SEDIMENTOLOGICAL AND HYDROGEOLOGICAL STUDIES OF CHORWAD–MADHAVPUR AREA JUNAGADH DISTRICT, GUJARAT, INDIA

A THESIS
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By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled " SEDIMENTOLOGICAL AND HYDROGEOLOGICAL STUDIES OF CHORWAD-MADHAVPUR AREA, JUNAGADH DISTRICT, GUJARAT, INDIA" in fulfilment of the requirement for the award of the Degree of Doctor of Philosophy in Applied Geology, submitted in the Department of Earth Sciences, University of Roorkee is an authentic record of my own work carried out during the period October 1977 to September, 1981 under the supervision of Dr. B.B.S.SINGHAL and Dr. B. PARKASH.

The matter embodied in this thesis has not been submitted by me for the award of any other degree.

12 OCT 1981

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ABSTRACT

The present study is an endeavour to understand geohydrological aspects eg.,hydraulic characteristics and hydrochemistry of the groundwaters in limestones of the Gaj and Miliolite Formations (Tertiary and Quaternary) occurring in the Chorwad-Madhavpur area along the southwest coast of Saurashtra. In addition to this, the stratigraphy of these formations has been worked out as this was not studied in detail by previous workers. Also an attempt has been made to examine the development of porosity due to solution activity and diagenetic changes as groundwater occurrence and movement is influenced by these aspects.

Detailed study of the Gaj and Dwarka Formations could not be carried out because of the scarcity of outcrops,whereas a detailed study of the Miliolite Formation has been made. The Quaternary carbonate sediments of the Saurashtra coast have baffled the geologists ever since the term 'Miliolite' or 'Miliolite limestone' was first proposed by Carter in 1849. The early workers described it as an oolitic limestone containing the foraminifera Miliolina. Srivastava (1968) was the first who gave a detailed petrographic classification of these limestones.Mathur and Mehra (1975), proposed a new stratigraphic classification for the Miliolite limestone. They renamed the 'Miliolite limestone' as Miliolite Formation, while Sub-Recent deposits were referred as Chaya Formation which were put under

the Porbandar Group. This classification has been followed in the present study also.

Based on field observations of vertical sections at different places in the area and petrographic studies, the author in the present study has divided the Miliolite Formation into three lithofacies, i.e., lithofacies I,II and III. The lithofacies I and II have been again sub-divided into lithofacies IA,IB, and IC, and IIA, IIB, and IIC respectively.

Petrographic study of the limestones beloging to the Miliolite Formation indicates that the rocks include calcarenites, calcirudites, chalk (micrite), and pelletoid calcarenites. It is not essentially an oolitic limestone as described by earlier workers. Neomorphism is very common. Sparry calcite occurs both as cement and neomorphic grains.

Scanning electron microscopic study indicates the presence of micro and macroporosity of both intergranular and intragranular types. Microporosity is generally intragranular. Vuggy and channel porosity is common. The porosity has been developed by the dissolution of carbonate grains and skeletal material. Primary porosity is also not obliterated due to diagenesis. Calcite crystal growth and formation of dolomite are also noticed. Lithofacies I, IIA and IIB of the Miliolite formation having extensive secondary porosity act as major aquifers.

Diagenesis of carbonate rock took place successively in (1) stagnant marine phreatic zone (2) active marine zone (3) mixed freshwater and marine water zone (4) freshwater phreatic zone, and (5) freshwater vadose zone mainly during a marine regression.

Regarding the environment of deposition, the lithofacies 1A might have been deposited in lagoons and IB and IC by fluvio-marine action during a transgressive phase. Lithofacies IIA and IIB have been formed in the littoral zone dominated by strong wave action and transitional zone between littoral and shelf zone respectively. Lithofacies IIC contains abundant foraminifera, i.e., *Cibicides*, *Uvigerina*, *Bulimina*, *Cassudilina*, *Bolivina*, *Eponides*, *Nonionella*, *Fissurina*, and *Lagena* which suggest relatively deeper water biofacies and most probably an outer shelf marine environment. Lithofacies III is pelletic calcarenite which has been formed by the action of wind by reworking the deposits formed as a thin sheet in lagoons left behind the regressing sea.

The hydrogeological studies in Gaj Formation and Miliolite Formation have been carried out in the area under study.

Rainfall is one of the most important factors which influence the ground water levels. The small though significant values of correlation coefficient between rainfall and groundwater levels indicate that although rainfall affects the water levels, other factors such as irrigation, pumping, etc. are also responsible for groundwater fluctuations.

A study of the trend surface maps of water-level data indicates that the general groundwater flow is towards south, southwest, and west from the central part of the area. In the western part, the groundwater flow is from the coast towards inland and a groundwater trough is seen. This might be because of the overdevelopment of groundwater for irrigation purposes.

A comparison of pre-monsoon (March) and post-monsoon (October) groundwater levels in the Gaj Formation and the Miliolite Formation shows that the groundwater fluctuation is more in Gaj Formation. This indicates difference in the geohydrological characteristics of Gaj Formation and Miliolite Formation.

A number of pumping tests were conducted in dug and dug-cum-bore wells tapping the Miliolite Formation and the Gaj Formation with a view to study the aquifer characteristics. The drawdown data have been used to determine transmissivity (T) by Papadopulos-Cooper method and Boulton and Streltsova method and storativity (S) by Papadopulos-Cooper method. From recovery data also T was determinedby using Theis recovery method. It is observed that the T values obtained from Boulton and Streltsova's method are comparable with those obtained from the later part of recovery data, using Theis equation. The transmissibility of Miliolite Formation is higher as compared with the Gaj Formation.

The specific capacity determined from recovery data indicate that it is higher in the Miliolite Formation than in the Gaj Formation. The productivity values as determined from specific capacity data also indicate that the limestones belonging to the Miliolite Formation are more productive than the Gaj Formation.

A total of 67 groundwater samples were collected from wells tapping the Miliolite Formation, Gaj Formation and Deccan Trap basalts during February,1979 and 29 samples during October,1979 for chemical analysis.It has been observed that the groundwater in the coastal belt within the Miliolite Formation is quite saline. Trend surface maps of various ions (except HCO_3^-) indicate an increase in concentration towards the coast. Hydrochemical sections from inland towards the coast in the direction of groundwater flow also show a similar trend. The high $Cl^-/(CO_3^{2-} + HCO_3^-)$ ratios, increase in salinity with pumping, the total alkalinity/total hardness ratio which is < 1,the primary and secondary saline nature of water samples, all indicate mixing of modern sea-water with groundwater. The mixing of sea-water and fresh water is on account of over pumping at isolated places and also due to the ingress of sea water along the creeks and rivulets at the time of high tides.

The positive base exchange index values of most of the waters from the Miliolite Formation indicate base exchange of Na^+ present in the mixture of groundwater and sea-water,with the Ca^{2+} present in the clays of Miliolite Formation. This is further evidenced by comparing a hypothetical groundwater with that of sea-water by comparing the percentage reacting values of $Na^+ + K^+ + Ca^{2+}$ of groundwater with those of sea water. The plotting of hydrochemical data in Hill-Piper diagram indicates that groundwater from the Gaj Formation is mainly of secondary alkaline type while those from the coastal belt in the Miliolite Formation are of primary saline and secondary saline type. It has also been observed that groundwater further inland in the Miliolite Formation has low salinity. Therefore, a belt of highly saline water is restricted only in the coastal region. Earlier,i.e.,till about ten years back, in this belt groundwater was fresh. All these observations indicate that salinity is due to intrusion of modern sea-water, later modified by various processes.

Carbonate equilibria studies show that most of the waters are saturated with respect to calcite. In the Gaj Formation, the waters in the north are undersaturated in nature. In the Miliolite Formation, near to the coast, in many places, the waters are of undersaturated nature.

It is seen that the groundwaters from Miliolite Formation are of poor quality and hence not suitable for domestic and irrigation purposes. Even then the people use this water for various purposes because of the non-availability of better quality water. The groundwater of the Gaj Formations are of better quality and can be used for various purposes.

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CONTENTS

LIST OF FIGURES

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LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 RATIONALE

The Chorwad-Madhavpur area of southwest Saurashtra coast of India consists mainly of carbonate rocks of Tertiary and Quaternary ages.

Carbonate rocks have received considerable attention world over in the past thirty years, especially regarding their diagenesis, carbonate chemistry, and the microstructure of calcareous skeletons. The most recent development is the study of porosity and diagenetic features in limestones with the help of electron microscope. Also description and genesis of karst in limestones have been studied intensively. In the recent past lot of work has also been done on the hydrogeology and hydrochemistry of karstic terranes. However, in India, only a modest beginning has been made recently in the study of these rocks though they are found to be fairly extensively developed in the Indian stratigraphic units of all ages from Pre-Cambrian to Pleistocene.

In India, the utilisation of groundwater for domestic, irrigation, and other purposes is gaining importance, as 80% of precipitation takes place in four months of the year, i.e., from June to September and the availability of storage sites is limited. Moreover, large scale horizontal expansion of agriculture is not possible because of the nonavailability of lands. The advent of high yielding varieties of crops, change in the cropping patterns, and also widespread droughts the country experienced locally have resulted in a spectacular expansion in exploitation of groundwater in India and in the process, the limestone regions as well have received due attention.

The Chorwad-Madhavpur area is of special interest as it is underlain mainly by carbonate rocks, where groundwater exploration has been extensive in recent years and the coastal tract is experiencing problems of higher salinity. Therefore the lithostratigraphy of the area was to be worked out as it was not known earlier in detail.

Further, it was also planned to investigate the development of porosity and diagenetic history as this might throw light on the occurrence of groundwater. From the point of view of groundwater availability and causes of salinity, hydraulic characteristics of the aquifers and hydrochemistry were studied.

1.2 LOCATION

The area taken up for study lies along the southwest coast of Saurashtra (Fig.1). Saurashtra forms one of the three geographic units of Gujarat, the western most state of India. Arabian sea borders it towards west and south while the north and east coasts are bounded by the Gulfs of Kutch and Cambay respectively.

The area under investigation falls between latitudes 20° 54' 2" and 21° 18' 15" and longitudes 69°55'50" and 70° 22' 18" and covers parts of Survey of India topographic sheets 41 G/15, 41K/4 and 41 G/16, 41 K/8 and 41 L/5 and 41 L/1. The area extends from near Veraval to Madhavpur. The important places are Mangrol, Chorwad, Gadu, Veraval, Sil, and Madhavpur. Madhavpur comes under

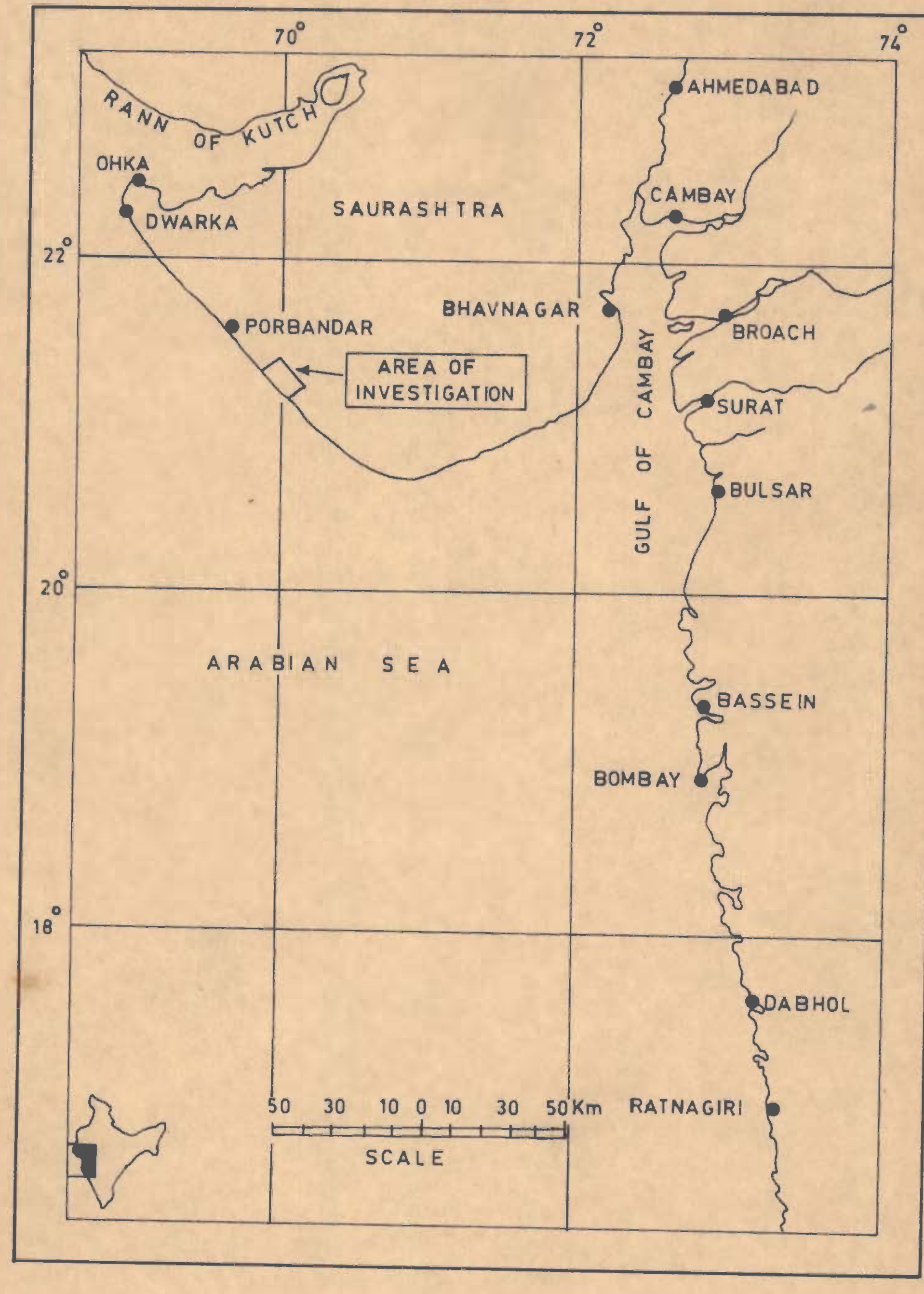


FIG. 1.1 _ MAP OF THE WEST COAST OF INDIA SHOWING AREA INVESTIGATED IN SAURASHTRA.

Porbandar taluka of Junagadh district, whereas Veraval and Mangrol are Taluka head quarters of Junagadh district. Mangrol, almost in the middle of the area under study lies at a distance of 160 kms from Rajkot, the most important town of Saurashtra region is 82 km from Porbandar, and 380 km from Ahmedabad, the State's capital.

1.3 CLIMATE

The study area lies in the monsoon belt and enjoys a tropical climate. It is a drought prone area with erratic rainfall.

1.3.1 Rainfall

The rainfall variability is high. The average annual rainfall at Mangrol is 635 mm based on rainfall for the last 12 years. The lowest rainfall (264 mm) during this period was in 1974. Most of the rainfall (about 90%) occurs between mid June to mid-September. Generally June receives the maximum rainfall. The remaining 10% occurs during November to February. Thus, the rainfall with respect to time is not uniformly distributed. Winter is usually rainless, fair weather period.

1.3.2 Temperature

The mean annual temperature at Veraval is 25.5°C. The summer temperature (during April to June) varies from 25°C to 35°C. Winter lasts from early December to middle February. January is the coldest month of the year. The minimum temperature during this period never goes below 15°C and the average temperature is around 20°C. From the end of February onwards the temperature rises gradually, and the maximum is reached in May. April and May are the driest months of the year with hardly any rains. The sea breeze penetrates 20 to 30 km inland, lowering the temperature. Further inland there is not much spatial variation in temperature.

1.3.3 Humidity

The humidity percentage is highest during summer and generally ranges from 70 to 80 percent. In winter the percentage is much lower. A high humidity is often associated with cloudiness and the rains in the months of July and August. It shows wide variation during the day time. The moisture content varies with the temperature and is highest during the morning hours.

1.4 SOILS

In the coastal belt, the soils are derived from the Miliolite limestone. They occupy an elongated strip varying from 4 to 10 km in width. Adjacent to this, towards inland from the coast, Gaj clays and limestones occur. The areas occupied by clays form a desolate terrain.The soils can be classified as calcic camosols. The soil cover is generally not thick (25 to 100 cm). The physical characteristics of soil do not constitute any restriction for good crop production. The water holding properties are favourable and sufficient quantity of water can be stored in the soil profile which is available for crop growth. The coastal soils constitute good agricultural land and do not constitute any soil management problems.

1.5 LAND USE AND AGRICULTURE

Most of the area is profitably utilized except where there are outcrops or stony waste. Large variety of crops are produced including groundnut, cotton, millet, pulses, wheat, onion and sugarcane. The choice of the crops lies with the individual farmers and cash crops attract them most. The area between Madhavpur and Chorwad was supposed to be a very fertile land and the area was green looking because of the orchards of coconut, vegetables and mangoes. However, because of deterioration in water quality, wilting of trees started and the crop yield has been reduced. Presently the greenery is gradually decreasing.

Natural vegetation is restricted to agriculturally unproductive areas. Xerophytic flora which are able to endure prolonged drought, grow in sandy soils of the coast. Cactii and creosote bushes grow in the area. Some creepers and long rooted grasses are also present. There are no trees which can yield timber. Casuarina plantation is also common along the coast in many places.

1.6 PREVIOUS WORK

No detailed work on the Geology of the present area under investigation has been done by any previous worker, but the regional geology of Saurashtra (Fig. 1.2) has been described by some people. Among these include the works by Carter (1849), Fedden (1884), Chapman (1900), Sastri and Pant (1959), Srivastava (1968a,b), Biswas (1971), Verma and Mathur (1976, 1977a,b, 1978), Lele (1973, 1975), Govindan et al (1973,1976), Rajaguru and Marathe (1977), Marathe et.al. (1977), Agrawal and Roy (1977), Mathur (1978), Verma (1979) and Hussain et al. (1980). The oldest rock formations is the Deccan Trap of Cretaceous to Eocene age followed by Gaj and Dwarka Formations of

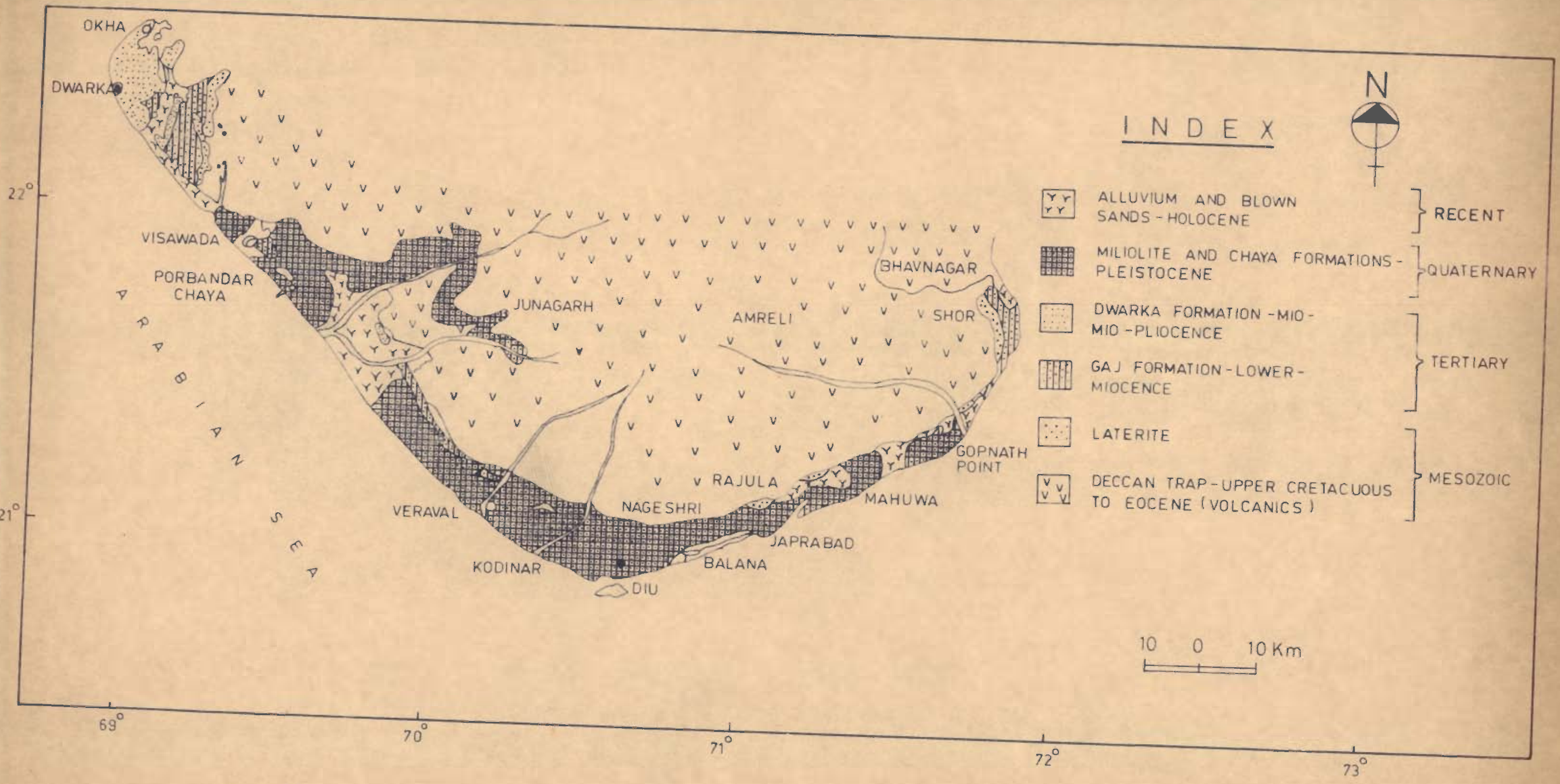


FIG. 1.2 _ GEOLOGICAL MAP OF SOUTHERN COAST OF SAURASHTRA PENINSULA (After G.S.I).

Lower Miocene age. The Tertiary sediments are overlain by the Miliolite and Chaya Formations. Recent sands and alluvium are the youngest. The only work about the study area is on the Quaternary deposits by Sastri and Pant (1959, 1960). A review of the geology of Saurashtra is given in Chapter 2.

As far as the hydrogeology of the area is concerned, somewhat systematic survey has been done by the officers of the Public Works Department (PWD), Gujarat Government (1975) (presently Gujarat Water Resources Development Corporation) and C.G.W.B. (1976). Two different views on the salinity of this region have been put forward. According to the former the salinity is due to sea-water intrusion, whereas according to the latter, it is because of use and reuse of groundwater for irrigation purposes and poor drainage conditions. Desai et al. (1979), based on hydrogeochemical studies concluded that salinity is due to sea-water intrusion. They also opined that the aquifer material is also playing an important role in modifying the chemistry of the mixed water (sea-water + native groundwater) by base exchange phenomenon.

1.7 HYDROGEOLOGY OF LIMESTONE TERRANES - A REVIEW

More than one fourth of the continental areas is occupied by exposed and covered carbonate rocks mainly limestones and dolomites. Besides their economic importance as a mineral resource, carbonate rocks contain in places, large amounts of ground water. These rocks were not considered to be good aquifers earlier.

Even though limestones and other fractured rocks cover larger area near the land surface than porous granular sands, clays and gravels, still greater attention was given to the latter from hydrogeological point of view. Carbonate terranes at places show karstic characteristics. Large springs, scarcity of water locally in a region of appreciable precipitation and loss of surface streams, are common features in areas underlain by karstified carbonate rocks. In recent years these aspects have been studied in detail.

The yield and circulation of water in carbonate rocks vary widely. This depends mainly upon the development of secondary porosity such as fissures and solution cavities produced by the solvent action of circulating water. The solution activity will start only when the limestones act as a medium of transmission. The pathways for water during the initial stages are bedding planes and joints. The permeability increases when the openings are enlarged, when water undersaturated with respect to calcite or aragonite moves into and out of the limestone. The rate at which solution occurs depends mainly upon the solubility of the rock material, the chemical character of groundwater, and the rate of circulation. Increase in permeability will lead to various changes such as progressive lowering of water table, enlargement of caves and changes in topography with time.

Solution of rocks will produce two types of karstic features. They are (1) surficial features that do not reach more than a few metres below the land surface, and (2) karst features that affect the permeability of rocks and circulation of water below the surface, such as dolines, solution cavities, solution shafts etc. With the declining of water levels, as the base levels are lowered, caves will be exposed in the zones of aeration, and the circulating water again modifies them.

Due to down cutting of perennial streams, the base level may change downwards. In such cases lateral solution openings will be produced because of the groundwater discharge into the streams.

In coastal areas where the karst systems are exposed to the sea, sea-level is a controlling factor in the discharge of water into the sea. The relation of fresh water head to the salt-walt head determines the maximum depth at which the system is exposed to sea-water.

There has been considerable debate whether there exists a water table in carbonate rock terranes. Now it is an accepted fact that where carbonate rocks occur at or near the land surface in such a way that it lies in the ground water circulating system, the existance of a water table may be presumed, but if the rock is almost impermeable the water table may be locally discontinuous or absent (Le Grand and La Moreaux, 1975).

Thus it is clear that the ranges of hydrologic conditions within carbonate rocks are generally broad. This causes limitations on generalisations that one would like to make.

1.8 METHOD OF INVESTIGATION AND SCOPE OF WORK

Geological mapping of the Chorwad-Madhavpur area was carried out on 1:50,000 scale during March 1978 and September 1979 and the various lithological units were marked. Lateral and vertical variations in the Miliolite Formation were studied and rock samples were collected in a systematic manner from various locations for laboratory studies. Samples of chalk were also collected with a view to study the microfauna. The geomorphological analysis of the area was carried out on the basis of aerial photographs.

The laboratory investigations included the study of thin sections, X-ray analysis of limestone and clay samples, chemical analysis of rocks, microfaunal study of chalk, and scanning electron microscope (SEM) study of limestones.The data from these are utilised in deciphering the depositional environments and the diagenetic changes in the Miliolite Formation.

In hydrogeological investigations, pre-monsoon and post-monsoon water levels were collected from the wells. These data were used for the study of ground water flow direction and water level fluctuations. Pumping tests were carried out in the field and data were analysed by various methods to get an idea of the hydraulic characteristics of aquifers. Ground water samples were also collected for different seasons (February 1979 and October, 1979) with a view to study the chemical quality of water, the causes of salinity, and lateral and seasonal variation of ground water quality. The data regarding the reduced levels of wells were collected from the Gujarat Water Resources Corporation and Central Ground Water Board.

Chpater 2 entitled 'GEOLOGY OF SAURASHTRA - AN OVERVIEW' gives a brief account of the different stratigraphic units met with in Saurashtra peninsula and the views put forward by various workers about these deposits. The Quaternary carbonate sediments of Saurashtra coast are porblematic and views of various authors are briefly reviewed in this Chapter.

Chapter 3 entitled 'GEOMORPHOLOGY, GEOLOGY AND SEDIMENTOLOGY' describes the geomorphology of the area in detail with special emphasis on the karstic features observed in the limestones belonging to the Miliolite Formation. Various lithostratigraphic units of the area are described. Based on the study of vertical sections and petrography, the rocks belonging to the Miliolite Formation have been divided into three lithofacies,i.e.,lithofacies I, II and III. The lithofacies I and II have again been sub-divided into IA, IB, IC, and IIA, IIB and II C respectively. A detailed petrographic investigation of these rocks have been carried out. A study on the foraminifers present in the lithofacies II C has also been made. Various carbonate minerals in different limestone samples of Miliolite Formation are recognized by X-ray diffraction analysis. Chemical analysis data of limestone samples have been utilised to classify the rocks. Scanning electron microscope (SEM) studies of limestones belonging to Miliolite Formation have also been carried out. Based on these observations an attempt has been made to decipher the diagenetic histiry, and also the environments of deposition.

The hydrogeological aspects of the different rock types met with in the area,i.e.,the Deccan trap basalts, Gaj Formation and Miliolite Formation form the subject matter of Chapter 4, entitled 'GEOHYDROLOGY'. In this chapter, the hydrogeologic properties of the various rock types and the aquifer parameters as determined from pumping test analysis with special emphasis on

FIG. 3.2 A GENERAL VIEW OF INLAND MOUND (LITHOFACIES III OF THE MILIOLITE FORMATION). LOCALITY: KANKASA.

FIG. 3.3: WAVE CUT CLIFF SEEN NEAR CHORWAD BANDAR. DUE TO WEATHERING AND EROSION THE CLIFF IS BEING GRADUALLY DISTROYED.

the Miliolite and Gaj Formations have been discussed. Trend surface analysis has been used to study the water level data.

Chapter 5 entitled 'HYDROGEOCHEMISTRY' deals with the chemistry of the groundwaters occurring in the Gaj and Miliolite Formations. An attempt has been made to see the reasons of salinity of these waters. Areal distribution of various ions have been studied by trend surface technique. Principal component analysis was used to see the interrelationship of various ions. Discriminant technique was applied for discriminating the groundwaters occurring in the Miliolite and Gaj Formations and also to discriminate the waters of different seasons. The suitability of these waters for various purposes is also discussed.

The final chapter 6 which is titled 'SUMMARY AND CONCLUSIONS' summarises and integrates the results of chapters 1 to 5. The salient findings of the investigations are brought out and important conclusions are drawn.

In short, this study attempts to unravel the environments of deposition, the nature and development of porosity, and the diagenesis of the limestones belonging to the Miliolite Formation, and to correlate porosity development and the geohydrologic characteristics of the Miliolite Formation. It also tries to understand the geohydrologic and hydraulic characters of the Gaj and Miliolite Formations, and the chemistry of waters occurring in these two Formations.

CHAPTER 2

GEOLOGY OF SAURASHTRA - AN OVERVIEW

2.1 INTRODUCTION

In the following sections, the views put forward by various workers on different rock formations of Saurashtra which are also present in the area under study have been briefly reviewed. The oldest rock formations met with are the Deccan Trap basalts, which are overlain unconformably by the Gaj and Dwarka Formations of Tertiary age and the Miliolite and Chaya Formations of Quaternary age. Beach sands, sand dunes, and alluvium are the youngest rocks of Recent age.

2.2 DECCAN TRAP

The most prominent and widely distributed of all rock formations of the Saurashtra peninsula is the Deccan Trap which is by and large of tholeiitic basalt composition.

Wadia (1966) assigned Uppermost Cretaceous to Eocene age to these trap rocks. Pascoe (1973) believed that outpouring of the Deccan trap lavas commenced before the end of Cretaceous and continued through the Palaeocene to the Lower Eocene.

2.3 TERTIARY

2.3.1 Gaj Formation

The Deccan Trap basalts are overlain, with an erosional unconformity by the Gaj Formation which was formerly known in Indian stratigraphy as 'Gaj series' or 'Gaj beds'. Fedden (1884) mapped the Gaj rocks as small detached outcrops in the fringe of coastal alluvium round the southern limit of Trap area. The Gaj Formation consists mainly of alternating beds of pale yellow limestones and yellow or grey calcareous clays. Verma (1979) reported that the Gaj Formation in general is calcareous in the higher horizons and argillaceous towards the base. Drill hole data indicate that the Gaj Formation is nearly 300 m thick near the coast.

Based on their microfaunal content, the rocks have been assigned Aquitanian to Burdigalian (Lower Miocene) age (Pascoe, 1973; Wadia, 1966). These are considered to have been deposited in an estuary or broad mouth of a river during marine regression (Fedden, 1884; Pascoe, 1973; Wadia, 1966).

2.3.2 Dwarka Formation

Formerly it was known as Dwarka beds in Indian stratigraphy. They conformably overlie the Gaj beds and can be distinguished in being highly arenaceous. These were named after the place Dwarka in Saurashtra and were first mapped and so named by Fedden (1884). No detailed work on the Dwarka Formation has been done after Fedden's initial account. Fedden (1884) also included in this formation a group of highly fossiliferous limestones, called by him as "coast-fringing rocks". Fedden (1884) noted the presence of a number of broken fragments of molluscs and Balanus and some foraminifers. The lamellibranchs and gastropods of the Dwarka Formation are difficult to identify because of their high degree of recrystallisation. The clays associated with Dwarka limestone are reported to be highly arenaceous in composition and usually devoid of fossils. Verma and Mathur (1973 a,b,c) reported a number of foraminifera, viz. Lepidocyclina (Nephrolepidina) sp., Miogypsina (miogypsina) Sp., and Archaias (Taberina) malabarica, from the limestone of Dwarka. "Coast-fringing rocks" of Fedden (1884) have been included under Chaya Formation by them. Fedden assigned Mio-Pliocene age to these formations. Based on the larger foraminifera, Verma and Mathur (1973c) believe that the lower part of the Dwarka Formation is of Lower Miocene age. They could not assign any upper age limit to the Formation.

2.4 QUATERNARY

The whole of Saurashtra coast exposes deposits of Quaternary rocks. These Quaternary deposits previously known as 'Miliolite', 'Miliolite Limestone ' or Miliolite rocks have baffled the geologists ever since the name 'Miliolite' or 'Miliolite limestone' was first proposed by Carter in 1849. He described this as an oolitic limestone rich in foraminifera belonging to the family 'Miliolidae '.

Fedden (1884) was the first worker to give a detailed description of these limestones along with four other biogenically rich Quaternary rocks of Saurashtra peninsula. According to him it is a "finely oolitic freestone, almost devoid of sand and other particles, the nuclei of the oolitic grains being mostly organic". Stratigraphically younger rocks were described by him as 'Littoral Concrete', 'Dead Coral reefs' and Oyster beds.

Foote (1898) described similar rocks from Kodinar area of southern Saurashtra. According to him foraminifera predominate these rocks and their tests form the nuclei for the oolitc grains.

2.4.1 Origin and Age of Miliolite Formation

After a study of coastal and inland limestones of Miliolite Formation of Saurashtra Peninsula, Fedden (1884) suggested that this limestone is the product of littoral marine accumulation.

Evans (1900) opined that these carbonate rocks have been formed in shallow waters, in the intertidal zone as littoral accumulations. He considered that the inland Miliolite Formations occurring at Junagadh (his "Junagarh limestone") were formed due to wind action on the ancient coastal sediments.

Chapman (1900) favoured the transportation action of the wind as the possible mode of accumulation of the limestone, based on the worn and polished nature of the foraminifera contained in the limestones of the Miliolite Formation. He believed that some of the coastal calcareous rocks were deposited in shallow marine waters.

Sastri and Pant (1959) studied the limestones of the Miliolite Formation and other calcareous Quaternary deposits of southern Saurashtra coast with emphasis on their bearing on the eustatic changes in the sea-levels during Quaternary period. They concluded that during the Pleistocene, the sea stood nearly 4.5 m above the present sea level and submerged a large part of the coastal tract. According to them these limestones are the product of Pleistocene marine transgressions. Sastri and Pant (1960) reported a number of foraminifera from these limestones and assigned a Pleistocene to Recent age to these rocks.

It was Strivastava (1968 a,b) who first made a detailed petrographic study of the limestones of the Miliolite Formation of Porbandar-Veraval area. According to him, the "Miliolite limestone" consists mainly of a succession of calcarenites, calcirudites, coquinoid bands, and minor carbonate mud. Based on the field and petrographic studies Srivastava (1968a) concluded that these sediments were formed in agitated, warm, and shallow waters, and that during the Pleistocene the sea-level stood much higher than at present. He suggested that the entire Saurashtra was down-faulted in the Pleistocene causing widespread marine transgression during which the foramation of these rocks took place. This was followed by uplift during the post-Pleistocene times.

Glennie (1970) attributed an aeolian origin for the Miliolite Formation. He explained that the sea-level was lowered during the Quaternary polar glaciation, exposing broad areas of present continental shelf of Saurashtra and wind transported the calcareous material to the interior parts.

Biswas (1971) studied the Miliolite Formations of Saurashtra and Kutch and suggested that the coastal deposits formed under marine conditions while the rocks in the interior were derived from the disintegration of the coastal limestone and redeposited by the action of wind. He assigned Early Pleiostocene age to the coastal Saurashtra rocks and Late Pleistocene to Early Holocene age to the inland limestones.

Lele (1973,1975) ascribed a marine origin to the Miliolite Formation on the basis of field and sedimentological studies of the Quaternary deposits of Bhadar valley in Saurashtra. Based on archaeological finds, Lele (1973) assigned pre-Middle palaeolithic age to the Formation. Sperling and Goudie (1975) while commenting on the work of Lele (1973), advocated an aeolian origin for a substantial part of these deposits. They also opined that there may be more than one type of foraminiferal limestone of the Pleistocene age.

The Miliolite Formation of Hiran valley of southern Saurashtra was investigated by Rajaguru and co-workers (Govindan, et al.1975, 1977; Rajaguru and Marathe, 1977; Marathe et al. 1977). Marathe et al. (1977) recorded the occurrence of brownish clay bands within the Miliolite Formation. According to them clay and chalk bands are similar to the modern clays and chalks in the tidal flat environment and tidal-pool environments. This indicates a fluctuating depositional environment from high energy littoral to low energy tidal pool. Based on detailed geomorphological, petrological and archaeological investigations, they came to the conclusion that the Miliolite Formation is fluvio-marine in origin which occurs upto 20 km inland from the coast and 75 m above mean sea level, while those occurring above 75 m are of aeolian and fluvio-marine origin. Based on the discovery of Lower and Middle Palaeolithic tools in the fluvial gravels underlying the earlier and later limestones of the Miliolite Formation, they assigned Middle Pleistocene age for the rocks which occur in the higher reaches, while Late-Pleistocene age was given to coastal rocks.

Agrawal and Roy (1977), and Agrawal et al. (1978) after field and SEM studies on the coastal as well as inland Miliolite Formations concluded that the limestones occurring at the interior highlands are of aeolian origin.

Bhat and Patel (1977) commented on the depositional environments of the rocks of the Miliolite Formation based on a study of the geometrical characters of pseudo-oolites. According to them these limestones are of marine origin.

A substantial contribution to the miliolite problem has been made by the G.S.I. officers (Verma and Mathur, 1973, 1976, 1977, 1978, Mathur, Verma and Mehra, 1975, 1976; Mathur and Mehra, 1975, Mathur and Verma, 1976; Mathbr, 1978; and Verma, 1979). They gave a revised classification of Quaternary carbonates of Saurashtra. Mathur (1978) has evaluated the sedimentological and depositional aspects, whereas Verma (1979) has investigated microfaunal contents. According to them the coastal and inland Miliolite Formations are both marine as well as aeolian types of deposits. Verma and Mathur (1978) considered many of the interior deposits to be marine and explained them as typical valley-fill deposits in the 'Ria Valleys' related to considerably high strand lines. Based on the study of pellets and textural characteristics of Recent carbonate sands (beach and dune sands), Mathur (1978) came to the conclusion that the depositional conditions favourable for lime deposition, pelletisation and dune formation, still continue to pregail. So the present day model of sedimentation is only slightly different from that prevailing during the deposition of the Miliolite Formation.

Verma (1979) placed the Miliolite Formation under two categories based on the altitude at which they occur, i.e., (a) low level deposits occurring upto 75 m above the present sea level, and (b) high level deposits that occur above the 75 m contour. On the basis of mode of origin, he again subdivided both these categories into two viz. (a) deposits of marine origin and (b) deposits of aeolian origin. Based on the field studies he has given some criteria for distinguishing between deposits of marine and aeolian origin.

Gupta (1972, 1977), and Gupta and Amin (1974) dated corals and shells from raised beaches of the Saurashtra coast by radiometric methods and suggested that their measured ages fall in three well defined groups. Accordingly, they postulated that the sea level during 6000, 30,000, and 120,000 years B.P. was 2 to 6 m higher than the present sea-level.

Recently Hussain et al. (1980) dated the limestones of the Miliolite Formation of Saurashtra by ^{234}U, ^{230}Th ^{231}Pa, and ^{14}C methods. They got lower ages from ^{14}C dating. They attributed this due to a recent influx of sea-water or groundwater because man made ^{14}C is present in surface waters, ocean waters and in atmospheric precipitation. The activity ratio $^{234}U/^{238}U$ for five samples, which are from both coastal and inland locations gave identical ratios, and an average age of 157,000 years. So they concluded that the corals which grow in shallow waters and the Miliolite

Formation both coastal and inland, were formed around the same period, i.e., (1-1.7) x 10^5 years B.P.

2.4.2 Neotectonics

There is difference of opinion among the various workers on the tectonic stability of Saurashtra peninsula during the Quaternary period. Some people consider that the Saurashtra peninsula was tectonically unstable whereas according to others this region was stable and the presence of raised beaches and marine terraces are due to eustatic changes of sea-level.

2.4.2.1 Studies Favouring Tectonic Instability

According to Poddar (1964), the Quaternary tectonics of Saurashtra is mainly controlled by faults bounding the Peninsula on all sides. He explained that these were pre-existing basement faults reactivated during the Quaternary period.

Krishnan (1968) believed that during the whole of Tertiary era, areas of Kutch and Kathiawar were under the sea. It was only in the Pleistocene times that this was raised apparently above sea-level. He also opined that the Mio-Pliocene deposits of Saurashtra were raised up probably in late Pliocene, contemporaneously with the final down-faulting of the western coast of India.

Srivastava (1968b) suggested that the entire Saurashtra was down-faulted in the Pleiostocene causing widespread marine transgression during which the limestones belonging to the Miliolite Formation were deposited. According to him there has been no actual folding in the Quarternary times. This was followed by uplift in the sub-Recent continuing till historic times.

Geomorphological studies of the Saurashtra region using Landsat imageries and aerial photography were carried out by Sood et al.(1977, 1978). They concluded that this region was subjected to tectonic uplifts during the Quaternary. They also opined that the Saurashtra region had a complex history involving both tectonic activity and eustatism.

2.4.2.2 Studies Favouring Tectonic Stability

Some workers believe in the stability of the Saurashtra region during the Quaternary period, especially during Holocene. They include Sastri and Pant (1959), Gupta (1972, 1977) Agrawal et.al. (1978), Rajaguru and Marathe (1977) and Verma and Mathur (1977, 1978). They explained the presence of raised beaches and marine terraces due to the eustatic changes of sea-level. According to Verma and Mathur (1977,1978) and Verma (1979) the presence of Miliolite Formation at varying heights above the present sea-level is due to the eustatic changes of the sea during the Pleistocene and Holocene times rather than any epeirogenic changes.

Thus, from the foregoing it can be seen that the Miliolite Formation occurs both along the Saurashtra coast and also inland areas of Saurashtra peninsula. These have been reported to occur at considerable distances from the present coast-line and at considerable altitudes (upto 220 m above m.s.l.). Regarding the various theories on the origin of these limestones, they have been thought to be purely marine and purely aeolian to mixed aeolian and marine and fluvio-marine in origin.

2.5 STRATIGRAPHIC SEQUENCE OF SAURASHTRA

2.5.1 Classification

As mentioned previously, the Deccan Traps form the base over which the sediments of Tertiary and Quaternary occur unconformably. The sequence of Tertiary and Quaternary sedimentaries of the Saurashtra coast was first given by Fedden (1884) (Table 2.1). He considered miliolite, raised beaches (Littoral concrete, Dead coral reefs, and oyster beds), rann clays, sand dunes and fresh water alluvium as Quaternary deposits and grouped them as 'Alluvium'. He opined that some of the rocks included under the Dwarka beds might be of the Pleiostocene age and must be separated on closer examination. He also described one of these rocks as 'coast fringing rock'.

Sastri and Pant (1959) gave a new classification of the Quaternary deposits after a study of the Veraval-Mangrol coast. They subdivided the Quaternary rocks into chronostatigraphic units viz. Pleistocene, Sub-Recent and Recent rocks (Table 2.1).

Marathe et al.(1977) have constructed a composite litho-stratigraphic section (Table 2.1) of the rock units encountered in the Hiran valley of southern Saurashtra. The stratigraphic column presented by them shows that there are two major rock-units (Rock Unit I and Rock Unit II), each characterised by calcirudites of fluvial origin at the base grading into the miliolite bearing calcarenite of marine origin at the top. They opined that the rock units I and II were deposited during two major marine transgressive phases in Middle Pleistocene (?) and Late Pleistocene times respectively.

Mathur and Mehra (1975, 1978) after a study of the Quaternary rocks of Porbandar area and a reconnaissance of the rest of the Saurashtra peninsula proposed another classification (Table 2.1). They gave 'Formation' status to the two of the three stratigraphic units suggested by Sastri and Pant. The 'Miliolite Limestone' was renamed as 'Miliolite Formation' while 'Sub-Recent deposits' were referred as Chaya Formation. The coast fringing rocks of Fedden were taken out from 'Dwarka beds' and grouped with the newly proposed Chaya Formation. The Miliolite Formation has been further subdivided (Mathur and Mehra, 1975; Mathur et al. 1976, Mathur, 1978) into Dhobalia Talav Member and Adatiana Member. The former is characterised by an interbedded sequence of calcarenites and micrites and the latter by pelletoid calcarenites. They grouped the Miliolite and Chaya Formations under Porbandar Group, and assigned Early Pleistocene and Late Pleistocene ages respectively. The Miliolite and Chaya Formations are approximate equivalents of Rock Units I and II of Marathe et al. (1977).

Verma (1979) proposed a lithostratigraphic classification of Tertiary - Quaternary succession in Delvada- Jafrabad area, southern Saurashtra (Table 2.1). He placed both the Gaj and Dwarka Formations in a new group, called Negeshri Group. The new group was created for the purpose of expressing the natural relations of associated Gaj and Dwarka Formations.

A comparison of stratigraphic sequence given by different workers is given in Table 2.1.

CHAPTER 3

GEOMORPHOLOGY,GEOLOGY AND SEDIMENTOLOGY

3.1 INTRODUCTION

In the present investigations, the geomorphological study of the area has been carried out with special reference to karstic features. Based on the study of outcrops and vertical sections from different places a lithostratigraphic succession for the Chorwad-Madhavpur area has been proposed. Deccan Trap basalts form the basement over which lies unconformably the sediments belonging to the Nageshri Group and the Porbandar Group. Beach sands and alluvium are the youngest. Because of the scarcity of outcrops, the rocks belonging to the Nageshri Group,i.e.,Gaj and Dwarka Formations could not be studied in detail. A detailed geological and sedimentological investigation of the Miliolite Formation has been carried out. Based on the petrographic and scanning electron microscopic studies, an attempt has been made to decipher the diagenetic history of the sediments. A detailed microfaunal study of the chalk (micrite) beds occurring in the Miliolite Formation has also been carried out. Based on all these factors interpretations regarding the environments of deposition has been made.

3.2 GEOMORPHOLOGY

The geomorphologic features of the area have been studied with the aid of aerial photographs, a detailed physiographic map, and field observations.

The Girnar hill ranges, composed of Deccan traps, constitute the most striking feature of southern Saurashtra and this lies just outside in the north-western part of the area under investigation. From these hill ranges the land gently slopes towards the sea. The most important physiographic features of the area can be classified into four broad groups. They are

(i) Coastal Plain: Coastal plains are the present products of continuing erosional and accretional processes through time. They are regional features of low relief bounded seaward by shore and landward by high lands. In the area under study, it is a gently sloping, but undulating plain land. It extends from the base of the Girnar hills towards the Arabian sea. The elevation of this plain drops from 50 m above mean sea level to about 10 m above mean sea level towards the sea over an average distance of 18 km.

(ii) Coastal depressions: Within varying distances from the sea, the coastal plain slopes rather steeply and depressions are formed between the southern edge of the plain and the coastal ridges. The width of the depressions varies from less than a kilometer to about 15 km. On the basis of their size and location, the depressions can be classified into three types (a) ghed (b) inland depressions, and (c) coastal depressions.

(a) Ghed: It is a local name for big depressions. These occupy vast areas and are seen in the north western part of the area covering Mekhri and Madhavpur and extending beyond upto Porbander. This is called as the Sorthi Ghed.

(b) Inland depressions: Small depressions are seen at the eastern part of the Sorthi Ghed. They are located between Sil and Ajak, north of Ajak, and north west of Atroli villages.

(c) Coastal depressions. They are narrow almost linear and continuous from Madhavpur to Veraval and occupy areas adjoining coastal ridges.

(iii) Coastal ridges: Another striking feature is the presence of two sets of ridges consisting of semiconsolidated to consolidated limestones, running almost parallel to the sea and also parallel to each other, broken only in places, along the entire coast length of the area. They are narrow, having a width of only a few tens of metres. Their elevation varies from 7 m to 30 m above mean sea level.

(iv) Inland mounds and ridges:

In many places small elongated mounds or ridges occur towards inland portions such as near the villages Gadu, Chorward, Budecha, Arena, Sepa and Kankasa (Fig.3.1, 3.2). The height of these generally ranges from 3 to 8 m. They generally strike in a NE-SW direction.

Four small seasonal rivers drain the area viz. Netravati, Noli, Yangdi and Meghal. Netravati river flows through Chandwana, Menaj, Talodra and Sil villages and finally reaches the sea. Noli is another river flowing from the Deccan Trap country, which passes through the limestone terrane. The part of the river which flows through Deccan Traps shows dendritic pattern. Its tributary Langdi meets at Khorada Nes and the river finally joins the sea.

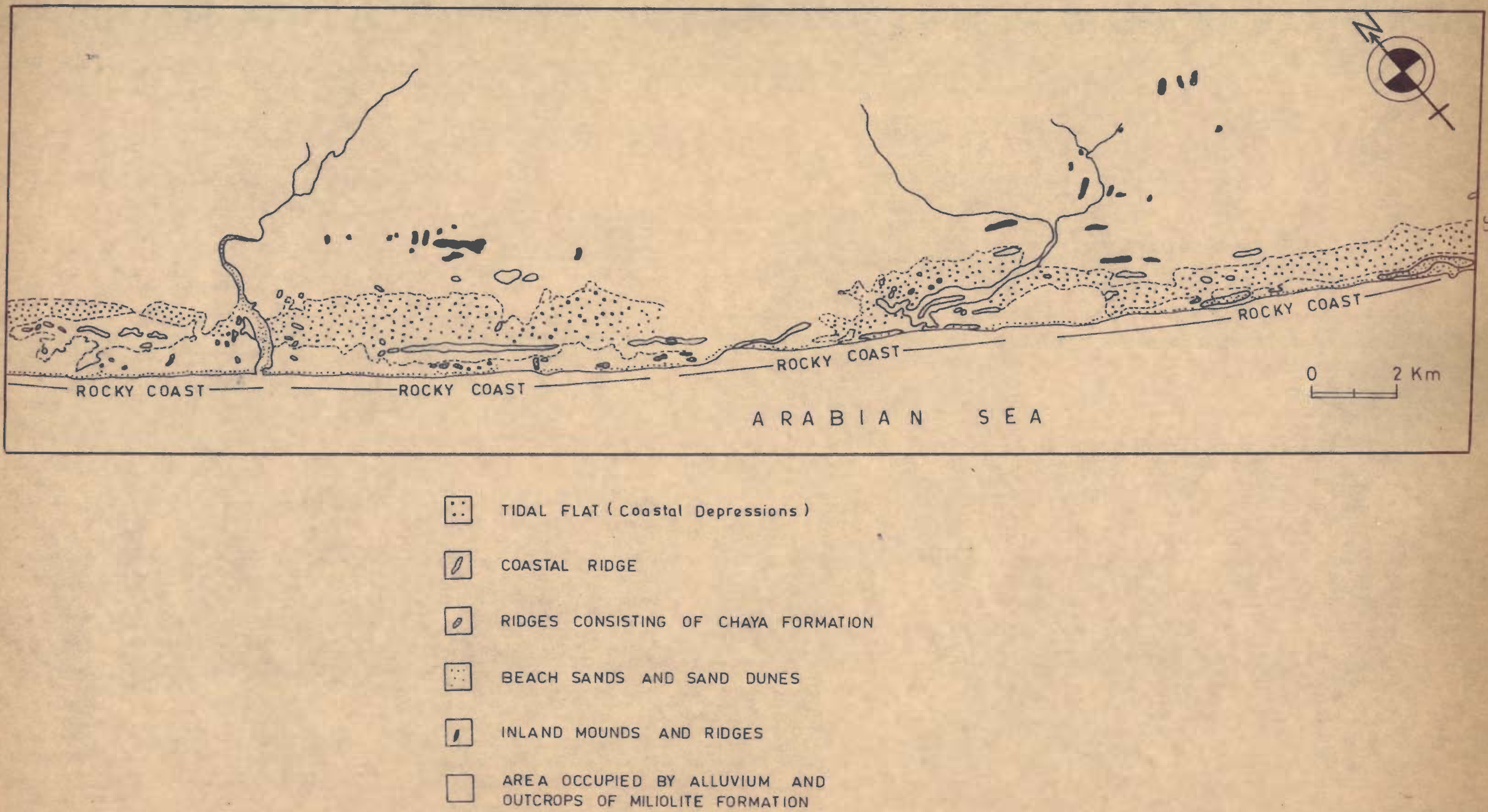


FIG. 3.1 _ GEOMORPHOLOGICAL MAP OF MADHAVPUR-CHORWAD COAST BASED ON AIR PHOTO INTERPRETATION

Meghal is a bigger river, with a broad flood plain. They all flow in a NE to SW direction. The total length of these rivers are not much. They generally discharge relatively small quantity of water and sediments to the coast.

One side of the area is bounded by the Arabian sea. The coast line extends in a NW to SE direction. The present day coast line is only a temporary line of contact between land and sea and reflects the sum of all the influences which have operated on them since they were originally established. The coast line in the present area is fairly straight and forms a part of the south-western coastline of Saurashtra which looks as if it is knife cut. Vertical cliffs having a height of 10 m which are the result of wave action are also present (Fig. 3.3). Wave cut platforms are common (Fig. 3.4). They are generally exposed during the low tide. Sometimes these platforms are visible farther away from the coast. Wave cut platforms occupying the foreshore of the cliff are also noticed. Wide bays occur in the areas where the limestones are less competent giving rise to some irregularity of the coast line with cliffs alternating with wide bays. The shore line in the area in many places can be called as 'indented' because of the development of rocky cliffs, promontories, and embayments. At Chorwad, erosion has produced a pedestal rock, i.e., a big block resting on two small blocks (Fig. 3.5). It might be because of removal of clayey material due to undercutting by wave action.

In the aerial photographs, tidal flats can be recognised by tonal contrast. Some times rill markings are also seen. These tidal flats occur in between the coastal ridges, nearer to the mouths of

FIG. 3.2

FIG. 3.3

FIG.3.4 WAVE CUT PLATFORM EXTENDING TO THE SEA. LOCALITY: CHORWAD BANDAR.

FIG.3.5 PEDESTAL STRUCTURE SEEN NEAR CHORWAD BANDAR.

FIG. 3.4

FIG. 3.5

rivers. In the Meghal river, three river terraces on one side, and two on the other side can be recognised. These indicate either tectonic activity or eustatic changes of sea level.

In the study area sandy beaches are common along the coast. Their width varies depending on the presence of cliffs and wave cut platforms.The beach material consists mainly of calcareous sand and ranges from shingle (material ranging in size from 25 to 800 mm) to fine sand.

A number of sand dunes occur as detached patches along the coast. These are active dunes and are oriented in ENE-SSW direction.

Sand bars are produced at the mouths of rivers. During rainy season, these are opened and river water flows into the sea, but during high tides sea water enters into these areas again and gradually the bars develop. None of the rivers forms a delta. This is because of the sluggish nature of the rivers with little sediment carrying capacity.

3.2.1 Karst

"Karst" is a German word, originated from the Indo-European word "Kar" meaning rock and the Slovenian word "Kras" (Roglic, 1972, p.2). In Yugoslavia the terms "Krš " and "Carsus" are also used. The term "Krs" is Serbo Croation for "rock" or "stone" and "Kras" is the Slovenian word for a bleak waterless place (Williams, 1970, in Stringfield, Rapp and Anders, 1979).

Karst includes the circulation of water in fractures, fissures, joints and other cavities and the development of corresponding forms in soluble, mostly carbonate rocks (Roglic,1972).

Karst is essentially a morphological feature. The genesis of karst features depends, in general, upon the primary properties of rocks, their position in the stratigraphic sequence, tectonic disturbances and climate (Herak and Stringfield, 1972).

Karst features may be divied into two groups: (i) Surficial features that do not extend far below the surface; and (2) Karst features such as sink holes, solution shafts, solution cavities and caverns that may affect the circulation of water deep below the surface (Stringfield, Rapp and Anders, 1979). Both types of these features are noticed in the area under study which are described below:

3.2.1.1 Limestone Pavements

In many places, such as near Chorwad, Kukaswada, Rahij, Lohej and Sil villages the limestones outcrop in the form of pavements. The surfaces of these are generally barren, but other karstic features are common (Fig. 3.6).

3.2.1.2 Karren (Lapies)

These are the most characteristic features of calcareous surfaces. This feature is seen in many parts of the area. The limestone pavements are cut by vertical joints and fissures and along these surfaces, elongated channels called karren (Fig.3.6,3.7,3.9) are formed. These are considered to be developed by differential solution process (Herak and Stringfield, 1972).

3.2.1.3 Grike

Vertical carving is called a grike. This is seen at the surface of the outcrops where vertical joints are absent. The

FIG.3.6 LIMESTONE PAVEMENT AND KARREN, IN THE LITHOFACIES II B OF THE MILIOLITE FORMATION. LOCALITY: LOHEJ.

FIG.3.7 KARREN IN THE MILIOLITE FORMATION (LITHOFACIES III) LOCALITY: RAHIJ.

FIG. 3.6

FIG. 3.7

diameter of these varies from 2 cm to 15 or 20 cm. In well sections and drill cuttings, this feature is very commonly seen (Fig.3.8). In many places, they occur as shallow dish like depressions and they are called as "Kamenica" (Roglic,1972).

3.2.1.4 Clint

Horizontal carving is designated as a clint. This is also seen in many places where the rocks are compact and hard. Sometimes when alternate laminae of hard and relatively soft material are present, the softer part is generally removed by solution and they show a cellular structure (Fig. 3.10, 3.11). In borehole samples when the rock is hard and compact, horizontal solution cavities having small diameters representing clint features are common.

3.2.1.5 Doline

'Doline' is a Serbian word meaning a little dole or valley. It is commonly used as the equivalent of sink hole in karst areas. According to Monroe (1970, in Stringfield, Rapp, and Anders, 1979), 'doline' is a basin or funnel-shaped hollow in limestone, ranging in diameter from a few to several hundred metres. He divided dolines into two groups viz. solution dolines and collapse dolines.

In the present area under investigation dolines are not common. One such doline having a diameter of about 35 m is seen near the village Makhtupur. It seems to have been formed by the solution of the carbonate rocks. The walls of this are not very steep.

FIG.3.8 GRIKES IN LITHOFACIES III OF THE MILIOLITE FORMATION. LOCALITY: RAHIJ.

FIG.3.9 KARREN AND DEVELOPMENT OF CLINT IN LITHOFACIES III OF THE MILIOLITE FORMATION. LOCALITY: RAHIJ.

FIG. 3.8

FIG. 3.9

FIG.3.10 DEVELOPMENT OF CLINT IN LITHOFACIES III OF THE MILIOLITE FORMATION ALONG BEDDING- PLANES. LOCALITY: SEPA.

FIG.3.11 HONEYCOMB LIKE STRUCTURE FORMED BY SOLUTION OF LIMESTONE (LITHOFACIES III). LOCALITY: NEAR BUDECHA.

FIG. 3.10

FIG. 3.11

3.2.1.6 Caves

Caves are generally horizontal passages. Drill hole data of the region indicate that cavities are present from 0.50 m above mean sea level (msl) to 18 m below sea level. Near the village Husainabad, in a well cutting, a big cavity having diameter of about 1.5 m is seen. Another smaller one is present near Mangrol towards Bandar. The caves present below sea level might have been formed when the sea-level was much lower than the present day level and these might have been submerged below the water table later.

3.3 GEOLOGY

3.3.1. Introduction

Geologically, the area consists of Daccan Trap basalts which form the basement, over which lies unconformably the rocks belonging to the Nageshri Group of Tertiary age,i.e.,the Gaj Formation and Dwarka Formation which are in turn overlain by the Porbandar Group of Quaternary age (Fig. 3.12). The youngest rocks are the Recent beach sands, sand dunes and freshwater alluvium. In the present investigations, because of the absence of any outcrops, Deccan Trap basalts have not been studied.

3.3.2 Lithostratigraphic classification

Based on the study of vertical sections from different places (Fig. 3.13) in Chorwad-Madhavpur area, the following lithostratigraphic succession (Table 3.1) has been proposed. Latest nomenclature of various lithostratigraphic units as proposed

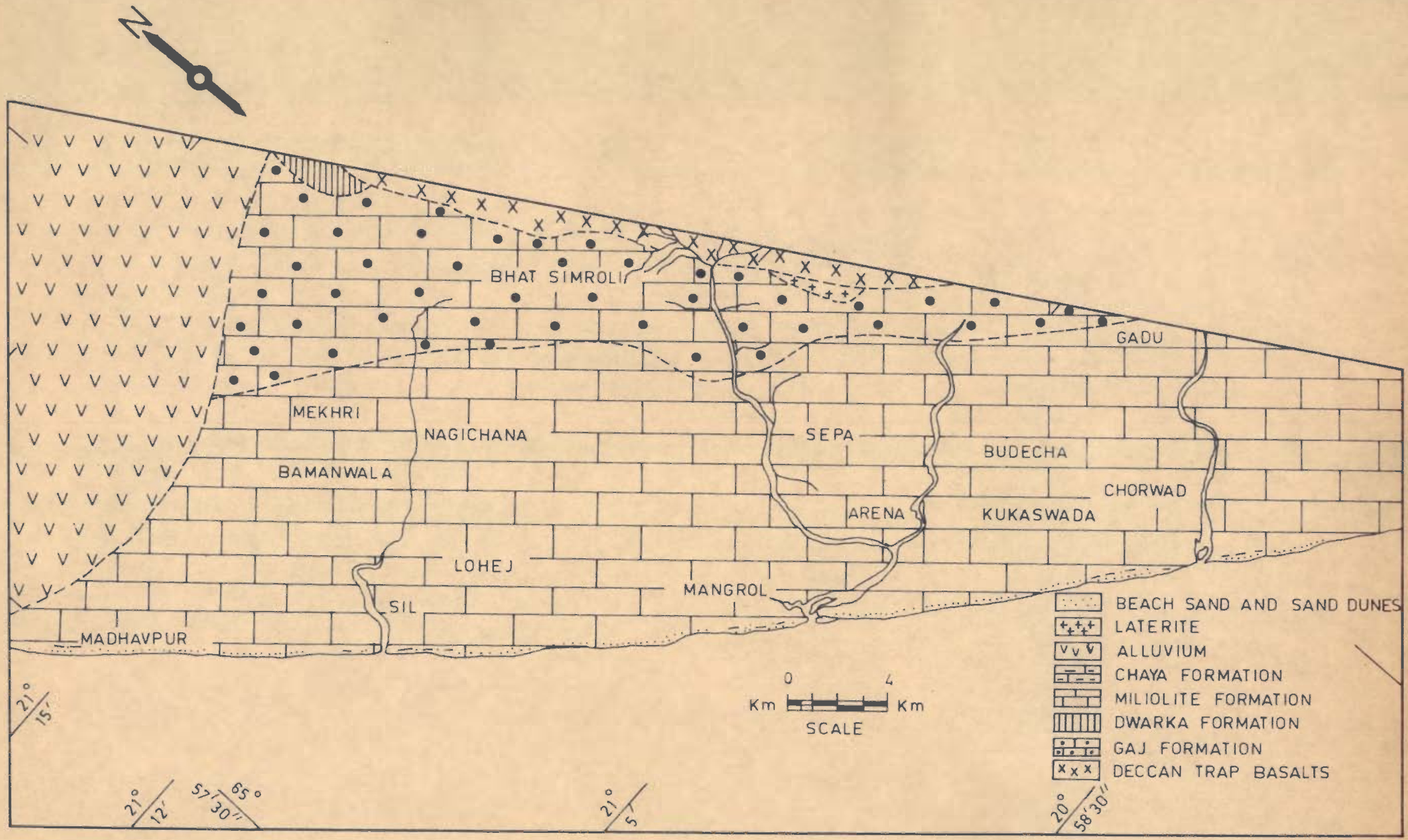


FIG. 3.12 _ GEOLOGICAL MAP OF CHORWAD - MADHAVPUR AREA .

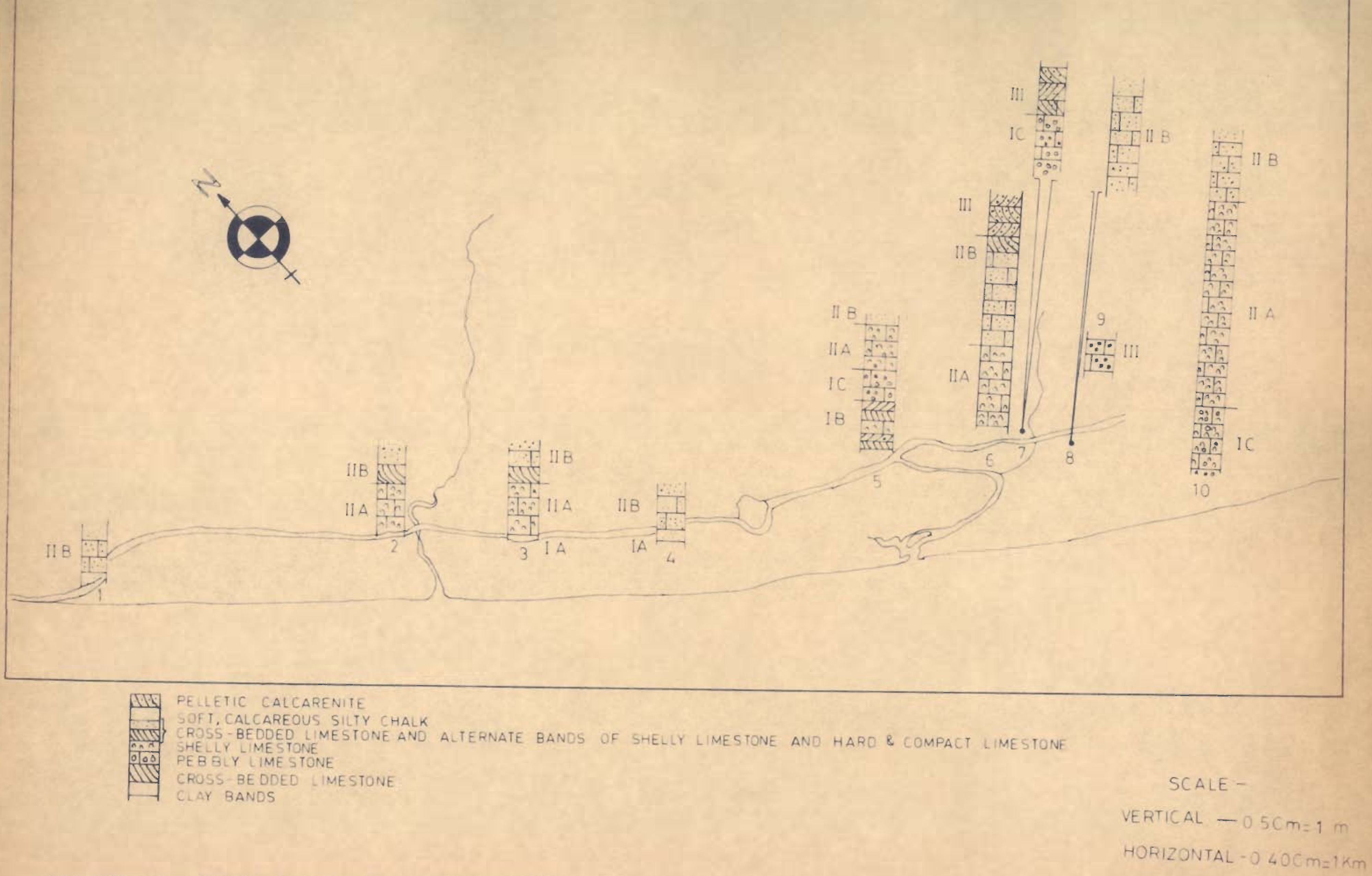


FIG. 3.13 _ VERTICAL SECTIONS AT DIFFERENT LOCATIONS BASED ON OUTCROP STUDIES (SECTIONS 1-9) AND BORE HOLE DATA (SECTION 10)

Table 3.1: Lithostratigraphic Succession of Chorwad-Madhavpur Area

Stratigraphic Unit			Lithology	Age
Recent Deposits			Beach sands, coastal sand dunes, mud flats, and fresh water alluvium	Holocene
PORBANDAR GROUP	Chaya Formation		Semiconsolidated to consolidated limestones (Calcirudites); shell limestones, coral reefs and oyster beds.	Holocene to Mid-Pleistocene
	Miliolite Formation	Lithofacies III	Pelletic limestones (Calcarenites)	
			Unconformity	
		Lithofacies III	C Relatively soft, calcareous, silty, chalk (Micrite) B Cross-bedded limestone and alternate bands of shelly and vuggy limestone and fine grained compact limestone A Shell limestone	
		Lithofacies I	C Pebbly limestone B Crossbedded compact limestone A Clay bands	
			OVERLAP	
NAGESHRI GROUP	Dwarka Formation		Flaggy arenaceous limestones interbedded with calcareous clays	(?)Mio-Pliocene
	Gaj Formation		Hard, compact, yellowish limestones with abundant fossils and interbedded with calcareous clays	Lower Miocene
			EROSIONAL UNCONFORMITY	
Deccan Trap			Laterite and Basalt	Upper Cretaceous to Lower Eocene

by Mathur (1978) and Verma (1979) has been adopted in the present study. The Miliolite Formation of Mathur (1978) and Verma (1979) have been subdivided into three lithofacies, i.e., Lithofacies I, II and III..

3.3.3 Nageshri Group

3.3.3.1 General Aspects

The rocks of Nageshri Group overlying the Deccan Trap, are present along the northern parts of the area. The outcrops are, however, discontinuous, being at places covered by the Quaternary sediments.

The Nageshri Group of sediments in the present area under investigation, belong to two formations, viz. the lower Gaj Formation and the upper Dwarka Formation. The latter was not reported previously from this area. These formations run parallel to the present coastline. Verma (1979) had included these two Formations under a new group, called Nageshri Group, after the town of Nageshri.

3.3.3.2 Gaj Formation

The Deccan Trap basalts are overlain with an erosional unconformity by the Gaj Formation. In the area under investigation the exposures are very few and the outcrops occur as detached patches. Good sections of this formation are available for observation in dug wells. It is difficult to get an idea of variations in lithology and thickness because of the absence of any deep cut river or <u>nala</u> section. The formation can be traced almost continuously from east to west. Generally it occupies a very narrow belt. The Gaj Formation consists mainly of limestones in the older and alternate bands of clays and limestones in the younger horizons. The limestone is exposed near its contact with the Deccan trap, while the calcareous clays are exposed south of it forming almost flat barren terrain. Drill hole data indicates that the Gaj Formation is nearly 300 m thick near the coast. Outcrops of limestone can be seen near the village Bhat Simroli and Budecha in Langdi river cutting. Exposures of clays can be seen near to the village Vallabhgadh. The beds are practically horizontal. About 2 km from Char towards khamidana they are resting on laterite.

3.3.3.2.1 Lithology

Litholgically, the Gaj Formation consists mainly of alternating beds of pale yellow to deep ochrous limestones and yellow or grey calcareous clays. The limestones are highly fossiliferous and contain molluscs, echinoderms, bryozoans and foraminifers. They are sometimes thickly bedded and hard, compact and massive. Sometimes the clays show mud cracks (Fig.3.14) when they are exposed to the atmosphere. The grey shales are not exposed on the surface. In the area under study the grey shale was found in some freshly dug wells. X-ray diffraction study of the yellow clay indicates that the clay minerals present are montmorillonite, illite, and chlorite (Fig.3.17).

3.3.3.3 Dwarka Formation

3.3.3.3.1 General aspects

In the area under investigation Dwarka Formation was not reported earlier. During present investigations it was seen near Khamidana and Panchala villages. In Khamidana it occurs as a small ridge (Fig.3.15). The beds are generally horizontal but at the village Khamidana they show folding which might be due to the slumping of intervening clay bands (Fig. 3.16).

3.3.3.3.2 Lithology

Lithologically the Dwarka Formation consists of thinly laminated highly flaggy, arenaceous limestones interbedded with clays. Thickly bedded hard, compact, massive, yellowish limestone is also present. The laminations are horizontal, as well as wavy. In Khamidana, at the base of the exposure, small scale depressions having a diameter of 0.2 to 0.3 cm and a depth of 0.1 cm are seen along the bedding planes. These resemble rain prints. These are at times filled by brownish chocolate coloured iron oxide in the form of small dots. Here three bands of chert are seen which show, small scale folding.

The limestones contain lot of broken shell fragments. Some lamellibrachs and brachiopods are also present, but their characteristic features have been obliterated by recrystallisation. Some amount of rounded to subrounded quartz grains are also present. The clays associated with Dwarka limestones are highly arenaceous in nature.

FIG.3.14 MUD CRACKS IN CLAYS BELONGING TO THE GAJ FORMATION. LOCALITY: NEAR VALLABHGADH.

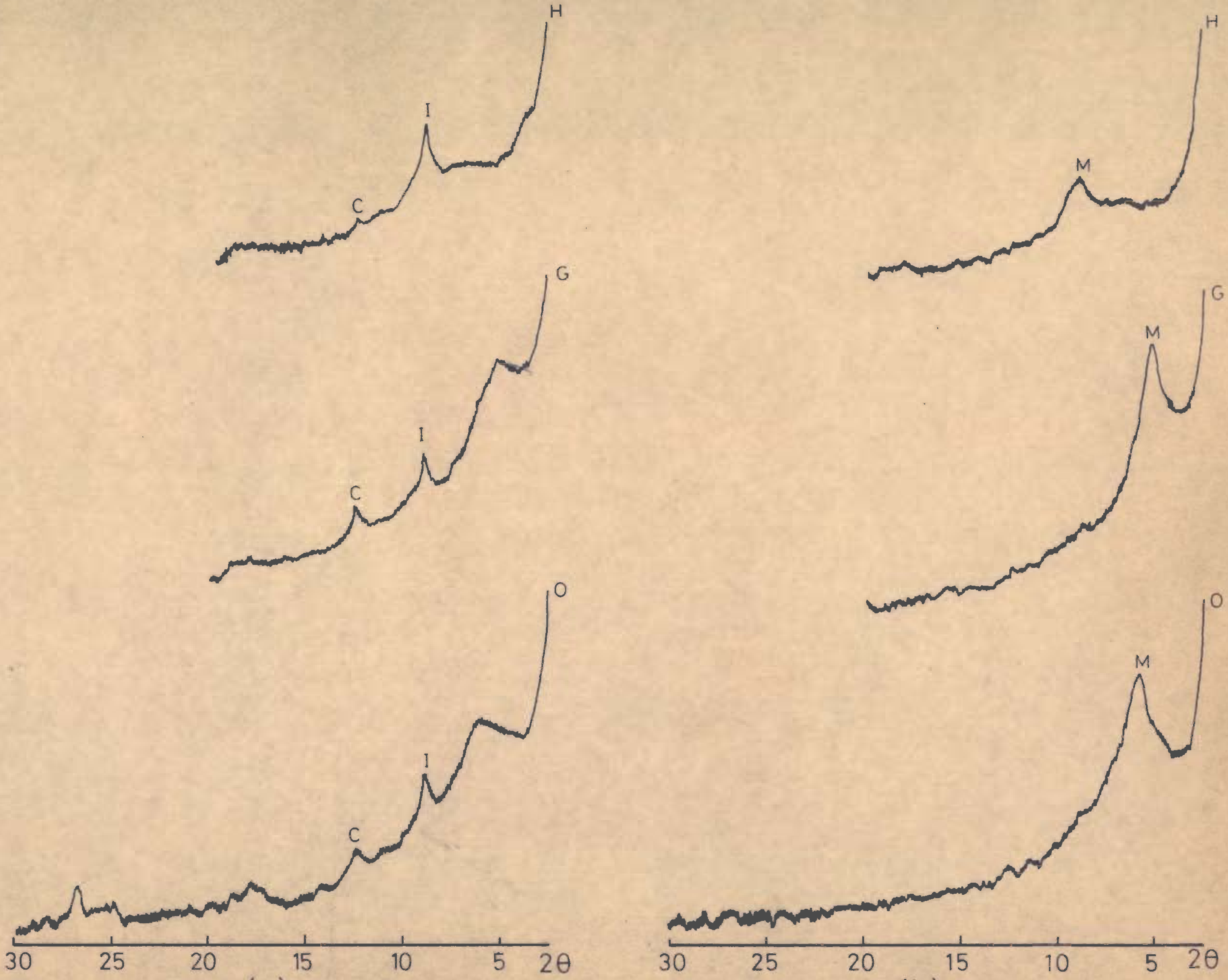
FIG.3.15 EXPOSURE OF DWARKA FORMATION. BANDS OF LIMESTONE AND CLAY CAN BE SEEN. LOCALITY: KHAMIDANA.

FIG. 3.16 FOLDING DUE TO SLUMPING BY REMOVAL OF CLAY MATERIAL IN THE DWARKA FORMATION. LOCALITY: KHAMIDANA.

FIG. 3.14

FIG. 3.15

FIG. 3.16



(a) (b)

FIG.3.17_X-RAY DIFFRACTION PATTERNS OF CLAY MINERALS FROM GAJ FORMATION

C-Chlorite; I-Illite; M-Montmorillonite; O-Ordinary; G -Glycolated; H-Heated.

3.3.4 Porbandar Group

The Nageshri Group of rocks are overlain by the consolidated and semi-consolidated carbonate sediments belonging to the Porbandar Group. The two divisions of this Group, i.e., the Miliolite Formation and the Chaya Formation are recognised in the area.

3.3.4.1 Miliolite Formation

The term 'Miliolite' or 'Miliolite limestone' was used previously to include all the consolidated and semiconsolidated carbonate deposits of Post-Tertiary age of Saurashtra. Mathur and Mehra (1975) used the term Miliolite Formation in a restricted sense to include only the calcarenites and the associated micrites which are devoid of mega fossils. These are underlain by the older rock formations viz. the Deccan Trap, Gaj and Dwarka Formations. Mathur and Mehra (1975) and Mathur et al. (1976) further subdivided the Miliolite Formation into two viz. Dhobalia Talav Member and Adatiana Member. Adatiana Member is characterised by pelletoid calcarenites whereas Dhobalia Talav Member is an interbedded sequence of calcarenites and micrites. In the present area understudy, it was found difficult to recognize the subdivisions of the Miliolite Formation. Hence the Miliolite formation has been divided into three lithofacies I, II and III as described in section 3.3.2.

A large part of the coastal region is occupied by these limestones. They occur from the sea coast to 10 to 15 km inland. The limestone is white, dirty white, or pale brown in colour, quite often showing vuggy nature when it is composed more of shells and is less compact. The thickness of the Miliolite Formation is not uniform throughout. It ranges from a couple of metres to about 40 m in the area under investigation. The maximum exposed thickness is seen to be 10 m near Sepa.

3.3.4.2 Lithofacies

As discussed previously, the Miliolite Formation has been subdivided into three lithofacies, i.e., lithofacies I, lithofacies II and lithofacies III. Lithofacies I and lithofacies II are again subdivided into three sub-units.

3.3.4.2.1 Lithofacies I A

This represents thin clay bands ranging in thickness from 1.5 to 3.0 cm. They are reddish brown in colour and highly calcareous in nature which occur at the bottom of the exposures near Makhtumpur. It seems to have been deposited in lagoonal environment.

3.3.4.2.2 Lithofacies IB

The lithofacies IB is a cross-bedded limestone (Fig.3.18) sometimes containing large pebbles having a maximum size of 3 cm. Smaller pebbels of 1 cm in diameter are also not uncommon. The pebbles are of Gaj limestone. The thickness of the facies is 1 m and this is well exposed in the Noli River section. Planar cross-beds are seen which show variable palaeocurrent directions. The thickness of foresets laminations varies from 0.5 to 2.5 cm. The contact between laminations are sharp. The grains seem to be fused together.

FIG.3.18 CROSS-BEDDED LIMESTONE BELONGING TO LITHOFACIES IB, OVERLAIN BY FLAT BEDDED LIMESTONE OF LITHOFACIES IC. LOCALITY: NOLI RIVER SECTION.

FIG. 3.18

3.3.4.2.3 Lithofacies IC

This overlies the lithofacies I B and the contact between them is erosional in nature. This lithofacies is a pebbly and shelly limestone. From the bottom to near top, of the lithofacies the size of the pebbles increase and the maximum size seen is 8 cm. Again the size of the pebbles decreases towards the top, but the limestone becomes more vuggy, sometimes showing thin laminations. The larger pebbels present are sometimes distributed randomly. The pebbels are mostly of Gaj limestones and clays. Some quartz pebbels are also noticed. The size of shells also varies. The thickness of this facies varies from 3 m to 6 m and is exposed in Noli river section, Langdi river section near Langodra, and at Arena and is also met within the borehole near Chorwad.

3.3.4.2.3.1 Petrography

Thin section and modal analysis studies of the different facies belonging to Miliolite Formation, collected from different vertical sections have bean done. The rocks have been named using Folk's (1962) textural classification.

Early workers (Carter,1849; Fedden, 1884; and Foote,1898) described the limestones belonging to the Miliolite Formation as composed mainly of oolitic grains. Among recent workers Srivastava (1968a) described six different varieties of limestones from the the Miliolite Formation viz. biopelsparite, pelsparite, biosparite, biosparrudite, intrasparrudite, and micrite. In this "Formation" he had included rocks beloging to the newly classified Miliolite Formation and Chaya Formation. Later workers (Mathur and Mehra,1975; Mathur et al., 1976; Mathur, 1978; Verma,1979 and others) described that the most common rock type of Miliolite Formation is pelletoid calcarenite consisting essentially of sand sized pellets with very minor amounts of oolites.

Petrographic study indicates that lithofacies I B and C are biocalcarenites and calcirudites consisting essentially of shells and shell fragments with varying amounts of fossils, and sometimes containing pellets, oolites, superficial oolites, quartz grains and intraclasts (Fig.3.19). Near the village Langodra, the rocks contain pellets which are less than 50% of the allochems present. Generally along the borders of shells a thin micrite envelope is seen (Fig. 3.21, 3.22, 3.23). The grains are cemented together either by sparry calcite or by micrite. The word cement is used here after Bathurst (1975) "for all passively precipitated space filling carbonate crystals which grow attached to a free surface". Both intergranular and intragranular cement is noticed. The shells contain sparry calcite as well as micrite. In many cases fibrous calcite is also seen (Fig. 3.20). Sparry calcite occurs as cement in inter and intragranular spaces and also as neomorphic grains. It is very difficult to differentiate sparry calcite cement and neomorphic grains. In order to distinguish the sparry calcite cement, and the neomorphic spar, the criteria described by Bathurst (1975, p.417-419 and 484-493) have been followed. Wherever the shells contain sparry calcite cement, the size of these crystals increases away from the walls towards the centre (Fig.3.21). Similar is the case with intergranular cement. Sometimes the longest axes of the crystals are seen perpendicular to the shell walls. Occasionally, two generations of cement can be seen.

FIG.3.19 BIOCALCARENITE FROM THE LITHOFACIES IC CONTAINING SHELLS, FOSSILS AND PELLETS. LOCALITY: NEAR LANGODRA.

FIG.3.20 SHELL CONTAINING FIBROUS CALCITE IN LITHOFACIES IC. LOCALITY; CHORWAD.

FIG.3.21 SHELL FILLED WITH CALCITE CEMENT. SIZE OF CALCITE CRYSTALS INCREASES AWAY FROM THE WALLS. MICRITE ENVELOPE IS ALSO SEEN. LITHOFACIES IC. LOCALITY: CHORWAD.

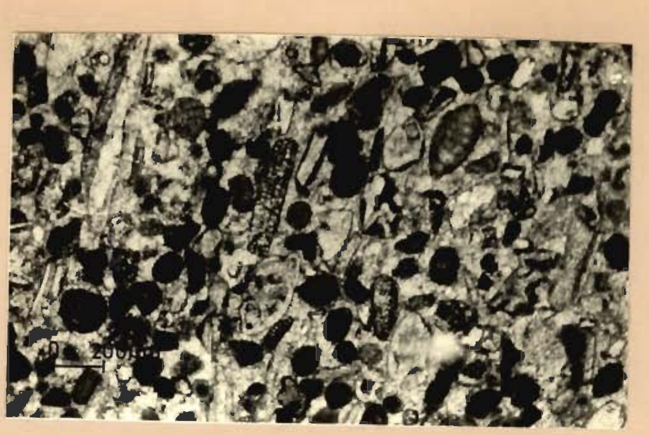


FIG. 3.19

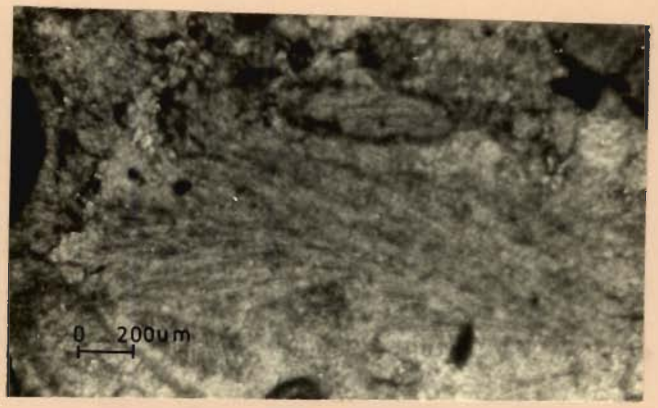


FIG. 3.20

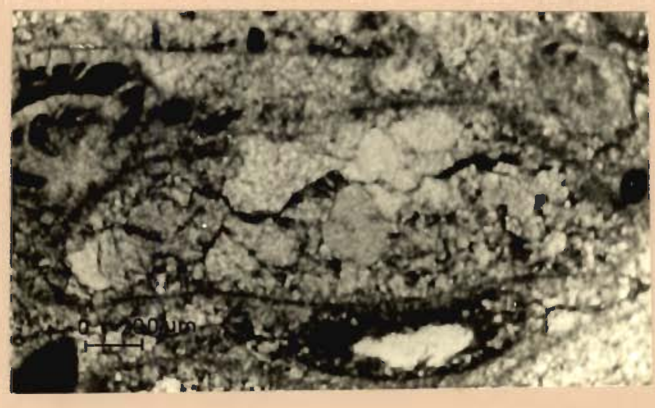


FIG. 3.21

In such cases, isopachous scalenohedral calcite cement is present inside the grains (shells) and equigranular calcite cement overlies this.

Neomorphic grains are common. At times they occur as granular mosaic, but the inter crystalline boundaries are not regular. Neomorphic spar is common in intergranular and intragranular spaces. In the shell fragments, sometimes relics of micrite surrounded by spar, i.e., floating relics and original shell structures are partly visible (Fig.3.22). Floating relics of micrite can also been se[illegible] in neomorphic spar (Fig. 3.23).

Syntaxial rims are common around fossils (Fig. 3.24, 3.25). At times, because of recrystallisation, it is very difficult to distinguish different shell fragments, as the sparry calcite occurs as a mosaic. However, the outlines of these are generally preserved with thin micrite envelopes as is noticed on examination (Fig. 3.26). The outlines of former shells is at places indicated by the strings of dust like particles. Sometimes it becomes difficult to distinguish between replaced shells and sparry calcite cement because of the poor preservation of shell outlines.

Fossils are numerous. The walls are generally filled with micrite and the chambers either with micrite (Fig. 3.27) or with sparrite. Sometimes a coating of ferrugenous material can be seen along the borders (Fig. 3.27). Syntaxial rim is common. Pellets are generally few in number, but at the village Langodra the percentage of pellets is high, still it never exceeds 50% of the allochems. The ratio of pellets to fossils varies from

FIG. 3.22 AN EYE-SHAPED PATCH OF MICRITE IS SEEN SURROUNDED BY SPARRY CALCITE INSIDE A SHELL INDICATING NEOMORPHISM. IT FORMS A FLOATING RELICT. LITHOFACIES IC. LOCALITY: CHORWAD.

FIG. 3.23 FLOATING RELICS. MICRO CRYSTALLINE CALCITE IS SURROUNDED BY SPAR IN THE INTRAGRANULAR SPACE. SHELL FRAGMENT ALSO CONTAINS NEOMORPHIC SPAR. MICRITE ENVELOPE SURROUNDING THE SHELL IS PRESENT. LITHOFACIES IC. LOCALITY: CHORWAD.

FIG. 3.24 SYNTAXIAL RIM AROUND A FOSSIL. LITHOFACIES IC, LOCALITY: CHORWAD.

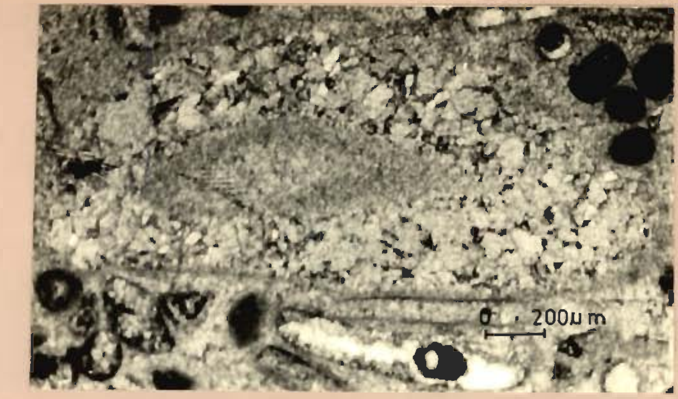


FIG. 3.22

FIG. 3.23

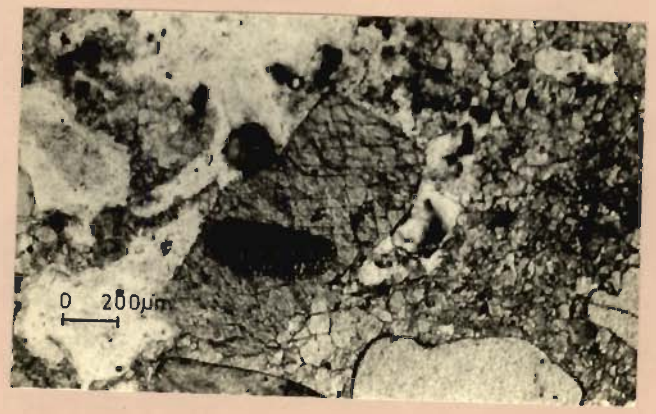


FIG. 3.24

FIG.3.25 SYNTAXIAL RIM AROUND A FOSSIL IN LITHOFACIES IB. LOCALITY: NOLI RIVER SECTION.

FIG.3.26 MOSAIC OF ELONGATED CALCITE SPARS FORMED BY RECRYSTALLISATION. THIN LINES SEPARATING THE CASTS OF SHELLS ARE POSSIBLY MICRITE ENVELOPES. LITHOFACIES IC, LOCALITY: CHORWAD.

FIG.3.27 FORAMINIFERAL WALLS AND CHAMBERS FILLED WITH MICRITE - POSSIBLY A SUB-MARINE CEMENT. LITHOFACIES IC. LOCALITY: CHORWAD.

FIG. 3.25

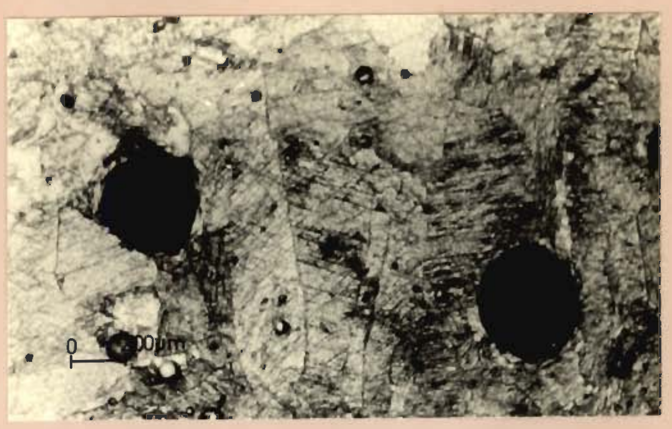


FIG. 3.26

FIG. 3.27

0·10:1 to 0·82:1. Neomorphism of pellets is common (Fig.3.28,3.29). It can be seen that the pellets are being transformed to microspar as is evidenced by the presence of relicts of micrite within microspar. In many cases the rounded outlines of pellets are lost and patches of micrite were seen among microspar giving rise to the grumeleuse structure (Fig.3.29). In one case a fossil in the form of pellet can easily be distinguished.

Oolites and superficial oolites are present, but their percentage is very small. Superficial oolite is a type of oolite in which the thickness of the accretionary coating is less than the radius of the nucleus. Recrystallisation of oolites and superficial oolites is very common (Fig. 3.30, 3.31). In recrystallised ones, original concentric layers can be made out, even though they contain sparry-calcite. Partly recrystallised oolite is also present (Fig. 3.32).

Quartz grains occur in sub-angular to sub-rounded form. Some intraclasts are also present, but they are in negligible quantities. Lithoclasts of Gaj limestone which are sub-rounded in form are also present (Fig. 3.33).

3.3.4.2.4 Lithofacies II A

Lithofacies II A consists of white to cream coloured, porous, and vuggy limestone containing essentially of shells and fossils, occurring above the pebbly limestone. Sometimes they show a brownish colour, especially when they are exposed. They are flat bedded and the thickness varies from 2 to 15 m. Vertical variations in the size of the shell fragments can be seen, but without any

FIG.3.28 NEOMORPHISM OF PELLET. INSIDE OF THE PELLET IS FILLED WITH NEOMORPHIC SPARS WHICH IS SYNTAXIAL WITH THE ADJACENT CEMENT. LITHOFACIES IC. LOCALITY: NEAR LANGODRA.

FIG.3.29 CLOTTED STRUCTURE (GRUMELEUSE STRUCTURE). THE CLOTS SEEM: TO BE RECRYSTALLISED PELOIDS SURROUNDED BY MICROSPARS. LITHOFACIES IB. LOCALITY: NOLI RIVER SECTION.

FIG.3.30 RECRYSTALLISED OOLITE. COARSE CALCITE SPARS AT THE CENTRE AND ROUGH CONCENTRIC RINGS ARE DISCERNIBLE TOWARDS THE BOUNDARY. LITHOFACIES IC. LOCALITY: CHORWAD.

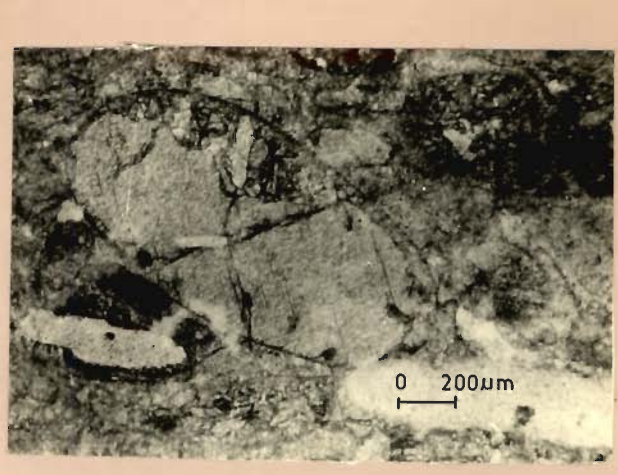


FIG. 3.28

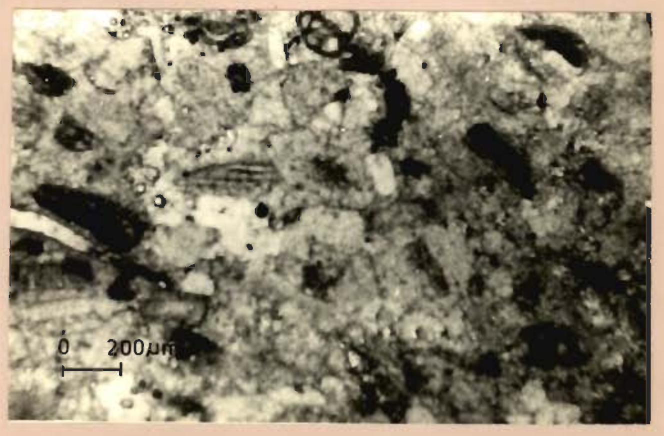


FIG. 3.29

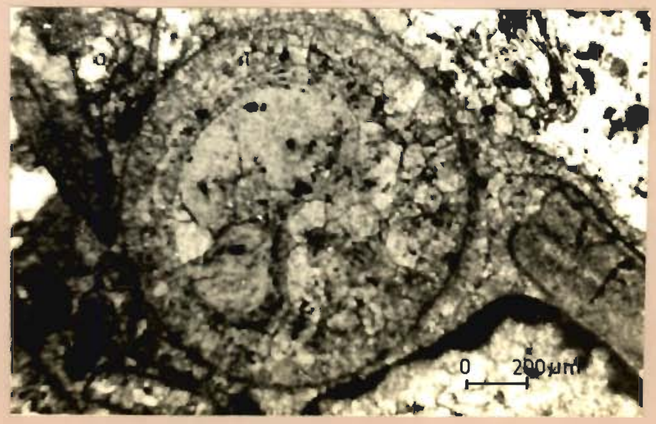


FIG. 3.30

FIG.3.31 RECYRSTALLISED SUPERFICIAL OOLITES. OOLITIC COATING OF THE TWO GRAINS TOGETHER IS VISIBLE TOWARDS LEFT. LITHOFACIES IC. LOCALITY: NEAR LANGODRA.

FIG.3.32 PARTLY NEOMORPHOSED OOLITE. NEOMORPHISM HAS TAKEN PLACE TOWARDS THE CENTRE OF THE GRAIN. LOCALITY: CHORWAD.

FIG.3.33 LITHOCLASTS OF THE GAJ LIMESTONE. LITHOFACIES IC. LOCALITY: NEAR LANGODRA.

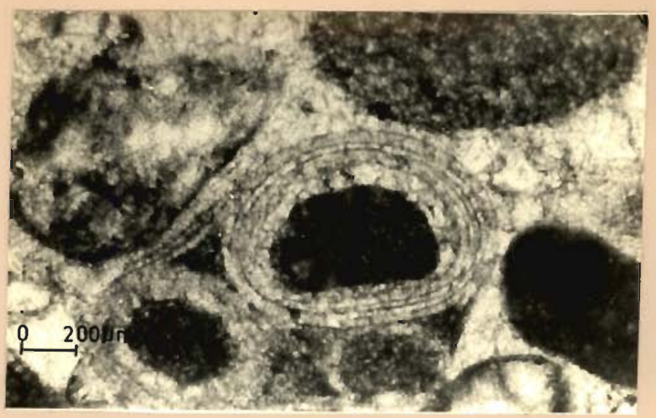


FIG. 3.31

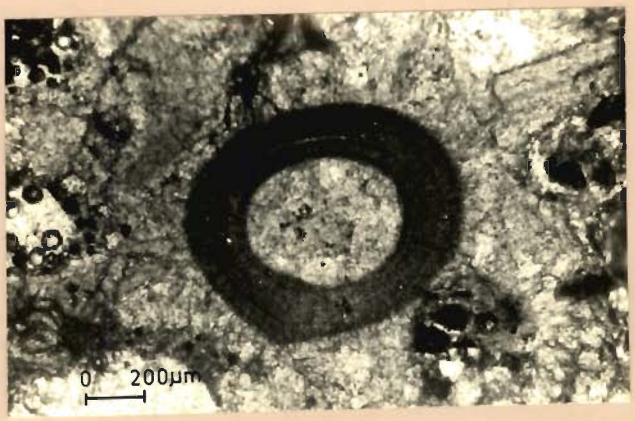


FIG. 3.32

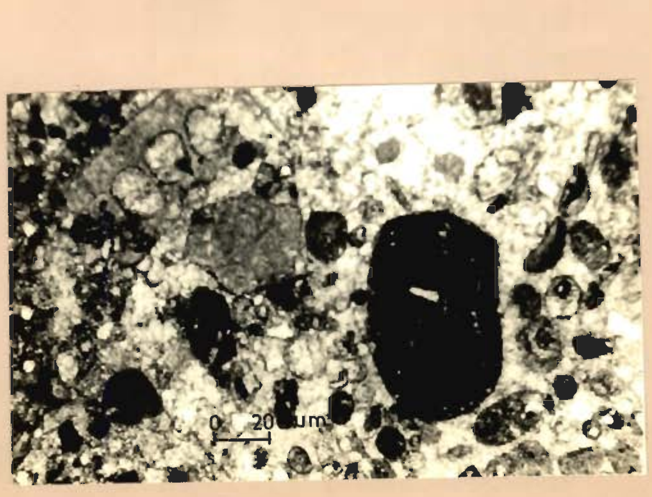


FIG. 3.33

regularity. Occasionally they contain big shell fragments. The limestone is generally vuggy and both bigger and finer vugs are visible in vertical sections in quarries and also in the core samples. Numerous solution channels (grikes) can be seen in these rocks ranging in diameter from 1.5 cm to 5 cm extending in length from 6 to 20 cm. In the zones where the vugs are big, solution cavities are rare or absent, but when the vugs are small, the frequency of solution cavities are more. The solution cavities are more pronounced when the rock is compact and the shell fragments are smaller in size. No fillings are seen in these cavities. This lithofacies is exposed at Sil, Lohej, and Arena villages and is also encountered in the borehole near Chorwad.

3.3.4.2.5 Lithofacies II B

Lithofacies II B is a dirty white to brownish coloured rock consisting almost wholly of shells. They occur either as cross-bedded limestone or as alternate bands of shelly and vuggy limestone and fine grained compact limestones. The cross-bedding is of herringbone type (Fig. 3.34). The cross-bedded portion resembles in their shell content and physical properties the lithofacies II A. The maximum thickness of this cross-bedded portion is seen to be 1.5 m in a quarry at Sil (Fig.3.34). The dips of the cross-bedding is more (15° towards south) than that seen in the lithofacies I B. Sometimes torrential cross-bedding is also noticed. These structures comprise sets of uniformly dipping strata bound above and below by essentially horizontal planes. The dips of

FIG.3.34 HERINGBONE TYPE CROSS-BEDDING IN LITHOFACIES II B OF THE MIOLITE FORMATION. LOCALITY: SIL.

FIG. 3.34

the cross-strata range from 18° to 28°. This type of cross-stratification was observed in well cuttings near Kankasa and Mukhtupur. No solution channels have been noticed in this lithofacies.

When there are alternate bands of shelly and vuggy limestone and fine-grained compact limestones, they show rough laminations. The thickness of these bands varies from 0.5 to 2 cm. These are exposed in quarries near the villages Sil, Arena,Lohej, Sepa, and Madhavpur, and are also met with in bore hole near Chorwad and also as outcrops at various places. In Sepa, Arena, near Budecha and near Langodra, these rocks occur directly below the mounds belonging to the lithofacies III. They are horizontally bedded, but in surface outcrops they show dips in varying directions ranging from 18° to 22°, in many localities. These seem to be local phenomena and might have resulted because of the removal of underlying material by solution activity.

3.3.4.2.5.1 Petrography

Petrographically, the rocks of lithofacies II A and B are biocalcarenites and calcirudites consisting mainly of shells and shell fragments with fossils, numerous sub-angular quartz grains and a few pellets. Some amount of intraclasts, occasionally oolites and superficial oolites are also present. These are cemented together either by sparry calcite or micrite. The shells contain sparry calcite, micrite (Fig. 3.35) as well as fibrous calcite. Most of the sparry calcite is of neomorphic origin (Fig. 3.36). In the case of sparry calcite cement, coarsening of crystals away from the shell walls is common. Sometimes two generations of cement can be seen. In these, the early formed ones are scalenohedral in habit (Fig. 3.37; 3.38). In a couple of cases meniscus cement is present. Neomorphic spar is common in intergranular and intragranular spaces (Fig.3.40).

Syntaxial rims are seen around fossils and at times around grains (Fig. 3.39). In some shell fragments some of the sparry calcite crystals in the wall are syntaxial with the adjacent cement crystals. The neomorphic features are similar as in the case of lithofacies I A and I B. Neomorphism of shell fragments produces a granular mosaic, but a thin envelope of micrite indicates the outlines of the shells. Eventhough the micrite envelope is not seen in some cases, patches of microspar with greenish yellow colour surrounded by almost isotropic portions are visible. These seem to be produced by the neomorphism of the micrite envelope.

The amount of fossils present vary considerably. The chambers are filled either with microspar or with micrite. Ferrugenous coating along the borders and as infillings in chambers is also not uncommon. Sometimes ferrugenous matter is seen distributed randomly.

Pellets are present, but they are not numerous and ranges from 0 to 2.5% of total allochmes present. Pellets were thought to be of fecal in origin, but now it is recognised that many of them are skeletal particles that have been replaced by micrite (Bathurst, 1975). In the present case pellets can be seen forming around fossils (Fig. 3.41). Some pellets are seen to be changing to microspar. In such cases they have a greenish yellow colour.

FIG.3.35 BIOCALCARENITE BELONGING TO LITHOFACIES IIB. NOTE THE MICRITE FILLING INSIDE THE SHELL AND ALSO THE MICRITE ENVELOPE. IN THE FOSSIL AT THE TOP MIDDLE PORTION FERRUGINOUS INFILLING CAN BE SEEN. LOCALITY: CHORWAD.

FIG.3.36 NEOMORPHIC SPAR INSIDE SHELL FRAGMENTS. THE MICRITIC ENVELOPE IS THICK. LITHOFACIES IIB LOCALITY: CHORWAD.

FIG.3.37 TWO GENERATIONS OF INTRAGRANULAR CEMENT, THE EARLY FORMED ONES ARE SCALENOHEDRAL IN HABIT WHEREAS THE LATER FORMED ONES ARE EQUANT CRYSTALS. LITHOFACIES IIB, LOCALITY: CHORWAD.

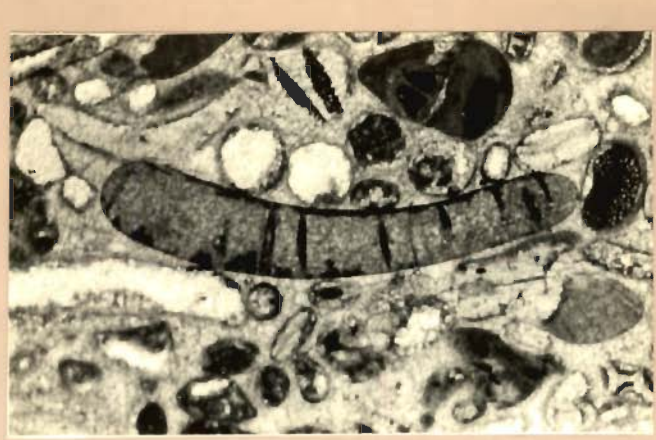


FIG. 3.35

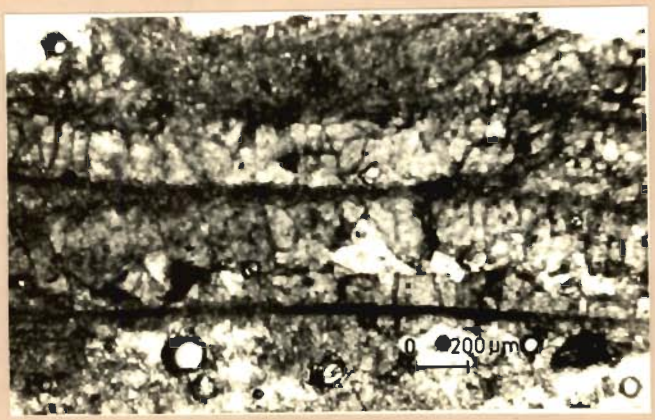


FIG. 3.36

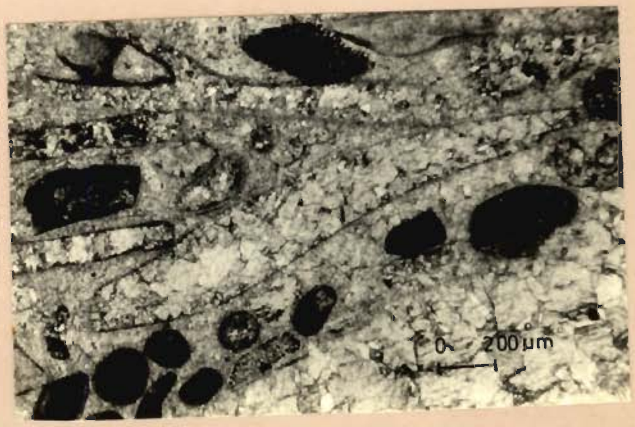


FIG. 3.37

FIG.3.38 SCALENOHEDRAL CEMENT INSIDE A GRAIN. LITHOFACIES IIB. LOCALITY: CHORWAD.

FIG.3.39 SYNTAXIAL RIM AROUND A GRAIN. NOTE THE CLOUDY APPEARANCE. LITHOFACIES IIA. LOCALITY: CHORWAD.

FIG.3.40 NEOMORPHIC SPARS IN INTERGRANULAR AND INTRAGRANULAR SPACES. LITHOFACIES IIB. LOCALITY: CHORWAD.

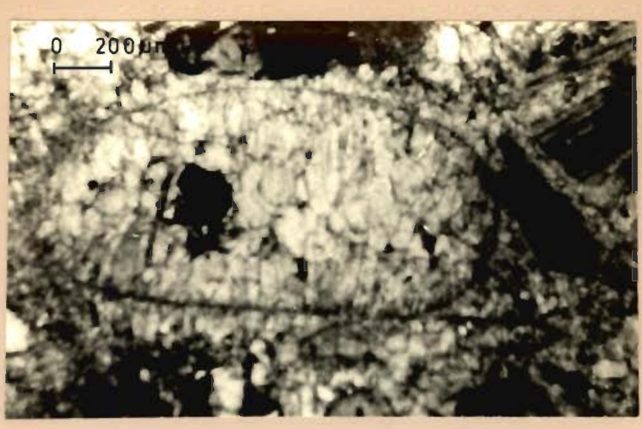


FIG. 3.38

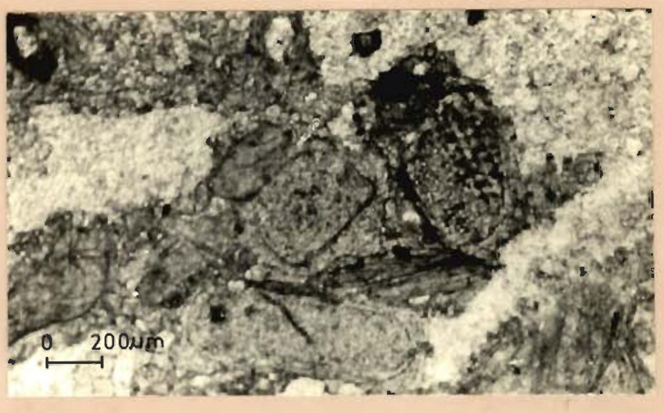


FIG. 3.39

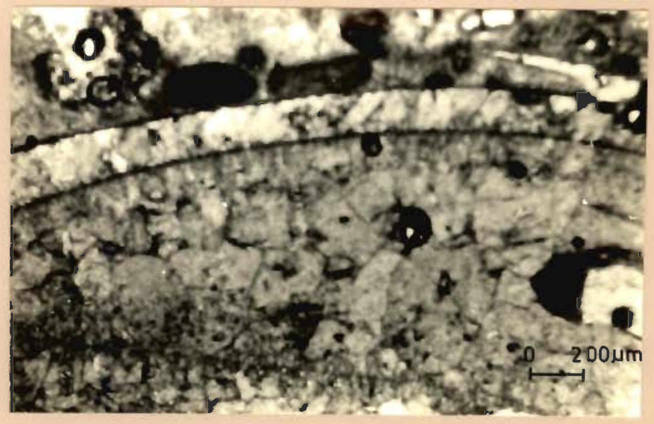


FIG. 3.40

Few oolites and superficial oolites (Fig. 3.42) have been noticed. Recrystallisation of oolite is common. In such cases concentric rings can be made out with difficulty (Fig. 3.43).

Quartz occur in minor amounts in the form of sub-angular to sub-rounded grains (Fig. 3.43). Epidote and felspar grains are present, but occur very rarely. Intraclasts are common (Fig.3.44) and sometimes contain pellets and fossils. Yellow coloured argillaceous material is present in some cases. Few basalt (trap) rock fragments are also noticed (Fig. 3.45).

X-ray analysis shows that montmorillonite, kaolinite, illite, and chlorite are present (Fig.3.46) in different lithofacies of the Miliolite Formation.

3.3.4.2.6 Lithofacies IIC

This lithofacies consists of moderately soft, calcareous, silty chalk (micrite) deposits. Not much attention has been paid to this facies by various workers on Miliolite Formation. The limestones are dirty white to light brownish coloured microcrystalline calcite occurring near to the surface and are overlain by the calcarenites. Sometimes the rocks of this lithofacies grade in to the overlying alluvium at the top. Generally they contain small nodules, probably concretions (Kankar). The maximum exposed thickness of this lithofacies is 3 m near Mangrol Bandar. Here at the bottom, it is very soft and without much nodules. Nowhere in the area the base of the lithofacies is seen and these rocks are observed only where new pits

FIG.3.41 FORMATION OF A PELLET AROUND A FOSSIL (SEEN AT THE CENTRE OF THE FIGURE). LITHOFACIES IIB. LOCALITY CHORWAD.

FIG.3.42 SUPERFICIAL OOLITE SURROUNDING A PELLET. LITHOFACIES IIB. LOCALITY: CHORWAD.

FIG.3.43 NEOMORPHIC SPAR INSIDE A SHELL. SUB-ANGULAR QUARTZ. GRAINS AND RECRYSTALLISED OOLITE ARE ALSO SEEN. LITHOFACIES IIB. LOCALITY CHORWAD.

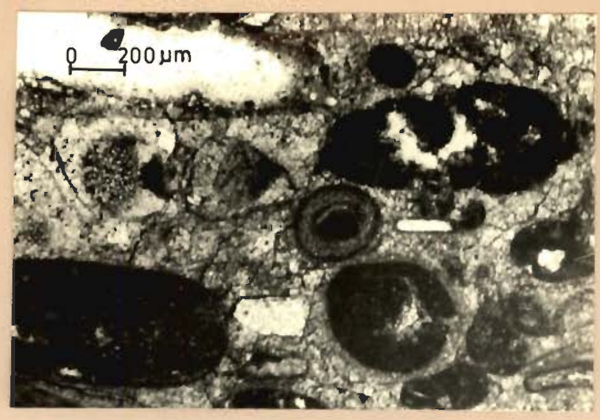


FIG. 3.41

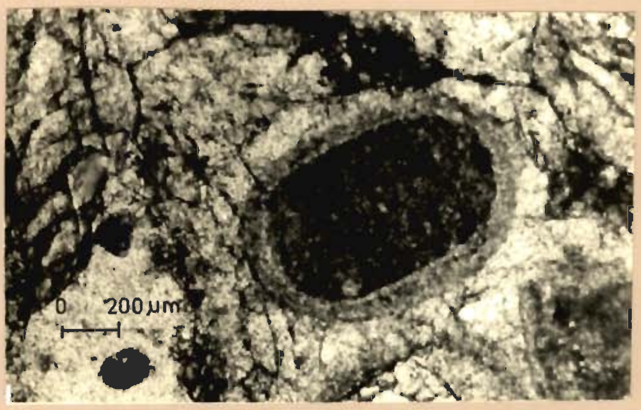


FIG. 3.42

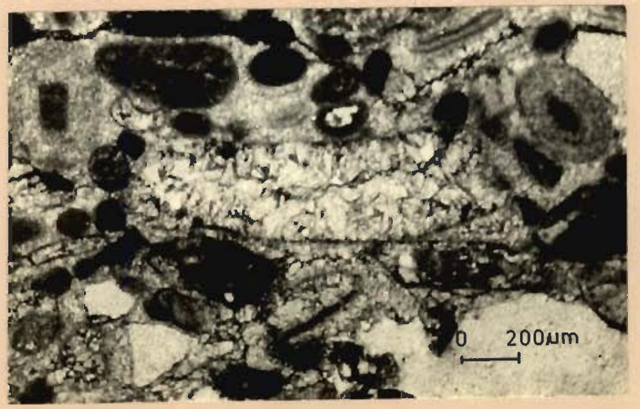


FIG. 3.43

FIG.3.44 INTRACLAST IN LITHOFACIES IIB. LOCALITY: CHORWAD.

FIG.3.45 TRAP ROCK FRAGMENT IN LIMESTONE OF LITHOFACIES IIA. LOCALITY: CHORWAD.

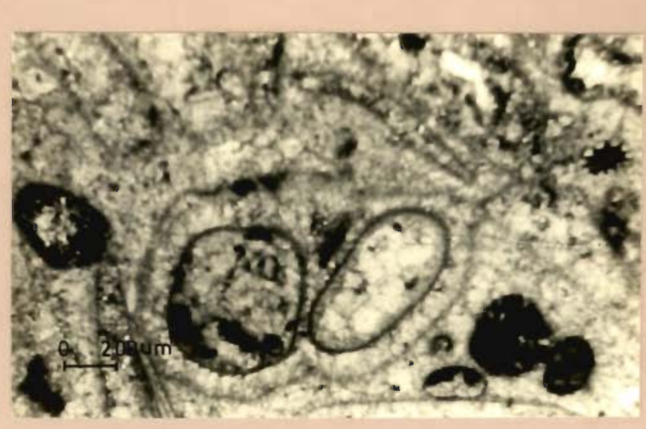


FIG. 3.44

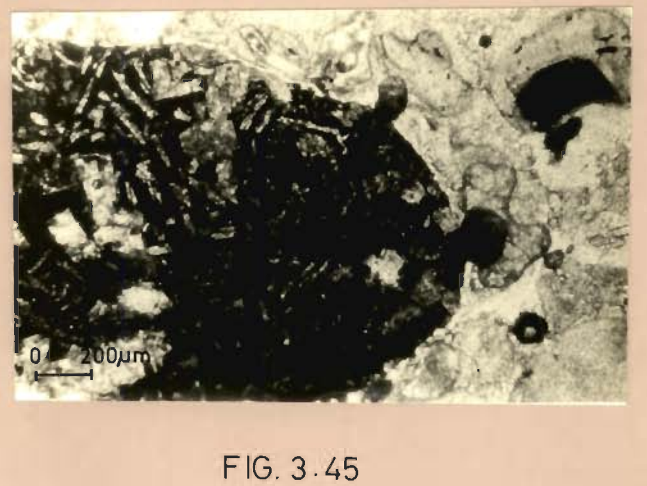


FIG. 3.45

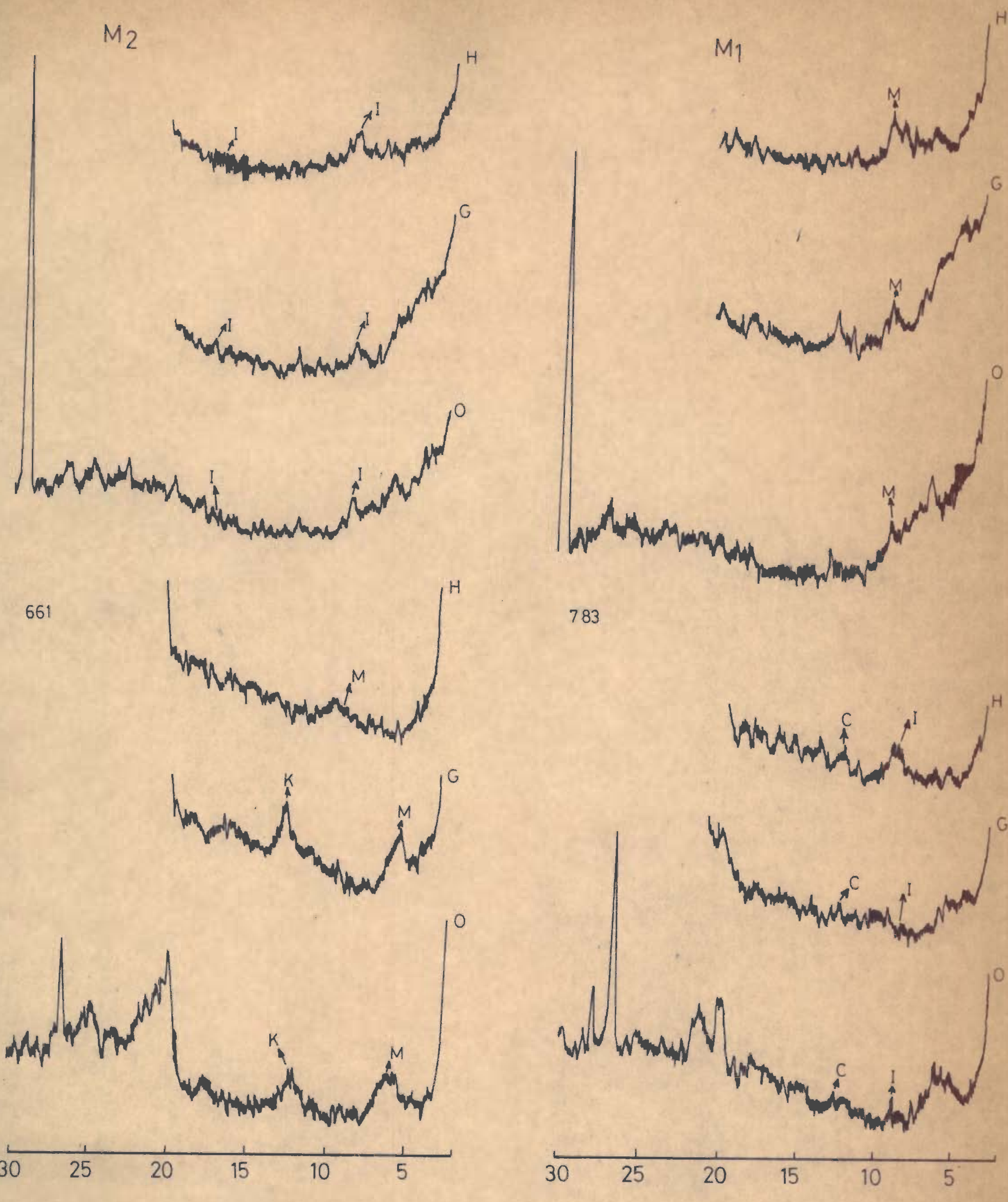


FIG. 3.46_ X-RAY DIFFRACTION PATTERNS OF CLAY MINERALS FROM CLAYS BELONGING TO THE MILIOLITE FORMATION

661_ LITHOFACIES IC; 783 - LITHOFACIES II B , M_1 , M_2 - LITHOFACIES II C

K - Kaolinite, I - Illite, M - Montmorillonite, C - Chlorite, O - Ordinary,

G - Glycolated, H - Heated.

are being dug out.

X-ray analysis indicate the presence of the clay minerals montmorillonite and illite (Fig.3.46) in this lithofacies.

3.3.4.2.6.1 Palaeontological Studies

Seven samples F_1 to F_7 of the lithofacies II C,i.e.,chalk (Micrite) were collected from a number of outcrops located at Goraj, Mankhetra, Langodra, Hussinabad, Sariyaj and Mangrol villages.

These samples were treated for foraminiferal recovery. A fairly rich assemblage of smaller foraminifera was recorded for the first time. In all, 37 foraminiferal species belonging to 24 genera and 17 families have been recorded. Out of these, 10 species are planktonic and the rest are benthonic. Four benthonic species appear to be new but they have been reported as indeterminate ones in the present text because of their low frequency in the material examined. Still more probe is necessary before assigning specific names to them. Illustrations of only 27 species recorded have been included in the present text (Fig.3.47 to 3.50) because of their excellent preservation. Illustrations of the rest of the forms could not be included because of their poor photographic reproduction.

Check-list of the smaller foraminifera recorded from the II C facies.

1) Ammobaculites americanus cushman
2) Lagenodosaria sp. indet.
3) Lagena gracillima (Seguenza)

4) Lagena hertwingiana Brady
5) " hispida Reuss
6) Olina globosa (Montagu)
7) " opiculate Reuss
8) Fissurina quadrata (Williamson)
9) Bolivina compacta sidebottom
10) " subreticulata Parr
11) " Sp. indet
12) Bulimina pupoides d' Orbigny
13) Reusella sp.indet
14) Uvigerina senticosa Cushman
15) Discorbinella monteyreyensis Cushman and Martin
16) Streblus beccarii (Linnacus)
17) Pararotalia nipponica (Asauo)
18) Elphidium hughesi Gushman and Grant
19) Globorotalia tumida tumida (Brady)
20) Globigerina bulloides d' Orbigny
21) " dutertrei d' Orbigny
22) Globigerinoides conglobatus (Brady)
23) " ruber (d'Orbigay)
24) " quadrilobatus sacculifer (Brady)
25) Globigerinoides quadrilobatus trilobus (Reuss)
26) Sphaeroidinella dehiscens (Parker and Jones)
27) " seminulina (Schwager)
28) Globigerinita glutinata (Eigger)
29) Eponides margaritiferus (Brady)
30) " repandus (Fishtel and Moll)

Fig. 3.47 SMALLER FORAMINIFERS FROM THE LITHOFACIES I

1. *Lagenodosaria* sp. indet.; x 320
2. Enlarged view of Fig. 1 showing the surface of the chamber; x 50
3. *Bolivina compacts* Sidebottom; x 320
4. *Bolivina* sp. indet.; x 320
5. *Bolivina subreticulata* Parr; x 320
6. *Bulimina pupoides* d'orbigny; x 320
7. *Reussela* sp. indet.; x 320
8. *Uvigerina senticosa* Cushman; x 320
9. *Discorbinella monteyreyensis* Cushman and Martin; x 320

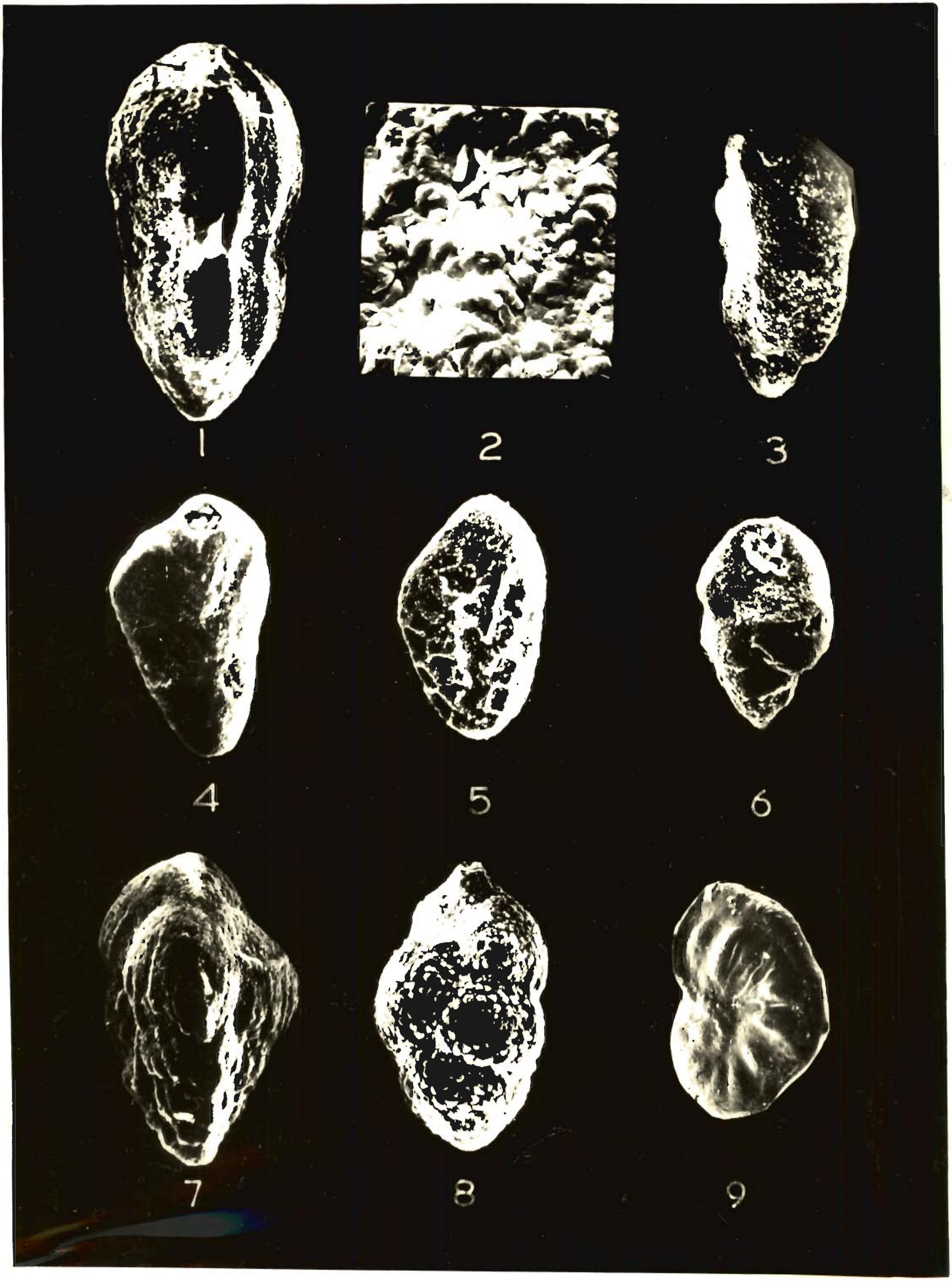


FIG. 3.47_ SMALLER FORAMINIFERS FROM THE LITHOFACIES II C

Fig. 3.48 SMALLER FORAMINERS, OSTRACODA, AND MICROGASTROPOD FROM THE LITHOFACIES IIC

1. *Streblus* beccarii (Linnaeus); x 160(Dorsal vi
2. *Pararotalia nipponica* (Asano); x 160(Ventral v
3. *Pararotalia nipponica* (Asano); x 160
4. *Cibicides C. mckannai* Galloway and Wissler; x
5. Enlarged view showing the test-wall surface near the umbilical region of Fig. 4; x 5
6. Eponides repandus (Fichtel and Moll); x 50
7. *Elphidium hughesi* Cushman and Grant; x 160
8. *Globorotalia tumida tumida* (Brady); x 160
9. *Globorotalia tumida tumida* (Brady); x 160 (Ventral view)
10. Ostracoda
11. Micro-gastropod

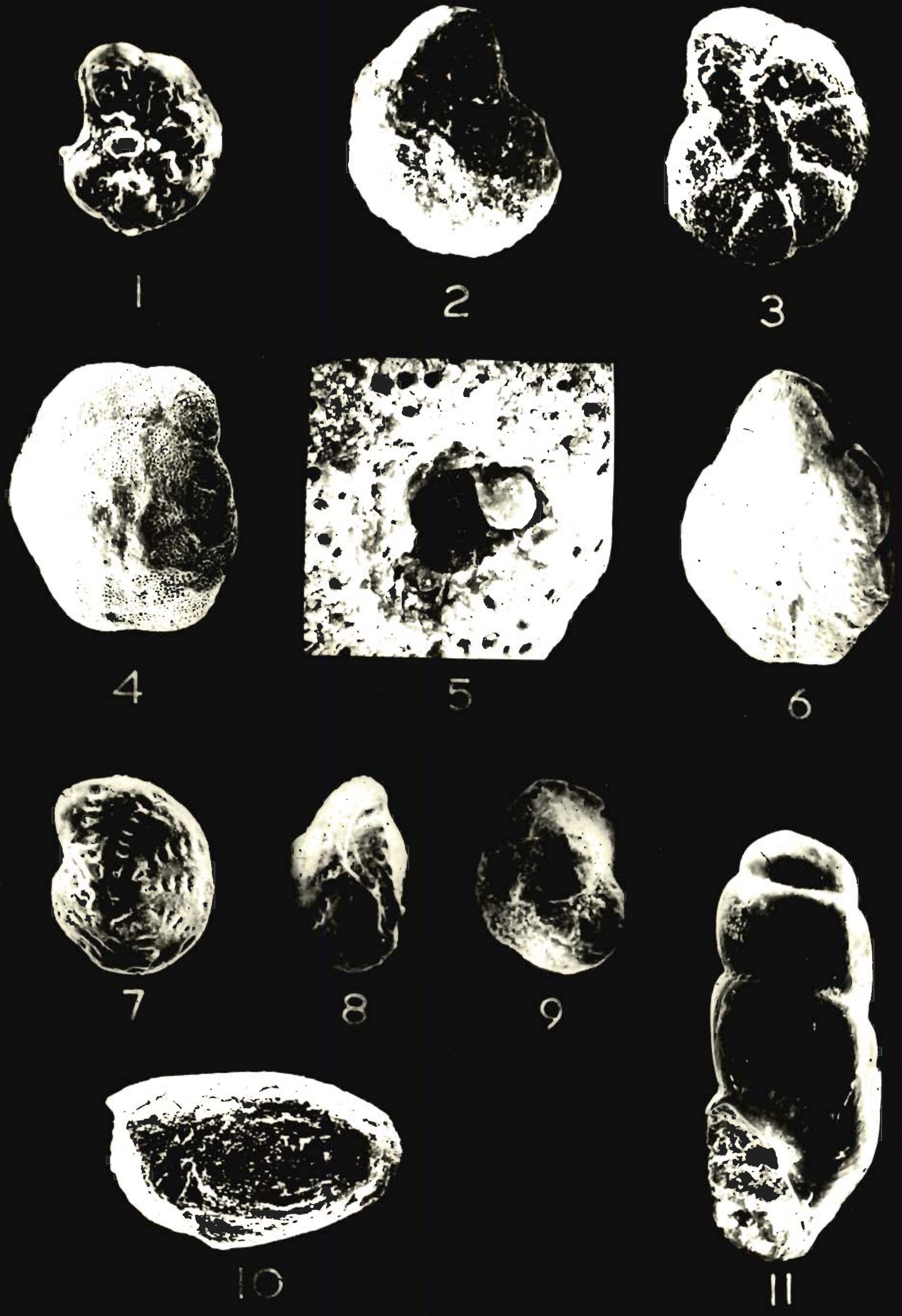


FIG. 3.48_ SMALLER FORAMINIFERS, OSTRACODA, AND MICROGASTROPOD FROM THE LITHOFACIES II C

Fig. 3.49 SMALLER FORAMINFERA FROM LITHOFACIES IIC

1. Globigerina bulloides d'orbigny; x 320

2. Globigerina dutertrei d'orbigny; x 320

3. Globigerinoides ruber (d'orbigny); x 320

4. Globigerinoides quadrilobatus (d' Orbigny)

   trilobus (Reuss); x 50

5. Enlarged view showing the test-wall surface of the apertural face of Fig. 3; x 5

6. Globigerinoides quadrilobatus(d'orbigny) trilobus (Reuss); x 160

7. Globigerinoides quadrilobatus (d' orbigny) sacculifer (Brady); x 50

8. Globigerinita glutinata (Egger) ; x 160

9. Fursenkoina sp. indet; x 320

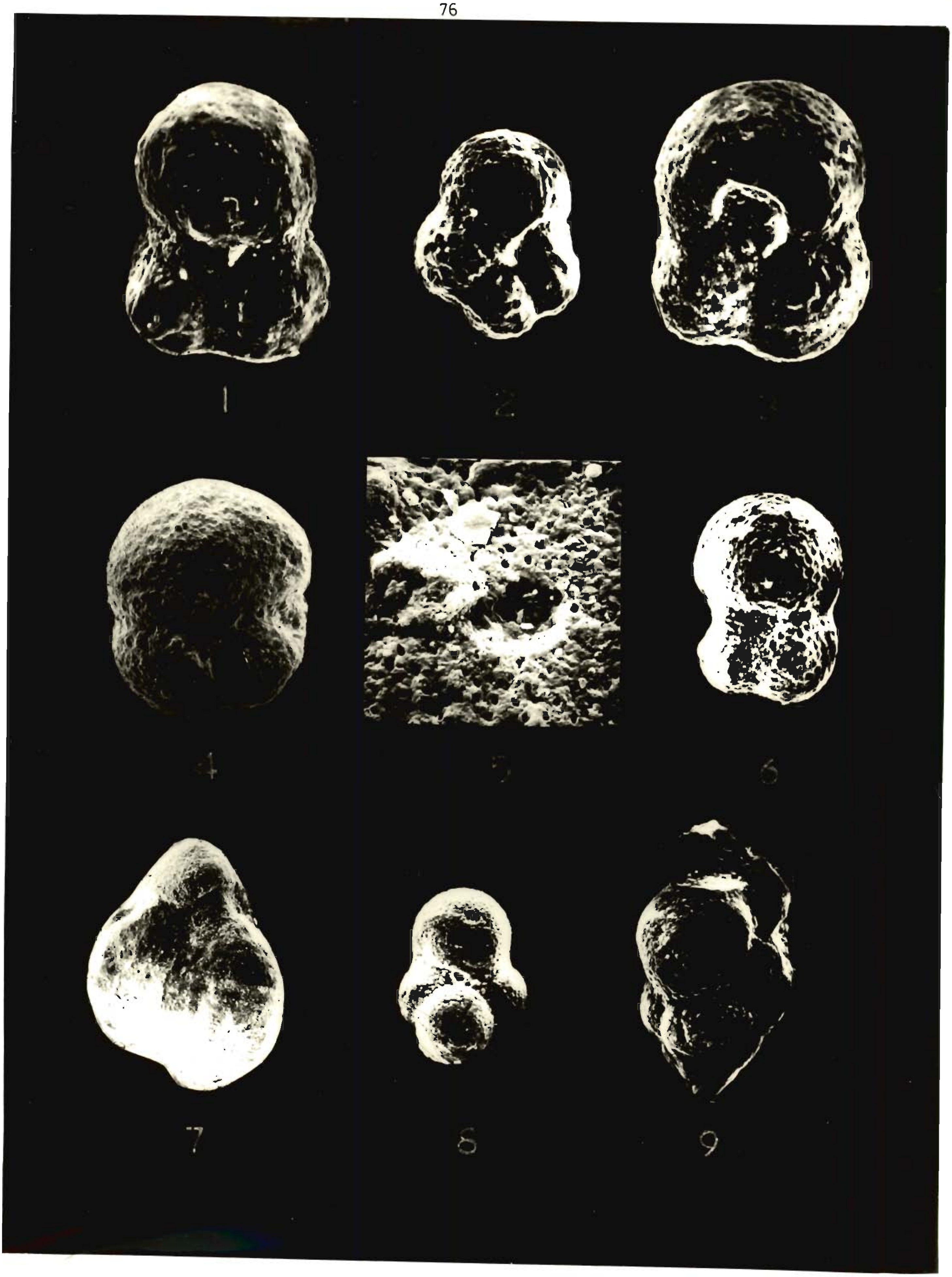


FIG. 3.49 _ SMALLER FORAMINIFERA FROM LITHOFACIES II C

Fig. 3.50 SMALLER FORAMINIFERA FROM LITHOFACIES IIC

1. Cassidulina minuta Cushman; x 320

2. Florilus labradoricus (Dawson); x 160

3. Florilus elongatus (D'orbigny); x 160

4. Nonionella clavata Cushman; x 160

5. Hanzawaia sp. indet; x 50
(Dorsal view)

6. Hanzawaina sp. indet; x 50
(Ventral view)

7. Enlarged view of the apertural face of Fig. 8; x 20

8. Hanzawaia sp.indet.; x 50
(Apertural view)

9. Enlarged view of the umbilical region of Fig.8; x 20

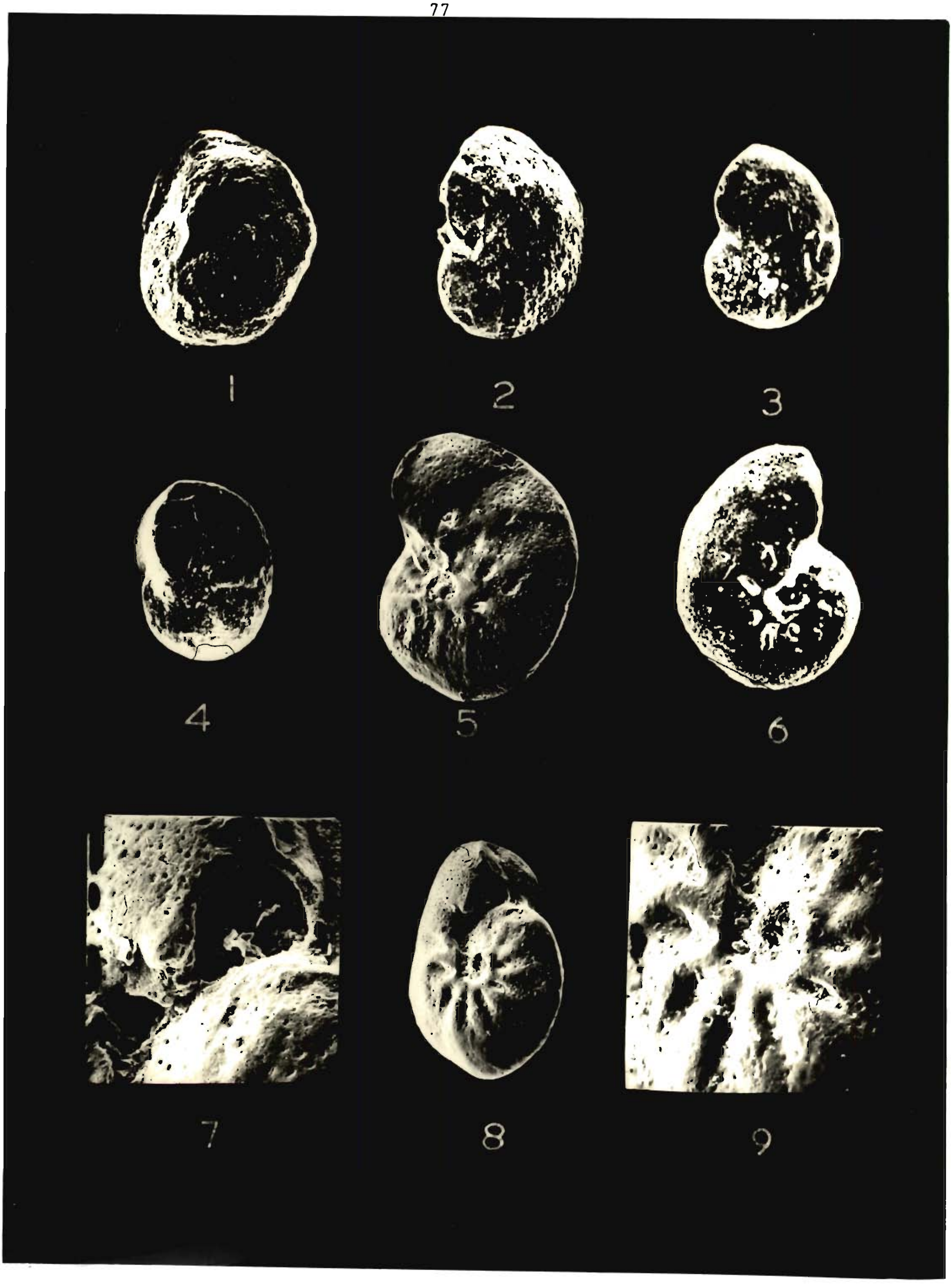


FIG. 3.50 _ SMALLER FORAMINIFERA FROM LITHOFACIES II C

31) Cibicides aff. C mckannai Galloway and Wissler
32) Fursenkoina sp. indet
33) Cassudilina minuta Cushman
34) Florilus elongatus (d' Orbigny)
35) " labradoricus (Dawson)
36) Nonionella clavata Cushman
37) Hanzawaia sp. indet

A survey of the published literature reveals that the foraminiferal studies of the limestones belonging to the Miliolite Formation and the lithic units of the Chaya Formation only have been carried out. No attempt has so far been made to analyse and examine the smaller foraminifera contained in the lithofacies II C, consisting of chalk.

The present study of the micrite samples belonging to the Miliolite Formation on the basis of smaller foraminifera reveals that almost all the forms recorded appear in the fossil form from late Mesozoic-Early Tertiary onwards. Also, the radiometric age of the Chaya Formation which is younger than the Miliolite Formation has been determined as ranging from 120,000 to 6,000 years B.P. (Gupta and Amin, 1974). Thus the stratigraphic positions of the lithofacies II C and their dominant foraminiferal composition is suggestive of late Pleistocene age. This inference agrees well with the conclusions drawn by Marathe et al. (1977) on the basis of archaeological studies.

3.3.4.2.6.2 Palaeoecology

Foraminifera provide the best knowledge to understand the environmental conditions because of their worldwide occurrence in great number and distribution in the sea according to the depth. In this respect, benthonic species are of particular importance as their presence or absence is greatly influenced by depth and hence to some extent by temperature variation.

In the following sections an attempt is made to establish the palaeoecology primarily on the basis of foraminifera found in this facies.

3.3.4.2.6.3 Foraminiferal Number

Studies (e.g. Bandy and Arnal, 1960) have shown that foraminiferal number increases off shore and greatest number occurs at the shelf and within upper bathyal depths and their number decreases into the lower bathyal zone where radiolarians occur in abundance. In the present investigations high foraminiferal content in the lithofacies II C have been recorded.

3.3.4.2.6.4 Planktonic-Benthonic Ratio

Benthonic foraminifera constitute their maximum population in shallow water near the shore. With the increase of depth their number decreases with increase in the number of planktonic foraminifera.

The foraminiferal assemblage of the micrite samples contains 30 to 40 per cent of planktonic forms of which the species of Globorotalia, Globigerina, Globigerinoides, Sphaeroidinella and Globigerinita constitute more than 20 to 30 per cent of the total planktonic population.

The population of the planktonic forms increases in the lithofacies II C as opposed to the overlying and underlying strata indicating the rise in the sea level resulting to a deep water column permitting a large number of planktonic forms to be present in the depositional area. The presence of characteristic near-shore shallow-water forms like Streblus, Pararotalia, Elphidium etc. asscoaited with planktonics like Sphaeroidinella in the micrites appear to be due to reworking.

A high foraminiferal number and the planktonic-benthonic ratio, as well as the variability of the planktonic forms in this lithofacies indicate deposition on the outer part of the continental shelf (depths between $C^{70}m$ to $C^{200}m$).

3.3.4.2.6.5 Percentage of Arenaceous Forms

Modern ecological work has shown that arenaceous genera such as Cyclammina, Bathysiphon, Ammobaculites, and Trochammina can exist under bottom conditions. Lowman (1949) found that abundant arenaceous population occurs in shallow, calm, brackish waters of the ocean.

Only one arenaceous species viz. Ammobaculites americanus Cushman which is a known deep-water form has been recorded in the present samples. This again indicates a depositional site far off from the coast line towards the open sea.

3.3.4.2.6.6 Percentage of Porcellaneous Forms

Works of Bandy (1956) indicated that porcellaneous forms particularly the Miliolids are more dominant in the intertidal zone and inner part of the continental shelf.

Total lack of miliolids in the present samples also suggest the area of deposition away from the coastline.

3.3.4.2.6.7 Characteristic Calcareous Benthonic Species

Common to abundant occurrence of Cibicides, Uvigerina, Bulimina, Cassidulina, Bolivina, Eponides, Nonionella, Fissurina, and Lagena in the micrite samples is indicative of relatively deeper water biofacies and most probably an outer continental shelf marine environment. Cibicides mekannai Galloway and Wissler which is abundant in the present samples most commonly occurs between the depths 55 to 91 m.

3.3.4.2.6.8 Temperature

Besides depth, temperature is also an important factor controlling the distribution of foraminifera.

The presence of the species like Globigerinoides quadrilobatus sacculifer (Brady), Globigerinoides conglobatus (Brady) and Sphaeroidinella (all dominant tropical species)in this facies suggests a tropical marine environment.

However, there are a few forms such as Globigerina bulloides d'Orbigny and Globigerinoides ruber (d'Orbigry) which occur abumdantly in the cold water faunal assemblage, occur sporadically in the present fauna. But the total absence of characteristic cold water species such as _G. crassa formis_, _G. inflata_, _G. truncatulinoides_ in the assemblage studied is suggestive of a tropical surface water temperature.

3.3.4.2.6.9 Size of the Fauna

The presence of smaller than the normal size (ranging from 0.14 to 0.35 mm) of the specimens, even including the planktonic ones indicates lowered temperature during the deposition of these beds. The lowering of the temperature was probably caused by glocio-inter-glacio-eustatic changes during the Pleistocene times. However, on the whole the area was in tropical climatic region as discussed earlier.

3.3.4.2.7 Lithofacies III

This lithofacies occur as small elongated mounds, running almost parallel to each other in a NE-SW direction which is also the direction of the prevailing wind. They are massive, cross-bedded or thinly flat bedded (Fig. 3.51, 3.52, 3.53) and are white in colour. The cross-beddings show variable directions dipping easterly and westerly. The thickness of each laminae is 0.2 to 1 cm but in some localities it is upto 1.5 cm. Generally the laminations are uniformly thick. The laminations are clearly visible on weathered surfaces. Almost alternate layers of white hard material and brownish or black laminations are present. The whiter portions are fine grained, compact, and hard whereas the brownish or black portion is coarser grained, less compact, and

FIG.3.51 PLANAR CROSS-STRATIFICATION IN LITHOFACIES III OF THE MILIOLITE FORMATION. LOCALITY: SEPA.

FIG.3.52 FLAT BEDDING CONSISTING OF THIN LAMINATIONS IN LITHOFACIES III. LOCALITY: SEPA.

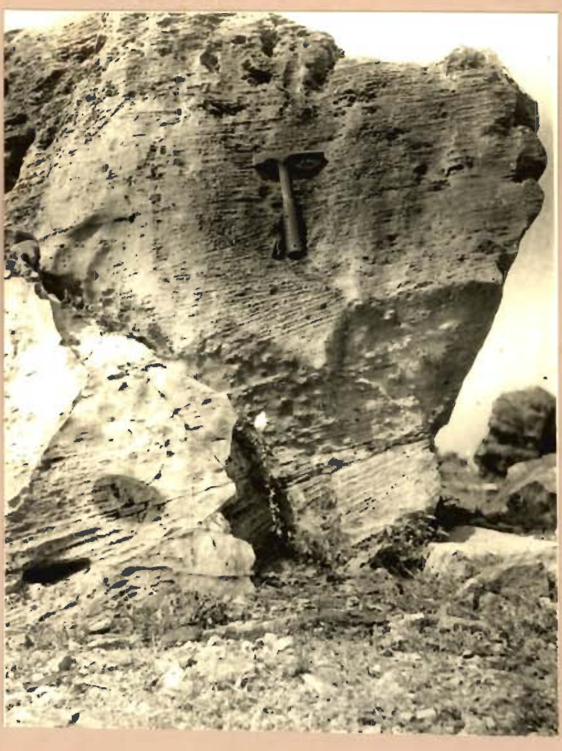


FIG. 3.51

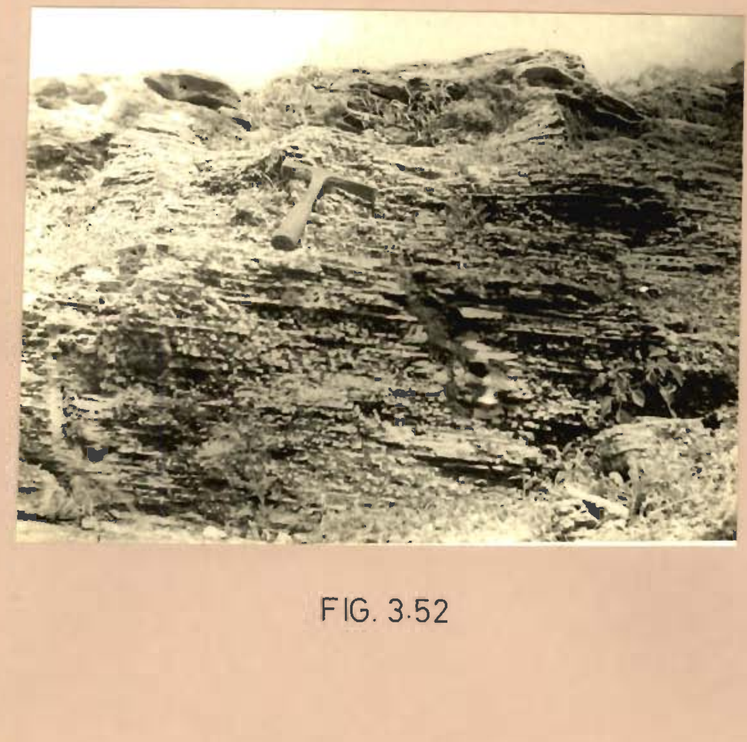


FIG. 3.52

FIG.3.53 SMALL SCALE CURRENT BEDDING OF VARIABLE DIRECTION IN LITHOFACIES III OF THE MILIOLITE FORMATION. LOCALITY: SEPA.

FIG. 3.53

more porous, with some small shell fragments and fossils. Solution activity has taken place along the bedding planes, and the hard portions generally project out. Because of solution activity, the rocks show honeycomb like structure (Fig. 3.11) at many places. Occasionally, minute cavities are seen along these laminations. At some places, the top portion contains numerous solution openings (grikes and clints) of different sizes (Fig.3.8). The diameter of these vary from 4 cm to 33 cm. Grikes and clints are seen to be interconnected in many places. The rocks of this facies are seen near the villages Kankasa, Sepa, Arena, and near Gadu. The maximum exposed thickness of this bed, about 12 m is seen at Sepa.

These are pelletic calcarenites and consist of pellets, fossils and shell fragments, with minor amounts of oolites, superficial oolites, quartz, epidote and occasionally rock fragments of the Gaj Formation and Deccan Trap (Fig. 3.54). The pellets constitute 37% to 67%, but in most of the cases they are more than 50% of the allochems. The fossils and shell fragments vary from 26% to 61.5% of allochems, but the common range is 26% to 42%. The percentage of oolites is very small and at Arena it decreases from bottom to top but near Budecha the reverse is noticed,i.e.,it increases towards top. This lithofacies has a limited grain size.

The pellets present are ovoid to sub-ovoid and occasionally spherical in shape (Fig. 3.54). They are mostly brownish in colour and generally do not show any internal structure. It is very difficult to recognise fecal pellets. However an internal arrangement of unoriented silt and clay size grains bound together by organic and carbonate matrix point to a fecal origin to atleast some of them. A large number of them seems to be worn out shell fragments or calcite grains which have assumed the shape of a pellet. In such cases the original shell structure has been obliterated by recrystallisation. SEM study indicates that they contain micritic material with lot of intergranular porosity developed due to solution activity.

The shells and fossils in these rocks are smaller in size when compared with the previously described rocks. They are filled with sparry calcite or micrite (Fig. 3.55). Sparry calcite occurs both as cement and neomorphic crystals. Brown stains of iron oxide are seen on the surface or borders of fossils.

Oolite occurs only in very minor amounts in these rocks.It ranges from 0 to 13% of total allochems. True oolites and superficial oolites are present(Fig. 3.54). Most of the oolites and superficial oolites seems to have lost their internal structure due to neomorphism. The proportion of the recognisable accretionary grains is much less than their true proportion at the time of deposition. This is based on the fact that in many cases the original concentric layering could be made out by the arrangement of clear crystalline calcite grains. In many cases the size of the accretionary grains seen are very small. The nucleus of the oolite and superficial oolites seems to be calcareous in nature. Quartz grains rarely form the nuclei. In many cases the superficial oolites have been formed around pellets but in such cases generally there is a very thin, clear, concentric ring, surrounding the pellets (Fig. 3.56) which appears optically distinct under the cross-nicols. In some cases two or three rings are visible. Generally the number of laminae surrounding a nucleus is very difficult to determine because of the frequent lack of distinct laminar contacts.

Small angular to sub angular grains of quartz are also present in minor amounts. Epidote and rock fragments of the Gaj and trap rocks occur rarely. Some algae can also be identified.

3.3.4.3 X-ray study of limestones

X-ray diffraction techniques is useful in carbonate mineralogy studies, because it can be used to determine quantitatively the mineral composition of a carbonate sediment. An XRD-6 General Electric Diffractometer with nickel filtered copper alpha-radiation (Cu Kα)operating at 36 KVP located at Institute of Petroleum Exploration, Dehradun and also the one at Delhi University,Delhi was used for analysing 49 limestone samples from the Miliolite Formation.

The limestone samples were finely crushed and sieved. Care was taken so that the grinding was not severe, so that calcite is not altered to aragonite. -200 mesh size samples were taken and mixed with finely ground (-200 mesh) fluorite to serve as an internal standard. Calcite, dolomite, and quartz were identified by scanning with the goniometer over a 2 θ range of 25° to 35°. This range records peak for quartz at 26.62° (3.343 Å d), peak for calcite at 29.49° (3.035 Åd) and dolomite peak at 30.98°(2.886 Åd) to 31.40° (2.8474 Åd). The CaF_2 standard peak is recorded at 28.3°.

FIG.3.54 PELLETIC CALCARENITE CONTAINING PELLETS, FOSSILS, SHELLS, OOLITE AND SUPERFICIAL OOLITE. LITHOFACIES III. LOCALITY: ARENA.

FIG.3.55 PELLETIC CALCARENITE SHELLS CONTAIN SPARRITE AS WELL AS AS MICRITE. NOTE THE MICRITIC ENVELOPE AROUND THE SHELLS. LITHOFACIES III. LOCALITY: BUDECHA.

FIG.3.56 SUPERFICIAL OOLITE FORMED AROUND A PELLET IN LITHOFACIES III. LOCALITY: ARENA.

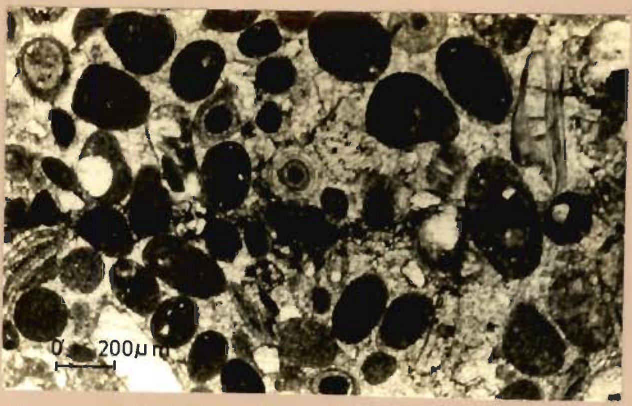


FIG. 3.54

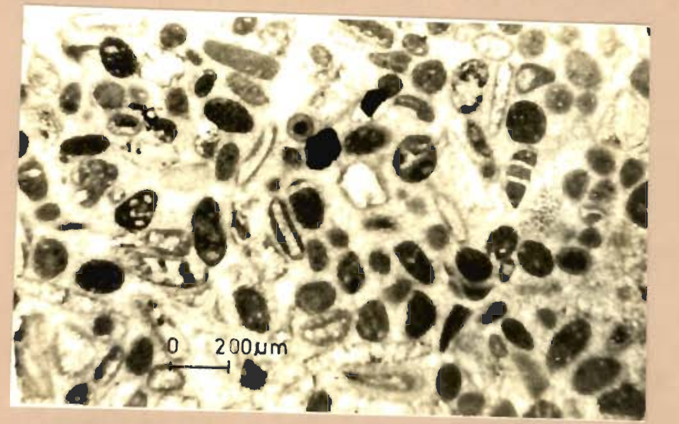


FIG. 3.55

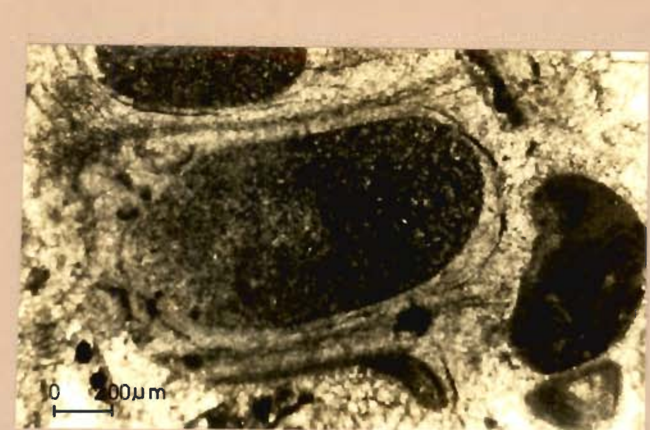


FIG. 3.56

These calcite and dolomite peaks are the peaks of greatest intensity, they are relatively free of interference from peaks of other minerals and they are also close together (Gulbrandser,1960 in Rao, 1977). The X-ray diffractograms for different samples are given in figures 3.57 to 3.62. It can be seen that the minerals present are low Mg- calcite, dolomite and silica. The proportions of these were determined (Table 3.2) according to the method suggested by Johns, Grim, and Bradley (1954).

During the chemical analysis of the limestone samples, the insoluble residue was also separated as described later(Section 3.3.4.4), and the weight percentage of this was computed. The estimate of dolomite/calcite ratio in the rocks and the insoluble residue weight percentage are obtained from independent procedures and these were plotted, i.e., insoluble residue vs. dolomite/calcite ratio (Fig. 3.63). A perusal of the plot shows no apparent relationship between these two variables. This indicates that the clay minerals present in the limestones have not contributed Mg needed for the formation of dolomite. Some authors (Fairbridge,1957; Bisque and Lamish, 1959; Chilingar, 1956; Murray,1960, and Schmidt, 1964) have shown that there is a relation between these two, whereas others (Goldich and Parmalee,1947; Zenger,1965; Lumsden, 1974; Jain, 1974; and Rao, 1977) opined that there is no relationship between them.

3.3.4.4 Chemical Analysis of Limestones

The limestone samples of Miliolite Formation were crushed to fine powder and -200 mesh size was taken for analysis. 10 ml of

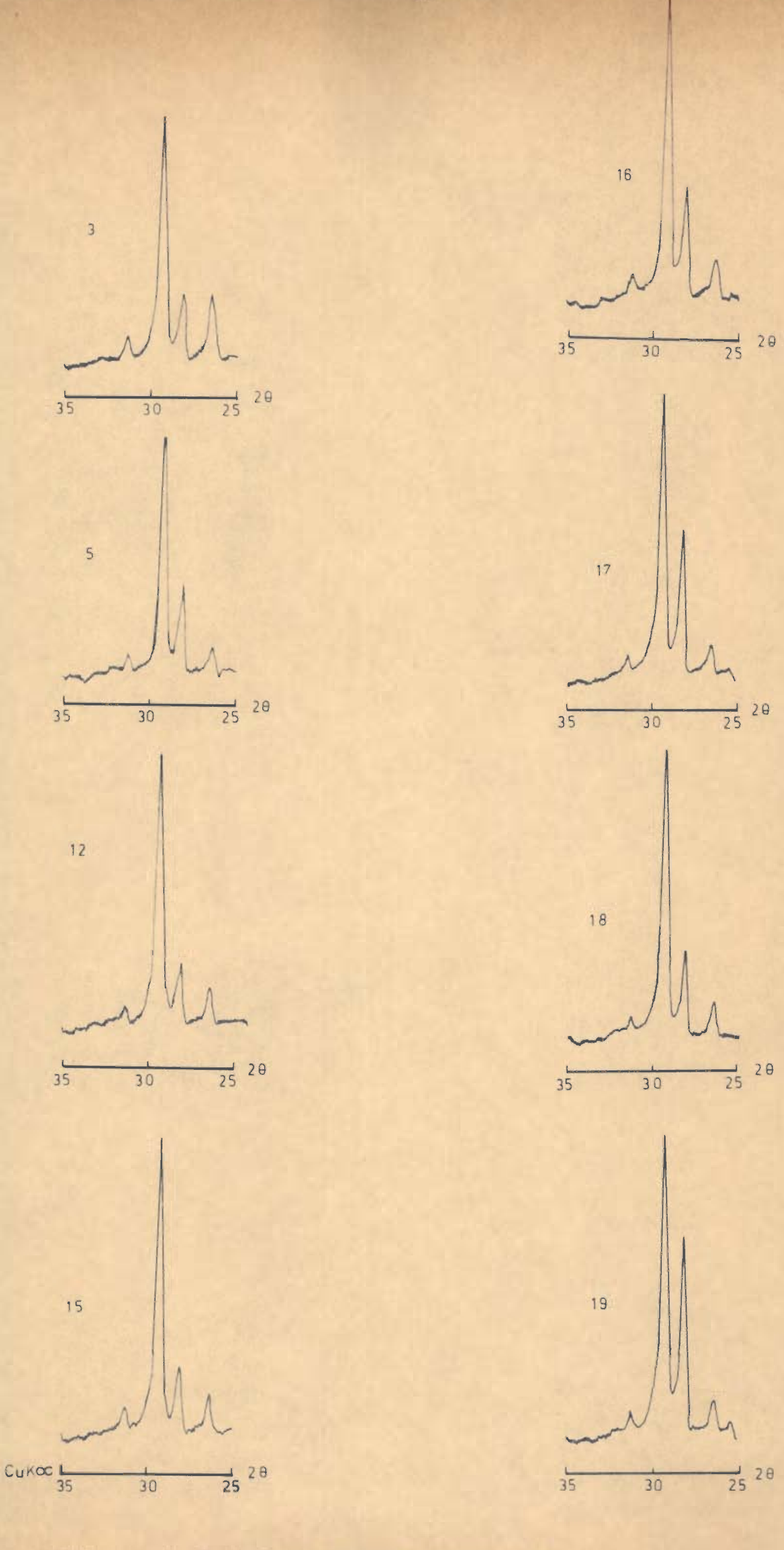


FIG. 3.57 _ X-RAY DIFFRACTION PATTERNS OF LIMESTONE SAMPLES FROM TH
MILIOLITE FORMATION

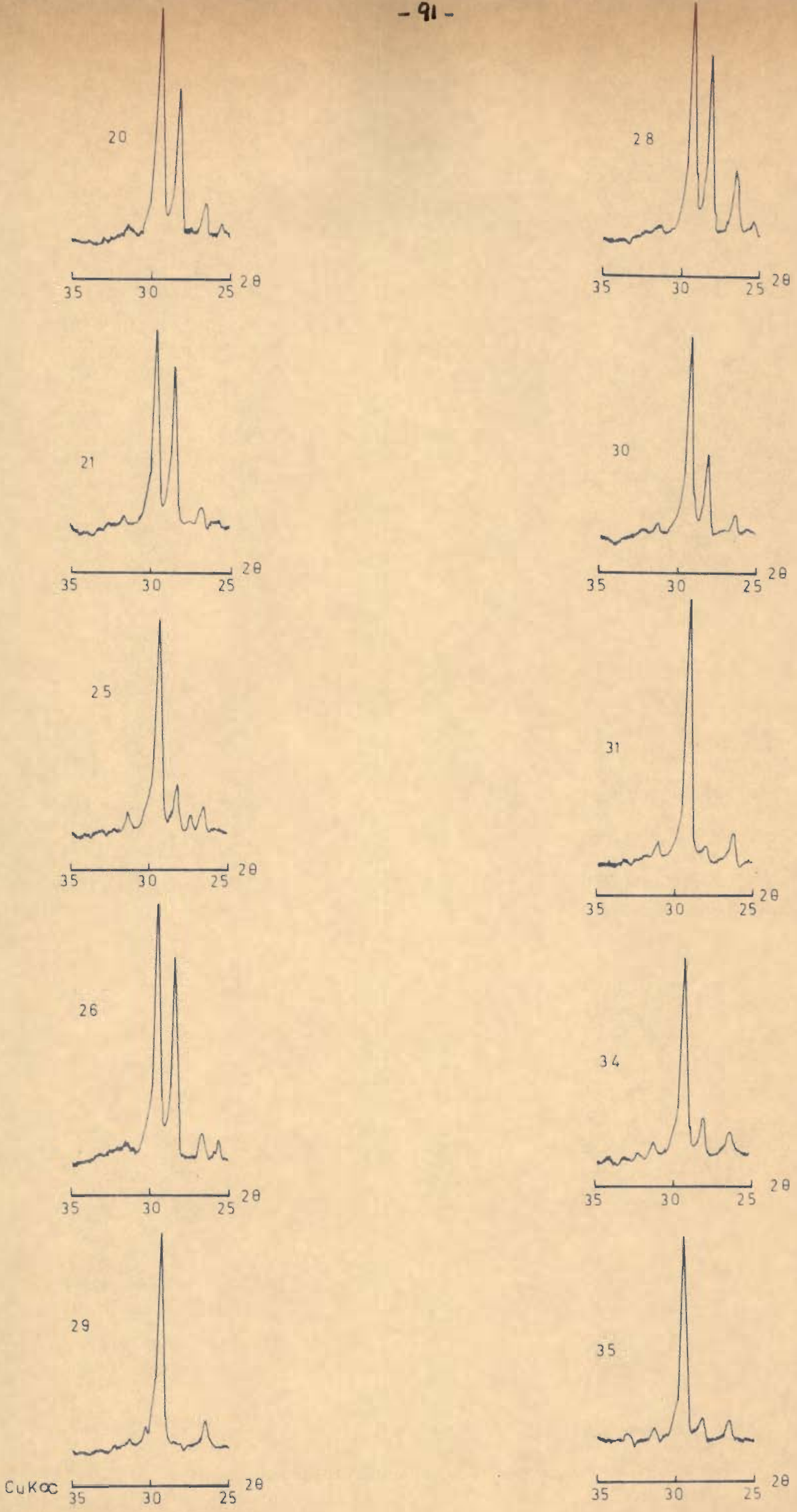


FIG. 3.58 _ X-RAY DIFFRACTION PATTERNS OF LIMESTONE SAMPLES FROM THE MILIOLITE FORMATION

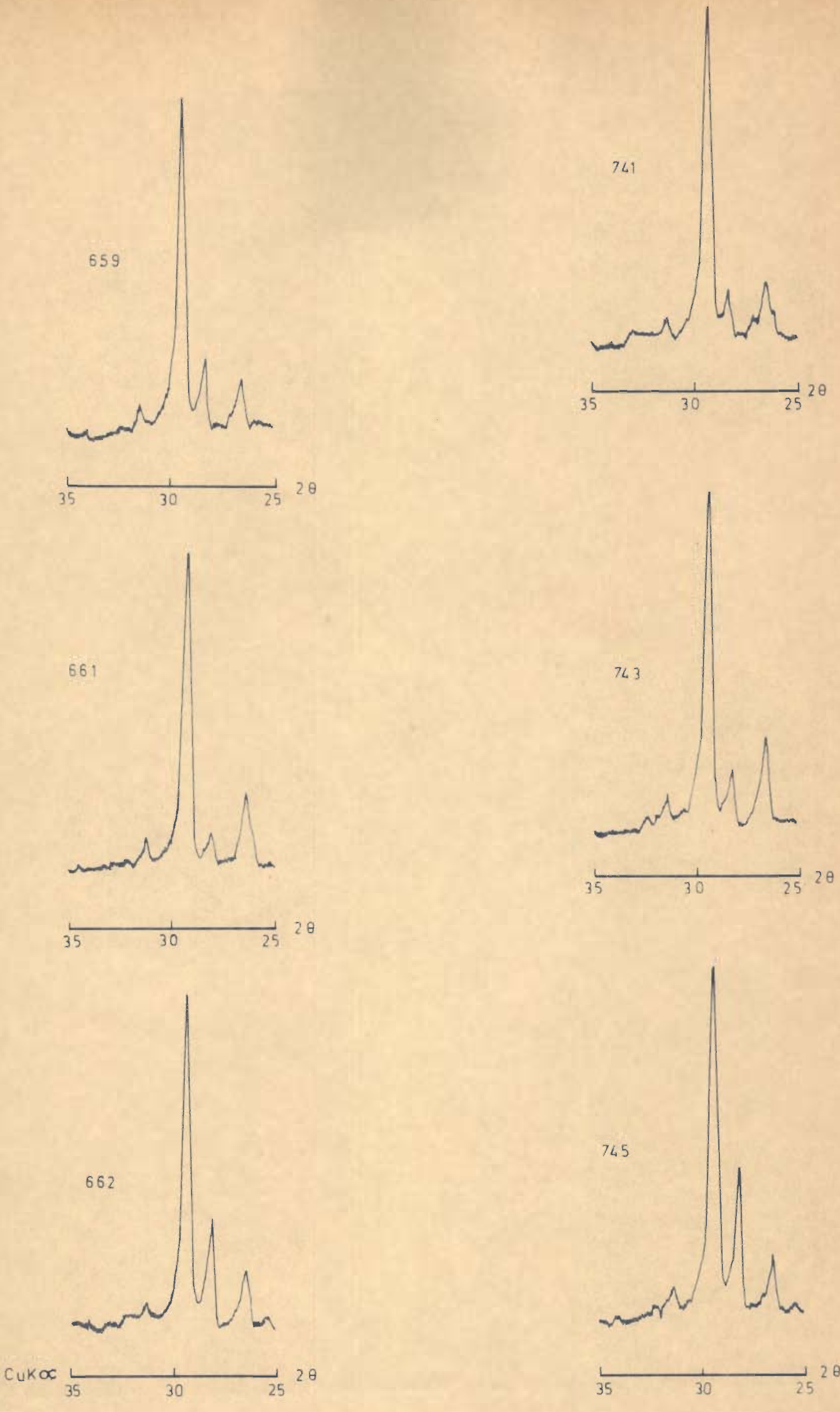


FIG 3.59 _ X-RAY DIFFRACTION PATTERNS OF LIMESTONE SAMPLES FROM THE MILIOLITE FORMATION

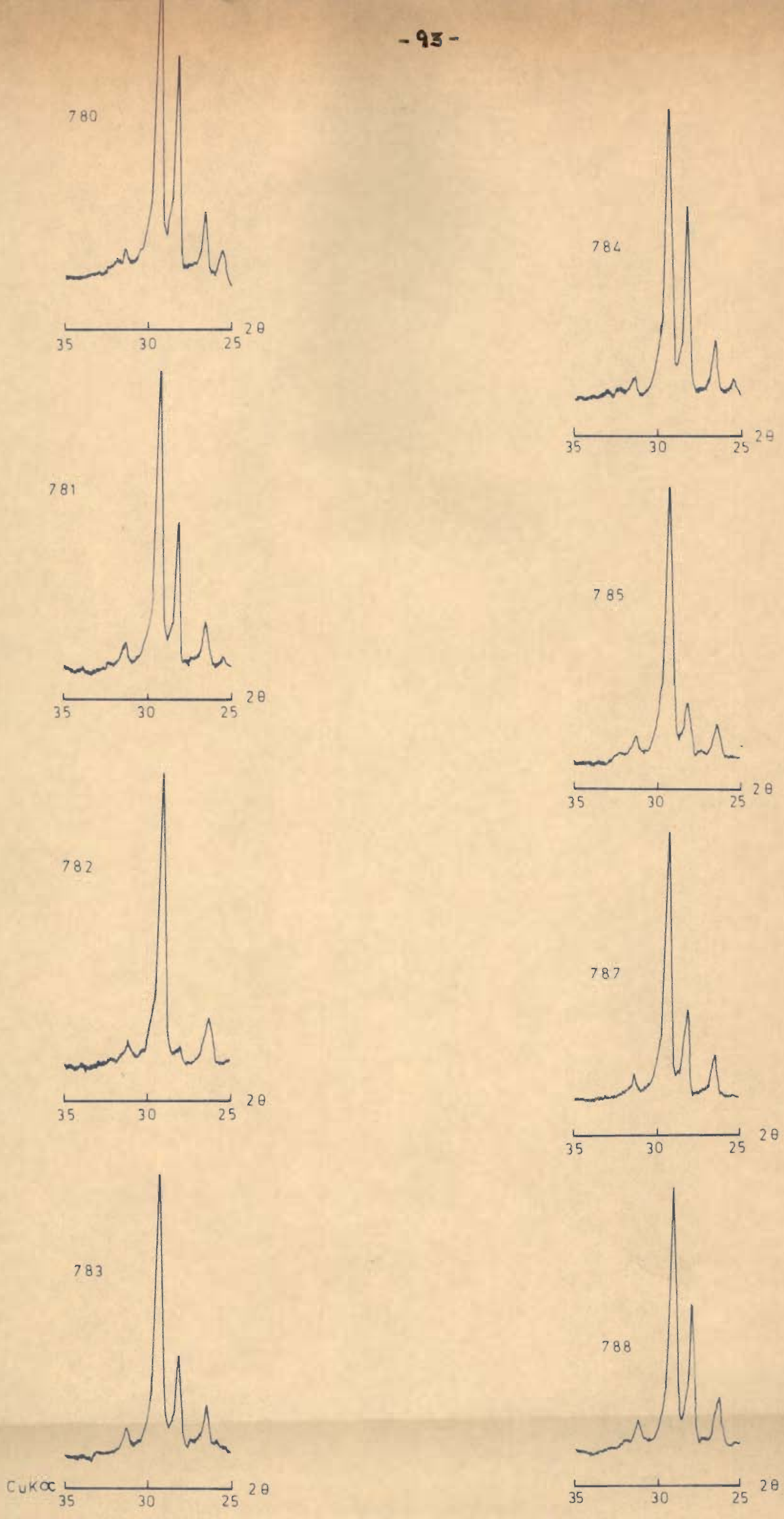


FIG. 3.60 _ X-RAY DIFFRACTION PATTERNS OF LIMESTONE SAMPLES FROM THE MILIOLITE FORMATION

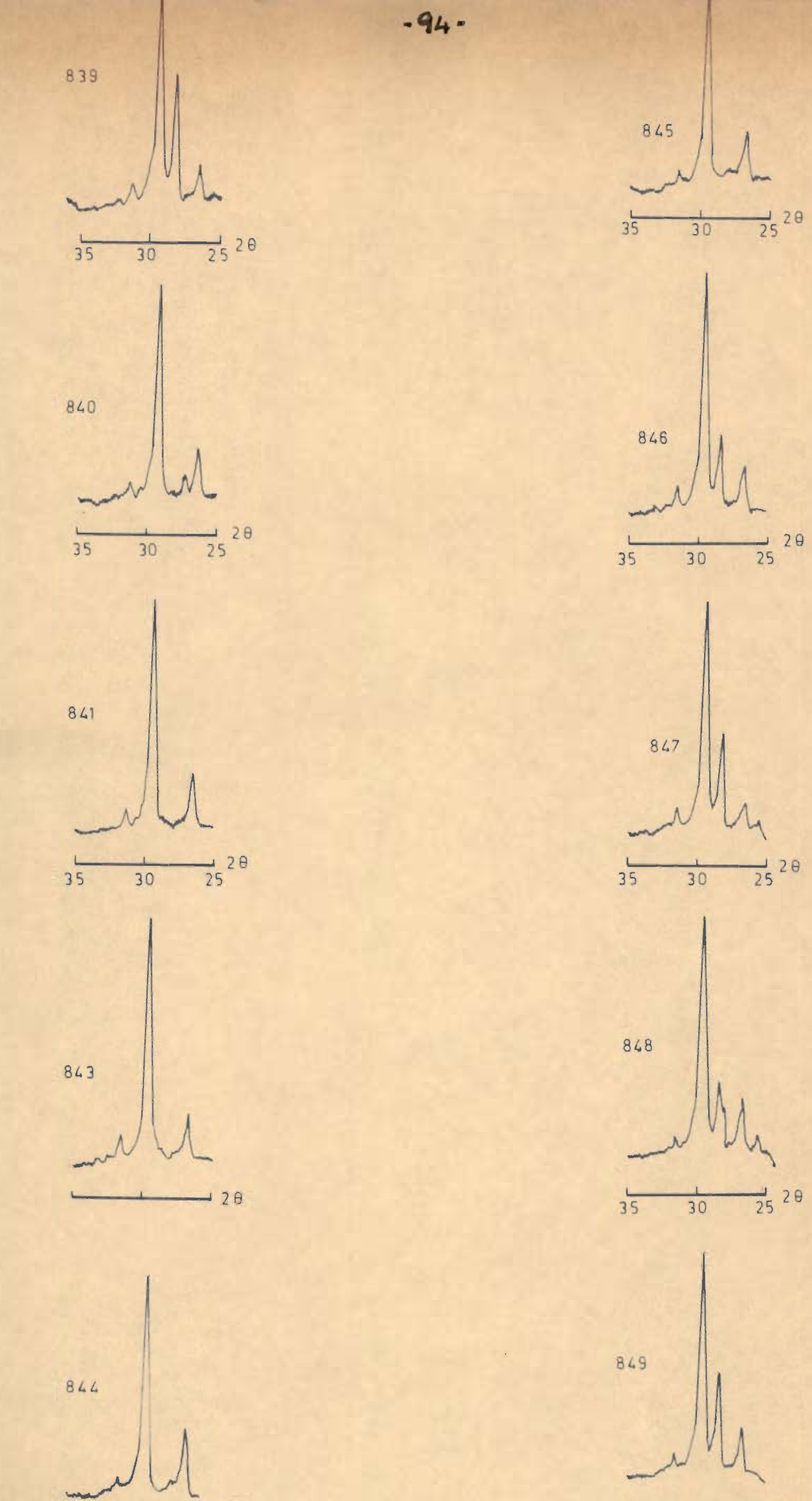


FIG. 3.61 _ X-RAY DIFFRACTION PATTERNS OF LIMESTONE SAMPLES FROM THE MILIOLITE FORMATION.

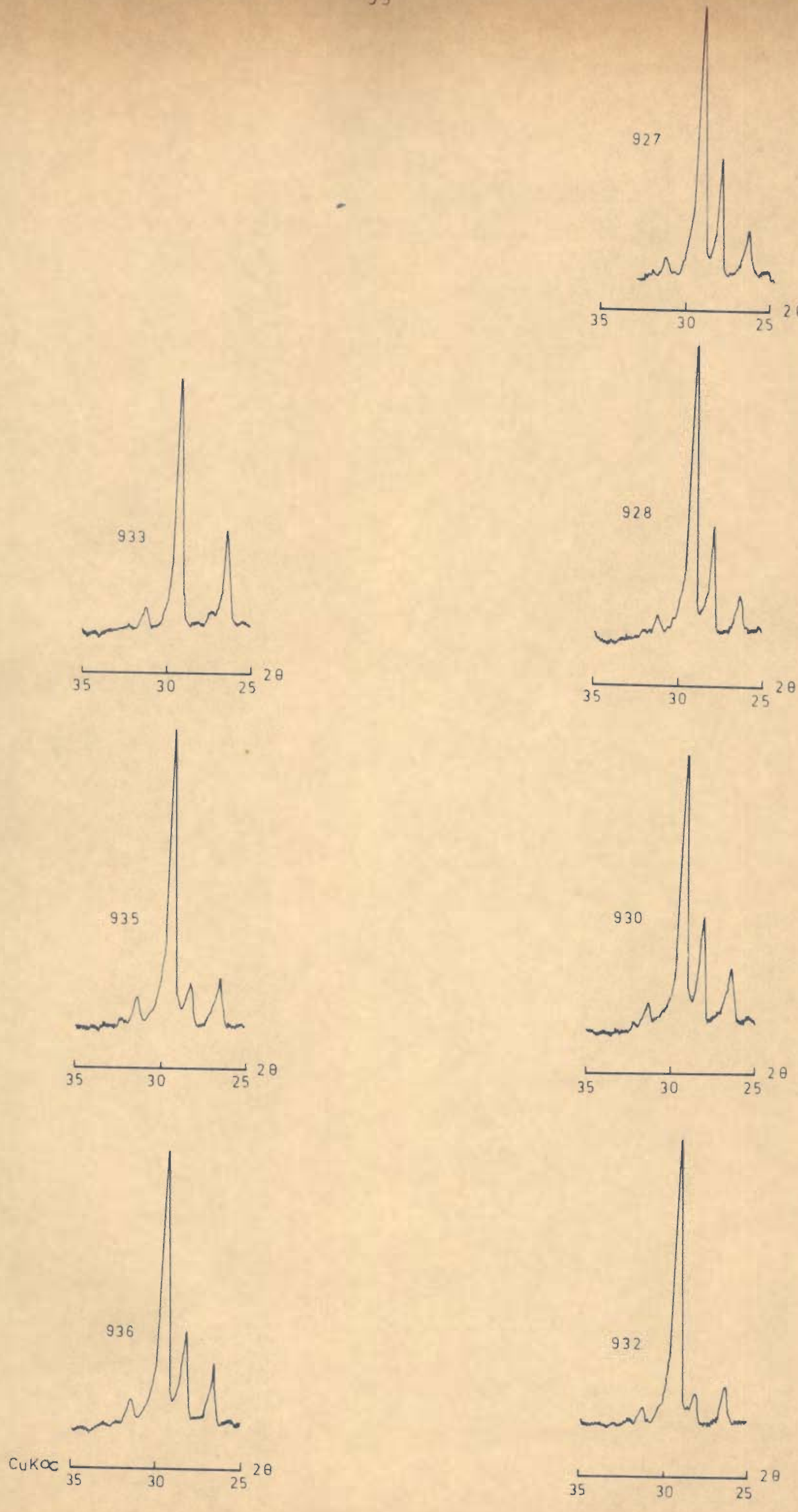


FIG. 3.62 _ X-RAY DIFFRACTION PATTERNS OF LIMESTONE SAMPLES FROM THE MILIOLITE FORMATION

Table 3.2 . Dolomite/Calcite Ratio and Insoluble Residue in Different Lithofacies of the Miliolite Formation.

No.	Insoluble Residue %	Dolomite/Calcite
3	5.02	0.126
5	4.03	0.107
12	4.27	0.094
14	3.70	0.072
15	5.31	0.101
16	2.69	0.108
17	12.55	0.092
20	4.83	0.099
21	9.50	0.088
22	37.27	0.118
25	4.23	0.059
26	5.40	0.144
28	4.84	0.094
30	3.12	0.092
31	6.92	0.112
34	6.26	0.096
35	14.02	0.112
659	16.70	0.125
661	15.49	0.10
843	4.85	0.108
845	11.26	0.103
848	4.28	0.118
884	9.15	0.119

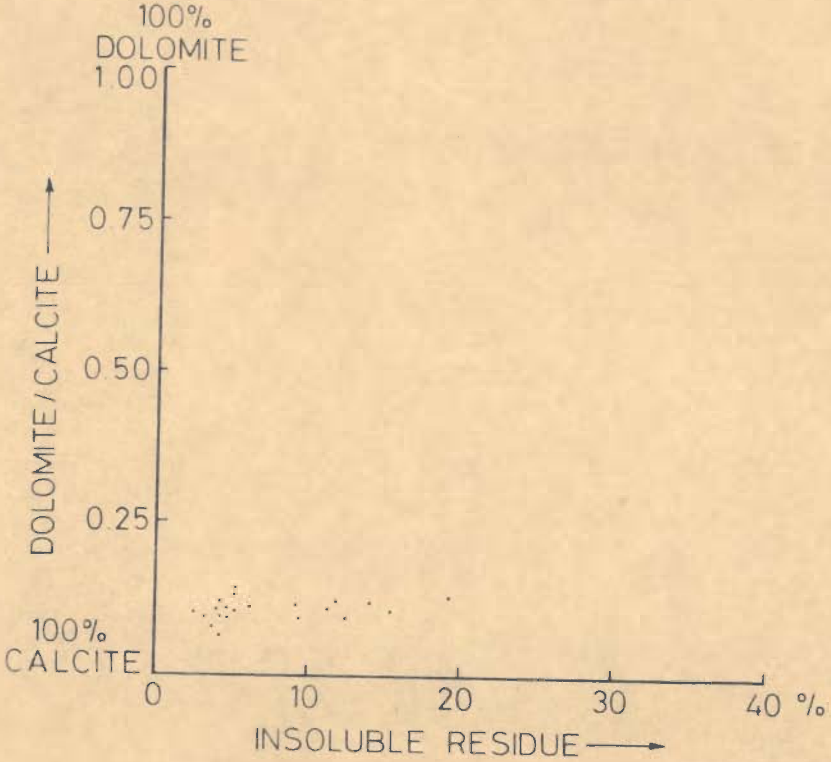


FIG 3.63 _ PLOT OF DOLOMITE - CALCITE RATIO Vs INSOLUBLE RESIDUE

concentrated HCl and 2 ml of concentrated HNO_3 were added to 1 gm of the powdered sample, kept in a beaker and evaporated on a hot bath. Afterwards distilled water was added and the solution was filtered and made to 250 ml. The filtrate was ignited in a crucible and weighed accurately after cooling. From this the insoluble residue percent was calculated.

From the solution prepared, Ca and Mg were determined by E.D.T.A. titration and Sr was determined by Atomic Absorption Spectrophotometer. The results are given in Table 3.3.

The Ca, Mg and insoluble residue are plotted (Fig.3.64) after Leighton and Pendexter (1962). Based on this plotting, the limestones belonging to the Miliolite Formation are classified as limestone and impure limestone. Out of the 19 samples only 3 fall in the field of limestone. Others are impure limestones.

The Sr content is seen to be high which varies from 575 to 3000 ppm Slightly lower concentration of Sr,i.e., 575 ppm and 738 ppm is seen in pebbly limestone belonging to the lithofacies I C, whereas the higher Sr content,i.e., varying from 738 to 3000 ppm is seen in limestones belonging to the lithofacies II A and II B.

Kinsman (1969) has summarised the available knowledge regarding substitution of Sr into carbonate minerals. According to him precipitation of calcite results in a discrimination against Sr by the crystal, with consequent concentration of Sr in the solution. Successive recrystallisation, therefore, results in the lowering of the Sr content. Bathurst (1975) has shown that

Table 3.3 Chemical Analysis data of Limestone of the Milliolite Formation

Sample No	% Ca	CaO %	$CaCO_3$ %	%Mg	MgO %	$MgCO_3$ %	Insoluble residue%	Sr(ppm)
3	36.41	50.95	90.89	1.15	1.9	3.90	5.02	1500
5	30.45	42.60	88.49	2.05	3.40	7.1	4.03	1300
12	36.09	50.50	90.09	1.39	2.3	4.81	4.27	1500
14	35.91	50.25	89.29	1.33	2.2	4.6	5.79	1075
15	36.94	51.68	92.20	0.96	1.60	3.35	3.70	1188
16	33.27	46.55	83.05	3.08	5.10	10.66	5.31	888
17	36.99	51.76	92.34	1.21	2.01	4.18	2.69	1126
20	31.60	44.22	78.88	3.28	5.44	11.38	9.5	750
21	20.90	29.24	52.60	3.68	6.11	12.78	35.16	800
22	33.07	46.27	86.11	2.3	3.41	7.97	5.30	738
25	33.41	46.75	83.26	3.28	5.44	11.38	4.76	1100
26	32.95	46.10	82.24	3.16	5.24	10.96	6.07	788
28	34.98	48.95	87.32	2.42	4.02	8.41	4.23	1900
30	36.65	51.28	91.48	0.97	1.61	3.37	4.84	1850
31	36.07	50.47	50.03	1.76	2.92	6.11	3.12	3000
34	33.20	46.45	82.87	2.17	4.92	10.29	6.92	1838
35	35.04	49.03	87.43	1.82	3.02	6.31	6.25	868
659	33.64	47.07	80.40	1.35	2.24	4.68	14.02	738
661	31.83	44.54	79.46	1.15	1.90	3.97	16.50	575

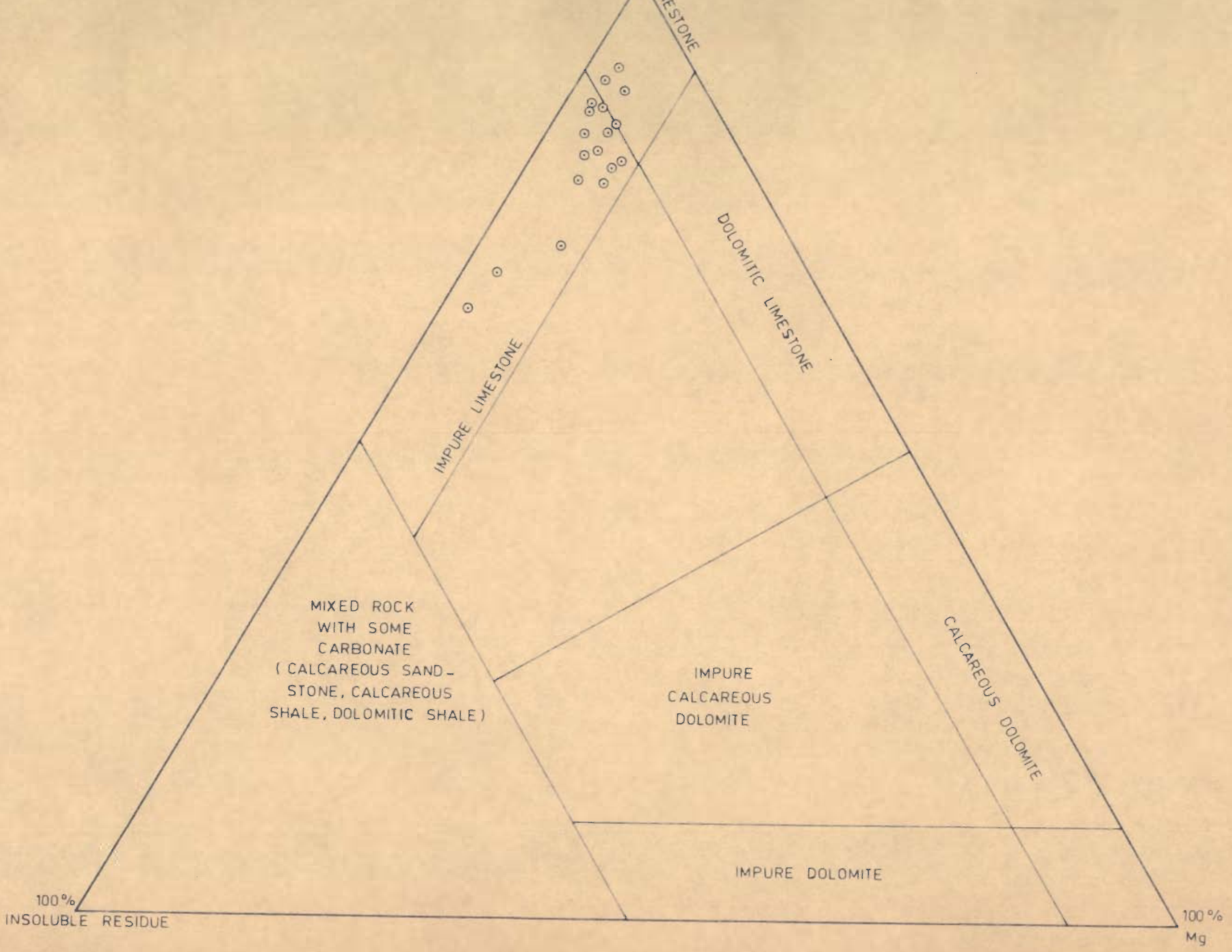


FIG. 3.64 _ LIMIT OF MIXED CARBONATE ROCKS (After Leighton and Pendexter, 1962)

there is a fall in the Sr from a dominant 3000 - 6000 ppm in the sediments to 50-150 ppm in lithified limestones.

The higher content of Sr in the limestones of the Miliolite Formation is because of their young age and the solution and reprecipitation of calcite on a limited scale.

3.3.4.5 Scanning Electron Microscope Studies

The Scanning Electron Microscope (SEM) was orginally used for the visual examination of surfaces of specimens, using secondary or back-scattered electrons leaving the surface on which the incident electron probe impinged. The early workers who stressed the importance of SEM in geological studies include Shoji and Folk (1964), Gillot (1969), Pittman and Duschatko (1970), Timur et al. (1971), and others. These people have dealt with microporosity and their importance. There have been a number of SEM studies during the last decade on certain aspects of ancient carbonate rocks, including chalks and caliche deposits, and also recrystallisation in the Pleistocene fossils. Recently it has gained importance in the recognition and interpretation of diagenetic fabrics as well. The diagenetic studies have been made by Longman and Mench (1978), Longman (1980) and Steinen (1978).

3.3.4.5.1 Method of Study

In the present study the limestone samples have been examined under the scanning electron microscope installed at the U.S.I.C. Roorkee University and also at the Institute of Petroleum Exploration, Dehra Dun.

3.3.4.5.2 Sample Preparation

The samples for study were broken from the hand specimens with a small cutting chisel. Small fragments of the sample were mounted on steel plugs approximately 1 cm in diameter. Loose debris were removed from the surface by gently blowing air over the surface. These surfaces were then sputter coated with a gold-palladium alloy under vaccum to attain a surface conductivity layer of approximately 300 Å thickness.

The coated specimens were mounted on the goniometer stage of the SEM and were viewed at various angles under different magnifications.

3.3.4.5.3 Results and Interpretations

The limestones are characterised by the presence of pore spaces. Two types of pore spaces are common in the specimens examined. They are (i) large pores and pore throats (interconnections between large pores) related to intergranular porosity; and (2) micropores (pores whose average diameter is less than $\frac{1}{16}$ mm as defined by Coequette and Pray 1970) and associated pore throats commonly related to intercrystalline or intra particle porosity.

In the present study it is noticed that intergranular porosity varies from vuggy and channal (Fig. 3.65,3.66,3.67, 3.69, 3.70,3.74) to micropores (Fig. 3.72, 3.73). Vuggy and channel porosity are the result of partial dissolution of calcite grains. Lack of cementation (Fig. 3.67,3.75) is another cause of this

FIG.3.65 VUGS PRODUCED DUE TO SOLUTION OF LIMESTONE IN LITHOFACIES IIB.

FIG.3.66 INTERGRANULAR VUGS NOT FILLED WITH ANY CEMENT IN LITHOFACIES IIB.

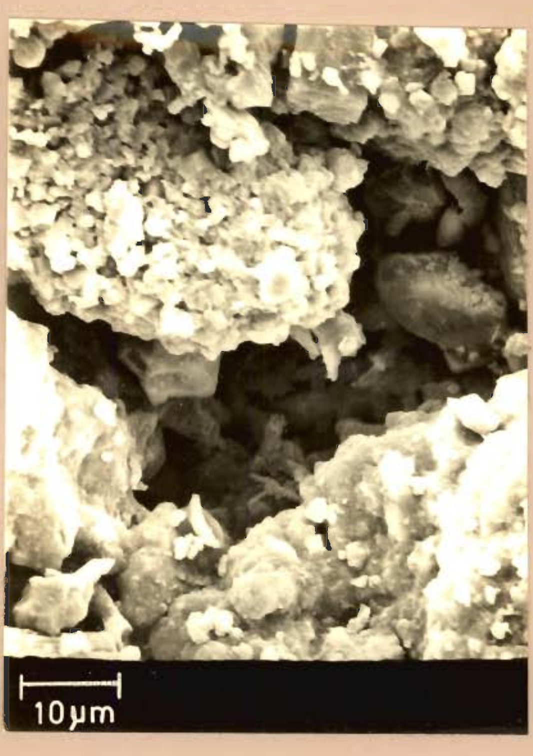


FIG. 3·65

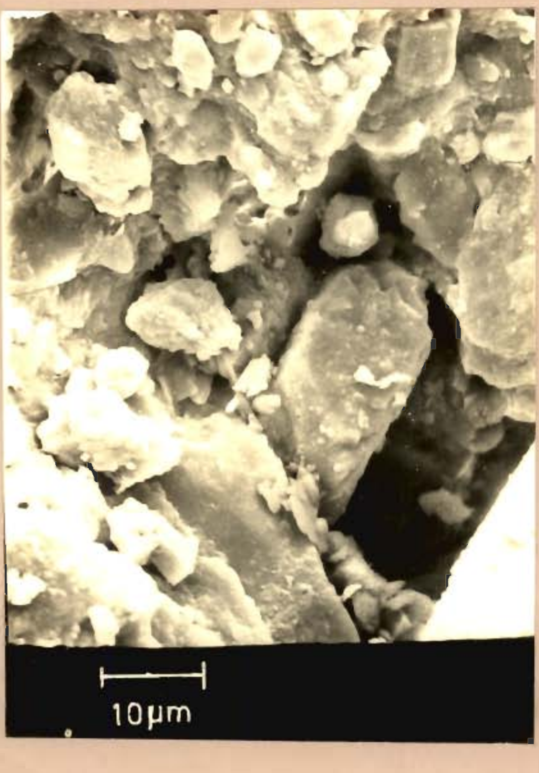


FIG. 3·66

FIG.3.67 MICRITE AND PART OF A PELLET WITH INTERGRANULAR VUGGY POROSITY. NOTE THE ABSENCE OF MENISCUS CEMENT AROUND THE PELLET. LITHOFACIES IIB.

FIG.3.68 CALCITE CRYSTAL BETWEEN MICRITIC ALLOCHEMS. INTERGRANULAR VUGGY POROSITY IS VERY PROMINENT. LITHOFACIES IIB.

FIG. 3.67

FIG. 3.68

FIG.3.69 VUGGY POROSITY PARTLY FILLED WITH RHOMBIC CALCITE CEMENT. THE RHOMBS ARE LESS WELL FORMED THAN DOLOMITE RHOMBS AND HAVE ROUNDED EDGES. LITHOFACIES III.

FIG.3.70 VUG PRODUCED DUE TO SOLUTION OF LIMESTONE. IT IS PARTLY FILLED WITH RHOMBS OF CALCITE. NOTE THE COARSENING OF CRYSTALS FROM THE WALLS TOWARDS THE CENTRE. LITHOFACIES IC.

FIG. 3·69

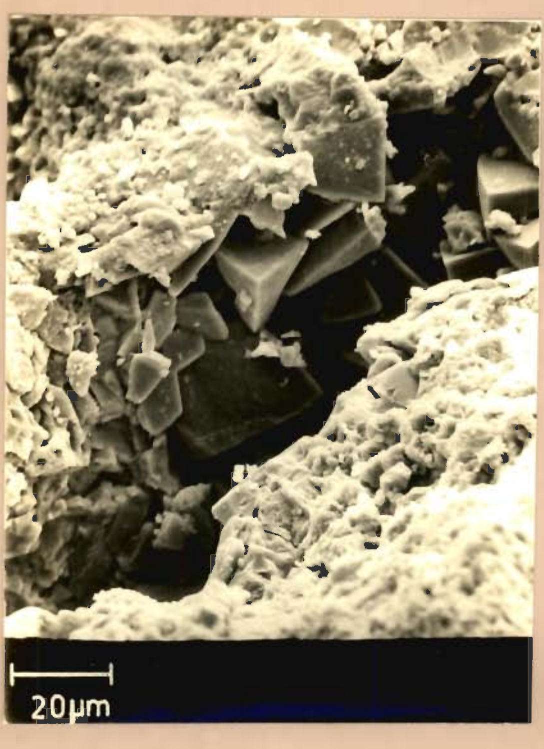


FIG. 3·70

type of porosity. Even in cement, micropores can very well be seen.

Intragranular porosity is common in pellets. The pellets contain micrite and not aragonite. During the transition of aragonite to calcite primary microporosity will be generally modified, i.e.,the pore geometry is changed. Another reason for the porosity is the solution of the micrite grains.

Intragranular porosity is seen in a few cases in microspars (Fig. 3.76) and also fossils. These are due to the dissolution.

A striking feature noticed is the presence of minute openings between calcite crystals in apparent contact (Fig.3.78,3.79). They are very thin uncemented planar pores between adjacent crystals. Wardlaw (1976) suggested the term"interboundary-sheet" pores (ISP) for such "cracks". In the present study they seem to be growth phenomenon, because ISP's are observed adjacent to crystals showing zoning. These are not seen in micrites. Longman and Mench (1978) also noticed such ISP's in some dolomites of the Edwards limestone of south central Texas. Wardlaw (1976), based on experiments, explained this as a result of the presence of a water film capable of supporting a shear stress.

Micrite occurs as distinct subrounded crystals (Fig.3.71,3.72, 3.73). Some portions are tightly cemented whereas others are not and show intergranular microporosity (Fig.3.72, 3.73). The micropores are interconnected. Sometimes crystals size distribution is bimodal and coarser crystals occur as clusters surrounded by micrite (Fig.3.72). The coarser crystals are of similar size and do have

FIG.3.71 FINE GRAINED MATRIX. VUGGY POROSITY IS WELL DEVELOPED. LITHOFACIES IIB.

FIG.3.72 FINE-GRAINED MATRIX WITH CLUSTERS OF COARSE CRYSTALS. COARSEST CRYSTALS MIGHT HAVE GROWN INTO OPEN MOLDIC PORE SPACE. NOTE THE INTERGRANULAR MICROPOROSITY. LITHOFACIES III.

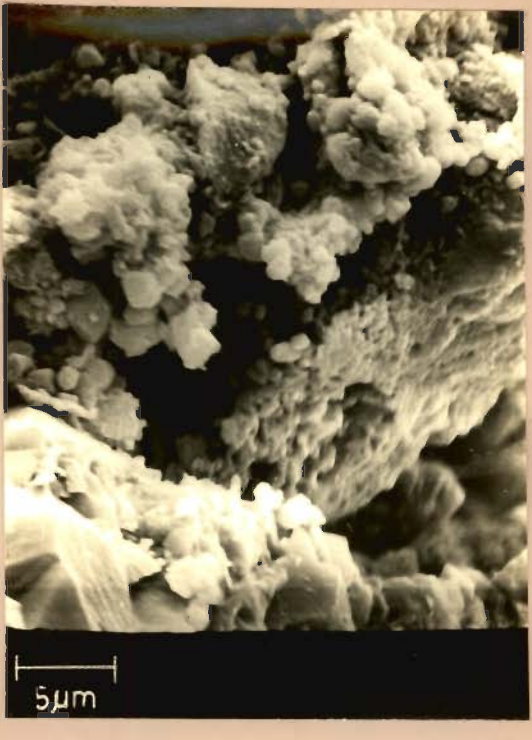


FIG. 3.71

FIG. 3.72

FIG.3.73 MICRITE GRAINS WITH INTERGRANULAR MICRO POROSITY. LITHOFACIES IIB. MAGNIFICATION: X 640.

FIG.3.74 PELLET_ AND INTERGRANULAR POROSITY SEEN IN LITHOFACIES IIB. MAGNIFICATION: X 40.

FIG.3.75 VUGGY POROSITY SURROUNDING A FOSSIL. NO CEMENT IS PRESENT. LITHOFACIES IIB. MAGNIFICATION: X 80.

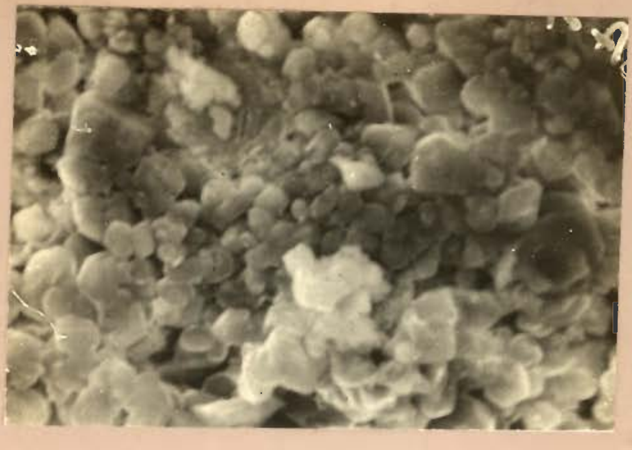


FIG.3.73

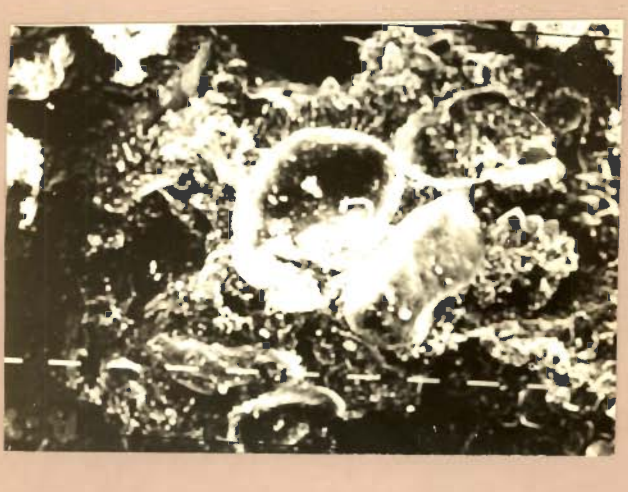


FIG. 3.74

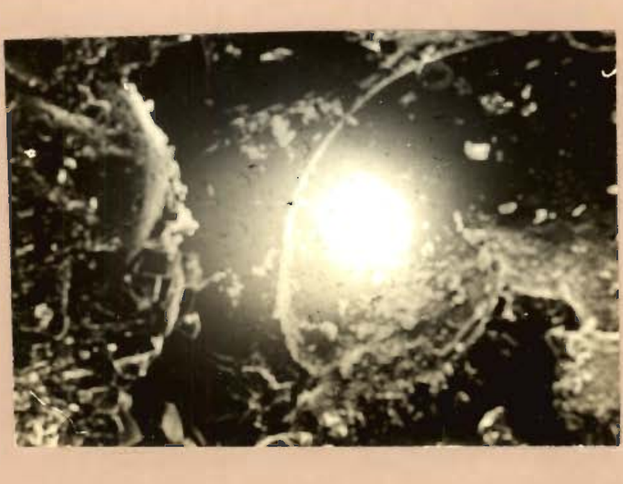


FIG. 3.75

distinct crystal faces. These crystals might have been produced by the neomorphism of micrite. The neomorphism of micrite to microspar results in an increase in grain size and a decrease in total surface area. Smaller grains dissolve more easily because of higher surface area to volume ratio and provide Ca CO_3 for enlargement of other grains thus decreasing the free energy of the system.

Sparry calcite cement is common. Sparry calcite have different shapes (Fig. 3.69, 3.77) and occur as equant, tabular, pyramidal, scalenohedral and rhomboidal crystals. They have well developed crystal faces. Most of the rocks are partly cemented showing vuggy porosity. In many cases the vugs and channels are lined with sparry calcite having a variety of shapes. Rhombic crystals are common. The crystals coarsen towards pore centres.

Zoning of calcite is very clearly seen on account of distinct thin layers representing growth stages of the rhombs (Fig.3.78, 3.79).

Dolomite crystals also have been noticed (Fig. 3.80). The development of dolomite is common, which is represented by zoning (Fig. 3.81, 3.82, 3.83). The zoning may be due to relative rates of crystal growth or due to a change in composition. Leaching of dolomite is also observed (Fig.3.84).

3.3.4.6 Diagenesis

Limestone is prone to alteration, in both pre and post consolidation phases. Most important are the changes in texture

FIG.3.76 INTRAGRANULAR AND INTERGRANULAR POROSITY. LITHOFACIES IIA. MAGNIFICATION: X 1188.

FIG.3.77 SPARRY CALCITE CEMENT WITH SOME INTERGRANULAR POROSITY. LITHOFACIES III.

FIG. 3.76

FIG. 3.77

FIG.3.78 CALCITE POLYHEDRA WITH INTERBOUNDARY PORE SPACES. ZONING IS VERY CLEARLY SEEN. LITHOFACIES III.

FIG. 3·78

FIG.3.79 CALCITE POLYHEDRA WITH VERY THIN INTERBOUNDARY PORE SPACE. LITHOFACIES IIB.

FIG. 3.80 RHOMBIC AND SCALENOHEDRAL CALCITE WITH DOLOMITE CRYSTALS. INTERGRANULAR POROSITY PRESENT. LITHOFACIES IIB. MAGNIFICATION: X 2500.

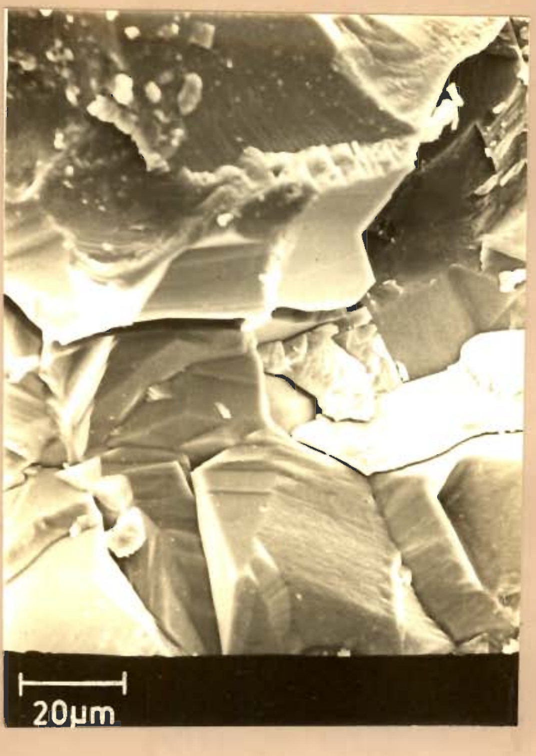


FIG. 3.79

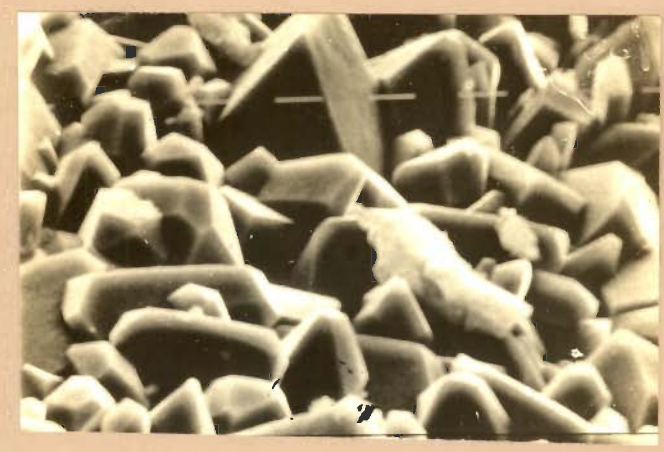


FIG. 3.80

FIG.3.81 A PARTIALLY DEVELOPED DOLOMITE. LITHOFACIES IIA. MAGNIFICATION: X 320.

FIG.3.82 DEVELOPMENT OF DOLOMITE. PARALLEL RIDGES AND GROOVES. LITHOFACIES IIB. MAGNIFICATION: X 104.

FIG.3.83 SECONDARY POROSITY CONSITING OF SLIT LIKE OPENINGS DUE TO THE DEVELOPMENT DOLOMITE. LITHOFACIES IIA. MAGNIFICATION: X 640.

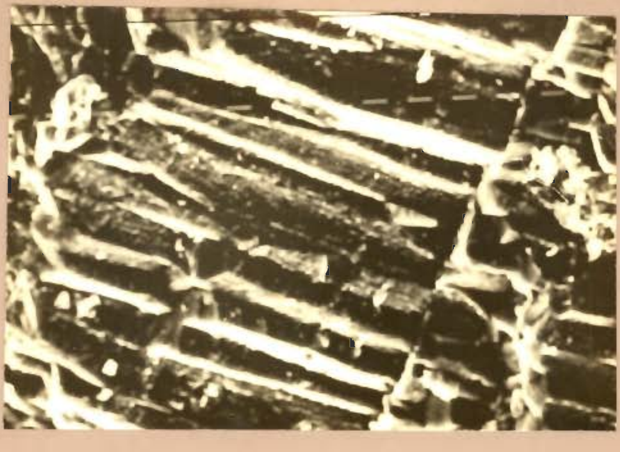


FIG. 3.81

FIG. 3.82

FIG. 3.83

FIG.3.84 RHOMBIC DOLOMITE SHOWING SOLUTION FEATURE ON THE SURFACE OF A CRYSTAL DUE TO DE-DOLOMITISATION. LITHOFACIES IIB. MAGNIFICATION: X 320

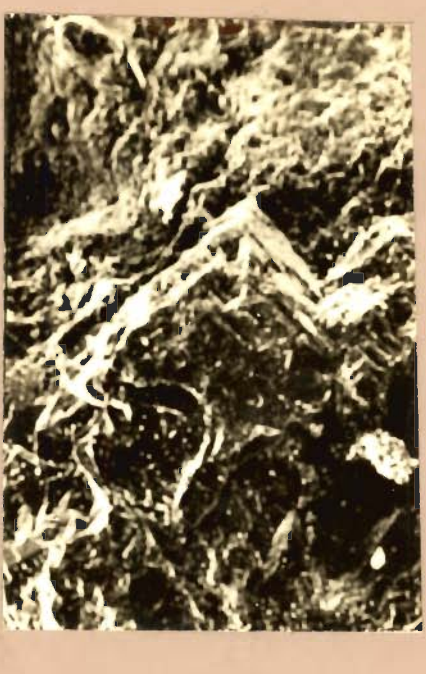


FIG. 3.84

and composition which lead to the formation of dolomite. Diagenetic environments may be independent of depositional environments and may change through time.

Until recently various workers on carbonate rocks have discussed in general about the diagenesis in the subaerial, freshwater environment. Based on petrographic studies of Pleistocene carbonates of Bermuda, Land (1967) described the diagenetic changes and divided the developments into five stages, which was supported by isotopic studies (Gross, 1964; Friedman, 1964; Land, 1967). Based on the study of various workers (Land, 1970; Schoedder, 1973; Matthews, 1974; Longman, 1980; and others) four major diagenetic environments at the shallow depths can be distinguished. They are (i) freshwater vadose zone (above the water table) (2) fresh water phreatic zone (below the water table), (3) mixed freshwater - marine phreatic zone (below the water table), (4) marine phreatic zone.

In the present study except from Chorwad, all the other samples studied are from sediments in the vadose zone presently. At Chorwad, the samples collected from the top 6 m are from the vadose zone and the remaining samples are from the present mixed freshwater-marine phreatic zone. As described in section 3.3.4.3, X-ray analysis of the different samples indicate the presence of low Mg-calcite and dolomite and absence of aragonite. The limestones belonging to the Miliolite Formation can be grouped in Land's last stage (5th) of diagenetic developments because of the total absence of aragonite and high Mg-calcite, and the presence of low Mg-calcite.

Petrographic studies indicate that the limestones of the Miliolite Formation are characterised by the presence of micrite envelopes around shells and shell fragments. This feature has attracted various workers (Friedman, 1964; Bathurst,1966; 1975; Winland, 1968). According to them, the micrite envelope, apparently formed centripetally in carbonate grains by precipipitation of micrite in vacated algal bores, is initially composed of micritic aragonite or high Mg-calcite. Based on the laboratory experiments Kendall et al. (1966 in Bathurst, 1975) opined that during diagenesis the grain was dissolved and the organic matter of the envelope remained as a mould. According to Bathurst (1975) the microcellular structure of the organic matter from which aragonite crystals have been dissolved was later filled with calcite and its growth was restricted to the same micritic crystal size.

As discussed in earlier sections, the limestones are characterised by the presence of fibrous calcite, sparry calcite or micrite cement within the shells.

In the active marine phreatic environment the dominant cements are Mg-calcite and aragonite. Mg-calcite cement generally occurs in the form of micritic or steep sided rhombic crystals distributed as isopachous crusts on the grains and the aragonite cement as fibrous crystals (Longman, 1980). The presence of fibrous calcite and micrite indicate that at least some cementation has taken place in the active marine phreatic zone. Even though fibrous aragonite, micritic or fibrous Mg calcite cements can occur in the marine vadose zone (Longman,1980), the absence of meniscus and pendent textures in the present study, rules out this possibility.

As stated earlier, X-ray study indicates that dolomites occur in minor amounts (1.5 to 9.0%) in the limestones of this area. Further SEM study also indicates the presence of dolomite crystals and formation of dolomites. Studies by various workers (Land,1973 ; Badiozamani,1974) show that the important diagenetic process taking place in the mixed zone is the formation of dolomite. For dolomitisation to occur some process contributing to increased water circulation in the mixing zone is necessary. Tides can produce some movement in exceptionally porous rocks (Ladd and Schlanger, 1960 <u>in</u> Longman,1980). So it can be deduced that the limestones were once in the zone of mixing, when the formation of dolomite started. However the lower percentage of dolomite indicates that the rocks did not remain in the mixing zone for a very long period. Other diagenetic processes occurring in mixing zones at the freshwater end of this zone include slight cementatation, generally micritic to bladed calcite, minor neomorphism of aragonite to calcite, leaching of aragonite, and neomorphism of Mg-calcite to calcite. In many cases the shells and intergranular spaces are occupied by micrite. Atleast part of this also might have been produced in the mixing zone.

Longman (1980) divided the freshwater phreatic zone in to three sub-zones viz.(i) undersaturated zone or zone of solution near the water table characterised by the presence of moldic and vuggy porosity (2) active saturated zone. In this zone extensive rapid neomorphism of marine sediments to calcite occurs. Cement is common and widespread. Equant calcite cement and coarsening of crystals towards the pore centres and syntaxial overgrowths are characteristics of this zone. (3) stagnant freshwater phreatic zone. In this zone little additional cementation takes place. Recrystallisation of aragonite to calcite may be an important process, but often occurs within the grains along a narrow front. So structures of the aragonite grain are often preserved after neomorphism to calcite. In the present study, as stated earlier, many of the shell fragments contain fibrous calcite which indicates diagenesis in the stagnant fresh water phreatic zone, because the fibrous nature might be the original structure of the aragonite preserved. Similarly micritic Mg-calcite present in the shells also might have become micrite with low Mg-calcite.

The rocks are also characterised by the presence of calcite cement, often as equant crystals, with the coarsening of crystals towards the pore centre. This indicates that the aragonite crystals that were present in the shell fragments have been dissolved in the active saturated zone, whereas the outlines of the shells were preserved by the thin micritic envelope. Later on the moulds have been filled by calcite cement. Sometimes two generations of cement are noticed, where the first generation is in the form of scalenohedral calcite overlain by equant crystals. Syntaxial overgrowths are also common. These indicate diagenesis in the active saturated zone.

Most of the rocks are characterised by the presence of vuggy and channel porosity. This is an indication of diagenetic changes in the undersaturated zone. However this criterion cannot be used for differentiating diagenetic changes in the undersaturated zone, because vuggy porosity can be produced in the vadose zone also.

Neomorphic spars (microspars and pseudospars, but microspars are not numerous) are common in these rocks. Neomorphism includes all transformations between one mineral and itself or a polymorph (Folk, 1965, p.21). The most important form of recrystallisation in carbonate rocks is the neomorphism of micritie to microspar. The factors controlling the formation of neomorphic spar are still not understood. Even though the neomorphic spar occurs widely, its actual growth has not been observed either in the field or in the laboratory (Bathurst, 1975). Bathurst, (op. cit) described three types of neomorphic replacement. They are (1) patchy sparry replacement of detrital micrite, (2) sparry replacement of skeletal fabrics, such as the walls of molluscs or foraminiferids, and (3) replacement of detrital micrite by the outward syntaxial growth of crystals in the walls of allochems. All these features have been noticed in the present study. Rounded grains containing sparry calcite with faint concentric rings are also evidences of neomorphism of micrite to sparrite in oolitic grains. Chafetz (1972) and Folk (1974) considered that weathering of limestones helps in the formation of microspars and pseudospars. According to Longman (1977), the formation of microspar is possible only by removal of Mg^{2+} ions. Porosity also influences their formation. All these conditions are met with in the area under study because these features are common in the samples from the vadose zone and these factors might be controlling the formation of the neomorphic spars in the present case. But it is surprising that the characteristic vadose zone cements are absent. It is possible that the neomorphism might have obliterated these features.

The thin section and electron microscopic study indicates the presence of both primary and secondary porosity in the Miliolite Formation. The primary porosity is due to the lack of complete cementation. Intergranular spaces are not completely filled with cement. Secondary porosity is due to the solution of limestone and also due to the formation of dolomite crystals. The solution of limestones has produced small intergranular and intragranular pore spaces, as well as karstic features - which account for the major portions of porosity and permeability in these rocks.Intragranular porosity does not contribute much towards the movement of groundwater in this formation.

From the foregoing, the general diagenetic history of the limestones belonging to the Miliolite Formation can be summarized as follows:

Stage 1. Deposition of marine carbonte sediment consisting of foraminifers, molluscs, algae and echinoderm fragments with minor amounts of quartz and occasionally rock fragments. Some amount of micrite in the form of aragonite or high Mg-calcite might also have been deposited along with this.

Stage 2. Starting of diagenesis in the relatively stagnant marine phreatic environment. The micrite envelopes are formed by the action of boring algae. Some amount of intragranular cementation also might have taken place.

Stage 3. Change into an active marine phreatic environment in which cementation by fibrous aragonite and Mg-calcite occurred.

Stage 4. Subaerial exposure where there is a mixing of fresh and marine waters and which resulted in the formation of dolomite.

Stage 5. Diagenesis in the freshwater phreatic zone. Cementation in the pore spaces started. The cement coarsens towards pore centres.

Stage 6. Continued diagenesis in the freshwater phreatic zone. Aragonite and high Mg-calcite are leached to produce moldic porosity. These pores have been filled with sparry calcite cement. At the same time because of some conditions prevailing at that time and which is difficult to explain, in many cases neomorphism of aragonite and high Mg-calcite grains without undergoing a solution stage has taken place. This is represented by the presence of micrite and fibrous calcite inside shell fragments and also absence of aragonite and presence of micrite inside pellets. The stages 5 and 6 must have been of short duration, because in most cases intergranular spaces are not completely filled with cement.

Stage 7. The limestones have been exposed to the freshwater vadose zone. Solution of limestone took place. Vuggy porosity was produced. Neomorphism of micrite to pseudospar also has taken place.

3.3.4.7 Envrionment of Deposition

The Miliolite Formation has been divided into three lithofacies based on the field characteristics. Lithofacies IA represents thin clay bands towards the bottom. This is seen only in the northwestern portion of the area. This might have been deposited in lagoons during a regressive phase. Lithofacies IB and C are characterised by the presence of planar cross-bedding and also conglomerates and small pebbles. The rocks belonging to this facies are exposed along the river courses and also met with in a bore hole at Chorwad. This represents a fluvial process and the deposition might have taken place along the old river channels affected by tides. I B was deposited by migration of dunes in the lower flow regime whereas I C was deposited in the plane low phase of the upper flow regime.

Lithofacies II A contains mainly shell fragments and II B is characterised by the presence of herringbone type of cross-bedding and alternate bands of compact limestone and shelly limestone. Such cross-beds are common in outer, sea-ward parts of shelves, down slope from beaches where long shore currents exist (Thomson and Thomasson, 1969; Stricklin and Smith, 1973; as quoted by Wilson,1975). These are caused by scour and subsequent fill by mega ripples formed in moderately strong currents. Towards the shore, where the wave base impinges on the sea-floor, turbulent bottom conditions will prevail resulting in the winnowing away of lime mud and hence skeletal sands will be piled up in to shoals and bars. Lithofacies II A and II B might have been deposited in the littoral zone dominated by strong wave action and transitional area between littoral and shelf zones respectively. On the basis of foraminiferal studies of similar limestones occurring near Jaffrabad along the south east coast of Saurashtra, Verma (1979) has indicated the presence of abundant Miliolids, *Ammonia*, and *Elphidium* together with sporadically occurring species of planktonic foraminifera, confirming the depositional environmental deductions made above.

Lithofacies II C is a chalky bed. This contains a lot of foraminifera, especially benthonic species and suggest a site of deposition on the shelf and most probably on outer part of the shelf.

The lithofacies II A and II C are comparable in all respects to Y and X zones of Irwin (1965) whereas II B reprepresents a transition between these two facies. However, his model of carbonate sedimentation cannot be exactly used in this context because of the non-existence of lagoons,i.e., Z zone.

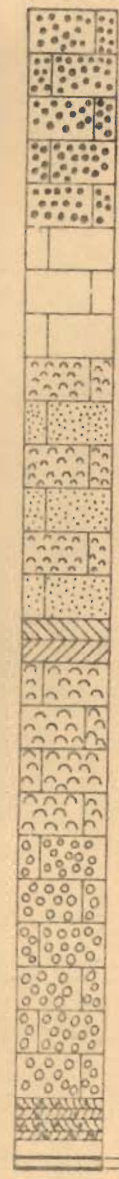
Marathe et al. (1977) recognised two transgressions of the sea during the deposition of Miliolite Formation. Further based on petrographic, archaeological and ^{14}C dating they opined that these took place during Mid Pleistocene and Late Pleistocene (20,000 to 30,000 years B.P.) times. The lithofacies I and II in the present study seem to have been deposited during the later transgression of the sea.

Lithofacies III is pelletic calcarenite. It occurs as parallel linear ridges in the field parallel to the present dominant wind direction and show planar cross-bedding. These features suggest that they have been deposited by the wind action by reworking of older sediments. However, abundant pellets indicate that older sediments were deposited in lagoons left behind by a regressing sea.

A composite section showing the different lithofacies of Miliolite Formation is given in Fig. 3.85.

3.3.5 Chaya Formation

The name 'Chaya Formation' was first proposed by Mathur and Mehra (1975) for a group of rocks which are white to dirty white in colour and consolidated to semi-consolidated in nature. Sometimes they contain lot of shell fragments and fossils. This forms the upper part of the Porbandar Group. Mathur and Mehra (1975) have included under Chaya Formation the 'Coast-fringing rocks' 'Oyster beds', and 'Dead coral reefs' of Fedden (1884), and Sub-Recent deposits of Sastri and Pant (1959).



		ENVIRONMENT OF DEPOSITION
LITHOFACIES III	PELLETIC CALCARENITE THE FACIES OCCURS AS ELONGATED MOUNDS IN THE FIELD AND IS EITHER CROSS-BEDDED OR THINLY LAMINATED. CROSS-BEDS SHOW VARIABLE DIRECTIONS SOLUTION CAVITIES ARE NUMEROUS AND IT STARTS ALONG THE BEDDING PLANES.	REGRESSIVE LAGOONAL SHEET DEPOSITS REWORKED BY WIND
LITHOFACIES II C	MODERATELY SOFT, CALCAREOUS, SILTY, CHALK (MICRITE) CONTAINS CLAY MINERALS LIKE MONTMORILLONITE AND ILLITE. RICH IN FORAMINIFERA AND INCLUDE PLANKTONIC AND BENTHONIC FORMS THESE INCLUDE THE DEEPER WATER BIOFACIES SUCH AS CIBICIDES UVIGERINA, BULIMINA, CASSIDULINA, BOLIVINA, EPONIDES, NONIONELLA, FISSURINA, AND LAGENA.	SHELF ZONE
LITHOFACIES II B	CROSS-BEDDED OR FLAT-BEDDED SHELL LIMESTONE AND ALTERNATE BANDS OF I HARD COMPACT LIMESTONE AND SHELL LIMESTONE. CROSS-BEDDING IS PLANAR AND TABULAR PLANAR. THE THICKNESS OF FLAT LAMINATED BANDS VARIES FROM 0.5 TO 2 Cms. NEOMORPHISM IS COMMON. SPARRY CALCITE OCCURS BOTH AS CEMENT AND NEOMORPHIC GRAINS. QUARTZ GRAINS, PELLETS, OLLITES, AND SUPERFICIAL OLLITES ARE PRESENT, BUT NOT VERY COMMON	LITTORAL ZONE AND LITTORAL TO SHELF ZON
LITHOFACIES II A	SHELLY LIMESTONE IT CONSISTS MAINLY OF SHELLS AND FOSSILS SIZE OF SHELLS VARIES WITHOUT REGULARITY FROM BOTTOM TO TOP. SOME AMOUNT OF INTRACLASTS, DETRITAL QUARTZ AND OCCASIONAL PELLETS, OOLITES AND SUPERFICIAL OOLITES ARE PRESENT. THE LIMESTONES ARE ESSENTIALLY HORIZONTALLY BEDDED AND ARE POROUS AND VUGGY NATURE. SOLUTION CAVITIES ARE COMMON ESPECIALLY WHEN THE LIMESTONE IS COMPACT AND SHELL FRAGMENTS ARE SMALLER IN SIZE.	LITTORAL ZONE AFFECTED BY WAVES
LITHOFACIES I C	PEBBLY LIMESTONE CONTAINS LOT OF PEBBLES AND CONGLOMERATES THE SIZE OF THESE VARIES AND THE MAXIMUM SIZE IS 8 Cm. TOWARDS TOP THE LIMESTONE IS VUGGY. THEY CONTAIN LOT OF FOSSILS WHICH ARE SMALLER IN SIZE. PEBBLES ARE MOSTLY OF GAJ LIMESTONE AND CLAYS. THE SIZE OF SHELLS VARIES. CONSISTS MAINLY OF SHELLS AND FOSSILS BUT SOMETIMES THE AMOUNT OF PELLETS IS SEEN TO BE ABOUT 45% OF THE ALLOCHEMS. NEOMORPHISM IS COMMON. THE BEDS ARE FLAT BEDDES.	FLUVIAL PROBABLY AFFECTED BY TIDES
LITHOFACIES I B	CROSS-BEDDED COMPACT LIMESTONE OCCASIONAL PEBBLES ARE PRESENT. CROSS-BEDDING IS PLANAR AND SHOW VARIABLE DIRECTIONS. SHELLS ARE SMALL IN SIZE	
LITHOFACIES I A	THIN BANDS OF BROWNISH CALCAREOUS CLAYS	LAGOONAL

MARINE TRANSGRESSION

FIG 3.85 _ COMPOSITE SECTION SHOWING THE DIFFERENT LITHOFACIES OF MILIOLITE FORMATION

The limestones occur as ridges along the coast. The exposed surface of the limestone is generally in the form of a hard duricrust. On weathering, at times, it gives a 'honey-comb' structure. Below this hard duricrust, the limestone is soft and brittle and easily breaks under the pressure of fingers.

These limestones contain a rich assemblage of marine invertebrates, like molluscs, echinoids, and corals. These might possibly be of marine origin and the deposition might have taken place in the intertidal zone.

3.3.6 Sand Dunes, Beach Sands and Alluvium

In many parts of the coast, sand dunes are common. They rise only few metres above sea level. The dune sand is highly calcareous. Some of the dunes are more or less stabilised and at times lithified. It is very well seen near Mangrol coast forming calcrete deposits.

Beach sands occur all along the coast, in the intertidal zone. They are highly calcareous and contain a large number of broken shell fragments, micro organisms and rock fragments.

River sand and alluvium is present along the river courses. They are not very thick and sometimes on the river banks these occur as semiconsolidated deposits.

CHAPTER 4

GEOHYDROLOGY

4.1 OCCURRENCE OF GROUNDWATER

As described in the previous chapter, the rock formations met within the area under investigation are Deccan Trap basalts unconformably overlain by the Gaj and Dwarka Formations of Tertiary age, which in turn are overlain by Quaternary limestones belonging to the Miliolite and Chaya Formations. Only three wells tapping the Deccan trap basalt have been studied. Dwarka Formation is of restricted occurrence in the area and no wells are tapping this formation. So, in the present study the groundwater conditions in the Miliolite and Gaj Formations have only been studied in detail. All these geological formations occurring in the coastal area contain porous and permeable zones which act as aquifers. A total of 110 wells tapping these formations have been inventoried during March 1978 and October 1978.

The exploitation of groundwater in the area is through dug and dug-cum-bore wells. Most of the wells are rectangular in shape. The average cross-sectional area of the rectangular wells is 3.2 x 2.1 m. The depth of the wells varies from 4.0 m. to 32 m below ground level. From the bottom of the wells drill holes having a diameter of 10 to 15 cm are put. Such drill holes are more common in wells tapping the Gaj Formation than those in Miliolite Formation. Both vertical and horizontal borings are made, but vertical ones are more common. Boring is generally carried out with the help of hydraulic rotary machines. The draft from the wells are by using electric motors or oil engines. The groundwater is utilised mainly for domestic and agricultural purposes. Even though the groundwater occurring near to the coast is of poor quality, in many instances these waters are being used for domestic and irrigation purposes. This aspect is dealt with in detail in Chapter 5. The general hydrogeologic properties of the different formations is given below.

4.1.1 Deccan Trap

The Deccan Trap basalts occurring in the area under study are of massive and amygdaloidal types. They occur at the northern border of the area. In some places even though they are altered to laterite, the thickness of the weathered portion is not much and hence no wells tap laterite. The porosity in basalt is of secondary nature which is due to the presence of joints and fractures. Because of the absence of any surface outcrops, these features could not be studied in detail.

The wells range in depth from 20 m to 27 m below ground level. The wells are of dug type and are rectangular in shape. Frequency distribution of well depth and depth to water level are shown in Tables 4.1 and 4.2.

4.1.2 Gaj Formation

The Gaj Formation consists essentially of alternating bands of limestones and clays. Generally the upper horizons (upto about 30 m) are under unconfined condition. The limestone is fossiliferous hard, and compact in nature. The rocks are characterised by the presence of double porosity, i.e., porosity of blocks and porosity of fissures. Porosity of blocks is primary in nature and is due to the presence of intergranular pore spaces. The limestones contain clay particles also. Hence even though the rocks are porous, permeability is very much reduced. Secondary porosity is developed by the presence of fractures, joints, and solution openings. The solution openings are very few, probably because the presence of clay is detrimental in the solution of limestone.

Generally, the groundwater occurs at deeper levels in the Gaj Formation. The depth to water level is partly controlled by topography, because, the areas occupied by these rocks are at higher elevations than those occupied by Miliolite Formation. The depth of the wells varies from 4.7 m to 32 m below the ground surface. Frequency distribution of well depth and depth to water level are shown in Tables 4.1 and 4.2. Majority of the wells are in the depth range of 10-15m below ground level.

4.1.3 Miliolite Formation

The groundwater in the Miliolite Formation occurs under unconfined conditions. The Miliolite Formation occupies the coastal part comprising the coastal ridges, coastal depressions and a part of the coastal plain. The maximum thickness of this formation is reported to be 40 m. As discussed in the Secti 3.3.4.5.3, these limestones contain intergranular, intragranular, channel, and vuggy porosity. More over, the Miliolite Formation is characterised by the presence of karstic features. In most cases the primary intergranular porosity is not destroyed by diagenesis as is evidenced by microscopic and SEM studies. The presence of vuggy and channel porosity and karstic features indicate the solution of limestones.

Solution of rocks will produce two types of karstic features (Stringfield, Rapp, and Anders, 1979). They are (1) surficial features that do not reach more than a few metres below the land surface, and (2) karst features that affect the permeability of rocks and circulation of water below the surface such as solution cavities, dolines etc. Both these types of karstic features are met with in the present area under study as described in section 3.2.1. The superficial features present are in the form of grikes, clint, and karren. These are observed in areas where there is no soil cover and the rocks are hard and compact (lithofacies III of Miliolite Formation). Joints present in the limestone are widened by the solution activity to produce karren. Similarly grikes and clints are formed by the dissolution of carbonate grains when rain water passes through intergranular pore spaces.

These various types of secondary porosities are extensively developed in lithofacies I,IIA and IIB of the Miliolite Formation which form the major aquifers. Of these facies, lithofacies I is of limited areal extent restricted to regions close to modern large streams whereas lithofacies IIA and IIB underlie large tracts.

Drill hole data indicate that there is a solution cavity zone in the Miliolite Formation in the depth range of +2.47 m to

-18.89m. The water level elevations with reference to mean sea level ranges from 3.48m to -1.67m. This means that solution activity is more pronounced below the water table. Many workers (e.g. Swinnerton, 1949 etc.) have noticed that under water table conditions, the zone of greatest permeability will be just below the water table because this is the zone of greatest circulation and solution. The lowering of the water table also takes place as a result of increase in permeability because of the enlargement of solution openings. It is probable that in the Miliolite Formation also, the lowering of water table has taken place. This is evidenced by the presence of big solution cavities above the water table near Husainabad (Shardagram) and near Mangrol.

As mentioned earlier, karst openings extend below the present sea-level. This is an indication of lower stands of sea during the Pleistocene, after the deposition of sediments had taken place. During this period, circulation of water and solution might have taken place below the present sea-level producing solution openings. Such phenoma has also been reported by other workers (eg. Le Grand and La Moreaux 1975).

The data about the depth of wells and water levels is shown in Table 4.1 and 4.2. Majority of wells fall within the depth range of 5 m to 10 m. The wells located near to the coast are of shallow depth.

Table 4.1 Summary Statistics of Dug wells in Miliolite Formation Gaj Formation, and Deccan Trap Basalts

Lithology	Depth of the well (m)			Depth to Water Level(m)Pre-monsoon			Depth to Water level(m)Postmonsoon			Water Level Fluctuation(m)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Miliolite Formation	21.0	27.0	8.59	2.90	17.0	9.40	2.80	18.15	6.23	0.15	4.20	1.25
Gaj Formation	4.7	32.0	16.30	6.60	28.0	14.93	1.60	21.70	8.60	0.90	9.10	4.99
Deccan Trap Basalts	20.0	27.3	25.60	17.73	20.5	19.60	4.48	7.28	5.45	9.51	14.37	11.94

Table 4.2: Summary Statistics of Dug Wells in Miliolite Formation Gaj Formation and Deccan Trap Basalts

	Formation			Depth to Water Level March 1978			October 1978		
Depth range (m)	Miliolite formation	Gaj Formation	Deccan Trap Basalts	Miliolite Formation	Gaj Formation	Deccan Trap Basalts	Miliolite Formation	Gaj Formation	Deccan Trap
0-5	2	0	0	10	1	1	7	17	2
5-10	20	4		18	4	1	26	25	2
10-15	15	24	0	7	11	0	9	8	1
15-20	10	10	1	8	7	1	8	3	0
20-25	3	13	2	1	2	0	0	3	0
25-30	0	2	1	0	2	0	0	0	0
30-35	0	1	0	0	0	0	0	0	0
40-45	0	2	0	0	0	0	0	0	0
Total	50	56	4	44	27	3	50	56	5

4.2 GROUNDWATER LEVELS

The study of historic groundwater level data are important in the evaluation, development, and management of groundwater. These data are used to assess the changes in storage and its response to rainfall, evaporation, draft, and irrigation. The data on ground water levels also help in the analysis of flow patterns in an area. Water levels in wells generally fluctuate due to recharge and discharge processes. The vacillation in groundwater may also be due to external causes, such as barometric pressure, earthquakes and other artificial factors. The influence of all these factors may operate singly or in combination resulting in long term, seasonal or daily changes in ground water levels. Long term and seasonal fluctuations are of considerable interest to hydrogeologists.

4.2.1 Relationship between Rainfall and Groundwater Levels

Rainfall is one of the most important factors which influences groundwater levels. In the present case an attempt has, therefore, been made to study the intensity and periodic variation of precipitation and to investigate as to how it affects the groundwater levels in the region. The periodic distribution and intensity of rainfall and the corresponding ground water level fluctuations are shown in Figs. 4.1 - 4.3, for 16 wells tapping Miliolite Formation, Gaj Formation and Deccan Trap basalts during the years 1977 to 1979. Most of the rainfall occurs during four months of the year, i.e., from

June to September. Occasional rains occur in November also. December to May is a dry period during which normally no rains takes place. A perusal of the hydrographs (Fig. 4.1 to 4.3) indicates that the water table rises with rainfall and during the non-rainy mohths the water table gradually declines. This is more pronounced in the Gaj Formation (Vallabhgadh, Goraj, Rudalpur and Sepa villages) and Deccan Trap rocks (Seriakhan, Simroli) than in Miliolite Formation (Kalej,Khambhalia, Kukaswada, Mangrol, Mangrol Bandar, Sil, and Jhariawara villages). Eventhough peak to peak correlation between the rainfall and water levels is not very good, water level rises to their maximum during September or October, i.e., generally at the end of the rainy season.The maximum fall in ground water level is observed generally in May and sometimes in June, i.e., just before the onset of the monsoon.

An attempt has been made to compute correlation coefficient between the rainfall in the preceding month and groundwater levels of the succeeding month, in order to study the effect of rainfall on water levels quantitatively. Pearsons linear correlation coefficient 'r' was calculated using the equation 4.1.

$$r = \frac{1 \quad (x_i - \bar{x})(y_i - \bar{y})}{n \quad \sigma x \quad \sigma y} \qquad (4.1)$$

where n denotes the number of pairs of values of the two variables, $\bar{x}$ - the mean of x_i values, $\bar{y}$ - the mean of y_i values, σ x standard deviation of x_i values and σ y standard deviation of y_i values.

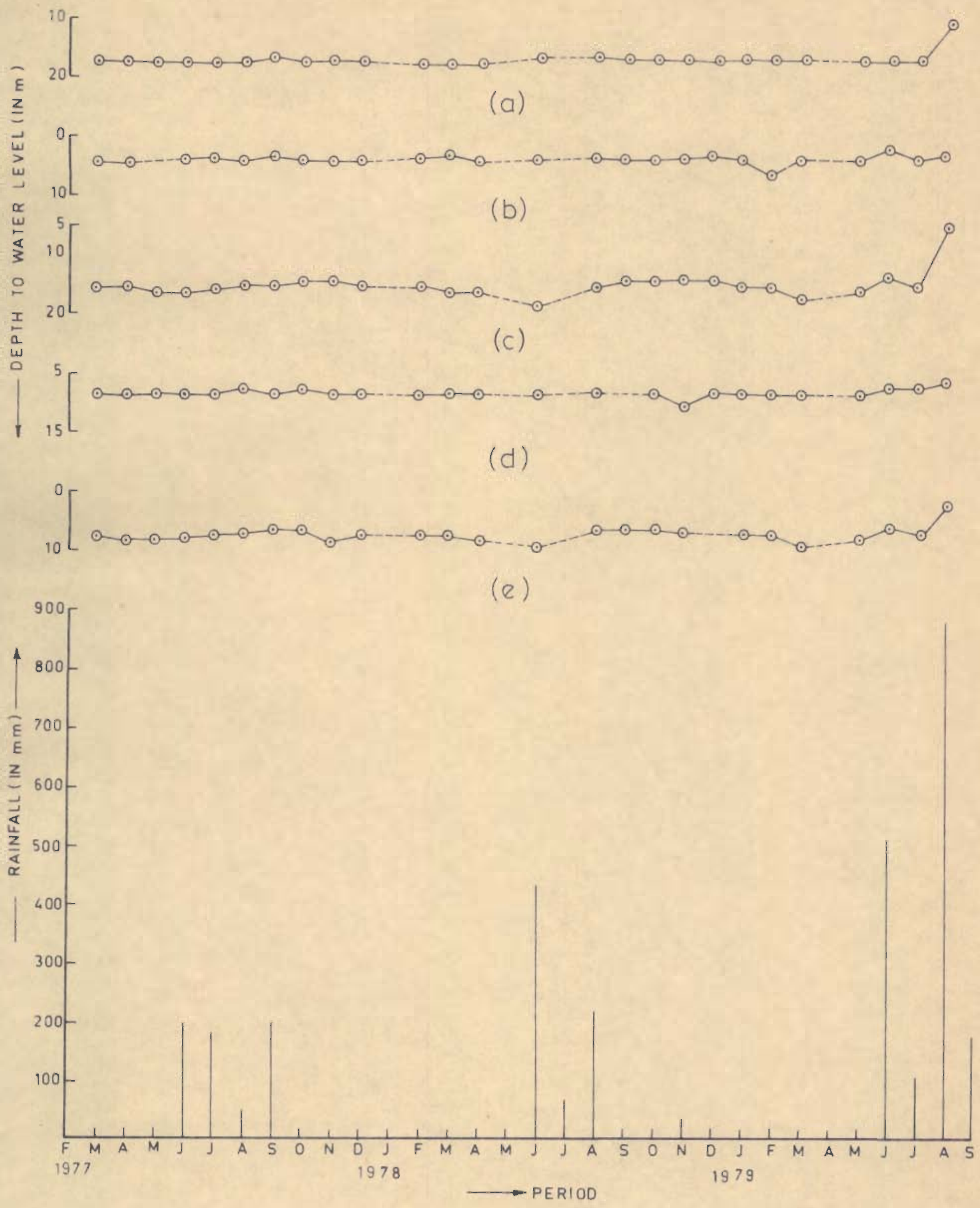


FIG. 4.1 _ HYDROGRAPH SHOWING RAINFALL AND GROUNDWATER LEVEL IN WELLS TAPPING MILIOLITE FORMATION

(a) KALEJ, (b) MANGROL BANDAR, (c) BAMANWARA, (d) SIL

(e) JHARIAWARA

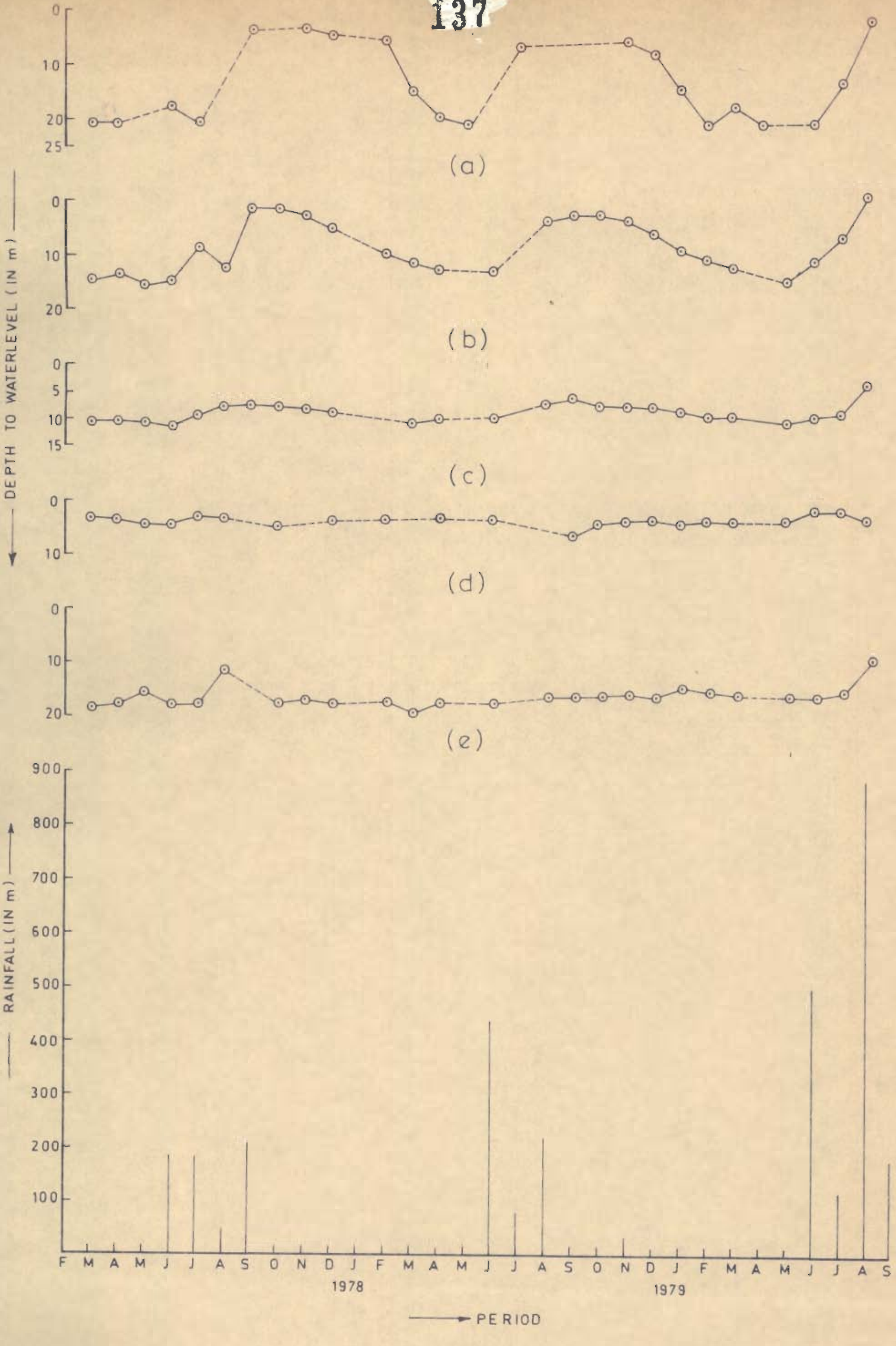
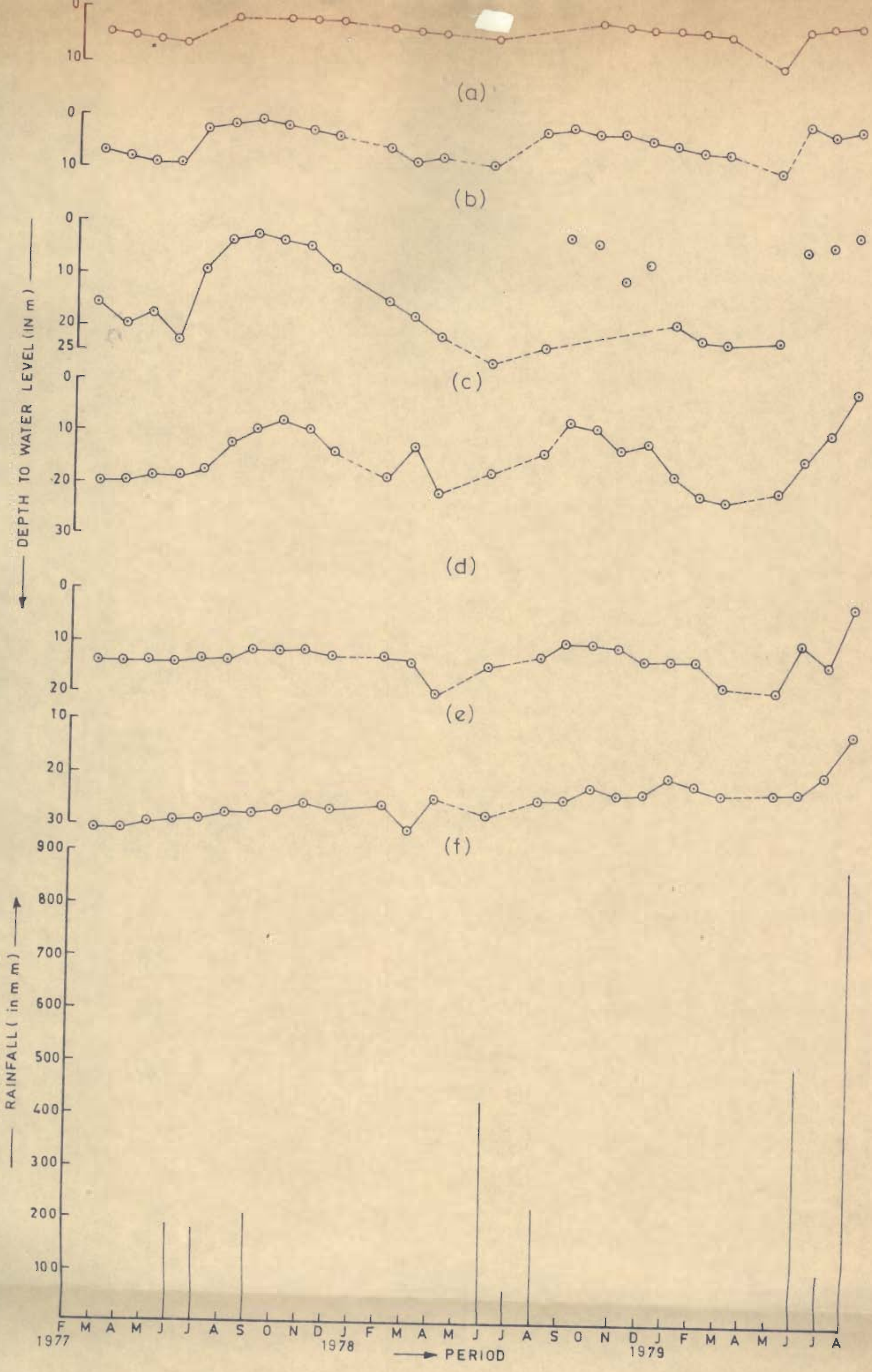


FIG. 4.2 _ HYDROGRAPH SHOWING RAINFALL AND GROUNDWATER LEVEL.
(a) SERIAKHAN (b) SIMROLI (c) KUKASWADA (d) KHAMBHALIA (e) MEKHRI.
a and b-WELLS IN DECCAN TRAPS c,d and e-WELLS IN MILIOLITE FORMATI



IG. 4. 3_ HYDROGRAPH SHOWING RAINFALL AND GROUNDWATER LEVEL IN GAJ FORMATION

(a) BUDECHA (b) VALLABHAGADH (c) GORAJ (d) GORAJ (e)

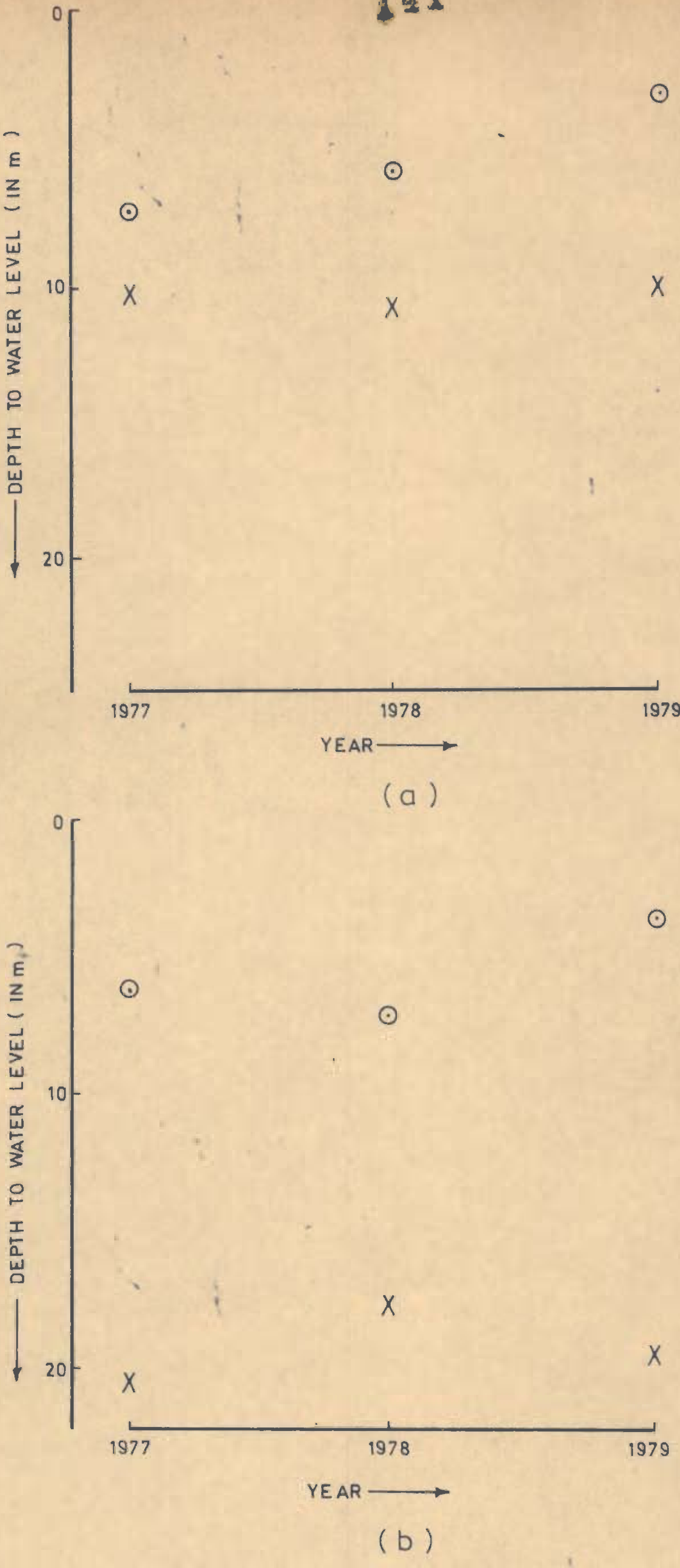
The values of correlation-coefficient determined for different observation wells are given in Table 4.3. The correlation coefficients are negative. This means that as the rainfall continues the depth to water level from the ground surface decreases, i.e., the water table becomes shallower. The value of r varies from -0.05 to -0.59. The small, though significant values of correlation coefficient indicate that although the rainfall affects the water levels, it is not the only factor responsible for fluctuation of ground water levels in the area but other factors such as irrigation, evapotranspiration, groundwater discharge etc. also play a role. Further, the water levels are measured on any day in a month without considering the nature of rainfall which may occur either on a single day or may be scattered.

4.2.2 Analysis of Hydrographs of Pre-Monsoon and Post-Monsoon Water Levels

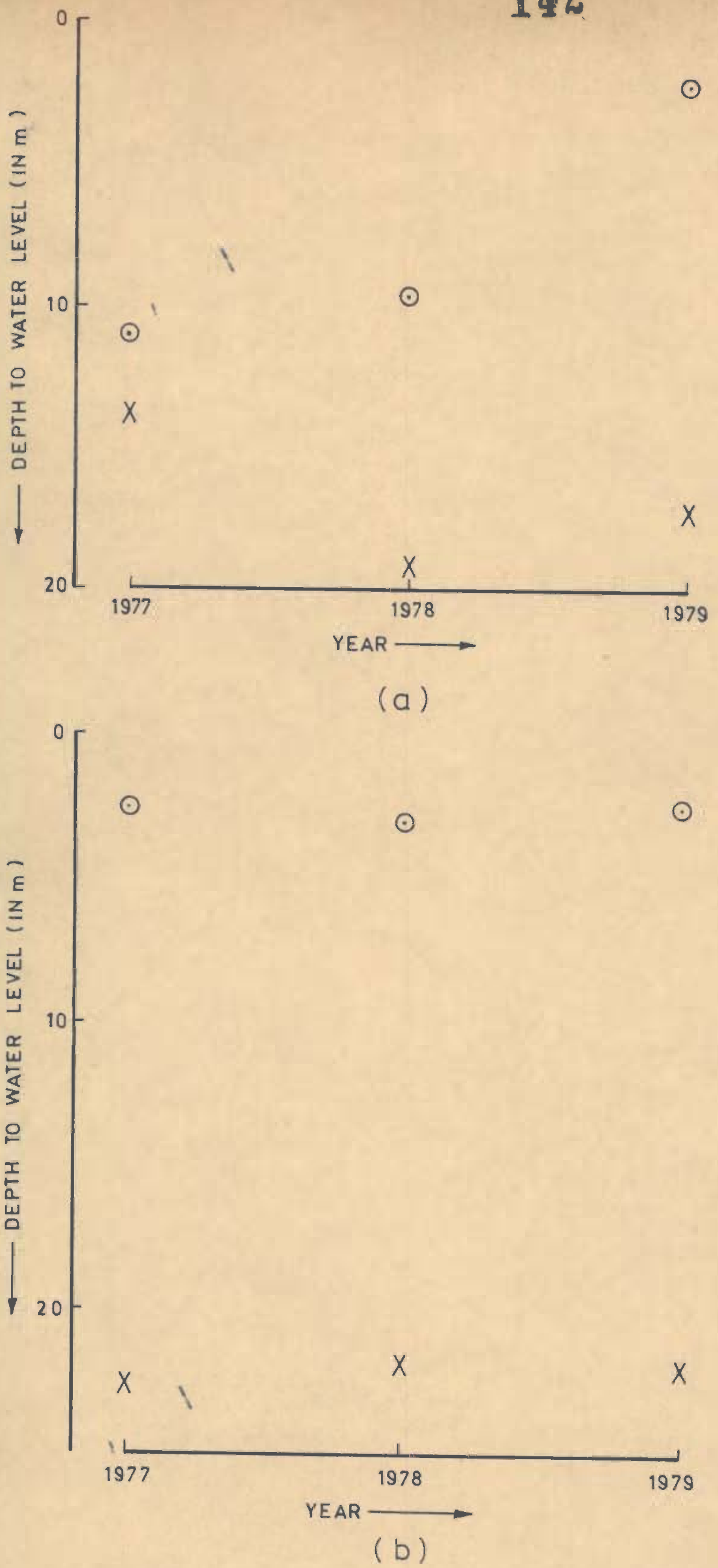
The pre-monsoon (June) and post-monsoon (October) water levels in a particular year were plotted against time in years for 4 wells tapping waters in the Miliolite Formation, Gaj Formation and Deccan trap basalts, in order to find out the trends in the water level fluctuations with time. It is seen (Fig.4.4) that in the Miliolite Formation and Deccan Traps the shallowest water levels (post-monsoon) show a rising trend, whereas the deepst water levels (pre-monsoon) have remained more or less the same with time. The rise in trend of the post-monsoon water levels seems to be due to an increasing trend in precipitation during the previous years. In Gaj Formation at Rudalpur, a rise in the trend of the post-monsoon

TABLE 4.3 Correlation Coefficients based on Linear Correlation

Geohydrological Station	Total No. of observations	Correlation between rainfall in the preceeding month and water level in the succeeding month	Correlation coefficient at 95% confidence interval
Msnkhetra	27	-0.59	- 0.33
Kalej	27	-0.59	- 0.33
Bamanwara	27	-0.52	-0.33
Jhariawara	27	-0.53	-0.33
Goraj	26	-0.45	-0.33
Goraj	26	-0.42	-0.33
Simroli	26	-0.39	-0.33
Mekhri	26	-0.52	-0.33
Khambhalia	26	-0.08	-0.33
Khambhalia	24	-0.05	-0.344
Budecha	22	-0.31	-0.378
Rudalpur	26	-0.15	-0.33
Vallabhgadh	26	-0.45	-0.33
Sil	27	-0.53	-0.33



G. 4.4_ PLOTS OF PRE-MONSOON (X) AND POST-MONSOON (⊙) WATERLEVELS IN DIFFERENT YEARS (a)_KUKASWADA (MILIOLITE FORMATION), (b)_ SIMROLI (DECCAN TRAP BASALT)



. 4.5_PLOTS OF PRE-MONSOON (X) AND POST MONSOON (⊙) WATERLEVELS IN DIFFERENT YEARS (a)_ RUDALPUR (GAJ FORMATION), (b)_ GORAJ (GAJ FORMATION) water levels and a lowering of pre-monsson water level is noticed, whereas at Goraj, the pre-and post-monsoon water levels have remained more or less constant (Fig.4.5). These indicate that water levels are governed by rainfall in the area and also differences in the water levels in these two areas, i.e., at Rudalpur and Goraj show that local recharge might be taking place.

The depth to water level in the Miliolite Formation varies from 2.90 m to 19.40 m and 2.80 m to 17.90 m below ground level for the pre-monsoon (March) and post-monsoon (October) periods respectively for the year 1978. In the case of Gaj Formation the water levels, especially the pre-monsoon levels are deeper and vary from 6.60 m to 28.0 m and 1.60 to 21.70 m below ground level for pre-monsoon (March) and post-monsoon (October) periods respectively, for the year 1978. Similarly, the depth to water level in Deccan Traps varies from 17.73 to 19.13 m and 5.13 to 7.28 m below ground level for pre-monsoon(March) and post-monsoon (October) periods respectively for the year 1978.

4.3 WATER TABLE MAPS

The level of free groundwater with reference to a known datum can be represented by contours. Such contour lines joining points of equal elevation of groundwater levels with reference to mean sea level form the water table contour map. These maps are of help in determining the hydraulic gradient, the direction of groundwater movement, as well as groundwater recharge and discharge and also variations in the aquifer permeabilities. The trend surface technique is a more efficient and convenient method than manual plotting and contouring of water level data. Therefore, in the present study trend surface technique has been used.

4.3.1 Trend Surface Analysis

Fast developing groundwater research has made available a vast amount of areally distributed data. A statistical approach to the evaluation of this huge amount of groundwater data has, therefore, become highly imperative particularly because of limitations of the usual subjective methods in drawing useful conclusions. One statistical technique that offers considerable promise is fitting polynomial trend surface by least square method to the areally distributed groundwater data, including water table data obtained from different wells tapping the same aquifer.

The usefulness of the trend surface analysis in geological problems has been advocated by Whitten in a long series of papers (see Mather, 1976, p. 519). Earliest applications of the method were made in Geophysics by Grant (1957) and Oldham and Sutherland (1955), and in Geology by Miller (1956) and Krumbein (1956, 1959). The discussion and relevant bibliography of the technique is given in all the recent books on statistical applications to Earth Sciences

(Krumbein and Graybill, 1965; Harbough and Merriam, 1968; Davis, 1973; Mather, 1976).

In ground water studies Johnson and Goodell (1961) and Rockaway (1970) investigated the groundwater dynamics of the aquifers by fitting polynomial surfaces to the groundwater levels. Both these studies showed that mathematically computed surfaces are representative of the actual piezometric surfaces and residuals from trend were functions of the permanent geological or hydrological conditions which controlled the groundwater movement. Rockaway (1970), using residual maps, was able to delineate areas which could or could not support greater groundwater withdrawals.

In the present investigation trend surface analysis has been used to study the water table and analyse the distribution of chemical ions in groundwater. Second order trend surface of the following form has been fitted by least square method to water level data:

$$y = b_0 + b_1 u + b_2 v + b_3 uv + b_4 u^2 + b_5 v^2 \ldots \qquad 4.2$$

Third order trend surfaces of the following form have found to be useful for studying distributions of various ions in groundwater as desribed later:

$$y = b_0 + b_1 u + b_2 u + b_3 uv + b_4 u^2 + b_5 u^2 + b_6 uv + b_7 uv^2 + b_8 u^3 + b_9 v^3 \ldots \qquad 4.3$$

where y is the measured variable, u and v are coordinates of the well on an orthogonal reference system and $b_o, b_1 \ldots$ are the coefficients.

4.3.2 Trend Surface Analysis of Water Level Data

In the present study, first to third order trend surfaces, and percentage of variance explained by the trend were obtained for water table data using a computer program by Mather (1976) and adopted to Roorkee University DEC20 computer system. It was found that the second order polynomial surface provide satisfactory trends and only these are included and discussed in the text.

Table 4.4 Coefficients of Second Order Polynomial Surface, Percent sum of Squares Explained and "F" values for Water Levels for Different Seasons

Period		Coefficients of second order Polynomial surface						Percent sum of squares explained	'F' Value
		b_o	b_1	b_2	b_3	b_4	b_5		
March	1978	1.32	0.72	-6.87	-0.05	0.37	0.64	28.94	40.9*
October	1978	1.13	0.45	-7.19	-0.03	0.32	0.89	79.31	44.0*
June	1979	5.08	0.08	-7.65	-0.02	0.32	0.87	95.66	15.5*

* Significant at $\alpha = 0.05$

Second order trend surface for the water table for March 1978, October 1978, and June 1979, are given in Figs. 4.6 to 4.8. The coefficient of second order polynomial equation, total sum of squares, percent sum of squares explained, and test of significance of trend as indicated by 'F' value are given in Table 4.4. These bring out the following points:

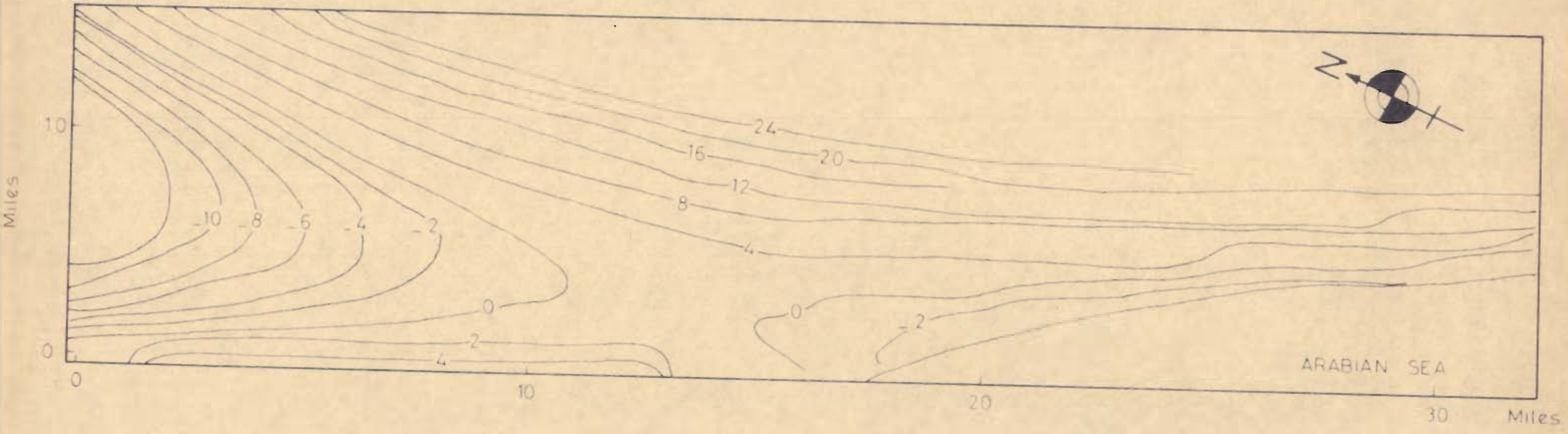


FIG.4.6_ TREND SURFACE MAP OF WATER LEVEL IN METRES WITH REFERENCE TO M.S.L. FOR MARCH, 1978

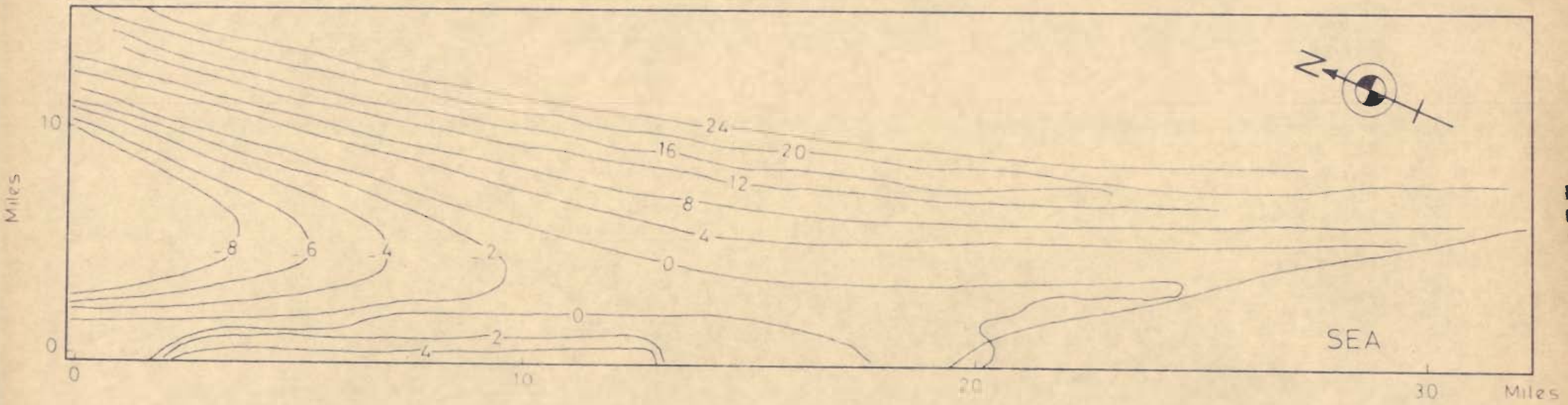


FIG 4.7_ TRENDSURFACE MAP OF WATER LEVEL IN METRES WITH REFERENCE TO MSL FOR OCTOBER, 1978

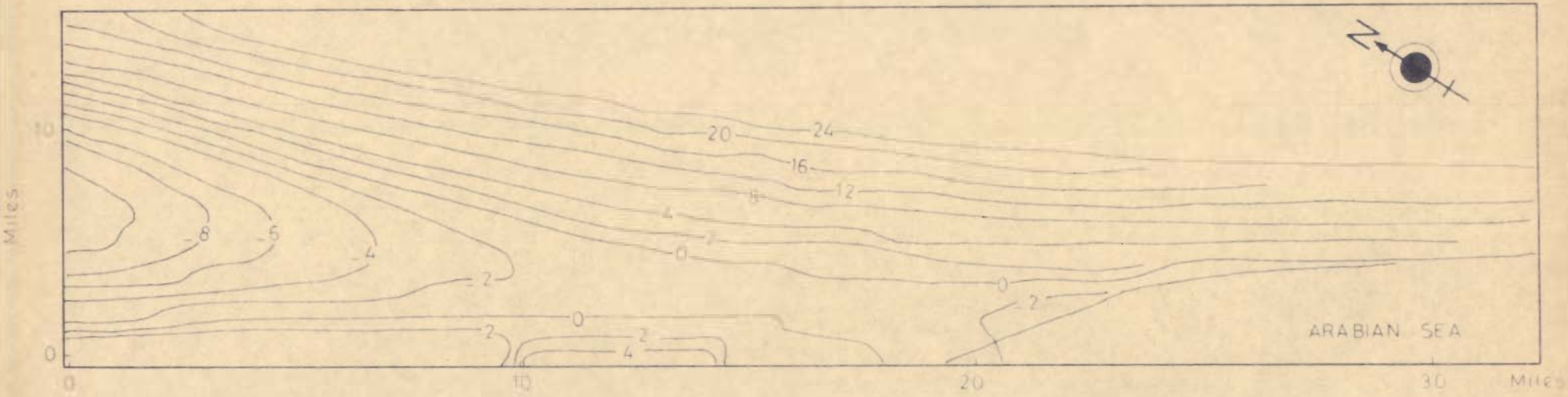


FIG 4.8_ TREND SURFACE MAP OF WATER LEVEL IN METRES WITH REFERENCE TO MSL FOR JUNE, 1979

1. From a central area in the northeast, trend surface slopes to southwest, and west. This may be the general direction groundwater flow.
2. In the westempart of the area near to the coast, the water-table is above the mean sea level and further inland it is below m.s.l. A ground water trough is present here.
3. The contour lines are more widely spaced near to the coast, than those inland.
4. When the pre-monsoon and post-monsoon water-tables are considered it can be seen that the configuration of the trend surfaces remain more or less the same.

However, it is well known that in fractured and karstic rocks groundwater contours may not be good indicators of flow directions and conclusions should be checked with data obtained from other approaches viz. tracer studies and other hydrochemical studies.

In villages Bamanwara and Kankasa, the water-table is below the m.s.l. These are the places where there is large scale exploitation of groundwater at present.

In the Miliolite Formation the contour lines are widely spaced while in the Gaj Formation they are closely spaced. This may indicate that the Miliolite Formation is more permeable as compared with the Gaj Formation.

A comparison of pre-monsoon (March) and post-monsoon (October) groundwater levels in the Miliolite Formation and Gaj Formation for the year 1978, has been made. The maximum fluctation

(4.10 m) in the Miliolite Formation was observed at Husainabad while in the Gaj Formation the maximum fluctuation (9.10 m) was observed at Kankana and Kanek villages. Even though the maximum fluctuation in water level in Miliolite Formation is 4.10 m, generally the fluctuation is less than 2.0m, whereas in Gaj Formation the fluctuation is more than 3 m.

4.4 HYDRAULIC CHARACTERISTICS OF THE AQUIFERS

Aquifer as a fully developed source of water depends mainly on two inherent characteristics. They are (a) its ability to transmit and (b) its ability to store water. These can be expressed in terms of coefficient of transmissibility or transmissivity (T) and, coefficient of storage or storativity (S) respectively. These are defined as given below:

4.4.1 Transmissivity(T)

Transmissivity is the rate of flow of water under a unit hydraulic gradient through a vertical strip of the aquifer of unit width over the whole saturated thickness of the aquifer at the prevailing water temperature. It is therefore, a product of the average permeability and the saturated thickness of the aquifer. It is expressed in m^2/day.

4.4.2 Storativity (S)

The storage coefficient or storativity of an aquifer is defined as the volume of water that a vertical column of aquifer of unit surface area releases from or takes into storage as the average head within this column declines by a unit depth.

It is dimensionless. In the case of the water table aquifers, the storage coefficient can be regarded to be equal to the specific yield.

The specific yield is defined as the ratio of the volume of water that a rock or soil will yield by gravity to its own volume. The storage coefficient in unconfined aquifers ranges from 0.05 to 0.3 while in confined aquifers it is of the order of 10^{-3} to 10^{-5}.

The hydraulic properties of aquifers and confining beds may be determined by means of pumping test.

4.5 PUMPING TESTS

4.5.1 Introduction

A pumping test is one of the most useful means of determining hydraulic properties of aquifers. The effect of pumping a well at a known constant rate is measured in the pumped well and in observation wells penetrating the aquifer. A pumping test also will provide data about the yield and drawdown in the well, from which the specific capacity of a well can be determined. The specific capacity is a measure of the effectiveness or productive capacity of the well.

The pumping test is generally carried out in a representative part of the area to be investigated. Depending on the amount of information desired, the required degree of accuracy, and also on the availability of funds, the number of observation wells can be fixed. The observation wells should not be either too near or too far from the pumped well. The distance to be kept between the pumping well and the observation well depends upon the type of the aquifer. In the case of confined aquifers the cone of depression expands faster and the loss of head may be measurable at greater distances. In unconfined aquifers, the propagation of hydraulic head loss is rather slow. The loss of hydraulic head caused by pumping is measurable within short distance of the pumped well, unless the period of pumping is extended for several days. The observation wells are usually kept within a distance of 300 m.

Generally two types of measurements are done during pumping tests. They are (a) measurements of water level, and (b) measurements of the discharge rate. Most important part of the pumping test is measuring the depth to water in the pumping well as well as in the observation wells, many times during the course of the test, and as accurately as possible.

In order to obtain analytical solutions for aquifer parameters and well conditions, assumptions have to be made regarding the release of water from storage, type of flow and boundary conditions. Idealisation of the aquifer and boundary conditions is necessary. Aquifers are assumed to be homogeneous, isotropic and infinite in areal extent. Analytical solutions for several aquifer systems under different conditions were worked out more rigorously in the recent years by different scientists.

Excellent accounts are given by Walton (1962,1970), Ferris et al. (1962), Hantush (1964),Kruseman and De Ridder (1970) and Singhal (1977). A brief and critical evaluation of available groundwater models has been done by Walton (1979).

4.5.2 Pumping Tests in Hard Rock Aquifers

The use of standard methods of aquifer test analysis in hard rock aquifers has long been a subject of debate. Crystalline rocks, carbonate rocks and other consolidated rocks as a medium of groundwater flow possess anisotropy and heterogeneity. The hard rocks are characterised by secondary porosity due to the presence of joints, fissures, foliation planes and solution cavities.

In karstic rock terranes, the circulation of water takes place both in individual isolated fractures and voids and in their systems where a hydraulically single flow is formed. Generally under natural conditions, a single flow system prevails. However, the flow may concentrate in separate zones confined to tectonic zones (Babushkin et al., 1975) because of fall in ground water level due to withdrawal of water. In this case, the groundwater flow in the main rock mass may be of complicated character.

Some quantitative evaluation and interpretation of flow in fissured rocks started only recently. In developing fissure flow models it is considered that the flow properties are due to the presence of fissures and the storage of water is associated with intergranular porosity. The aquifer is considered to be made up of blocks and fissures in a regular pattern and is having a double porosity, i.e., porosity of blocks and that of fissures. Based on this, models have been developed by various workers including Papadopulos (1967), Rofail (1967), Snow (1969), [redacted] [redacted] and Boulton and Streltsova (1976a,b). An excellent review of different models of fractured media consisting of a single fracture of given extent and orientation and also fractured formation as two coexisting systems of porous blocks and anisotropic fissures, developed by various workers, has been made by Streltsova (1976) and Streltsova and Adams (1978). The works by different authors on the practicability of pumping tests in crystalline rocks and limestones is briefly described below.

4.5.3 Crystalline and volcanic rocks:

Walton and Stewart (1961) applied the non-equilibrium formula and got meaningful values for hydraulic properties from aquifer test in Snake River basalt. The departure of the early part of the curve from the type curve was described by them as due to the heterogeneity of the aquifer.

Singhal (1977) opined that the usual pumping test methods can be used in hard rock areas when there is a uniform development of secondary porosity and permeability in the whole rock mass and the fractures or solution cavities are interconnected.

Carlsson and Carlstedt (1977) used statistical analysis and calculated average values of transmissivity and permeability from specific capacity data in different Swedish bed rocks. They got a wide range of results for Archaean crystalline rocks.

Uhl and Sharma (1978) analysed the drawdown and recovery data for the crystalline rock aquifers of Satpura Hill region, Central India and found that T values calculated from recovery data are higher than those computed from drawdown data.

Radhakrishna and Venkateswarlu (1980) analysed a long duration pumping test data in the ultramafic rock area of Sukhinda valley, Orissa. They tried graphical analysis by different methods and came to the conclusion that the inconsistency of T and S values derived from the later parts of nonleaky artesian type curve is due to leakance in the system and not because of the heterogeneity.

4.5.4 Carbonate Rocks

Csallany (1967) after a study of a number of pumping test analyses demonstrated the applicability of common aquifer tests and step-drawdown method for obtaining a regional picture of aquifer parameters in carbonate rocks.

Siddiqui and Parizek (1971) after a study of folded and faulted carbonate rocks in Central Pennsylvania, U.S.A. came to the conclusion that fracture trace wells are more productive than non-fracture trace wells. A fracture trace is a natural linear feature extending for less than a mile long that is visible prominently on an aerial photograph. According to Siddiqui and Parizek (1971), specific capacity indices of wells situated near or on single fracture trace or intersection of two or more fracture traces are high as compared with wells located in the interfracture trace area.

Eagon and Johe (1972) have noted that hydraulic characteristics seem to be inconsistent in the vicinity of bore holes in carbonate rocks. According to them, this may be of some importance during the beginning of a pumping test. These irregularities assume less importance, as the cone of depression becomes larger and covers a representative area of the aquifer. Some carbonate rock aquifers assume the hydraulic characteristics of a homogeneous media when larger areas are considered. In effect, when the cone encompasses a representative area of the aquifer, the resultant drawdown in the well represents the sum total effect of the hydraulic characteristics of the aquifer in the area encompassed by the cone, including any irregularities. They came to the conclusion that modified non-leaky artesian formula of Cooper and Jacob is best suited for these aquifers. They attributed the change in the slope of the time-drawdown plot to the dewartering the aquifer and concluded that the transmissivity will be truely representative only if it is determined from the data obtained prior to dewatering. The slope observed after dewatering is due to the reduction of T in the immediate vicinity of the well and it is not representative of the aquifer in the entire area encompassed by the cone of depression. They suggested the use of recovery data to overcome this difficulty as the dewatering affects the T values computed from drawdown data. They also noticed that the time-recovery relationship may be distorted as the zones are filled and the aquifer becomes completely artesian.

4.5.5 Pumping Tests in Large Diameter Wells

Large diameter dug and dug-cum-bore wells are quite common in India, especially in the hard rock formations. The large diameter wells serve as storage reservoirs for groundwater and are suitable in formations with low transmissivity.

The conventional pumping test methods eg. Theis equation is not applicable to analyse pumping test data from large diameter wells on account of significant effects of well storage.

Papadopulos and Cooper (1967) had first given an analytical solution for large diameter wells tapping confined aquifers. This method can be applicable in dug-cum-bore wells where the bore section taps the confined aquifer while drawdown measurements are taken in the dug well (Fig. 4.9). It is difficult to obtain reliable values of storativity, S, by this method as the lines for different values of β are almost parallel especially for tests of short duration of time. However, Papadopulos and Cooper's method has been used in India by earlier workers in a variety of geological formations for determining aquifer parameters (Narasimhan, 1968, Sammel, 1974 ; Venugopal, 1979; Radhakrishna et al., 1979).

Papadopulos and Cooper's method has serious limitations for large diameter wells tapping unconfined aquifers on account of variable abstraction rates and excessive well losses due to the vertical drainage of the aquifer.

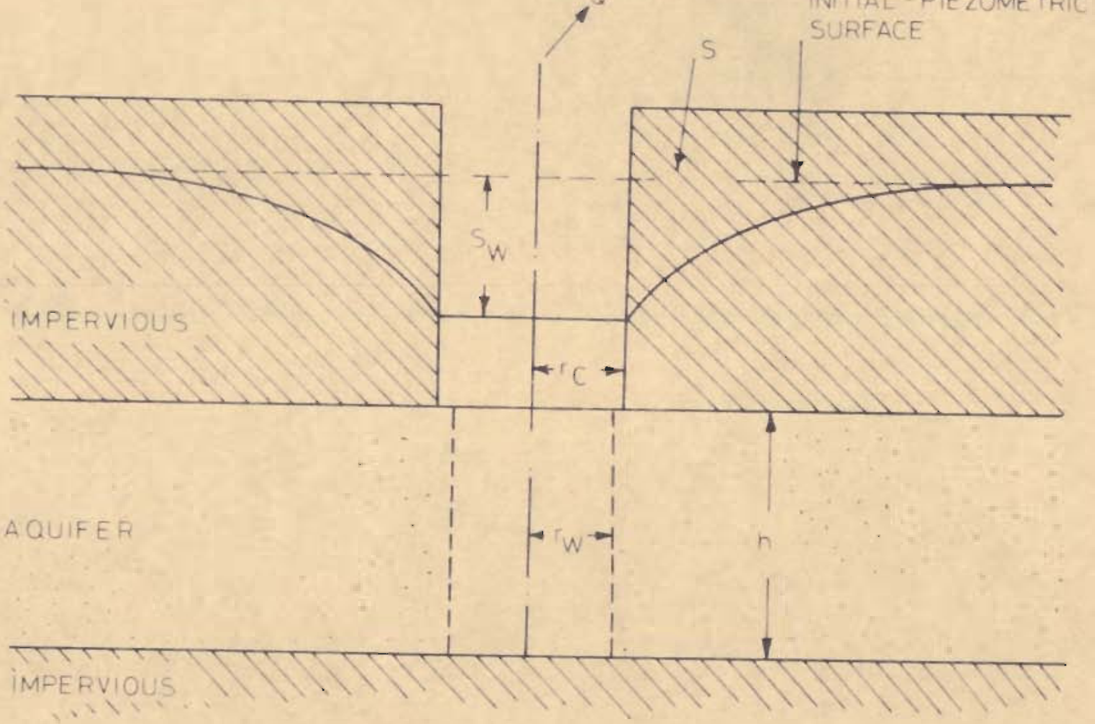


FIG 4.9 _ SCHEMATIC CROSS-SECTION OF A CONFINED AQUIFER PUMPED BY A LARGE DIAMETER WELL

To overcome the above problem of variable abstraction rates, Lai and Su (1974) have given the equation for the drawdown in and around a well of large diameter in a leaky aquifer induced by an arbitrary time-dependent pumping rate. The storage capacity of the well is taken into consideration and the leakage of the aquifer is taken to be linear. The effect of the storage capacity of the well on the drawdown is found to be significant when the time is not large or the ratio of the transmissivity, T, of the aquifer to its storage coefficient, S, is small. Though the method of Lai and Su (1974) considers variable abstraction rates but it would be difficult to precisely determine these variations in actual practice. Further this method also does not consider the flow conditions in an unconfined aquifer.

Boulton and Streltsova (1976) have given an analytical method for analysing pumping test data in large diameter wells having partial penetration in unconfined aquifers. The method involves curve matching technique with a family of type curves. The method does not consider decreasing abstraction rates and also effect of well losses. This method has, however, been used in the present study as the drawdown due to pumping were not excessive and hence the effect of vertical drainage and well losses were not significant.

Rushton and Redshaw (1979) have suggested numerical method for analysis of pumping test data. This involves a versatile method of solving the Theis differential equation by a discrete space-time numerical model. This method has the advantage that many necessary conditions can be included in a single numerical solution. Rushton and Holt (1981) have used the numerical method for analysis of drawdown and recovery data from large diameters wells tapping confined and unconfined aquifers from India. A comparison of results obtained from numerical methods and from Papadopulos method is also given. Numerical model is found to be more versatile. Their results indicate that while the analytical solutions and numerical model give effectively the same response for confined aquifers, the direct application of analytical solutions to unconfined aquifers may be unreliable when there is a significant decrease in saturated depths. Further inadequacies in the analytical solutions may arise due to well losses, the presence of boundaries, variable transmissivities within the aquifer or variable discharge rates. The numerical model has an advantage of introducing effects of decreasing abstraction rates and well losses in unconfined aquifers and therefore it is a more versatile method.

Herbert and Kitching (1981) have recommended numerical model by using recovery data from large diameter wells for the determination of aquifer parameters because the well losses, especially in the later stages of the recovery phase will be negligible and all water which flows into the well is derived from the aquifer. Therefore, recovery data will give better results than drawdown data.

In the present study, recovery data have also been used but these are analysed by the Theis method. The numerical methods could not be used in the present study as most of the literature on the subject was not available during the preparation of the thesis. Among the analytical methods Papadopulos and Cooper (1967), Boulton and Streltsova (1976) and Theis recovery methods have been used as discussed in the following section.

For reasons mentioned above, Boulton and Streltsova and Theis recovery method will be more applicable in the present situation. The results obtained by Papadopulos and Cooper method have been given for the sake of comparison.

4.5.6 Analysis of Pumping Test Data from Chorwad-Madhavpur Area

In the present study fourteen pumping tests were conducted by the author. The pumping test data for four wells obtained from the Gujarat Water Resources Development Corporation has also been made use of. All the tests were carried out in the existing large diameter wells. They are either dug wells or dug-cum-bore wells. Most of the wells are rectangular in shape and the average cross-section is 3.20 x 2.10 m. Generally the length varies from 2.70m to 3.5 m, the width 1.50 to 3.0 m and depth 4 to 28 m. From the bottom of the well bores are drilled varying from 10 cm to 15 cm in diameter. Both vertical and horizontal borings are made, but vertical ones are most common. The depth of bore holes varies from

15 to 30 m. The borings are more common in wells tapping the Gaj Formation than in Miliolite Formation. The wells tap the upper portions of the Miliolite Formation and the Gaj Formation which are generally under water table conditions. As described in Section 3.2.1 limestones belonging to the Miliolite Formation are karstified and solution openings are common. The pumping tests were of short duration, i.e., not more than 4½ hours. The wells were pumped at constant rates of discharge. As it was not possible to have any observation wells, the drawdown and recovery measurements were taken in the pumping well itself. Data from one such pumping test is given in Appendix 1 while the data from other tests have been plotted and analysed by various methods (Fig. 4.12 to 4.25). The methods used in the present study are (i) Papadopulos and Cooper's method (ii) Boulton and Streltsova's method , and (iii) Theis recovery method. The specific capacity of the wells was determined by using Slichter's recovery formula.

4.5.6.1 Papadopulos and Cooper's Method

The Papadopulos and Cooper's equation can be written as

$$s_w = \frac{Q}{4 \pi T} F (u_w, \beta) \qquad .. \qquad .. \qquad 4.4$$

where $F (u_w, \beta)$ is the well function for an artesian aquifer with production well storage capacity for which numerical values are given by Papadopulos and Cooper. From this data a family of type curves can be drawn of $F (u_w, \beta)$ against $\frac{1}{u_w}$ for various values of β (Fig. 4.10).

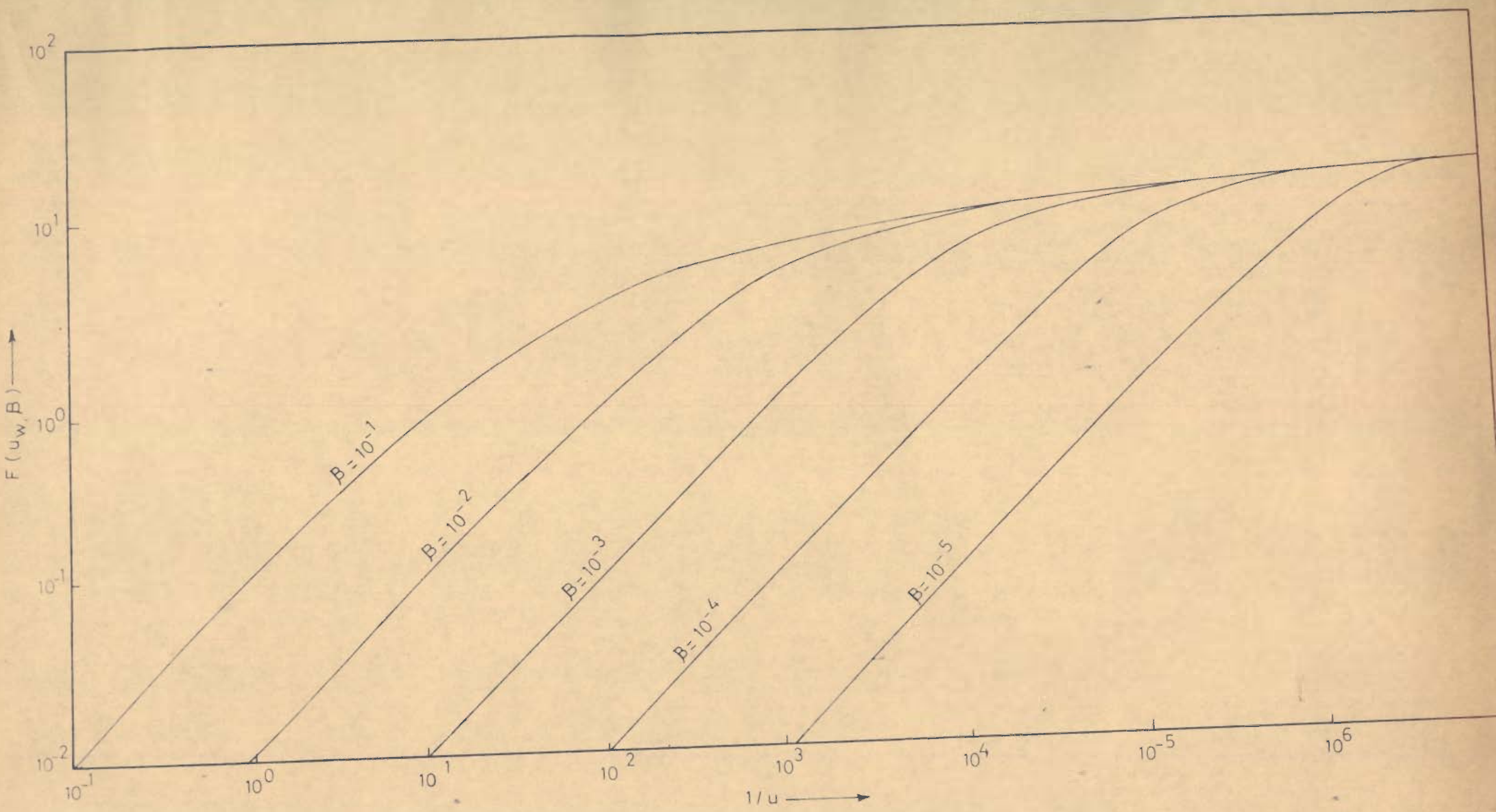


FIG. 4.10 _ FAMILY OF PAPADOPULOS-COOPER'S TYPE CURVES. F(u_W . β) VERSUS $1/u_W$ FOR DIFFERENT VALUES OF β.

$$u_w = \frac{r_w^2 S}{4 T t} \quad \cdots \quad \cdots \quad 4.5$$

$$\beta = \frac{r_w^2 S}{4 Tt} \quad \cdots \quad \cdots \quad 4.6$$

$$\bar{\beta} = \frac{r_w^2 S}{r_c^2} \quad \cdots \quad \cdots \quad 4.7$$

In this method, the analysis of the pumping test data is done by matching the data curve plotted on a double log sheet, with one of the type curves. A match point is selected. The values of F (U_w, β), $\frac{1}{u_w}$ and β are read from the type curve sheet, ans s_w and t from the data sheet. These values are substituted in equations 4.4 and 4.5 and T and S are computed. While matching the data curve with the type curve, most of the points in the data curve should fall on the curved part of the type curves. The almost straight portion of the type curves corresponds to periods when most of the water is derived from storage within the well. So much so, points of the data that fall on this portion of the type curves do not adequately reflect the aquifer characteristics. Therefore, the match point found by matching the data curve with the straight line part of the type curves may give wrong estimate of aquifer constants.

The determination of S by this method is not very reliable. The shapes of the type curves differ only slightly, when β differs by an order of magnitudes. Therefore, computed value of S will change when the data plot is moved from one type curve to another of different values of β .

In the present study, the T and S have been determined by this method and are given in Tables 4.5 - 4.6 The T values determined by this method for the Miliolite Formation vary from 172 to 1906 m^2/day and S from 1.89×10^{-4} to 1×10^{-2}. Similarly for the Gaj Formation, the T ranges from 108 to 626 m^2/day and S from 4.26×10^{-5} to 9.55×10^{-2}. The data curves are given in Figs.4.12 to 4.18.

4.5.6.2 Boulton and Streltsova's Method

Papadopulos and Cooper's method, although takes into account the effect of well storage, it is applicable only to a fully penetrating well in a confined aquifer.

Boulton and Streltsova(1976) have derived equations for the drawdown in partially penetrating wells under unconfined (water-table) conditions. The drawdown at any point in the aquifer is a function of the depth of that point below the water table. The assumptions in this method are:

1. The aquifer is compressible and in general anisotropic, the horizontal and vertical permeabilities being constant.
2. The aquifer is underlain by a horizontal impermeable bed, which may be at any depth below the bottom of the pumping well.
3. The aquifer is pumped at a constant rate from the instant $t = 0$.

The equation in the abbreviated from can be written as

$$s = \frac{Q}{4\pi T} W(u_A, \beta; S, \rho, l', y') \qquad 4.8$$

where $W(U_A, \beta, S, \rho, l' y')$ = well function for water table aquifer with partially penetrating wells and production well storage capacity (dimensionless).

Values of $W(u_A, \beta, S, \rho, l', y')$ are given by Boulton and Streltsova (1976) in terms of a selected range of $1/u_A, \beta, S, \rho, l'$ and y'. From these a family of type curves can be drawn (Fig.4.11).

The data curve plotted on a double log sheet with drawdown versus time was matched with one of the type curves and a suitable match point was selected. The values of $1/u_A$, $W(u_A, \beta, S, \rho, l', y')$, β and were read from the type curve and t and s from the data curve. These values were then substituted in equation 4.8 and the transmissivity were calculated. The data curves are given in Figs. 4.12 to 4.18).

Storage coefficient could not be found out because there were no observation wells.

Transmissivity determined by this method for the Miliolite Formation varies from 109 to 971 m^2/day and for the Gaj Formation it varies from 32 to 259 m^2/day (Tables 4.5 and 4.6).

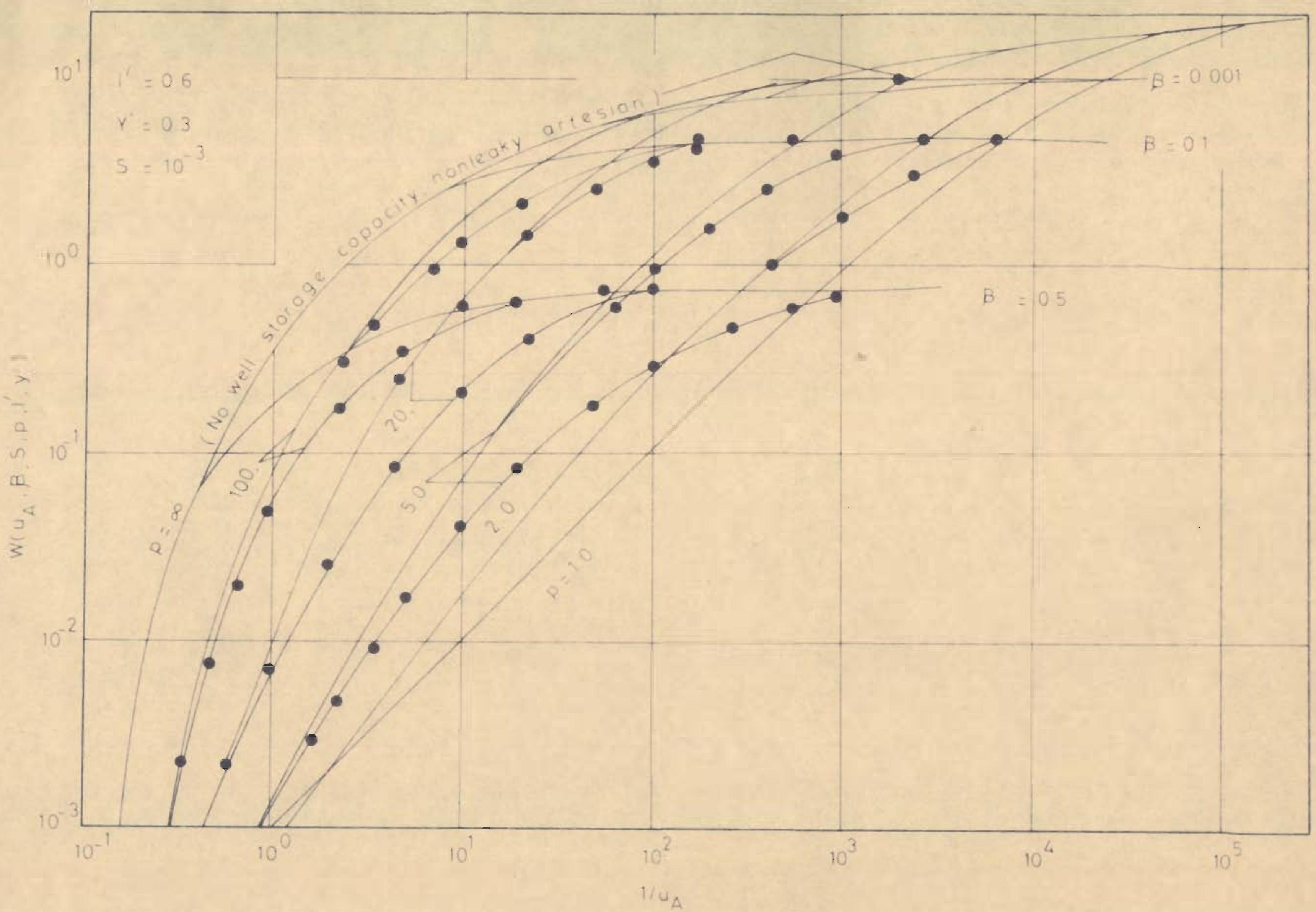


FIG. 4.11_TYPE A CURVES FOR WATER—TABLE AQUIFER WITH PARTIALLY PENETRATING WELLS AND PRODUCTION WELL STORAGE CAPACITY (after Boulton and Streltsova, 1976.)

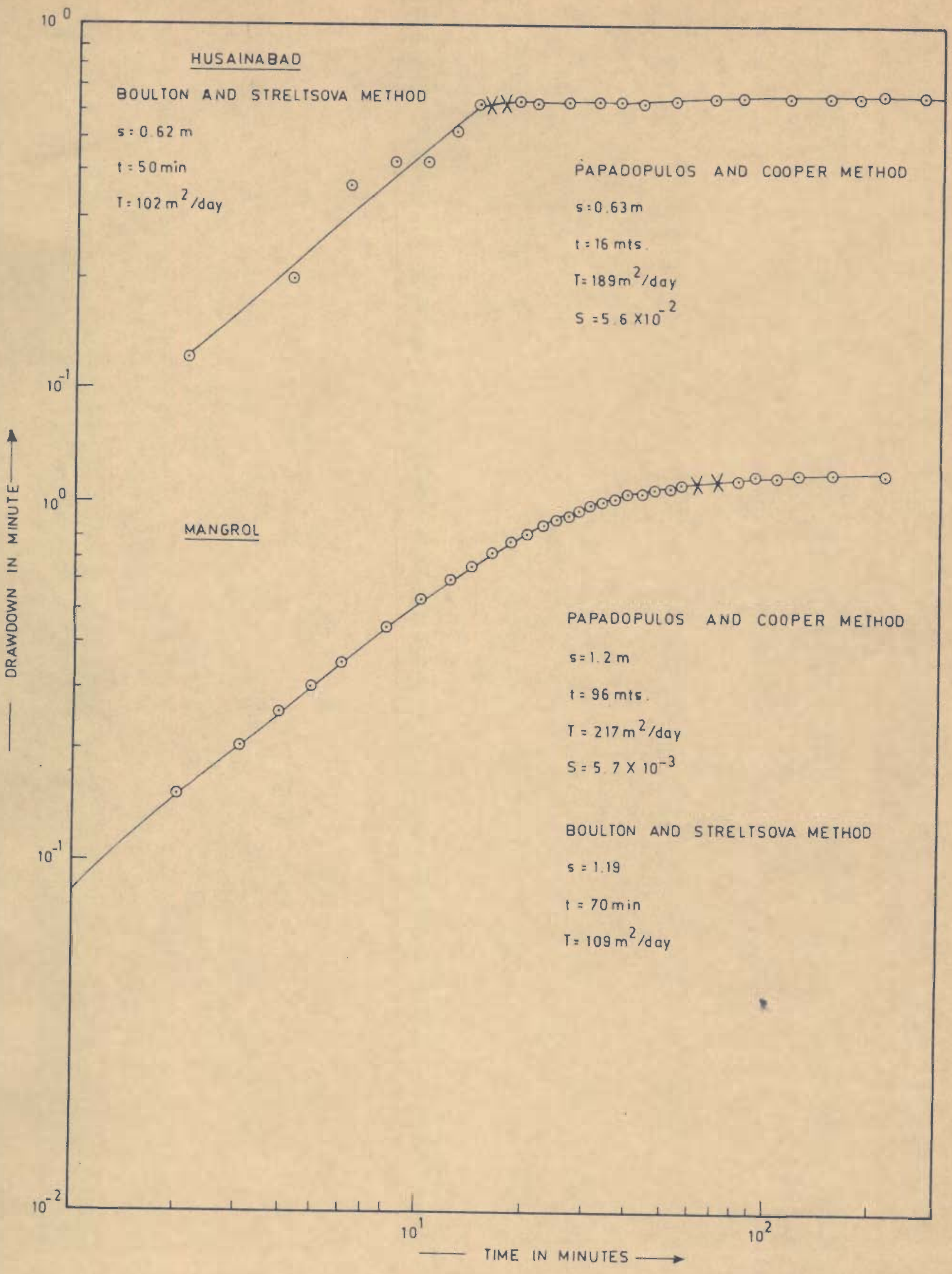


FIG. 4.12 _ DATA PLOTS OF TIME DRAWDOWN FOR DUG WELLS IN THE MILIOLITE FORMATION.

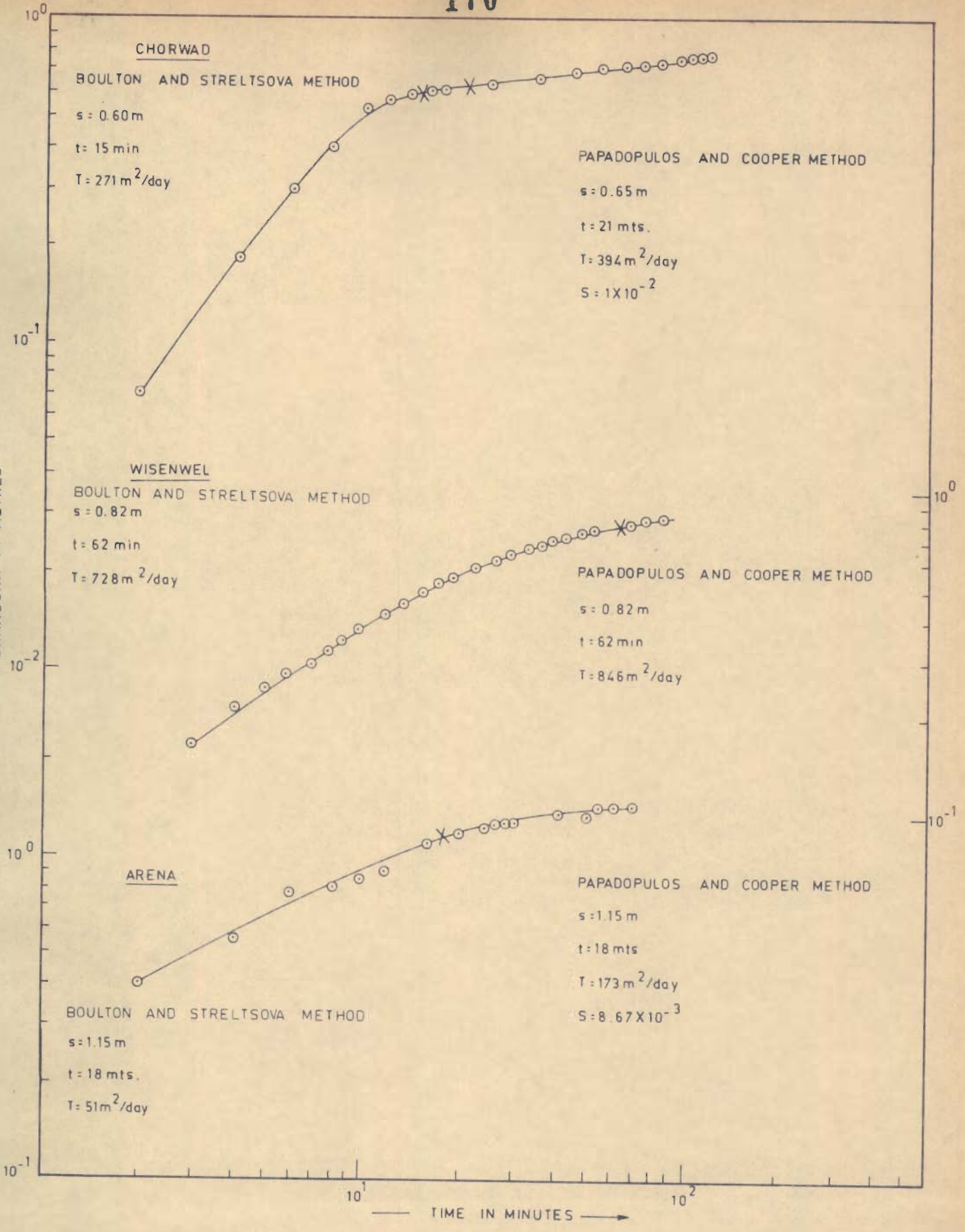


FIG. 4.13 _ DATA PLOTS OF TIME DRAWDOWN FOR DUG WELLS IN THE MILIOLITE FORMATION.

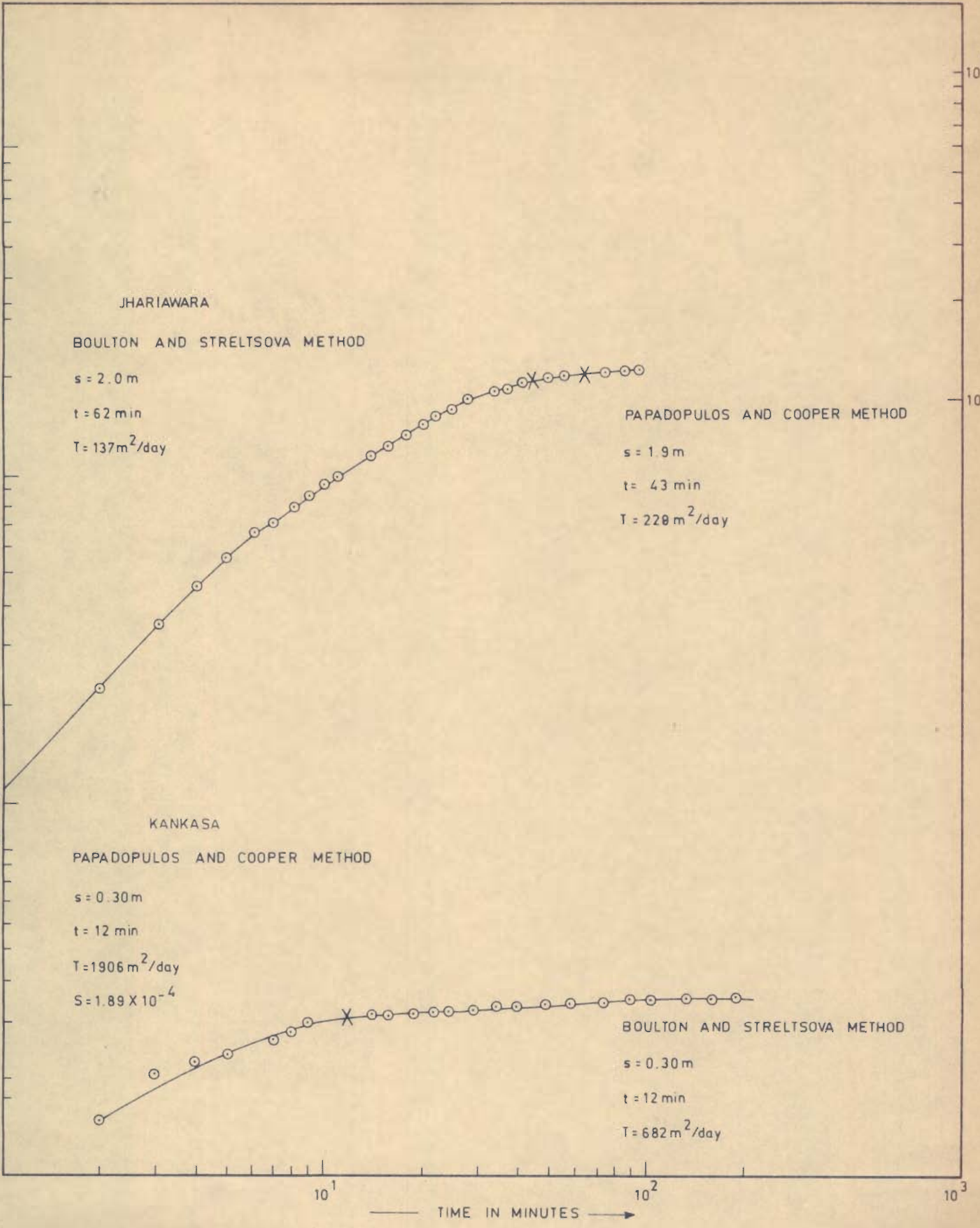


FIG 4.14 _ DATA PLOTS OF TIME DRAWDOWN FOR DUG WELLS IN THE MILIOLITE FORMATION.

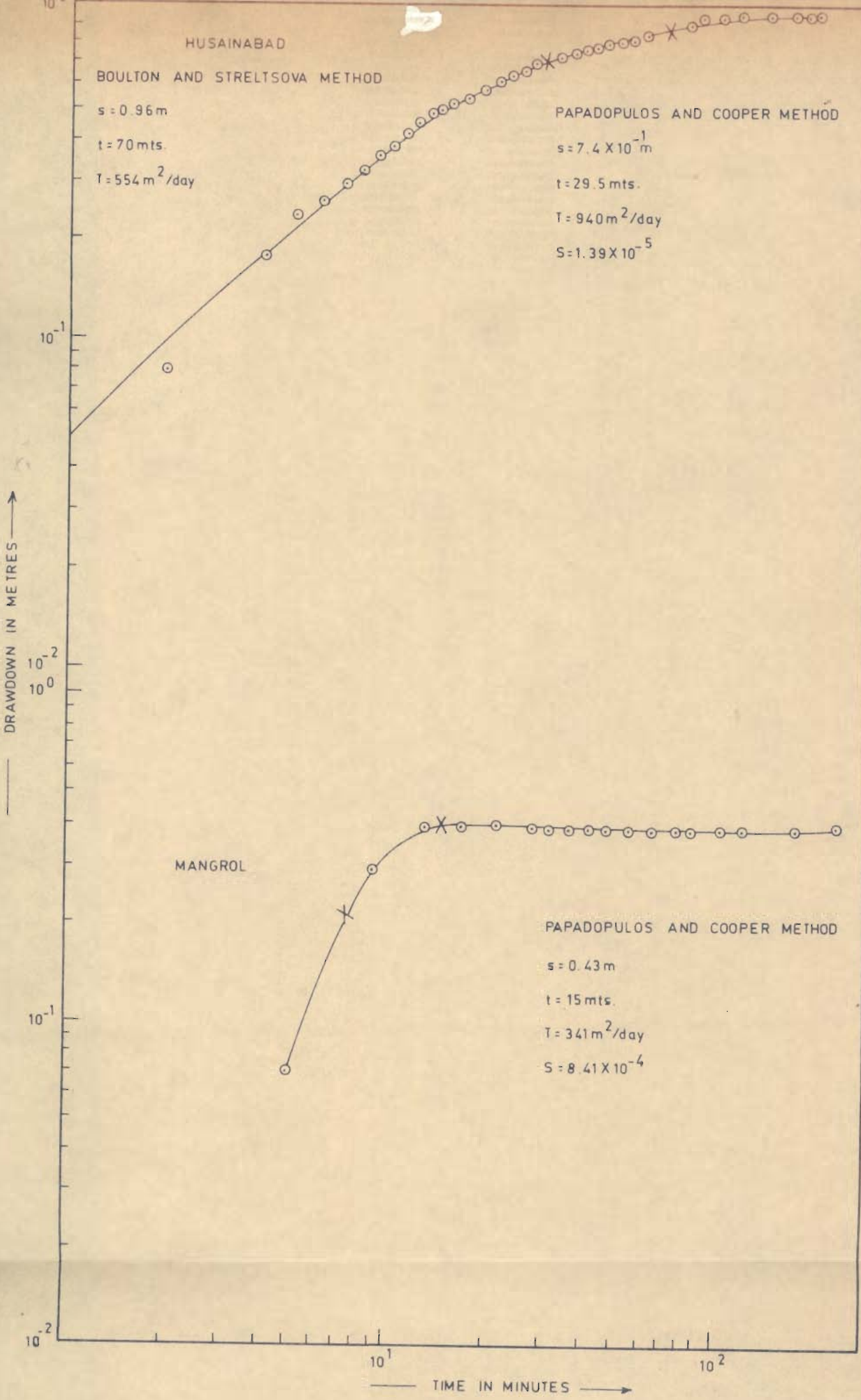


FIG. 4.15 _ DATA PLOTS OF TIME DRAWDOWN FOR DUG WELLS IN THE MILIOLITE FORMATION.

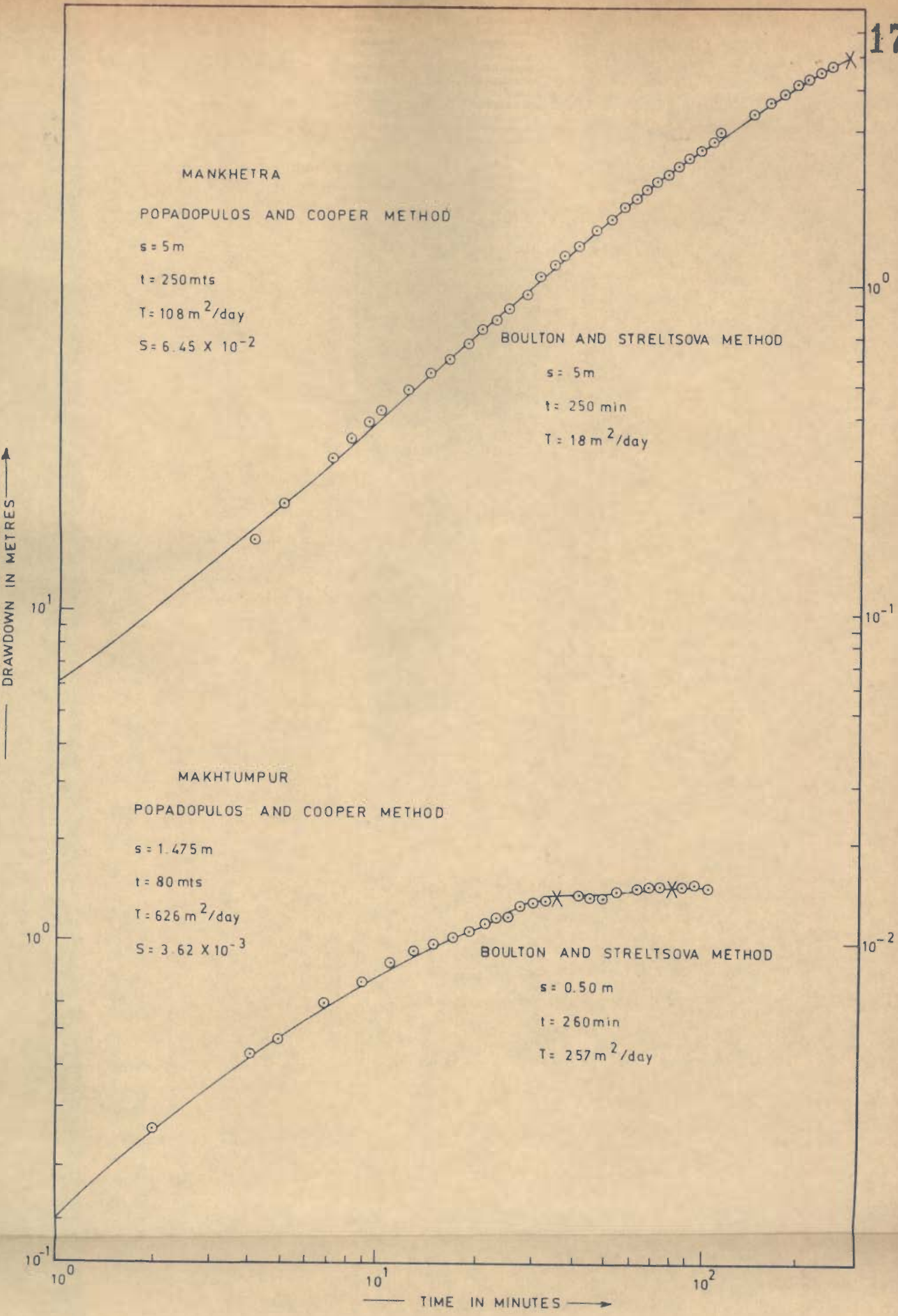


FIG. 4.16 _ DATA PLOTS OF TIME DRAWDOWN FOR DUG WELLS IN THE GAJ FORMATION

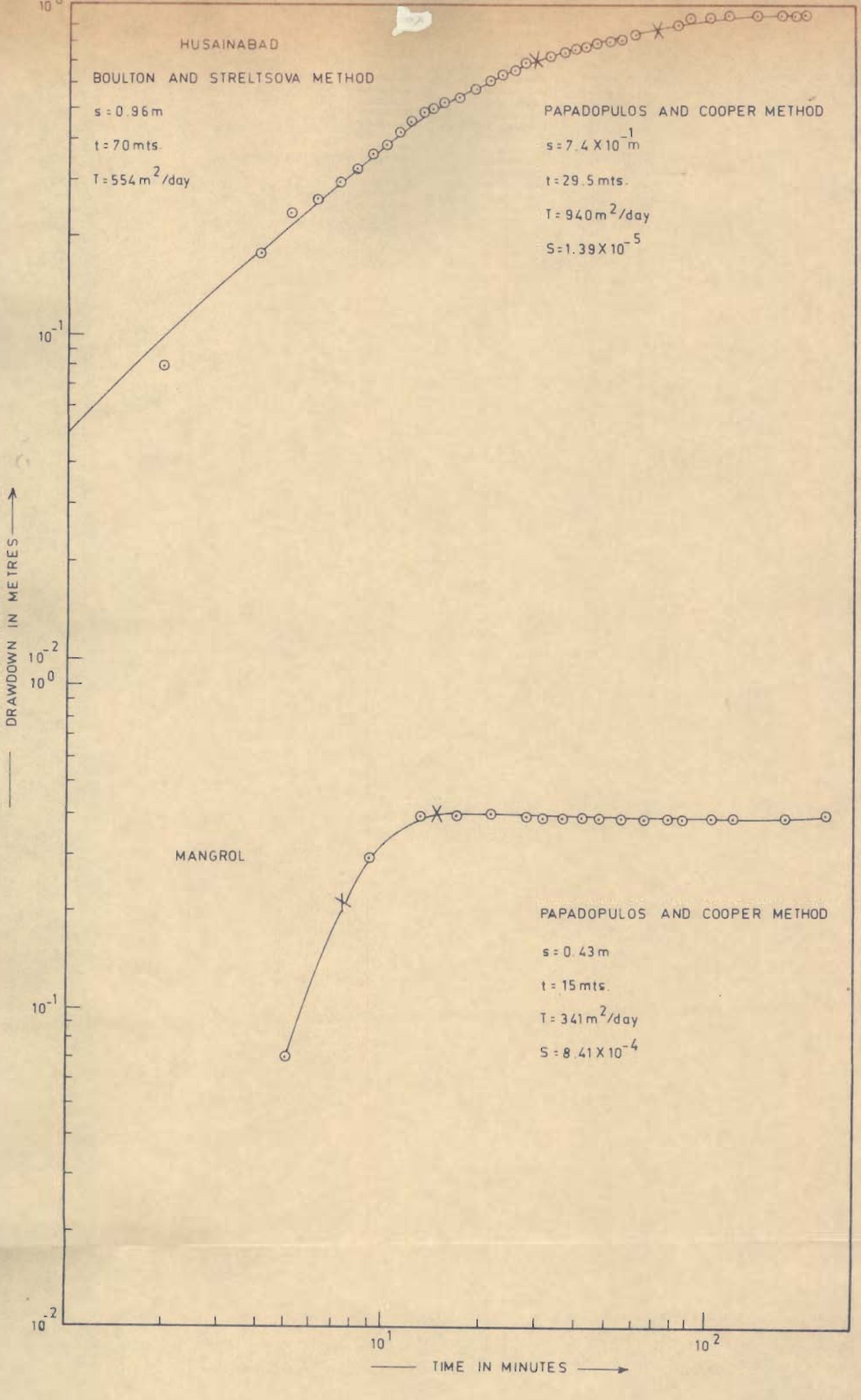


FIG. 4.15 _ DATA PLOTS OF TIME DRAWDOWN FOR DUG WELLS IN THE

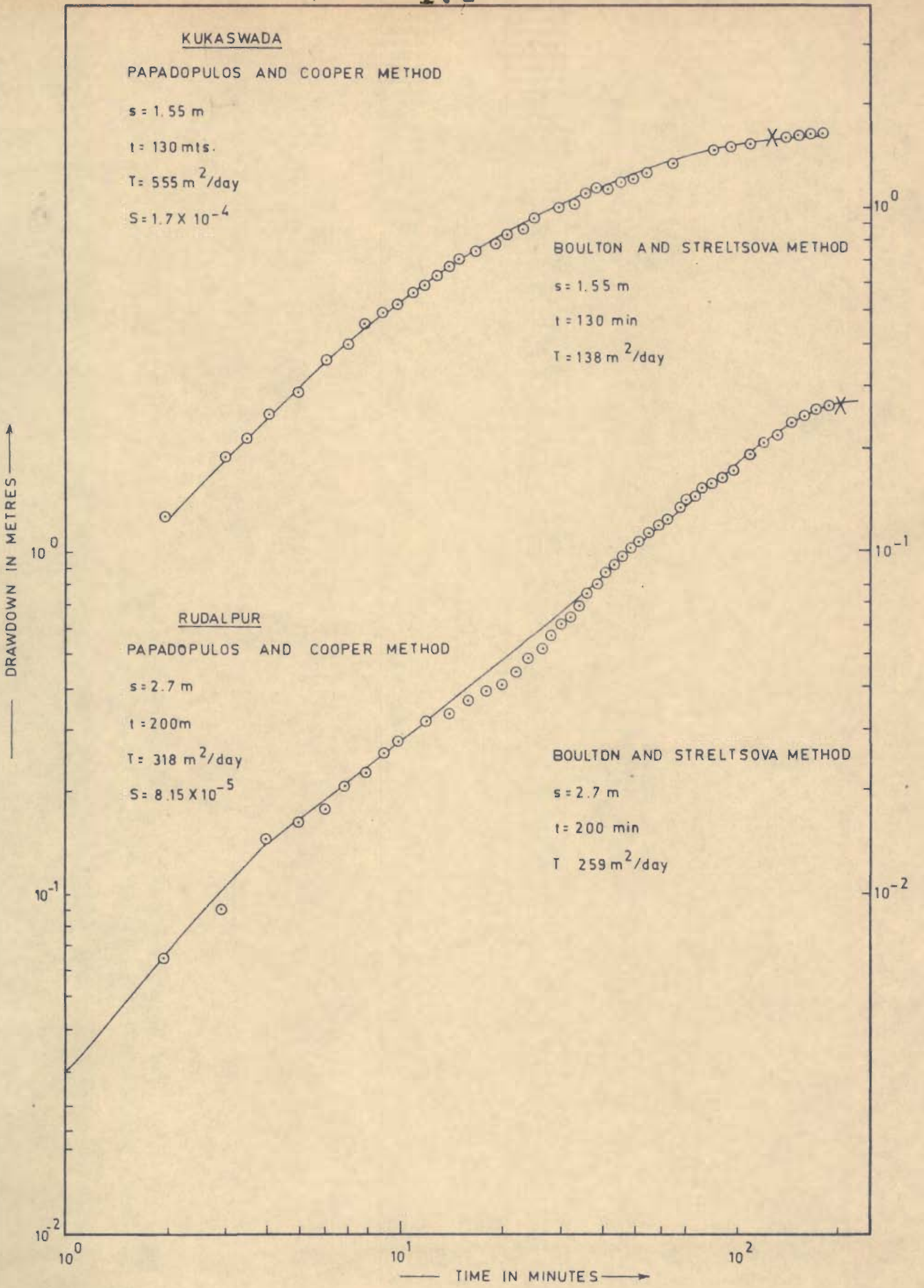


FIG. 4.17 DATA PLOTS OF TIME DRAWDOWN FOR DUG WELLS IN THE GAJ FORMATION.

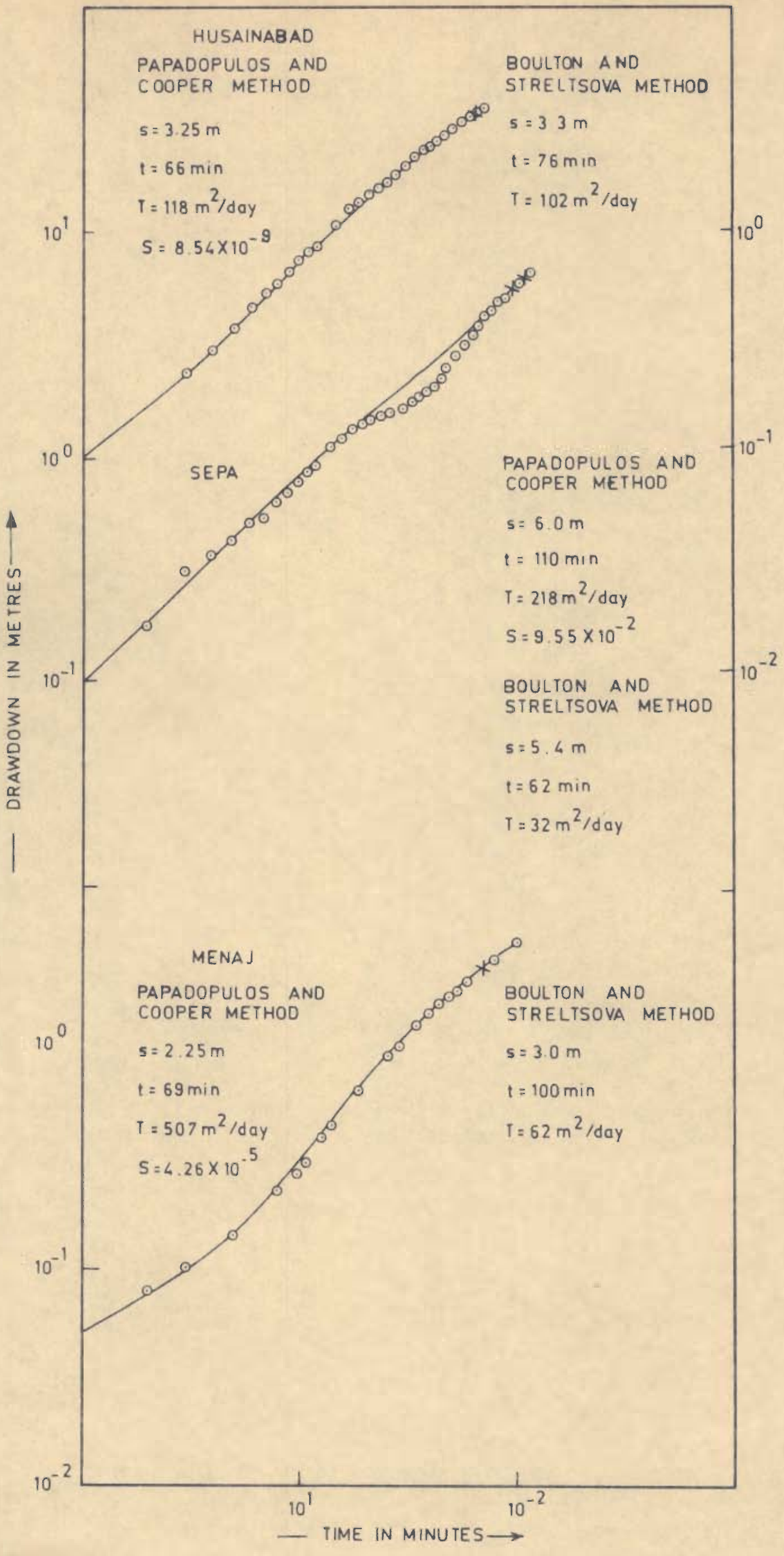


FIG. 4.18 _ DATA PLOTS OF TIME DRAWDOWN FOR DUG WELLS IN THE GAJ FORMATION.

4.5.6.3. Theis Recovery Method

The recovery formula is applied by plotting the residual drawdown s', against t/t' on a semilogarithmic paper, s' is plotted on the arithmatic scale and t/t' on the log scale. In the present study an attempt has been made to determine T using the Theis recovery formula, because in this case, the well storage effects are minimised. The plots of s' against log t/t' are shown in Figs. 4.19 to 4.25.

The recovery data in general from wells tapping the Gaj Formations indicate very small recovery in the beginning. It is difficult to assign a definite reason for such variations but it could be attributed to low transmissivity of the Gaj Formations. Anomalous trends in recovery data have also been reported by Sammel (1974) and Rushton and Holt (1981). The effect of aquifer heterogeneity and complex flow conditions in fractured unconfined aquifers will be more in the early part of recovery phase. Therefore in the present study, mostly later part of recovery data are considered for computing transmissivity (Tables 4.5 and 4.6).

A comparison of T values obtained by various methods (Tables 4.5 and 4.6) indicate that in most cases transmissivity obtained by Boulton and Streltsova's method and by Theis recovery method are quite comparable while Papadopulos and Cooper method has given higher values.

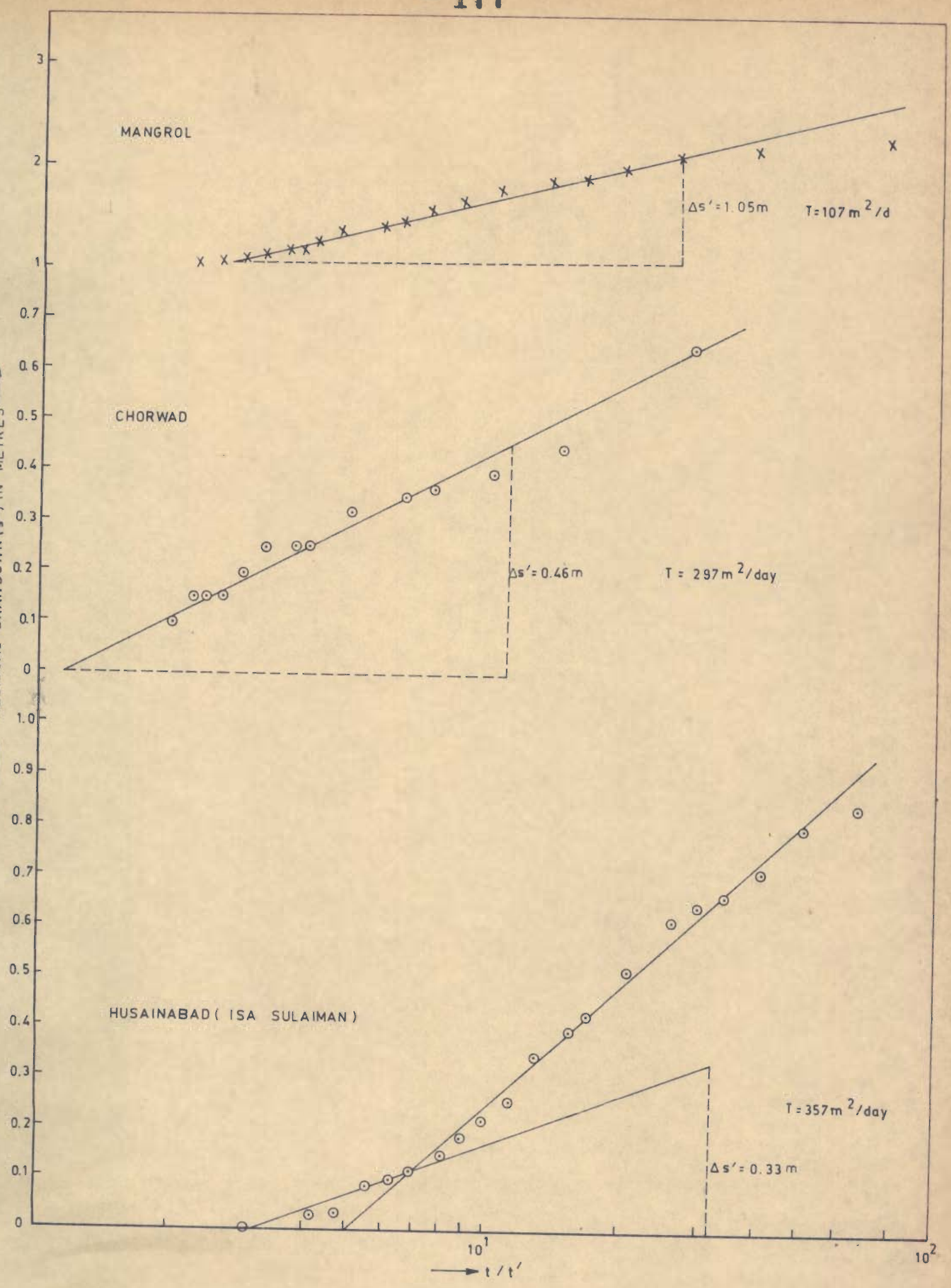


FIG. 4 .19 _ PLOTS OF DUG WELL RECOVERY.

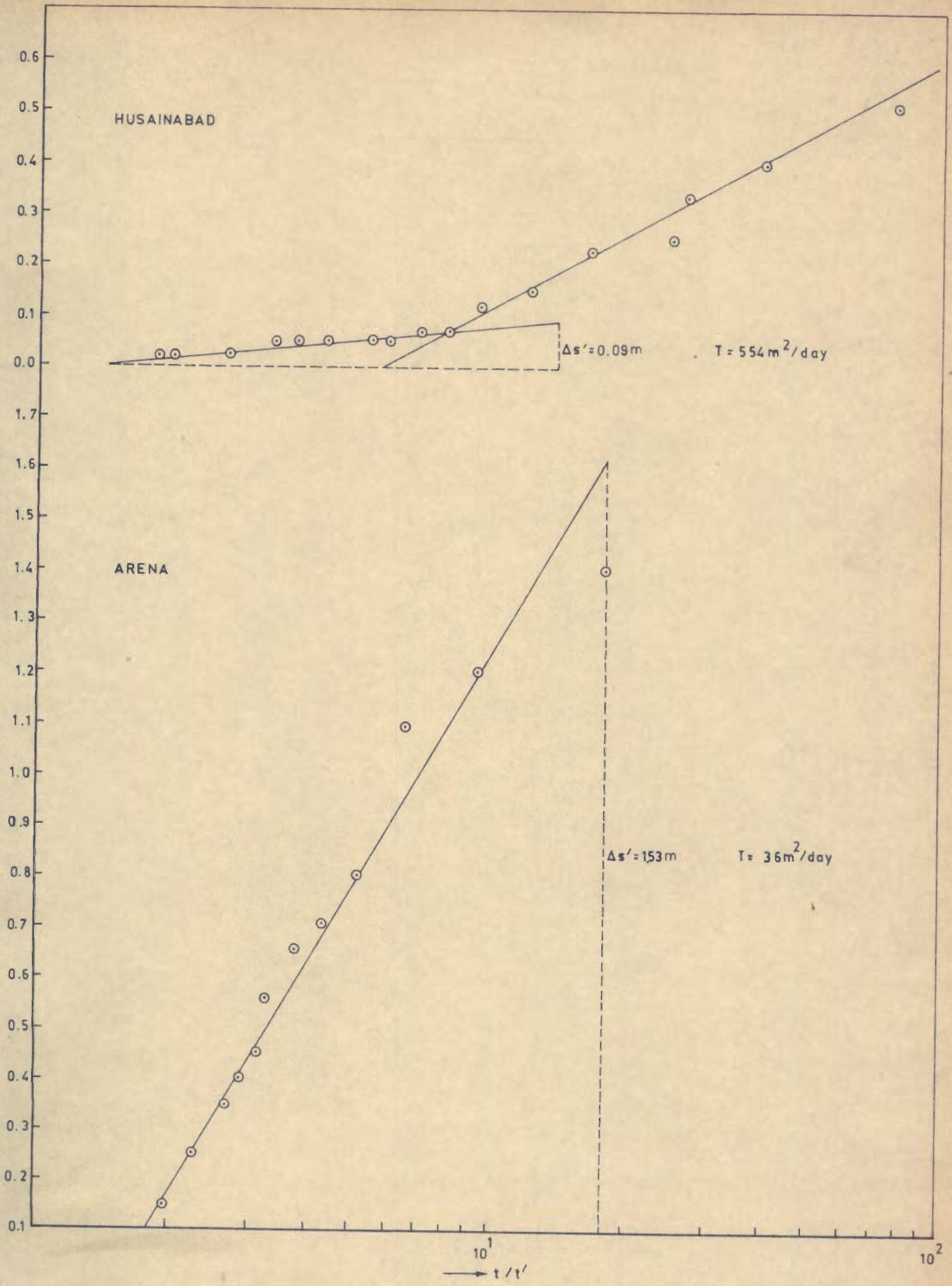


FIG. 4.20_PLOTS OF DUG WELL RECOVERY.

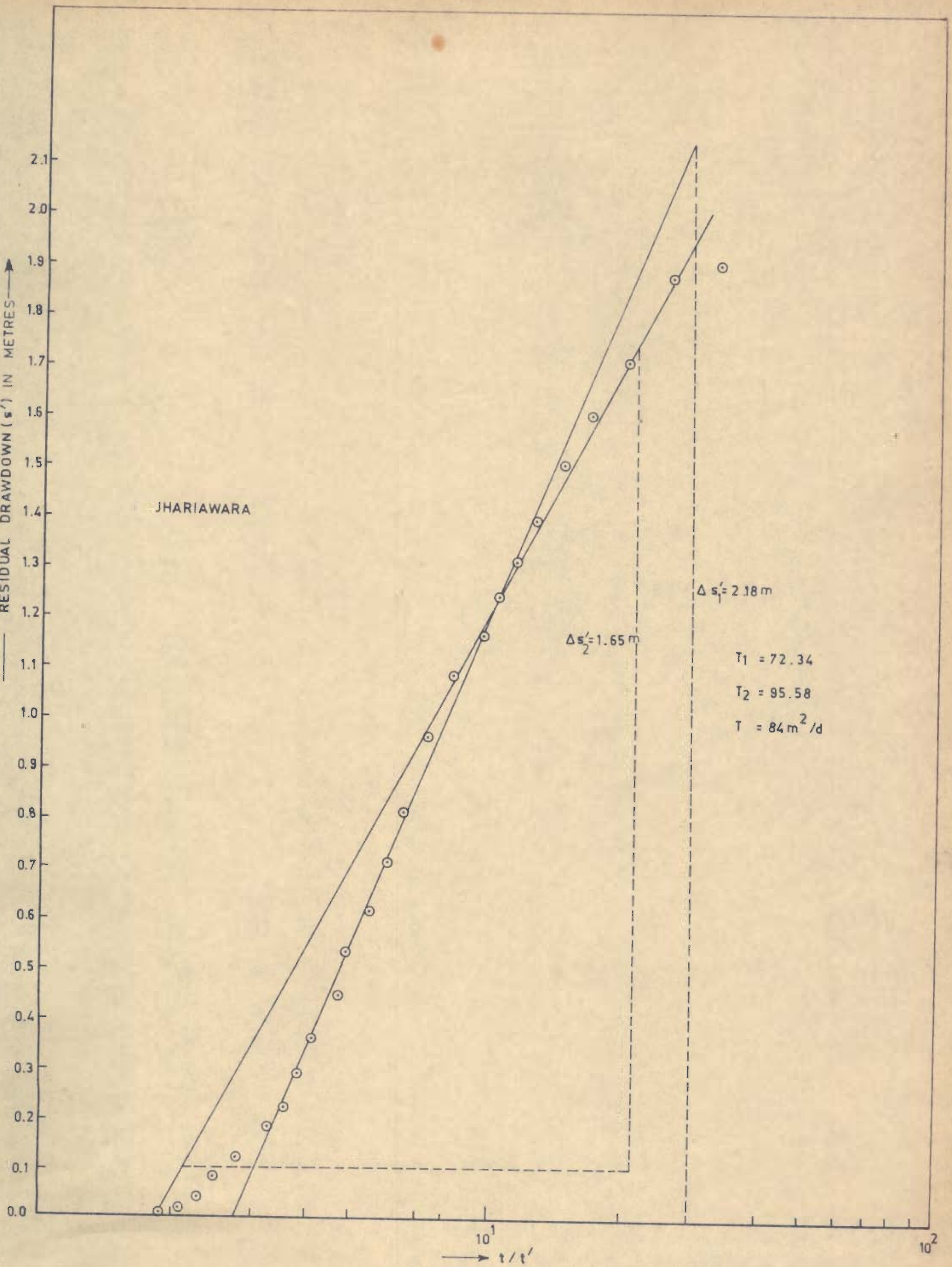


FIG. 4.21 _ PLOTS OF DUG WELL RECOVERY.

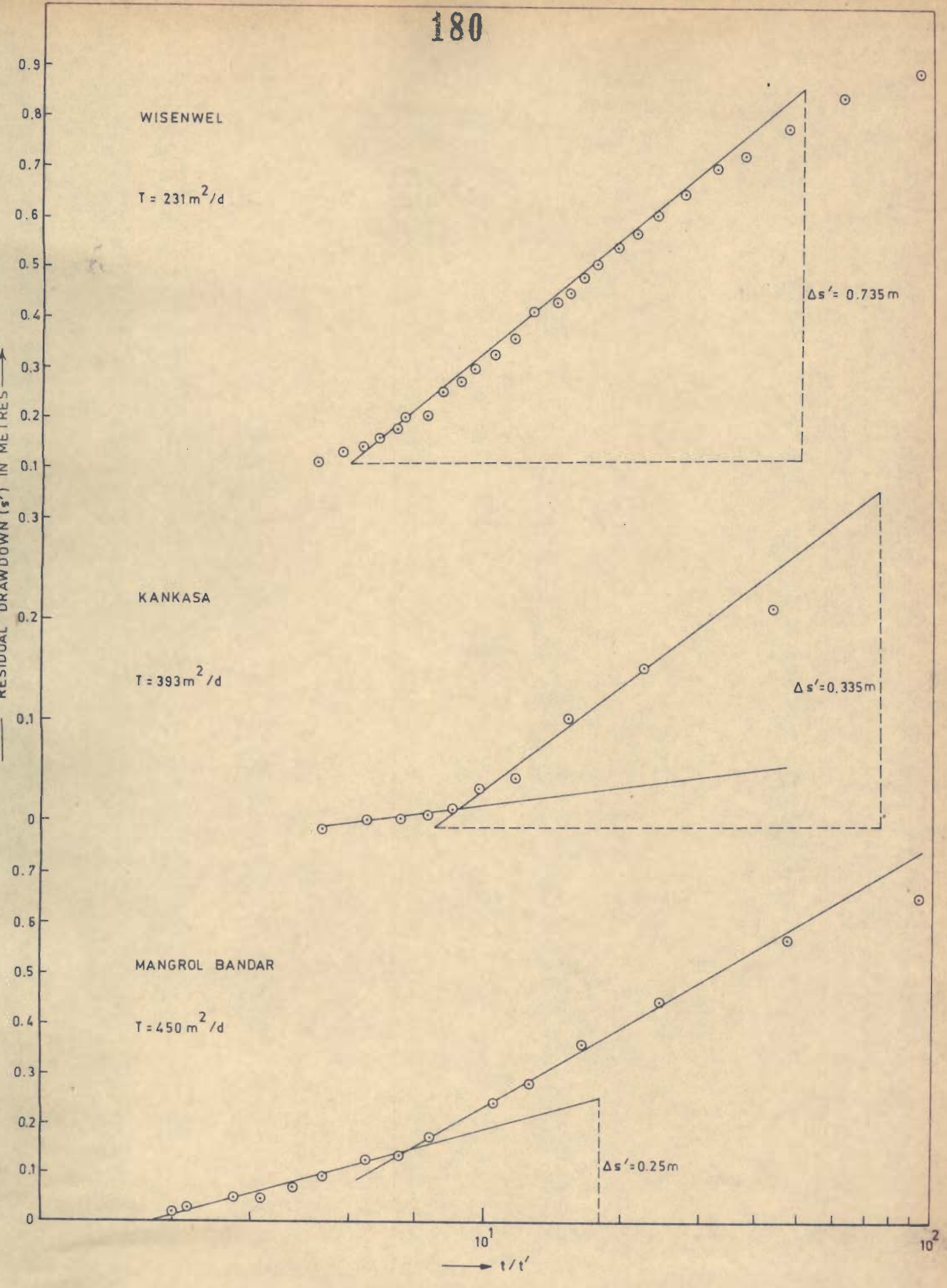


FIG. 4.22_ PLOTS OF DUG WELL RECOVERY.

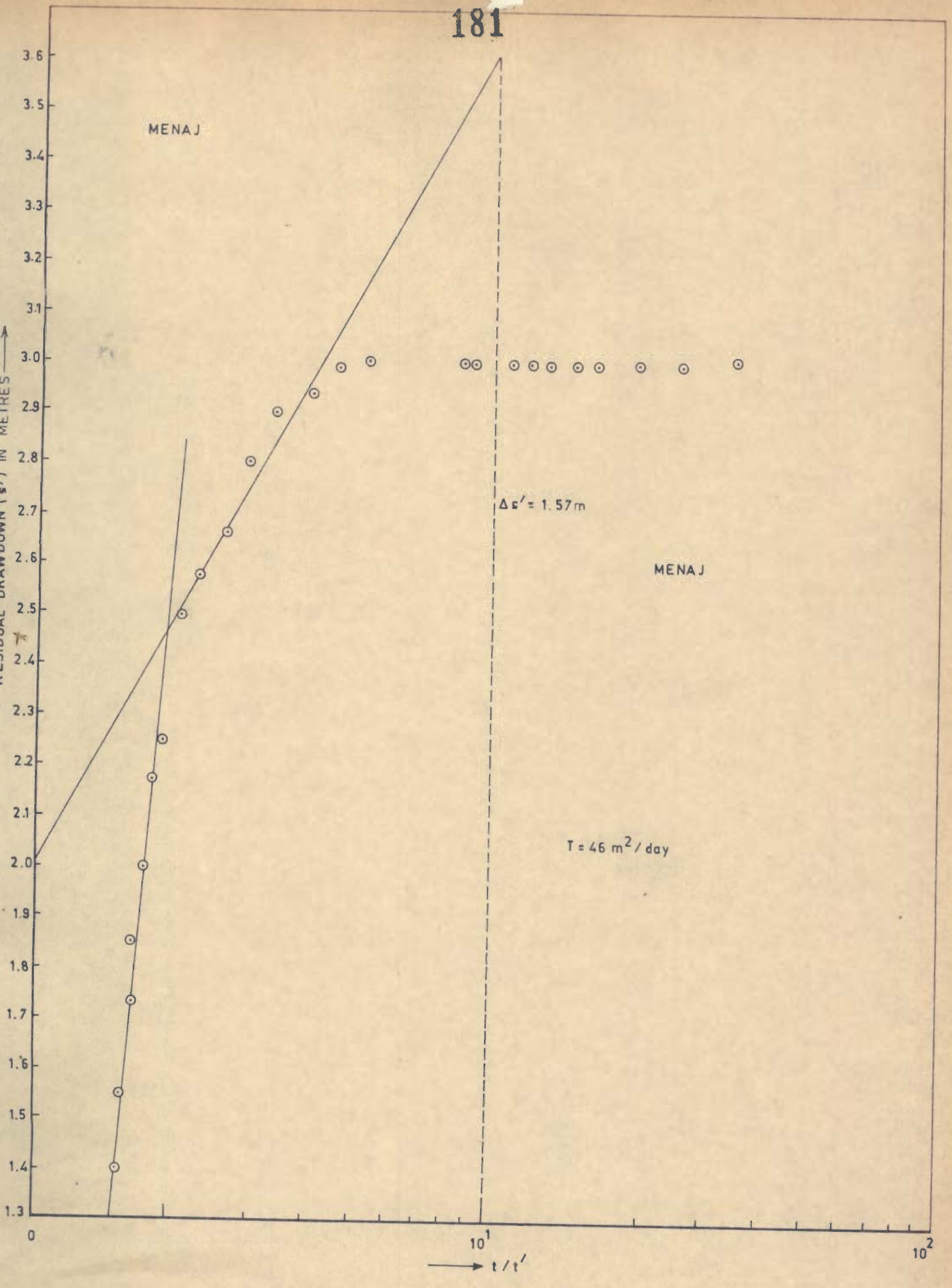


FIG. 4.23 _ PLOTS OF DUG WELL RECOVERY.

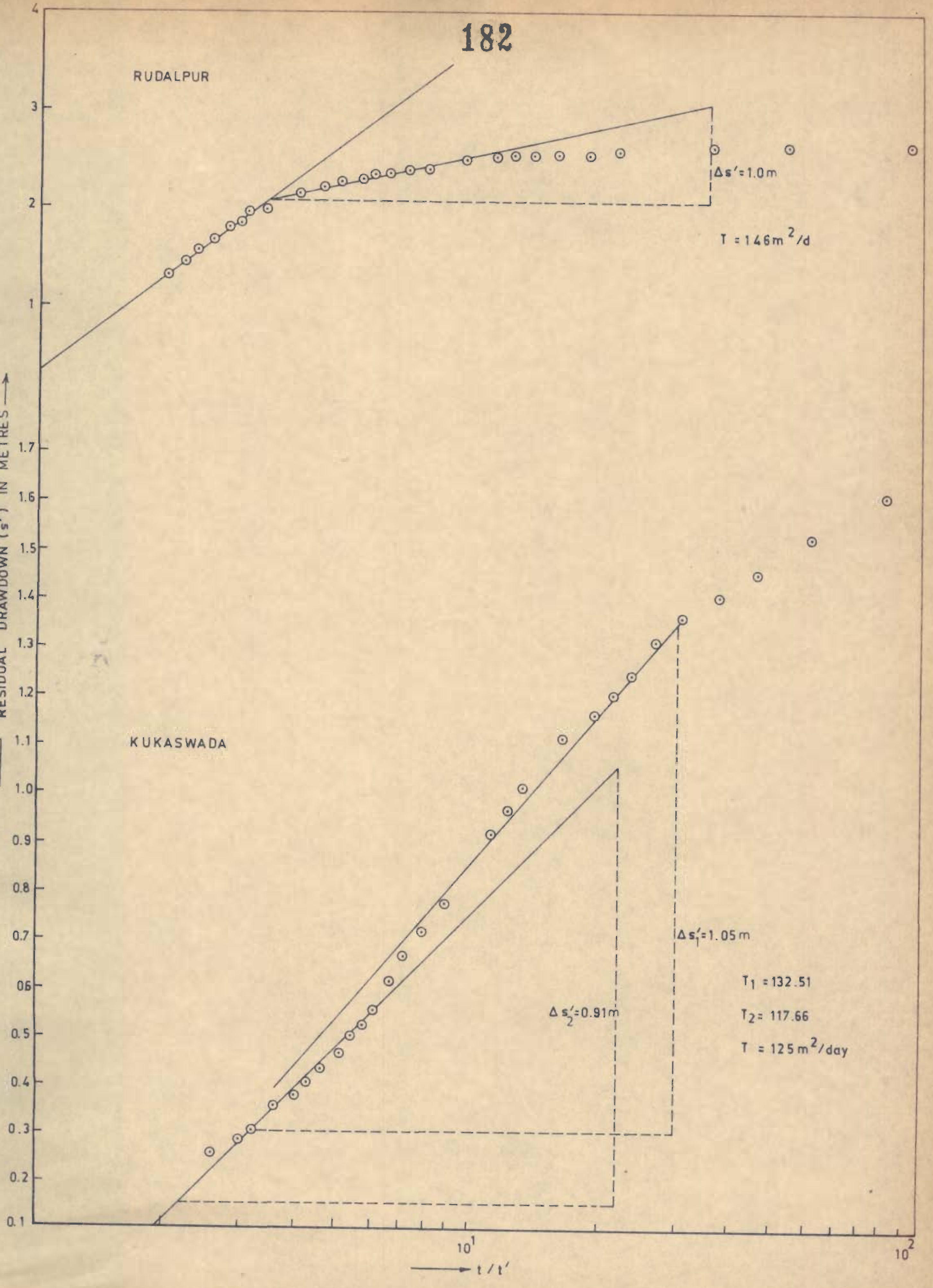


FIG. 4.24 _ PLOTS OF DUG WELL RECOVERY

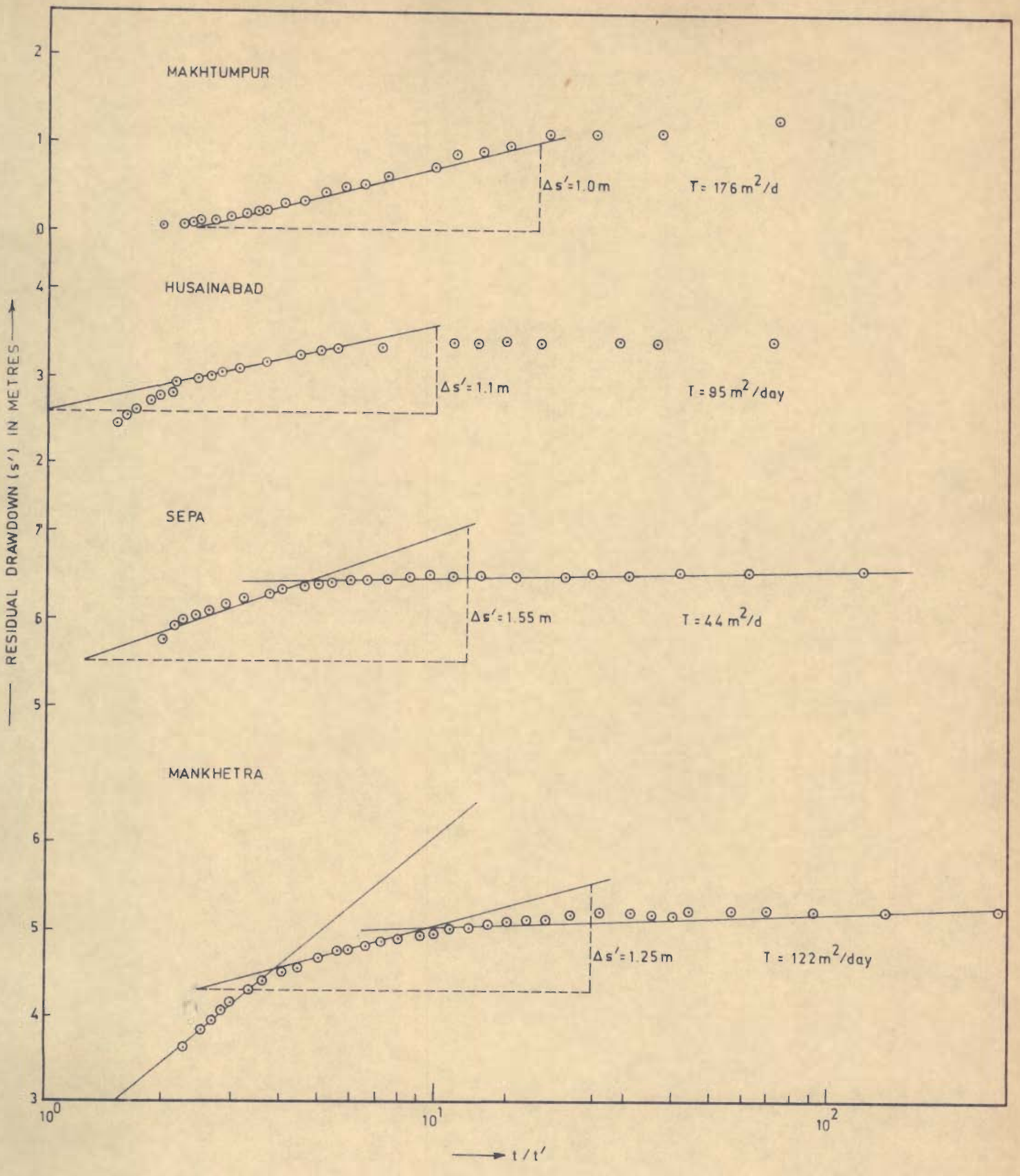


FIG. 4.25 _ PLOTS OF DUG WELL RECOVERY

Table 4.5: T Values for Miliolite Formation Calculated by Different Methods and S values by Papadopulos and Cooper Method

Village	Papadopulos and Cooper's method T(m^2/d)		Boulton and Streltsova's method T(m^2/d)	Recovery Method T(m^2/d)	Remarks
Husainabad	940	1.39×10^{-4}	554	357	Middle part of recovery is taken
Jhariawara	227	7.277×10^{-3}	137	84	Middle part of recovery is taken
Wisenwel	846		728	231	-
Kankasa	1906	1.89×10^{-4}	682	393	Later part of recovery is taken
Mangrol Bandar	533	1.614×10^{-2}	..	450	Later part of recovery is taken
Husainabad	189	5.6×10^{-3}	909	554	Later part of recovery is taken
Chorwad	394	1×10^{-2}	971	297	Later part of recovery is taken
Arena	172	8.6×10^{-3}	51	36	Later part of recovery is taken
Mangrol	216	5.7×10^{-3}	109	107	-

Table 4.6: T values for Gaj Formation Calculated by Different Methods and S values by Papadopulos and Cooper's Method

Village	Papadopulos and Cooper's method T (m^2/d)	S	Boulton and Streltsova's method T (m^2/d)	Recovery method T(m^2/d)	Remarks
Husainabad	118	8.5×10^{-9}	102	95	Middle/Later part of recovery is taken
Rudalpur	318	8.15×10^{-5}	259	146	Middle part of recovery is taken
Makhtumpur	626	3.62×10^{-3}	111	176	Later part of recovery is taken
Menaj	507	4.26×10^{-5}	62	46	Later part of recovery is taken
Sepa	218	9.55×10^{-2}	32	44	Later part of recovery is taken
Kukaswada	555	1.7×10^{-4}	138	125	Average of later and middle part is taken
Mankhetra	108	6.45×10^{-2}	175	195	Middle part is taken

4.5.6.4. Specific Capacity

Specific capacity is the ability of well to yield water. According to Todd (1959) it is a measure of the effectiveness of the well. The specific capacity of a well may be defined as the yield of the well per unit drawdown which is generally expressed as litres per minute per metre of drawdown. A high specific capacity indicates that the aquifer tapped by the well has a high coefficient of transmissibility. In addition to this, the other factors affecting the specific capacity are: the coefficient of storage, the depth of penetration of the well below the regional water table, the size of the well, the entrace losses, and the duration of pumping period. In the case of large diameter open wells, it is erroneous to use discharge drawdown method to find out the specific capacity, because during the initial periods of pumping the water mainly comes from the dead storage and the instantaneous release of water from the aquifer is generally negligible. Hence, the recovery data should be used.

Using the recovery data, the specific capacity of large diameter dug wells can be computed using Slichter's formula (Wenzel, 1942). Slichter's formula is not useful for determining aquifer constants, but it can be used to compare the performance of wells of similar types in similar geological environments.

The specific capacity values calculated by this method (Fig. 4.26) are given in Table 4.7 - 4.8. It can be seen that the specific capacity is high in the case of wells tapping Miliolite Formation where it ranges from 132 to 1882 lp min/m of drawdown. In the case of the Gaj Formation C ranges from 8 to 1057 lp min/m of drawdown.

Walton (1963) proposed the term specific capacity index obtained by dividing the specific capacity by the saturated thickness of the aquifer tapped. It is expressed as discharge per unit drawdown for unit saturated thickness of aquifer. The specific capacity index is useful for comparing the yield characteristics of bored wells. Walton showed the usefulness of specific capacity data in the study of individual units of multi unit aquifers as contributors of water. He also demonstrated that specific capacity index can be used to predict well yields in parts of an aquifer for which well data is lacking.

Narasimhan (1965) suggested unit area specific capacity, i.e., specific capacity/area of well cross-section, in the case of dug wells to compare the yield characteristics. In dug wells the yield depends not only on the thickness of the aquifer tapped, but also on the cross-sectional area of open well.

Singhal (1973) proposed specific capacity index for open wells. In dug wells the yield depends on total surface area of the well face contributing flow to well and suggested the term specific capacity index which is obtained by dividing

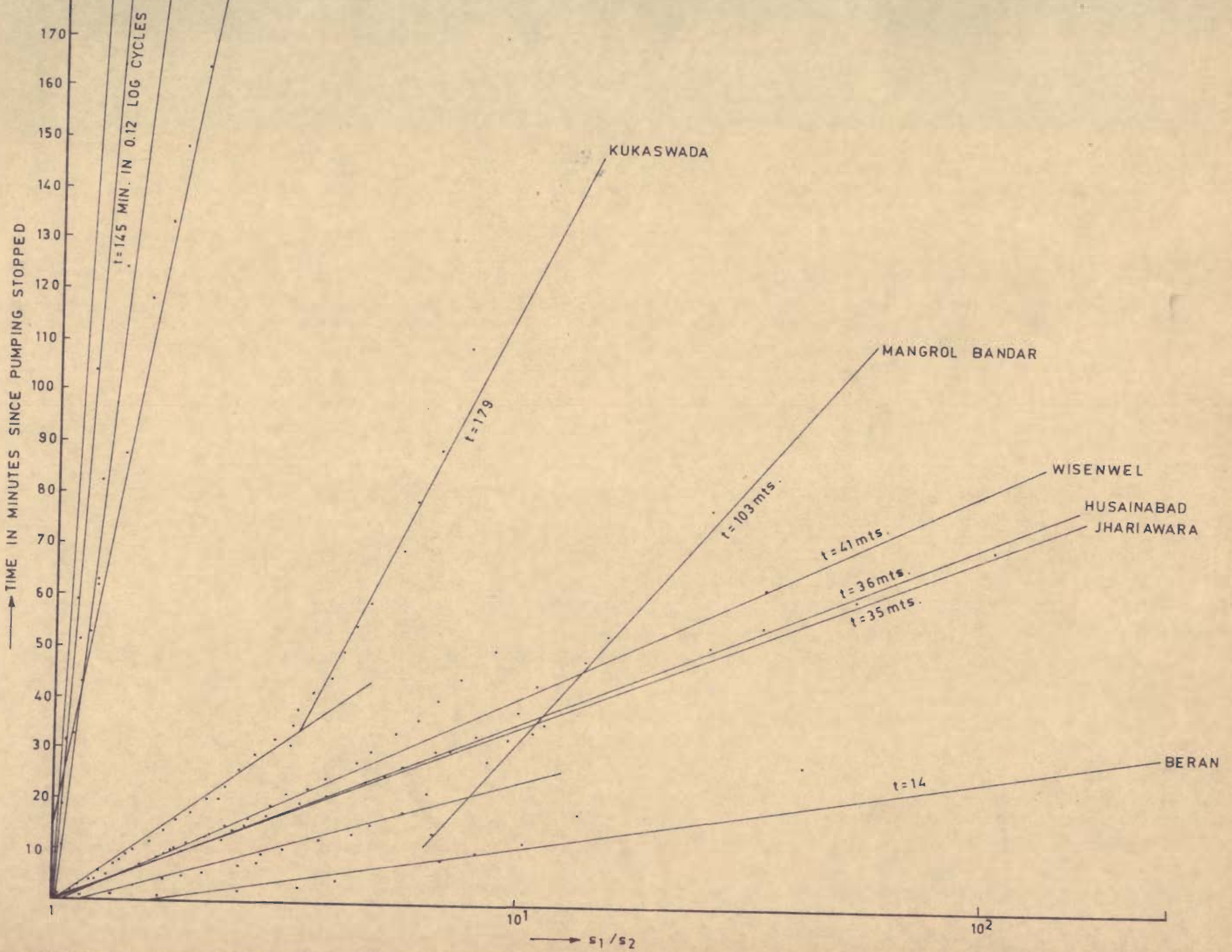


FIG. 4.26 – PLOTS OF RESIDUAL DRAWDOWN VERSUS TIME SINCE PUMPING STOPPED.

the specific capacity by the surface area of the aquifer tapped by the well.

In the present study, unit area specific capacity and specific capacity index (Singhal, 1973) values were determined (Tables 4.7 and 4.8). It can be seen that the specific capacity index values, i.e. productivity values are generally higher in the Miliolite Formation than in Gaj Formation. When the productivity values have been plotted against total depth of the well and also depth to static water level (Fig. 4.27) it is seen that there is no definite relation between them.

4.6 SUMMARY

The geohydrological aspects of Deccan Trap basalts, Gaj Formation and Miliolite Formation of the area under investigation have been studied. All these geological formations occurring in the coastal area contain porous and permeable zones which act as moderate to good aquifers. In Deccan Trap basalts the porosity is of secondary type which is due to the presence of joints and fractures. The wells range in depth from 21 to 27 m below the ground surface.

The Gaj Formation consists essentially of alternating bands of limestones and clays. Generally the upper horizons (upto about 30 m) are unconfined in nature. These rocks are characterised by double porosity, i.e., porosity of blocks and porosity of fissures. The depth of wells varies from 7 m to 32 m below ground level, but majority of them fall in the depth range of 10-15 m.

Table 4.7: Specific Capacity, Specific Capacity Index and Unit Area Specific Capacity for the Wells in Miliolite Formation

Sl. No.	Village	Specific capacity (lpmin/m. d.d.)	Specific capa-city Index $\frac{(\text{specific capacity})}{2\pi rh^*}$ (lpm/m d.d./m^2)	Unit area specifi capacity $\frac{(\text{specific capacit}}{\pi r^2}$ (lpm/m.d.d./m^2)
1.	Husainabad	361	29.64	63.89
2.	Jhariawara	279	114.43	65.68
3.	Wisenwel	325	14.00	56.08
4.	Kankasa	1843	352.35	373.86
5.	Mangrol Bandar	132	10.78	23.92
6.	Husainabad	767	36.05	85.22
7.	Chorwad	185	11.54	41.11
8.	Arena	714	44.75	79.33
9.	Mangrol	1882	245.76	209.11
10.	Mangrol	977	143.56	77.63

* r = radius of the well

h = saturated thickness of the aquifer tapped

Table 4.8 Specific Capacity, Specific Capacity Index and Unit area Specific Capacity for the Wells in the Gaj Formation

Sl. No.	Village	Specific capacity l/min/m d.d.	Specific capacity Index $\left(\frac{\text{specific capacity}}{2\ rh^*}\right)$ lpm/m.d.d./m^2	Unit area specific capacity $\left(\frac{\text{specific capacity}}{r^2}\right)$ lpm/m.d.d./m^2
1.	Husainabad	24.00	9.46	3.32
2.	Rudalpur	21.00	0.58	2.78
3.	Makhtumpur	175.00	65.79	27.74
4.	Manaj	20.00	0.50	6.36
5.	Sepa	8.00	2.66	1.47
6.	Kukaswada	180.00	2.89	35.38
7.	Mankhetra	11.00	0.66	1.67
8.	Beran	1057.00	118.96	164.26

* r = radius of the well

h = saturated thickness of aquifer tapped

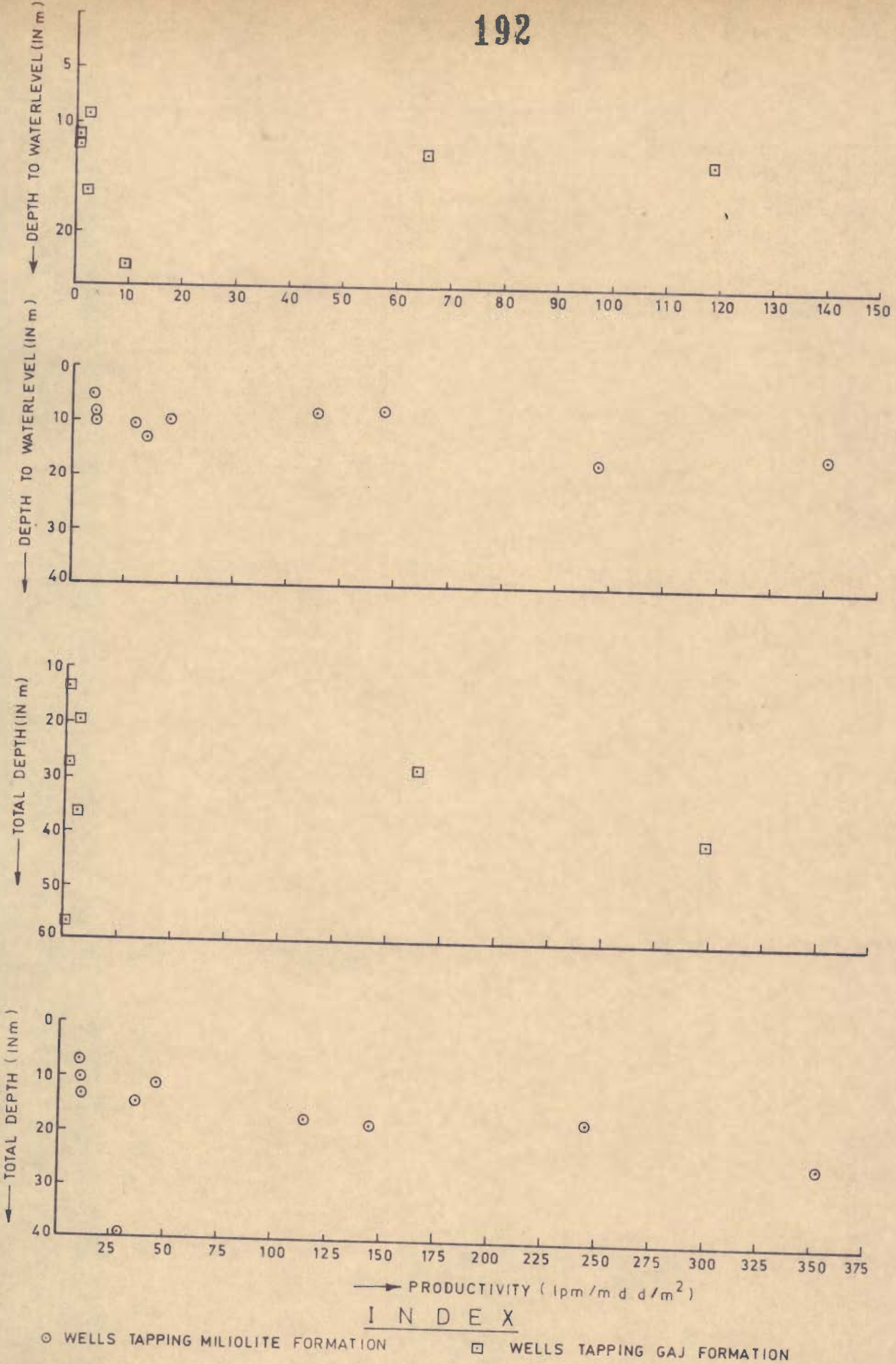


FIG. 4.27 – PLOTS OF PRODUCTIVITY VERSUS TOTAL DEPTH AND DEPTH TO STATIC WATER LEVEL.

Miliolite Formation occupies the coastal area in which ground water occurs under unconfined conditions. Intergranular and intragranular porosity, and karstic features produced by the solution of limestone are very common. Majority of wells tapping this formation are of 5 m to 10 m in depth.

Rainfall is one of the most important factors which influence the groundwater levels. Hydrographs of rainfall and monthly ground water levels indicate that as the monsoon proceeds the ground water level rises and during the non-rainy months the water table gradually declines. The values of correlation coefficient indicate that although the rainfall affects the water levels, it is not the only factor responsible for the fluctuation of water levels, but other factors such as irrigation,pumping etc. also play an important role. There is a rising trend for water levels with years during the post-monsoon period whereas the pre-monsoon water levels have remained more or less same in the previous years in the case of wells tapping the Miliolite and Gaj Formations and Deccan trap basalts. The rising trend in the water levels during the post-monsoon period seems to be due to increase in precipitation during these years.

Trend surface analysis of water level data indicates that the general groundwater flow is towards southwest and west from the central area. In the western part of the area, the groundwater flow is from the coast towards inland. This might be because of the overdevelopment of groundwater for irrigation purposes. The configuration of the trend surfaces for pre-monsoon and post-monsoon periods remains more or less same.

Lower permeability is indicated by closeness of the contour lines in the Gaj Formation, whereas in the Miliolite Formation more widely spaced contour lines indicate higher permeability. The groundwater level fluctuations are higher in the Gaj Formation than in the Miliolite Formation, thereby indicating differences in their geohydrological characteristics.

The drawdown data from pumping tests on large diameter wells were utilised to determine T by Papodopulos- Cooper's method, Boulton and Streltsova's method and S by Papadopulos - Cooper's method. From recovery data also T was determined by using Theis' recovery method. Numerical model for analysis of pumping test data could not be used. The transmissivity values obtained by Boulton and Streltsova method are quite comparable with those obtained from later part of recovery data using Theis equation. Miliolite Formation has higher transmissivity values (51 - 909 m^2/d) compared to Gaj Formation(3.2-259 m^2/d).

The specific capacity of wells determined from recovery data indicate that it is higher in the Miliolite Formation than in Gaj Formation. The specific capacity varies from 185 to 1882 lpm/m of drawdown in the Miliolite Formation and 11 to 180 lpm/m of drawdown in the Gaj Formation. The productivity values as determined from specific capacity data indicate that the Miliolite Formation are more productive than the Gaj Formation.

CHAPTER 5

HYDROGEOCHEMISTRY

5.1 INTRODUCTION

Finding water in adequate quantity is not every thing, it has to be also of suitable quality. In coastal regions groundwater is frequently saline and therefore, in many cases the key factor is not the quantity of water only but also its quality. Hence, the hydrogeological studies are incomplete without the study of the chemical quality of water.

Hydrochemical study seeks to determine the chemical composition of groundwater and the relationship between water quality and composition of the rock. Hydrogeochemistry has not developed as rapidly as other aspects of hydrology. Interest in this branch is a development of the recent past. It is increasingly gaining prominence in regional hydrogeological studies. The application of the principles of chemical thermodynamics - the law of mass action, the concept of free energy etc. have helped in understanding of the major controls on the interaction between water and aquifer materials (Schoeller, 1959; Garrels and Christ, 1965; Back and Hanshaw, 1970; Plummer, 1975; Thrailkill, 1976; Wigley and Plummer, 1976).

Groundwater is never found in its pure state in nature. The presence of dissolved ions in water changes some of its physical properties, e.g., electrical conductivity etc. Most of the natural water circulating in the hydrological cycle can be categorised as 'dilute solutions'. Hence the general principles of solution chemistry can be applied to them to study the various equilibria occurring at the interfaces of water - solid and interactions occurring in the aquous system to investigate the various factors that control the concentration and distribution of dissolved constituents in natural waters. These dissolved substances characterise the quality of water and its suitability for various purposes.

In the case of limestone aquifers, the distribution of chemical species in ground water is not random. Generally it is controlled by the various processes and reactions of diagenesis including recrystallisation, dolomitization and cementation, by dissolution and reprecipitation of minerals during the flow of groundwater and by mass transfer of chemical species . We can see the physical manifestation of this interplay of hydrology, sedimentology, mineralogy and water chemistry in nature. It is evident in landscape modification, karst features, porosity and permeability distribution, as well as in the establishment and operation of local and regional flow systems. The observed chemical character of water in carbonate aquifers is both a control on the physical parameters indicated above and a response to them (Hanshaw and Back, 1979). Thus the chemical character of groundwater reflects the combined effects of chemical activity between water and limestone and the flow pattern within the aquifer. A combined study of general water chemistry and mineral saturation of the water, is helpful to identify the principal areas of recharge and to identify which geochemical process control the chemical character of water. An attempt in this regard has been made in the present study.

The composition of natural water is determined by chemical analyses. In the present study the analysis of water samples collected from wells tapping Miliolite and Gaj Formations have been done and the data from these have been used for various purposes such as classification, correlation etc. The data have been compiled and plotted in various graphs and trilinear diagram (Hill-Piper), because graphical representation is one of the most illustrative method of representing the analytical data. They are helpful in the detection and identification of mixing of waters of different compositions, and also the chemical processes that might be taking place during the flow of ground water in individual horizons, both areally and in time. The data have been plotted in U.S. Salinity diagram and Wilcox diagram in order to find the suitability of groundwater for irrigation. Statistical analysis (Principal component Analysis and Discriminant Analysis) of the data have been done for studying the inter-relationship of different ions and also for discriminating waters from different rocks and also waters of different seasons. Trend surface maps of different ions have also been prepared to study the areal variation in water chemistry.

5.2 COLLECTION AND ANALYSIS OF WATER SAMPLES

5.2.1 Collection of water samples

For a detailed hydrogeochemical study and for establishing the causes of salinity in the coastal aquifers, systematic groundwater sampling was done. A total of 67 samples were collected during February, 1979 for studying the lateral and seasonal variations in water quality. Sample points were selected in such a manner, that they are evenly distributed in the area as far as possible. The sample locations are shown in Fig. 5.1. All the water samples were collected either from dug wells or from dug cum bore wells.

5.2.2 Methods of Analyses

5.2.2.1 Physical Analysis

The colour and turbidity of the water was determined visually. The temperature of ground water was measured at the time of collection of the samples.

5.2.2.2 Chemical Analysis

The commonly determined constituents in water analysis are expressed as ions and include cations, i.e., sodium (Na^+). potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}), and anions, i.e., sulphate (SO_4^{2-}) chloride (Cl^-), carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-).

The water samples collected during the various field trips were analysed in the Geochemical Laboratory of the Department of Earth Sciences, University of Roorkee, Roorkee. The analysis for Na^+ and K^+ were done by Flame Photometer and SO_4^{2-} by SPECOL (Carl Zeiss Spectrophotometer) and by gravimetric methods. Other cations as Ca^{2+} and Mg^{2+} and anions Cl^-, CO_3^2, and HCO_3^- were determined by volumetric methods. pH was determined by a pH meter

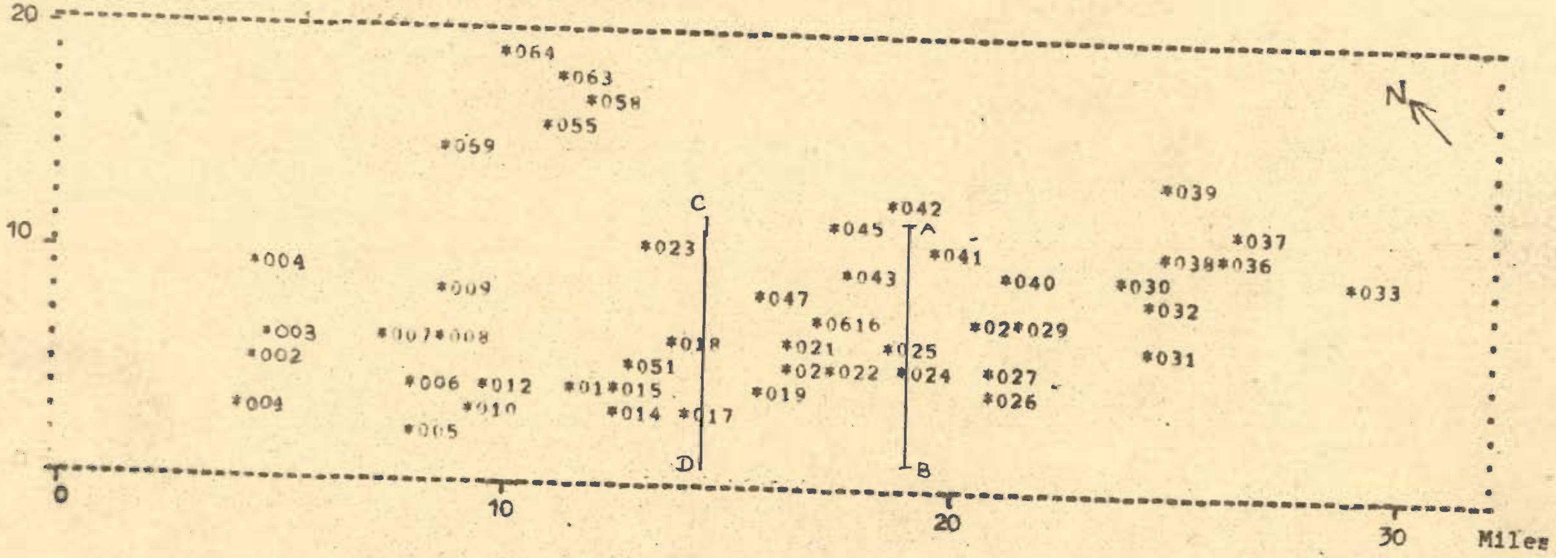


Fig. 5.1 LOCATION OF WELLS FROM WHICH WATER SAMPLES HAVE BEEN ANALYSED FOR THEIR CONTENT OF DIFFERENT IONS, E.C., ALKALINITY, pH AND TEMPERATURE.

(Philips PR 9405 L model) and electrical conductivity by conductivity bridge (Philips PR 9500 model). Total dissolved solids (T.D.S) was determined by evaporating the water at 110°C and was also calculated from the electrical conductivity measurements. The details of the different methods of analysis are given by Rainwater and Thatcher (1960) and Indian Standard Institution (1968).

The results of the chemical analysis of ground waters collected during February 1979 are given in Table 5.1. The concentration of various constituents are expressed in ppm and epm.

5.2.3 Accuracy of Analysis

Before the chemical analysis data of the water samples are utilized for any purpose, it is very important to check the accuracy and completeness of the analysis. There are a number of methods for checking the accuracy of the data. The methods used by the author in the present study are the following:

(i) Cation anion balance method

When the analytical data are represented in epm, the sum of the cations should be theoretically equal to the sum of all anions. The difference between the two sums should not be great. In the present study, a margin of 16% was given, because the analysis was partial and they were not analysed for boron, strontium, iodine, nitrate, silica etc.

(ii) Electrical conductance method:

The electrical conductivity expressed in micromhos/cm at 25°C when multiplied by a factor which usually lies between 0.55 and 0.85 is equal to the T.D.S. in ppm. It is an approximate method of checking the analytical data.

(iii)) Method of comparing T.D.S. values:

The values of total dissolved solid (expressed in ppm) determined by evaporating a known quantity of sample and weighing the residue must be nearly equal to the sum of the dissolved constituents expressed in ppm except HCO_3^-. Half of the HCO_3^- concentration is added to the sum of all the ions present to calculate T.D.S.

In the present study, the above mentioned checks have been done and the analytical data were found to be fairly accurate.

5.3 QUALITY OF WATER FROM DIFFERENT AQUIFERS

Water samples collected during February 1979 are from three different litholgic units, i.e., the Miliolite Formation, Gaj Formation, and Deccan Trap basalts. Only two samples were collected from wells tapping basalts. The analytical data is presented in Table 5.1.

In general, these waters are colourless and odourless. They mostly have no taste except that those waters from Miliolite Formation which are saline, have a bitter taste. The temperature varies from 18°C to 29°C for the groundwater from the

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Miliolite Formation, 20°C to 29.5°C for the water wells tapping Gaj Formation and 24°C for the wells tapping basalts. There are slight fluctuations in the water temperature during the course of the year.

The quality of water in this coastal belt is poor, and quality deteriorates towards the coast. In most cases the Cl content, electrical conductivity, and total dissolved-solids are very high.

5.3.1 Specific Electrical Conductance

The ability of a substance to conduct electrical current is called electrical conductance and the conductance of a one centimeter cube at a particular temperature is known as specific electrical conductance which is expressed in mhos per centimetre or micromhos/cm. Conductance of water is a function of both temperature and type of ions and their respective concentration in water. The specific electrical conductance readings are usually adjusted to 25°C so that further variations are a function only of the concentration and type of dissolved constituents. Normal ground water has a conductance of 30 to 2000 micromhos/cm. Calcium-bicarbonate and calcium sulphate water generally have the lowest conductance and sodium chloride water the highest conductance.

The specific electrical conductance of ground waters tapping the Miliolite Formation are generally high, especially, those from near the coast. It ranges from 699 to 9990 micromhos/cm. In the case of waters from the Gaj Formation, this is generally low, ranging from 499 to 3681 micromohos/cm. Of these only 4 samples show specific electrical conductance greater than 2000 micromhos/cm, whereas all the other samples show a lower value.

5.3.2 Total Dissolved Solids (T.D.S.)

Generally the rain water contains only small quantities of dissolved matter. It will start dissolving minerals of the soil and rock as soon as it reaches the earth. The amount and character of the mineral water dissolved by rain water depend upon so many factors, such as the chemical composition and physical structure of the rocks with which they have been in contact, the temperature, the pressure, the period of contact, the minerals already in solution etc.

In the area under investigation, the T.D.S. is higher in the waters from the Miliolite Formation than those from the Gaj Formation. In the former case it ranges from 454.5 to 6494 ppm and in the latter case 324.6 to 2392.30 ppm. The T.D.S. is high in the samples collected from near to the coast and gradually decreases inland. The higher T.D.S. near to the coast may be attributed to the mixing of the sea water with ground water.

5.3.3 Hydrogen Ion Concentration (pH)

pH is the negative logarithm (to the base of 10) of hydrogen ion concentration in moles per liter.

In the area under study the range in pH for waters tapping the Miliolite Formation is 6.6 to 8. Majority of water samples are in the range 7 to 7.5. Only five samples show pH less than 7. The waters from the Gaj Formation have a pH between 7 and 7.8. Therefore, majority of ground waters in this region are alkaline in nature.

5.3.4 Hardness

In spite of wide usage, the property of hardness is difficult to define exactly and several definitions are in common use. Over the years, the property of hardness has been associated with effects observed in the use of soap or with the encrustations left by some types of water. As the hardness is a property not attributable to a single constituent, some convention is used for expressing concentrations in quantitative terms. Hardness is caused mainly by the presence of Ca^{2+} and Mg^{2+} ions in water. The total hardness is a measure of these constituents and is conventionally expressed in terms of an equivalent quantity of calcium carbonate. Thus:

$$\text{Total Hardness TH(in ppm)} = \text{Ca} \times \frac{\text{Ca CO}_3}{\text{Ca}} \quad \text{Mg} \frac{\text{Ca CO}_3}{\text{Mg}} \qquad (5.1)$$

where TH is measured in parts per million of calcium carbonate, Ca and Mg are in ppm and ratios in equivalent weights.

By substituting the values of equivalent weights of Ca CO_3, Ca^{2+}, Mg^{2+} in the equation (5.1) we have

$$TH = 2.497\ Ca + 4.115\ Mg$$

The value of total hardness can also be calculated in equivalents per million by dividing these values by 50 (the equivalent weight of $Ca\ CO_3$). According to Hem (1970) a reasonable practical definition of hardness is " the effect of alkaline-earth cations".

Carbonate hardness, where reported, includes that portion of the hardness equivalent to bicarbonate + carbonate (alkalinity). If the hardness exceeds the alkalinity (in mg/l of $Ca\ CO_3$ or other equivalent units), the excess is termed "noncarbonate hardness" and is frequently reported in water analyses.

5.3.4.1 Range of Hardness Concentration:

According to Hem (1970), the adjectives "hard" and "soft" as applied to water are inexact. Durfer and Becker (1964, in Hem, 1970) use the following classification:

Hardness range (mg/l of $Ca\ CO_3$)	Description
0 - 60	soft
60 -120	Moderately hard
121 -180	Hard
More than 180	Very hard

According to the American Water Works Association (Bean 1962, in Hem, 1970) "ideal" quality of water should not contain more than 80 mg/l of hardness. The maximum limit of hardness, above which troubles may arise as given by W.H.O. (1961 in Holdon,1970)for European Standards is 500.

In the area under study, except in a few cases, the waters are very hard. In the Miliolite Formation, it varies from 170 to 4044 ppm and in the Gaj Formation, it varies from 150 to 1306 ppm.

5.3.5 Alkalinity

The alkalinity of a water represents the total content of dissolved bicarbonate, normal carbonate and hydroxide. It is generally expressed in terms of calcium carbonate. In water chemistry, alkalinity is defined as the ability of the solution to neutralise acid.

In general the alkalinity of waters from the Miliolite Formation is lower than that of the Gaj Formation. In the former case the range is between 80 ppm and 450 ppm and in the latter case it is between 195 ppm and 550 ppm. The reason for this is that the concentration of bicarbonates is more in the waters of the Gaj, when compared with that of the Miliolite Formation.

For the waters in the area under study, the ratio of total alkalinity (TA) to total hardness (TH) was determined. An excess of TA over TH indicates the presence of bicarbonate of sodium. The factor TA/TH can sometimes be used for recognizing sea water. Generally free sodium bicarbonate and sulphates and chlorides of calcium and magnesium will not occur together in natural waters because of the chemical reactions involved between them. When sodium-bicarbonate is present ($TA/TH < 1$) then we can assume that the water is not contaminated with the sea water, because the sea water contains more of chlorides and sulphates of Ca and Mg and so they can be precipitated as carbonate by reacting with sodium bicarbonate.

In the area under study, in the water tapping the Miliolite Formation, the above factor is less than 1 in majority of cases, except for three samples which are also undersaturated with respect to calcite as discussed in Section 5.4.11. This indicates that sea water intrusion has taken place in the coastal part. Regarding the water from the Gaj Formation, many of them (10 samples) show that this factor is greater than one indicating the presence of sodium-bicarbonate type of water.

5.3.6 Sodium

The primary source of Na^+ in natural waters is by the weathering of sodium bearing felspars in igneous rocks. In sediments, sodium may be present as an impurity in the cementing material or as soluble sodium salts deposited with the sediments. It can also be present, as a result of the entrance of sea water at a later time. The ratio of Na^+/Ca^{2+} in groundwaters may change by cation exchange. When sea water intrusion takes place in the coastal aquifers, the Na^+ ions will be adsorbed by clay minerals and Ca^{2+} will be released. In the present study the effect of ion exchange has been discussed in section 5.4.8.

In the area under study, the hydrochemical data(Table 5.1) show that the Na^+ content in the waters from the Miliolite Formation ranges from 47.0 ppm to 1700.0 ppm, about 28% samples fall in the range 500 to 1000 ppm. Higher Na^+ content is seen in waters occurring near to the coast. The ground water from the Gaj Formation has low Na^+ concentration (10 to 605 ppm), about 65% samples having Na^+ between 10 and 100 ppm.

5.3.7 Potassium

The main sources of K^+ for natural waters are igneous rocks. Because, the K^+ bearing minerals are more resistant to chemical weathering than Na^+ minerals, the occurrence of K^+ in natural waters is very small. The solubility of K^+ is also very high and from natural waters K^+ can be removed only by sorption, ion exchange and precipitation during evaporation. The K^+ content of natural waters is usually not more than 10 to 15 ppm.

The K^+ content is generally high (9 to 410 ppm) in waters from Miliolite Formation. Majority of water samples (91.7%) have K^+ in the range of 9 to 100 ppm. The potassium content is relatively low in the waters from the Gaj Formation varying from 4.5 and 66 ppm. Most of the samples collected fall in the range 4.5 to 50 ppm.

5.3.8 Calcium

Calcium is an alkaline-earth metal generally present in considerable amount in ground water. This is derived from various rocks. In many igneous and metamprphic minerals calcium is an essential constituent. Calcium carbonate is easily soluble in water if there is an abundant supply of H^+. In ground waters the presence of carbondioxide is very important, because if

CO_2 is added, then solution will continue and if it is removed, precipitation may occur.

Pure water can dissolve about 5 ppm of Ca^{2+}. The actual solubility in nature is greater because some CO_2 is almost always present. The solubility of Ca CO_3 increases as the partial pressure of CO_2 increases. The concentration of CO_2 in the air present in soil can be from 10 to more than 100 times the concentration in the atmosphere. With the added carbondioxide, soil water can probably contain 100 ppm or more of Ca^{2+} (Hem,1970). Groundwater may generally be undersaturated, saturated or oversaturated with respect to calcite. This aspect is described in Section 5.4.11

In the area under study, Ca^{2+} content is high in waters from the Miliolite Formation where it ranges from 12 to 1500 ppm, majority being in the range 250 to 1000 ppm. In the Gaj Formation the Ca^{2+} content is low, ranging from 20 to 300 ppm and majority of them fall in the range 20 to 100 ppm.

5.3.9 Magnesium

In igneous and metamorphic rocks, Mg^{2+} is a component of ferromagnesian minerals which can be added to ground water by their weathering. Another common source of Mg^{2+} in ground waters is dolomite in sedimentary rocks. Most limestones also contain a moderate amount of Mg.

The solubility of $MgCO_3$ is controlled by partial pressure of CO_2 as in the case of $CaCO_3$. $MgCO_3$ is more soluble in pure water than $CaCO_3$1

Generally, water from dolomite should contain equal amount of Ca^{2+} and Mg^{2+} in terms of epm if the water is at or below saturation. The reason is that equal amounts of the two ions will be dissolved during the solution process. Sometimes Mg^{2+} may get concentrated when the water is near or above saturation because some amount of Ca^{2+} can be lost by precipitation.

Waters in which Mg is the predominant cation are generally uncommon. In most natural fresh waters, Mg^{2+} is much lower than Ca^{2+} (Hem,1970). The Mg^{2+} content of natural waters range from about 1 to 40 ppm. The values in excess of this are found in water from rocks rich in Mg^{2+}.

Mg^{2+} content is more in waters from the Miliolite Formation than those from the Gaj Formation. The Mg^{2+} content of the water samples from the Miliolite Formation ranges from 6 to 608 ppm but commonly fall in the range 6 to 100 ppm. Certain samples show very high concentrations, viz. the samples collected from the villages Sil Bandar, Jhariawala, Mangrol, Khambhalia, and Sidhokar. Except Jhariawala and Sidhokar the other locations are situated within 1.5 kms from the sea coast. The Mg^{2+} content in waters from the Gaj Formation ranges from 6 to 228 ppm and majority fall between 6 and 100 ppm.

5.3.10 Sulphate

The element sulphur when dissolved in water generally occurs in the fully oxidized state complexed with oxygen as the anion sulphate, SO_4^{2-}. The source of SO_4^{2-} in ground water is sedimentary rocks, but igneous rocks also may contribute small amounts. Deposits of gypsum and anhydrite are important sources of sulphates in water. SO_4^{2-} also occurs in rain, especially in industrial areas.

The concentration of the SO_4^{2-} ion in natural waters is very variable. Groundwaters in limestones or sandstones, not containing a high proportion of SO_4 minerals, may contain 30 to 50 ppm. The concentration tends to increase with the length of time the water is in contact with the rock. The SO_4^{2-} concentration may be reduced due to sulphate reduction.

The SO_4^{2-} content of waters from the Miliolite Formation ranges from 12 to 388 ppm and the majority fall in between 12 and 100 ppm. In the case of the Gaj Formation, the range is between 6.5 to 50 ppm. The effect of sulphate reduction has been discussed in Section 5.4.6 and 5.4.8.

5.3.11 Chloride

Important sources of chloride are sedimentary rocks, especially evaporities. It can also be present in connate water in all marine sediments and also in incompletely leached marine deposits.

In arid regions chloride accumulates in the soil, but in humid climates it is normally leached. Vertical migration can take place seasonally in the soil profile in semiarid regions.

Chloride ions may be present in large amounts in groundwater in coastal regions due to salt water intrusion. This aspect is discussed at a later part of this Chapter.

Chloride is present in all natural waters and concentrations are normally less than 50 ppm. High concentrations are seen in Na^+ rich waters.

In the area under study, Cl^- concentration is high (63 to 4025 ppm) in groundwaters from the Miliolite Formation near to the coast. 50% of the samples have Cl^- in the range of 500 to 1500 ppm while 28% samples have 1500 to 3000 ppm of it.Only five samples had Cl^- below 500 ppm. There is an increase in Cl^- towards the coast. This aspect is discussed in Section 5.4.8.

In the case of waters from the Gaj Formation the range is 35 to 1235 ppm, but majority fall in the group 25 to 200 ppm.Only 20.7% of the samples from wells tapping the Gaj Formation show a concentration between 500 and 1500 ppm.

5.3.12 Carbonate and Bicarbonate

Limestones and the relatively small amounts of calcareous material in other sedimentary rocks are the main sources of carbonate and bicarbonate ions in natural waters. It is also derived from the carbondioxide in the atmosphere and the CO_2 present in the soils. Calcium bicarbonate is almost completely dissociated (Eq. 5.1a) in dilute solution:

$$Ca\,CO_3 + H^+ \rightarrow HCO_3^- + Ca^{2+} \quad .. \quad .. \qquad 5.1a$$

The second step in the dissociation is (Eq.5.2b)

$$HCO_3 \rightarrow CO_3^{2-} + H^+ \qquad 5.2b$$

but this takes place to any significant extent when the pH is greater than 8.2.

As explained in Section 5.3.5 alkalinity is a measure of the bicarbonate and carbonate ions in solution. The bicarbonate content of groundwater due to CO_2 derived from the air and soil is normally less than 450 ppm. Concentrations over 1000 ppm sometimes occur in waters which are low in Ca^{2+} and Mg^{2+} and especially where processes releasing CO_2(such as sulphate reduction) are occurring in the groundwater reservoir.

The carbonate content in the waters from the Miliolite Formation and the Gaj Formation are very small and it is present only in a few cases. The bicarbonate content in water from the Miliolite Formation varies from 97 to 458 ppm. Majority of them fall in the range 200 to 400 ppm. Similarly the range of HCO_3^- in the Gaj Formation is 12.9 to 445 ppm, but 75.9% of the samples have 250 to 400 ppm. The higher concentration of bicarbonate is due to the solution of carbonate rocks.

Cumulative frequency curves for different ions (ppm values) and total hardness, alkalinity and EC., are shown in Figs. 5.2 and 5.3 to demonstrate the variation of the above constituents in groundwater samples.

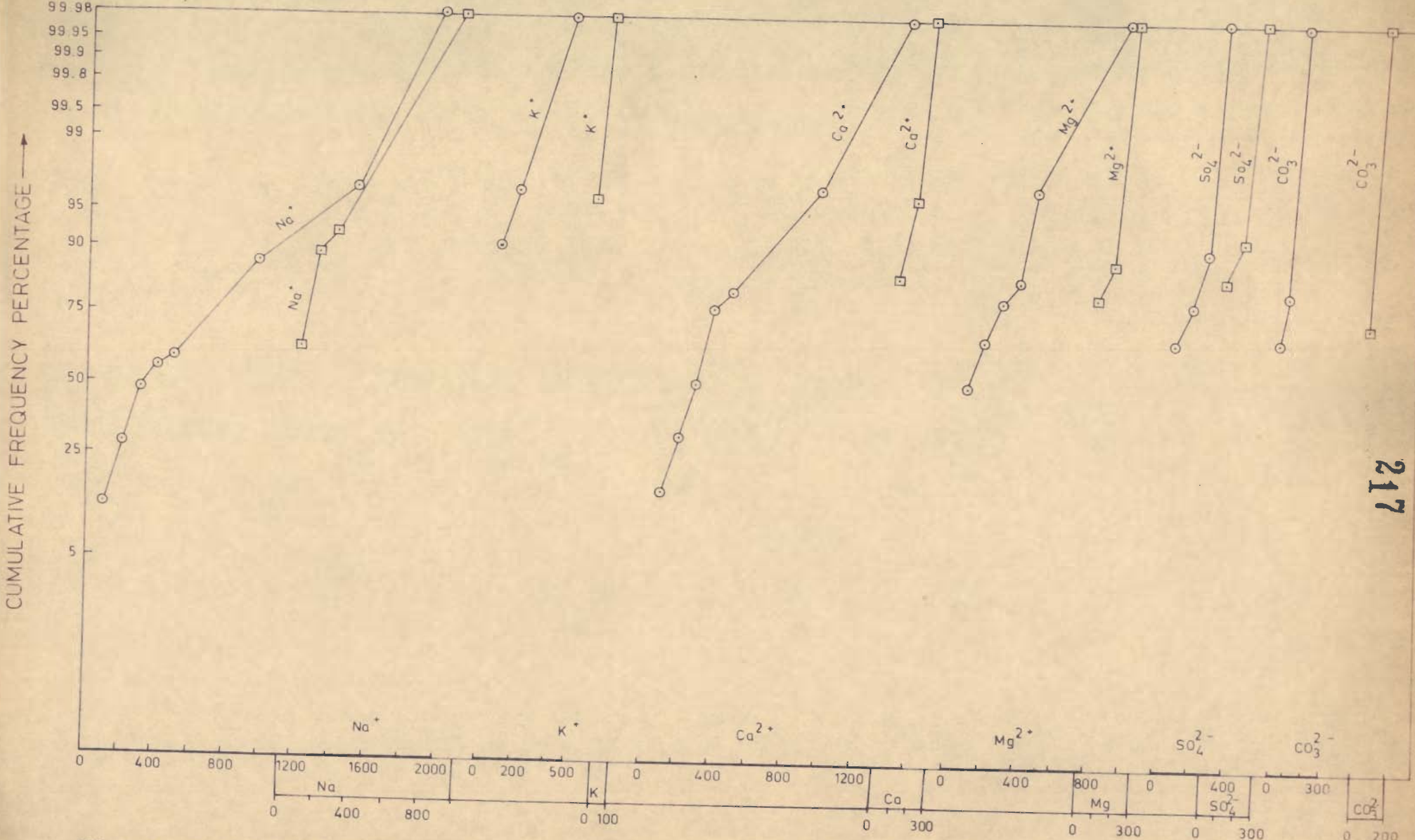


FIG.5.2 – CUMULATIVE FREQUENCY CURVES FOR Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, CO_3^{2-}. THE UPPER SCALE IN THE ABSCISA IS FOR WATERS FROM MILIOLITE FORMATION AND THE LOWER ONE FOR THE WATERS FROM GAJ FORMATION ⊙ – MILIOLITE FORMATION

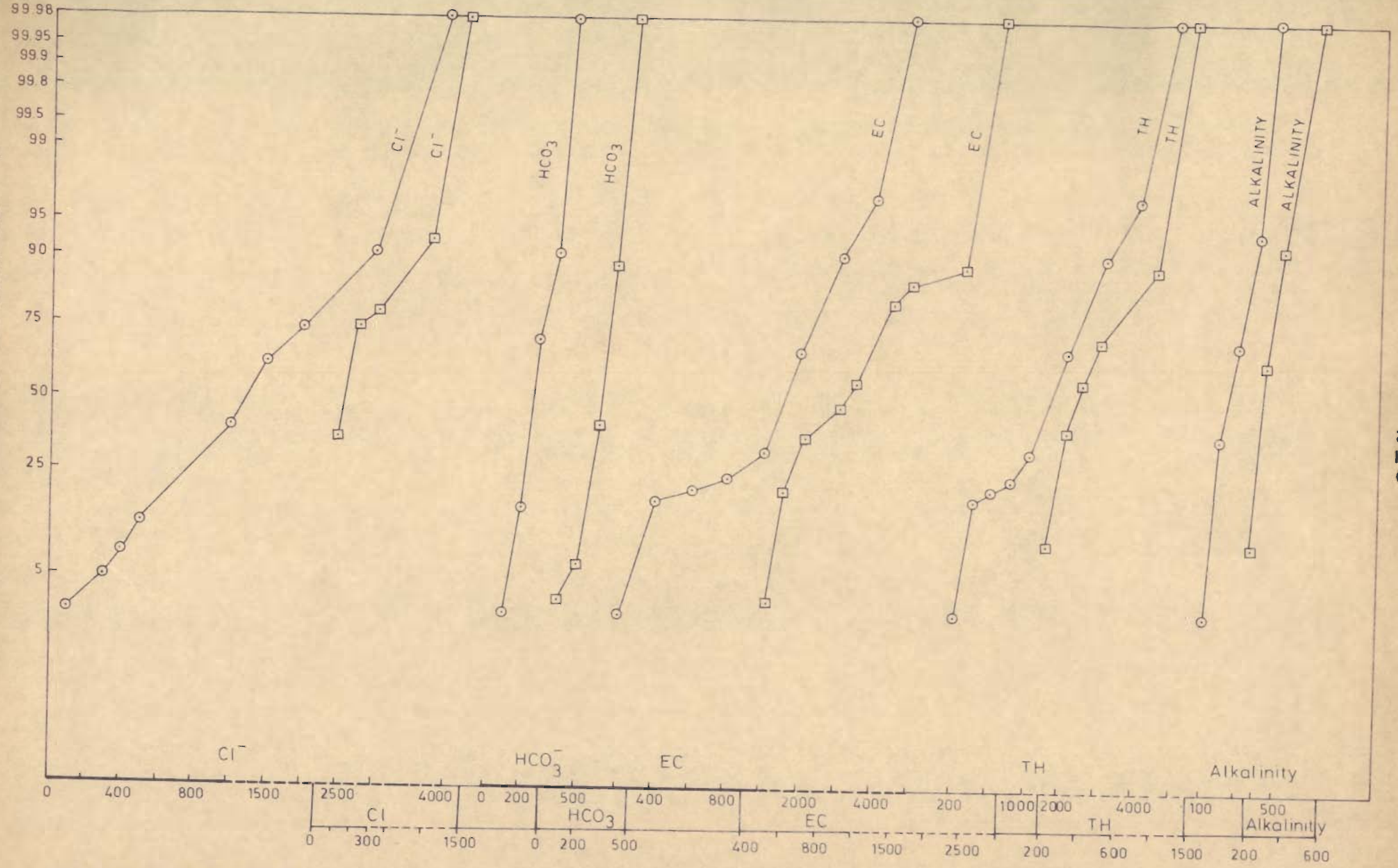


FIG. 5.3_ CUMULATIVE FREQUENCY CURVES FOR Cl^-, HCO_3^-, EC, TOTAL HARDNESS AND ALKALINITY. THE UPPER SCALE IN THE ABSCISA IS FOR WATERS FROM MILIOLITE FORMATION AND THE LOWER ONE FOR THE WATERS FROM GAJ FORMATION. ⊙ MILIOLITE FORMATION GAJ FORMATI

5.4 ANALYSIS AND INTERPRETATION OF HYDROGEOCHEMICAL DATA

5.4.1 Introduction

Almost the whole of the Saurashtra coast i.e., from Miyani north of Porbandar to Una in the southeast is affected by the problem of salinity of groundwater. Before 1970, the area between Madhavpur and Chorwad was supposed to be a fertile land, with luxuriant growth of vegetation. Since then, because of an increase in salinity of groundwater, the growth of vegetation and crop yields have been adversely affected.

Two different views about the cause of groundwater salinity have been put forward, one by the P.W.D., Gujarat Government (1975) and Desai et al. (1979)and the other by Mendhekar and Pandey (1976) of the Central Groundwater Board. According to the P.W.D., Gujarat Govt. and Desai et al., the salinity is due to sea water intrusion. However, Mendhekar and Pandey (1976) have opined that sea water intrusion is not the cause of salinity in this region but it is due to the use and reuse of groundwater for irrigation purposes and poor drainage conditions.

In the present study, as mentioned earlier, water samples collected during February 1979 tapping the Miliolite Formation and Gaj Formation have been analysed for major cations and anions. The data have been studied by trend surface analysis for areal distribution of various ions and hydrochemical sections. Ionic ratios have also been determined. The data have been plotted in Hill-Piper trilinear diagram. Principal component analysis has been made for determining the interrelationship of different ions. Based on this an attempt has been made to determine the cause of salinity in the coastal tract.

5.4.2 Areal Changes in Water Quality

Areal distribution of various ions, pH, electrical conductivity, alkalinity and temperature of groundwater for the month of February'79 have been studied using the technique of trend-surface analysis discussed earlier in Section 4.2. The contours on the third order polynomial surface for different variates are depicted in Figs. 5.4 to 5.14. The coefficient of the third order polynomial equation, total sum of squares, percent sum of squares explained and test of significance of trend as indicated by 'F' value are given in Table 5.2.

The following generalisations can be made from figures 5.4. to 5.14 and Table 5.2:

1. Except for alkalinity and HCO_3^- trend surfaces for all variables are significant at $\alpha = 0.20$. It suggests that probably HCO_3^- and alkalinity values are distributed without a significant pattern.
2. Trend surfaces for Mg^{2+}, Ca^{2+}, K^+, Na^+, Cl^-,SO_4^{-2} HCO_3^-, alkalinity and EC indicate that values for these variables except HCO_3^-, increase towards, E,SE,S, and SW.
3. Also from the central region, Mg^{2+}, K^+,pH, alkalinity and temperature decrease towards north and Ca^{2+},SO_4^{2-}, HCO_3^- increase towards west.
4. Comparison of trend surfaces for pH and temperature (Fig.5.13, 5.14) indicate that there are significant changes from the

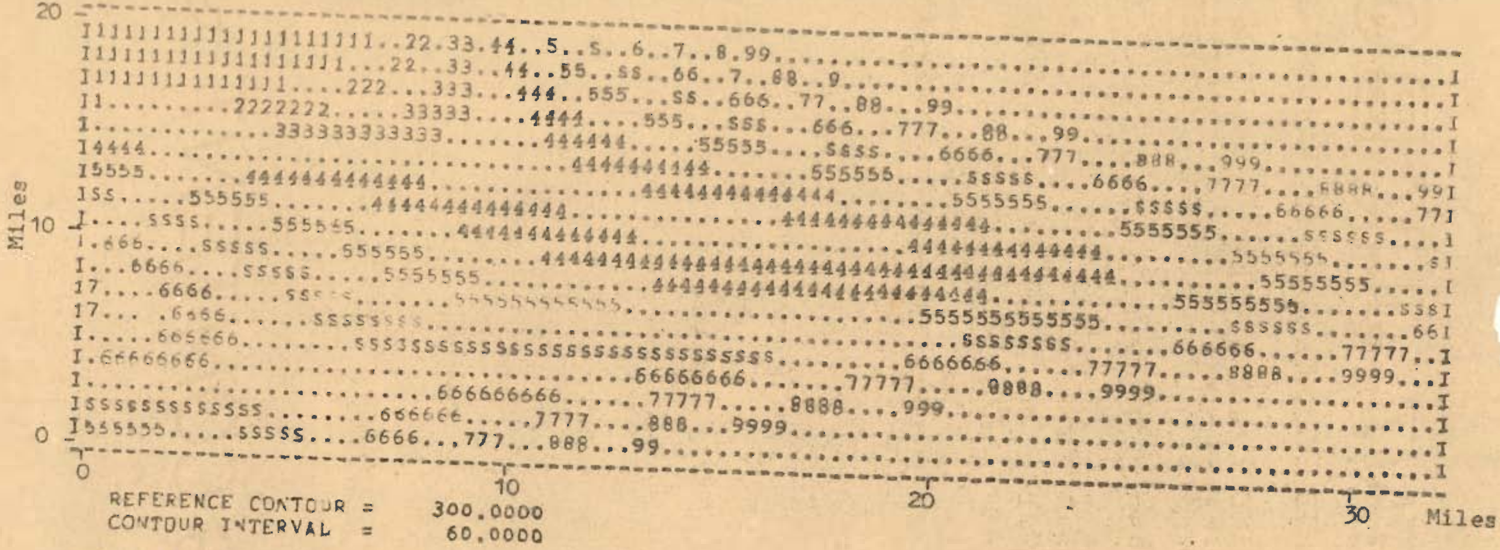
central region outwards in all directions and usually both varyn sympathetically, i.e., increase in one variable is accompanied by another. However, in a direction from central region towards northeast decrease in temperature is accompanied by increase in pH.

5. The trend of change of different ions in N,NE and E directions are difficult to explain on account of pausity of data.
6. When the comparison of trend surfaces of water table, i.e., flow direction and chemical data is done it is seen that the ionic concentrations increase towards the coast in the direction of groundwater flow.

5.4.3 Hydrochemical Sections

A hydrochemical section along line AB (Fig. 5.10) in the direction of groundwater flow from land towards the coast using the trend surface maps for different ions has been drawn (Fig. 5.15a). The data from trend surface maps are taken so that the curves get smoothened. Another hydrochemical section (Fig.5.15b) has also been drawn in the direction of flow on the basis of absolute values of ionic concentration in groundwater from different wells. Both these figures distinctly indicate an increase in the concentration of all the ions except HCO_3^- towards the coast. Values of HCO_3^- decrease from land to coast.

A perusal of Figs. 5.15b further indicate that there is an abrupt increase in the concentration of various ions within a distance of about 3 km from the coast. Such a trend would indicate effects of sea water intrusion.

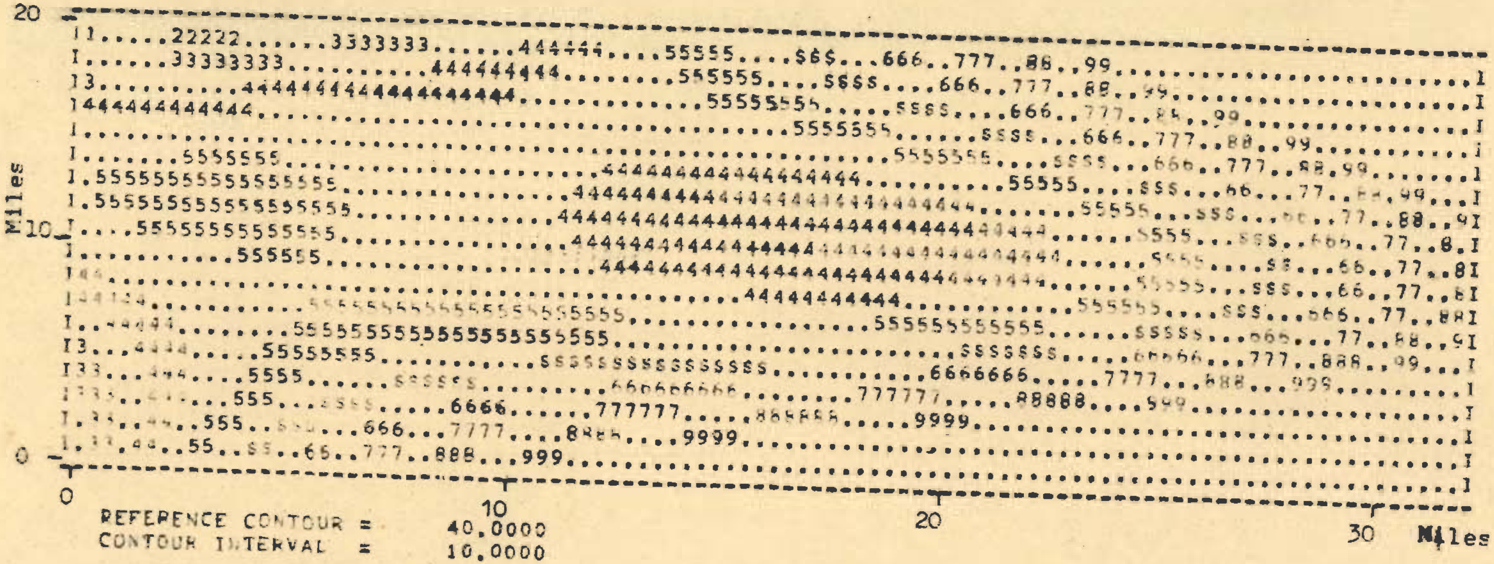


```
REFERENCE CONTOUR =     300.0000
CONTOUR INTERVAL  =      60.0000

KEY TO CONTOUR VALUES

111111    -300.0000AND BELOW
......    -240.0000   TO   -180.0000
222222    -180.0000   TO   -120.0000
......    -120.0000   TO    -60.0000
333333     -60.0000   TO      0.0000
......       0.0000   TO     60.0000
444444      60.0000   TO    120.0000
......     120.0000   TO    180.0000
555555     180.0000   TO    240.0000
......     240.0000   TO    300.0000
SSSSSS     300.0000   TO    360.0000
......     360.0000   TO    420.0000
666666     420.0000   TO    480.0000
......     480.0000   TO    540.0000
777777     540.0000   TO    600.0000
......     600.0000   TO    660.0000
888888     660.0000   TO    720.0000
......     720.0000   TO    780.0000
999999     780.0000   TO    840.0000
......     840.0000   AND ABOVE
COORDINATES OF MAP CORNERS ARE:
     TOP LEFT              0.0000      10.0000
     TOP RIGHT            32.0000      10.0000
     BOTTOM LEFT           0.0000       0.0000
     BOTTOM RIGHT         32.0000       0.0000
```

Fig. 5.4 THIRD ORDER TREND SURFACE FITTED TO VALUES OF Na^+ CONTENTS(ppm) OF GROUNDWATERS FROM DIFFERENT WELLS.



```
REFERENCE CONTOUR =      40.0000
CONTOUR INTERVAL  =      10.0000

KEY TO CONTOUR VALUES

111111     -60.0000AND BELOW
......     -50.0000  TO     -40.0000
222222     -40.0000  TO     -30.0000
......     -30.0000  TO     -20.0000
333333     -20.0000  TO     -10.0000
......     -10.0000  TO       0.0000
444444       0.0000  TO      10.0000
......      10.0000  TO      20.0000
555555      20.0000  TO      30.0000
......      30.0000  TO      40.0000
$$$$$$      40.0000  TO      50.0000
......      50.0000  TO      60.0000
666666      60.0000  TO      70.0000
......      70.0000  TO      80.0000
777777      80.0000  TO      90.0000
......      90.0000  TO     100.0000
888888     100.0000  TO     110.0000
......     110.0000  TO     120.0000
999999     120.0000  TO     130.0000
......     130.0000  AND ABOVE
COORDINATES OF MAP CORNERS ARE:
      TOP LEFT            0.0000      10.0000
      TOP RIGHT          32.0000      10.0000
      BOTTOM LEFT         0.0000       0.0000
      BOTTOM RIGHT       32.0000       0.0000
```

Fig. 5.5 THIRD ORDER TREND SURFACE FITTED TO VALUES OF K^+ CONTENTS (ppm) OF GROUNDWATERS FROM DIFFERENT WELLS.

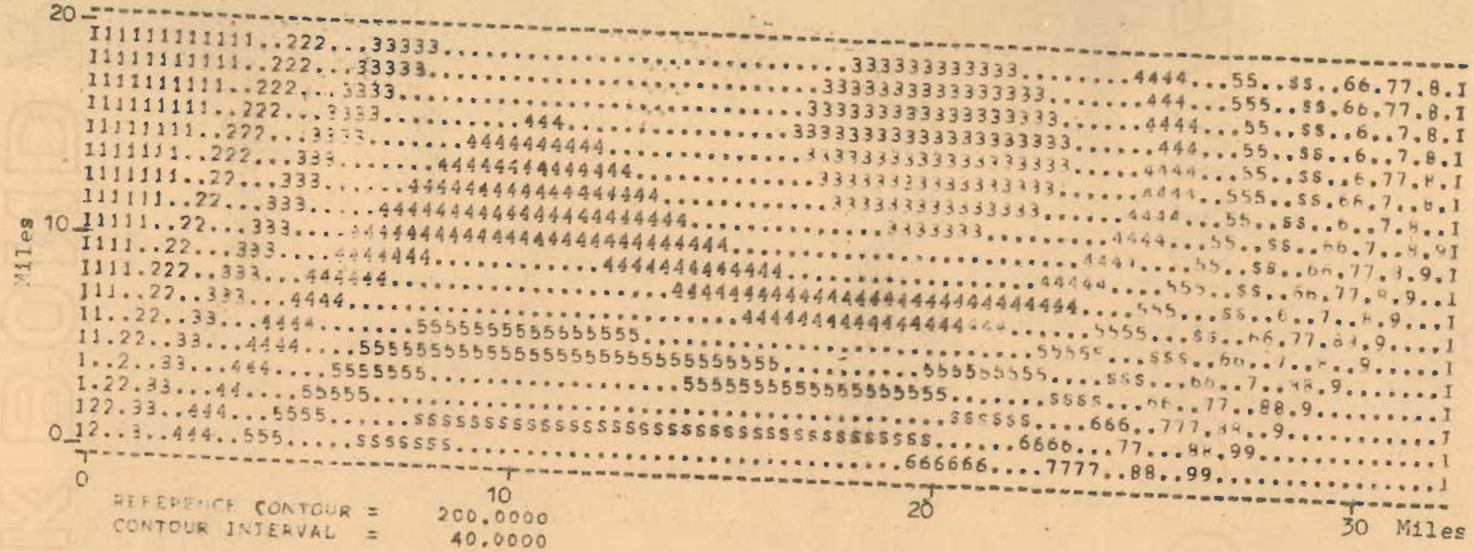
FIGS. 5.4 TO 5.14 TREND SURFACE MAPS OF VARIOUS IONS, E.C., ALKALINITY, pH AND TEMPERATURE. THE AREA OF STUDY IS DEMARCATED IN FIG. 3.12. THE TREND OF ORDINATE IN ALL THE FIGURES STRIKES N 40° E.

```
REFERENCE CONTOUR =     200.0000
CONTOUR INTERVAL  =      50.0000

KEY TO CONTOUR VALUES


333333   -100.0000  TO    -50.0000
......    -50.0000  TO      0.0000
444444      0.0000  TO     50.0000
......     50.0000  TO    100.0000
555555    100.0000  TO    150.0000
......    150.0000  TO    200.0000
$$$$$$    200.0000  TO    250.0000
......    250.0000  TO    300.0000
666666    300.0000  TO    350.0000
......    350.0000  TO    400.0000
777777    400.0000  TO    450.0000
......    450.0000  TO    500.0000
888888    500.0000  TO    550.0000
......    550.0000  TO    600.0000
COORDINATES OF MAP CORNERS ARE:
     TOP LEFT              0.0000      10.0000
     TOP RIGHT            32.0000      10.0000
     BOTTOM LEFT           0.0000       0.0000
     BOTTOM RIGHT         32.0000       0.0000
```

Fig.5.6 THIRD ORDER TREND SURFACE FITTED TO VALUES OF Ca^{2+} CONTENTS (ppm) OF GROUNDWATERS FROM DIFFERENT WELLS.

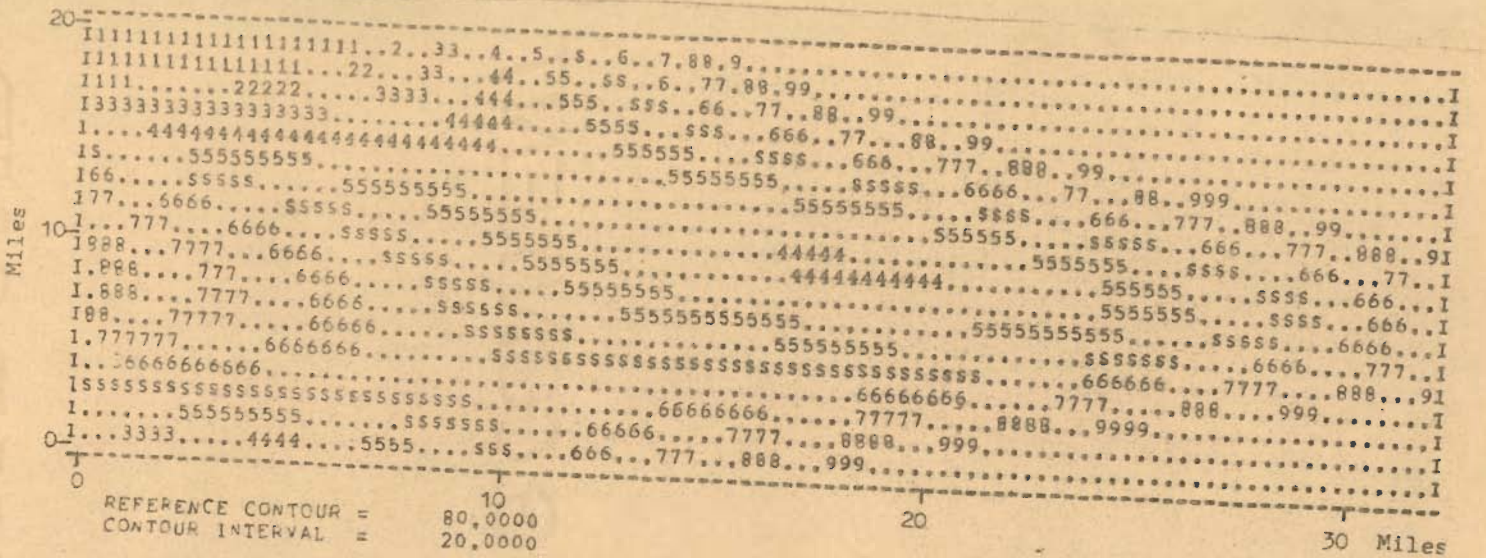


```
REFERENCE CONTOUR =   200.0000
CONTOUR INTERVAL  =    40.0000
```

```
KEY TO CONTOUR VALUES

111111    -200.0000AND BELOW
......    -160.0000   TO    -120.0000
222222    -120.0000   TO     -80.0000
......     -80.0000   TO     -40.0000
333333     -40.0000   TO       0.0000
......       0.0000   TO      40.0000
444444      40.0000   TO      80.0000
......      80.0000   TO     120.0000
555555     120.0000   TO     160.0000
......     160.0000   TO     200.0000
SSSSSS     200.0000   TO     240.0000
......     240.0000   TO     280.0000
666666     280.0000   TO     320.0000
......     320.0000   TO     360.0000
777777     360.0000   TO     400.0000
......     400.0000   TO     440.0000
888888     440.0000   TO     480.0000
......     480.0000   TO     520.0000
999999     520.0000   TO     560.0000
......     560.0000   AND ABOVE
COORDINATES OF MAP CORNERS ARE:
     TOP LEFT             0.0000     10.0000
     TOP RIGHT           32.0000     10.0000
     BOTTOM LEFT          0.0000      0.0000
     BOTTOM RIGHT        32.0000      0.0000
```

Fig.5.7 THIRD ORDER TREND SURFACE FITTED TO VALUES OF Mg^{2+} CONTENTS (ppm) OF GROUNDWATERS FROM DIFFERENT WELLS.

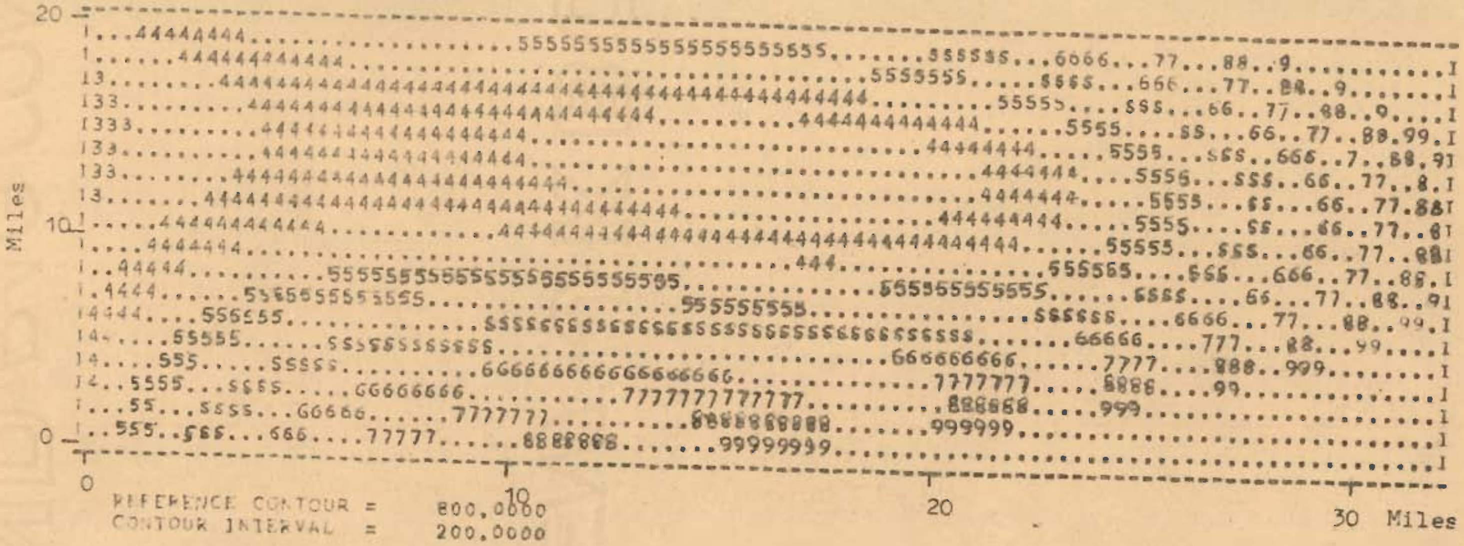


```
REFERENCE CONTOUR =     80.0000
CONTOUR INTERVAL  =     20.0000

KEY TO CONTOUR VALUES

111111   -120.0000AND BELOW
......   -100.0000  TO   -80.0000
222222    -80.0000  TO   -60.0000
......    -60.0000  TO   -40.0000
333333    -40.0000  TO   -20.0000
......    -20.0000  TO     0.0000
444444      0.0000  TO    20.0000
......     20.0000  TO    40.0000
555555     40.0000  TO    60.0000
......     60.0000  TO    80.0000
$$$$$$     80.0000  TO   100.0000
......    100.0000  TO   120.0000
666666    120.0000  TO   140.0000
......    140.0000  TO   160.0000
777777    160.0000  TO   180.0000
......    180.0000  TO   200.0000
888888    200.0000  TO   220.0000
......    220.0000  TO   240.0000
999999    240.0000  TO   260.0000
......    260.0000  AND ABOVE
COORDINATES OF MAP CORNERS ARE:
   TOP LEFT              0.0000      10.0000
   TOP RIGHT            32.0000      10.0000
   BOTTOM LEFT           0.0000       0.0000
   BOTTOM RIGHT         32.0000       0.0000
```

Fig. 5.8 THIRD ORDER TREND SURFACE FITTED TO VALUES OF SO_4^{2-} CONTENTS (ppm) OF GROUNDWATERS FROM DIFFERENT WELLS.

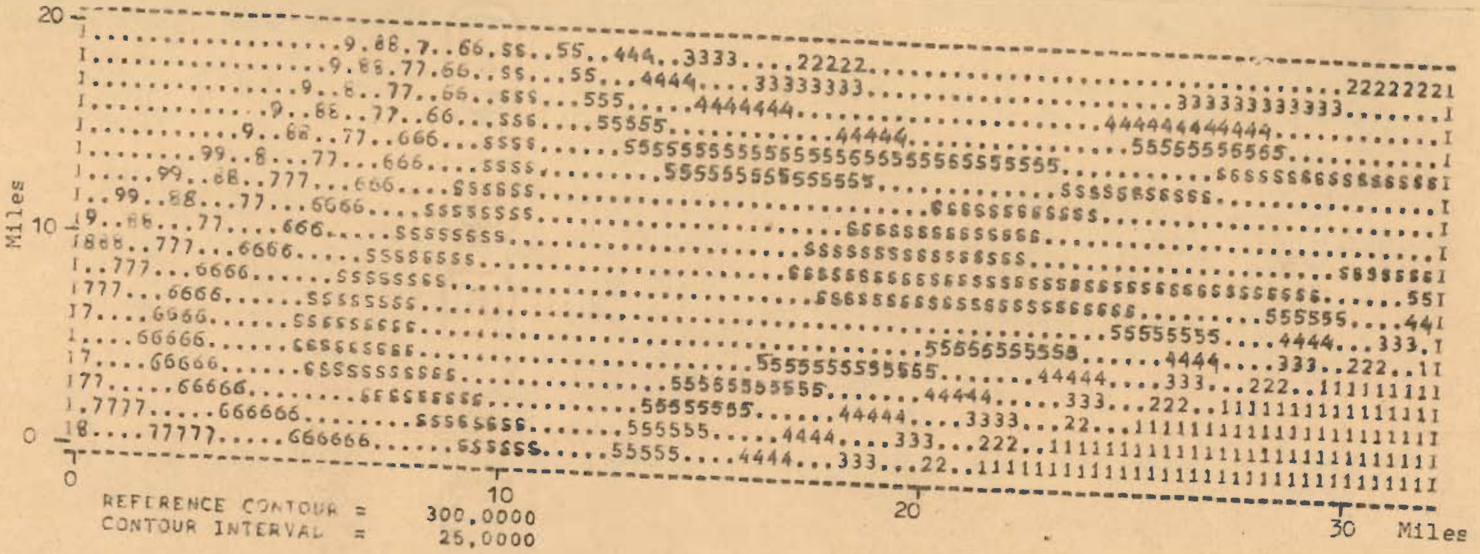


```
REFERENCE CONTOUR =     800.0000
CONTOUR INTERVAL  =     200.0000

KEY TO CONTOUR VALUES

333333   -400.0000  TO   -200.0000
......   -200.0000  TO      0.0000
444444      0.0000  TO    200.0000
......    200.0000  TO    400.0000
555555    400.0000  TO    600.0000
......    600.0000  TO    800.0000
555555    800.0000  TO   1000.0000
......   1000.0000  TO   1200.0000
666666   1200.0000  TO   1400.0000
......   1400.0000  TO   1600.0000
777777   1600.0000  TO   1800.0000
......   1800.0000  TO   2000.0000
888888   2000.0000  TO   2200.0000
......   2200.0000  TO   2400.0000
999999   2400.0000  TO   2600.0000
......   2600.0000  AND ABOVE
COORDINATES OF MAP CORNERS ARE:
    TOP LEFT             0.0000     10.0000
    TOP RIGHT           32.0000     10.0000
    BOTTOM LEFT          0.0000      0.0000
    BOTTOM RIGHT        32.0000      0.0000
```

Fig. 5.9 THIRD ORDER TREND SURFACE FITTED TO VALUES OF Cl^- CONTENTS (ppm) OF GROUNDWATERS FROM DIFFERENT WELLS.

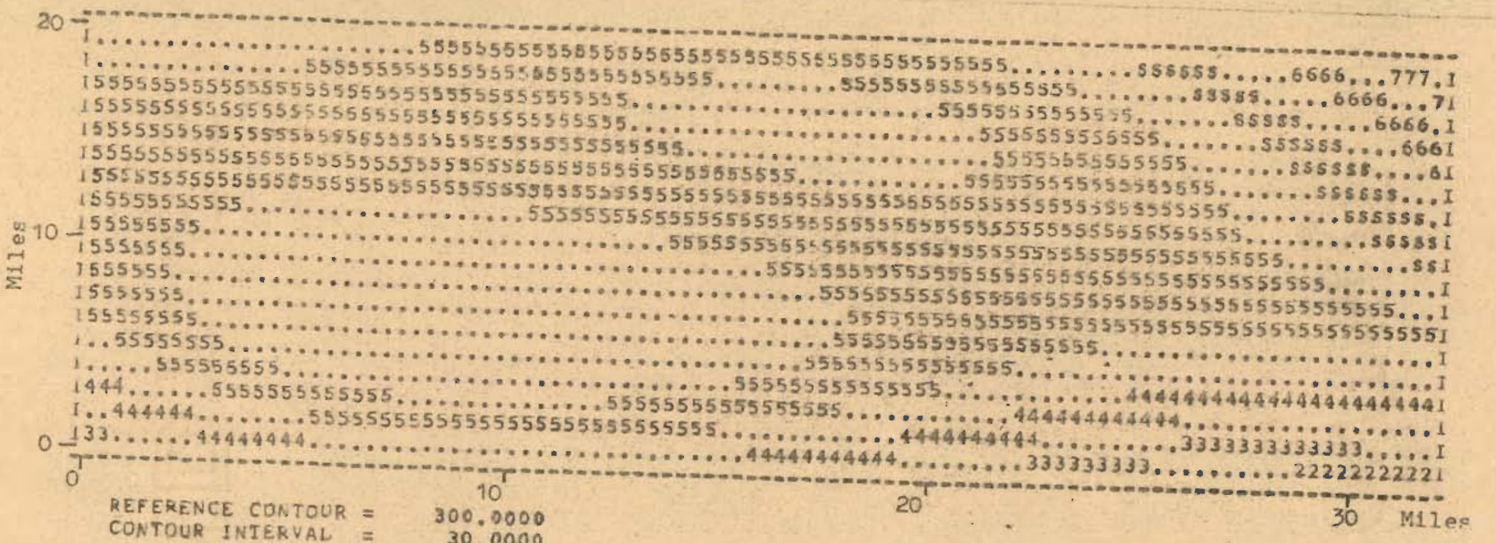


```
REFERENCE CONTOUR =     300.0000
CONTOUR INTERVAL  =      25.0000

KEY TO CONTOUR VALUES

111111        50.0000AND BELOW
......        75.0000   TO     100.0000
222222       100.0000   TO     125.0000
......       125.0000   TO     150.0000
333333       150.0000   TO     175.0000
......       175.0000   TO     200.0000
444444       200.0000   TO     225.0000
......       225.0000   TO     250.0000
555555       250.0000   TO     275.0000
......       275.0000   TO     300.0000
$$$$$$       300.0000   TO     325.0000
......       325.0000   TO     350.0000
666666       350.0000   TO     375.0000
......       375.0000   TO     400.0000
777777       400.0000   TO     425.0000
......       425.0000   TO     450.0000
888888       450.0000   TO     475.0000
......       475.0000   TO     500.0000
999999       500.0000   TO     525.0000
......       525.0000   AND ABOVE
COORDINATES OF MAP CORNERS ARE:
     TOP LEFT                0.0000      10.0000
     TOP RIGHT              32.0000      10.0000
     BOTTOM LEFT             0.0000       0.0000
     BOTTOM RIGHT           32.0000       0.0000
```

Fig: 5.10. THIRD ORDER TREND SURFACE FITTED TO VALUES OF HCO_3^- CONTENTS(ppm) OF GROUNDWATERS FROM DIFFERENT WELLS.



REFERENCE CONTOUR = 300.0000
CONTOUR INTERVAL = 30.0000

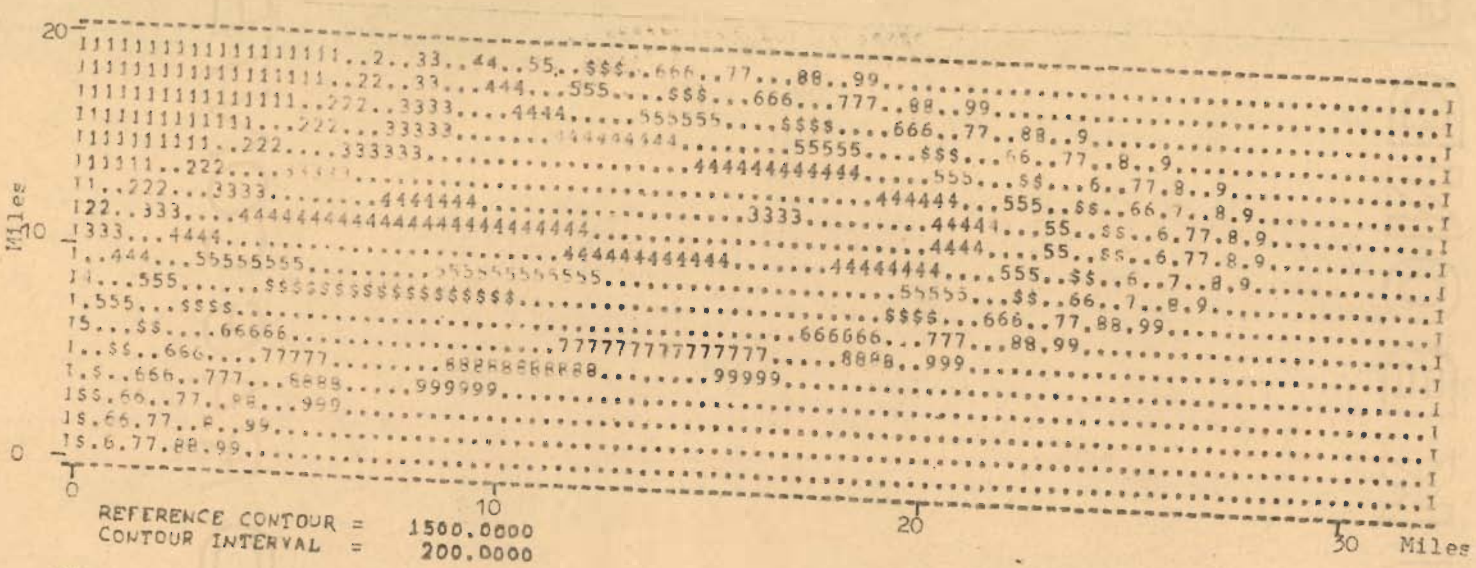
KEY TO CONTOUR VALUES

222222	60.0000	TO	90.0000.
......	90.0000	TO	120.0000
333333	120.0000	TO	150.0000
......	150.0000	TO	180.0000
444444	180.0000	TO	210.0000
......	210.0000	TO	240.0000
555555	240.0000	TO	270.0000
......	270.0000	TO	300.0000
SSSSSS	300.0000	TO	330.0000
......	330.0000	TO	360.0000
666666	360.0000	TO	390.0000
......	390.0000	TO	420.0000
777777	420.0000	TO	450.0000
......	450.0000	TO	480.0000

COORDINATES OF MAP CORNERS ARE:

TOP LEFT	0.0000	10.0000
TOP RIGHT	32.0000	10.0000
BOTTOM LEFT	0.0000	0.0000
BOTTOM RIGHT	32.0000	0.0000

Fig. 5.11 THIRD ORDER TREND SURFACE FITTED TO VALUES OF ALKALINITY CONTENTS(ppm) OF GROUNDWATERS FROM DIFFERENT WELLS.

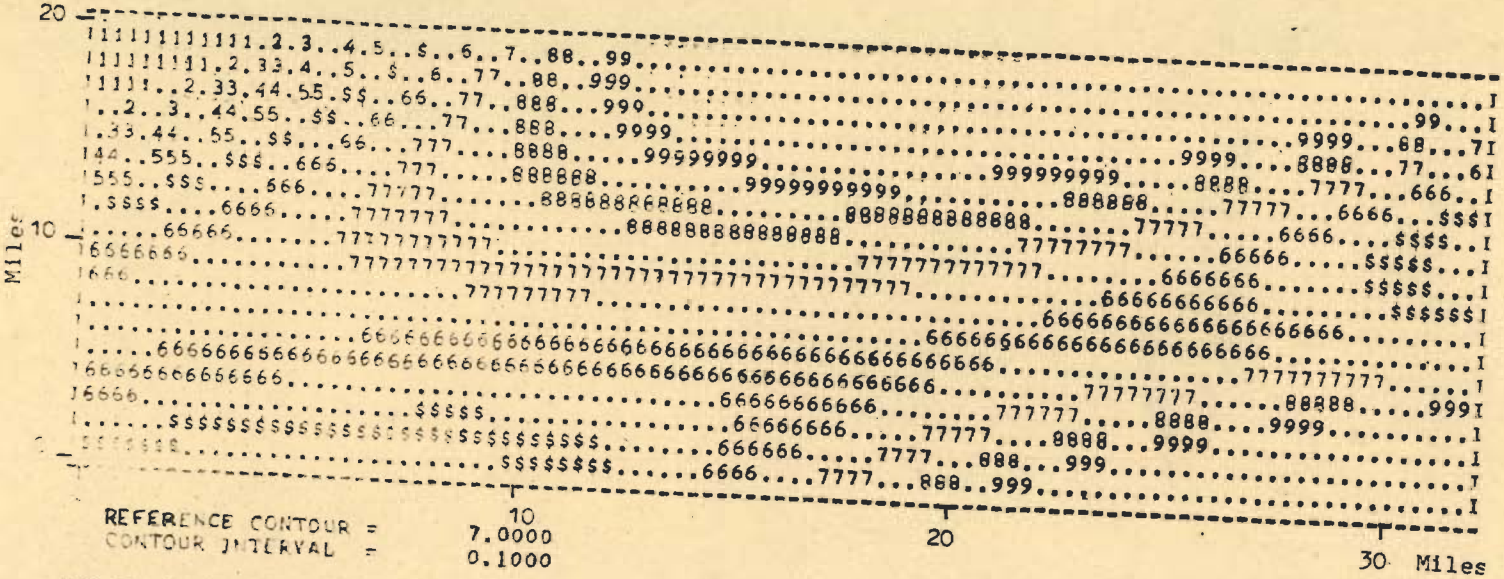


```
REFERENCE CONTOUR =    1500.0000
CONTOUR INTERVAL  =     200.0000

KEY TO CONTOUR VALUES

111111   -500.0000AND BELOW
......   -300.0000  TO   -100.0000
222222   -100.0000  TO    100.0000
......    100.0000  TO    300.0000
333333    300.0000  TO    500.0000
......    500.0000  TO    700.0000
444444    700.0000  TO    900.0000
......    900.0000  TO   1100.0000
555555   1100.0000  TO   1300.0000
......   1300.0000  TO   1500.0000
$$$$$$   1500.0000  TO   1700.0000
......   1700.0000  TO   1900.0000
666666   1900.0000  TO   2100.0000
......   2100.0000  TO   2300.0000
777777   2300.0000  TO   2500.0000
......   2500.0000  TO   2700.0000
888888   2700.0000  TO   2900.0000
......   2900.0000  TO   3100.0000
999999   3100.0000  TO   3300.0000
......   3300.0000  AND ABOVE
COORDINATES OF MAP CORNERS ARE:
    TOP LEFT             0.0000     10.0000
    TOP RIGHT           32.0000     10.0000
    BOTTOM LEFT          0.0000      0.0000
    BOTTOM RIGHT        32.0000      0.0000
```

Fig. 5.12 THIRD ORDER TREND SURFACE FITTED TO VALUES OF ELECTRICAL CONDUCTIVITY (MICRO MHOS/CM) OF GROUNDWATERS FROM DIFFERENT WELLS.

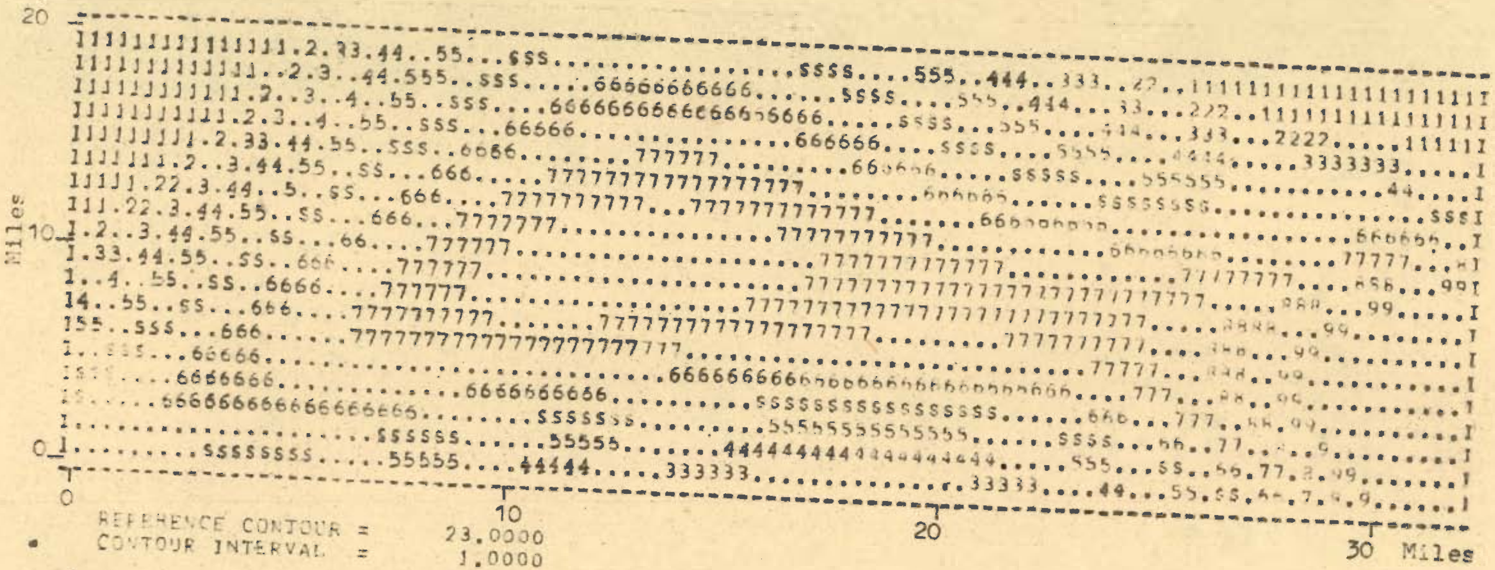


```
REFERENCE CONTOUR =        7.0000
CONTOUR INTERVAL  =        0.1000

KEY TO CONTOUR VALUES

111111      6.0000AND BELOW
......      6.1000  TO      6.2000
222222      6.2000  TO      6.3000
......      6.3000  TO      6.4000
333333      6.4000  TO      6.5000
......      6.5000  TO      6.6000
444444      6.6000  TO      6.7000
......      6.7000  TO      6.8000
555555      6.8000  TO      6.9000
......      6.9000  TO      7.0000
$$$$$$      7.0000  TO      7.1000
......      7.1000  TO      7.2000
666666      7.2000  TO      7.3000
......      7.3000  TO      7.4000
777777      7.4000  TO      7.5000
......      7.5000  TO      7.6000
888888      7.6000  TO      7.7000
......      7.7000  TO      7.8000
999999      7.8000  TO      7.9000
......      7.9000  AND ABOVE
COORDINATES OF MAP CORNERS ARE:
    TOP LEFT            0.0000     10.0000
    TOP RIGHT          32.0000     10.0000
    BOTTOM LEFT         0.0000      0.0000
    BOTTOM RIGHT       32.0000      0.0000
```

Fig.5.13 THIRD ORDER TREND SURFACE FITTED TO pH VALUES OF WATERS FROM DIFFERENT WELLS.



```
   REFERENCE CONTOUR =      23.0000
   CONTOUR INTERVAL  =       1.0000

 KEY TO CONTOUR VALUES


 111111       13.0000AND BELOW
 ......       14.0000  TO      15.0000
 222222       15.0000  TO      16.0000
 ......       16.0000  TO      17.0000
 333333       17.0000  TO      18.0000
 ......       18.0000  TO      19.0000
 444444       19.0000  TO      20.0000
 ......       20.0000  TO      21.0000
 555555       21.0000  TO      22.0000
 ......       22.0000  TO      23.0000
 SSSSSS       23.0000  TO      24.0000
 ......       24.0000  TO      25.0000
 666666       25.0000  TO      26.0000
 ......       26.0000  TO      27.0000
 777777       27.0000  TO      28.0000
 ......       28.0000  TO      29.0000
 888888       29.0000  TO      30.0000
 ......       30.0000  TO      31.0000
 999999       31.0000  TO      32.0000
 ......       32.0000  AND ABOVE
COORDINATES OF MAP CORNERS ARE:
    TOP LEFT               0.0000       10.0000
    TOP RIGHT             32.0000       10.0000
    BOTTOM LEFT            0.0000        0.0000
    BOTTOM RIGHT          32.0000        0.0000
```

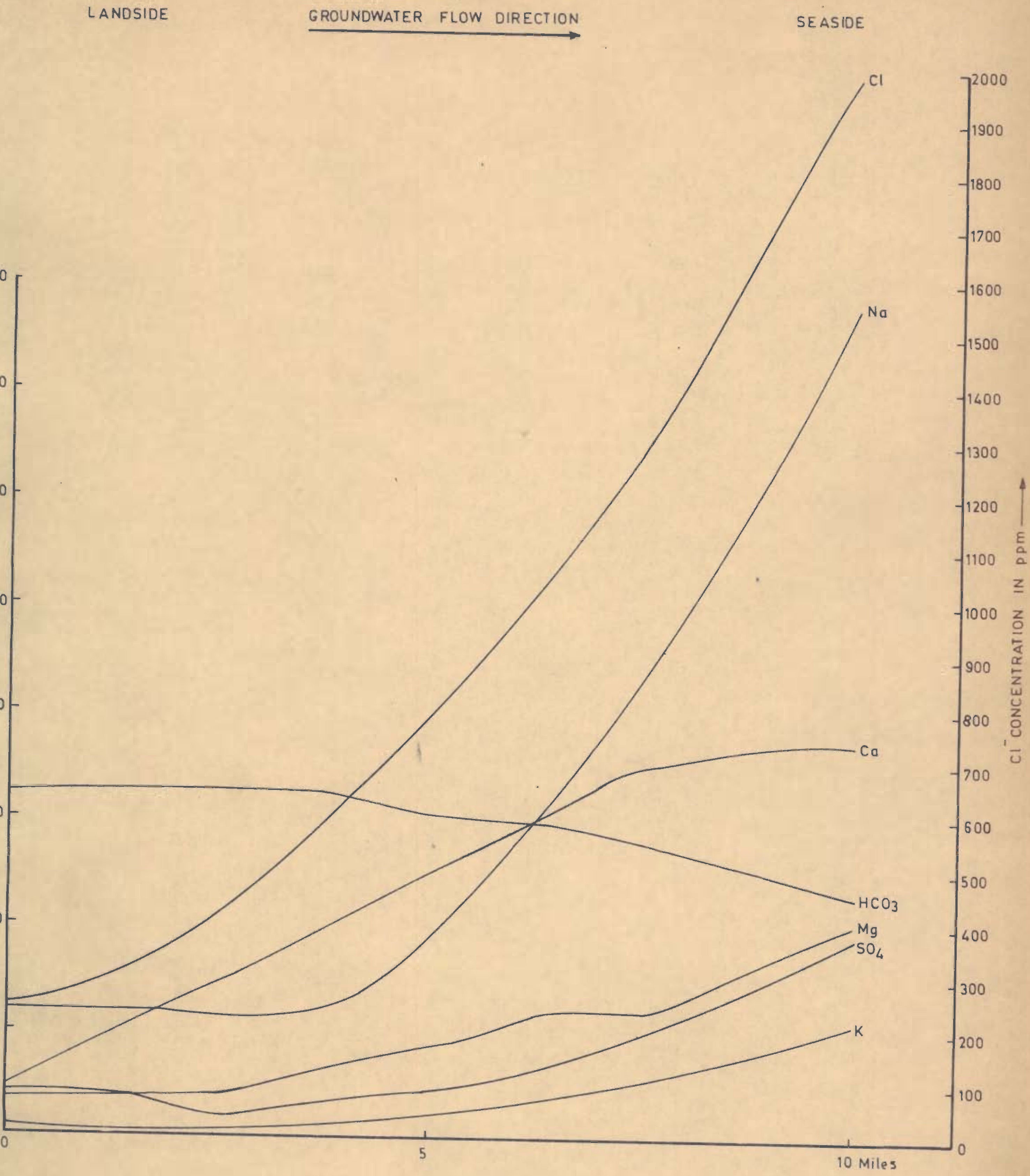
Fig.5.14 THIRD ORDER TREND SURFACE FITTED TO TEMPERATURE (oC) OF GROUNDWATERS FROM DIFFERENT WELLS.

Table: 5.2: Coefficients of Third Order Polynomial Surfaces, Percent Sum of Squares Explained and Calculated "F" Values for Different Ions and Alkalinity, EC, pH, and Temperature of the Groundwaters.

Variables	Coefficients of **third** order polynomial surface										Percent sum of squares explained	'F' value
	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9		
Na^+	198.56	19.94	226.70	2.12	35.15	36.84	0.01	-0.05	4.16	0.35	33.19	2.68*
K^+	23.51	19.11	-0.64	-0.65	-5.18	3.57	0.01	0.04	0.39	-0.38	29.97	2.31*
Ca^{2+}	-75.32	44.32	81.93	-1.49	-6.73	-20.86	0.02	0.21	-0.25	0.19	37.61	3.26*
Mg^{2+}	-90.82	77.10	-34.72	-5.66	-1.02	1.84	0.14	-0.08	0.28	-0.16	32.02	2.54*
SO_4^{2-}	-51.07	13.16	146.40	0.08	-13.80	-21.18	0.006	0.06	1.47	0.44	22.28	1.55*
Cl^-	241.40	283.04	-33.51	-14.23	-44.99	-18.18	0.33	0.39	0.29	0.18	46.54	4.70*
HCO_3^-	453.2	-18.97	-52.05	0.88	0.85	13.07	-0.04	0.26	-0.89	-0.24	11.72	0.72NS
Alkalinity	138.58	20.07	61.57	-1.27	-2.11	-10.90	0.02	0.09	-0.007	0.63	3.69	0.21NS
EC	164.81	516.73	-27.50	-22.55	120.64	-35.32	0.81	-1.08	13.93	-1.31	49.28	5.25*
pH	7.07	-0.04	0.17	0.00	0.0006	-0.02	0.00002	-0.001	0.004	-0.001	37.74	3.33*
Temperature	24.16	0.16	0.39	-0.09	0.52	-0.56	40.003	-0.01	-0.009	0.02	39.48	3.52*

NS- Not significant at $\alpha = 0.20$

* Significant at $\alpha = 0.20$



G.5.15.a _ HYDROCHEMICAL SECTION ALONG LINE AB (MARKED IN FIG 5.1) USING TREND SURFACES FOR DIFFERENT IONS IN FIGS. 5.4 TO 5.14

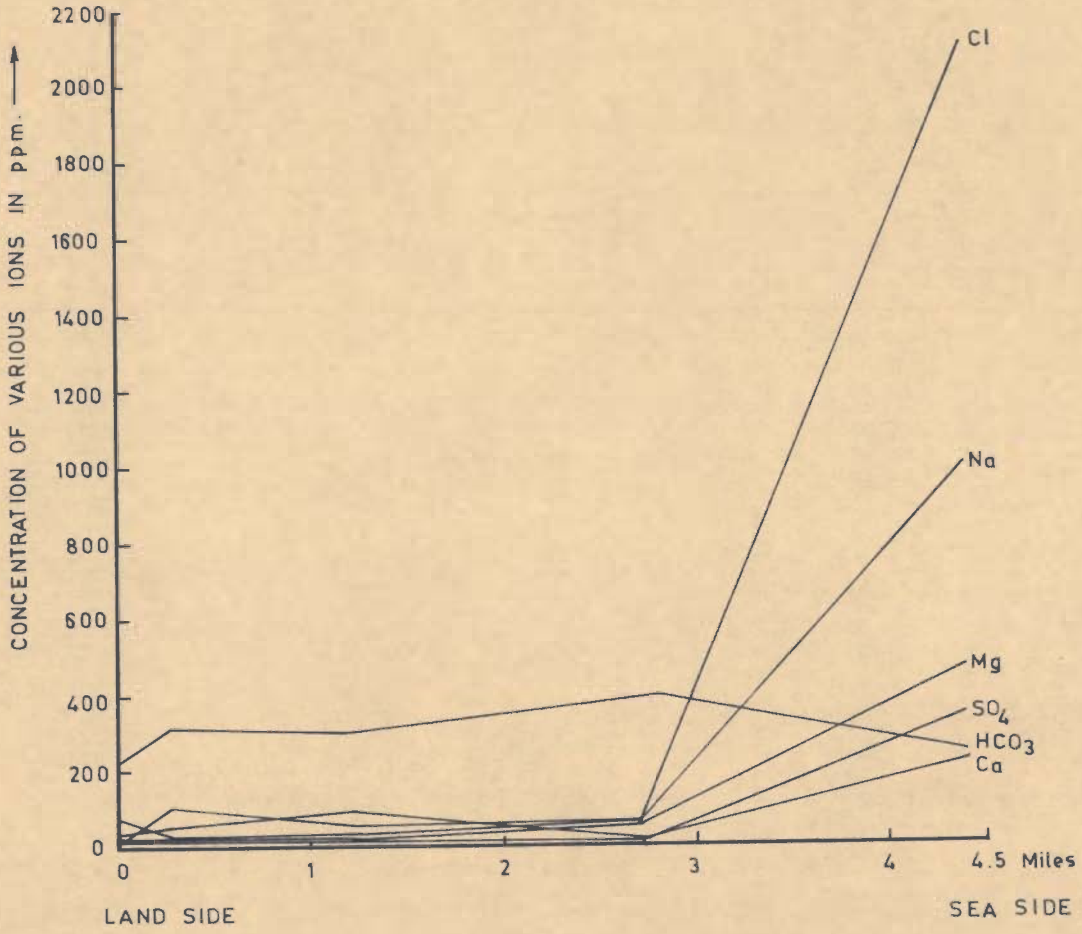


FIG. 5.15b_ HYDROCHEMICAL SECTION ALONG FLOW DIRECTION FROM INLAND TO COAST.

5.4.4 Hill-Piper Diagram and Hydrochemical Facies

In the Hill-Piper trilinear diagram, there are three distinct fields for plotting, i.e., two triangular fields and a central diamond shaped field. The percentage epm values of major cations are plotted in the left triangular field and the anions are plotted in the triangular field at the right. These two points are projected to the central diamond shaped field, which gives the overall composition of groundwater sample in terms of certain cation and anion pairs.

The Hill-Piper diagram can be divided into 9 parts each characterised by a separate type of water (Fig. 5.16a), as explained below:

Area 1	Alkaline earths exceed alkalies
Area 2	Alkalies exceed alkaline earths
Area 3	Weak acids exceed strong acids
Area 4	Strong acids exceed weak acids
Area 5	Carbonate hardness (secondary alkalinity) exceeds 50 percent

Area 6 Non carbonate hardness ("Secondary salinity") exceeds 50 percent

Area 7 Non carbonate alkali ("primary salinity") exceeds 50 percent that is chemical properties are dominated by alkalies and strong acids.

Area 8 Carbonate alkali ("primary alkalinity") exceeds 50 percent here plot the groundwater which are inordinately soft in proportion to their content of dissolved solids.

Area 9 No one cation - anion pair exceeds 50 percent

The chemical data of groundwater samples collected during February 1979 were plotted in the Hill-Piper diagram (Fig.5.17). The chemical classification of groundwater from the Miliolite and Gaj Formations are given in Table 5.3. It brings out the following points:

i) 25 groundwater samples from the Miliolite Formation and 26 samples from the Gaj Formation fall in the area where alkaline earths exceed alkalies.

ii) 12 samples from the Miliolite Formation and 8 from Gaj Formation fall in the area where alkalies exceed alkaline earths. Only one sample from the Miliolite Formation and 19 samples from Gaj Formation falls in the category where weak acids exceed strong acids.

iii) 36 samples from the Miliolite Formation and 11 from the Gaj Formation fall in the category where strong acids exceed weak acids.

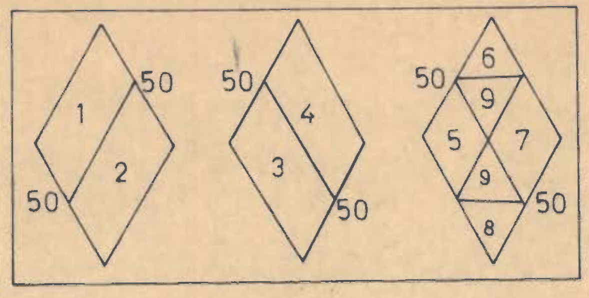


FIG.5.16a_DIFFERENT AREAS IN HILL-PIPER DIAGRAM

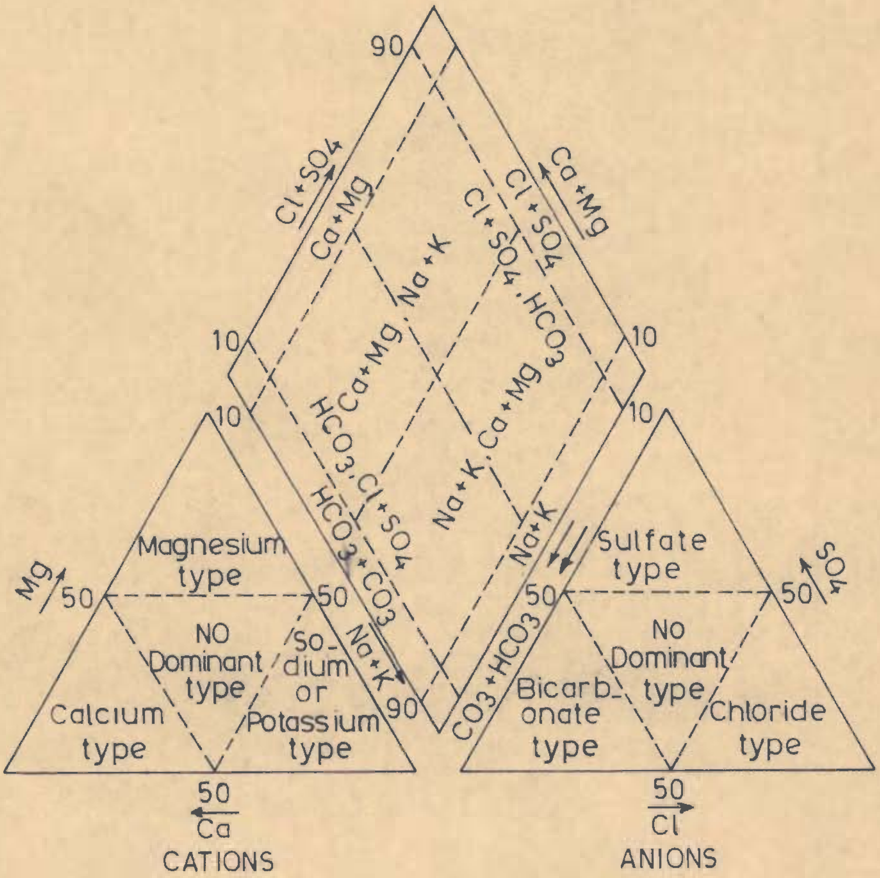


FIG.5.16b_DIAGRAM SHOWING HYDROCHEMICAL FACIES (AFTER BACK,1966)

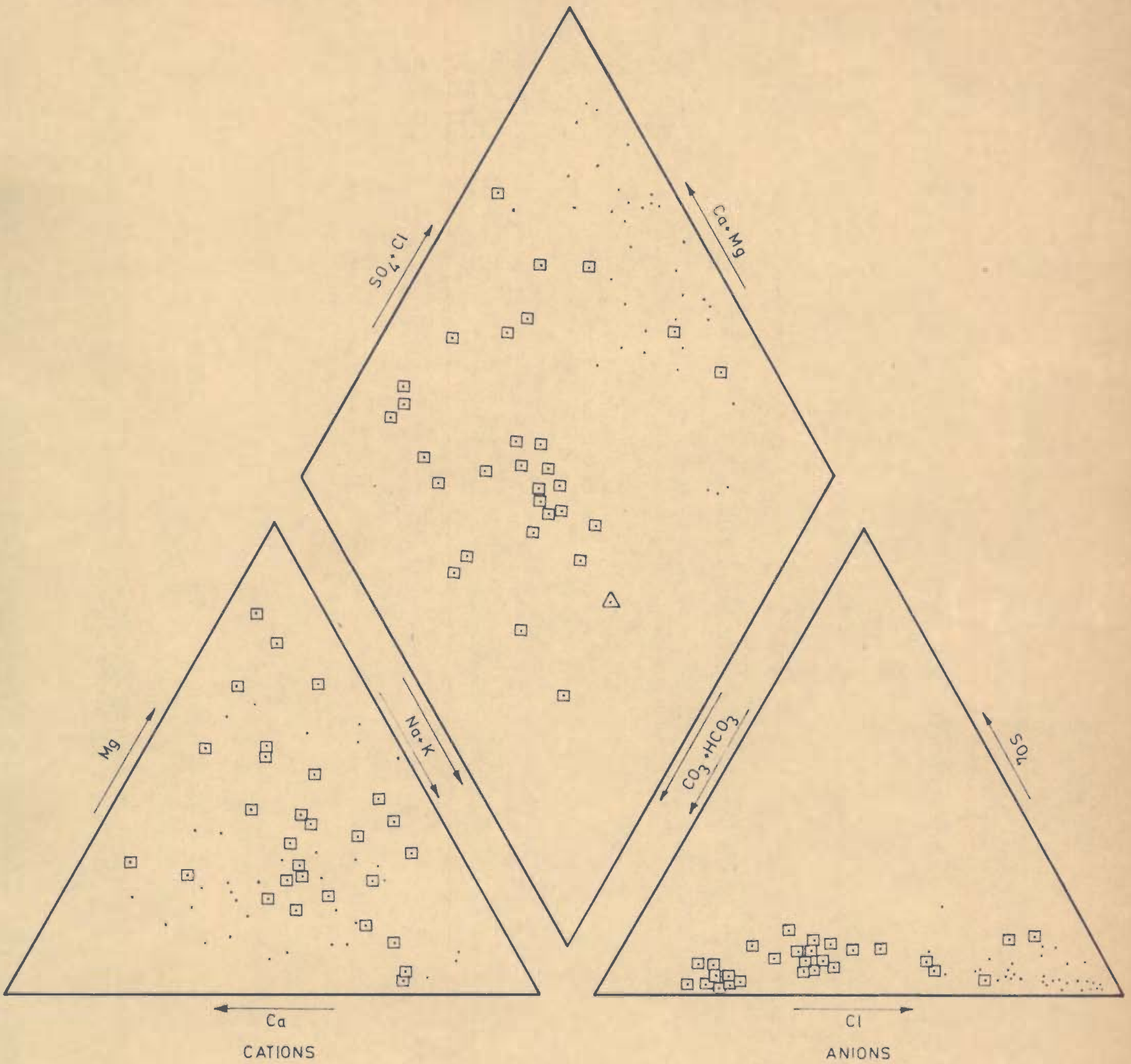


FIG 5.17 – PLOTTING OF HYDROCHEMICAL DATA IN HILL-PIPER TRILINEAR DIAGRAM.

∷ MILIOLITE FORMATION ⊡ GAJ FORMATION

△ DECCAN TRAP BASALT

Table 5.3 : Classification of Groundwater Samples with respect to Hill-Piper Diagram

Area	Miliolite Formation		Gaj Formation	
	No.of water samples	%	No of water samples	%
5	1	1.52	18	27.28
6	17	25.75	1	1.52
7	12	18.18	2	3.03
9	6	12.12	8	11.13

A perusal of the table indicates that majority of groundwaters from Miliolite Formation collected from wells situated inland from the coast to a distance of 3 to 5 kms fall in groups 6 and 7, characterised by secondary and primary salinity. On the other hand most of the water samples from the Gaj Formations belong to group 5 thereby indicating secondary alkalinity. Some of the water samples from the Gaj Formation belong to group 9 showing that no cation-anion pair exceeds 50%.

The hydrochemical data along the flow direction as indicated by trend surfaces of groundwater levels have been plotted in Fig. 5.18. The data plots do not fall on a straight line, as it should be, if there is a simple mixing of sea-water with groundwater. This non-linearity might be because of the base exchange.

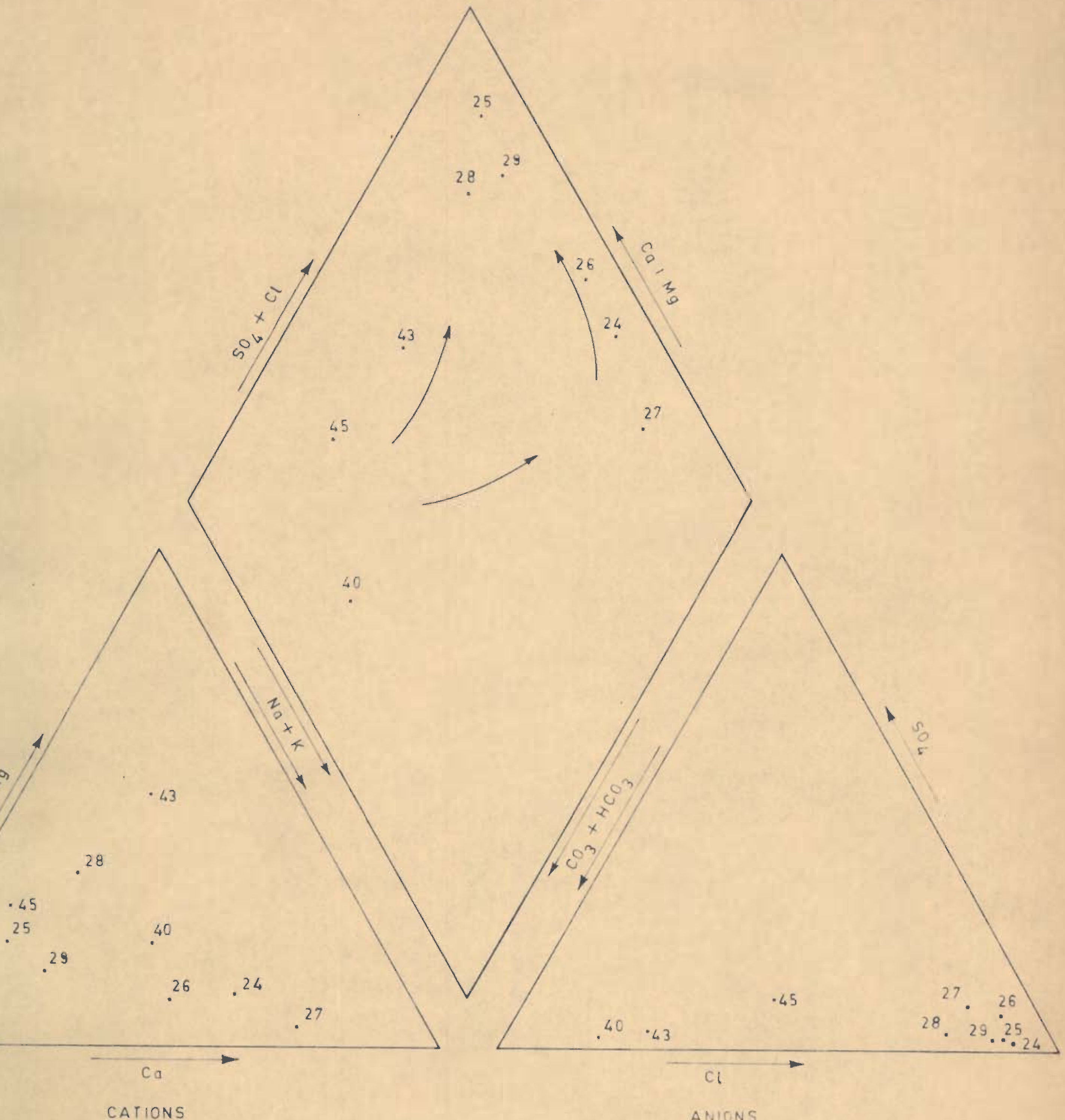


FIG 5.18 _ PLOT OF HYDROCHEMICAL DATA ALONG DIRECTION OF FLOW. ARROWS IN THE DIAMOND DIAGRAM INDICATE FLOW DIRECTION.

This aspect has also been discussed in Section 5.4.8.

Back (1966) used Hill Piper's trilinear diagram to identify the various chemical types of water. Figure 5.16b shows the various hydrochemical facies designated in the diamond shaped field The sub-areas serve as a basis for specific classification of hydrochemical facies. These can be studied in terms of anions or cations or both. For example Ca^{2+} + Mg^{2+} facies indicates that water may be either calcium type or magnesium type.

In the present study, the waters of Chorwad-Madhavpur area are classified into 8 hydrochemical facies based on Figure 5.17.

Table 5.4: The total number of samples from Miliolite Formation and Gaj Formation falling in Different Hydrochemical facies

Hydrochemical facies	Miliolite Formation	Gaj Formation
Calcium-Magnesium-Sulphate-Bicarbonate	0	1
Calcium-Magnesium-Bicarbonate-chloride-sulphate	1	1
Calcium-Sodium-Chloride-Sulphate	8	0
Calcium- Sodium-Chloride-sulphate-Bicarbonate	14	6
Calcium-Sodium-Bicarbonate-Chloride-Sulphate	1	16
Sodium-Calcium-Chloride-Sulphate	4	0
Sodium-Calcium-Chloride-Sulphate-Bicarbonate	7	2
Sodium-Calcium-Bicarbonate-chloride-Sulphate	1	3

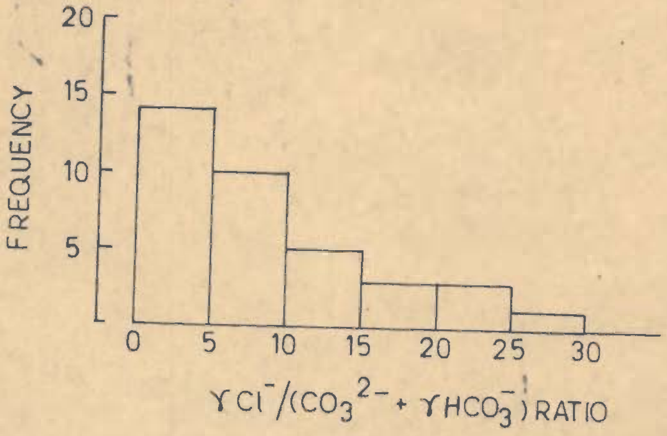
From Table 5.4 it can be seen that most of the waters from the Miliolite Formation belong to Ca-Na-Cl-SO_4-HCO_3 facies and Ca-Na-Cl- SO_4 facies whereas those from the Gaj Formation belong to Ca-Na-HCO_3-Cl-SO_4 facies and Ca-Na-Cl-SO_4-HCO_3 facies. The groundwaters from the Miliolite Formation and Gaj Formation, are of different hydrochemical facies. Fig. 5.17 also indicates that the change from one facies to another is not gradational. This could be due to the fact that the groundwater in the Miliolite Formation is affected by sea water intrusion while in Gaj Formation there is no such influence.

5.4.5 $Cl^-/(CO_3^{2-} + HCO_3^-)$ ratio

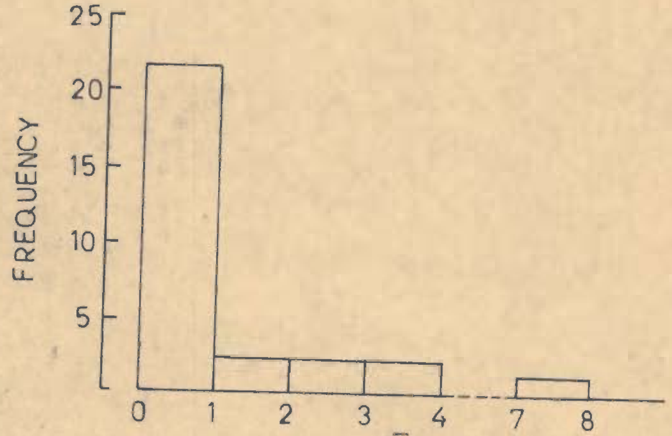
Generally, chloride is the dominant ion of sea-water which normally occurs only in small amounts in fresh groundwater, while HCO_3^- is the most abundant anion in groundwater. Also Cl^- is little affected by different processes of modifications such as base exchange and sulphate reduction, which may take place within the aquifer. So Revelle (1941) suggested that the chloride/bicarbonate ratio can be used as a criterion to evaluate sea water intrusion and ratios higher than 1 should be characteristic of mixing of sea water and freshwater.

Distribution of chloride/bicarbonate ratios from the Miliolite Formation and Gaj Formation are shown in Fig. 5.19 a and b. Most of the samples from the Miliolite Formation have a ratio higher than one and the maximum value of 27 is observed for a well from Veraval suggesting sea water intrusion.

In the Gaj Formation only five groundwater samples collected from 6 to 12 km away from the coast have ratios higher than one. Also wells with higher ratios are distributed randomly. The Gaj formation is known to contain connate water at deeper horizons. So the reason for higher chloride to bicarbonate ratio in these isolated cases may be attributed to the mixing of fresh groundwaters and connate water.



(a)



(b)

FIG. 5.19 _ HISTOGRAMS DEPICTING THE DISTRIBUTION OF THE RATIO $\gamma Cl^-/(\gamma CO_3^{2-}+\gamma HCO_3^{2-})$ (a) - IN MILIOLITE FORMATION (b) - IN GAJ FORMATION

5.4.6 Chloride Ratios.

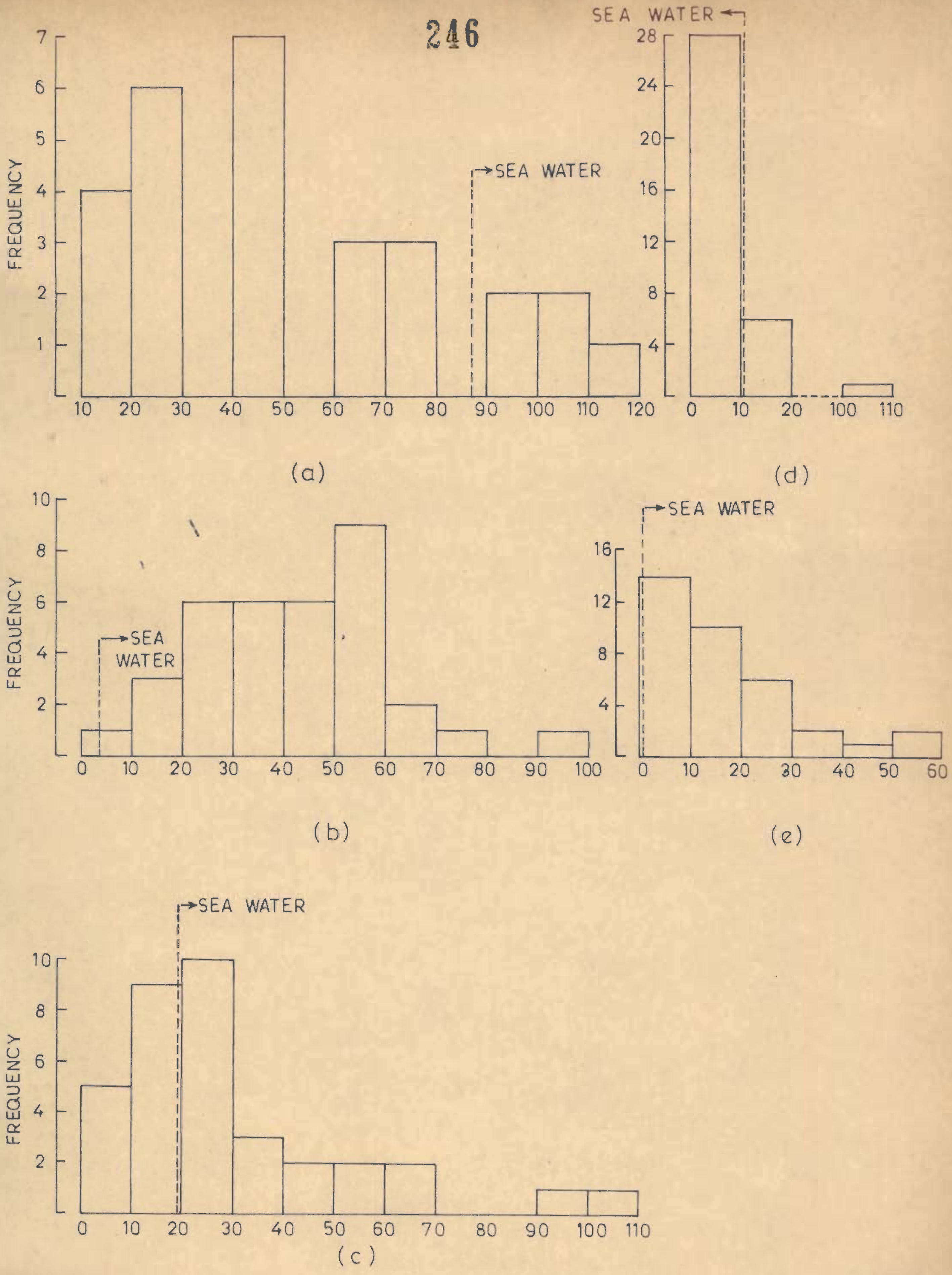
As mentioned earlier, chloride ions are little affected by chemical processes which may take place within the aquifer. So the geochemical variations can be studied by expressing concentrations as a proportion of chloride concentration for the particular water (Johns, 1968). The chloride ratio of a particular ion can be expressed as

$$\frac{\text{ionic concentration in epm}}{\text{Chloride concentration in epm}} \times 100$$

These ratios especially of Na^+, Ca^{2+}, Mg^{2+} and SO_4^{2-} can provide excellent means of finding out the role of oceanic salts in the genesis of a particular groundwater (Johns,1968).

Cl^- is an important constituent of all the groundwaters occurring in the Miliolite Formation. The distributions of chloride ratios of the major ions in these waters are exhibited in the form of histograms in Fig.5.20a,b,c,d, and e. Also chloride ratios for sea water after Johns (1968) are marked on the histograms. It is obvious from the figures that in majority of cases Na^+/Cl^- ratio is lower and Ca^{2+}/Cl^- and Mg^{2+}/Cl^- ratios are higher than those of sea water. This suggests the possibility of cation exchange. Ca^{2+} amd Mg^{2+} may have been added to the water and Na^+ may have been removed from it. The higher Na^+/Cl^- ratio in a few samples than the sea water is difficult to explain.

The figures 5.20d and e also indicate that SO_4^{2-}/Cl^- ratio



IG. 5.20_ HISTOGRAMS SHOWING THE DISTRIBUTION OF CHLORIDE RATIO OF OCEAN WATER AND DIFFERENT IONS OF GROUNDWATER a-Na, b-Ca, c-Mg, d-SO, e-HCO_3

5.4.7 Change in quality of water with Pumping

In order to determine any change in water quality with pumping, groundwater samples were collected from two wells tapping the Miliolite Formation situated near to the coast and another well situated about 5 km inland from the sea coast and also from two wells tapping the Gaj Formation. The water samples were collected before the pump started and then at intervals of one hour after pumping, for the wells situated near to the coast.

A perusal of hydrochemical data given in Tables 5.5 and 5.6 shows that in wells located near the coast tapping the Miliolite Formation (Mangrol) there is a distinct increase in E.C. and T.D.S., and also other cations and anions due to pumping. However, in wells tapping the Miliolite Formation away from the coast (Kankasa) and in the Gaj Formation (Menaj and Mankhetra) there is no such change in water quality (Tables 5.5 and 5.6).

5.4.8 Mixing of Water and Base Exchange

In order to find out the effect of mixing of fresh groundwater and sea-water and other accompanying geochemical changes, the $\gamma\ Mg^{2+}/\gamma\ Ca^{2+}$ ratio was plotted (as suggested by Back and Hanshaw, 1970) against Cl^- (Fig.15.21). In case of simple mixing of waters, the data points should lie on a straight line which should pass through the plot for sea-water. However, figure 5.21 suggests that it is not a simple case of

TABLE 5.5: Location and Distance of the Wells from Coast, Time of Collection, E.C., T.D.S., and Cl^- Content of Waters During Pumping

Location	Distance from the coast	Time	Electrical conductivity mhos/cm at 25°C	T.D.S. ppm	Chloride ppm	Bicar bonat ppm
Mangrol Bandar	300m	Before pumping	8741	5681	1788	
		After 1 hour pumping	11210	7000	3960	
		After 2 hour pumping	11210	7000	4040	
		After 3 hour pumping	12330	7700	4080	
Mangrol	1 km	Before pumping	9990	6494	2098	
		After 1 hour	13450	8400	5048	
		After 2 hours	14010	876	5200	
		After 3 hours	14570	9100	5280	
		After 4 hours	14570	9100	5296	
Kankasa	5 km	Before pumping	2119	1377	349.4	
		After 3 hours	2057	1337	341.6	
Menaj	7 km	Before pumping	1399	909	152.3	408.40
		After 1 hour 40 mts.	1399	909	158.1	401.55
Mankhetra		Before pumping	1008	604	128.0	375.15
		After 3 hours	896	560	128.0	311.10

Table 5.6 : Hydrochemical Data of Water Samples Collected Before and After Pumping

Location	Time	Na^+	K^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}	Cl^-	HCO_3^-	Alkalinity	Total hardness	EC mhos/cm	pH	Temp °C
Mangrol	Before pumping	1010	410	220.94	466.94	352.00	2098.94	386.5	325.0	2471.9	999.0	7.05	25
	After 4 hour of pumping	2260	365	266.53	629.88	540.00	5296.60	387.3	317.5	3257.5	14570		28
Menaj	Before pumping	93	19.5	80.16	34.00	103.00	152.30	408.4	295.0	340.0	1399.0	7.5	29
	After 1 hr 40 mts	200	19.0	32.10	63.20	42.0	158.15	401.5	392.5	340.0	1399.0		30

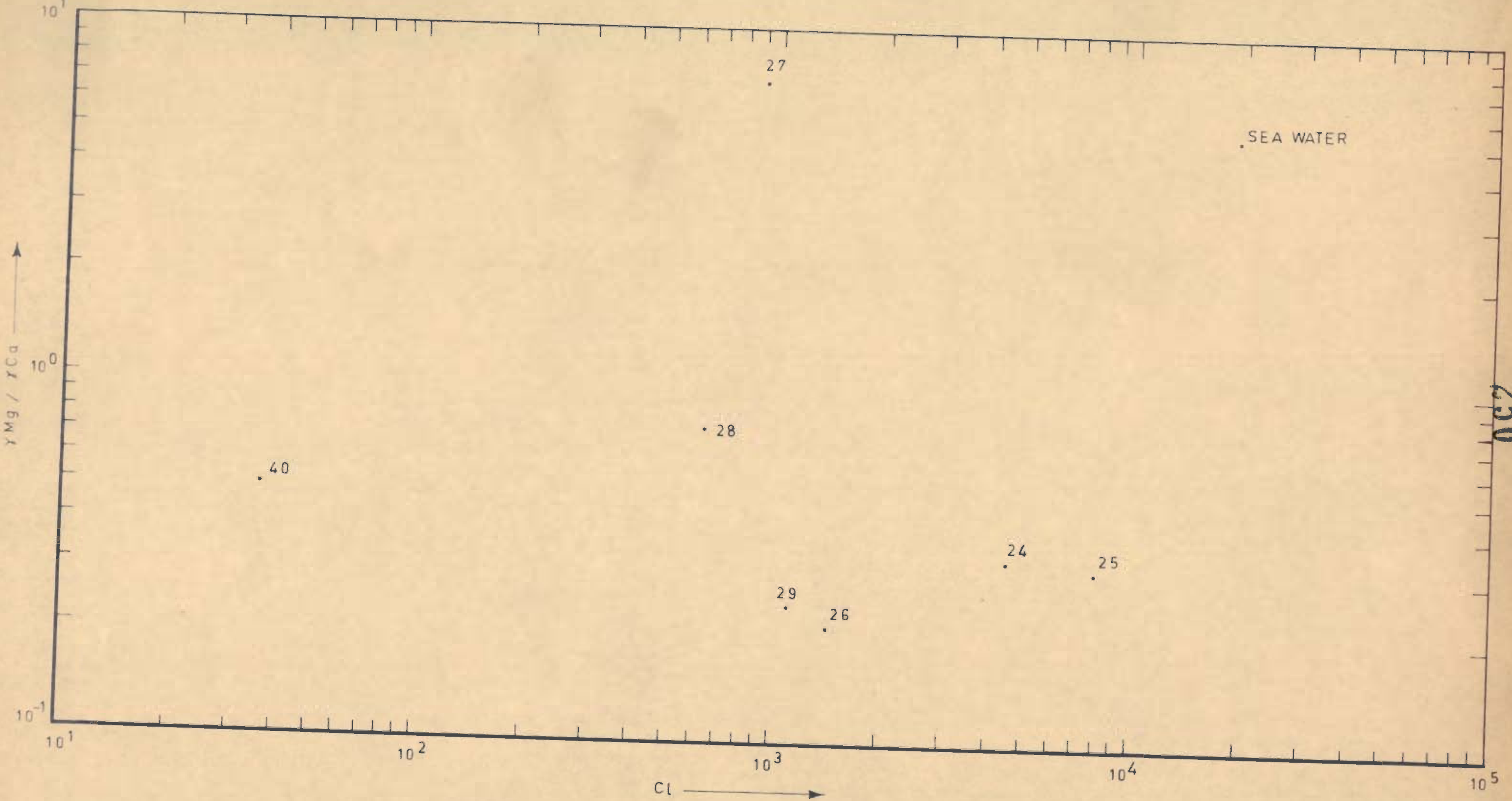


FIG 5.21 _ PLOT OF Cl⁻ VERSUS γMg/γCa

mixing, but probably dissolution of aquifer material and base exchange may also be taking an active part in modifying the quality of water.

When sea-water comes in contact with the aquifer, the ions adsorbed on the surface of the mineral grains may be replaced leading to base exchange. Ions are not equally replaceable. The relative ease of exchangeability of cations is given by the series (Davis and De Wiest, 1966, p.92).

$$Li^{+} > Na^{+} > K^{+} > Mg^{2+} > Ca^{2+} > Si^{2+} > Ba^{2+}$$

Schoeller (1959) gave the following index to find out the degree to which base exchange has taken place when Na^{+} and K^{+} of water are exchanged with Mg^{2+} and Ca^{2+} in the aquifers. In such cases, the base exchange index will be positive.

$$\text{Base exchange index} = \frac{Cl^{-} - (Na^{+} + k^{+})}{Cl^{-}}$$

Base exchange index for all water samples except one from the Miliolite Formation is positive. It is suggestive of base exchange wherein Na^{+} present in the mixed water has replaced adsorbed Ca^{2+} in clays (mainly illite and montmorillonite) which occur in the Miliolite Formation (see section 3.3.4. 2.5.1).

In the process of base exchange and oxidation - reduction the total equivalent amount of base and acid radicals remain unchanged because ionic balance must be preserved(Revelle,1941).

In the present study, the percentage reacting values of the ions were calculated and in most of the cases it is seen that Ca^{2+} + Na^{+} + K^{+} of groundwater is nearer or slightly greater than Ca^{2+}+Na^{+}+ K^{+} of sea water (Fig . 5.22). It can therefore, be inferred that during mixing of sea-water with groundwater, an ion to ion exchange of bases has taken place. The hydrochemical changes due to mixing of sea-water and fresh groundwater can also be studied as suggested by Back and Hanshaw (1970). Generally the Cl^{-} concentration is not affected by base exchange. A concentration factor can be found out by dividing the Cl^{-} content of sea-water with the Cl^{-} of groundwater. The composition of a hypothetical groundwater can be obtained by multiplying the concentration of an ion in ppm by this factor. By this process we make the Cl^{-} content of groundwater to be equal to that of sea-water and then compare the relationship of other constituents of the hypothetical groundwater with that of ocean water. In the present study the comparability has been calculated and is presented in the form of histogram (Fig.5.23a to 5.23f). It is seen that Ca^{2+} and Mg^{2+} are high and Na^{+} is less in majority of cases. Similarly SO_4^{2-} is lower in most cases and HCO_3^{-} is higher than that of sea water. This indicates that probably Na^{+} present in the mixture of groundwater and sea-water has been replaced by the adsorbed Ca^{2+} ions present in the aquifer material. The lower content of SO_4^{2-} can be attributed to sulphate reduction.

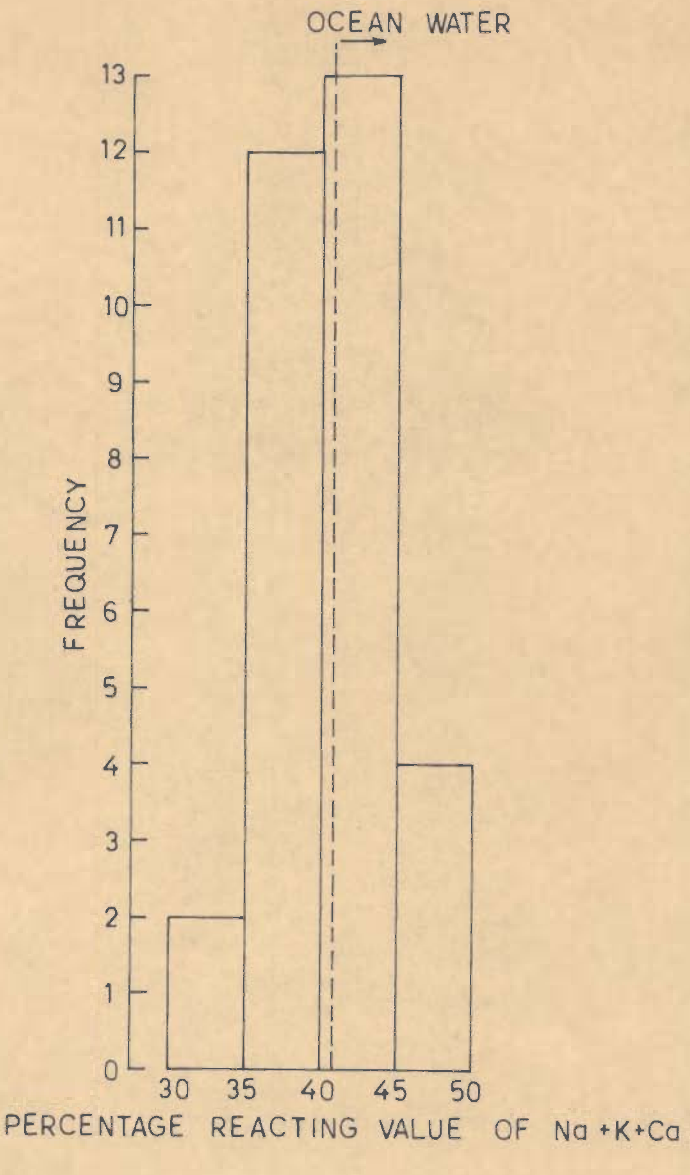


FIG. 5.22 – HISTOGRAM DEPICTING THE DISTRIBUTION OF PERCENTAGE REACTING VALUE OF Na+K+Ca OF GROUNDWATER AND OCEAN WATER.

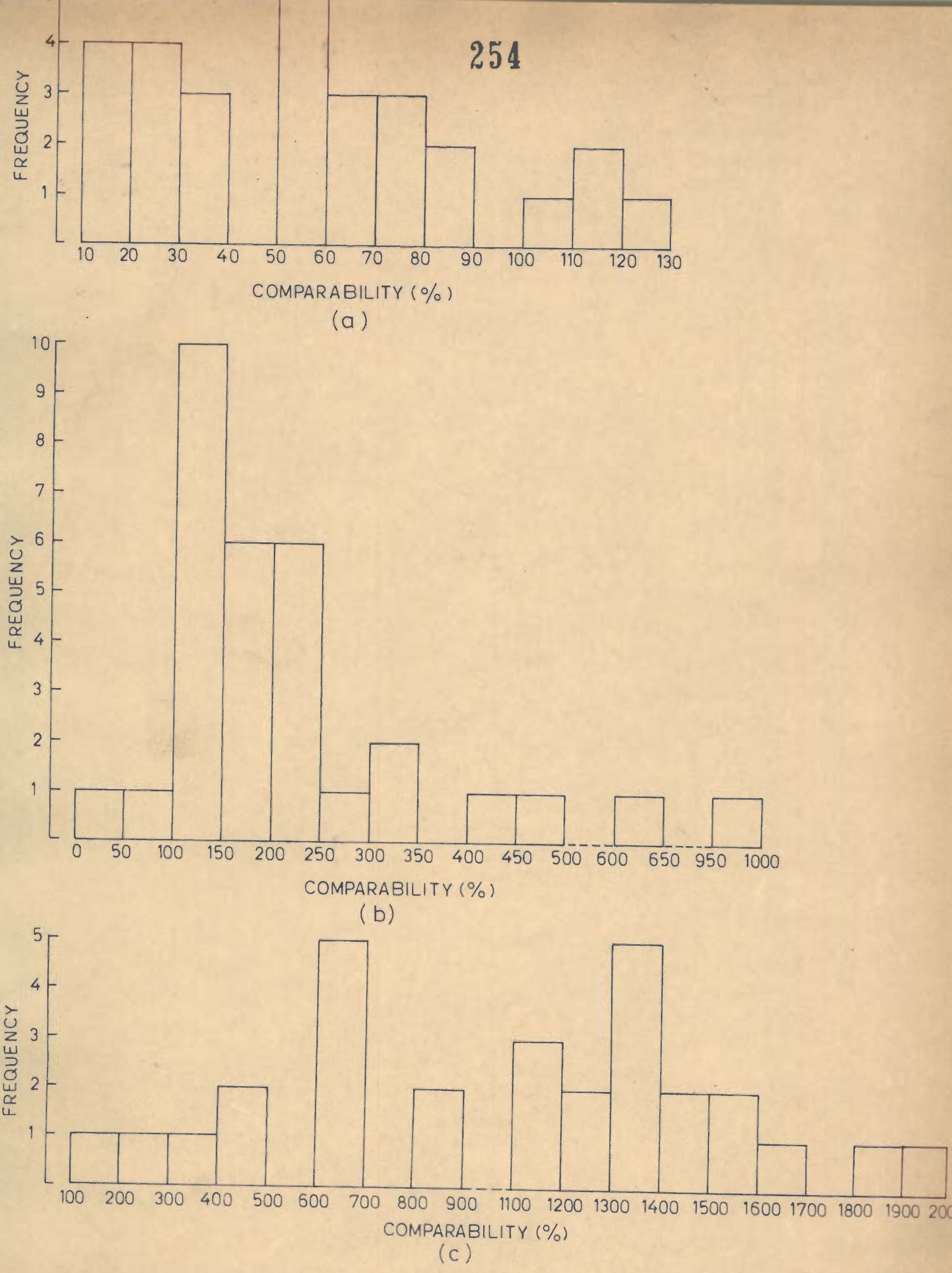


FIG. 5.23_HISTOGRAMS SHOWING COMPARABILITY OF GROUND WATER FROM THE MILIOLITE FORMATION WITH OCEAN WATER. a-Na, b-K, c-Ca

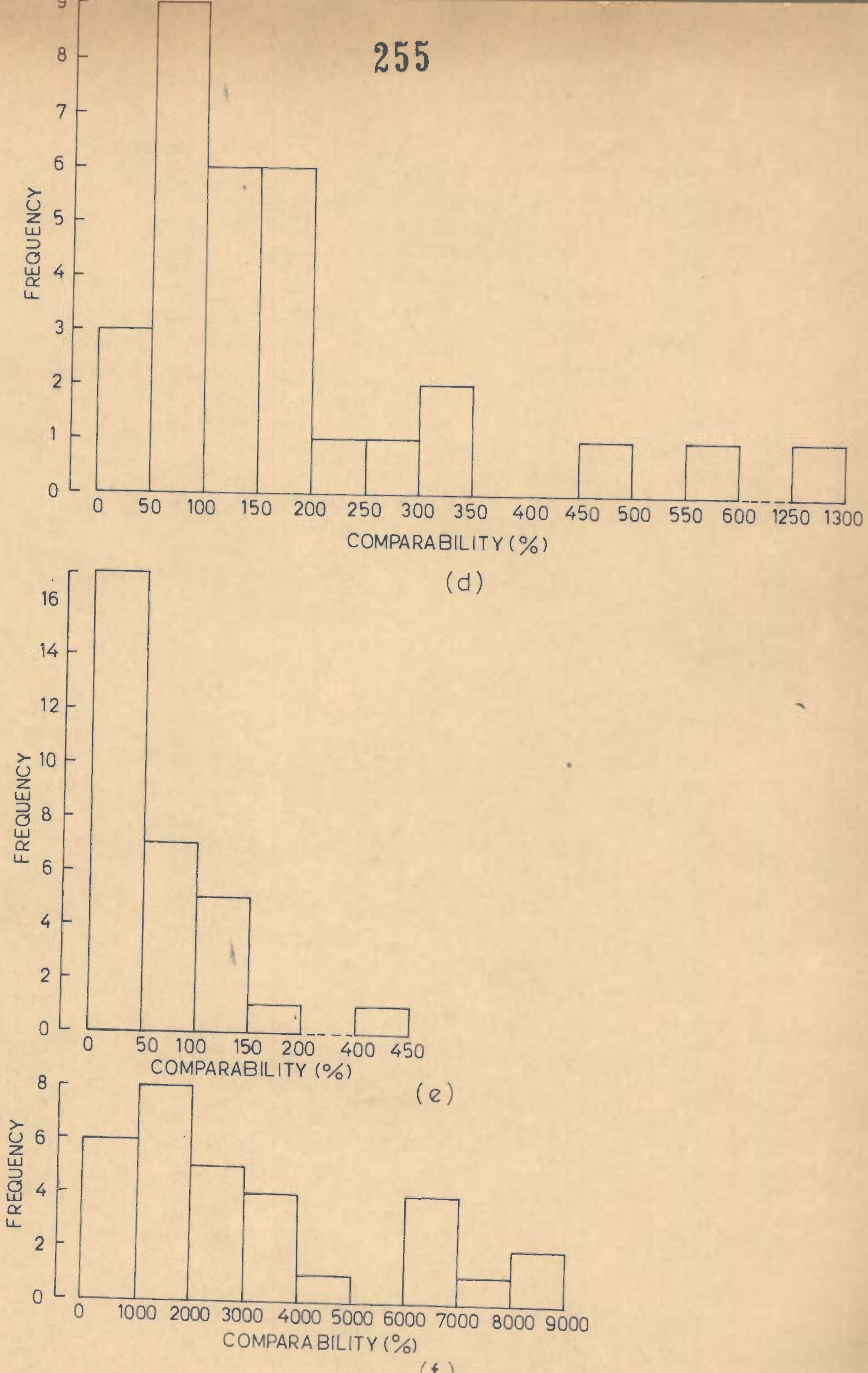


FIG.5.23_ HISTOGRAMS SHOWING COMPARABILITY OF GROUNDWATER FROM THE MILIOLITE FORMATION WITH OCEAN WATER d-Mg, e-SO_4, f-HCO

5.4.9 Principal Component Analysis (PCA)

In hydrochemical studies graphical representation is generally done (Back, 1961; Zaporozec, 1972) for comparing various types of water and for understanding their origin and the flow patterns.

There are some limitations for graphical interpretation of groundwater quality (Dalton and Upchurch,1978). They are

1. there is a finite number of variables that can be considered,
2. the variables are generally limited to major ions and
3. spurious relationships may be introduced by the use of some of the procedures. The spurious results are produced because of the use of closed - number systems to compute the trilinear diagram. Chayes (1960, 1971) has shown that by converting numbers to proportions with a constant sum, i.e., 100%, the numbers may no longer be independent. For example, in calculating the anion proportions for the trilinear diagram, Cl^-, SO_4^{2-} and HCO_3^- plus CO_3^{2-} must sum to 100 per cent. Therefore, any increase in concentration in one or two of the variables forces an apparent, but perhaps false, decrease in the third variable. This will complicate the interpretation of hydrochemical facies from trilinear diagrams.

To avoid the limitations of graphical interpretation of hydrochemical facies, Lawrance and Upchurch (1978)used factor analysis, a multivariate technique to classify water facies on the basis of chemical data. They showed that it can be used in much the same way as the graphical methods. Dalton and Upchurch (1978) opined that factor analysis should not substitute hydrogeochemistry any more than the graphical methods do. Instead it should be used as a tool for exploring and understanding the variability and controlling processes of the data. During hydrochemical investigations large quantities of data can be processed rapidly and systematically. Principal component analysis (PCA) is another multivariate technique. It is much simpler than factor analysis and is not based on the somewhat elaborate set of assumptions involved in factor analysis. These assumptions have been criticised by Matalas and Reihr (1967). Parkash and Bajpai (1972) also have shown the usefulness of PCA in study of the behaviour of different ions in groundwater.

In the present study, the hydrochemical data were subjected to principal component analysis. Computations were performed on DEC-20 computer using a program developed by Wahlstedt and Davis (1968).The correlation matrix and principal components are listed in Tables 5.7 and 5.8 respectively.

The first principal component (Table 5.8) is weighted on both positive and negative direction and the loadings are well distributed over major ions like Na^+, Ca^{2+}, Mg^{2+} and also EC. This explains for 39.61% of the total variance of the cluster of samples. The component in the normalized direction

Table 5.7: Correlation Matrix for Different variables

	Na^+	K^+	Ca^{++}	Mg^{++}	SO_4^{--}	Cl^-	CO_3^{--}	HCO_3^-	Alkalinity	E C.	pH	Temp.
Na^+	1.0											
K^+	0.514	1.000										
Ca^{2+}	0.603	0.294	1.000									
Mg^{2+}	0.513	0.510	0.305	1.000								
SO_4^{2-}	0.576	0.531	0.162	0.475	1.00							
Cl^-	0.819	0.4998	0.796	0.661	0.399	1.000						
CO_3^{2-}	0.172	0.149	0.187	0.024	-0.082	0.180	1.00					
HCO_3^-	0.048	0.078	-0.238	-0.642	0.214	0.187	-0.215	1.000				
Alkalinity	0.108	0.169	-0.088	-0.608	0.166	-0.084	0.416	0.420	1.000			
E.C.	0.719	0.694	0.664	0.703	0.404	0.863	0.163	-0.127	-0.013	1.000		
pH	-0.277	-0.303	-0.392	-0.413	0.367	-0.433	0.087	-0.142	-0.163	-0.348	1.00	
Temp	-0.294	-0.263	-0.243	0.090	-0.142	-0.237	-0.284	0.690	-136	-0.277	0.150	1.000

Table 5.8: First Three Components of Different Variables (ions) in Groundwater. Samples of the Miliolite and Gaj Formations.

Variable	Component I	Component 2	Component 3
Na^+	0.385	0.056	0.031
K^+	0.332	0.682	-0.016
Ca^{2+}	0.321	-0,272	0.157
Mg^{2+}	0.336	-0.055	0.281
SO_4^{2-}	0.280	0.304	0.258
Cl^-	0.424	-0.193	0.025
CO_3^{2-}	0.092	0.053	0.671
HCO_3^-	-0.026	0.598	-0.218
Alkalinity	0.038	0.586	0.317
EC	0.419	-0.115	0.007
pH	-0.245	-0.161	0.190
Temp.	-0.147	-0.117	-0.441
Eigen value percent contribution to total variance	39.61	14.70	12.95

form is C_1=0.385 (Na^+) + 0.3322 (K^+) + 0.321 (Ca^{2+}) + 0.336 (Mg^{2+}) + 0.28(SO_4^{2-}) + 0.424 (Cl^-) + 0.092 (CO_3^{2-})- 0.026 (HCO_3^-), 0.038 (Alkalinity) + 0.489 (.E.C.)-0.245 (pH)- 0.147 (temp).

The second principal component which accounts for 14.70% of the total variance is mainly loaded on the HCO_3^- and alkalinity and to some degree SO_4^{2-}. Since alkalinity depends on HCO_3^- content this component may be considered to be influenced by HCO_3^- content and to a lesser degree by SO_4^{2-}. The vector direction cosine is C_2 = 0.056 (Na^+) + 0.182 (K^+)- 0.272(Ca^{2+}) - 0.055(Mg^{2+}) + 0.304 (SO_4^{2-}) - 0.193 (Cl^-) +0.053 (CO_3^{2-}) + 0.598 (HCO_3^-) +0.586 (Alkalinity) -0.115(E.C.)- 0.161(pH) - 0.117 (Temp).

The third component accounts for 12.95% and is loaded on CO_3^{2-} and alkalinity. The alkalinity depends upon CO_3^{2-} also. Moreover, the CO_3^{2-} is present only in a few cases and so this component is not very useful in the present study. The first three components cumulatively explain 67.26% of the total variance.

Third order trend surface fitted to component 1 scores of different wells (not given here) indicate that the values are increasing towards the coast and the maximum value is near to the sea. Of course, the values are also high in the NE portion of the area. This can be explained as due to the paucity of data. The direction in which the values are increasing is SW. The loading of the first principal component is on the major ions and E.C. is almost uniform. The higher values near to the coast may be explained due to the mixing of sea water with groundwater. These results are in conformity with those obtained from trend surface analysis of hydrochemical data.

5.4.10 Discriminant Analysis

A population described by K variables may be considered as a cluster of sample points in K dimensional space. A second population, described by the same K variables is the computation of a K dimensional plane that most efficiently separates the two clusters. The "locations" of the two populations are described by the K dimensional coordinates of their multivariate means. The degree of distinctness of the two groups is measured by the "distance" between these means. The details of this technique are given by Davis (1973).

In the present study, for discrimination between the waters from the Miliolite Formation and Gaj Formation, the values of constants to the variables (Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, CO_3^{2-} HCO_3^-, alkalinity) and the percentage contribution of each variable for the discriminant function are given in Table 5.9 which indicate that the important characters for discrimination are higher E.C., SO_4^{2-}, and Cl^- in waters from the Miliolite Formation and higher alkalinity in the waters from the Gaj Formation. Discriminant score for each sample of either group has been determined. The mean of the discriminant score 'R' for the waters from the Miliolite Formation is -21.4386. The mean of discriminant scores 'R_2' of the waters from the Gaj Formation is -25.5605. The discriminant index 'R_0' is -23.4995.

It is clear that there is a distinct discrimination between the waters from the Miliolite Formation and the Gaj Formation. The higher content of Cl^-, SO_4^{2-} and EC in the Miliolite Formation near to the coast may be due to the mixing of modern sea water and groundwater. The higher alkalinity of waters from Gaj Formation is because of the higher HCO_3^- content.

Discriminant technique was also applied for the waters from the Miliolite Formation for two seasons, i.e., February 1979, and October 1979 to determine whether there is any distinct seasonal difference. For discrimination between the waters of these two seasons, the values of constants to variables (Na^+, K^+, Ca^{2+}, Mg^{2+} SO_4^{2-}, Cl^-, HCO_3^-, total hardness, E.C., and pH) and the percentage contribution of each variable as determined are given in Table 5.10 which indicate that the important characters for discrimination are Ca^{2+}, HCO_3^-, and pH. The discriminant score for each sample of either group has been determined. The mean of the discriminant score 'R_1' for pre-monsoon data (February 1979), is -38.9524. The mean discriminant scores 'R_2' of the post monsoon period (October'79) is -50.9239. The discriminant index 'R_0' is - 44.9382. It is clear that there is a distinct discrimination between the waters in the pre-monsoon and post-monsoon periods. The major changes are seen in Ca^{2+} and HCO_3^- contents. The contribution of Cl^- and EC to discriminant function are negligible, thereby indicating that there is no change in salinity with season.

Table 5.9 : Variables, Constant and Percent Contribution of Each Variable for Discriminant Function in Differentiating waters from the Miliolite and the Ga Formations

Variable	Constant	Percent contribution
Na^+	-0.0005	-4.0873
K^+	-0.0004	-0.4047
Ca^{2+}	-0.0007	-4.0505
Mg^{2+}	-0.0090	-21.3439
SO_4^{2-}	0.0141	18.6544
Cl^-	0.0007	20.0060
CO_3^{2-}	0.0192	1.5120
HCO_3^-	-0.0029	2.7695
Alkalinity	-0.0151	15.1429
EC	-0.0008	55.6709
pH	-2.8162	14.7909
Temp	-0.0267	1.3404

Table 5.10: Variables, Constant, and Percentage Contribution of Each Variable for Discriminant Function in Differentiating waters from the Miliolite Formation for Different Seasons

Variable	Constant	Percent added
Na^+	-0.0088	-1.4160
K^+	-0.0111	-0.0857
Ca^{2+}	-0.0204	17.9210
Mg^{2+}	-0.0028	-1.9491
SO_4^{2-}	-0.0024	-1.2890
Cl^-	0.0048	0.1591
HCO_3^-	0.0393	55.8635
T.H.	0.0024	5.9067
E.C.	0.0004	-1.3782
pH	-6.6704	26.2676

5.4.11 Carbonate Equilibria Studies

Significant advances have been made in the recent past in the understanding of karst processes by studies of the carbonate equilibria of karst waters. Most features of a karst, including the pattern of development of the aquifer, are due to the solution of limestone. So much so, the state of saturation with respect to calcite and other abundant minerals is of prime importance to an understanding of karst. The chemical characteristics of **groundwater** percolating through the openings in limestones can be helpful in explaining the precipitation of calcium carbonate. The operation of these geological processes depends upon the equilibrium between Ca CO_3 in the rocks and the groundwater. In order to find this, the concepts of thermodynamics to **groundwater** can be applied. The hypothesis is that the law of mass action provides a thermodynamic model which can describe the geochemical system of a carbonate aquifer. The study of the departure from chemical equilibrium between **groundwater** and the minerals of an aquifer is helpful in delineating the major areas of recharge and in predicting areas subject to solution or deposition of minerals. Laboratory studies have established (Back and Hanshaw, 1970) that solution of carbonate minerals is influenced by pH, temperature, effect of other ions in solution, and carbondioxide.

In the present study, an attempt has been made to determine the equilibrium conditions of calcium carbonate in **groundwater** with which it is in contact. The degree of calcium carbonate saturation in groundwater has been determined from the chemical data of water samples collected from the area under investigation.

5.4.11.1 Method of Calculation

The first step in the study of carbonate equilibria is to convert the concentration of different ions from ppm value to units of molality using the relation:

$$\text{molality} = \frac{\text{ppm} \times 10^{-3}}{\text{Formula weight}} \qquad 5.1$$

The next step is calculating the ionic strength I of the solution in order to correct the departure of activities from molalities using the equation:

$$I = \frac{1}{2} \Sigma\, m_i\, Z_i \quad .. \quad .. \qquad 5.2$$

where m_i = the molality and Z_i = the charge of each ion in solution. The value of I is then used in determining the values of Ca^{2+} HCO_3^- and CO_3^{2-} using Debye - Hueckel equation (eq.5.3).

$$\text{Log } r = \frac{-AZ_i^2 \times \sqrt{I}}{1 + a_i\, B \sqrt{I}} \qquad 5.3$$

where r = the logarithm to the base 10 of the activity coefficient r, a = the hydrated radius of the ion, A and B are temperature dependent constants, Z_i = the charge of each ion in equation and I = ionic strength.

The activity of an ion is expressed as:

$$(Ca^{2+}) = m\, Ca^{2+}\, \gamma\, Ca^{2+} \qquad 5.4$$

where m Ca is molaity and γ is the activity coefficient. The dissociation of H_2CO_3 is given by

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \quad .. \qquad .. \qquad 5.5$$

$$\text{and } HCO_3 \rightleftharpoons H^+ + CO_3 \quad .. \qquad .. \qquad 5.6$$

The values of Ca^{2+}, HCO_3^- and CO_3^{2-} are substituted in equation 5.7 to obtain the value of m CO_3 for each sample:

$$m\ CO_3 = \frac{10^{-10.3}\ m\ HCO_3^- \quad HCO_3^-}{(H^+) \quad CO_3^{2-}} \qquad 5.7$$

This value, together with the values Ca and CO_3 are substituted in equation 5.8 for finding out mCa.

$$m\ Ca = \frac{10^{-8.3}}{\gamma Ca\ \gamma CO_3\ m\ CO_3} \qquad 5.8$$

m Ca is then converted to parts per million using the euqation 5.1, which gives the theoretical concentration of Ca^{2+} in water at given pH and temperature. These theoretical concentrations are compared with analytical values of Ca^{2+} for understanding whether the water is in equilibrium with calcite of the aquifer, undersaturated or oversaturated.

In order to determine departure from equilibrium of water with respect to calcite, the value of

$$\frac{\text{analysed } Ca^{2+} - \text{calculated } Ca^{2+}}{\text{analysed } Ca^{2+}}$$

has been plotted against ionic strength, for the various water samples (Figs. 5.24 and 5.25)

Before discussing these results, some points have to be borne in mind. pH is an important factor in the carbonate equilibria studies. So the pH measurements should be made in the field itself. The pH values reported in the present study, however, were determined in the laboratory on account of the non-availability of a portable pH meter.

A second source of error can be in the determination of CO_3^{2-} and HCO_3^- which should also be determined in the field . for the sake of greater accuracy.

There can also be errors in the EDTA method of determining Ca^{2+} which can be evaluated by finding Ca^{2+} by other methods and checking the values found by EDTA method.

Further limestones are not pure $Ca\,CO_3$, but contain magnesium carbonate also. This possibility cannot be completely ruled out in the limestones as is indicated by the X-ray analysis. The present study was conducted using the values of equilibrium constants for pure, ordered phase of $Ca\,CO_3$.

Inspite of the above limitations, the possibility of the oversaturated nature of groundwater in the carbonate terranes in general and in the area under study in particular cannot be completely ruled out. Figs.5.24 and 5.25 show that 10 samples from the Miliolite Formation and 9 samples from the Gaj Formation are undersaturated with respect to calcite. The rest, i.e., the majority are of oversaturated character as their plots lie above the zero line.

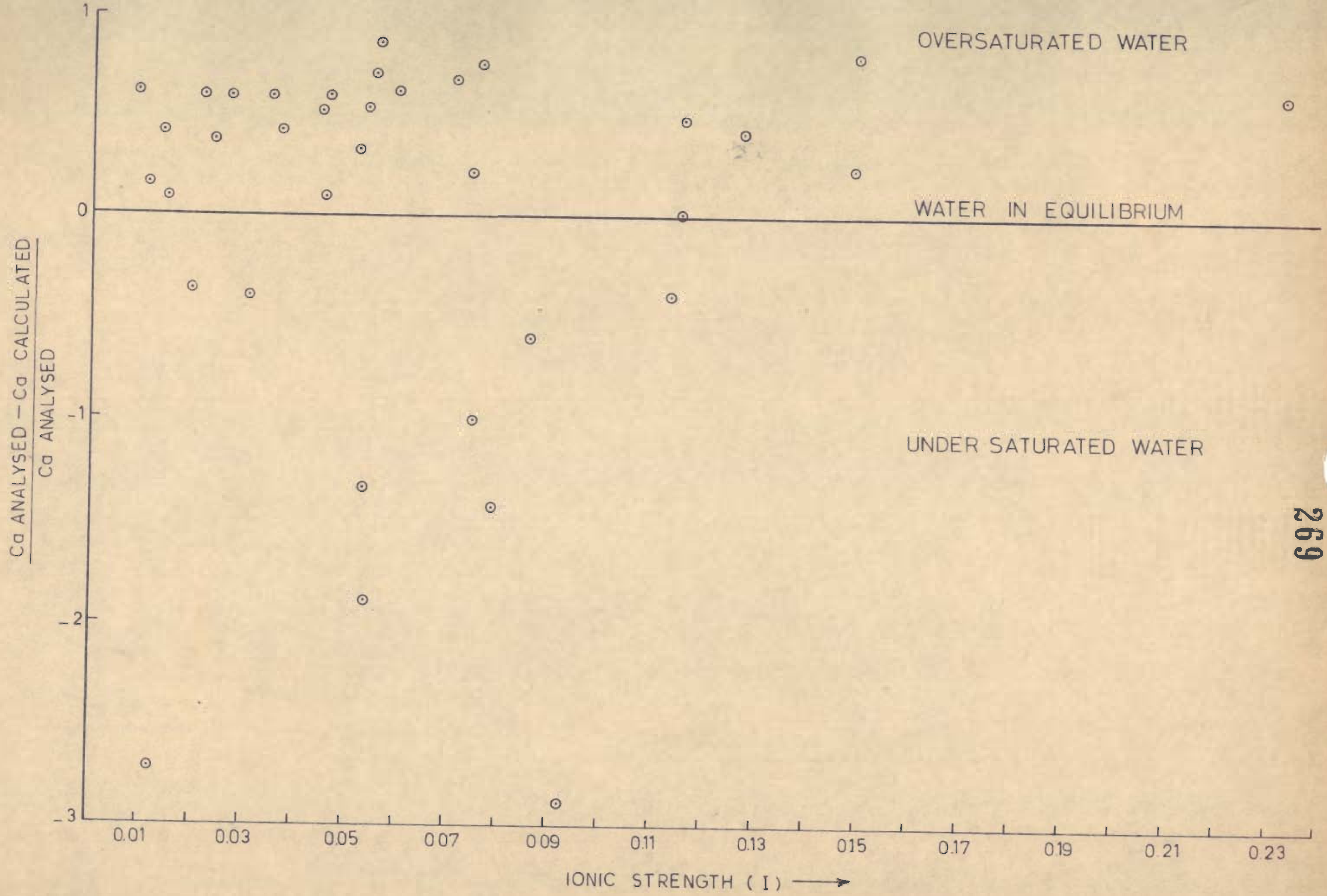


FIG. 5.24 _ PLOTS OF IONIC STRENGTH VS $\frac{\text{Ca ANALYSED} - \text{Ca CALCULATED}}{\text{Ca ANALYSED}}$

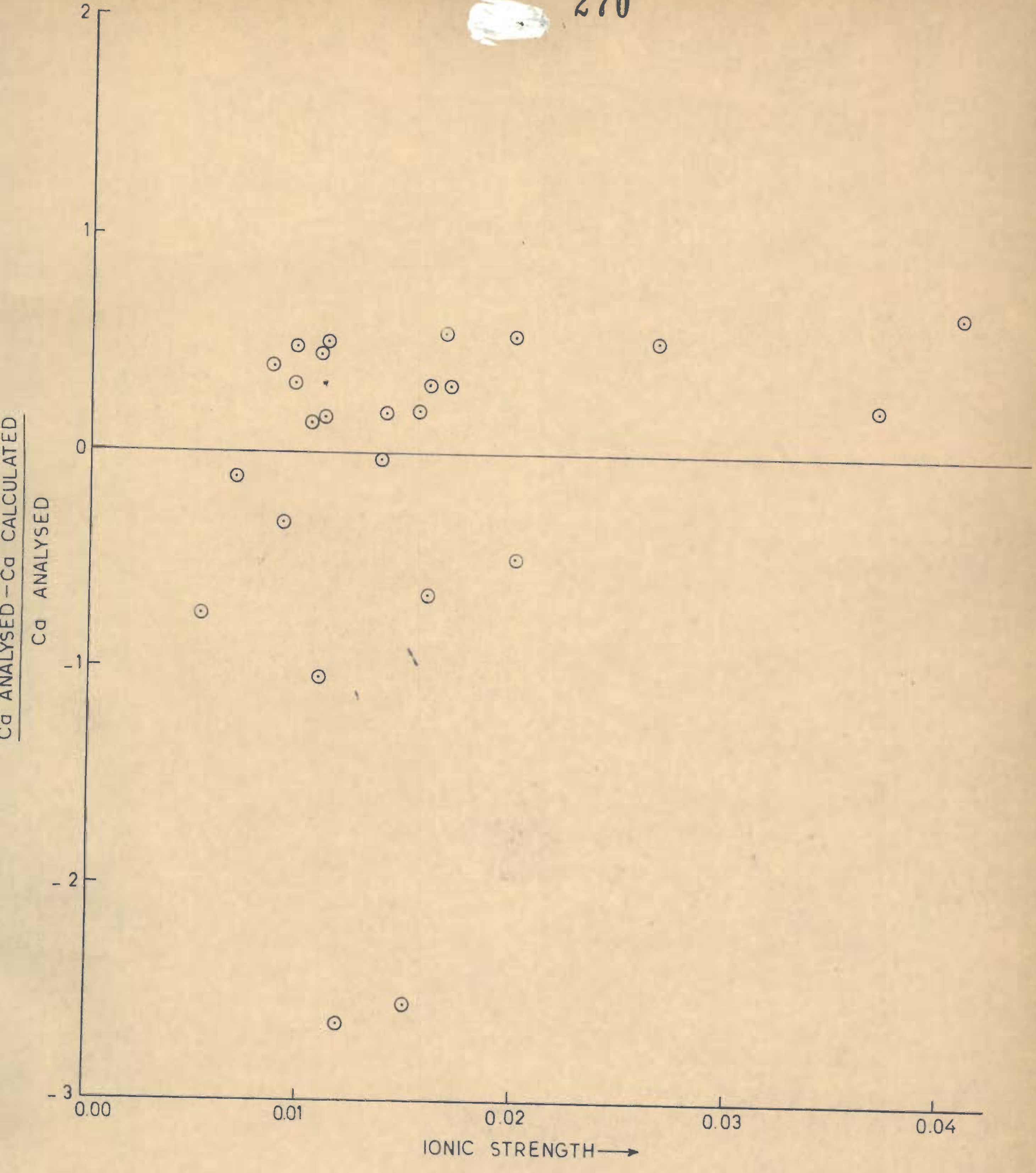


FIG.5.25_ PLOTS OF IONIC STRENGTH VS $\frac{\text{Ca ANALYSED} - \text{Ca CALCULATED}}{\text{Ca ANALYSED}}$

IN GROUNDWATER FROM THE GAJ FORMATION

From the accompanying map (Fig. 5.26) it can be seen that waters from some wells situated near to the coast and tapping the Miliolite Formation are of undersaturated nature. When mixing of fresh and salt water takes place, additional calcium carbonate can go into solution. If the ground water is saturated with respect to calcite, and mixing of salt water with this water takes place, the ionic strength of the groundwater will increase, which causes a decrease in activity. So much so, the molality of Ca^{2+} must increase through greater solution of limestone so that the activity will remain at the value required for saturation. In the area under investigation, the reason for undersaturated nature of groundwater near to the coast can be attributed to the mixing of sea water with groundwater . Of course it can be seen that all the waters are not undersaturated along the coast.In except two cases, all the other areas showing the undersaturated nature are places where even now large scale exploitation of groundwater is taking place, giving rise to greater mixing of sea water and fresh groundwater.

The waters show undersaturated nature near the villages Kalej and Mekhri Nani where there are surface depression (Ghed). In this area, the groundwater is salty as sea water enters through the river Madhuvanti. Here also mixing of salt water with groundwater may be responsible for the undersaturated character with respect of carbonate minerals. As described earlier, the Miliolite Formation is karstified. Solution activity must be taking place in localities wherever the water is undersaturated.

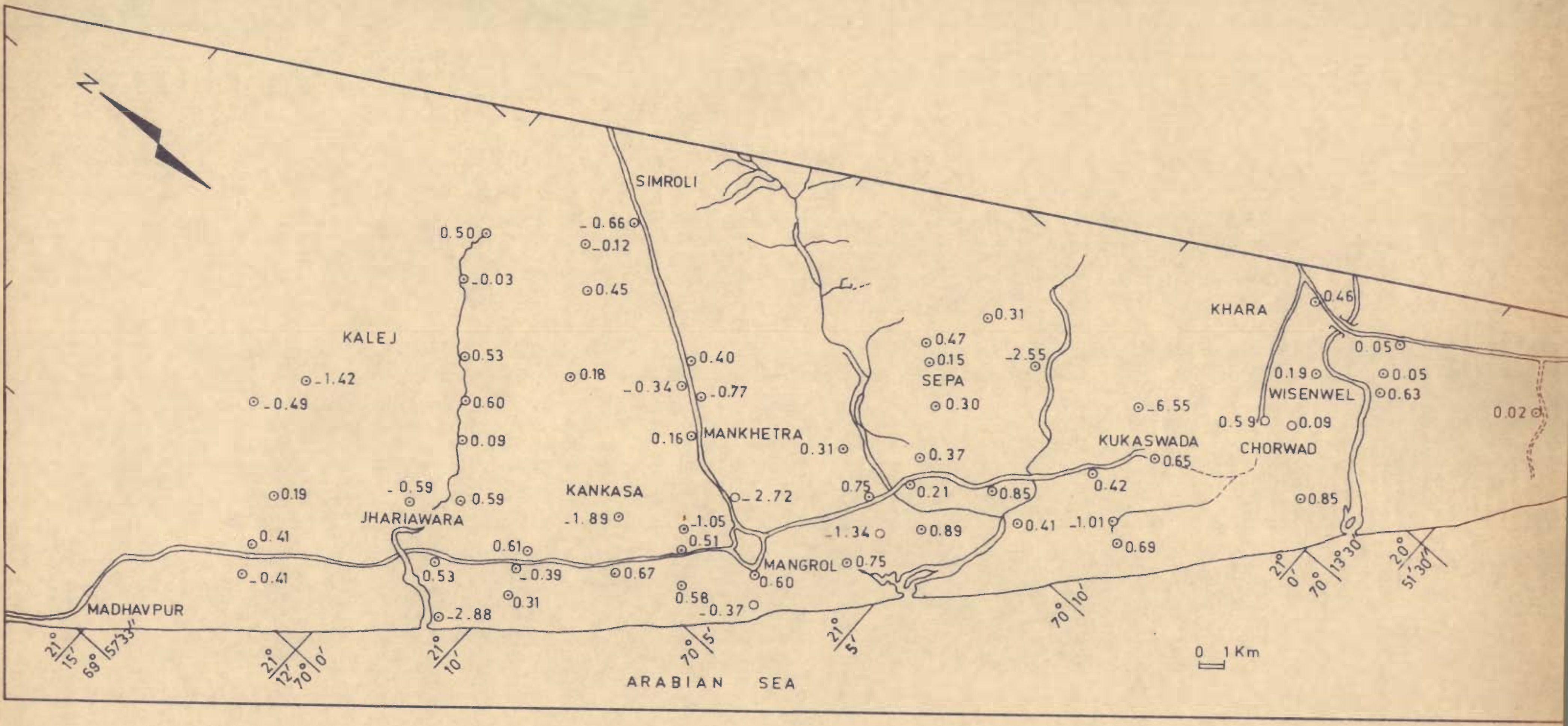


FIG. 5. 26 _ MAP SHOWING THE DEGREE OF $CaCO_3$ SATURATION AT DIFFERENT LOCALITIES.

Groundwater in the Gaj Formation is generally of undersaturated nature. However, from the accompanying map (Fig.5.26) it can be seen that the values do not follow a definite pattern. Near Vallabhagadh and Chingariala villages the undersaturation may be due to the fact that these are areas of recharge and so the groundwater has not moved longer distances and therefore, the residence time must be short. Elsewhere the water is saturated to oversaturated.

In recent years, various workers (Thrailkill,1968, Runnels,1969, Badiozamani, 1974, and Plummer, 1975), based mainly on experimental data, have shown that mixing of two waters saturated with calcite at differing CO_2 partial pressures can produce solution that are undersaturated with calcite. This will increase the capacity of that water to dissolve more calcite. According to Thrailkil (1968), the major factors causing undersaturation are (i) temperature effect, (2) mixing effect and (3) flow rate.

Plummer (op.cit.) showed that the amount of undersaturation in mixtures is a function of $_pCO_2$, temperature, ionic strength, degree of calcite saturation and pH of solutions before mixing. According to him mixing of sea water and fresh calcium-bicarbonate water can produce undersaturated mixture. This can happen irrespective of whether both the solutions are saturated or supersaturated with calcite prior to mixing.

In the present study also the undersaturated nature of the groundwater near to the coast can be attributed to the mixing of sea water with fresh groundwater. There are evidences of mixing of sea water and fresh groundwater on account of over pumping at many places. Further, along the creeks and rivulets, sea water enters during high tides which gets entrapped and infiltrates to the ground causing mixing of groundwater and sea water.

5.4.12 Discussion

There are distinct differences in the chemical characteristics of groundwater from the Gaj and Miliolite Formations. Groundwater in the Miliolite Formation is rich in Na^+ and Cl^- The concentration of these two elements are more near to the coast than those away from the coast. The concentration of K^+, Ca^{2+}, Mg^{2+} and SO_4^- are in the order of 9 to 100 ppm, 250 to 1000 ppm, 10-1000 ppm, and 12 to 100 ppm respectively. In comparison with this, groundwater in the Gaj Formation has K^+, Ca^{2+}, Mg^2 and SO_4^- ranging between 4.5 to 50 ppm, 20 to 100 ppm, 6 to 100 ppm and 6.5 to 100 ppm. Discriminant analysis shows that the waters from the Miliolite Formation and Gaj Formation can be distinguished and the differences are in Cl^-, SO_4^- and EC which are higher in the waters of the former and also alkalinity, which is higher in the latter. In both the waters hardness is high. Regarding alkalinity, it is more in the wells tapping the Gaj Formation than those from the Miliolite Formation. The reason for this is the higher concentration of HCO_3^- in the waters of Gaj Formation. The higher HCO_3^- content can be attributed to the solution of carbonate rocks.

In the present study, special attention has been paid to find out the causes of salinity in this region. The plotting of hydrochemical data in Hill-Piper diagram shows that the waters from the Miliolite Formation are of primary and secondary saline type. Hydrochemical sections indicate an abrupt increase in salinity in a narrow tract of abut 3 km. width parallel to the coast. According to the hydrochemical facies of Back, the water from Miliolite Formation belong to Ca-Na-Cl-SO_4-HCO_3 facies and Ca-Na-Cl-SO_4 facies. These characters along with higher concentration of Na^+ and Cl^- near the coast, the ratio of total alkalinity to total hardness being < 1, high $Cl^-/(CO_3^{2-} + HCO_3^-)$ ratios and increase in E.C. and Cl^- with pumping point towards sea-water intrusion. There are also evidences of change in water quality due to base exchanges as inferred from positive values of base exchange index, the lower chloride ratios for Na^+ and higher chloride ratios for Ca^{2+} and Mg^{2+}. The lower values of Na^+ and higher Ca^{2+} and Mg^{2+} for the hypothetical groundwater which has Cl^- equal to that of sea water also indicate that base exchange has taken place. When the γ Mg/γ Ca against Cl^- concentration was plotted in the direction of groundwater flow, the points do not fall in a straight line which also should pass through the plot of sea water, indicating that it is not a simple case of mixing of sea water and groundwater. The waters have also undergone SO_4^{2-} reduction as evidenced by lower chloride ratio for SO_4 and higher ratio for HCO_3^-. The lower SO_4^{2-} value and higher HCO_3^- value for the hypothetical groundwater than the sea-water also indicate this.

Trend surface maps show that there is an increase in concentration of various ions except HCO_3^- towards the coast in south and SW direction. Principal component analysis indicate that in component 1 explaining the variance therein has almost uniform loading for major ions and this is reflected in EC and thereby the T.D.S. Its value near the coast increase towards the sea. These are suggestive of sea-water intrusion.

The salinity of groundwater in the coastal tracts is a resent phenomenon. Wells near to the coast which used to supply fresh groundwater till about ten years have now turned saline.

Discriminant technique when applied for waters tapping the Miliolite Formation for the pre-monsoon and post-monsoon periods show that there is a discrimination between them. There is an increase in Ca^{2+} and decrease in HCO_3^-. Minor contribution of Cl^- and E.C. to the discriminant functions indicate that there is no change in salinity with seasons.

The carbonate equilibria studies indicate that many of the waters from the Miliolite Formation especially near the coast are undersaturated with respect to calcite. On the other hand waters from the Gaj Formation are over saturated. However, at some places in the Gaj Formation as well groundwater is of undersaturated nature. This could be due to heterogeneity in the flow regime within the limestone.

The above discussion indicates that the main causes of high salinity in the coastal belt is due to the intrusion of modern sea water. Further there are evidences of effect of rock lithology and other geochemical processes viz.base exchange, and SO_4 reduction in modifying the water quality. Based on the individual ion concentrations and combinations and also the various ratios, the zone of mixing in the Miliolite Formation in the coastal belt of Chorwad-Madhavpur area has been demarcated (Fig. 5.27). This zone extends upto 3 to 5 kms inland from the coast.

The other possibility of these saline waters in the coastal tract to be of connate origin appear to be remote for the following reasons. Wells which were giving fresh water till about 10 years back have now turned to be saline. An increase in salinity with pumping near the coast is observed. A uniform belt of high salinity along the coast upto a distance of 3 to 5 km inland occurs in the Miliolite Formation. In case the salinity was of connate type,one would have expected such waters in the Miliolite Formation inland also. There is an abrupt increase in salinity and concentration of various ions (except HCO_3^-) in the coastal belt as evidenced by hydrochemical sections. The various hydrochemical changes in groundwater from land to coast discussed earlier also indicate that the saline waters have evolved as a result of intrusion of modern sea water which has been modified by various processes.

In addition to various criteria used in this work, Lloyd et al. (1982) has laid emphasis on iodide as a criterion for distinguishing between modern sea water and those groundwaters resident in an aquifer for a long period in various hydrogeologic environments. Boron could also be a useful indicator (Davis and De Wiest, 1966) in such studies. However, in the present study due to the non-availability of laboratory facilities iodide and boron could not be determined. It was also not possible to determine the age of these waters.

Future studies on trace elements and minor ion chemistry coupled with dating of saline waters may help in obtaining better insight into the origin of these waters.

5.5 SUITABILITY OF WATER FOR VARIOUS PURPOSES

One of the important purposes of hydrochemical study is to determine the suitability of water for various uses. This study is of importance in the investigated area, as the water is mainly used for domestic and irrigational purposes.

5.5.1 Quality Criteria of water for Domestic Use

The water used for domestic purposes should be devoid of colour, turbidity, coliform bacteria and should have a pleasant odour and taste. Table 5.11 and 5.12 give the chemical quality criteria for domestic use and drinking water standards.

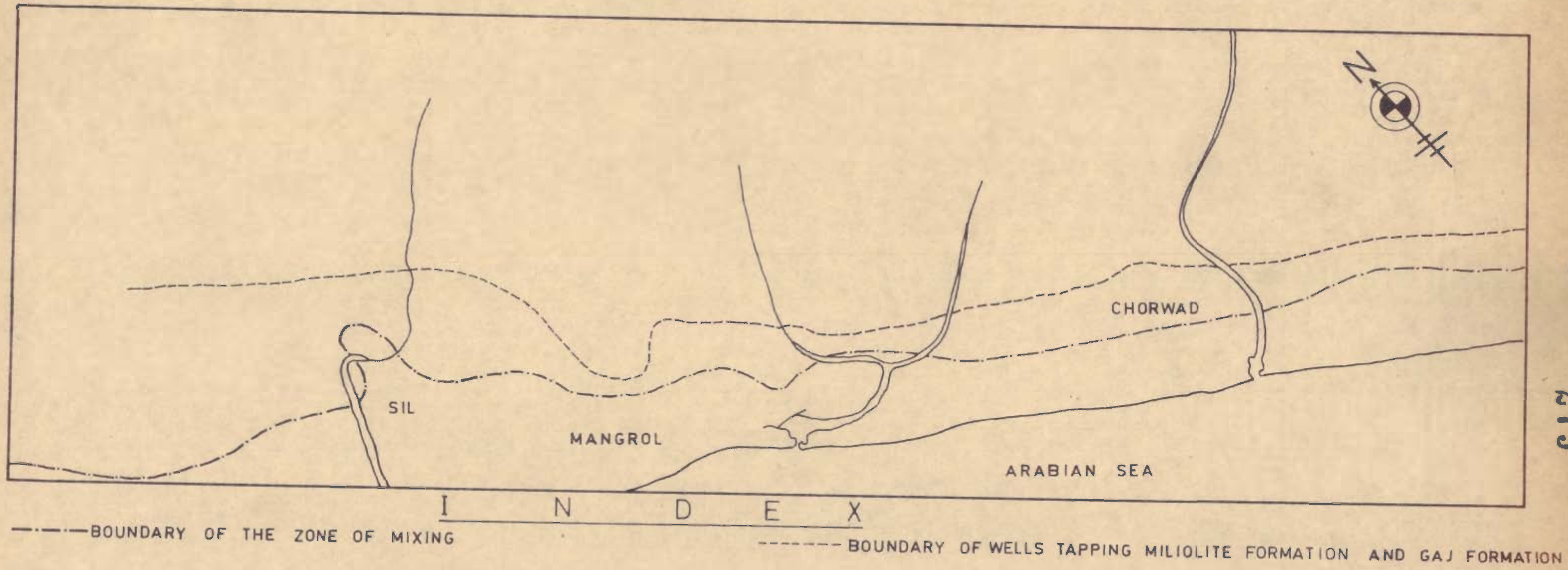


FIG. 5.27 – DIAGRAM SHOWING THE ZONE OF MIXING

Table 5.11: Quality Criteria of Waters for Domestic Uses (After Davis and De Wiest 1966)

	For Drinking	For general household work	
	ppm	Good ppm	Poor ppm
HCO_3^-	500	150	500
Ca^{2+}	200	40	100
Cl^-	250		
Mg^{2+}	125	20	100
Na^+	200	100	300
k^+			
SO_4^{2-}	250	100	300
T.D.S.	1500	300	2000

A perusal of Table 5.1 indicates that the waters from the Miliolite Formation, especially those near to the coast contain high concentrations of Na^+, Cl^-, Ca^{2+} and Mg^{2+} and therefore are not suitable for drinking and other household work. The waters from the Gaj Formation in general are good and only very few samples show higher concentrations of Ca^{2+} and Cl^-. However in the absence of better quality, water from the Miliolite Formation is also being used locally for drinking and other domestic purposes.

Table 5.12: Drinking water Standards (in ppm) (after Holdon)

	U.S.P.H. 1962		W.H.O.1963		Europe-W.H.O. 1961	India I.S.I.
	Desirable	Maximum allowable	Desirable	Maximum permissible	Upper limit	
Cl	250	..	200	600	350	600
SO_4	250	..	200	400	250	..
Ca	..	..	75	200	..	..
Mg	..	..	50	150	..	..
T.D.S.	500	..	600	1500	..	..
pH	..	..	7 to 8.5	6.5 to 9.2	..	6.0 to 9.0
Hardness	..	..	..	Min.100	..	..
Boron	..	..	..	..	..	..
Fluoride	..	..	..	..	..	..
Cyanide	..	..	..	..	..	1.5
Selenium	..	..	..	..	..	0.01
Lead	..	..	..	..	..	0.05
Total chromium	..	0.05	..	..	..	0.10
Ar	0.01	0.05	..	..	..	0.05
Fe	0.30	..	0.30	1.0	..	0.20
Mn	0.05	..	0.05	0.5	..	
Zn	5.0	..	6.0	15.0	..	

5.5.2 Quality of Water for Irrigational Purposes

Agricultural sector utilizes large quantities of ground water. The suitability of groundwater for irrigation is contingent upon the effects of mineral constituents of water on both the plant and soil. Because of the presence of the dissolved mineral constituents, the application of irrigation waters to soils may markedly affect soil properties. So much so, the interpretation of the analytical data of water in terms of crop production and most effective use, although difficult, is of prime importance. The changes in the properties of the soil, which take place on irrigation may be either beneficial or detrimental. It depends upon the composition and concentration of dissolved constituents in the water used, original characteristics of the soil, climate of the area, nature of the crop, and water management practices etc.

Generally, under geochemical classifications, the procedures mainly directed to classify the chemical data are those related to irrigation uses. The classifications adopted in the present study are mainly based on those of Scofield (1940), Wilcox (1955) and U.S. Salinity Laboratory diagram.

The important constituents of water, which affect plants and soil are T.D.S., Na^+, B, CO_3^{2-} and HCO_3^-. Greater concentrations of these constituents causes salinity hazards, sodium hazard, boron hazard, and bicarbonate hazard. On the basis of these constituents and electrical conductivity, suitability of groundwater for irrigation can be determined.

5.5.3 Wilcox Diagram

In addition to its contribution to total salinity, excessive Na^{+} in irrigation water may create a specific problem as a source of toxicity to certain sensitive crops. Moreover, by the base exchange phenomena, Ca^{2+} in the soil is exchanged with Na^{+} of water, and the latter reduce the permeability of soil. According to Wilcox (in Todd, 1959), the magnitude to which irrigation waters could promote loss of exchangeable Ca^{2+} and Mg^{2+} from the soil can be approximately predicted on the basis of percent sodium $(\% \, Na) = \frac{(Na + K) \, 100}{Ca + Mg + Na + K}$, where all ionic concentrations are expressed in epm, and electrical conductivity.

The chemical data of waters from the area of investigation were plotted in the Wilcox diagram (Fig. 5.28). Except a few samples all the others from the Miliolite Formation fall either outside the area of the figure or in doubtful to unsuitable or unsuitable fields. This indicates that these waters are unsuitable for irrigation purposes. The waters which are good to permissible occur 4 to 6 km away from the coast.

5.5.4. U.S. Salinity Laboratory Diagram

The scientists of U.S. Salinity Laboratory (in Todd,1959) have suggested 'Sodium Adsorption Ratio' (SAR) for evaluating the suitability of water for irrigation purposes. The sodium adsorption ratio is given by the equation(5.9), where all the

$$SAR = \frac{Na}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \qquad 5.9$$

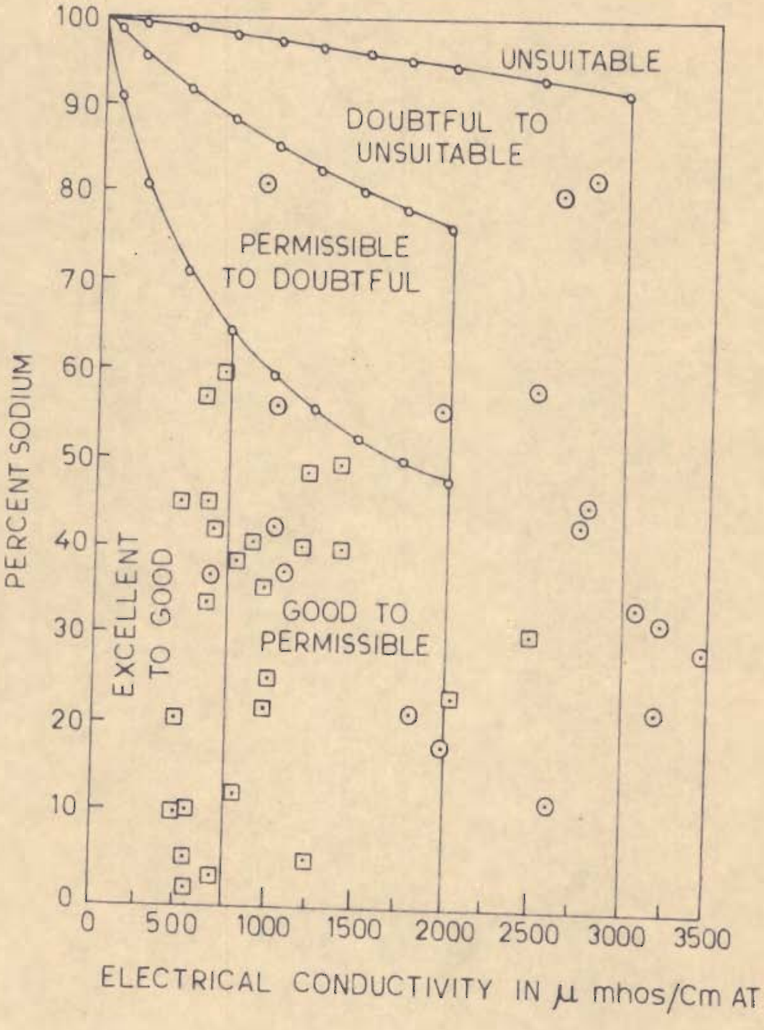


FIG.5.28_DIAGRAM FOR CLASSIFICATION OF IRRIGATION WATERS BASED ON ELECTRCAL CONDUCTIVITY AND PERCENT SODIUM (AFTER WILCOX).

⊙ – WATER SAMPLES FROM MILIOLITE FORMATION.

⊡ – WATER SAMPLES FROM GAJ FORMATION.

constituents are expressed in epm. The SAR concept is based on the theoretical differences in the behaviour of monovalent and divalent cations in base exchange reaction.

The values of SAR are plotted against the specific conductance, on a semilog paper, E.C. on the log scale and the SAR on the arithmatic scale. Direct indication of the salinity and sodium (alkali) hazards can be obtained from the data plots in the diagram. In the figure C_1, C_2, C_3, C_4, and C_5 represent water classes with increasing hazards for total salt concentration and S_1, S_2, S_3 and S_4 represent water classes for increasing hazards of exchangeable sodium accumulation in the irrigation soils. The chemical data from the area under description is plotted in this diagram (Figs. 5.29 and 5.30) and the results are given in Table 5.13. It can be seen from the Fig. 5.29 that many of the water samples from the Miliolite Formation belong to C_4 S_1 class indicating low sodium hazard and very high salinity hazard. A good number also show medium and high sodium and high sodium hazard and very high salinity hard. Eight samples fall outside the diagram and they have extremely high salinity hazard. Only three samples have high sodium hazard. Others belong to the class low to medium sodium hazard. From this it can be seen that majority of the waters are having very high salinity hazard.

Most of the water samples from the Gaj Formation indicate low sodium hazard and medium to high salinity hazard. (Fig. 5.30). In general the groundwaters from the Gaj Formation are of better quality.

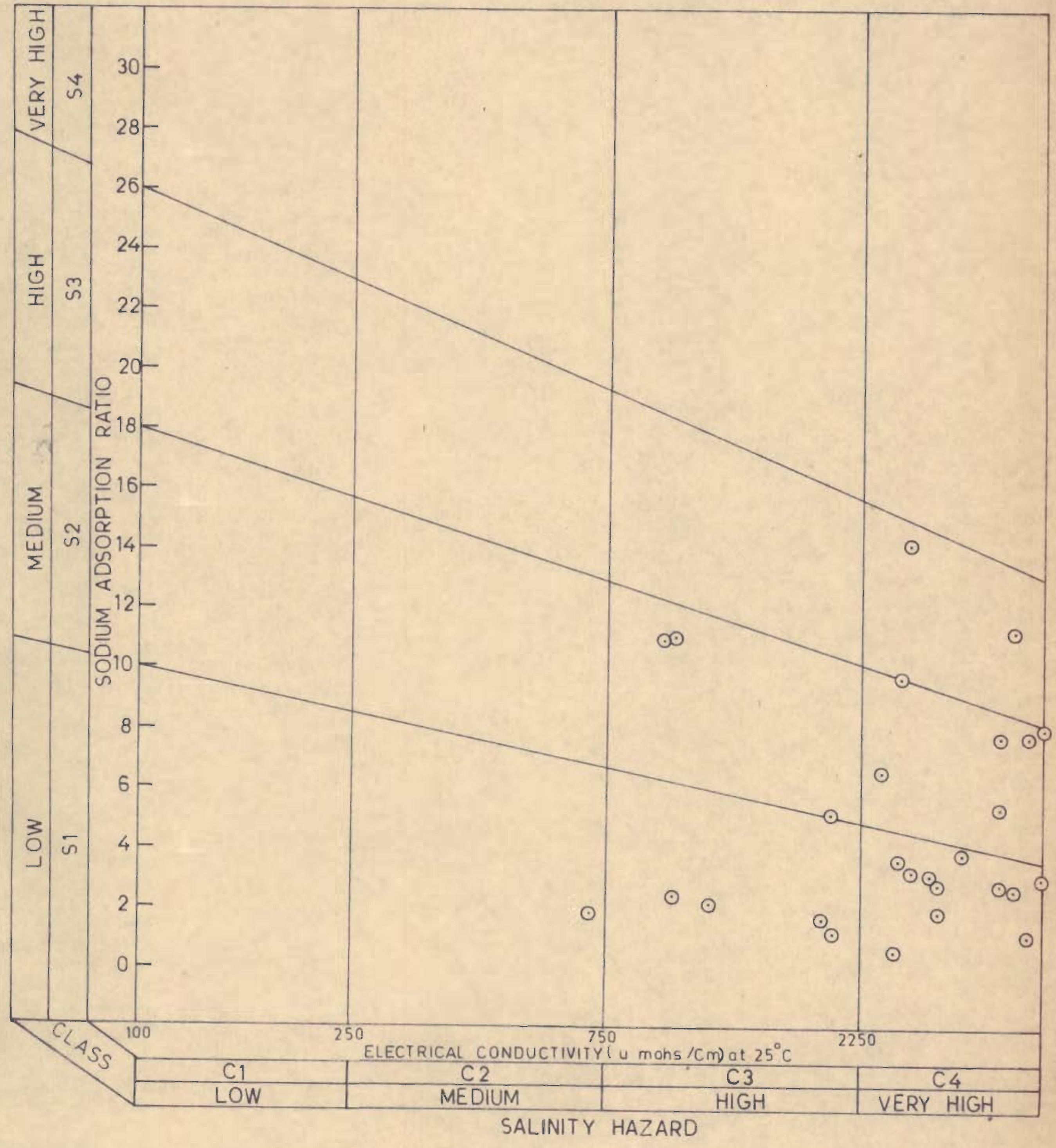


FIG. 5.29 – PLOTTING OF HYDROCHEMICAL DATA IN U.S. SALINITY LABORATORY DIAGRAM FOR WELLS TAPPING MILIOLITE FORMATION.

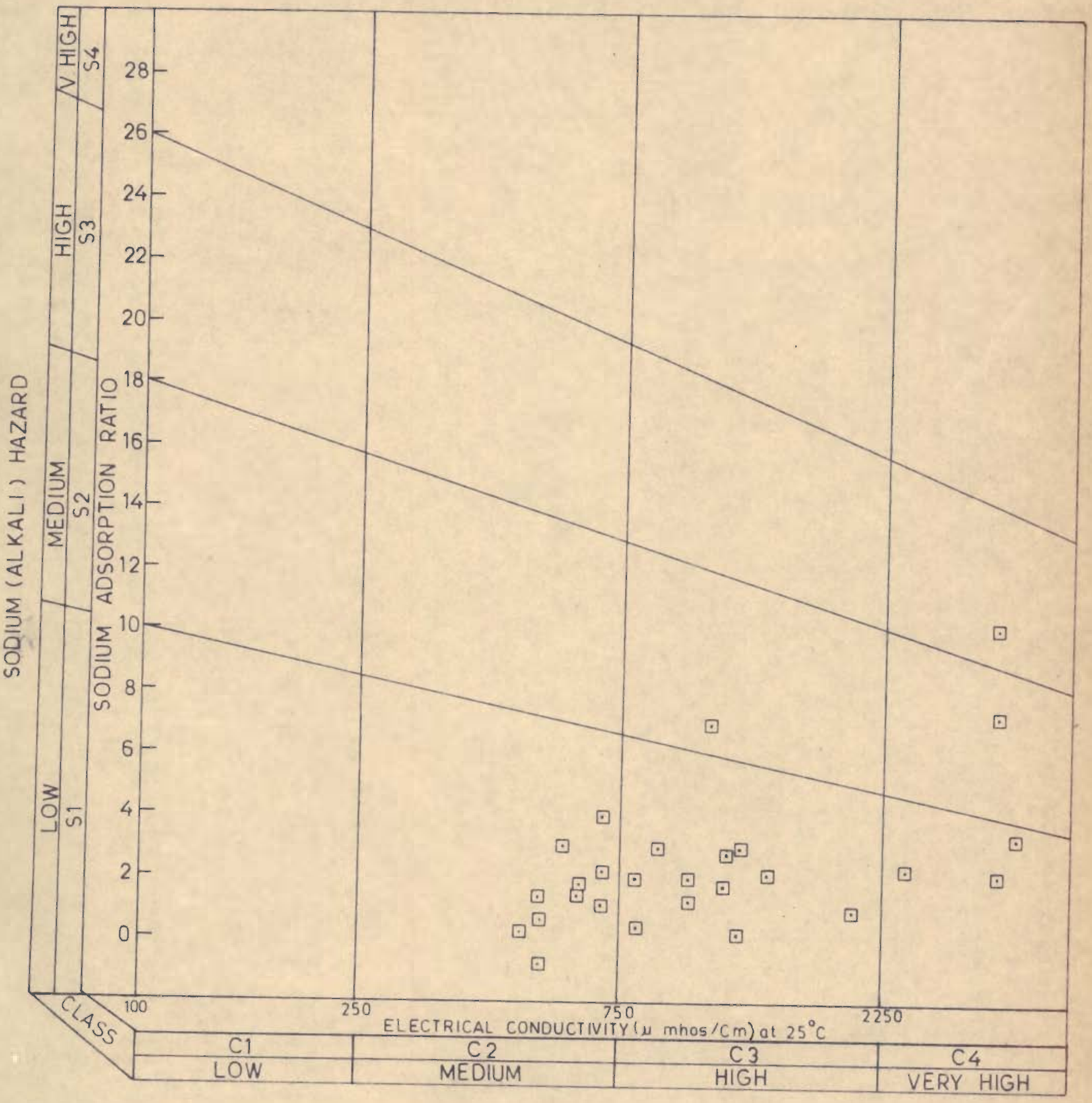


FIG. 5.30 _ PLOTTING OF HYDROCHEMICAL DATA IN U.S. SALINITY LABORATORY DIAGRAM FOR WELLS TAPPING GAJ FORMATION.

Table 5.13: Number of samples from the Miliolite Formation and th
Gaj Formation Falling in Different Classes and
their Characteristics

Miliolite Formation	Gaj Formation	Class	Characteristics
1	11	C_2 S_1	Low sodium hazard and medium salinity hazard.
4	12	C_3 S_1	Low sodium hazard and low salinity hazard.
3	1	C_3 S_2	Medium sodium hazard and high salinity hazard.
11	3	C_4 S_1	Low sodium hazard and very high salinity hazard.
5	1	C_4 S_2	Medium sodium hazard and very high salinity hazard.
3	1	C_4 S_3	High sodium hazard and very high salinity hazard.

5.5.5 Scofield's Classification

A classification of irrigation waters based on total dissolved solids, boron, and percent alkalies expressed in ppm, has been suggested by Scofield (1940). The classification of groundwaters of the study area as per this scheme is given in Table 5.14.

Table 5.14 : Number of Samples of Ground Water Falling in Different Classes According to the Classification of Scofield (1949)

Constituent	Formation	Class I 0-150 ppm	Class II 150-500 ppm	Class III Over 500 ppm
Chloride	Miliolite Formation	1	4	31
	Gaj Formation	17	6	6
		Under 60%	60-75%	Over 75%
Percent alkalies $\frac{(Na+k)}{(Na^{+}+k^{+}+Ca^{2+}+Mg^{2+}}$ in epm)	Miliolite Formation	32	1	3
	Gaj Formation	27	2	1

Class I : Waters regarded as entirely safe for irrigation under ordinary conditions of climate and soil even for sensitive crop plants.

Class II Waters which may be safe for certain conditions or certain crops, yet may be unsafe under other conditions or for other crops.

Class III Water with concentration of one or more constituents too good to be safe for irrigation use or atleast unsafe in a great majority of cases.

Although the percent alkalies in most of the groundwater samples from the Miliolite Formation is less than 60%, the Cl^- content in majority of cases is over 500 ppm indicating that the water is unsafe for irrigation purposes. Majority of waters from the Gaj Formation fall in class I thereby showing that these are safe for irrigation under ordinary conditions of climate and soil even for sensitive crops. Only few samples belong to the Class III.

5.5.6 Residual Sodium Carbonate (R.S.C.)

A high content of bicarbonate ions in water is also injurious for agricultural purposes. If its concentration is high, then Ca^{2+} and Mg^{2+} will tend to precipitate as carbonates in the soil. As a result of this the relative proportion of Na^+ increases in the soil. Generally, this value is expressed in terms of "Residual Sodium Carbonate" which is defined as:

$$\text{Residual Sodium Carbonate} = (CO_3^{2-} + HCO_3^{2}) - (Ca^{2+} + Mg^{2+})$$

where all constituents are expressed in epm.

According to R.S.C. the waters can be rated into 3 main types as shown in the Table 5.15.

Table- 5.15

Rating	Residual Sodium Carbonate
Good	1.25 milliequivalents
Medium	1.25 - 2.50 "
Bad	2.5 "

The water samples from the Miliolite Formation in the area under description have R.S.C. varying from -76.76 to 1.2 milliequivalents and that of the Gaj Formation varies from -30.05 to 1.6 milliequivalents indicating thereby that there is no bicarbonate hazard. Only one sample from the Miliolite Formation show a high R.S.C. value.

5.5.7 Summary

It is seen that the waters from the Miliolite Formation, especially those from near to the coast are not suitable for drinking and other domestic use because of the high concentration of Na^+, Cl^-, Ca^{2+} and Mg^{2+} and high hardness. The waters from the Gaj Formation are in general of good quality, except at a few places where they contain higher concentrations of Ca^{2+} and Cl^-.

Sodium adsorption ratio and percent sodium when plotted in U.S. Salinity Laboratory diagram and Wilcox diagram indicate that the waters from the Miliolite Formation are not suitable for irrigation purposes whereas those from the Gaj Formation are of better quality. Residual sodium carbonate values indicate that there is no bicarbonate hazard. Inspite of the high saline nature of the waters from the Miliolite Formation, in the absence of better quality water, local people are using these waters for irrigation purposes. The application of such waters are deleterious for the growth of plants. The effect of using this water is seen in the wilting of trees and a decrease in crop production. Change of cropping pattern, i.e., by cultivating some salt tolerent crops might be helpful.

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CHAPTER 6

SUMMARY AND CONCLUSIONS

In the present study an attempt has been made to work out the hydraulic characteristics and to understand the hydrogeochemistry of the groundwaters of the Gaj and Miliolite Formations (Tertiary and Quaternary ages) in the Chorwad-Madhavpur area, Gujarat, India. Also investigation was carried out to decipher the diagenetic changes and the development of porosity in the limestones belonging to the Miliolite Formation as these affect the occurrence and movement of groundwater in the limestones. Detailed stratigraphy had also to be worked out for this area as it was not known earlier.

The Chorwad-Madhavpur area forms a part of south-west Saurashtra coast, Gujarat, India. The oldest geological formations met with in the area are the Deccan Trap basalt of Eocene to Cretaceous age which are overlain unconformably by the Gaj and Dwarka Formations of Tertiary age constituting the Nageshri Group and by the Porbandar Group of sediments, i.e., the Miliolite and Chaya Formations of Quarternary age. The youngest are the beach sands and alluvium.

Based on field observations of vertical sections at different places, and petrographic studies, a composite lithostratigraphic section has been prepared for the Miliolite Formation. This formation has been divided into three lithofacies, i.e., lithofacies I, II and III. The lithofacies I & II have again been sub-divided into lithofacies IA,IB, and IC, and IIA,IIB and IIC respectively.

Lithofacies IA is in the form of thin clay bands which might have been deposited in lagoons. Lithofacies IB is pebbly bed and IC is fine grained compact and cross-bedded limestone. These might have been formed along river channels influenced by tides. Lithofacies IIA is shell limestone and IIB is cross-bedded shelly limestone and hard and compact limestone. Facies IIA and IIB might have been deposited in the littoral zone dominated by strong wave action and transitional zone between littoral and shelf zone respectively. The rocks of the lithofacies IIC, which is chalky band occurring interbedded in the limestone has been studied for their foraminiferal content, which suggest relatively deeper water biofacies and most probably an outer shelf marine environment. Lithofacies I and II seem to have been deposited during marine transgression that took place from early Late Pleistocene ($<$ 30,000 years B.P.) to Late Pleistocene (20,000 years B.P.). Lithofacies III is pelletic calcarenite and formed in a thin sheet of lagoon left behind the regressing sea. It was later reworked by the wind action, and deposited as loose sediments in the form of ridges.

Petrographic study of limestones belonging to the Miliolite Formation indicates that the rocks include calcarenites, calcirudites, chalk (micrite), and pelletoid calcarenites. It is not essentially an oolitic limestone as described by earlier workers. Sparry calcite occurs both as cement and neomorphic grains. Neomorphism is very common. The shells contain either micrite or sparrite. The outlines of the shells are preserved by a thin envelope of micrite.

The limestones belonging to the Miliolite Formation are characterised by various types of porosity. SEM study indicates the presence of micro and maco porosity which are both of intergranular and intragranular type. Microporosity is intragranular,i.e., it is seen within grains and pellets. Vuggy and channel porosity is also common. These types of porosity have been developed by the dissolution of carbonate grains and skeletal particles. Primary porosity is also preserved and is not obliterated due to diagenesis. Some c. cementation has also taken place along channels and rhombs of calcite crystals can be seen projecting towards the centre. Crystal growth is also shown by the presence of zoning. Dolomite crystals are also present. Dolomitisation has imparted higher porosity to these rocks. The storage and movement of groundwater in the Miliolite Formation is controlled mainly by vuggy and channel porosity which are of intergranular type. The intragranular pores on the other hand, on account of their very small size, are not very effective in this respect.

The lithofacies I and IIA and IIB of the Formation have extensive development of secondary porosities and act as major aquifers in the area.

Seven stages in the diagenetic history of the limestones belonging to the Miliolite Formation can be deciphered. The first stage,e.g. the deposition of marine carbonate sediment consisting of algae, foraminifera, molluscs, and echinoderm fragments, with small quantities of quartz and rock fragments. Some amount of micrite is deposited in the form of aragonite or high Mg-calcite. Second stage is the starting of diagenesis in the relatively stagnant marine environment. The micrite envelopes are formed by the action of boring algae. Some amount of intragranular cementation has also taken place. Next stage is the cementation by fibrous aragonite and Mg-calcite in the active marine phreatic environment. Fourth stage is the formation of dolomite. This has taken place under a mixed fresh and marine water environment. Fifth stage is the diagenesis in the freshwater.phreatic zone resulting in the formation of cement. This was short lived because in most cases intergranular spaces are not completely filled with cement. The next stage is again of diagenesis in the freshwater phreatic zone. Neomorphism of aragonite and high Mg-calkcite grains without undergoing a solution stage has taken place during this period.The last stage is the exposure of the limestones into the fresh water vadose zone. Vuggy porosity was developed due to the solution of limestone. Neomorphism of micrite to pseudospar also took place. Therefore the diagenesis has taken place during a marine regression from marine to phreatic water conditions.

After establishing stratigraphic framework and investigating the development of porosity in carbonate rocks of the area, an attempt was made to study the geohydrological and hydrochemical characteristics of the various formations.

Trend surface technique has been used for analysing the water level data. The trend surface maps indicate that the general groundwater flow is towards south west, and west from the central part of the area. In the western part near the coast the groundwater flow is from the coast towards inland due to a groundwater trough. This might be because of the over development of groundwater for irrigation purposes. The configuration of trend surfaces for pre-monsoon and post-monsoon periods remain more or less the same. Lower permeability of the Gaj Formation is indicated by closeness of water table contours, whereas in the Miliolite Formation more widely spaced contours indicate higher permeability. The groundwater level fluctuation is more than 3 m in Gaj Formation and it is generally less than 2 m in the Miliolite Formation. The difference in groundwater level fluctuation indicates differences in the geohydrological characteristics of the Gaj Formation and the Miliolite Formation. Rainfall is one of the most important factors which influences the groundwater levels.

The hydraulic properties of aquifers can be determined by means of pumping test. Crystalline rocks, carbonate rocks and other consolidated rocks as a medium of groundwater flow possess anisotropy and heterogeneity. Hence the use of standard methods of aquifer test analysis in hard rock aquifers has long been a subject of debate. Some quantitative evaluation and interpretation of flow in fissured rock has been started only recently.

In the present study pumping tests were conducted on dug and dug-cum-bore wells. The pumping test data from 16 wells have been used to determine transmissivity (T) by Papadopulos-Cooper's method, Boulton and Streltsova's method and Theis recovery method and storativity (S) by Papadopulos-Cooper's method. It is observed that the T values determined by Boulton and Streltsova's method and Theis recovery method are quite comparable. The Papadopulos and Cooper's method gives higher values of T. The later part of recovery data is found to be more reliable for determining T values by Theis method. Transmissivity of the Gaj Formation varies from 32 to 259 m^2/day while in the Miliolite Formation it ranges from 51 to 971 m^2/day. Wide variations in T could be due to heterogeneous character of carbonate aquifers. The storage coefficient computed by Papadopulos-Cooper's method is not very reliable. This is because the shapes of the type curves differ only slightly, when β differs by an order of magnitudes. Therefore, the computed value of S will change when the data plot is moved from one type curve to another of different values of β . Numerical methods could not be used for computing aquifer parameters.

The specific capacity of wells determined from recovery data indicate that it is higher in the Miliolite Formation than in the Gaj Formation. The specific capacity varies from 185 to 1882 lpm/m of drawdown in the Miliolite Formation and 11 to 180 lpm/m of drawdown in the Gaj Formation. From the specific capacity, specific capacity index values, i.e., productivity values have also been calculated. Productivity values indicate that the Miliolite Formation are more productive than the Gaj Formation.

The hydrochemical data of groundwaters from 67 wells collected during February, 1979 and 29 wells during October 1979 from both the Miliolite and Gaj Formations have been analysed and plotted in various ways with a view to find out the chemical evolution of water and causes of salinity in the coastal tract. Trend surface maps for various ions indicate an increase in their concentration towards the coast, i.e., generally in a south west direction. The hydrochemical sections drawn from land towards the coast in the direction of groundwaters movement indicate an abrupt rise in the concentration of various ions in the narrow belt of about 3-5 km width parallel to the coast.

The plotting of hydrochemical data in Hill-Piper diagram shows that the waters from the Gaj Formation and the Miliolite Formation are of distinct hydrochemical types. The groundwater from the Gaj Formation is mainly of secondary alkaline type while those from the Miliolite Formation are of primary saline and secondary saline character. Discriminant analysis also show that the groundwaters from the Miliolite and the Gaj Formations can be discriminated on the basis of Cl^-, SO_4^{2-} and electrical conductivity, which are higher in groundwaters from the Miliolite Formation.

The waters from the Miliolite Formation belongs to calcium-chloride-sulphate, and calcium-sodium-chloride-sulphate-bicarbonate facies, whereas most of the waters from the Gaj Formation belong to calcium-sodium-bicarbonate-chloride-sulphate facies and also calcium-sodium-chloride-sulphate-bicarbonate facies. The change from one facies to another is not gradual.

Observations by G.W.R.D.C. indicate that the wells in the coastal tract which now have saline water were earlier giving fresh water till about 10 years back. It shows that groundwater salinity in this area is comparatively a very recent phenomenon. Further, the salinity of groundwater in wells located near to the coast increases with pumping while no such effect is observed in wells in the same formation (Miliolite) further inland.

The above observations along with the ratio of total alkalinity/total hardness being < 1 and the high $Cl^-/(CO_3^{2-}+HCO_3^-)$ ratio indicate that the salinity in the coastal tract is on account of intrusion of modern sea-water due to over pumping. The modern sea-water may also enter the aquifer via creeks and rivulets along which sea water is observed to flow inland during high tides. The positive base exchange index values, Cl^- ratios, comparison of the hypothetical groundwater with sea-water and plotting of the ratio $r\,Mg / r\,Ca$ against Cl^- concentration are suggestive of base exchange between the Na^+ present in the mixture of groundwater and sea-water with the adsorbed Ca^{2+} ions present in the clay minerals (illite and montmorillonite) of the Miliolite Formation.

As has been discussed in Chapter 2, the Miliolite Formation was deposited under mainly marine conditions. Later diagenetic processes under phreatic conditions have been operative as is evidenced from petrographic studies. Under such an evolutionary history one could think that the saline waters in these formations could also be of connate character. However, the present study does not indicate such an origin for the following reasons as indicated earlier also:

(1) Wells which were giving fresh water till about 10 years back have now turned to be saline.

(2) Salinity increases with pumping near the coast.

(3) A uniform belt of high salinity along the coast upto a distance of 3 to 5 kms inland occurs in the Miliolite Formation. In case the salinity was of connate type, one would have expected such waters in the Miliolite Formation further inland also.

(4) Abrupt increase in salinity and concentration of various ions (except HCO_3^-) in the coastal belt as evidenced by hydrochemical sections.

(5) Diagenetic changes in the Miliolite Formation as brought out by petrographic and mineralogic studies show that phreatic/vadose water condition have been in existence in the recent times indicating flushing out of marine connate water from these stratigraphic horizons.

(6) The Miliolite Formation has limited thickness (40 m) has widespread solution cavities and has only few thin impervious horizons of limited aereal extent,therefore the likelihood of connate water to be retained are remote.

Therefore it could be concluded that the saline waters in the Miliolite Formation occurring along the coastal tract of Chorwad-Madhavpur area appear to be a result of modern sea-water intrusion modified by mixing with freshwater and by processes of base exchange and SO_4^{2-} reduction. This salinity has developed only during the last 10 years or so due to over pumping which is also evidenced by reversal of groundwater table gradient. Further studies on dating of these waters and minor ion chemistry may help in a better understanding of the origin of these waters.

The groundwaters from the Miliolite Formation,especially those from near to the coast are not suitable for drinking and other domestic use because of the high concentration of Na^+, Cl^-, Ca^{2+}, and Mg^{2+}, high hardness, and high T.D.S. content. The waters from the Gaj Formations are in general of good quality, except at a few places where they contain higher concentration of Ca^{2+} and Cl^-. Most of the waters from the Miliolite Formation are unsuitable for irrigation purposes. The waters which fall in the zone good to permissible, occur 4 to 6 km away from the coast. In general, the waters from the Gaj Formation are of good quality except a few and can be used for irrigation purposes.

From the foregoing, the following conclusions can be made:

(1) The different rock formations met within the area are the Deccan Trap basalts, Gaj and Dwarka Formations, and the Miliolite Formation and the Chaya Formation. The youngest are the beach sands, sand dunes and alluvium.

(2) The limestones belonging to the Miliolite Formation can be petrographically classified into calcarenites, calcirudites, chalk (micrite) and pelletoid calcarenites.

(3) The Miliolite Formation can be divided from bottom to top in to three lithofacies, i.e., lithofacies I, II and III. Lithofacies I has been deposited in lagoons and along river channels influenced by tides. Lithofacies II was deposited in the littoral zone affected by strong wave action to outer continental shelf zone. Lithofacies I and II seem to have been deposited during a marine transgression that took place from early Late Pleistocene ($<$30,000 years B.P.) to Late Pleistocene (20,000 years B.P.). Lithofacies III was formed due to reworking by wind action of deposits formed in a thin sheet of lagoon left behind the regressing sea.

(4) The limestones belonging to the Miliolite Formation are characterised by the presence of karstic features. Solution cavities are present below and also above the present mean sea level. During Late Pleistocene after the deposition of Miliolite Formation, the sea level stood at lower levels than at present. During this period solution of limestones might have taken place below the present sea-level.

(5) The limestones of the Miliolite Formation contain micro and macro porosity which are both of intergranular and intragranular types but macroporosity is generally intergranular. Primary porosity has not been obliterated due to diagenesis.

(6) The limestone of the Miliolite Formation have undergone diagenesis under active marine to fresh water vadose diagenetic environments during the last major marine regression of sea witnessed by the present area.

(7) Lithofacies I, IIA & IIB of the Miliolite Formation are the major aquifers with extensive development of secondary porosity.

(8) Pumping test analysis shows that the Miliolite Formation has higher transmissivity than the Gaj Formation. The T values varies from 51 to 971 m^2/day in the Miliolite Formation and from 32 to 971 m^2/day in the Gaj Formation.

(9) There are evidences of mixing of modern sea water and fresh ground water on account of over pumping at isolated places and also due to the ingress of sea water along the creeks and rivers at the time of high tides, in a narrow coastal belt of 3-5 km width in the Miliolite Formation.

(10) There are evidences of Mixing of modern sea-water and groundwater, and modification of the mixed water by base exchange and sulphate reduction in Miliolite Formation near to the coast.

(11) The evolution of porosity and the hydrogeological history of the Miliolite Formation can be as follows:

(a) Deposition of the limestones beloging to the Miliolite Formation mainly under marine (lagoonal to outershelf) conditions and hence saturation of intergranular spaces with saline water.

(b) Marine regression leading to low stands of sea level resulted in flushing out of connate water by freshwater. Development of solution cavities upto a depth of 18.8 m from the present day sea-level . Diagenesis in the fresh water phreatic/vadose zone producing intergranular and intragranular porosity and other mineralogical and textural changes.

(c) Rise of mean sea level took place during recent times. Ingress of sea water along rivers and creeks at high tides and over pumping of aquifer (Miliolite Formation) during the last ten years has caused sea-water intrusion in the coastal tract.

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Pumping Test Data

Appendix-1

Name of owner: Keshav Mankhetra

Date: 13.2.79 **Cross-sectional area of the well:**

3.3 x 2.00m r = 1. 449 m

Time in hours	Time since pumping started (in minutes)	P.W.L. in m	Drawdown in m
1	2	3	4
8.56	0	11.25	0
8.57	1	11.31	0.06
8.58	2	11.33	0.08
8.59	3	11.37	0.12
9.00	4	11.41	0.16
9.01	5	11.46	0.21
9.02	6	11.51	0.26
9.03	7	11.54	0.29
9.04	8	11.59	0.34
9.05	9	11.62	0.37
9.06	10	11.66	0.41
9.08	12	11.72	0.47
9.10	14	11.78	0.50
9.12	16	11.83	0.58
9.14	18	11.90	0.65
9.16	20	12.97	0.72
9.18	22	12.01	0.75
9.20	24	12.09	0.85
9.23	27	12.18	0.93
9.26	30	12.29	1.04
9.29	33	12.39	1.14

1	2	3	4
9.32	36	12.49	1.24
9.35	39	12.54	1.29
9.40	44	12.69	1.44
9.45	49	12.81	1.56
9.50	54	12.94	1.69
9.55	59	13.08	1.83
10.00	64	13.21	1.96
10.05	69	13.33	2.08
10.10	74	13.43	2.18
10.15	79	13.53	2.28
10.20	84	13.64	2.39
10.25	89	13.72	2.47
10.30	94	13.80	2.55
10.40	104	14.00	2.75
10.50	111	14.21	2.96
11.00	124	14.42	2.17
11.15	139	14.72	3.47
11.30	154	14.91	3.66
11.45	169	15.14	3.89
12.00	184	15.34	4.09
12.15	199	15.52	4.27
12.30	214	15.72	4.47
12.45	229	15.93	4.68
1.00	244	16.13	4.88
1.30	274	16.50	5.25
1.31	275	16.51	5.26

Recuperation Test

Time in hours	Time since pumping stopped (in minutes)	Water level in m.
1.31	0	16.51
1.32	1	16.49
1.36	5	16.46
1.40	9	16.43
1.46	15	16.38
1.48	17	16.36
1.50	19	16.33
1.53	22	16.31
1.56	25	16.29
1.59	28	16.26
2.02	31	16.23
2.05	34	16.20
2.10	39	16.16
2.15	44	16.12
2.20	49	16.08
2.25	54	16.04
2.30	59	16.00
2.40	69	15.91
2.50	79	15.82
3.00	89	15.76
3.15	104	15.65
3.30	119	15.54
3.45	134	15.43
4.00	149	15.33
4.15	164	15.22
4.30	179	15.12
5.00	209	14.94