CHAPTER - IV

LABORATORY STUDIES

(A) PETROGRAPHY

GENERAL

As stated in the previous chapter, the rocks of Himatnagar area comprise Aravallis, Delhis (intruded by Erinpura granites), Mesozoics together with Quaternary sediments of Recent to sub-Recent age. In this chapter the author has only given a broad account of petrography of the rocks of Aravallis, Delhis, Erinpura granites and Deccan Trap (Basalts), as the adequate account of which is available in published/unpublished literatures (Middlemiss, 1921; Gupta & Mukherjee, 1938; Heron and Ghosh, 1938; Pascoe, 1953; Rawal, 1972; Patel, 1972; Malpathak, 1979). However, on account of paucity of detailed petrographic studies of Himatnagar sandstones, the author, in this chapter has focussed his attention on the study of texture, mineralogy and the various diagenetic processes operative on these patchy arenaceous rocks. A critical scrutiny of a number of thin sections of these rocks from the study area has shown a vast array of the constituent minerals and their textures that are of great significance in unravelling the probable origin and provenance for the sandstones around Himatnagar. The broad mineral constituents of the various rocks encountered in the study area other than the Himatnagar sandstones, are given as per below.

ARAVALLIS

These mainly include mica-schists and quartzites.

1) Mica Schists

Texture : Schistose and well foliated

Mineral Assemblage :

Quartz-biotite-muscovite-staurolite-apatite-zircon-tourmaline-albite-oligoclase-magnetite-hematite.

2) Quartzites

Texture : Granoblastic-mosaic with ill defined flattened quartz grains.

Mineral Assemblage :

Quartz-biotite-muscovite-tourmaline-zircon-ironores.

DELHIS

Only quartzite rocks are exposed.

Quartzites

Texture : Granoblastic-mosaic with remnant rounded to sub-rounded quartz.

Mineral Assemblage :

Quartz-muscovite-biotite-tourmaline-apatite-zircon-opaques.

ERINPURA GRANITES

Texture : Equigranualr, coarse grained, holocrystalline and hypidio-morphic.

Mineral Assemblages :

Quartz-microcline-orthoclase-albite-oligoclase-biotite-muscovite-hornblende-pyroxene-apatite-zircon.

MESOZOICS

Himatnagar sandstones (details in subsequent pages)

DECCAN TRAPS (Mainly basalt)

Texture : Inequigranular, porphyritic.

Mineral Assemblage :

Labradorite-Augite-opaques.

HIMATNAGAR SANDSTONES

As the present study pertains to the Himatnagar sandstones, their petrography has been described in detail in the following text, and this has helped the author to understand the genesis, depositional environments and provenance of arenaceous components of the study area.

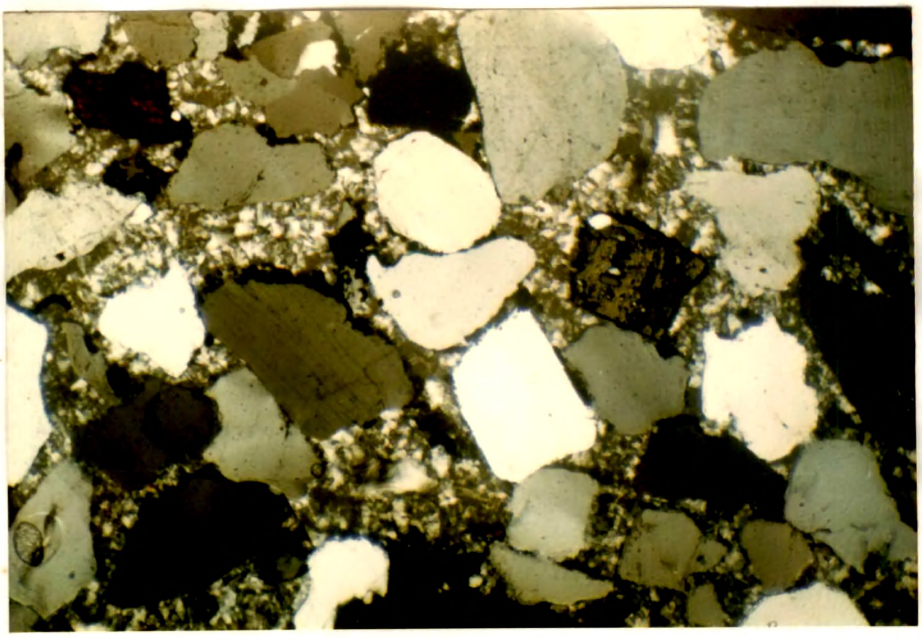
TEXTURE

The Himatnagar sandstones, on an average are medium to coarse grained and occasionally fine grained. They are sub-angular to angular with moderate to poor sorting. A few grains are seen abraded (chipped or grounded) with prominent corroded boundaries (Plate IV.I). Quartz enlargement, indicated by authigenic overgrowth of common occurrence in this sandstones (Plate IV.2).

MATRIX AND CEMENT

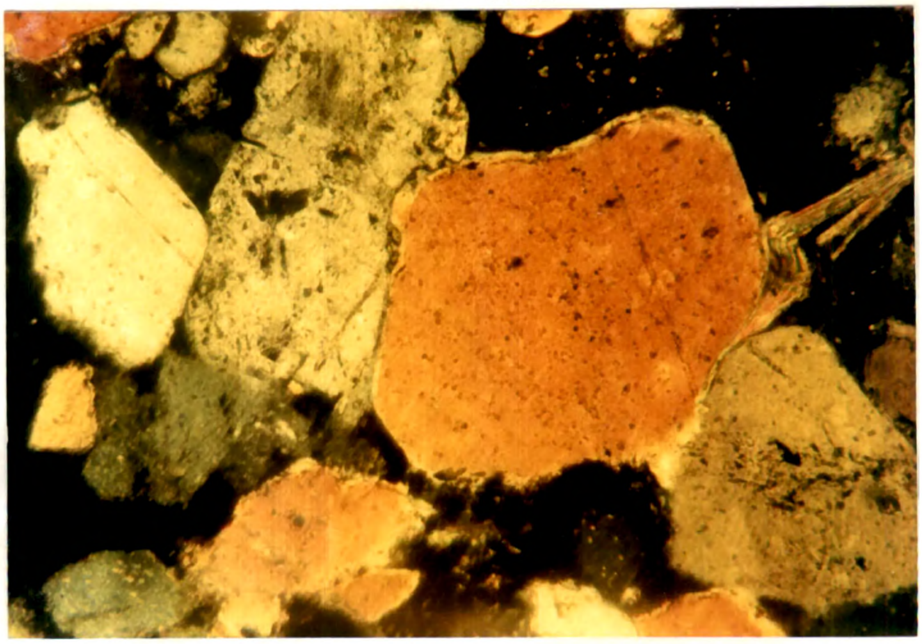
The matrix mainly comprises silt & clay and is less than 20 percent. The cementation has been brought under different environmental conditions and accordingly the loose quartz grains are bound together by different types of cementing materials. The cement is mainly siliceous and ferruginous, occasionally argillaceous and rarely calcareous. The cementation in the Himatnagar sandstone has been brought in mainly by the redoxomorphic and phyllomorphic stage of diagenesis. The

PLATE IV.1



Photomicrograph Showing Corroded Boundary in Quartz
(Crossed Nicols, x 45)

PLATE IV.2



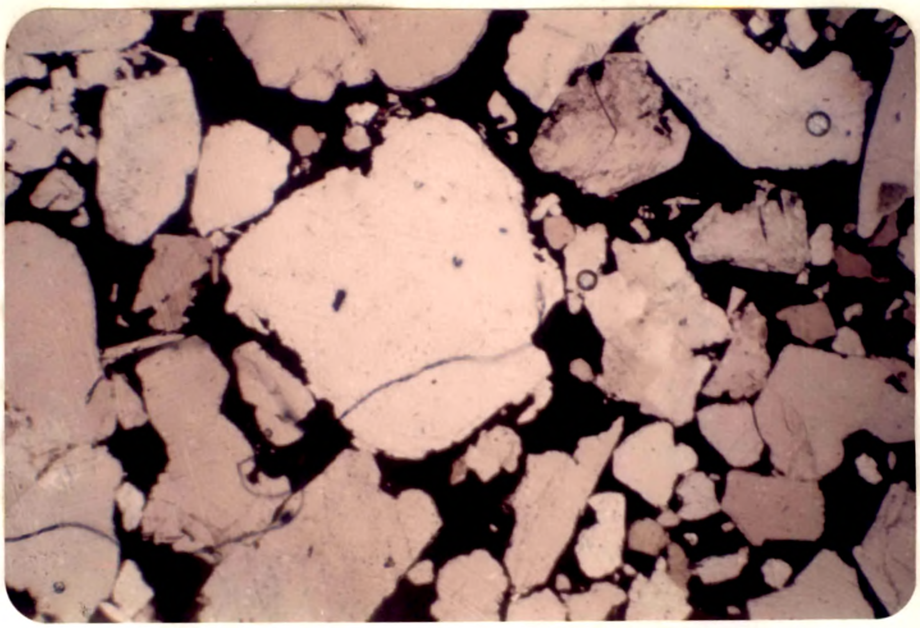
Photomicrograph Showing Authigenic Overgrowth in Quartz
(Crossed Nicols, x 90)

sandstones have been lithified predominantly by simple cementation. The silica and ferruginous cements (Plate IV.3) are dominantly seen in the riverbed and lowlying exposures through out the area. Here generally the thin layers of ferruginous sandstones are encountered within the silica cemented sandstones. The hill top exposures of sandstone in the eastern, northeastern and southeastern part of Himatnagar are characterised by cherty to chalcedonic cement (Plate IV.4). Near Ilol, the argillaceous cement is seen while at NW of Himatnagar in the river bed exposures near Kadoli the cementing material is calcareous (Plate IV.5). The replacement of cherty/chalcedonic cement by calcareous matter is also seen at few localities of hill top exposures.

MINERAL CONSTITUENTS

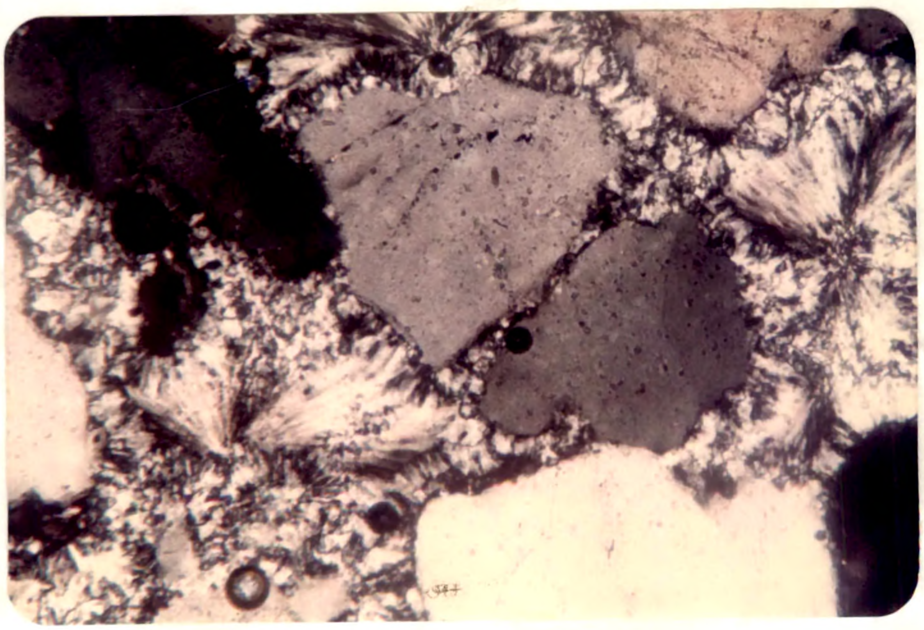
Himatnagar sandstone predominantly consist of quartz (>85%) with felspars (orthoclase, microcline, plagioclase, perthite), micas (muscovite, biotite), hornblende, chlorite, apatite, epidote, augite together with tourmaline, staurolite, zircon, topaz, olivine, ilmenite, rutile, sphene and opaques along with a few rock fragments of pelites and psammites. Quartz forms the most prominent mineral in the rock. It is anhedral, colourless with low R.I., weak birefringence showing 1st order grey/yellow polarisation colours and +ve uniaxial optic sign. Most of the grains are ice-clear in appearance and occasionally some are dirty. The grains show wavy or undulose as well as sharp extinction. Cleavage is absent but in few grains minor fractures

PLATE IV.3



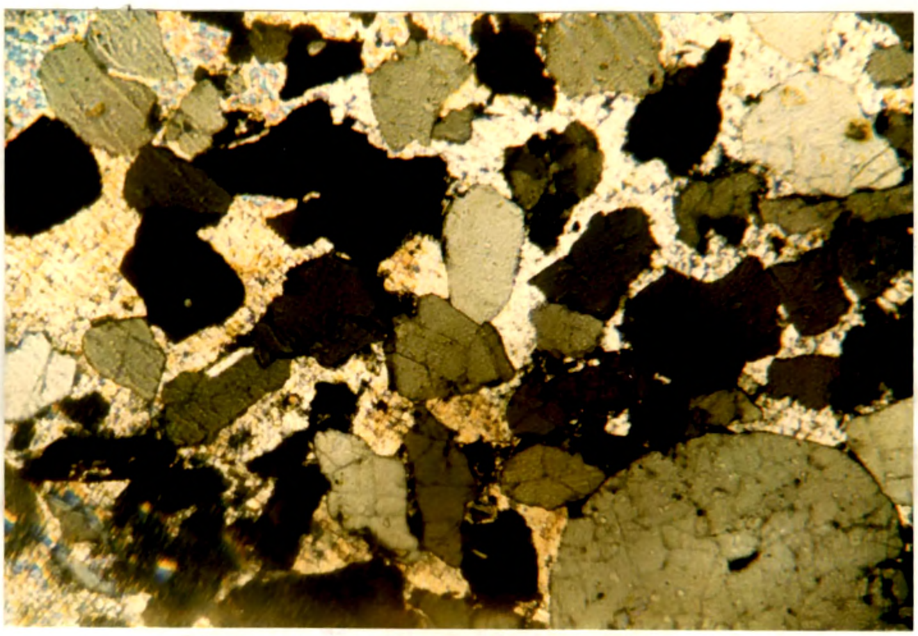
Photomicrograph Showing Ferruginous Cement in Sandstones
(Polarised Light, x 45)

PLATE IV.4



Photomicrograph Showing Cherty/ Chalcedonic Cement in Sandstones
(Crossed Nicols, x 90)

PLATE IV.5

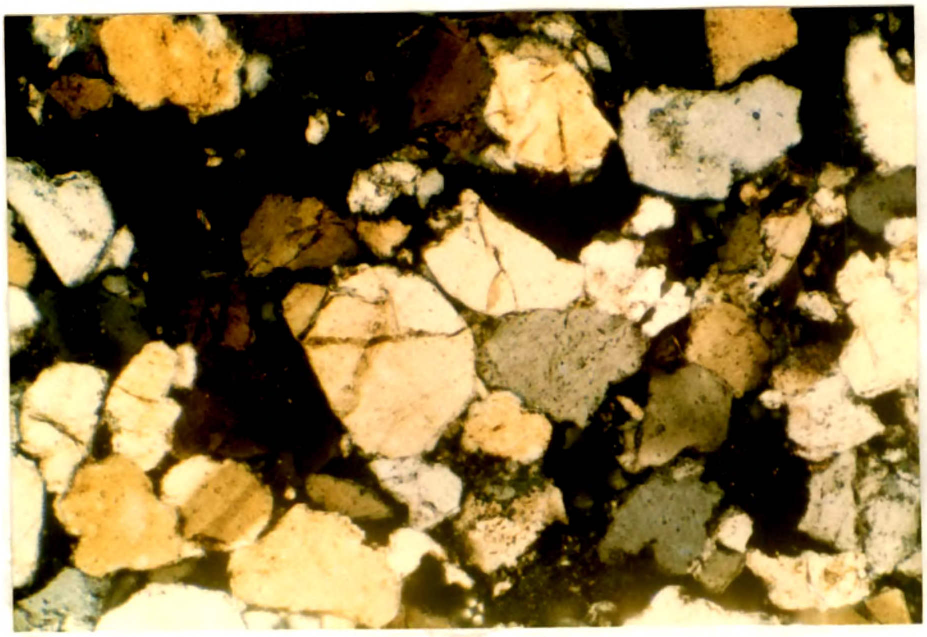


Photomicrograph Showing Calcareous Cement in Sandstones (Crossed Nicols, x 90) are clearly visible (Plate IV.6). The various quartz grains show either tangential (point) contact or line contact and only in a few sections the concave convex or sutured contact is visible (Plate IV.7). At few localities the rock sections show floating quartz all these suggest the different stages of compaction and cementation (diagenesis). Besides quartz, there are numerous light (felsic) and dark (mafic) minerals which, on average, constitute < 5% of the bulk mineral constituents. Their broad petrographic characters are mentioned in the following text.

The felspars are very scarcely seen in these rocks, wherever seen the orthoclase and microcline constitute the potassic felspar while albite-oligoclase form plagioclase felspars. Orthoclase is colourless and is characterised by low relief, weak birefringence, two sets of cleavage and biaxial negative optic sign. It gives bluish grey 1st order polarisation colour. Microcline is characterised by its cross hatching due to gridiron twinning. Perthite - an intergrowth of albite or other sodic plagioclase (oligoclase) with orthoclase or microcline is also seen in some sections. Plagioclase felspar are characterised by low R.I. and lamellar twinning with extinction angle upto 8°, indicating the felspars to be mostly of albite oligoclase range.

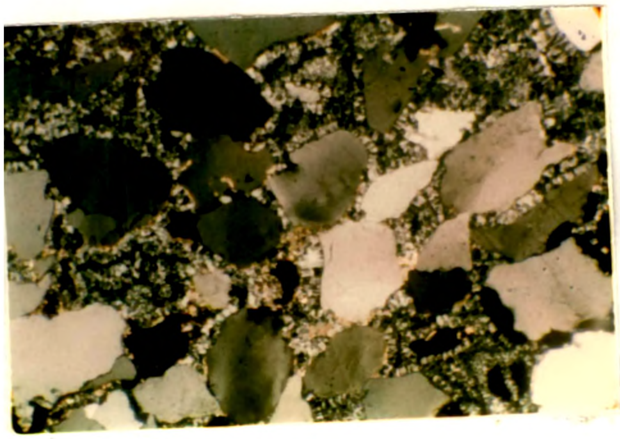
Both the varieties, muscovite as well as biotite, form either the discontinuous streaks & flakes or occur as minute fine grained groundmass (sericite).

PLATE IV.6

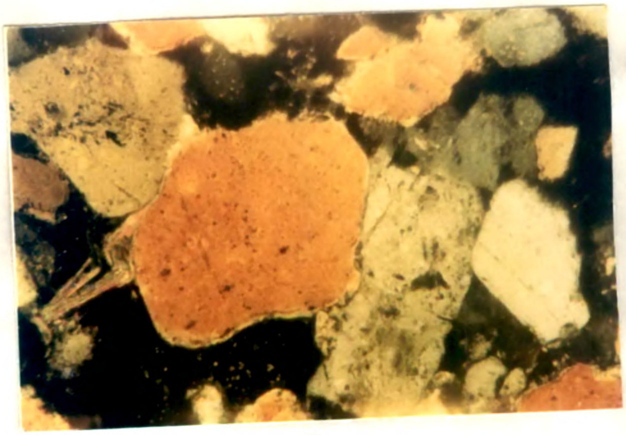


Photomicrograph Showing Fractures in Quartz
(Crossed Nicols, x 45)

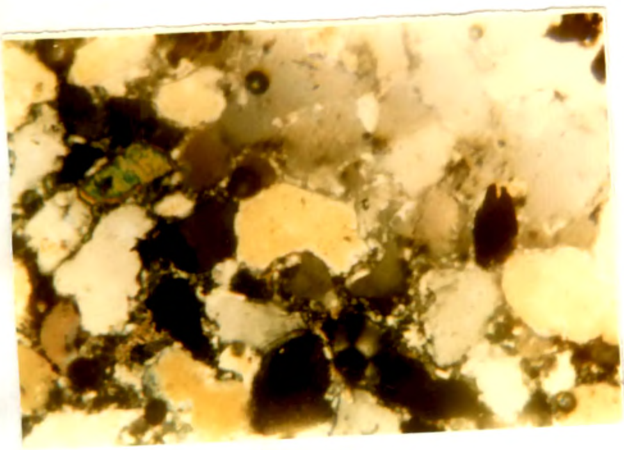
PLATE IV.7



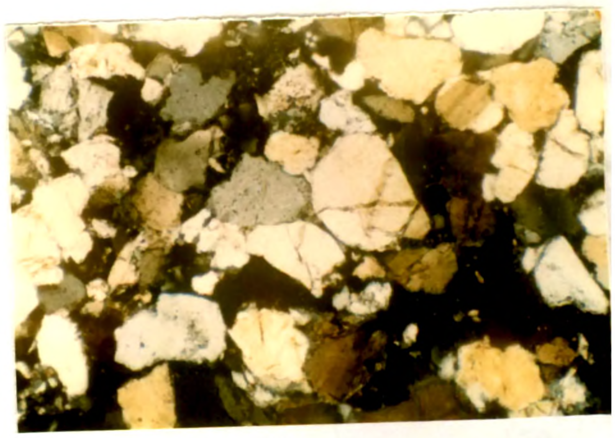
A



B.



C

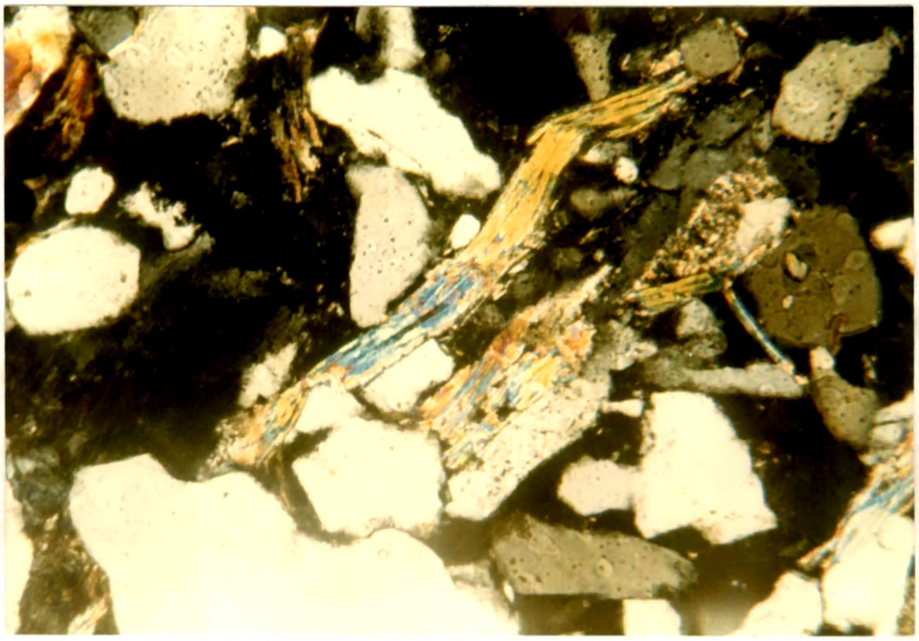


D

Photomicrograph Showing Different Types
of Grain Contacts in Sandstones
(a) Point Contact (b) Line Contact
(c) Concave-Convex Contact
(d) Suture Contact
(Crossed Nicols, x 30 (a & d), x 60 (b & c))

Muscovite is predominant over biotite and is colourless with low to moderate relief & moderate birefringence. It is characterised by one set of perfect cleavage; inclusions of zircon, rutile, tourmaline, apatite, quartz and iron ores are common. Occasionally they show the undulose extinction which may indicate their derivation from metamorphic rocks. At places muscovite alters to sericite. Small flakes of muscovite occur as inclusion within quartz grains also. Invariably they are seen lying approximately parallel to sedimentary laminations. The squeezing of mica flakes between more rigid quartz grains on account of the compaction has caused the bending of the mica flakes (Plate IV.8). Biotite is strongly pleochroic from yellow to dark brown. In few grains the pleochroic haloes are seen. It is also characterised by low R.I.strong birefringence and straight extinction. Inclusion of zircon, apatite, sphene etc. are occasionally seen. The foxy red variety may indicate its richness in titanium. The bending of flákes is also noticed in some grains. In few grains the biotite is seen altering to chlorite which can be recognised by its colour and very low birefringence. Hornblende is characterised by high relief, pleochroism (yellowish green to dark green), moderate birefringence and oblique extinction (15° to 25°). This forms the subhedral prismatic crystals in the matrix of sandstone. Chlorite occurs as isolated grains and can be identified by its feeble pleochroism in the shades of green and weak birefringence. Some chlorite grains are almost isotropic, other exhibit anamolous interference colours. Apatite occurs as small anhedral grains as well as small inclusion within quartz. It has high

PLATE IV.8

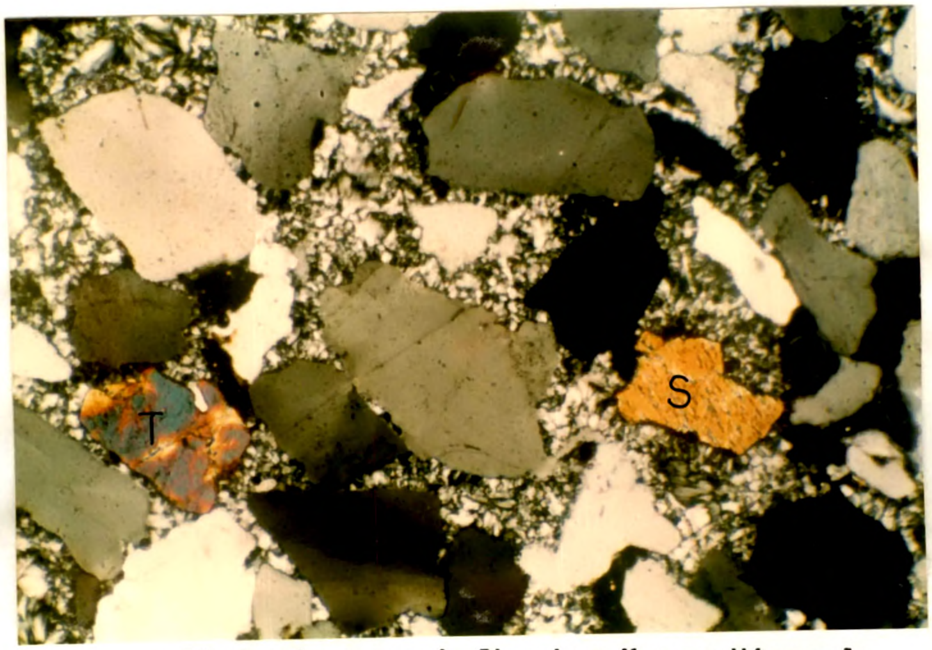


Photomicrograph Showing Bending of Micas in Sandstones (Crossed Nicols, x 45)

R.I., weak birefringence colourless and straight extinction. Epidote usually occurs as anhedral and shows pleochroism, in shades of green to colourless to pale green, high relief and strong birefringence. Calcite forms isolated grains and show twinkling, symmetrical extinction, very strong birefringence and high order polarisation colours.

A few scattered grains of **heavy minerals** are also encountered in some sections; the tourmaline and staurolite predominate them (Plate IV.9). Tourmaline occurs either as subhedral grains, dispersed throughout the groundmass or as inclusion within quartz. It shows straight extinction and pleochroism in different shades. Mainly two varieties of tourmalines are identified. Schorlite (Pleochroism from bluish to pink or brown to black) and Dravite (Pleochroism from light grey to dark brown and occasionally from colourless to light blue to dark blue). Staurolite forms scattered grains showing high relief, marked pleochroism (light yellow to dark yellow) and straight extinction. It contains opaque tiny grains of iron ores along cracks. Zircon occurs as small rounded grains and has very high relief with strong birefringence. Olivine occurs as isolated minute grains and usually colourless, high R.I., lack of well developed cleavage and presence of irregular cracks, parallel extinction. It alters to serpentine. Sillimanite forms subhedral needles and inclusion in the quartz. It is colourless with one set of cleavage and straight extinction. Augite is colourless and shows moderate to high relief, two sets of cleavages, intersecting at about 90° and gives 2nd order

PLATE IV.9



Photomicrograph Showing Heavy Minerals in Sandstones (T = Tourmaline, S = Staurolite) (Crossed Nicols, x 45) polarisation colours. Rutile is purple pink and/or opaque, and forms needles aligned in quartz grain. Sphene is pleochroic from light brown to dark brown and shows high relief and high order polarisation colours. Opaque grains of hematite and pyrite, small rock fragments (quartzite, phyllite and slate) are also encountered in few sections (Plate IV.10).

DISCUSSION

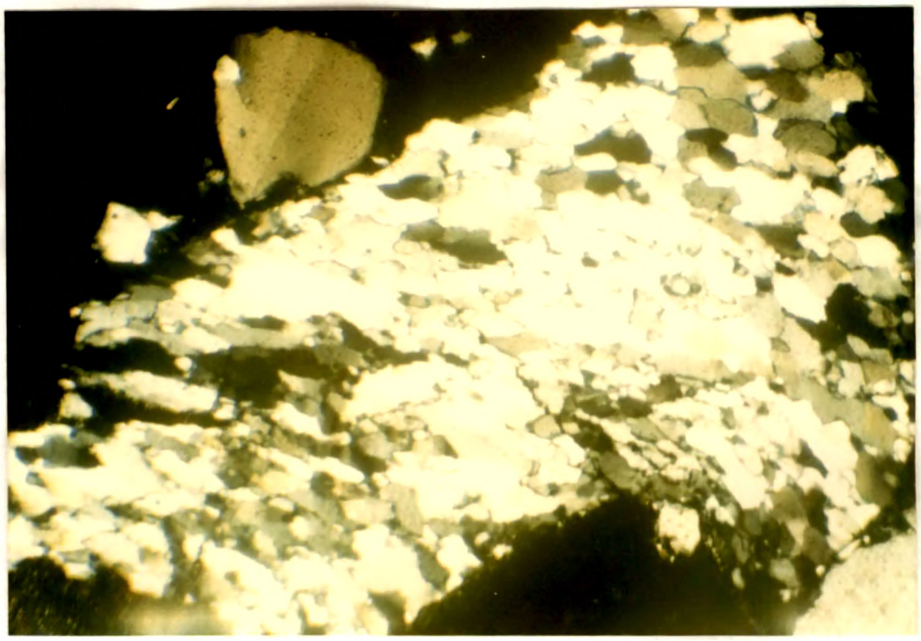
The thin section study of Himatnagar sandstone clearly reveals that the sand grains (quartz) of this rock are derived from two different suites viz.(a) quartz originating from metamorphic terrain and (b) quartz originating from igneous terrain. Their characteristics have been outlined as per below.

a) **Quartz Originating from metamorphic terrain**

(i) The grains derived from this suite are elongated (Plate IV.11) and have the length/width ratio around 1.75 suggesting its derivation from metamorphic terrains (Bokman, 1952). The tangential contacts of quartz grains rules out possibility of flattening of quartz grain after deposition. This indicates that the flattening of quartz was prior to the sedimentation and perhaps derived from the metamorphic provenance.

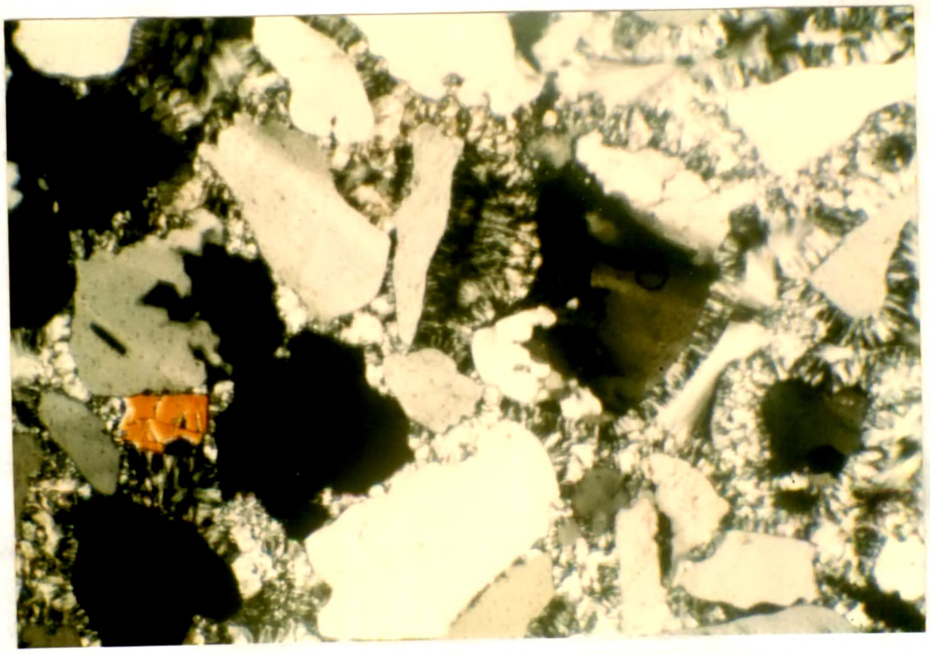
(ii) These quartz grains are polycrystalline which are composed of a number of separate grains with sharp boundaries, each

PLATE IV.10



Photomicrograph Showing Quartzite
Pebble in Sandstones
(Crossed Nicols, x 45)

PLATE IV.11



Photomicrograph Showing Elongated
Quartz Grains in Sandstones
(Crossed Nicols, x 45)

one large enough to be readily identifiable as quartz under crossed nicols; under polarised light they appear to be a single grain (Plate IV.12).

(iii) These quartz grains are strained and are characterised by strain shadows giving rise to undulatory, extinction (Plate IV.13).

(iv) Occasionally some quartz grains are cloudy with dust like particles and minute fluid-filled vaculoes (Plate IV.14).

(v) The inclusion of sillimanite, staurolite etc. in some quartz grains reveal its metamorphic provenance.

b) **Quartz derived from igneous terrain**

i) The quartz grains are more or less equant (Plate IV.15) with length : width ratio around 1.43 (Bockman, 1952).

ii) The quartz is monocrystalline, ice clear in appearance, without any fracture.

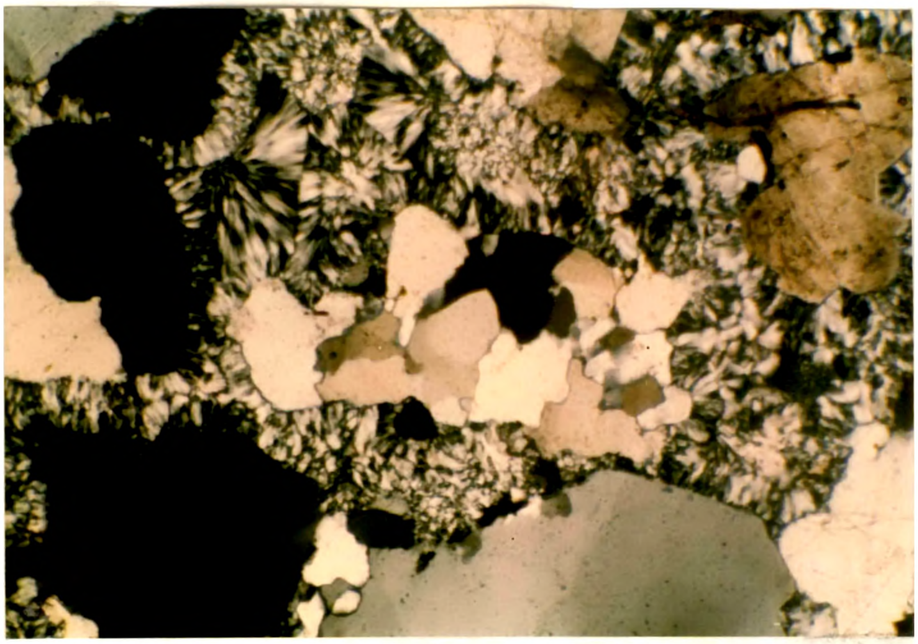
iii) The quartz is generally devoid of wavy or undulatory extinction. Extinction in the grain persists uniformly in all parts.

iv) Few quartz grains show corroded or embayed margins that indicate their derivation from igneous suite (Plate IV.1).

v) The quartz grains contain acicular, slender and irregular minute inclusions of rutile, zircon, tourmaline and apatite etc. (Plate IV.16).

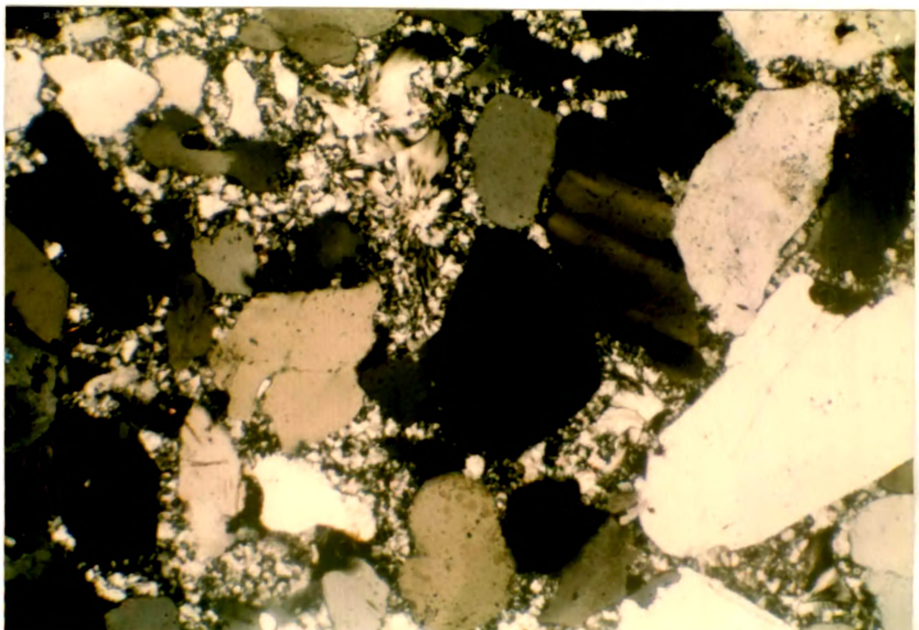
The presence of minerals like felspar (oligoclase,

PLATE IV.12



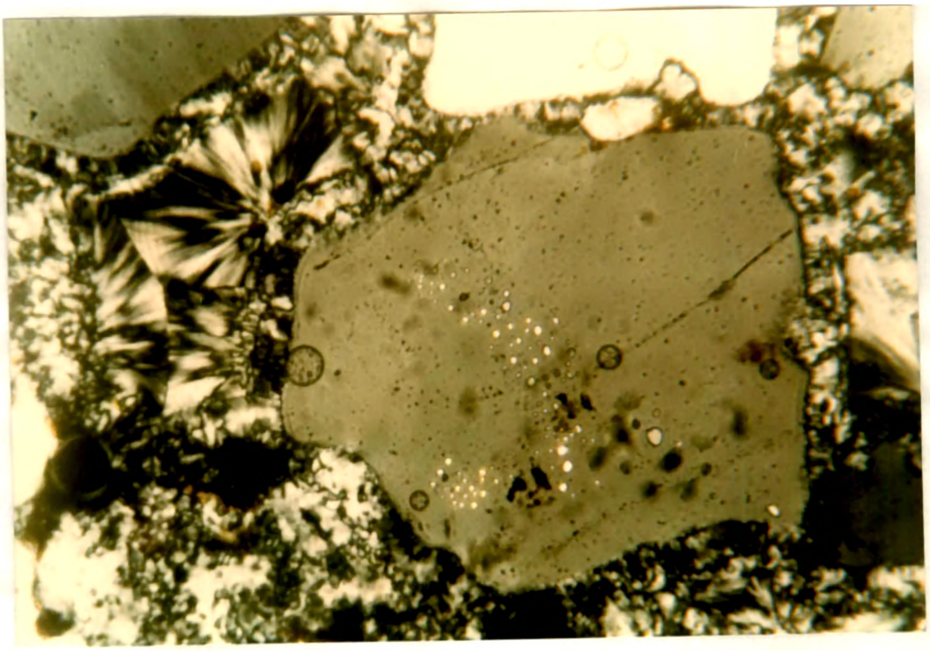
Photomicrograph Showing Polycrystalline Quartz in Sandstones
(Crossed Nicols, x 90)

PLATE IV.13



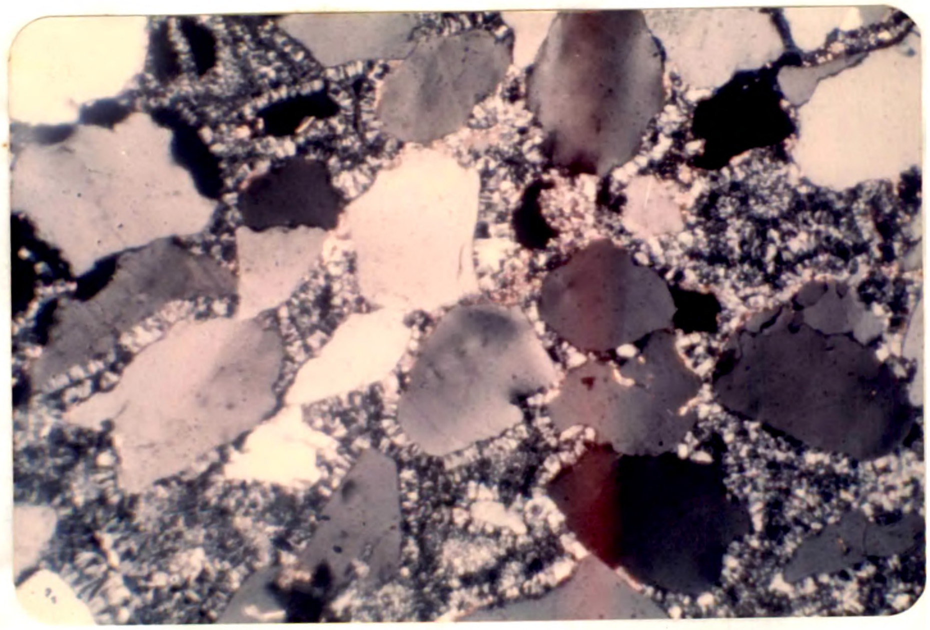
Photomicrograph Showing Undulatory Extinction in Strained Quartz
(Crossed Nicols, x 45)

PLATE IV.14



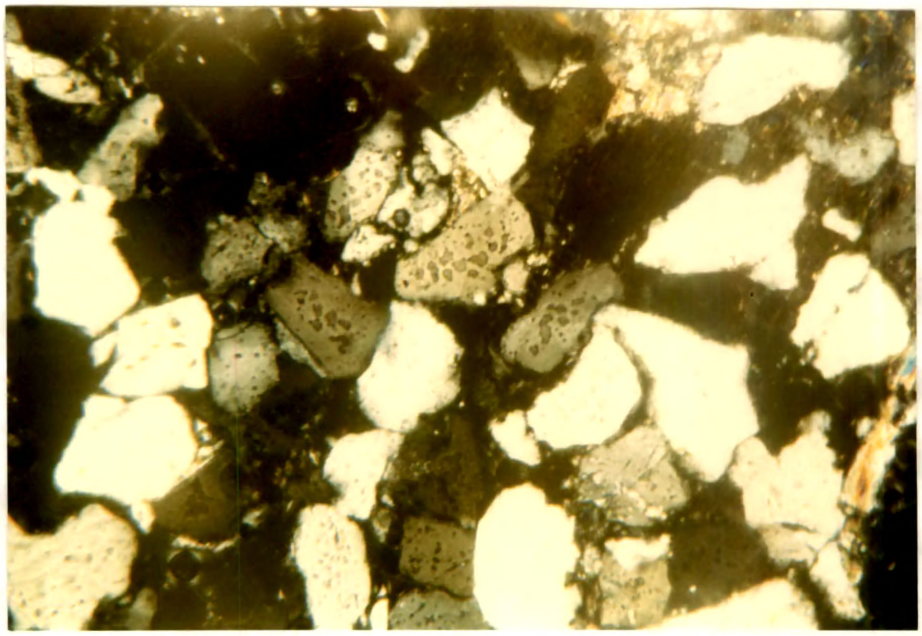
Photomicrograph Showing Fluid-Filled
Vacculoes in Quartz
(Crossed Nicols, x 90)

PLATE IV.15



Photomicrograph Showing Equant
Quartz Grains in Sandstones
(Crossed Nicols, x 45)

PLATE IV.16



Photomicrograph Showing Minute
Inclusions in Quartz
(Crossed Nicols, x 45)

microcline, perthite) apatite, zircon, sphene, augite, rutile, olivine, serpentine in the sandstone suggests the provenance from igneous suite while the association of minerals like staurolite, sillimanite and rock fragments of phyllites & quartzites points to their derivation from the metamorphic terrain. The angular to sub angular nature of quartz suggests less transportation hence the nearness of source material. When the provenance is of granitic terrain, there should have been abundant felspar in the sandstone but the Himatnagar sandstones show impoverishment in felspar content. The sandstones in general are quartz arenites or ferruginous quartz arenites and are characterised by mineralogical maturity.

DIAGENESIS

GENERAL

The diagenesis includes all physical, biochemical and physiochemical processes which modify sediments between deposition and lithification or cementation at low pressures and temperatures. In this chapter an attempt has been made to describe at length the diagenetic processes by which the loose sand grains have been consolidated subsequent to their deposition and transformed into "sandstone". A correct appraisal of the processes of diagenesis effective in consolidating the Himatnagar sandstones of N.Gujarat was all more important, because it has enabled the author to fully understand the bulk picture of the depositional environments under which these rocks have been formed.

Unlike carbonate diagenesis, where enormous literature is available; for sandstone diagenesis, only a few scanty published material is available (Waldschmith, 1941; Taylor, 1950; Held, 1955,1959; Pettijohn, 1957; Dapples 1959,1962, 1967, 1972 etc.) The most elaborate account of the sandstone diagenesis has been given by Dapples (op.cit.) as per below.

According to Dapples (1967), the chemical reactions which occur during each stage of diagenesis result in equilibrium mineral assemblages which are considered to identify the Ph and Eh of the interstitial fluids. Shifts in the directions of equilibria are indicated by corresponding changes in mineral assemblage. Although a secondary mineralogy characterised most of the diagenetic progression there may be also removal of detrital mineral matter to produce a simple residual mineralogy and special granular intersutured texture.

PROCESS OF LITHIFICATION

Lithification is the primary process of diagenesis and it mainly comprises compaction and cementation. Grains are bound together by several processes ranging from simple addition of cement to complex interlocking and welding of grains in which cement as such is not significant. Dapples (1967) has stated the following four processes of lithification with their broad characteristics.

SIMPLE CEMENTATION

A) Mineral precipitation

Crystallization of cement is due to permeating interstitial fluid only and the particles get lithified. Sand grains touch one another with point or tangential contact and held in position by simple cement precipitated in the interstitial pore space (Waldschmidt 1941; Taylor 1950). Calcite deposited in interstitial space of quartz is common and hematite precipitated in quartz pore spaces gives red colour of the rock, while opal or chalcedony in the intergranular space cause quartz and other grains to adhere. The resulting texture is the interlocking of grains and the aggregate ranges in degree of friability in inverse proportion to the amount of precipitated overgrowth.

B) Simple clay bond

Clay size particles occur either as interstitial fillings or as matrix. Sands are cemented as simple bond in which large grains are united through surface cohesion of the clay size particles. The rock (sandstones) of this type gets disaggregated when placed in water due to expansion of clays. The gluing action is due entirely to the cohesive of the clay size grains and water bonds.

COMPLEX BONDING

A) Grain solution

The chemical reaction takes place between the mineral grains and invading solutions, which bring the interlocking arrangement of the grains. The interlocking resulted either in concave-convex boundaries (Taylor 1950) or irregular (Sloss & Feray, 1948; Burma & Riley, 1955; Heald, 1955). Sometimes clay-quartz boundaries result from decomposition of felspar in the sediment where clay grains are seen either as preserved the original outline of the detrital felspar or are seen squeezed into interstices during compaction due to hydration and hydrolysis processes without reaction with contact mineral.

B) Intergranular reaction

The reaction takes place either between different minerals, replacing mineral with another and the development of third mineral along their common boundaries or the reaction between the clay size matrix and the large grains to produce a new mineral. The reaction could be during early or late burial and many workers consider them typical diagenetic.

STAGES OF DIAGENESIS

According to Dapples (1967) the diagenesis in the sandstones is brought about in three stages. In the early redoxomorphic stage of diagenesis characterised by mineral changes primarily due to oxidation and reduction reactions. This stage is typical of the unlithified sediments and passes into locomorphic stage. The locomorphic stage of diagenesis is characterised by prominent mineral replacement and typical of lithification of clastic sediments. In the advance phyllomorphic stage of diagenesis the progression towards metamorphism is characterised principally by authigenesis of micas and also felspars. The reaction tendencies or changes during these stages is described in brief as under :

A) Redoxomorphic stage (oxidation-reduction reactions)

In this stage of diagenesis, the mineral grains are constantly in a stage of movements without any physical or chemical equilibrium. The process of weathering helps in reduction of the minerals and leads to the concentration of resistates (quartz), precipitates (carbonate) and hydrolyzates (clay) components. The redoxomorphic changes initiates with initial compaction and ejection of fluids, leading to oxidation - reduction reactions. The chief reactants involved are iron oxygen, sulphur and carbon.

During the early stage of diagenesis ferruginous cement is more significant. In the oxidizing environments the oxygen gathers electron principally donated by iron bearing minerals to form stable hematite and related ferric oxides as matrix or pore filling. Here the mineralogical reactions between iron oxide and quartz (sand) grain is very little and grain matrix boundaries stand out very clearly. In oxidizing environment detrital biotite is unstable decomposing first to oxidized biotite and later to clay mineral and ferric oxides.

B) Locomorphic stage (cementation and mineral replacement)

During this intermediate stage of diagenesis, there is significant precipitation of mineral matter in the pore spaces, particularly as replacement of detrital mineral and primary cementation and development of induration takes place. This forms essentially a closed system where the chemical conditions are introduced by the infauna and the interstitial fluid. During this stage, individual particles come in contact, and when the deposition is slow the euqilibrium may be attained. The locomorphic changes are as under :

i) Chalcedony modification

In this stage the opal initially fills the interstitial pores which modifies to chalcedony or chert and finally to quartz. This modification is unidirectional and appears irreversible within the physical conditions of stability of sandstone.

Opal --> chalcedony --> quartz

This replacement is volume by volume and takes place in long span of times. The substitution of opal by fibrous chalcedony is commonly observed, where the chert precipitates and building up quartz grains giving rise to locally to highly silicified sandstone.

The replacement of clay and clay matrix by chert or chalcedony is not pseudomorphic, but rather a insitu substitution of one mineral for another. The chert replacing interstitial clay grades through microcrystaline quartz to detrital quartz or may be transitional into quartz overgrowth.

Precipitation of quartz directly as overgrowth on detrital grain is common during locomorphic stage of diagenesis. The quartz precipitate is in crystallographic continuity with detrital grain. The authigenic enlargement on individual grain can be usually distinguished from detrital quartz by lines of impurities, dirty surface of the original quartz grains which are clouded by minute inclusions. The boundaries of the grain will be minutely crenulated in contrast to its limpid authigenic rim or sometimes sharp euhedral crystals of overgrowth quartz.

ii <u>Calcite replacement of clay</u>

The carbonate cement tends to replace the earlier clay matrix and replacement is so complete that gives the impression that original particle size distribution contain virtually no clay minerals. The clay minerals like illite and kaolinite are flocculated by calcium ion and occupy less interstitial space allowing the remainder to be filled by the precipitated carbonate. Replacement of clay mineral by calcite is favoured by a PH (8) and high concentration of Ca^{+2} ion under which conditions certain clay minerals become unstable.

Besides aragonite replacement by calcite, a calcite replacement by dolomite and siderite and felspar replacement by calcite may occur in some of the sediments during this stage.

c) Phyllomorphic stage (Authigenesis of micas and felspar).

The diagenetic modifications which may take place on a lithified aggregates are associated with late burial history. One of the most significant aspect of the phyllomorphic stage is the appearance of equilibrium mineral phase. It depends upon the degree of acidity and stage of oxidation-reduction existing during phyllomorphic stage. During this stage clay mineral alteres into mica and well developed crystallised phyllosilicate minerals. The phyllomorphic reactions are favoured by increase in pressure and temperature. During this stage large crystal of authigenic mica transect some of the cement precipitated during locomorphic stage and selected authigenic mineral association are considered to be equilibrium mineral representing limited ranges in bulk compositions.

The precipitation or crystallisation of muscovite appears to be preferred over other micas either because its lattice is more readily developed from most of the clay minerals or perhaps it is stable under the most common condition of burial. The crystallisation of muscovite is preferred in oxidizing environment, chlorite preferentially crystallises under reducing conditions. However the co-existence of chlorite and muscovite indicates slightly more oxidizing environment during phyllomorphic stage.

DIAGENESIS IN HIMATNAGAR SANDSTONES

The textural and mineralogical studies observed in numerous thin sections clearly reveal all the three stages of diagenesis viz. redoxomorphic, locomorphic and phyllomorphic, that have brought the lithification predominantly by processes like simple cementation and complex bonding in Himatnagar sandstones.

Textural & mineralogical evidences

In few sections the diagenesis is evidenced by textural changes where the eatching and embayment of detrital grain by a crystalline mosaic with hazy or indistinct outline of original grain of pseudomorph replacement of one mineral by another is clearly visible. The quartz grains of these sandstones show authigenic overgrowth with sharp faces and this is another textural evidence for sandstone diagenesis (Plate IV.2). The interlocking crystalline mosaic texture found at some localities (Panpur, Ilol areas) suggests the diagenesis by chemical precipitation (Plate IV.17). As also the presence of ferruginous concretions found in Panpur exposures are the textural evidences (Plate III.8). The presence of authigenic micas in the interstitial quartz grains do suggest their development during diagenesis.

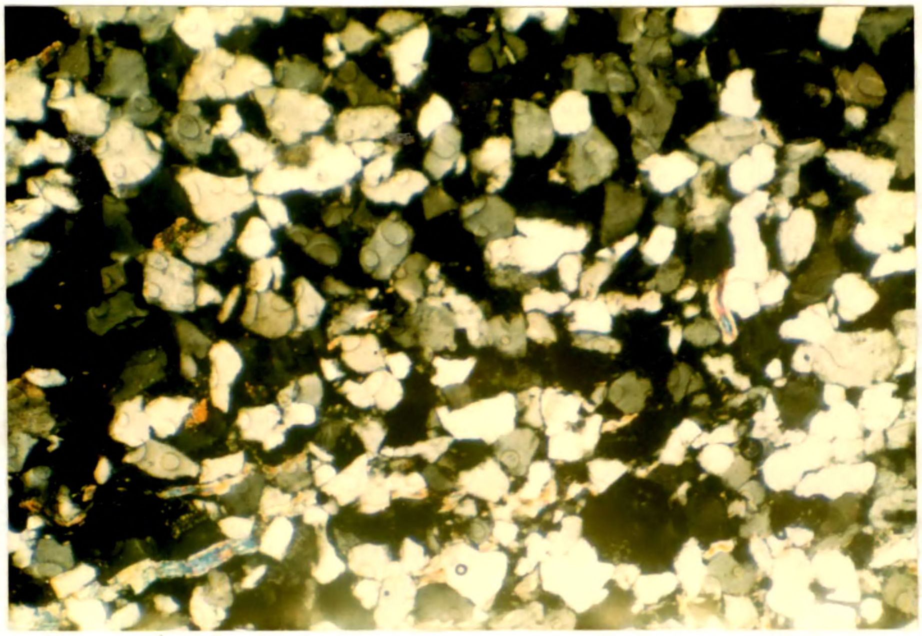
Stages of Diagenesis

The thin section studies provide ample data in support to decipher the various stages of diagenesis that the Himatnagar sandstones have undergone.

The early redoxomorphic stage of diagenesis is evidenced by their pink red colour due to crystallisation of opaque iron bearing minerals mainly hematite. This red pigment occurs in sandstone as (a) cementing material between the grains (Plate IV.3) (b) rim around quartz grain (Plate IV.18) and (c) isolated opaque grains in matrix and groundmass. The ferrugineous cement is seen in the number of lowlying and river bed exposures throughout the study area (Plate IV.19). It is suggestive of dominance of oxidizing environments during their deposition.

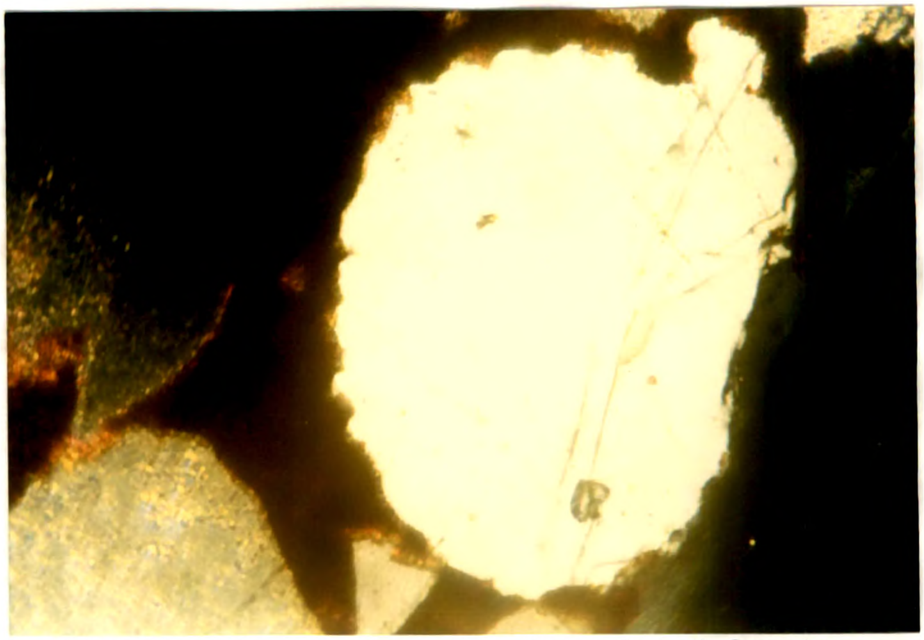
The intermediate locomorphic stage of diagenesis is recognised by the precipitation of primary cement (silica, chert,

PLATE IV.17



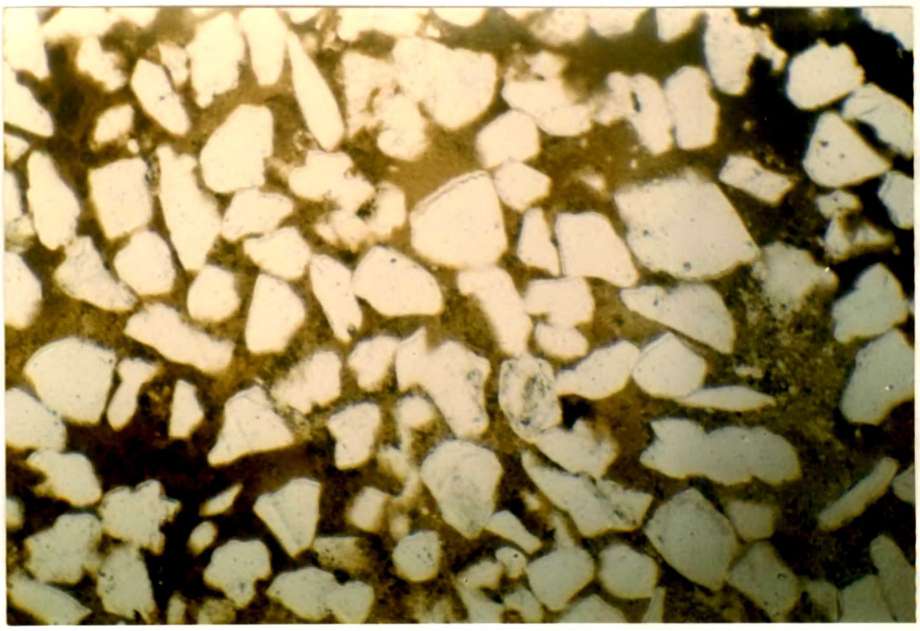
Photomicrograph Showing Interlocking
Texture in Sandstone
(Crossed Nicols, x 45)

PLATE IV.18



Photomicrograph Showing Crenulated Quartz
with Ferruginous Rim
(Crossed Nicols, x 120)

PLATE IV.19



Photomicrograph Showing Ferruginous Cement in Sandstones
(Polarised light, x 45)

chalcedonic, opal, argillaceous & calcareous) and authigenic overgrowth on quartz grain etc. in Himatnagar sandstones. The river bed and low lying exposures throughout the area possess predominantly siliceous cement. The thin sections of elevated ridges at Ghorwada, Berna, Gamdi, Wantra, Adpodra, Bodi & Phedhmala exhibit predominantly cherty to chalcedonic cement. At places opal cement is seen modified into cherty/chalcedonic cement (Plate IV.20); occasionally cherty/chalcedonic cement is replaced by calcareous cement (Plate IV.21). The Panpur exposures show authigenic overgrowth on quartz grains with line contact to concave-convex contact. The argillaceous cement of Ilol and calcareous cement of Sabarmati river bed exposures at Kadoli village indicates the locomorphic stage of diagenesis.

The phyllomorphic stage the advanced stage of diagenesis is represented in the Himatnagar sandstones by the presence of authigenic micas in the Hathmati river bed exposures near Himatnagar town and low lying exposures near village Panpur (Plate IV.22). The co-existence of chlorite and muscovite in sandstones occurring in the vicinity of Himatnagar town and also those lying NW indicate slightly more oxidizing environment during phyllomorphic stage.

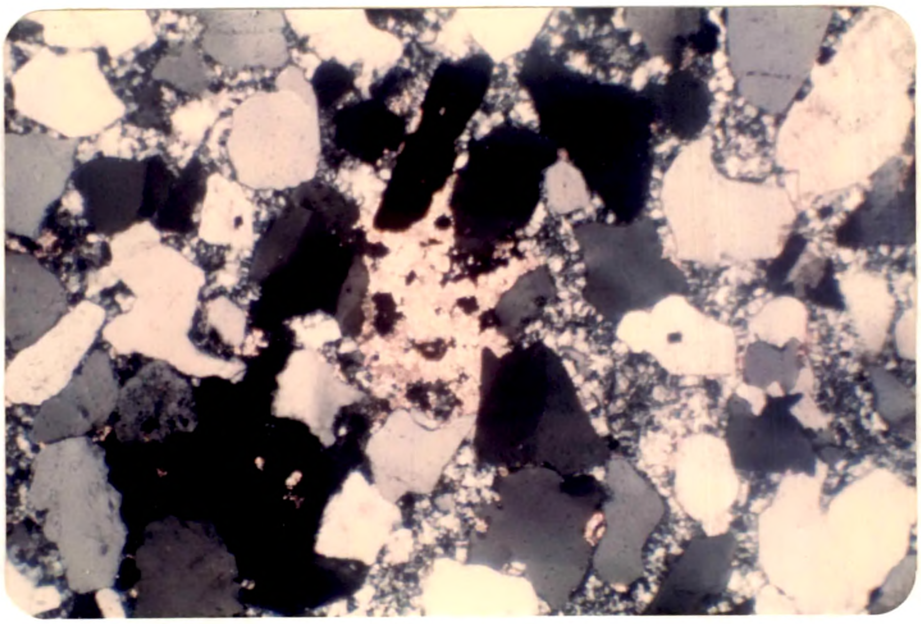
Source Material For Cementation

As mentioned earlier that the Himatnagar sandstones are cemented predominantly with siliceous and ferruginous minerals and occasionally argillaceous and calcareous material. The

PLATE IV.20

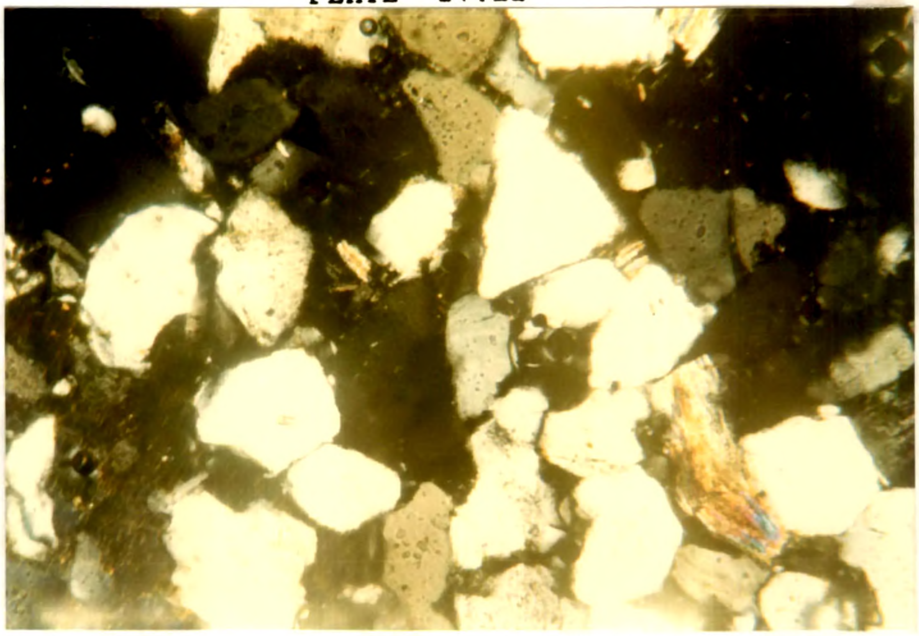
Photomicrograph Showing Modification of Opal into Chalcedony in Sandstones
O = Opal, C = Chert/Chalcedony, Q = Quartz
(Crossed Nicols, x 90)

PLATE IV.21



Photomicrograph Showing Replacement of Chert by Calcareous Cement in Sandstones
(Crossed Nicols, x 45)

PLATE IV.22



Photomicrograph Showing Authigenic Micas
in Sandstones
(Crossed Nicols, x 45)

probable source for the cementation could be due to one or more reasons for different types of cements.

Siliceous Cement

(a) Silica Cement

(1) The silica cement in the sandstones might have been derived from silica super saturated pore waters. The solubility of quartz in natural water at 25° c is above 10 ppm. The concentration of dissolved silica upto 80 ppm has been found in the natural water of modern sediment. In alluvial sands the shallow ground water of meteoric origin are constantly moving in course of supplying water to perennial streams and such extensive circulation may precipitate silica.

(2) The deep weathering of felspar and silicates by meteoric waters is a major source of silica. Here the hydrolysis of felspar grain by water containing carbon dioxide may precipitate excess of silica downdip in alluvial sands. Despite its nearness of provenance (Erinpura granite) the paucity of felspars in Himatnagar sandstone suggests deep weathering of granitic rocks. The chemical equilibrium is as per below :

$$2\ KAL\ Si_3O_8 + 2\ H + 2HCO_3 + 9\ H_2O \longrightarrow Al_2\ Si_2\ O_5\ (OH)_4 + 4\ H_4SiO_4 + 2K + 2HCO_3.$$

(3) The source of silica could be due to pressure solution.

The unconsolidated sand grains are subjected to pressure from the weight of overlying sediments. The two quartz grain bear high pressure and are strained. The strained portion of grain tend to go into solution which becomes super saturated in silica and precipitated around unstrained quartz. Thus the pressure solution simultaneously provides silica for precipitation as cement or authigenic overgrowth. The sandstones near Panpur and Himatnagar show these characteristics.

(4) The slowly rising ground water or during uplifting due to reduction in temperature the pore water supersaturated in silica may be expected to precipitate the excess of silica.

(5) The compaction of very fine grained sediments in early diagenetic history may expell silica rich water. The expelled water from smectile to illite diagenetic reaction in shale would provide si^{+4} ions.

(6) Silica can be derived by t ransformation of silicates including clay (Siever 1957).

(7) During recrystallisation process, amorphous silica or chalcedony is locally dissolved and is immediately reprecipitated as quartz.

(b) **Chert and Chalcedonic Cement.**

(1) The water in lateritic terrain may precipitate opaline silica or chert from the nearby source.

(2) Chert or chalcedony may be derived due to diagenetic modification from opal.

(3) Replacement of clay matrix and interstitial clay by chert or chalcedony.

Ferruginous Cement

The sources for the formation of the ferruginous cement could be from

(1) Mineral like biotite, tourmaline, hornblende in acid igneous rocks (Erinpura granites).

(2) Pyroxene,olivine and opaque ores in basic intrusives cutting the Pre-Cambrain in the nearby area.

(3) Minerals like staurolite, biotite, hornblende in metamorphic rocks like schists from the provenance area.

(4) The development of thin rim of hematite on quartz grain appears to be due to a chemical precipitation.

Argillaceous Cement

Argillaceous cement might have derived from the decomposition & disintegration of minerals in the weathering profiles of the argillaceous terrain and/or decomposition of biotite in oxidizing environment.

Calcareous Cement

The caleareous cement might have derived from $CaCO_3$ saturated water (Malkan, 1976) and/or replacement of clay matrix by carbonate material.

(B) PARTICLE SIZE ANALYSES

GENERAL

In order to understand the texture and probable depositional environment of Himatnagar sandstones, the particle size analyses of the sandstones from representative localities have been attempted. The granulometric studies was carried out for the sandstone samples from fining upward sequences, river bed exposures and the dug wells. Their depositional environments was made following the research contributions by Inman (1949), Folk and Ward (1957), Friedman (1961, 1967), Visher (1965,1969) etc.

Fifty grams of sandstone sample after disintegration and chemical treatment if any, is passed through standard mechanical sieves (half phi (ϕ) interval from -1 to 4.5 ϕ or ASTM Mesh 10 to 325 or 2000 to 44 micron opening) for fifteen minutes. From the retained weight of individual sieve the cumulative weight and cumulative percentage are worked out for representative value of Phi. The histograms/cumulative curves are prepared on arithmatic probability graph paper. The three straight line segments of cumulative curve reflect three modes of transport viz. (1)

suspension (2) saltation and (3) surface creep (Inman, 1949). The finer particles are held in suspension i.e. above the depositional interface due to turbulence. The truncation point between suspension and saltation generally varies and reflect the physical conditions at the time of deposition. In saltation population the medium fractions are deposited by interaction between traction carpet and graded suspension. It is also a product of moving grain layers. The amount of this population depends upon the stability of the moving bed layers and rate of deposition. The surface creep population is provenance controlled where in the coarser grains are deposited by sliding and/or rolling action reflecting the competence of the transporting currents. The truncation point with saltation is generally near -2 ɸ (0.25 mm); the point between Impact and Stoke's law of particle settling (Fuller, 1961). The cumulative curves are helpful to know the various statistical parameters by using the representative value of Phi (ɸ) against the cumulative percentage of 5,16,25,50,75, 84 and 95.

RESULTS & DISCUSSION

The sieving analyses of Himatnagar sandstones have been plotted on the cumulative curves (Fig. IV. 1 & 2). The statistical parameters obtained by using conventional formulaes from the cumulative curves have been shown in Table IV.1 The Graphic Mean (M_z) suggests that the sandstones are coarse to fine grained. Inclusive Graphic Standard Deviation (σ_I) indicates that they are poorly to moderately sorted. Inclusive Graphic

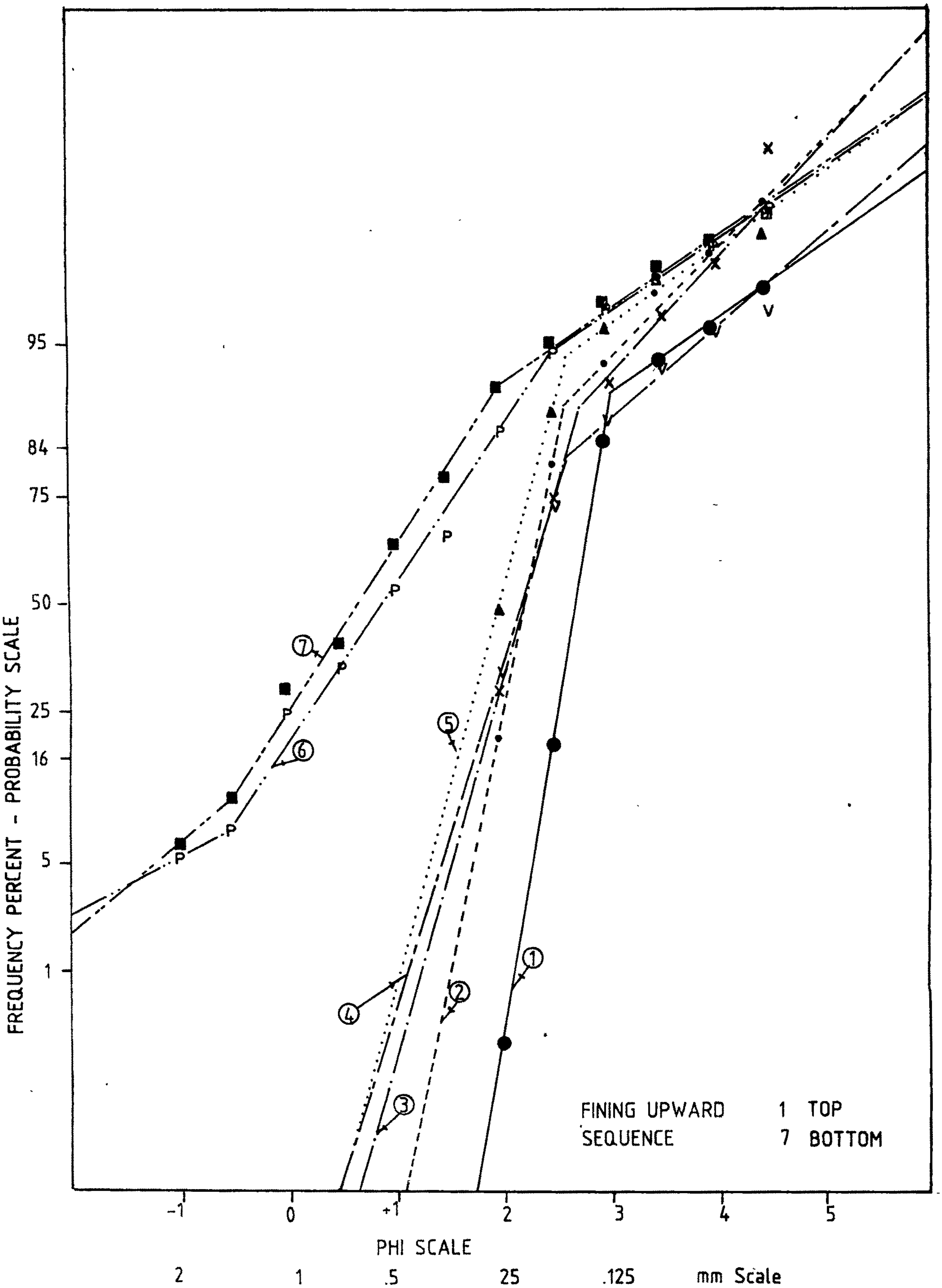


FIG IV 1 CUMULATIVE CURVES I - HIMATNAGAR SANDSTONES

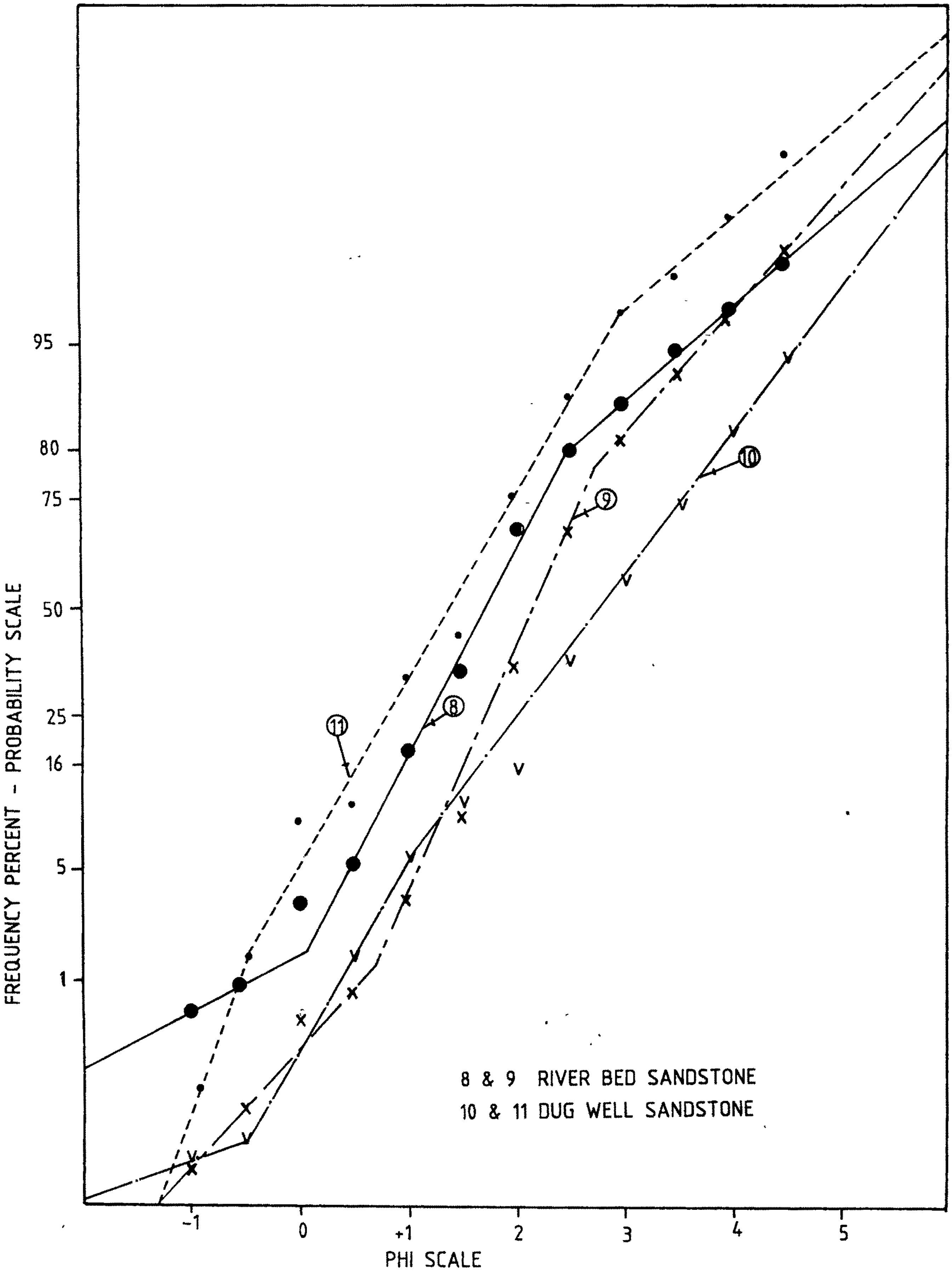


FIG. IV 2 CUMULATIVE CURVES II - HIMATNAGAR SANDSTONES

TABLE IV.1 STATISTICAL PARAMETERS OF PARTICLE SIZE ANALYSES OF HIMATNAGAR SANDSTONES

Sr No.	Graphic Mean	Inclusive Graphic Standard Deviation	Inclusive Graphic Skewness	Graphic Kurtosis	Simple Sorting Measures	Simple Skewness	Remark *			
							A	B	C	D
1	2.68	0.34	0.15	1.56	0.71	0.58	FS	VWS	FS	VL
2	2.23	0.37	0.16	1.51	0.74	0.48	FS	WS	FS	VL
3	2.20	0.47	0.13	1.25	0.88	0.45	FS	WS	FS	L
4	2.23	0.62	0.24	1.54	1.23	0.95	FS	MWS	FS	VL
5	2.0	0.42	0.05	1.08	0.73	0.15	MS	WS	NS	M
6	0.93	1.05	-0.02	1.12	1.85	-0.15	CS	PS	NS	L
7	0.5	1.05	0.01	1.21	1.93	0.05	CS	PS	NS	L
8	1.7	0.86	0.17	1.34	1.58	0.75	MS	MS	FS	L
9	2.27	0.69	0.14	1.30	1.28	0.55	FS	MWS	FS	L
10	2.88	1.01	0.05	1.18	1.83	-0.15	FS	PS	NS	L
11	1.43	0.8	0.03	1.04	1.4	0.0	MS	MS	NS	M

* A FS = fine sand, MS = medium sand, CS = coarse sand
B PS = poor sorting, MS = Moderate sorting, MWS = moderate well sorting,
Ws = Well sorting, VWS = very well sorting
C FS = fine skewed, NS = near symmertical
D VL = very leptokurtic, L = leptokurtic, M = mesokurtic

Locations 1 to 7 - Fining upward sequence in Hathmati river at Himatnagar
8 - Hathmati river at Himatnagar
9 - Sabarmati river at Arsoria
10 - Dug well near Gadhoda
11 - Dug well near Gadhoda

Skewness (SK_I) points to near symmetrical to fine skewed while the Graphic Kurtosis (K_G) shows that these sandstones are generally leptokurtic to very leptokurtic.

The cumulative curves indicate predominantly suspension and saltation population with surface creep population. The fine population (<0.25 mm) varies from 5 to 15 percent with suspension and saltation truncation point between 2 to 3 Phi. The saltation population has 70 to 80 percent of 0.75 to 0.25 mm (0.5 to 2 Phi) size particles. The surface creep population (0 to 10%) has maximum 2 mm particles size with truncation point with saltation between -0.5 to 0.5 Phi.

The results of sieving analyses represented on the plots (i) Inclusive Graphic Standard Deviation vs Inclusive Graphic Skewness (Fig IV.3) and (2) Simple Sorting Measure vs Simple Skewness Measure (Fig. IV.4) of Friedman (1967) indicate that the Himatnagar sandstones correspond to the river sands. The nature of the cumulative curves when correlated with the modern as well as ancient fluvial sands (Fig. IV.5) also suggest the dominance of fluvial environments for Himatnagar sandstones.

The surface creep population is absent in many fluvial sands as it is strongly provenance controlled. Whenever present, the fluvial environment being near to the provenance, the coarse grained particles may be deposited in the deepest part of channel during high energy (Visher, 1969). The studies of the fluvial sands of the ancient rocks by Visher (1969) indicate that

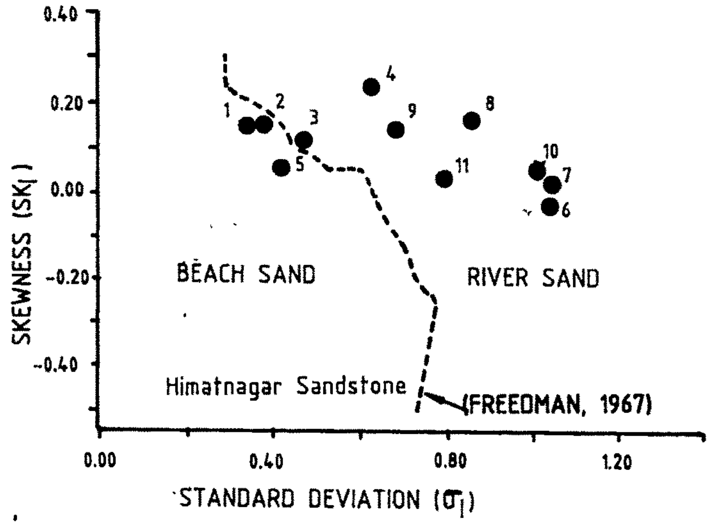


FIG. IV. 3 PLOT OF INCLUSIVE GRAPHIC SKEWNESS AGAINST INCLUSIVE GRAPHIC STANDARD DEVIATION FOR HIMATNAGAR S.STONES.

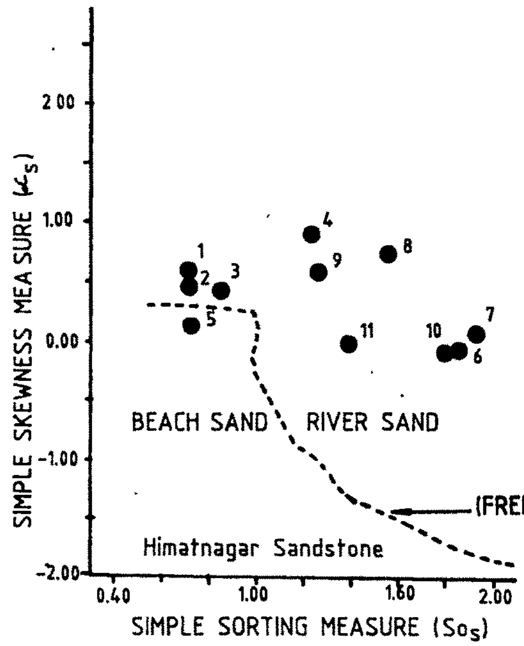


FIG. IV.4 PLOT OF SIMPLE SKEWNESS MEASURE AGAINST SIMPLE SORTING MEASURE FOR HIMATNAGAR SANDSTONES.

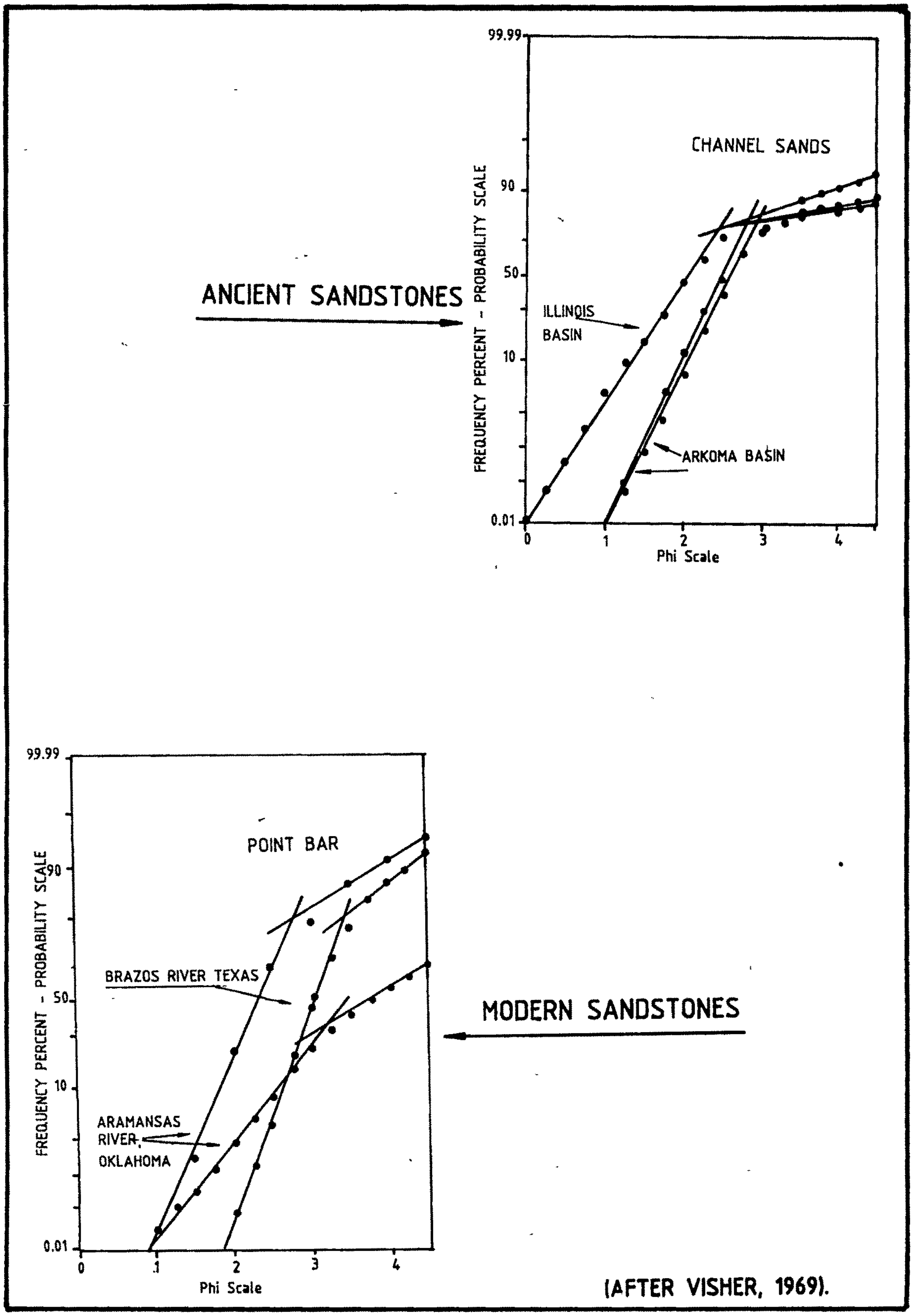


FIG. IV 5 ANCIENT AND MODERN FLUVIAL SANDSTONES suspension population varies from 2 to 30% and suspension and saltation truncation point between 2.75 to 3.5 Phi. According to Friedman (1967), the fine grained tail of cumulative curve is always present in river sands. The particle size analyses of Himatnagar sandstones match with these observations. The presence of coarse and fine tailed population in these sandstones has given positive skewness and poor sorting which is the characteristic of fluvial sands. The fluvial regime has unidirectional flow where the fine particles are moving along coarse grains. During sediment transport vertical motions are associated with irregular eddies in turbulent flow and supply of fine particles continues from upward directions hence these fine particles get confined within channel except flood stage (Visher, 1969). Thus the particle size analysis of the study area clearly suggest the dominance of fluvial environments for the deposition of Himatnagar sandstones.

(C) DRAINAGE STUDIES

General

The drainage basin analysis has become an useful tool in geomorphological studies in last many years. A systematic approach for quantitative analysis of a drainage basin has been represented in the classic research contribution by Subramanyan (1974) and the same methodology has been followed in drainage basin analysis of Himatnagar area. Accordingly the various parameters for drainage studies has been broadly delineated in the following paragraphs.

The stream order has been worked out as per the strahler's (1957) method, where the smallest unbranched stream segment is the first order stream, by merging of two first order segments second order stream form and so on. The number of stream segments in each order can be counted and graphical representation on the semilogarithmic paper generally yields straight line plots from which their best fitting regression exponential form can be obtained. The Bifurcation Ratios can be calculated by relating the number of streams of one order to the streams in the next lower order; the mean ratios is the average of the bifurcation ratios. Sometimes the local influence of lithology, lineaments etc. may give abnormal mean ratios which can be toned down by calculating the weighted mean ratio by considering the actual streams involved in the bifurcation ratios (Strahler; 1953). The length of streams in different orders can be measured by the length measuring device and total length and mean length for each order can worked out. The length ratios is the ratio of the mean length of a given stream order to the mean length of the next lower order stream. The graphical plots of mean lengths against stream orders on semilogarithmic paper generally yields straight line. The weighted mean length ratios can also be worked out. The area of stream orders can be measured planimetrically and mean area of each order can be obtained. The area ratio can be computed by taking the pairs of stream orders and mean area. Weighted mean area ratios can also be worked out. The semilogarithmic plots of mean basin area against stream order generally yields straight line. The drainage density gives the mean length of the stream within a basin per unit area (Horton, 1932) and is obtained by dividing the total stream length by the total basin area. Stream frequency refers to the number of streams per unit area (Horton, 1945) and is computed by dividing the total number of stream by the total drainage basin area.

STUDY AREA

Though the detailed quantification of drainage basins for entire Himatnagar area is beyond the scope of present study, the author has attempted linear aspects only for stream orders, stream numbers, bifurcation ratios, stream lengths, length ratios, stream areas, area ratios, drainage density and stream frequency for the small part of basin representing alluvium, sandstones, granites and quartzites which have been described as per below.

(i) Stream Orders

The stream order for various rock units have been worked out following strahler's (1957) system and accordingly the alluvium, sandstones and granites are the fourth order stream while that of quartzite is the third order stream (Table IV.2).

(ii) Bifurcation Ratios

The number of streams in each order, their Bifurcation Ratios, mean ratios and weighted mean ratios have been tabulated

TABLE IV.2 BIFURCATION RATIOS OF DRAINAGE BASINS

STREAM ORDER	ALLUVIUM				SANDSTONE				GRANITE				QUARTZITE			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
I	82				83				41				24			
		4.01	102	418.2		4.882	100	488.2		4.555	50	227.8		4.8	29	139.2
II	20				17				9				5			
		6.667	23	153.3		4.25	21	89.3		4.5	11	49.5		5.0	6	30.0
III	3				4				2				1			
		3.0	4	12.0		4.0	5	20.0		2.0	3	6				
IV	1				1				1							
TOTAL	106		129	583.5	105		126	597.5	53		64	283.3	30		35	169.2
MEAN		4.5				4.3				3.685				4.9		
WEIGHTED MEAN		4.5235				4.742				4.426				4.834		
FROM FIG. IV.6		4.217				4.217				3.876				4.897		

Column : 1 = Number of Stream, 2 = Bifurcation Ratios, 3 = No of Streams used in Ratios,

4 = Product of 2 & 3 Weighted Mean = Total of column 4 / column 3

in table IV.2. It is observed that the number of stream decreases as the stream order increases. The semilogarithmic plots of stream number against stream order yields straight line. (Fig. IV.8). This satisfy Horton's (1945) first Law of Stream Order i.e. "the number of streams of different order in a given basin tend closely to approximate an inverse geometric series in which the first term unity and the ratio is the Bifurcation Ratio". The most of the Bifurcation Ratios fall between 4 and 5 which is slightly higher than the universal range (3 to 4) for maturely dissected drainage basins. Occasional higher Bifurcation Ratio could be due to hard nature of rocks or due to lineaments, which might have retarded the merging of the streams of same order and joining directly to the higher order streams.

In the plots of stream order against stream number the best fitted regression exponential were obtained (Fig. IV.8). These regression coefficients represent logarithms of the Bifurcation Ratios (Strahler, 1968) viz. 0.625, 0.625, 0.488 and 0.69 for alluvium, sandstones, granites and quartzites respectively. The Bifurcation Ratios obtained from these coefficients are 4.217, 4.217, 3.076 and 4.897 which fairly well matched with their respective mean Bifurcation Ratios i.e. 4.5 (alluvium), 4.3 (sandstones), 3.685 (granites) and 4.9 (quartzites). The weighted mean Bifurcation Ratios also fairly match well with the mean ratios as well as most of the individual Bifurcation Ratios (Table IV.2) suggesting the normal development of drainage basins. However the slight departure in ratio values could be due to influence of lithology and/ or lineaments.

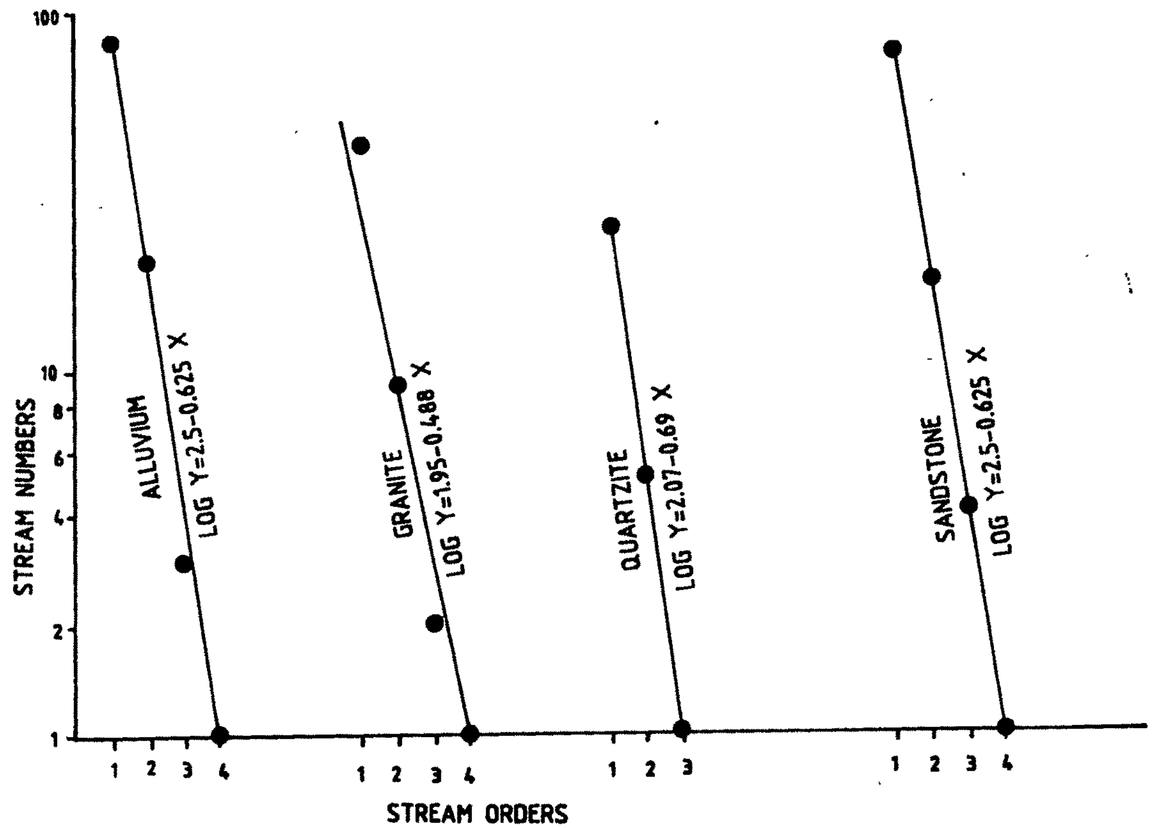


FIG. IV 6 SEMI-LOGARITHMIC PLOTS OF STREAM NUMBERS AGAINST STREAM ORDERS

(iii) Length Ratios

The stream lengths, the mean lengths, the length ratios, the mean length ratios and the weighted mean length ratios of different stream orders representing alluvium, sandstones, granites and quartzites have been shown in Table IV.3. It has been observed that the mean length of stream increases with stream order in direct proportion except for the third order stream of sandstones and granites. The semilogarithmic plots of mean stream length against stream order yields straight line plots excluding the third order data of granites and sandstones (Fig. IV.7). These data in general satisfy Horton's (1945) second Law of Stream Length which states that "the average lengths of streams of each of the different order in a drainage basin tend closely to approximate a direct geometric series in which the first term is the average length of the streams of the first order". The anomolous length of third order streams representing sandstones and granites could be due to preferential flow of streams along lineaments which might have resulted into abrupt integration of two third order streams in a short distance.

The length ratios obtained from the regression coefficients for the basins (Fig. IV.7) are 2.27, 2.13, 2.66 & 2.29 against their respective weighted mean ratios i.e. 2.12, 1.85, 4.76 & 2.1 for alluvium, sandstones, granites and quartzites (Table IV.3). The anomalous values of the mean length ratios could be due to the lineament configuration.

TABLE IV.3 STREAM LENGHTS AND LENGTH RATIOS OF DRAINAGE BASINS

STREAM ORDER	ALLUVIUM			SANDSTONE			GRANITE			QUARTZITE		
	1	2	3	1	2	3	1	2	3	1	2	3
I	36	0.44		60	0.723		25	0.61		15	0.625	
			1.25			1.71			5.65			1.6
II	11	0.55		21	1.235		31	3.444		5	1.0	
			6.06			0.81			0.36			4.5
III	10	3.33		4	1		2.5	1.25		4.5	4.5	
			1.5			9.0			6.0			
IV	5	5		9	9		7.5	7.5				
MEAN			2.94			3.84			4.0			3.05
WEIGHTED MEAN			2.12			1.85			4.76			2.1
FROM FIG. IV.7			2.27			2.13			2.66			2.29

Column : 1 = Total stream length, 2 = Mean length, 3 = Length ratio, Length in km.

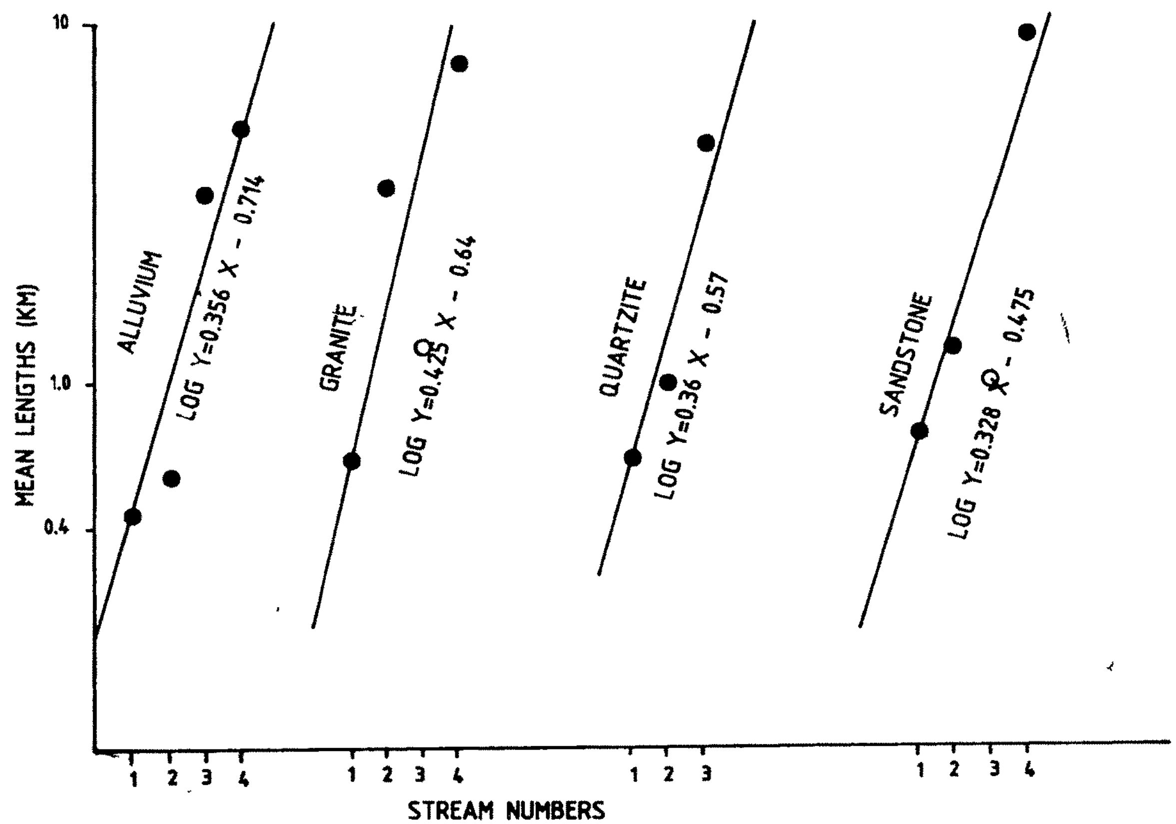


FIG IV 7 SEMI-LOGARITHMIC PLOTS OF THE MEAN STREAM LENGTHS AGAINST STREAM ORDERS.

The logarithmic plots of the total stream lengths against stream order (Fig. IV.8) are in general linear and satisfy the revised Law of Stream Length (Chorley, 1957) which states that "the total lengths of streams of each of the different stream order in a drainage basin tend closely to approximate an inverse logarithmic series in which the first term is the total length of streams of the highest order". The anomolous plots in respect of sandstones and granites also substantiate the influence of lineaments in drainage development.

(iv) Area Ratios

From values of the mean basin areas, the area ratios, the mean area ratios and the weighted mean area ratios representing alluvium, sandstones, granites and quartzites it has been observed that the mean area of basin increases with stream order (Table IV.4). The semilogarithmic plots of mean drainage basin area against stream order yields straight line (Fig. IV.9). This satisfy Schumm's (1956) Law of Drainage Basin Area which states" the mean drainage basin areas of streams of each order tend to approximate closely a direct geometric series in which the first term is the mean area of the first order basin". In these plots according to Chorley (1957) "the coefficient of the fitted regression represents the mean area ratio". The regression coefficients in Fig. IV.9 are 0.8, 0.741, 0.735 & 0.833 and mean area ratios obtained from these data are 6.31, 5.51, 5.43 & 6.81 against their weighted mean area ratios 5.64, 5.17, 11.30 & 6.34 for alluvium, sandstones, granites and quartzites respectively.

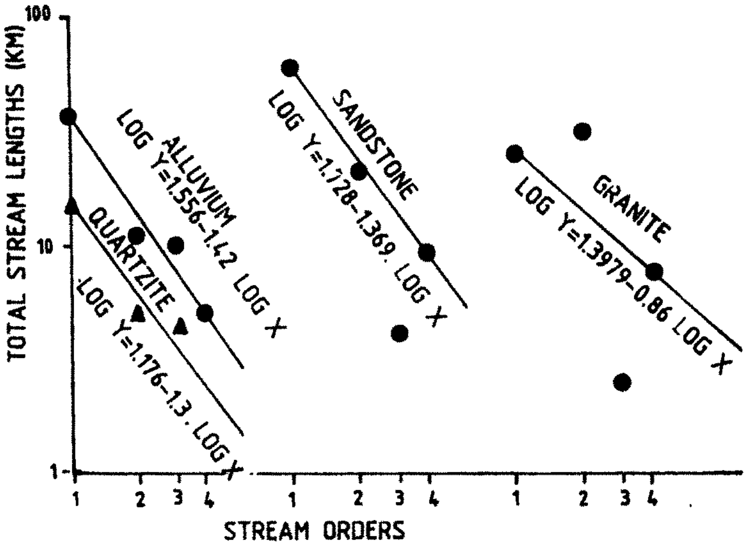


FIG IV 8 LOGARITHMIC PLOTS OF THE TOTAL STREAM LENGTHS AGAINST STREAM ORDERS.

TABLE IV.4 AREA RATIOS OF DRAINAGE BASINS

STREAM ORDER	ALLUVIUM		SANDSTONE		GRANITE		QUARTZITE	
	1	2	1	2	1	2	1	2
I	0.146		0.341		0.268		0.212	
		2.84		5.45		13.69		5.9
II	0.415		1.859		3.67		1.25	
		18.07		2.58		1.91		8.48
III	7.5		4.8		7.0		10.6	
		5.63		10.56		6.84		
IV	42.25		50.7		42.25			
MEAN		8.85		6.20		7.21		7.19
WEIGHTED MEAN		5.64		5.17		11.30		6.34
FROM FIG. IV.9		6.31		5.51		5.43		6.81

Column : 1 = Mean area, 2 = Area ratios, Area in km

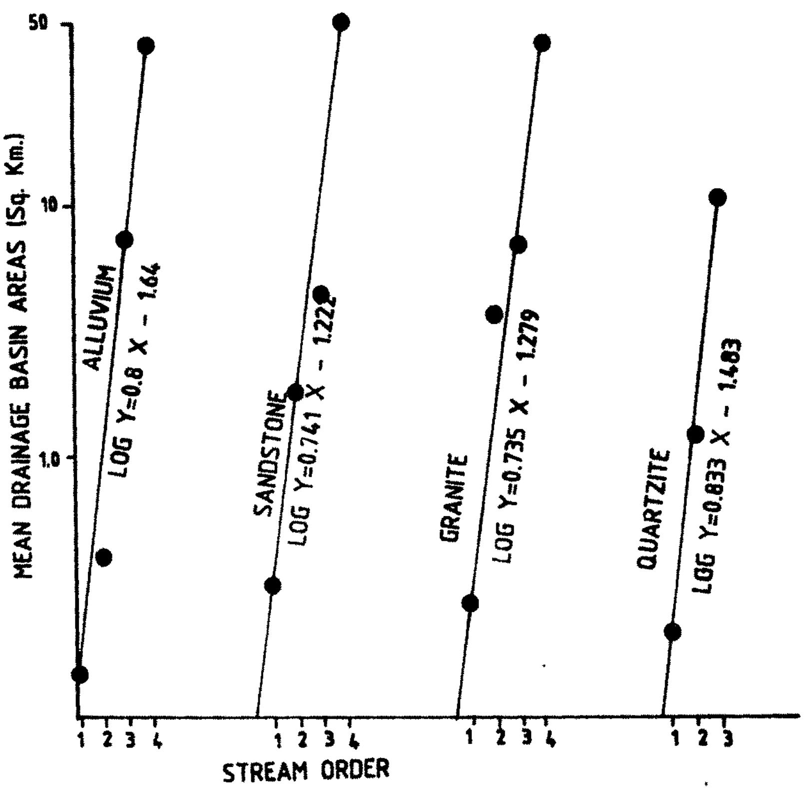


FIG. IV 9 SEMI-LOGARITHMIC PLOTS OF THE MEAN DRAINAGE AREAS AGAINST STREAM ORDERS.

The anomalous values in case of granites is due to the larger second order streams and small third order streams perhaps controlled by lineaments resulting into abrupt integration of two third order streams. The plots of stream lengths against contributing area (Fig. IV.10) and mean stream lengths against mean basin areas (Fig. IV.11) show straight line. The anomalous points in these plots could be due to the influence of lithology and lineaments.

(v) Drainage Density and Stream Frequency

The drainage density of the streams under study are 1.487, 1.854, 1.582 & 2.31 for alluvium, sandstones, granites and quartzites terrain respectively while these rocks respectively show stream frequency 2.51, 2.071, 1.254 and 2.84 (Table IV.5).

Thus the drainage analysis suggests that the lithology and lineaments has influence in the drainage development of Himatnagar area.

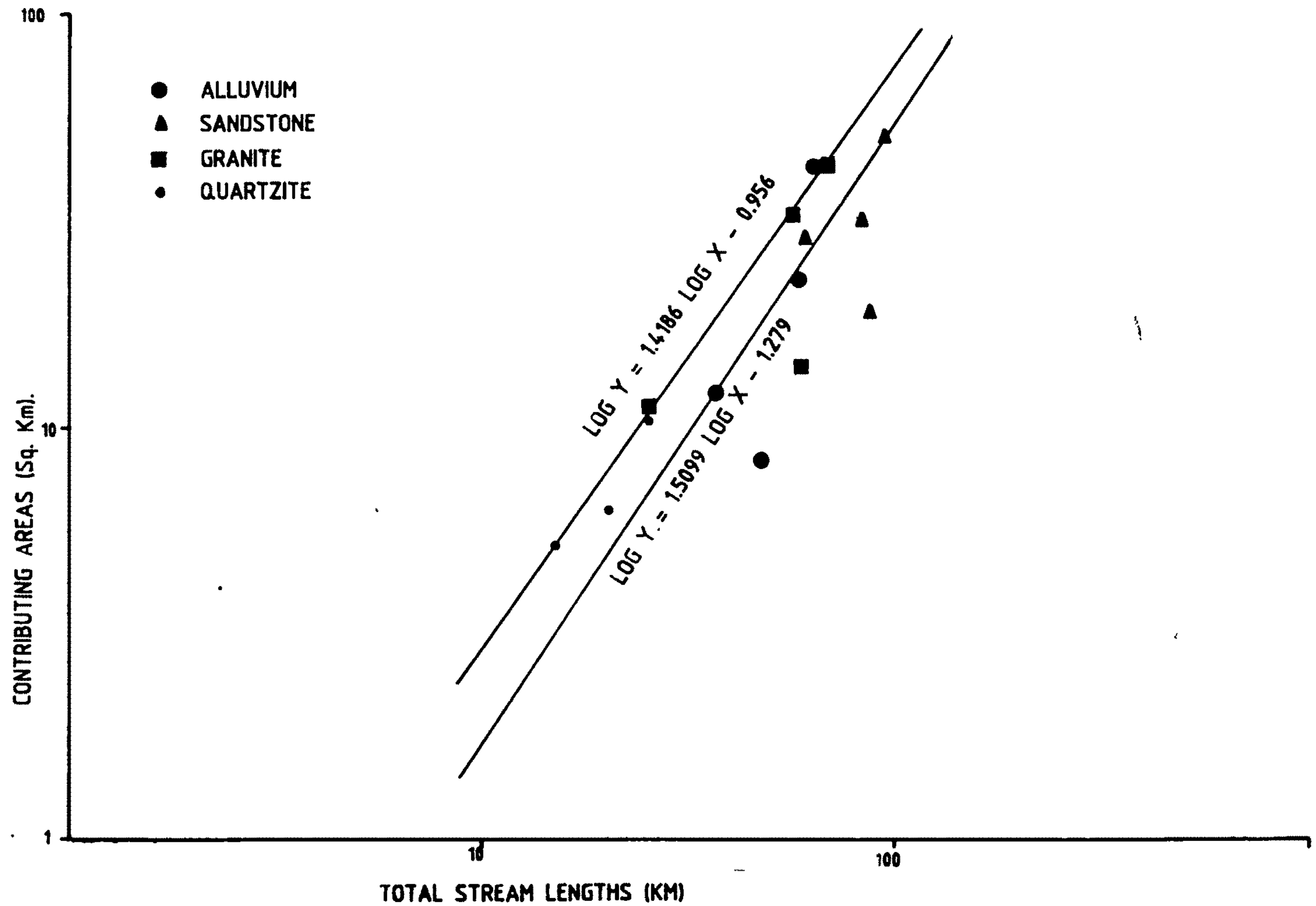


FIG. IV. 10 LOGARITHMIC PLOTS OF THE TOTAL BASIN AREAS AGAINST TOTAL STREAM LENGTHS

TABLE IV.5 TOTAL AREAS, TOTAL LENGTHS DRAINAGE DENSITY AND STREAM FREQUENCY OF DRAINAGE BASINS

STREAM ORDER	ALLUVIUM		SANDSTONE		GRANITE		QUARTZITE	
	1	2	1	2	1	2	1	2
I	12	36	20.3	60	11	25	5.1	15
II	8.3	47	31.6	81	33	56	6.25	20
III	22.5	57	19.2	85	14	58.5	10.6	24.5
IV	42.25	62	50.7	94	42.25	66		
DRAINAGE DENSITY	1.467		1.854		1.562		2.31	
STREAM FREQUENCY	2.51		2.071		1.254		2.83	

Column : 1 = Total area, (Sq.km), 2 = Total Length (km),

Drainage Density = Column 2/column 1

Stream Frequency = Total Stream/Total area