chapter iii

GEOLOGICAL SETTING

In order to set the scene for the description of the geology and geomorphology of the study area, a regional description of both these aspects has been made.

Regional Geology of Saurashtra

Two third of Saurashtra is occupied by the Deccan Trap, forming a generalised plateau. These Trappean rocks overlie the upper Mesozoic rocks which are exposed in the northern part of the Saurashtra. The Tertiary and Quaternary sediment fringe the Traps along the coastline.

The generalised geological succession in Saurashtra is given in Table 1 (after Shrivastava, 1963 in Ganapathi, 1981). A brief description of the geology is given below (after Ganapathi,1981).

Mesozoic Rocks

The Dhrangadhra Formation, exposed around Dhrangadhra and Than towns and occupying an area of 4,200 sq.km is the oldest rock type in Saurashtra. Oldham (1893) named them as 'Kathiawar beds", while Fedden (1884) denoted them as "Umia beds". Shrivastava and Rizvi (1960) denoted these beds as a "formation". This formation can be divided into two units : The lower consisting of soft yellow sandstones, with ferruginous concretions and intercalations of fossiliferous carbonaceous shales and thin coal seams; and the upper comprising of purplish or dark

TABLE -1

Generalized Stratigraphic Sequence Of The Saurashtra Peninsula (after Shrivastava, 1963)

Formation	Lithology	Environment	Age
Recent Deposit	Alluvium, coastal dunes and beach sand, Rann clays, mud flats, and soils etc.		Recent and Sub - Recent
	---- Unconformity ----		
Agate Conglomerates	Agate conglomerates and associated ferruginous sandstones.	Fluviatile	Pleistocene to Sub - Recent
Miliolite Formation	Calcarenites, Calcrudite, with intercalations of clays.	Littoral	
	---- Unconformity ----		
Dwarka Formation	Dark brown silty clays, yellowish calcareous clays and limestone with gypseous clays.	Littoral to epineritic	Upper most Miocene to Pliocene.
Piram Beds	Fossiliferous conglomerates, grits and sandy clays.		
	---- Unconformity ----		
Gaj Formation	Varigated shales, sandstones, marls, conglomerates and impure limestones with intercalation of gypseous clays.	Epineritic	Lower Miocene
	---- Unconformity ----		
Lateritic Rocks	Red, brown and yellowish brown laterites.		Paleocene
Deccan Trap Formation	Plutonic masses and dykes intrusive in the Trap flows.		Cretaceous to Paleocene
	---- Unconformity ----		
Wadhwan Formation	Red and brown colour sandstones with intercalation of shales.	Shallow marine	Middle Cretaceous (Albian to Cenomanian)
	---- Unconformity ----		
Dhrangadhra Formation	White and coloured felspathic sandstones with gritty layers, lenses of grey and yellowish shales and carbonaceous shales with coal layers and plant remains.	Deltaic	Juro-Cretaceous (Tithonian to Albian)
	---- Base not exposed ----		

coloured gritty sandstones with conglomeratic layers. The texture, structure and plant fossil point towards a deltaic depositional environment in areas of subsidence (Shrivastava, 1963).

The Dhrangadhra Formation is overlain by a thick sequence of red and brown coloured sandstones with intercalations of shales. Fedden (1884) denoted these rocks as Wadhwan sandstone after the town of Wadhwan. Shrivastava and Rizvi (1960) classified these rocks as Wadhwan Formation, and divided them into three members. The lithology and marine fossils in this formation point to a shallow marine environment of deposition.

Fedden (1884) regarded this formation as equivalent to the cherty members of the Bagh beds. According to Fox (1931) the Wadhwan sandstones were of Lower Cretaceous age similar to the Nimar sandstones of Narmada valley. Krishnan (1968) supported Fedden's view and further correlated these Wadhwan sandstones with the Umia plant beds of Kutch, the Himatnagar sandstones of Gujarat mainland and the Barmer sandstones of Rajasthan. Shrivastava (1963) assigned them Albian to Cenomanian age.

THE DECCAN TRAP

The Deccan Trap constitutes the most dominant formation of Saurashtra peninsula. Mainly consisting of lava flows, the trappean rocks show the usual varieties, viz., dark grey compact, porphyritic, vesicular and amygadoidal, etc. Rao et al.

(1962) and Shrivastava (1963) estimated an exposed thickness of about 600 m for this formation in Saurashtra. Besides the usual varieties of dolerites and basalts, many interesting differentiates have been encountered in the hills of Barda, Girnar, Osham and Gir Range.

On the whole, Infra-trappean beds are scarce in Saurashtra. However, according to Fedden (1884) a few hard bands, probably of consolidated volcanic material have been observed near Dhandhalpur. Volcanic ash beds occur in the Chotila hills.

Numerous dykes cut across the basalts and ideally follow the fracture pattern in the Traps. These dykes often provide remarkable topographic expressions to the major lineaments of the area. They vary considerably in size, ranging from a few to as much as 60 m in thickness. The dyke rocks are mostly coarse basaltic or doleritic in composition and usually devoid of vesicles. Acidic dykes are also not uncommon.

THE LATERITIC ROCKS

Resting over the Traps along its fringes, lateritic rocks form an important rock unit overlain in turn by the younger Tertiary and Quaternary deposits. Essentially comprising a residual alteration product of the Deccan Trap, the laterites are quite important from the point of view of their economic value. These occur as a narrow discontinuous band all over the periphery of peninsula, and forms fairly extensive exposures near Bhavnagar, Longdi, Jafrabad, Veraval and Bhatiya. Typically unstratified and mottled, the laterites show a wide range of colours like red, brown and yellowish brown, and bauxitic laterites provide a good source of aluminium ore.

TERTIARY ROCKS

Rocks of Lower Miocene age, resting over the Deccan Trap and the laterites along the peninsular fringe have been designated as Gaj Formation.

Originally, named as Gaj beds by Fedden (1884), these marine rocks show good exposures in Bhavnagar - Ghogha area and in Okha Mandal. In other places, as it is overlapped by younger formations, it does not outcrop on the surface.

Gaj rocks comprise variegated shale, sandstone, marls, conglomarates and limestones with intercalations of gypseous clays. Pascoe (1973) has reported the following invertebrates from these rocks : Bryozoa, Echiniodea, Pelecypoda, Gasteropoda, Cephalopoda, Crab and Foraminifera.

The rocks of Gaj Formation are considered to have been deposited in a shallow marine environment, perhaps under epineritic conditions (Fedden, 1884; Shrivastava, 1963; Pascoe, 1973; Wadia, 1975).

Beds resting over Gaj rocks in Okha Mandal were designated as Dwarka beds by Fedden (1884). Consisting of dark brown arenaceous clays and limestones with intercalation of gypseous clays, these were called Dwarka Formation by Shrivastava and Rizvi (1960). Rocks of Dwarka Formation are best exposed in the Okha Mandal area, where they rest disconformably over the Gaj rocks. Along the south coast near Jafrabad an isolated patch of Dwarka rocks has been reported by Verma and Mathur (1973). The Dwarkas are less fossiliferous as compared to the Gaj, except for some foraminifera and broken molluscan shell fragments. According to Shrivastava (1963) they were deposited under littoral to epineritic conditions and could be considered of Mio-Pliocene age.

In the Bhavnagar - Ghogha area the rocks equivalent to the Dwarka Formation are represented by Piram Beds. Resting disconformably over the Gaj rocks these are exposed in the intertidal area only and are well-known for their mammalian fossil content. Piram Beds comprise hard and well cemented fossiliferous conglomerates with intercalations of sandstones and clays. A rich mammalian fossil fauna are the characteristics of the conglomerate layers (Fedden, 1884 ; Rao & Jain, 1959).

While Fedden (1884) thought that these Piram Island rocks were deposited under shallow marine or estuarine conditions. Shrivastava (1963) has suggested fluviolittoral environmental conditions for these beds, assigning them a Mio-Pliocene age, correlatable with the lower part of Dwarka rocks of Okha Mandal area.

QUATERNARY ROCKS

The Quaternary rocks, are unique in the sense that they comprise most striking accumulations of carbonate sands over a dominant portion of the Saurashtra coast. Grouped into the Miliolite Formation, these include calcarenite and calcrudite with intercalations of clays. These carbonate deposits form 12 to 20 km wide belt all along the coast from Porbandar to Gopnath, overlapping the Gaj and Dwarka rocks and resting directly over the Trap at some places. Rocks of this formation also occur as outliers in Chotila, Junagadh, Chamardi hills as inland miliolites. These pelletoid and oolitic calcarenites characterised by a warm and shallow marine microfauna dominantly foraminifera, have remained highly controversial in respect to their mode of origin. It often aeolian accumulations - coastal dunes having originated by reworking of the coastal sands by stromy winds. According to Merh (1980, p.21) these Quaternary deposits are "partly marine partly aeolian, consisting of more than one generation of carbonate sands deposited under shallow marine conditions and subsequently reworked by winds to form coastal dunes, all this having taken place during the successive periods to transgression and regression of the Quaternary sea".

Stratigraphically equivalent to the Miliolite, and resting unconformably over the dissected hills of lateritic rocks in the coastal areas south of Ghogha, occurs a formation consisting of agate-bearing ferruginous sandstones. These rocks were mapped as "Rampur Formation" by Datta (1959) while Rao and Jain (1959) and Shrivastava (1968 b) described them as agate conglomerates and associated sandstones. Shrivastava (1968 b) thought that they were deposited under fluviatile conditions and assigned them a Pleistocene or Sub-Recent age.

Recent deposits include a variety of unconsolidated sediments of estuarine, marine, freshwater and subaerial origins. In the eastern Saurashtra, a belt of alluvium stretches eastward towards the plains of Gujarat and extends northward upto the Gulf of Kutch. The other alluvial covers are along the south-eastern coastal region and the western coast near the Bhadar and Ojat river mouths. The alluvial sediments comprise dark grey and black soil on the top, with underlying kankary or lateritic soil. The Okha rann clays consist of yellowish and grey saline clay and silt of marine origin. Saline marshes are common at the heads of the various creeks all along the coast. The coastal dunes and beaches are made up of carbonate sands from Okha to Gopnath point, whereas those between Shetrunji estuary and Ghogha consist of arenaceous sands. The soil cover, a product of "in situ" sub-aerial weathering varies from black cotton soil to yellowish brown sandy soil. The former is derived from the Trap while the latter has originated from the Tertiary rocks.

TECTONIC FRAMEWORK

The peninsula of Saurashtra shows a unique structural set up. Essentially bounded by a number of major faults on all sides (Poddar, 1964; Fig. 6); its rocks reveal an interesting fracture pattern related to the various faults. The Saurashtra peninsula as a whole might not be showing spectacular uplifts and subsidences as a single block, but there are ample evidences to suggest that its various parts did undergo differential movements essentially during the Quaternary period. The geological and geomorphological evolution of the different segments of the Saurashtra coastline is obviously controlled by these tectonic features.

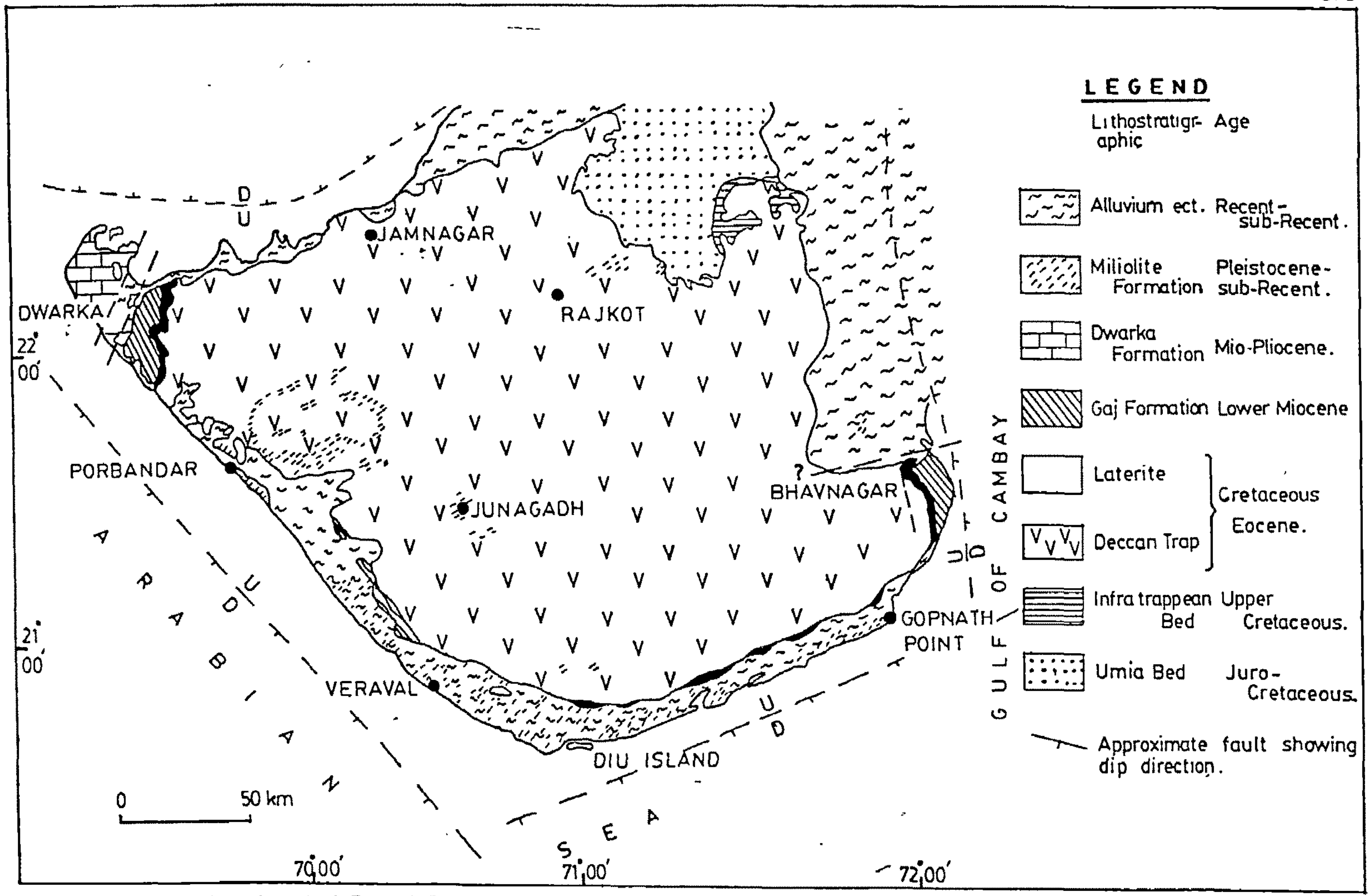
Following four major faults delimit the Saurashtra landmass :

1. Ghogha -Sanand Fault (Western Cambay Basin Border Fault),
2. Extension of Narmada Fault,
3. Gulf of Kutch Fault, and
4. West Coast Fault.

STRUCTURAL HISTORY

Shrivastava (1963) has ideally summarised the structural history of the Saurashtra peninsula in the following words: "A careful consideration of the geological and geophysical evidences in Gujarat appears to show that the structures of the region are mainly controlled by faults. The northern part of the plateau is bound by the little Rann and the Gulf of

FIG. 6



GEOLOGICAL MAP OF SAURASHTRA AND ITS TECTONIC FRAMEWORK.
(AFTER PODDAR'64)

Kutch, and it is likely that a concealed fault is present running in a general ENE - WSW direction, and probably the cause of a somewhat linear northern coastline of Saurashtra, and the rather abrupt termination of the Tertiary rocks of the Okha Mandal region and the Deccan Trap against this straight coastline. This fault may belong to the set of general east - west trending fault in Kutch. Rao et al. (1962) regarded the high dips in the Dhrangadhra Formation, at some places in the northern part of its exposure, and probably caused by a concealed fault beneath the alluvium. The gravity and magnetic work in the alluvial areas northeast of Dhrangadhra shows indications of an east - west faults in line with the north coast of Saurashtra. The above authors regard the area of the little Rann and the Gulf of Kutch as a zone of weakness; probably a graben or half graben".

"Similar faulting can also be said to have taken place along the western margin of Saurashtra which again shows a strikingly straight coastline between Okha and Kodinar. The fault is probably the extension of the fault which is believed to have caused the almost straight western coast-line of India. The southern coast-line also shows similar characters with some steep scarp faces. If it is due to a fault, the fault will almost certainly be the extension of the zone of weakness along which the Narmada faulting in the ENE - WSW direction has taken place. The northern coastline fault would be almost parallel to this fault. The eastern margin of the Saurashtra plateau is bound by the faults of the Cambay graben which are parallel to the west coast fault. Thus, it would appear that the almost rectangular Saurashtra peninsula is bound on all sides by faults on the continental slopes. It is noted that the Pleistocene Porbandar Formation overlies the older formations along the coast and in the central highlands of Saurashtra at high elevations e.g. on top of the Chotila hill (1,173 feet altitude) providing a clear proof of the elevation of the plateau in recent times.

It may be assumed that the movement was along fault planes, since folding movements have not affected the Porbandar beds. All these faults were active during Tertiary times, and till Late Pleistocene, but it is likely that they existed even earlier. The Saurashtra peninsula was subjected to submergence and emergence during different movements along the fault planes. As a result of the late upheaval of the Saurashtra block, the earth is evidently under considerable strain (Crookshank, 1938), indicating that certain instability still persist. Crustal adjustments by movements along similar faults also occurred in the Kutch region to the north of Kutch in 1819. The dislocation during this earthquake had a general E - W alignment parallel to the E - W fault trends of Kutch - Saurashtra region".

"Certain dykes in the southeastern Saurashtra are undoubtedly associated with faults. In all probability, there are many more faults in the peninsula which have not so far been brought to light. Dislocations along many of the faults occurred from time to time till Sub-Recent age".

"Field observations clearly indicate that the rocks in Saurashtra have not been subjected to intense folding since the Upper Jurassic times. The folding in the Mesozoic rocks here is of a very gentle nature as compared to the folding in the similar rocks just to the northwest, in Kutch. The dips recorded in the Trap are suggestive of gentle and regional tilting caused by movements of large blocks along fault lines, and by the intrusive plugs. Auden (1947) considers that the pattern of occurrence of dykes in Saurashtra is related to the folding in the Trap".

"The Post-Trappean tectonic history of Saurashtra in general, is characterised by the epirogenic movements along various fault planes from time to time. This feature has controlled the marine transgressions and regressions, and the Tertiary sedimentation along the coastal region. The greatest marine transgression in the known geological history of the peninsula occurred in the Pleistocene during which the Porbandar Limestones were formed. The upliftment commenced in the Late and Sub-Recent, and is probably still under progress. The exposed Tertiary sediments all along the coastal regions are almost unaffected by folding except those in the Ghogha area, where the gentle folding might be related to the regional movements along two faults".

NEOTECTONISM

Another important aspect of the Saurashtra tectonics has been brought out by Merh (1980), who has invoked a northward tilting of the peninsula during Quaternary period. While the northern coast of Saurashtra has been gradually submerging, the southern counterpart points to emergence. Thorat (1980) has carried out a critical analysis of the geomorphic and drainage attributes of the northern coast of Saurashtra and has come across numerous evidences to support a submerging coastline. In contrast, the geomorphological and geological attributes of the southwest and south coast, very clearly point to an emergent coast.

Neotectonic uplift is very well illustrated by the miliolite occurrences of the various rivers of southern Saurashtra. The rivers like Hiran, Shingavada and Machhundri perhaps follow fault lines. According to Merh (1980), these cut across miliolite, show variable thickness of these rocks within a short eastwest distance. This aspect has been explained by Dr. B. Roy (pers. comm.). He has worked on the southern Saurashtra coast and has reported that the miliolite rocks of same stratigraphic age occupy different topographic levels, and that some of the striking evidences of tectonism are observed in the river valley in the form of differential river gradients, variation in thickness of miliolites, convergence of terraces and antecedence of streams. Rivers Hiran and Sonarki offer good evidence of differential uplifts. The former has a steep gradient with a number of knick points, and is seen entirely cutting through a 60 m thickness of miliolite and finally flowing over the underlying Traps. The Sonarki river in direct contrast, which lies only 13 km west of Hiran, has a smooth profile, with a miliolite thickness of about 5 m only, and occurring at a maximum level of 25 m. Dr. Roy has stated, "I envisage certain down faulted pre-miliolite river valleys along which sea ingressed during transgressions. These linear weak zones, depressed to different depths, thus gave rise to variable thickness of miliolites, and these were subsequently uplifted along some prominent faults in varying amounts. Those differential movements along faulted blocks, probably correlatable with the major offshore lineaments have given rise to the confusing miliolite topography".

The structural set up and tectonism of the Saurashtra peninsula has been explained by Dr. S.P. Sychanthavong, invoking the concept of plate tectonics. His ideas have been summarised by Merh (1980) in the following lines, "He has divided the Saurashtra coastal area into following four main tectonic zones of instability with varying intensities of movements either vertical or lateral:

1. Western Cambay Basin Border Fault,
2. Narmada Fault,
3. Gulf of Kutch Fault, and
4. West-coast off-shore Fault.

The airphoto and satellite imagery reveal a fracture pattern, criss-crossing the entire Saurashtra, comprising three pairs of conjugate sets of fractures, parallel to the tectonic zones (1) and (2), (2) and (4) and (1) and (3). These tectonic zones and the related fracturing, according to Dr. Sychanthavong, are the manifestation of the stress distribution derived from the main stress field related to the northeastward movement of the Indian plate. This northeast direction represents the movement of the stress field which generates and distributes various kinds of forces into the above four tectonic zones.

Analysing his lineament data for the southern Saurashtra coast Dr. Sychanthavong also, has advocated the role of differential tectonism of subtectonic zones bound by a few major conjugate fracture sets, each sub-zone uplifting or sinking differently. Such a situation is adequately reflected in the heights and thickness of miliolites in the various river sections on the south Saurashtra Coast.

REGIONAL GEOMORPHOLOGY OF SAURASHTRA

General

The present surface configuration of Saurashtra, the variety of landforms, the drainage characteristics and the relief pattern - all these geomorphic facts, clearly reveal a complex interplay of tectonism, lithology and Cenozoic processes of erosion and deposition. A major portion of the peninsula, being made up of the Deccan lava flows, typically comprises a much dissected tableland, sloping seaward on three sides in the north, west and south. Its northeastern flank dips below the alluvial fringe of the mainland Gujarat. In a broad sense, taking into consideration the factors of altitude, slope and ruggedness of relief, the Saurashtra peninsula can be divided into three main geomorphological units as under (after Ganapathi, 1981):

1. the trappean highlands,
2. the coastal plains, and
3. the shoreline.

The above three units, show considerable diversity within each of them, depending on the rock types, their mode of occurrence and fracture pattern. The description has been made from Ganapathi, 1981.

THE TRAPPEAN HIGHLANDS

The central elevated portion of the peninsula, fringed on all sides by Tertiary and Quaternary deposits, marks the highlands considerably dissected by various rivers that flow out in all directions, the highlands provide a zig-zag outline and a rugged topography. The highlands roughly form three parallel elevated areas striking ENE - WSW, all connected by a NNE - SSW ridge (Fig. 7). The three elevated areas, themselves show much diversity and could broadly be divided into three types:

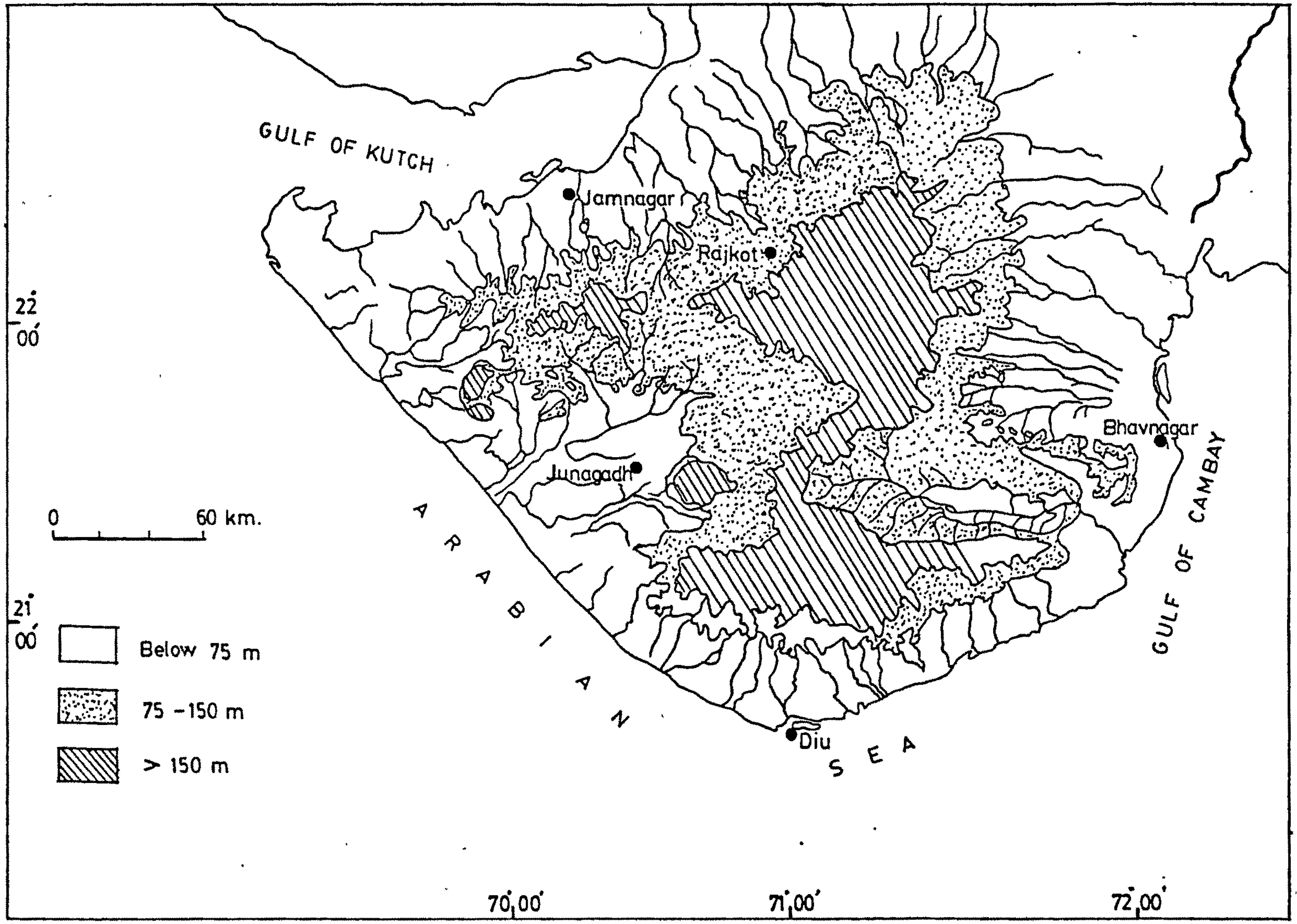
(1) Dissected tableland made up of subhorizontal or very gently dippling lava flows, showing uneven or rolling topography due to weathering along various joint planes. In some cases, the relicts of these tablelands stand out as isolated conical hills (e.g. Chotila hill 340 m). The altitudes of the various tablelands vary from 326 m to 643 m.

(2) Linear dyke ridges in various directioa, protruding above the basaltic surface. These generally show heights upto 10 m above the general level of the ground, and are made up of intrusive rocks like dolerites.

THE COASTAL PLAINS

The trappean highlands are fringed by a narrow 5 to 50 km wide coastal plain. Abutting against the rocky mainland, these plains show a maximum altitude of 50 m. On the whole, these

FIG. 7



PHYSIOGRAPHIC MAP OF SAURASHTRA.

plains are not so well developed, and comprise only a superficial soil and alluvial cover over the Traps, except in those areas where the Tertiary formations have been deposited. The attributes of these coastal plains differ in different coastal segments. Along the northern coast, they are made up of a very thin venner of residual soil over the Trap, never exceeding a few meters in thickness. The coastal segment between Dwarka and Kodinar in the west, is rather broad and somewhat better developed. Here, the plains consists of sporadic exposures of Gaj and Dwarka Formation as well as of miliolite accumulations in the form of island ridges and sheet rocks. The alluvial covers are restricted to the mouth of Bhadar and Ojat rivers.

The southern coast, again shows poor development of these plains, except in the area between port Victor and Talaja. But for a small proportion of Tertiaries, the rest of the southern coastal plains is made up of alluvium brought by the various rivers.

THE SHORELINE

The shoreline of Saurashtra shows considerable diversity and its various segments provide good examples of different types of shoreline. From the point of view of the geomorphology, the shoreline is divisible into following segments (after Ganapathi, 1981).

1. Shoreline between Jodiya and Okha (Northern shoreline)
2. Shoreline between Okha and Kodinar (Western shoreline)
3. Shoreline between Kodinar and Bhavnagar (Southern shoreline)
4. Shoreline north of Bhavnagar (Eastern shoreline).

Northern Shoreline

The shoreline overlooking the Gulf of Kutch, typically indicates submergence. The entire coastal segment extending from Jodiya in the east to Okha in the west, shows a highly indented shoreline, marked by deep inlets, numerous off-shore islands and and several estuarine river mouths. Thorat (1980) has recorded a number of evidences to support submergence, and according to him, apart from the total absence of sandy beaches along the present coastline and profuse growth of coral reefs, other diagnostic geomorphic features indicating submergence include (1) drowned beach ridges, (2) formation of extensive mudflats on landward side, (3) submergence stream channels, (4) truncation of stream basin area, (5) shortening of higher order stream channels, and (6) decreasing thickness of recent sedimentation on landward side.

Western Shoreline

The remarkably straight shoreline between Okha and Kodinar, has dominantly emergent aspects. It is a shore adjoining a low plain tract and the offshore profile is also gentle. The continental shelf is rather shallow and broad, extending for about 10 to 20 km. It is interesting to observe that this shoreline is a site of extending and continued carbonate sand (miliolite) formation since early Pleistocene. The shoreline is dotted with bars and spits that have grown at the mouth of the various streams. At several places, especially between Porbandar and Chorwad, series of 2 to 3 parallel beach ridges or dunes 10 to 20 m high extend for several kilometers at a stretch. There are evidences of the presence of a few submerged coastal ridges also. It is so striking to observe that along-with the remarkable straightness of the beach ridges, marshy patches are conspicuously developed near the estuarine mouths of the various rivers. These low level plains marking well defined intertidal zones of the estuaries, could be taken to indicate submergence, while the other evidences point to emergence. Such a shoreline would develop where the marine processes are related to a fluctuating sea-level.

Southeastern Shoreline

The coastal segment between Kodinar and Bhavnagar provides a typical example of a compound shoreline combining features of both emergence and submergence. Marked by well defined cliffs at many places, the shoreline is fairly indented and replete with rocky islands. The cliffs and islands comprise partly submerged dunes and point to a transgression that followed a regression, which is evident from the growth of recent coastal dunes, beaches and offshore sandbars.

Eastern Shoreline

The shoreline from Bhavnagar northward overlooking the Gulf of Cambay, marks the site of extensive deposition of sand bars, estuarine mudflats and offshore shoals, etc. Its morphology points to a prograding shoreline indicating a gradual retreat of the sea. The depth of the gulf sea is very shallow, with maximum depth of 30 m, such that during low tides vast areas are exposed above the waterline.

DRAINAGE

The drainage of Saurashtra provides an interesting example of a combination of lithologic and tectonic control in its evolution, most of the previous workers (Shrivastava, 1968b, Dixit, 1970) have taken the drainage pattern to be radial with streams flowing out to the sea in almost all directions from the central highlands. From the persual of the drainage map of Saurashtra (Fig. 8), it becomes evident that the trappean highlands form a 'Z' shaped watershed, which could be divisible into two well defined units - the northern and the southern, each typifying quite distinct drainage patterns (after Ganapathi, 1981).

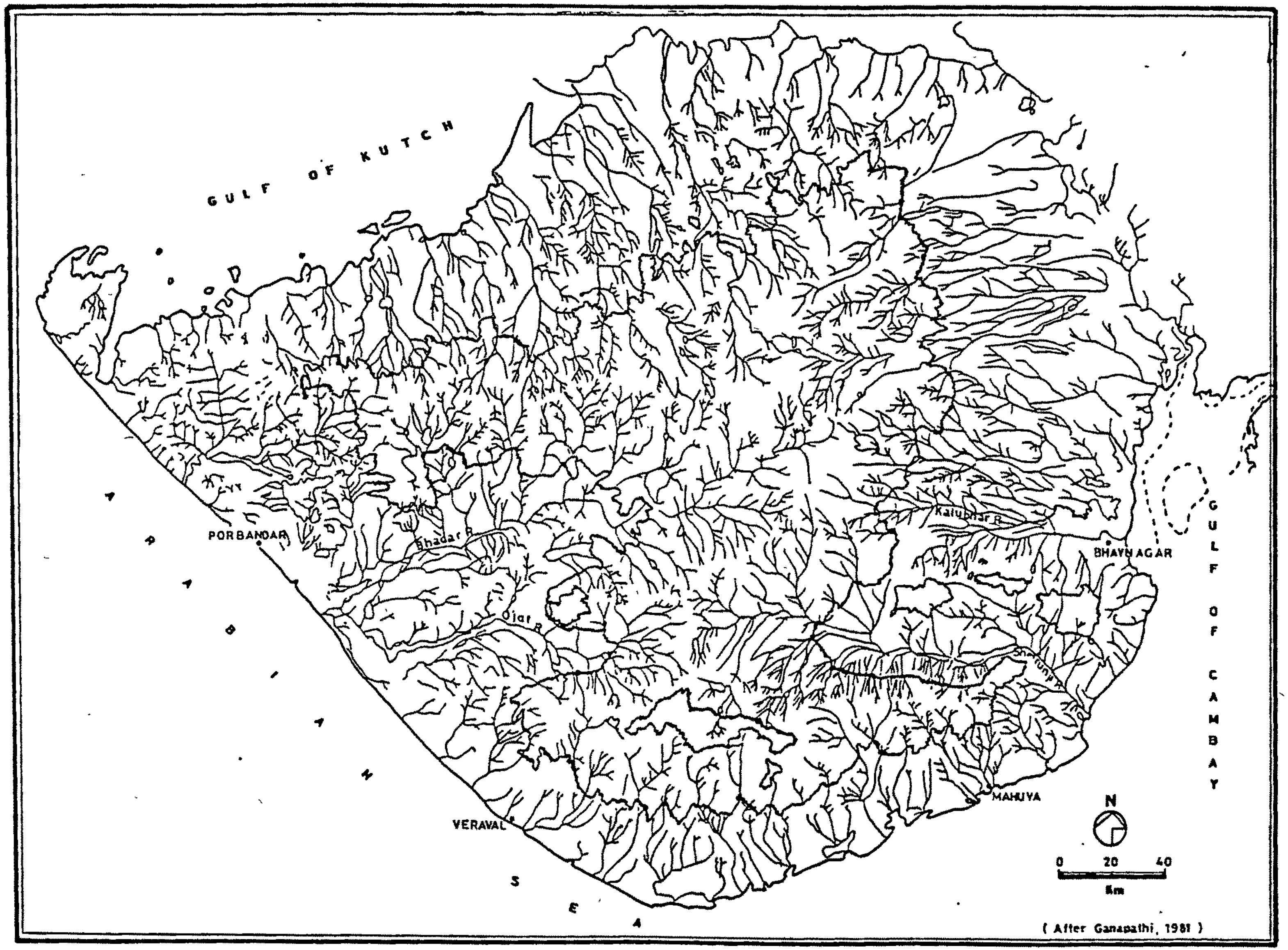


FIG. 8. DRAINAGE MAP OF SAURASHTRA

The Northern Unit

The Northern unit comprises an approximately ENE - WSW trending elevated ground, from which numerous small streams flow down in all directions. Various streams are more or less seasonal, except a few like Bhadar in the SW and Machhu in the north, and they are essentially slope controlled. Of the numerous streams that flow northward, Aji and Machhu are important. Aji river originates south of Rajkot and drains through basalt. Machhu emerges from southeast of Rajkot and flows through basalts in the upper course and Dhrangadhra sandstones in the middle and lower courses. River Machhu and its eastern streams debouch their waters in the little Rann, whereas Aji and its western streams meet the Gulf of Kutch. The rocks here have uniform resistance to erosion and the headward growth of insequent streams is governed primarily by the regional slope. The seaward slope has determined the north -ward flow of the various consequent streams. The insequent tributaries, that commonly make an acute angle with upstream parts of the consequent valleys have given rise to a branching drainage pattern of the dendritic type. Owing to the submergence of this coast during the late Quaternary period (Merh, 1980; Thorat, 1980) the streams have shortened their lower courses and often enough, many of the tributary branches are now converted into small independent streams on account of the drowning of the trunk streams. The streams that meet the Gulf of Kutch, thus, provide an ideal example of the phenomenon of drowning of their valleys due to the submergence of the coastline. Such drowned or disserveted rivers have been designated as 'detrunked' by Davis (1895, p. 129). The rivers that debouch their waters into the Little Rann also reveal the phenomenon of truncation of their lower course now buried beneath the Rann clays.

The courses of the east flowing rivers show their development during two stages. Initially they comprised consequent streams that flowed down the eastern slopes and emptied themselves into the Tertiary Gulf channel. With the withdrawal of the sea and the development of the alluvial plains (older alluvium) some of the rivers now tend to die out in the raised mud flats, south of Nal Sarovar (e.g. Wadhwan-Bhogavo river). On the other hand, several streams show a marked deflection south-eastward, ultimately meeting the Gulf of Cambay. Obviously, this phenomenon is related to the fall of sea level. Because of the retreat of the Gulf of Cambay in Recent times, the lower course of the Limbdi-Bhogavo was extended to form a tributary of the river Sabarmati, Bhadar meets the Gulf of Cambay south-east of Dhandhuka. On account of the above phenomenon, the upper courses show the usual dendritic pattern, while in the lower reaches meandering and water-logging is more common. The streams that flow westward are rather insignificant and either they meet the Arabian sea or they disappear in the Okha Rann. Essentially slope controlled, they on emerging from the highland around Barda, drain the coastal plains before meeting the sea.

The Southern Unit

The Southern unit (south of the Bhadar-Kalubhar line) exhibits a drainage pattern quite different from that in the north. Here, the various streams big and small, indicate a strong structural control. Almost all the major rivers flow along tectonic lineaments, while their tributaries or other smaller rivers follow either various joint sets or comprise slope controlled streams.

The hills of the east-west Gir Range provide the main watershed, to the south of which flow down numerous small streams to the Arabian sea. While some of these south flowing streams are essentially slope controlled, quite a few major ones flow along well defined fractures. The streams flowing east and west definitely follow faultlines.

The rivers that flow eastward show marked tectonic control. Emerging from the eastern slope of the N - S ridge which connects the Gir Range and Mandev ridge, Kalubhar and Shetrunji rivers flow along major faults. The latter is perennial, whereas the former is seasonal.

Kalubhar river is a consequent stream, flowing almost in a straightline and meets the Gulf of Cambay at Bhavnagar where it forms a tidal channel. Because of the prograding nature of this coastline, this post-Gaj river (Miocene) shows meandering in its lower course.

The drainage characteristics of the river Shetrunji provide many interesting features. The various segments of its course are completely controlled by a number of faults. It emerges from Dhundi hills (808 m) in the Gir Range and runs eastward meeting the Gulf of Cambay at Saltanpur, after flowing approximately 175 km through the trappean country. The headward erosion of this river is expanding fast at the expense of that of Dhadar.

In its upper course, this river, first flows due ENE along a lineament parallel to the Narmada Fault; then it follows a southeastern course, flowing along a fracture that could be related to the west coast fault. It is significant that in the upper portions of its course, the river and its tributaries show a typical reticulate pattern, a major factor in determining such a pattern being the abundance of fractures in the basaltic plateau through which the river flows. Finally, it is a swing due to east and all along its middle course it flows almost in a straightline for 80 km along the Shetrunji Fault. All along its right bank numerous tributaries, originating from the overhanging E - W fault scarp, flow down the steep slope. These tributaries of Shetrunji are consequent in origin and show a parallel drainage pattern. The lower reaches of the river following almost a southeasterly course again marks a major faultline. The river flows straight into the sea, forming an estuarine delta near its mouth.

The streams flowing due south originate from the Gir Range, and show variation in their lengths from 15 to 50 km comprising only gullies in their upper course these drain the coastal zone and finally meet the Arabian sea. Though these streams are seasonal, they are important from their genetic point of view. The pronounced seaward slope of the Gir Range has controlled the pattern of these streams, which show a parallel drainage flowing over the tilted coastal plain, the stream courses have been controlled by the slope and are consequent to origin. These streams provide an interesting example of the effect of sea level fluctuations on the coastal drainage during the Quaternary. Right near the coast, the phenomenon of valley entrenchment due to sea regression is encountered. The valley of rivers like Hiran, Shingavada, Macchundari and Dhantarvadi, all are typically seen downcutting their valleys very much near their mouths. In the upper segments of these streams, consequent tributaries have developed on the valley sides and on account of their cutting back up by headward erosion into the plateau, the overall patterns of the streams in their course are dendritic. In contrast, the lower courses with few tributaries are parallel to one another. According to Zornitz (1932) such a drainage cannot be called a parallel drainage, and should be included under dendritic pattern only.

Among the westerly flowing rivers, only the Bhadar and Ojat are important; other streams are more or less ephemeral and do not provide effective drainage. The two major post-Trappean but pre-Tertiary rivers are controlled by the ENE-WSW lineaments (parallel to the Narmada Fault). The extensive occurrence of miliolite sheets along the valleys of these rivers for several kilometers inland and their heights provides a good insight into the sea level fluctuations of the Pleistocene period.

Of the two, the Bhadar is the largest of the Saurashtra rivers with a length of 250 km. Originating in the central highland east of Jasdan, the river flows westwards and meets the Arabian sea at Navibandar, 30 km south of Porbandar. As the river flows through the plateau basalts of uniform resistance, it shows a 'dendritic' pattern. Though its overall drainage pattern is dendritic, erroneously suggesting lack of structural control, when examined in detail, its trunk stream as well as the various major lineaments.

The river Ojat has its origin in the Gir Range near Visavadar, and flowing due west it meets the Bhadar river near Navibandar. In its upper course along the Gir Range slope, a combination of structural fractures and slope have controlled the development of a dendritic drainage. The tributaries of Ojat show an interesting phenomenon. Along its left bank, the various smaller streams flow down the slope with a characteristic parallelism. But the terrain to the north of the river, shows an ideal example of annular drainage.

Flowing around the hill massif of Girnar, in a circular manner, the various tributaries meet the Ojat. Another important factor that has controlled the Ojat course especially in its lower reaches is geomorphic. Meeting a regressive sea coast, this sluggish river has been unable to cut across the conspicuous coastal dunes, and shows deflection in its course parallel to the dune ridges before meeting the Bhadar.

GEOLOGICAL SETTING OF THE STUDY AREA

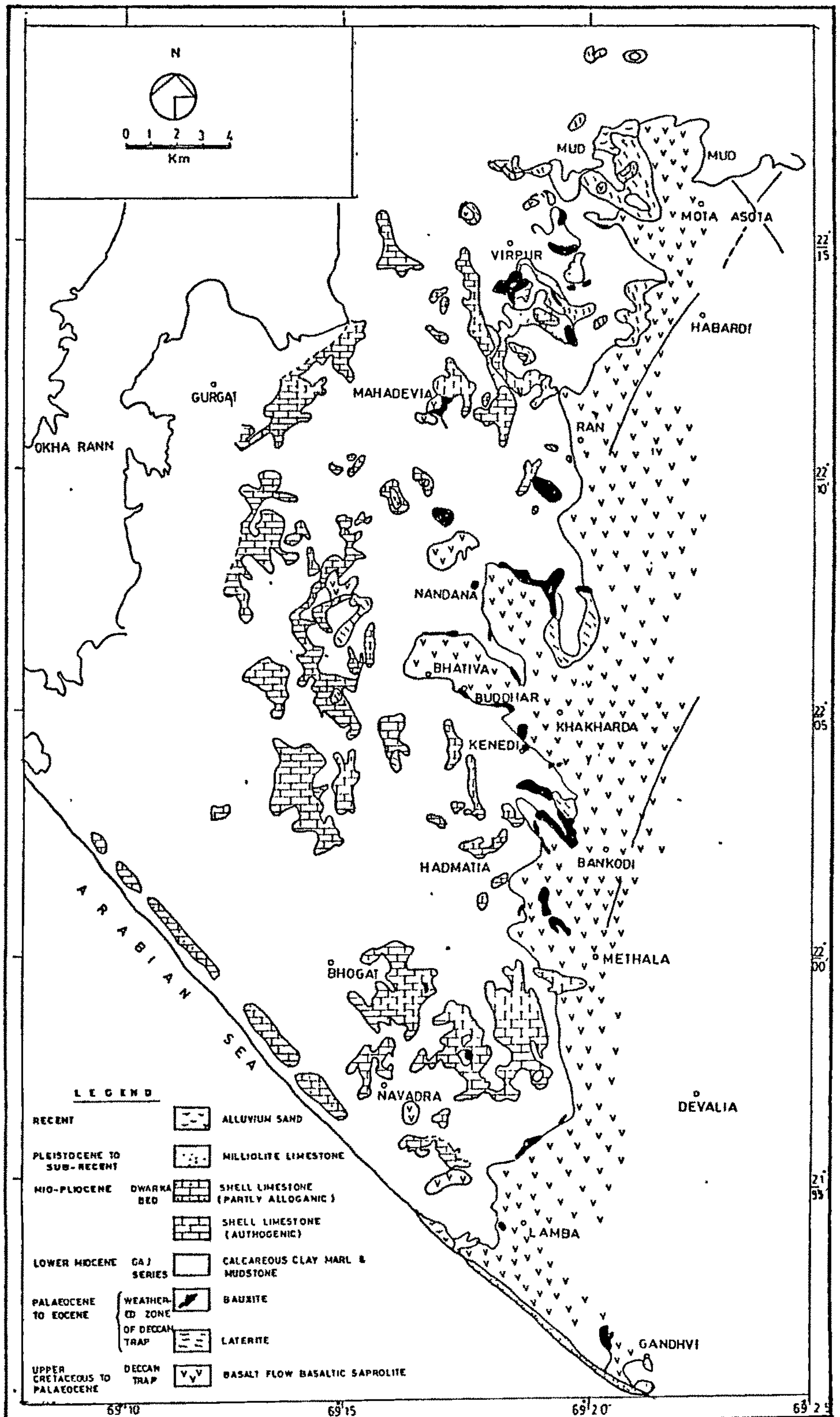
According to the present author, the generalised stratigraphy of the bauxite areas of Jamnagar district is follows (modified after Fedden, 1884) :

Age	Group	Litho-units
Recent		Soil and alluvium
Pleistocene to sub-Recent		Miliolite Limestone(oolitic) /base often conglomeratic
--------------UNCONFORMITY--------------		
Mio-Pliocene	Dwarka beds	Shell limestone and marl, mudstone
--------------DISCONFORMITY--------------		
Lower Miocene	Gaj series	Shell limestone,concretionary Limstone(foraminiferal) with clacareous clay, mudstone, marl, calcareous clay(frequently fossiliferous),mudstone,mixed clay zone(impersistent),black shale(grading to grey shale,rarely gypseous, often pyritiferous),transported bauxite,mixed clay zone, conglomerate
--------------UNCONFORMITY--------------		
Palaeocene to Lower Miocene	Weathered zone of Deccan Trap	Laterite-bauxite, Lithomargic zone, rare volcanoclastic lithomarge, basaltic saprolite, purple spotted clay(montmorillonitic), chocolate brown clay (ferruginous).
Upper Cretaceous Palaeocene	Deccan Trap	Basalt-dolerite dyke, gabbroboss, amygdular porphyritic, olivine basalt (flows) /base not encountered/

Three major stratigraphic breaks, recognised in the area, has subdivided the general geological succession into four groups (Fig. 9). From basalt to the laterite-bauxite zone, no plane of unconformity could be deciphered. The basalt flow appears to pass upward into a more and more decomposed state of the rock, generally giving rise to chocolate brown clays at first and purple bentonitic clays further above. Occasionally, however, these two types of clays are found to be mixed together in their zone of gradation or only the mixture of the two occurs without any distinctive horizon of any of them. The purple benetonitic clay horizon in turn, grades upwards into laterite-bauxite through an impersistent zone of lithomarge rich in Kaolinitic ferruginous clay and few oolites and pisolites of bauxite.The unconformity between the laterite -bauxite zone and the overlying sediments is evident from the conglomerate patches containing pebbels and fragments of laterite, high grade bauxite, pieces of altered and unaltered basalts - all set in a fossiliferous calcareous matrix with the Gaj fossils. Further, laterite-bauxite itself implies a stratigraphic hiatus. Wherever lenses of mixed clays of Gaj series rest directly over laterite-bauxite, they include fragments of the underlying rocks. Within the sedimentary succession, between the conglomerate and Dwarka beds, a number of local intra-formational breaks marked by impersistent fragmentary mixed clays are seen. The calcareous facies of the Gaj series of Lower Miocene zone is overlain by another

FIG. 9

GEOLOGICAL MAP OF BAUXITE DEPOSITS, JAMNAGAR DISTRICT



(AFTER B N. JAYARAM, A. MAJUMDAR, S S MUKUL, AHMED, M S G RAO & S K GADHAKS. 1970-72) horizon of limestone and mudstone. Miliolite limestone occurs invariably as patchy overlaps, generally upon the flanks of ridges of laterite, Gaj and Dwarka beds and sometimes even upon basalts.

BASALT

Basalts forming the oldest rock unit in the area are greenish, exfoliated, jointed, porphyritic and frequently with amygydules of zeolites, calcite, epidote and various soft and soapy secondary vesicle-fillings. Onion-skin spheroidal exfoliation (Rittman, p.73) is a common feature. At places, the exfoliation spheroids superficially resemble pillow structure. However, basalt exposed within the oval outcrop of the laterite is found to be in various degrees of decomposition. State of decomposition of basalt varies sharply across the flow rather than along it.

GABBRO

A gabbro boss, intrusive into the basalt flow, occurs west of Gandhvi at the southern end of the study area. The eastern boundary of the gabbro boss is chilled and occurs at about 50 m above ground level. The old Harshad-mata temple is situated on it (187' Spot height). The western flank of the boss is gently steeping westward.

DOLERITE DYKE

Dolerite grading to basalt occurs as dyke trending NNE and NNW. It is greenish to black, hard, often amygdular but much less altered than basalt. On the northern part near Ran village, a dolerite dyke 30 m wide, runs for about 1 km with a N25°E alignment. Further to the NNE a fine to medium grained basalt-dolerite dyke is exposed west of Habardi and east of Mota-Asota with a N30°E trend. About 1 km west of Habardi, the dyke wall forms a 4 m high vertical bank.

The second basalt dyke occurs at a distance of about 1.5 km east of Mota-Asota and trends N20°W-S20°E.

Chocolate brown clay and purple clay

A well defined zone of chocolate brown ferruginous clay and purple bentonitic clay occurs above the basalt flows, especially where the laterite-bauxite zone has developed. Purple clay is found to occur directly above recognisable basalt flows without any development of the chocolate brown clay. The purple clay is soft, rich in monmorillonite, powdery in nature, with characteristic small patches of greyish white clayey laths. The gross appearance of the clay, because of its fine grain size and powdery nature, may resemble that of a tuff bed. The presence of horizontally elongated clayey patches representing most probably the decomposed amygdales elongated due to the flowage of lava, suggest that it was originally a lava flow rather than a pyroclastic tuff bed. Although in a much altered state, the chocolate brown and purple clay resemble, both texturally and structurally, decomposed lava flow possibly of basaltic composition.

LATERITE-BAUXITE

The purple clay horizon gradually passes upward into laterite-bauxite zone. It occurs below the laterite-bauxite horizon and has developed especially where the bauxite deposits have developed. Differential erosion has removed the softer clay portions at many places leaving behind a relatively hard ferruginous rock with numerous cavities. These are noticeable in the scarp sections. Differential erosion of the softer clayey portion in many cases, has underout the scarp to such an extent, that the relatively harder ferruginous crust of laterite at the top is left overhanging. Thus, round to ellipsoidal voids or caves have commonly developed in the escarpments of laterite. The mottled laterite at many places contain lateral to lenticular bodies of bauxite. In such cases, the mottled laterite may occur to some extent above the bauxite deposit which, in turn, grades downwards into the lithomarge. Bauxite shows various colours generally grey, greyish white, creamy, yellowish brown, light pink and occasionally violet grey. The laterite-bauxite horizon is exposed in numerous isolated oval outcrops in the form of arcuate bands of variable width.

GAJ SERIES

The laterite-bauxite horizon is overlain unconformably by a sedimentary succession - the Gaj series, consisting principally of three main facies, viz. carbonaceous, argillaceous, and calcareous from bottom to top. However, these are all gradations and repetitious to some extent of the different facies.

Transported bauxite

A zone of transported bauxite deposit, may occasionally be encountered above the zone of mixed clay. Its transported character is clear from the association and arrangement of high grade, hand and compact bauxite within a matrix of arenaceous mudstone and mixed clays. The unassorted nature of such bauxite deposits indicate their transportation over a short distance from the nearby deposits. Thus, the transported bauxite forms eluvial deposits.

Mudstone, Calcareous clay and marl

Greenish mudstone above gradually passes up into bright yellow calcareous clay which is occasionally fossiliferous. Further upwards, yellowish calcareous clay is gradually mixed with greenish argillaceous clay, thus grading into marl.

Gypseous mudstone and marl

Gypsum occurs both as translucent greyish white lumps and as transparent selenite type. Gypsum plates are deposited parallel to the incipient bedding plane of the greenish mudstone. Therefore, gypsum is syngenetic with the mudstone.

Concretionary limestone

Above the gypseous mudstone appears the calcareous clay with foraminiferal concretionary limestone. It is generally yellowish to greyish white in colour. Over a major part of the area north of Lamba, brownish yellow calcareous clay is exposed. The common fossils in the calcareous clay are foraminifera, echinoids and gastropods. All these fossil assemblages point to a lower Miocene age of the Gaj Series.

Shell Limestone

Further upwards, brownish yellow, hard and massive limestone occurs. It forms a number of flat topped elongate table lands forming outliers over the underlying softer calcareous clays. There are several such ridges of shell limestone in between Mahadevia, Ran, and Mewasa, east of Pindara, north of Ran, west and south of Bhatiya, around Hadmatia and in between Navadara and Lamba.

DWARKA BEDS

Dwarka beds consisting essentially of fossil rich limestone, marl and black to grey shales overlie the shell limestone of the Gaj with a (?) disconformity. Dwarka limestone is less compact, richer in oyster shells, made up at places, entirely of fragmentary fossils.

MILIOLITE LIMESTONE

Miliolite limestone is the youngest rock unit in the area. It occurs in patches, overlapping the flanks of the limestone and laterite ridges and typically along the nala courses. The rock is generally dirty white, well bedded, medium to coarse grained with cross-beddings. On the slopes of lateritic ridges and limestone, miliolite limestone is generally thin and includes pebbels and fragments of the underlying rocks. The best outcrop of miliolite limestone is found 1.4 km SW of Mewasa village in the Dhand river section. Bedding plane on both the banks of the river dip at 10° to 15° towards the river bed.

STRUCTURES OF THE STUDY AREA

The lava flows of the area shows sub-horizontal dips (maximum 10°). They exhibit abundant close spaced vertical and horizontal joints and cracks. Below the oval and rounded outcrops of laterite-bauxite, basalt alongwith its weathered zone shows a quaquaversal dip of 6°-7°, thus forming a broad structural dome. The dome is characterised by a central depression of 5 to 40 m, where basalt is generally exposed.

There are two sets of basalt-dolerite dykes in the area. The major sets strike NNE varying between N 15°E and N 30°E and are exposed between Maletha to Mota-Asota. The second set strikes N20° W - S20° E and is exposed about 1.6 km west of Mota-Asota village.

A sub-rounded body of gabbro boss occurs to the SW of Gandhvi in the southern part of the study area, as an intrusive into the basalt flow. The contact between the intrusive and the basalt is near the south and west of the intrusive body.

The saprolite-laterite-bauxite forming the rim of the domal structure of basalt flow, exhibits a pseudostratification which also shows gentle radial outward dips of 2° to 7° (average 4°). The inner side of the rim is a steep escarpment (slope 75°-86°) facing inwards. At some places, however, the conical structure is incompletely developed and the laterite-bauxite is found to form an arcuate outcrop. From Bhatiya to north of Virpur, a stretch of about 20 km, there are many conical structures, of which a few are incompletely developed or the flank of laterite-bauxite has been partially eroded away. From Nandana to Mahadevia, the cones lie in a roughly NNW trend. From SE of Mewasa upto the Gulf of Kutch in the NNW, cones lie in a NNW alignment. From Virpur to NNW, cones lie in a NNW alignment. On the other hand, a number of conical features occuring between south of Mahadevia to Virpur, show a distinct NNE alignment.

The laterite-bauxite may show short length sub-vertical joints which are often confused with frequently developed exfoliation structures. However, the dominant sets of joints measured in laterite-bauxite, are (i) 90/N10° W, (ii) 90/N85° W, and (iii) 90/N60° E.

The shell limestone of the Gaj series may at places show an obscure bedding (dip 3° to 7°) which is defined by a depositional interface, grain size variation and occasionally by colour bands. The limestone forming a N-S ridge in between Mahadevia and Ran, shows a gentle 2° to 5° dip on the western flank and relatively steeper dip of 8° on the eastern flank. The major part is a gently escarpment.

The limestone forming flat topped ridges on the south and west of Mewasa and Pindara shows current bedding with northerly dips of 5° to 25°. The E-W strike false-bedding is at right angles to the N-S elongation of the ridges.

The shell limestone of the Dwarka bed shows well developed bedding plane with cross-beddings. It dips sub-horizontally (2° to 7°)? The cross-bedding may show dips upto 30°?

Miliolite limestone is always so well developed that it looks like stacks of books. Large scale cross bedding is very common. Bedding is defined by depositional interfaces and grain size variation. Graded bedding, both along bedding planes and the cross bedding is frequently observed. Miliolite limestone occurs generally along sub-horizontal to even 30° slopes, when it occurs in a river valley.

On the bank of Dhand river, SW of Mewasa, miliolite limestone shows an unusually high dip (70°) against the sub-horizontal beds of Gaj limestone. Thus, the high dip of the miliolite limestone seems to be due to post-depositional tilting during diagenesis. Near Harsad temple, on the southern part of the study area, thick miliolite limestone with large scale cross-bedding rests against the basic intrusive rock of the Deccan Trap and shows a high angle of dip (45°).