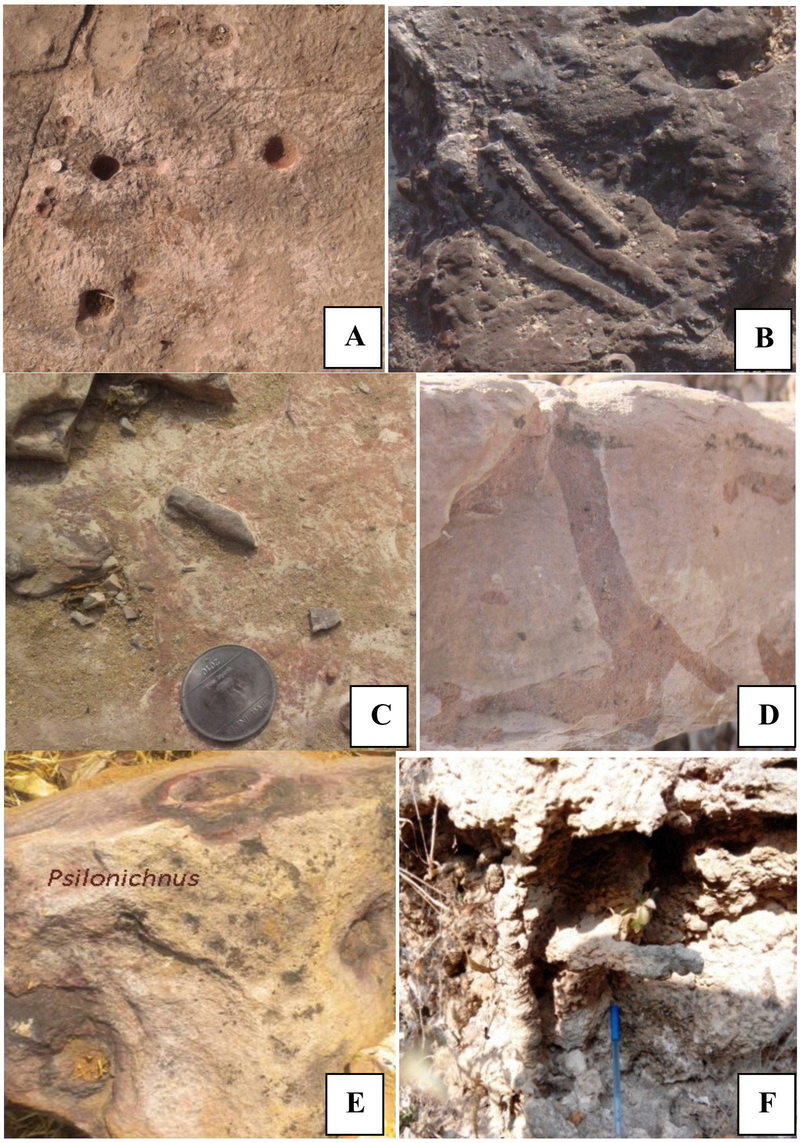


Plate 5.7: (A).*Phoebichnus* found in HorizontallyStratified Sandstone (HSS) lithofacies from Hathmati river section.(B).*Palaeophycus* found in HorizontallyStratified Sandstone(HSS) lithofacies from Hathmati river section. (C).*Planolites* found in Horizontally Stratified Sandstone (HSS) lithofacies from Hathmati river section. (D).*Psilonichnus* found in Horizontally Stratified Sandstone (HSS) lithofacies from Hathmati river section. (E).*Psilonichnus* found in Cross-stratified Sandstone (CS) lithofacies from Vantada hill. (F).*Psilonichnus* found in Planner Cross-stratified Sandstone (PCS) lithofacies near Sapteshwar bridge.

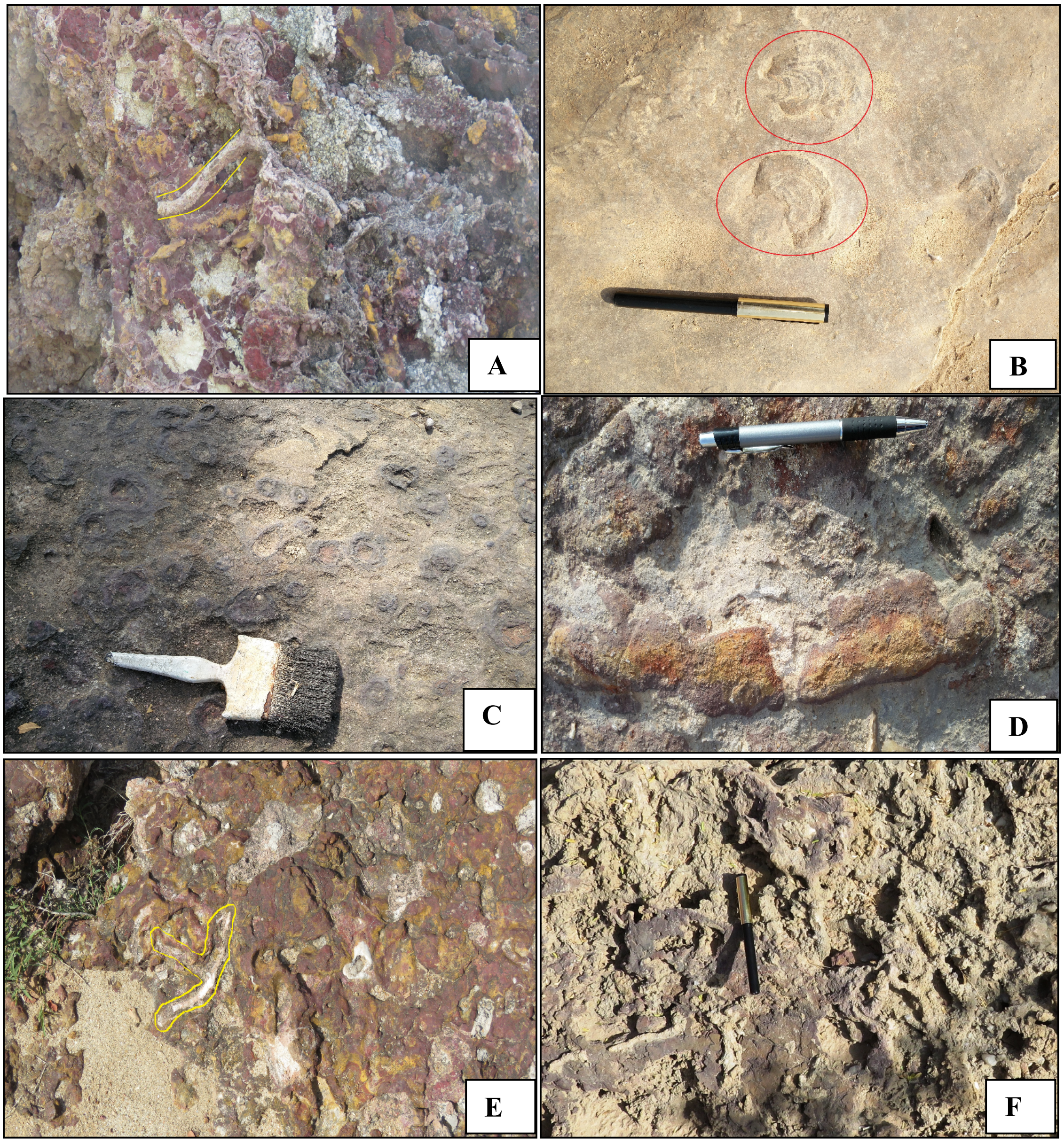


Plate 5.8: (A) *Planolites* in Ferruginous Sandstone, at Arsodiya village (B) *Rhizocorallium* in Sandstone of foreshore to upper shoreface environment, near Katti (C) *Rosselia* in Gritty Sandstone, near Katti (D) *Teichichnus* shifting in Gritty ferruginous sandstone, near Sapteshwar (E) *Thalassinoides* in Ferruginous Sandstone, at Arsodiya village (F) *Thalassinoides* and *Ophiomorpha* variant in Ferruginous Sandstone at Arsodiya village.

5.7.13 Wall Like Forms

Ichnogenus: *Teichichnus* Seilacher, 1955, p. 378.
(Figure 5.8 D; 5.10 C)

Diagnosis: *Teichichnus* are spreiten structures with wall like forms.

Description: *Teichichnus* is a simple horizontally or obliquely oriented burrow that shows vertically to obliquely oriented spreite.

Teichichnus is interpreted as a feeding burrow, probably made by a deposit-feeding bivalve that moved its burrow up or down in a vertical plane for systematic feeding. *Teichichnus* has a distinctive form produced by the stacking of thin 'tongues' of sediment, atop one another. These 'tongues' are often quite sinuous, reflecting perhaps a more nutrient-poor environment in which the feeding animals had to cover a greater area of sediment, in order to acquire sufficient nourishment.

Behaviour(s): Domichnia, Fodinichnia, Equilibrichnia? Dwelling and feeding burrow of a deposit feeder. Trace could possibly be an equilibrium structure.

Environmental Settings: Found in lower marine shorefaces, intertidal settings, lagoons, deep-marine fans and abyssal plains, and brackish water settings like marine estuaries.

Possible Trace Makers: Annelid worms.

Geologic Range: Cambrian-Recent.

5.7.14 Branched Structures – Y– T shaped Form

Ichnogenus: *Thalassinoides* Ehrenberg, 1944, p. 358.
(Figure 5.8 E and F; 5.9 A; 5.10 D and E)

Diagnosis: *Thalassinoides* is a branching burrow with horizontal, oblique or vertical box-like networks.

Descriptions: *Thalassinoides* is a branching burrow (Y or T shaped branches) with both horizontal, oblique, or vertical box-like networks and enlargements at junctions between some branches. *Thalassinoides* are burrows which occur parallel to the bedding plane of the rock. *Thalassinoides* is interpreted as a combined feeding and dwelling burrow, but has been observed as a boring in some cases. The probable trace maker is an arthropod. These are three-dimensional box-work of branched cylindrical burrows interconnected by vertical shafts.

Behaviour: Deposit-feeding and dwelling.

Environmental Settings: Shallow marine and deep marine turbidites.

Possible Trace Makers: Crustaceans.

Geologic Range: Cambrian-Recent and are extremely abundant in rocks worldwide, from Jurassic period onwards.

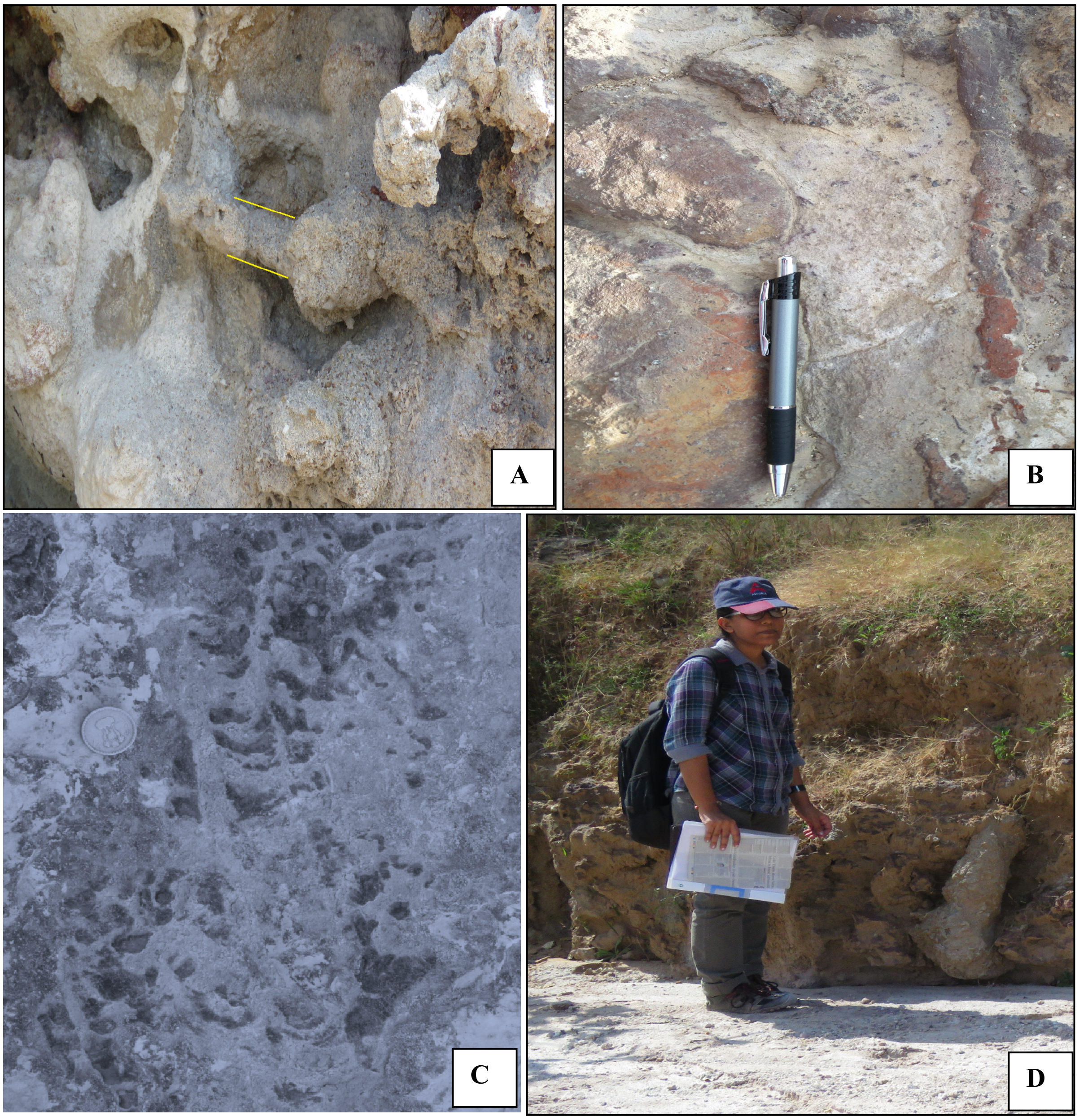


Plate 5.9: (A) *Thalassinoides* in Kaolinized bed, at Arsodiya village (B) vertical *Skolithos* in Ferruginous sandstone, near Sapteshwar (C) *Rhizocorallium* in ISS lithofacies near Sapteshwar bridge. (D) Unidentified vertebrate trace fossil found in gritty sandstone, this kind of trace fossils are rare in nature, trace fossil probably of any mammal, near Arsodiya village.

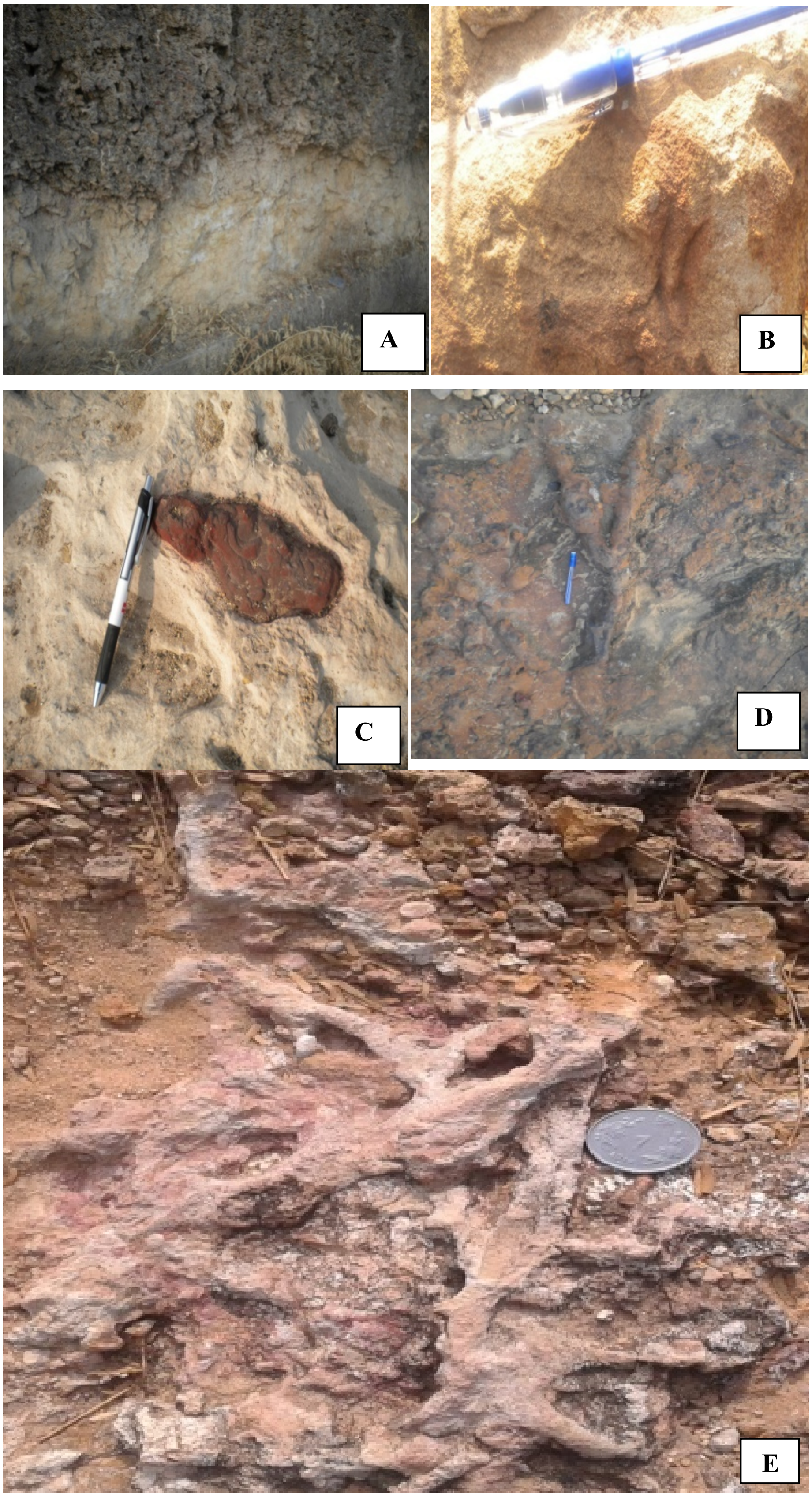

A
B
C
D
E

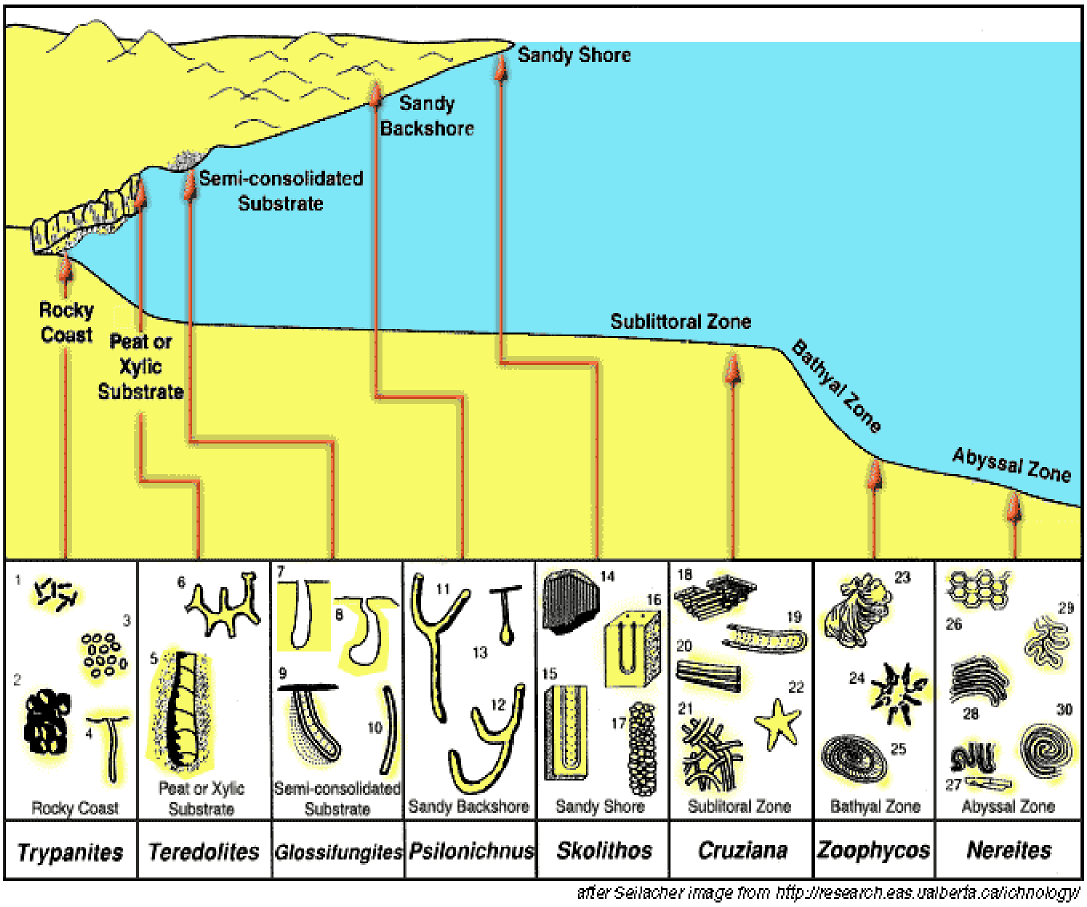
Plate 5.10: (A). *Skolithos* found in Horizontally Stratified Sandstone (HSS) at Sapteshwar. (B).*Skolithos* found in Cross-stratified Sandstone (CS) from Vantada hill. (C). *Teichichnus* found in Horizontally Stratified Sandstone (HSS) from Hathmati river section. (D).*Thalassinoides* found in Horizontally Stratified Sandstone (HSS) near Sapteshwar bridge. (E).*Thalassinoides* found in Horizontally Stratified Sandstone (HSS) near Sapteshwar Bridge.

Table 5.2: The different ichnogenus are found in their different lilthofacies.

Ichnogenus	**GPCSS**	**GW**	**PCSS**	**ISS**	**SS**	**CSS**	**HSS**	**BC**	**Lower Member**	**Middle Member**
Arenicolites				✓					✓	
Calycraterion					✓	✓				✓
Chondrites					✓	✓				✓
Circulichnus					✓	✓				✓
Cochlichnus				✓					✓	
Desmograpton				✓					✓	
Diplocraterion				✓					✓	
Gordia				✓					✓	
Gyrochorte				✓					✓	
Haentzchelinia				✓					✓	
Isopodichnus				✓					✓	
Lobichnus				✓					✓	
Monocraterion					✓	✓			✓	✓
Ophiomorpha			✓		✓	✓	✓		✓	✓
Palaeophycus					✓	✓	✓		✓	✓
Phoebichnus					✓	✓	✓		✓	✓
Planolites					✓	✓	✓		✓	✓
Psilonichnus						✓	✓			✓
Rhizocorallium				✓					✓	
Rosellia				✓					✓	
Skolithos			✓		✓	✓	✓		✓	✓
Teichichnus							✓			✓
Thalassinoides			✓		✓	✓	✓		✓	✓

5.8 Ichnofacies

An ichnofacies is an assemblage of trace fossils that provide an indication of the conditions that their formative organisms inhabited. Palaeontologist Adolf Seilacher pioneered the concept of ichnofacies, whereby the state of a sedimentary system at its time of deposition could be implied by noting the trace fossils in association with one another. Following figure shows distribution of common marine ichnofacies (Figure 5.11). While, table below depicts ichnological-sedimentological shoreface model (Table 5.3).

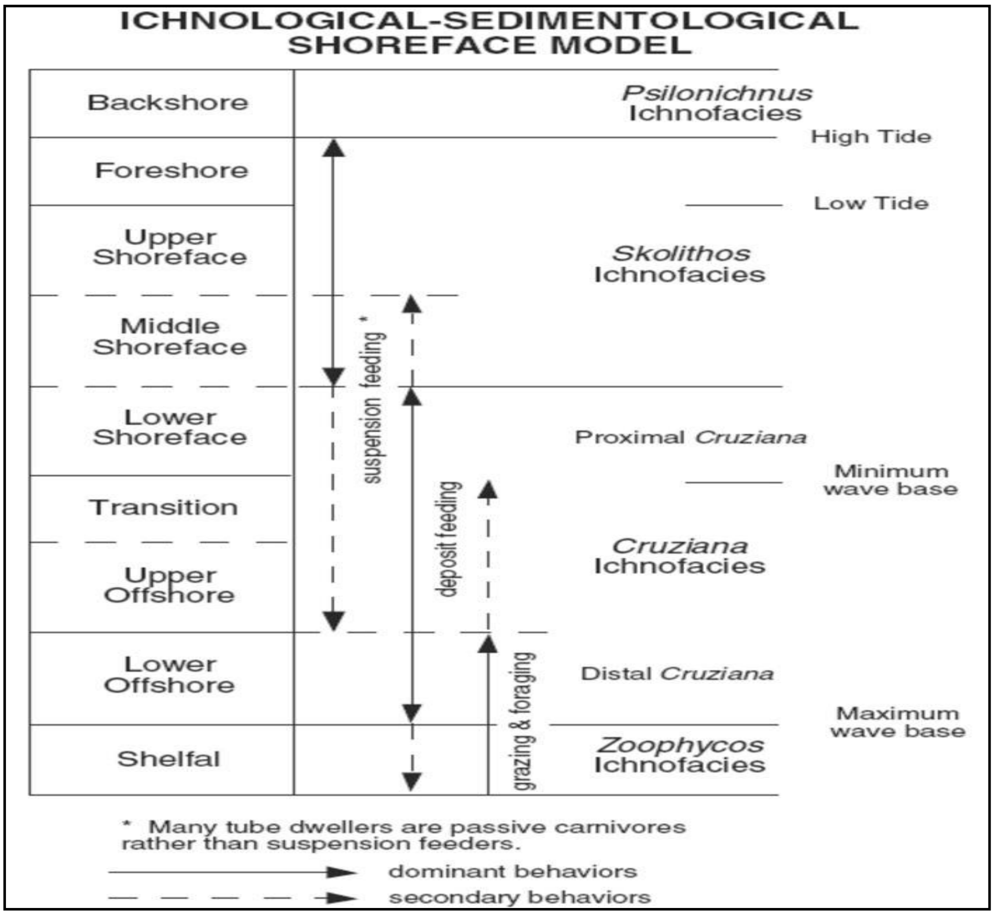


Distribution of Common Marine Ichnofacies

Typical trace fossils include: *1) Caulostrepsis; 2) Entobia; 3) echinoid borings; 4) Trypanites; 5) Teredolites; 6) Thalassinoides; 7, 8) Gastrochaenolites or related genera; 9) Diplocraterion (Glossifungites); 10) Skolithos; 11,12) Psilonichnus; 13) Macanopsis; 14) Skolithos; 15) Diplocraterion; 16) Arenicolites; 17) Ophiomorpha; 18) Phycodes; 19) Rhizocorallium; 20) Teichichnus; 21) Planolites; 22) Asteriacites; 23) Zoophycos; 24) Lorenzinia; 25) Zoophycos; 26) Paleodictyon; 27) Taphrhelminthopsis; 28) Helminthoida; 29) Cosmorhaphe; 30) Spirorhaphe.*

Figure 5.1: Distribution of common marine ichnofacies.

Table 5.3: Ichnological-sedimentological shoreface model.



Following ichnofacies have been identified in the study area as described below:

1. *Cruziana* ichnofacies, 2. *Skolithos* ichnofacies, 3. *Psilonichnus* ichnofacies.

5.8.1 *Cruziana* Ichnofacies

The *Cruziana* ichnofacies consist of number of trace fossils like *Thalassinoides, Palaeophycus*, *Planolites*, etc. which are preserved in Silty-Shale, Horizontally Stratified Sandstone and Cross-Statified Sandstone lithofacies. The *Cruziana* ichnofacies shows rich trace fossil diversity, with horizontal repichnia (*Cruziana*), cubichnia (*Calycraterion*), and vertical burrows. The ichnofacies is usually characterized by well sorted silts and sands to inter-bedded muddy and clean sands and moderate to intense bioturbation. Here, *Cruziana* ichnofacies are characterized by abundance and variety of horizontal structures, which suggest low energy conditions of deposition on an unconsolidated substrate in upper to middle shoreface environment. In the study area, the *Cruziana* ichnofacies is represented by *Chondrites, Circulichnus, Palaeophycus, Planolites* and *Teichichnus* in HSS and SS lithofacies, suggesting development of upper to middle shoreface environment at the time of deposition.

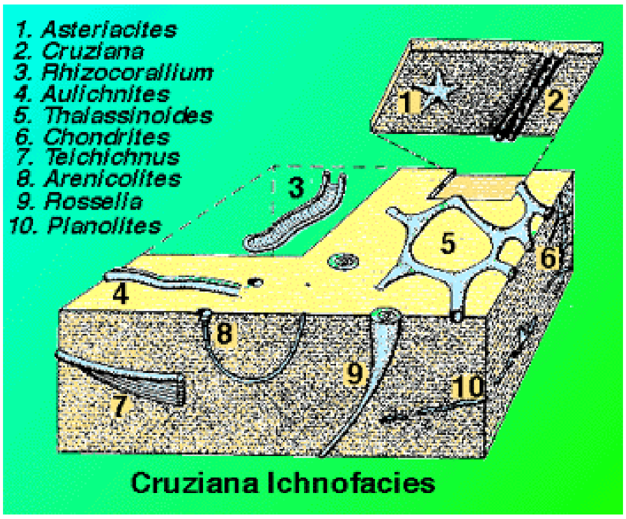


Figure 5.2: *Cruziana* Ichnofacies (after Benton and Harper, 1997).

This ichnofacies represents mid-shoreface to distal continental shelf situations, below normal wave base, but may be affected by storm activity.

5.8.2 *Skolithos* Ichnofacies

Skolithos, Monocraterion, Arenicolites traces constitute *Skolithos* ichnofacies. The *Skolithos* ichnofacies can be recognized by a low diversity of abundant vertical domichnia (*Skolithos, Diplocraterion*and *Arenicolites*), fodinichnia (*Ophiomorpha*) and Fugichnia. It is preserved in Cross-Stratified Sandstone, Silty-Shale, Horizontally Stratified Sandstone lithofacies, usually characterized by vertical, cylindrical or U-shaped dwelling burrows but horizontal structure may be present. *Skolithos* – represents high energy, shallow marine substrates. In this ichnofacies rapid sedimentation and frequent transportation is common indicating relatively high wave and current energy conditions along with clean, well sorted, loose or shifting substrate. Substrates serve mainly as anchoring medium for the organisms, most of which construct deeply penetrating, more or less permanent domiciles and because of shifting sediments, the dwelling burrows tend to have thick, reinforced wall linings (Frey and Pemberton, 1985). According to Pemberton and Mac Eachern (1995) animals are chiefly suspension feeders or passive carnivores.

Skolithos, Ophiomorpha, *Monocraterion* and *Diplocraterion* are common trace fossils. In the study area, this ichnofacies is represented by *Skolithos, Calycraterion, Monocraterion,* *Thalassinoides* and *Ophiomorpha* in CSS, HSS and SS lithofacies, suggesting development of foreshore to upper shoreface environment at the time of deposition.

The *Skolithos* ichnofacies was at first seen as occurring only in the intertidal zone, but it is also typical of other shifting sand environments, such as the tops of storm sand sheets and the tops of turbidity flows.

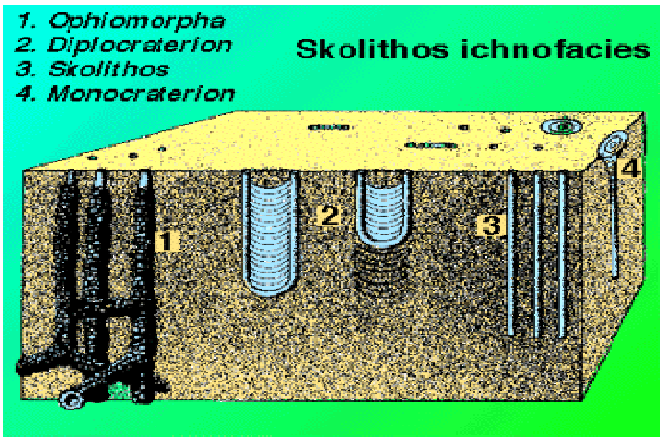


Figure 5.3: *Skolithos* Ichnofacies (after Benton and Harper, 1997).

All these traces typically indicate intertidal situations where the organisms have to be able to respond rapidly in stressful conditions. *Skolithos* ichnofacies represents foreshore to middle shoreface zone. This ichnofacies is typically developed, where rapid sedimentation and frequent transportation occurs. Thus it indicates relatively high levels of wave and current energy condition along with clean, well sorted, loose or shifting substrate.

5.8.3 *Psilonichnus* ichnofacies

The *Psilonichnus* ichnofacies shows a low diversity assemblage of small vertical burrows with narrow sloping T-shaped and Y-shaped burrows (*Psilonichnus*), root traces, and vertebrate footprints.

This ichnofacies is typical of backshore, dune areas, and supratidal flats on the coast. *Psilonichnus* – represents supra-littoral, moderate to low energy (beach – foreshore to backshore).

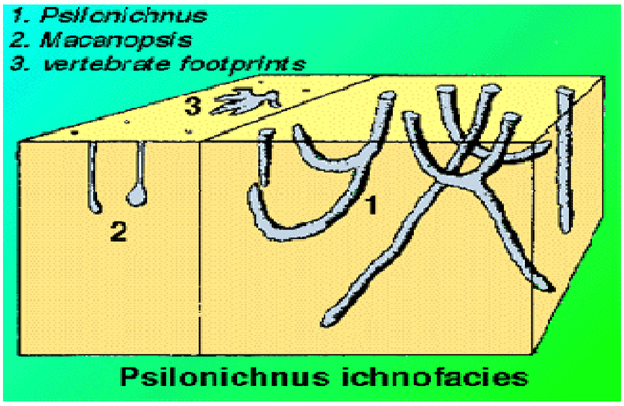


Figure 5.4: *Psilonichnus* Ichnofacies (after Benton and Harper, 1997).

Psilonichnus and *Macanopsis* are common trace fossils of the facies. In the study area, this ichnofacies is represented by *Psilonichnus* and *Phoebichnus* in CSS, HSS and SS lithofacies, suggesting development of foreshore environment at the time of deposition of the lithofacies.

5.9 Applications of Ichnofacies

The ichnofacies concept has been applied to petroleum exploration as an aid to interpreting depositional environments. The interpretation of sedimentary environments helps to assess potential petroleum reservoirs and source rocks on the basis of stratigraphic architecture; laterally adjacent facies succeeding one another vertically (Walther's Law) can be better discerned if the facies are distinctive and identifiable. Trace fossil assemblages provide an excellent supplementary tool for facies analysis, especially when body fossils are lacking.

A promising area for future applications of ichnofacies in facies analysis is in hydrogeology and other aspects of environmental geology. Hydrogeologists often must approximate many of the same parameters (porosity, permeability, facies architecture) sought by petroleum geologists, hence ichnofacies present another important set of data for these geoscientists.

Ichnofacies also indicate the evolution of palaeo-communities throughout geologic time. Trace fossils are evident in rocks from the Proterozoic Eon to the Pleistocene Epoch; hence their assemblages record organism's behaviour and the evolution of behaviour. This information is particularly valuable for interpreting the behaviour of organisms that rarely have body parts fossilized, adding another dimension to the palaeontological data set for evolutionary theory.

5.10 Discussion

In the study area, three ichnofacies have been recognised; viz. *Psilonichnus, Skolithos* and *Cruziana*.

The *Psilonichnus* ichnofacies is represented by *Psilonichnus* and *Phoebichnus* in CSS, HSS and SS lithofacies, suggesting development of foreshore environment at the time of deposition of the lithofacies.

The *Skolithos* ichnofacies is represented by *Skolithos, Calycraterion, Monocraterion, Thalassinoides* and *Ophiomorpha* in CSS, HSS and SS lithofacies, suggesting development of foreshore to upper shoreface environment at the time of deposition of the lithofacies.

The *Cruziana* ichnofacies is represented by *Chondrites, Circulichnus, Palaeophycus, Planolites* and *Teichichnus* in HSS and SS lithofacies, suggesting development of upper to middle shoreface environment at the time of deposition of the lithofacies.

CONCLUSIONS

The lower Cretaceous age of Himmatnagar Sandstone Formation represent wide range of conditions from low to high wave and current energy. This can be deduced by sedimentological and palaentological study of the area.

- Himmatnagar Sandstone Formation is divisible into three parts: Lower Member, Middle Member and Upper Member. Lower Member is exposed along Sabarmati River and its surroundings, Middle Member is exposed along Hathmati River and surroundings while Upper Member is deposited on both of these Members.
- Eight lithofacies have been identified in the Himmatnagar Sandstone Formation among which all are exposed in different parts of the study area. The lithofacies are 1. Basal Conglomerate (BC) lithofacies; 2. Horizontally-Stratified Sandstone (HSS) lithofacies; 3. Cross-Stratified Sandstone (CSS) lithofacies; 4. Silty-Shale (SS) lithofacies; 5. Intercalated Shale-Sandstone (ISS) lithofacies; 6. Planar Cross-Stratified Sandstone (PCSS) lithofacies; 7. Grey Wacke (GW) lithofacies and 8. Gritty-Pebbly Cross-Stratified Sandstone (GPCSS) lithofacies.
- Based on trace fossils, geometry of the beds, sedimentary structures and absence of roots of plants (which suggests transported nature), upper shoreface to foreshore and near-shore aeolian environment of deposition can be interpreted for Lower Member, while on the same bases upper shoreface to foreshore environment of deposition for Middle Member of Himmatnagar Sandstone Formation.
- While based on uneven erosional-unconformable lower contact in channel structures, south to southwest trough cross-stratification, presence of angular to sub-rounded gravely to cobbly fragments, absence of plants except wood logs, wide occurrence and limited thickness suggest deposition of Upper Member in fluvial to estuarine environment of deposition.
- Total 23 ichnofossils have been identified in the study area, such as *Arenicolites, Calycraterion,Chondrites,Circulichnus, Cochlichnus, Desmograpton, Diplocraterion, Gordia, Gyrochorte, Haentzchelinia, Isopodichnus, Lobichnus, Monocraterion Ophiomorpha, Palaeophycus, Planolites, Phoebichnus, Psilonichnus, Rhizocorallium, Rosselia, Skolithos, Teichichnus* and *Thalassinoides.* Most of the trace fossils indicate marginal marine to marine environment of deposition.

- Three ichnofacies have been recognized like *Psilonichnus* ichnofacies, *Skolithos* ichnofacies and *Cruziana* ichnofacies, which depicts aeolian to upper-middle shoreface environment of deposition. Upper Member repented cross-stratified sandstone, gritty pebbly beds, trough cross-stratification indicate fluvial to estuarine environment.

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