Geol. Bull. Univ. Peshawar, 1983, Vol. 16, pp. 65–83

PETROGRAPHY AND GEOCHEMISTRY OF THE SIWALIK SANDSTONE AND ITS RELATIONSHIP TO THE HIMALAYAN OROGENY

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ABSTRACT

The Siwalik molasse of post Eocene age, exposed along the western limb of the Makarwal Anticline (Surghar Range), has direct relationship with uplifting episodes of the Himalayan mountains present to their north. Detailed petrography of the sandstones together with chemical analyses of a few selected samples indicate varied mineral assemblages and major oxide proportions for Lower, Middle and Upper Siwalik. Thus the Siwalik molasse, which is hitherto classified on the basis of sandstone and shale proportions and the variations in their colour, may also be divided into different units on the basis of mineral assemblages and major oxide geochemistry, or at least these aspects can be used for subsurface correlation in limited domains of the Siwalik belt.

Regarding the source rocks, carbonates were major contributor along with other rocks during the deposition of the Lower Siwalik. The presence of igneous and metamorphic rock fragments along with medium to high grade metamorphic minerals suggest crystalline rocks as the source of the Middle Siwalik. Such a mineral assemblage has also been reported from the Middle Siwalik of India, indicating unroofing of crystallines on a regional scale in the source area. Common occurrence of zircon in the Middle Siwalik seems to have some relationship with recently reported radioactive mineralization. The Upper Siwalik seem to have been derived from the foredeep sediments (Lower and Middle Siwalik) which were involved in the southward prograding orogenic activity by the Pleistocene period.

INTRODUCTION

The foothills along the southern flanks of the Himalayas consist predominantly of molasse comprising sandstones, siltstones, mudstones and conglomerates. These sediments are believed to be a direct product of the Tertiary Himalayan orogeny. The detrital material eroding away from the rising Himalayas deposited in a linear basin intervening between the Himalayas in the north and the Indian shield to the south. The continuing orogenic activity and its southward progradation (Le Fort, 1975; Powell and Conaghan,1973) kept on feeding the basin with continuous supplies of detrital material, extending its regimes further to the south.

In India the Himalayan molasse sediments are restricted to a narrow belt (5–50km wide), however, in Pakistan they are exposed over considerable width (100km) mainly because of the tectonic control of NW Himalayan syntaxial bend, oroclines and reentrants (Sarwar and DeJong, 1979; Calkins *et al.,* 1975). These rocks have been, for the last one hundred years, the subject of geological investigations both in India and Pakistan. The various aspects of these studies include lithostratigraphic classifications, vertebrate palaeontology, structure and, recently, the magnetic reversal stratigraphy (McMahon, 1883; Oldham, 1893; Pascoe, 1919, 1964; Pilgrim, 1919; Wadia, 1932; Krynine, 1937; Krishnan *et al.,* 1940; Keller, 1977; Johnson et al., 1972; McMurtry, 1980; Raynolds, 1980). There is an apparent lack of petrographic and geochemical work on the Pakistani part of the Siwalik belt, although in India these aspects appear to have been given due attention (e.g., Ganju, *et al.,* 1962; Khakwal, 1969). These studies are useful not only that they can suppliment the stratigraphic divisions but they can be used to unravel the nature of the source rocks and unroofing history of their parent orogenic belts. Our's is an attempt in this context to add up some petrographic and geochemical data on the Siwalik rocks to the existing informations contributed by Krynine (1937), Keller *et al.,* (1977) and Chaudhri (1970. 1971).

This study is based on geological details of a selected traverse across the molasse sequence exposed in the western flank of the Surghur Range (Fig. 1). The study area is located in the southern part of the Karak district and is bounded by Lat. 32° 11′ – 20′, and long. 71° 42′ – 49′. Stratigraphically the molasse sequence of the study area falls in the Siwalik Group and the older molasse rocks of the Rawalpindi Group are missing. The Siwalik group is divisible into Lower, Middle and Upper Siwalik; the Lower and Upper Siwalik comprising over Chinji and Soan Formations, respectively, whereas the Middle Siwalik consists of Nagri and Dhok Pathan Formations. In this article, however, we have restricted ourselves to the terminology of Lower, Middle and Upper Siwalik.

The major part of this study is based on petrographic details of the sandstone samples from various stratigraphic levels in the sequence. Some of the samples have also been analyzed geochemically in order to observe the variations in major oxides across the sequence, with respect to the variations in modal composition. In addition, the paper contains a brief description of two measured sections in terms of fluvial stratigraphy, and a limited discussion of the provenance and environments of deposition of the sediments under consideration.

LOCAL GEOLOGY AND FLUVIAL STRATIGRAPHY

The study area is a part of the Surghar Range, which is the western extension of the Salt Range across the Indus River. Structurally it is a 9°S plunging anticline, with an approximately NS trend from Isakhel up to Makarwal where it follows an EW trend (Fig. 1). The eastern limb of the anticline is considerably disturbed and down-faulted along the Makarwal thrust (Farooqi, 1980) while the western limb is relatively less disturbed, exposing a sedimentary succession of Triassic to Pleistocene age. The outer part of the western limb, comprising Siwalik sequence and the main object of this paper, dips 56° and 40°. No major fault

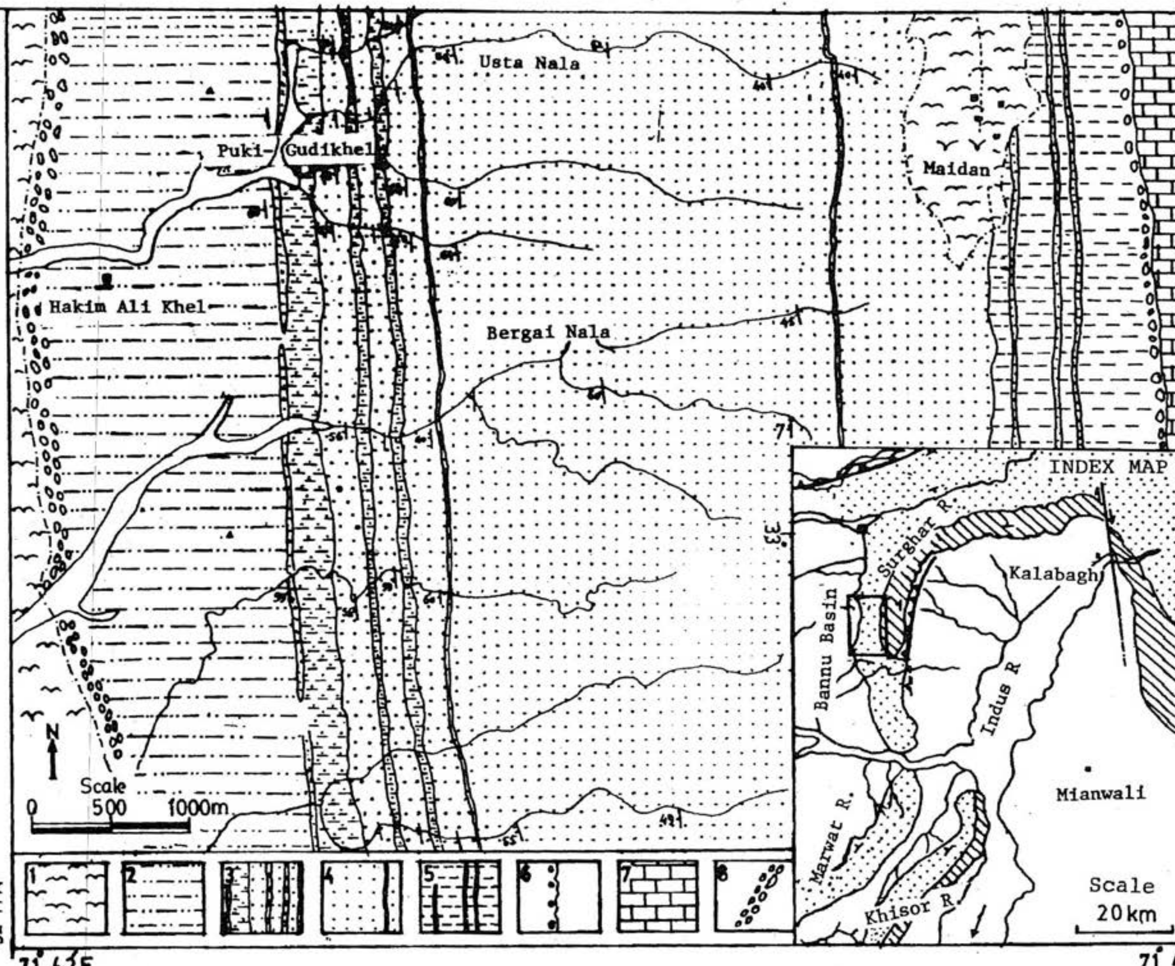

Fig. 1. Geological map between Puki-Gudikhel and Maidan, Surghar Range, Karak. (1) Alluviam. (2) Soan Formation, (3) Dhok Pathan Formation, (4) Nagri Formation, (5) Chinji Formation, (6) Unconformity, (7) Sakesar Limestone, (8) Conglomerate.

has been observed in this Siwalik sequence except some local block dislocations which do not have much extension. Joints, which are not common, generally make gentle angles with the bedding plane. Sedimentary structures like cross-bedding, graded-bedding, ripple marks, slumps in the .current-bedded rocks and heavy mineral layers are present in the sandstone beds. Lithologically the Siwalik sequence mainly comprises of alternate sandstone and shale with occasional thin beds of conglomerate. The mutual proportions of the three rock-types vary rather erratically across the whole Siwalik section.

At the base of the Lower Siwalik, a conglomerate bed of about 30 meter thickness separates marine deposit from fluviatile sediments, and is mainly composed of pebbles and boulders of Sakesar limestone. It is orthoconglomerate at the bottom and gradually changes into paraconglomerate towards the top. The rest of the Lower Siwalik unit comprises of reddish shale with subordinate brown grey sandstones. The sandstone is medium-bedded and normally devoid of cross-bedding.

The lower part of the Middle Siwalik (Nagri Formation) is entirely composed of sandstone with only a few shale beds in lower and upper parts which do not have much lateral extension. The fine- to coarse-grained sandstone normally occurs in thin to medium beds and is massive, cross-bedding being a common feature. Heavy mineral layers and clay balls are common while carbonaceous wood logs and limonite patches are rarely present. Hard bands, which are frequent in this part, range in size from a few centimeter up to tens of meter. They are commonly parallel to the bedding plane while inclined and rarely conjugate hard bands are also present. The conglomerate beds in the sandstone mainly comprise of pebbles of quartzite, limestone, metamorphic and igneous rocks. The upper part of the Middle Siwalik (Dhok Pathan Formation) is composed of alternating sandstone and shale beds with occasional thin beds of conglomerate. Sandstone is white to grey in colour, medium- to coarse-grained and characterized by well-developed cross-bedding. Clay balls, hard bands,. gradded bedding, heavy mineral layers and limonite patches are, however, comparitively less common. The thicknesses and colours of the shale beds vary from bottom to top. These are thin-bedded and dark greyish-black at the base and brownish, thick-bedded in the upper part of the unit.

The Upper Siwalik, composed of brownish sandstone and shale with conglomerate beds, are not well developed in the study area. The sandstone is medium-grained, loosely cemented, containing rare cross-bedding and heavy mineral layers. The conglomerates mostly carry pebbles from the Middle Siwalik. Thickness and lateral extension of the sandstone beds of Upper Siwalik is less than that of Middle and Lower Sikalik which may suggest high sinuosity fluvial system.

Fluvial Stratigraphy. Two measured stratigraphic sections, 4km apart in the upper part of the Middle Siwalik (Dhok Pathan Formation), are interpreted in terms of fluvial stratigraphy (Fig. 2). Allen's (1965) concept of fining upward cycle (i.e., laterally accreted channel deposit and vertically accreted flood plain

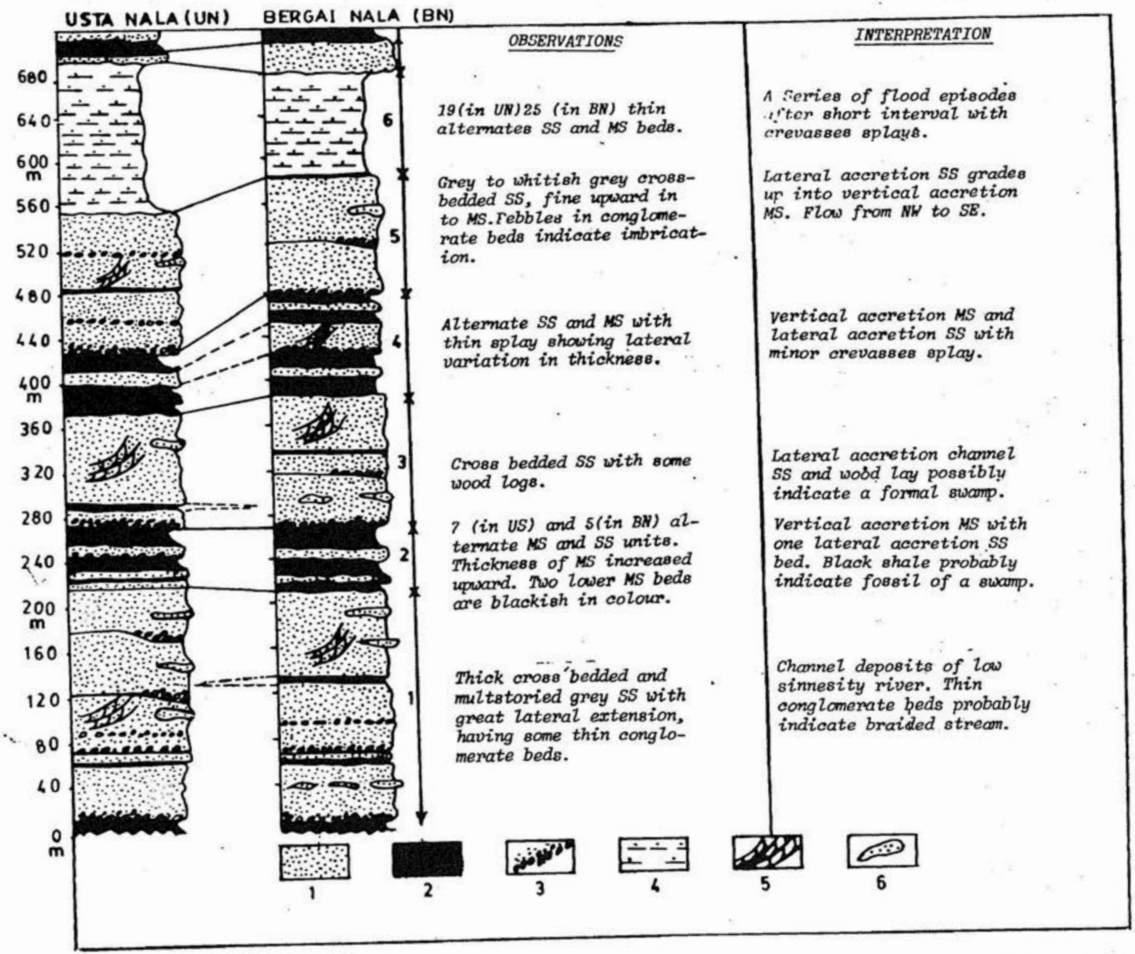

Fig. 2. Comparison of the measured stratigraphic sections. They are representing inter relationship of snadstone (SS), mudstone (MS) and their lateral variation in the Middle Siwalik (Dhok Pathan Formation). (1) Sandstone, (2) Mudstone, (3) Conglomerate, (4) Alternate sandstone and mudstone, (5) Cross-bedding, (6) Hard concretion.

deposit) is generally applicable. Thick, continuous sandstone beds, which are sometime superimposed on each other forming multistoried sequence, are suggestive of low sinuosity fluvial system. Possibly, river path was restricted during their deposition, thus indicating long duration of environments. This evidence is further supported from modern example of thick sandstone deposition in Jhelum river which is restricted between the Rohtas and Pabbi structures (Jhonson, pers. com.). Thin conglomerate beds in sandstone units are interpreted as channel lag deposit, the clasts of which are commonly extrabasinal except for Upper Siwalik, where these are mostly intrabasinal. These channel lag deposits are most characteristic of high energy braided stream (Reineck and Singh, 1975). The presence of mudballs provide an evidence that stream erosion was concurrent with stream deposition

Overbank mud facies is the product of suspended sediments during flood stage. This fact is also supported by sharp contact between channel sand and overbank deposits (Fig. 2). Some mudstone beds show bioturbation which gives an evidence of sub-aerial exposure (Thampson, 1970). Thin sandstone beds, present in

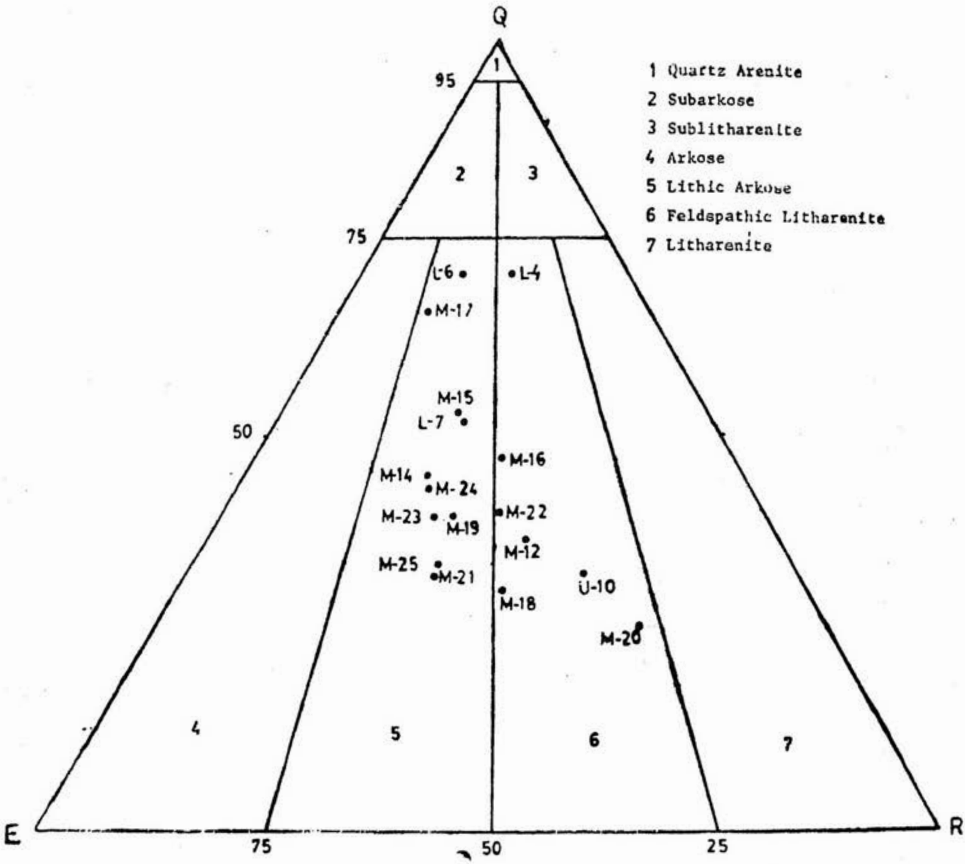

Fig. 3. Classification of Siwalik Sandstone, according to Folk's (1968) Q.R.F. diagram Q, Quartz; F, All feldspar; R, All rock fragments.

thick mudstone beds, are interpreted as crevasses splay. Modern examples of well-developed crevasses splay have been recorded by Coleman (1969) in Brahmaputra River.

PETROGRAPHY

The petrographic studies are confined to the sandstone units of the Siwalik Group. These are based on 35 representative thin sections from various stratigraphic levels across the sequence. The modal mineral composition is based on point counting. Most of the sandstones fall in the field of lithic arkose and feldspathic litharenite, when plotted in Folk's (1968) QRF diagram (Fig. 3). However, when classified on the bases of log SiO_2/Al_2O_3 vs. log Na_2O/K_2O diagram, 4 samples fall in the category of lithic arenite and 8 plot in the field of graywacke (Fig. 4). Both the classifications, however, cannot be considered satisfactory for these rocks because these ignore the carbonate fraction, which in some cases reaches up to 44%.

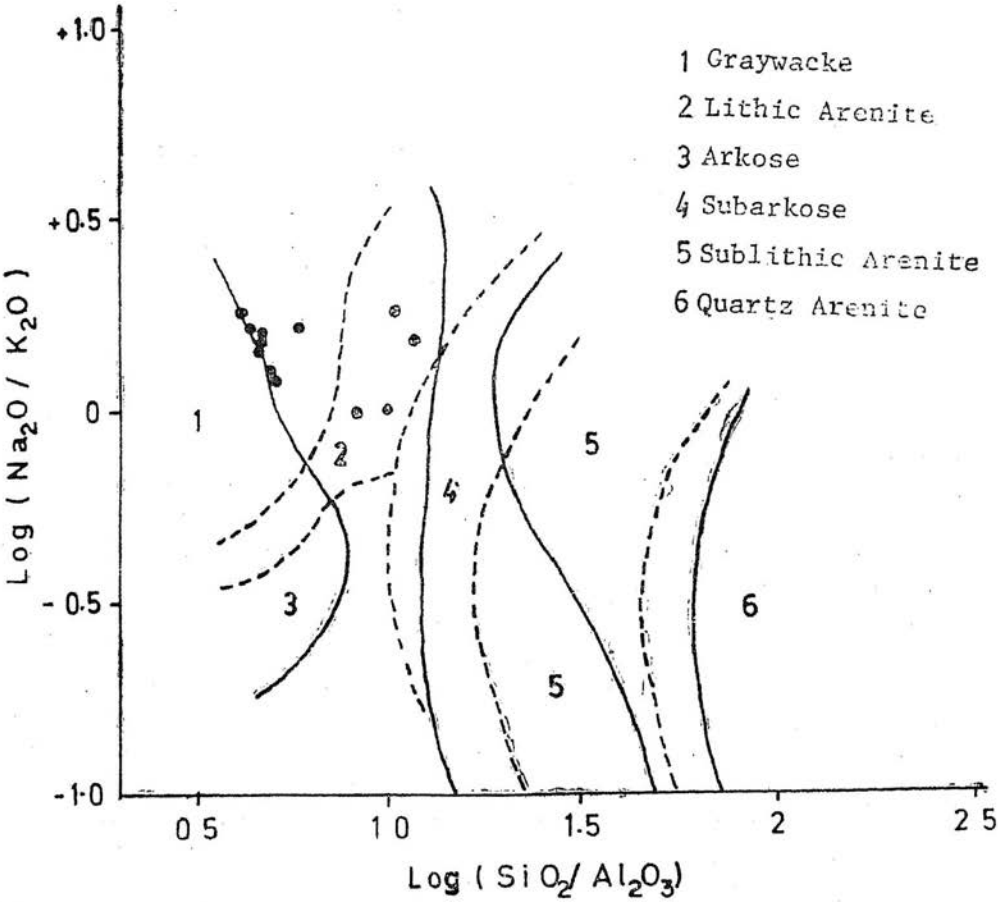

Fig. 4. Chemical classification of Siwalik sandstone on the basis of $SiO_2/Na_2O/Al_2O_3$ vs. K_2O (after Pettijohn, 1972)

feldspar increases upward in the sequence. The number of mineral species also increases in the sandstone of Middle and Upper Siwalik, with introduction of one or more of the minerals, hornblende, biotite, muscovite, garnet, chlorite, kyanite, staurolite, and pyroxene (Table 1). This implies a decrease in the degree of maturity across the sequence.

Texture : The detrital constituents of the sandstone in the lower part of the sequence are fine-grained, rounded to subrounded, and characterized by moderate to good sorting. Most of the grains are cement supported (Plate 1a) with point and cancavo-convex contacts. The upper sandstone, on the other hand, lacks uniformity in grain size and contains angular to subangular detrital grains. Point to cancavo-convex contacts, and less commonly sutured contacts are observed amongst the neighbouring grains. Overgrowth of the detrital quartz grains is common in the Middle and Upper Siwalik sandstone (Pl. 1b). This feature is lacking in the sandstone of the Lower Siwalik, where iron oxide coating and clay rims prevent quartz overgrowth (Pl. 1a). Most of the constituent grains in the Middle and Upper Siwalik sandstones are fractured, possibly due to diagenesis. This refracturing not only increases their angularity but also provides channel ways for calcite cement.

Mineralogy

Quartz. It generally makes the predominant detrital constituent of the sandstone from all stratigraphic levels in the sequence. It is fine- to medium-grained and rounded to subrounded in the Lower Siwalik and angular to subangluar in the Middle and Upper Siwalik. The grains are normally unicrystalline and have a straight extinction, however, composite grains with undulose extinction are also common. It is worth noting that the composite and strained quartz accompanies metamorphic rocks fragments when the latter make their appearance in the Middle Siwalik.

In general the quartz grains in the Lower Siwalik sandstone are devoid of inclusions, except for rare epidote, muscovite and ore. The Middle Siwalik sandstone, however, contains abundant zircon and epidote inclusions in the quartz grains. Subordinate quantities of sillimanite (Pl. 2a), apatite and ore also occure as inclusions. This feature of quartz may be useful in stratigraphic correlations and determination of provenance.

Feldspar. Feldspar makes the second predominent constituent after quartz. It reaches up to 13% in the Lower Siwalik, and up to 31% in the Middle and Upper Siwalik. Bulk of the feldspar consists of plagioclase and orthoclase, with minor amounts of microcline and perthite. Alteration varies from grain to grain and is mostly confined to orthoclase and plagioclase; microcline grains are less effected. Corrosion effect of calcite is comparatively stronger over the feldspars than the quartz. This replacement is either irregular or restricted to selected zones (along fracture, cleavage and twin lamellae). However, in hard bands, some of the plagioclase grains are partly or completely replaced by calcite (Pl. 1c). This and th occational calcite-filled frctures indicate post-depositional processes of cementation.

TABLE 1. MODAL COMPOSITION OF THE SIWALIK SANDSTONE

		L—4	L—6	L—7	M—12	M—19	M—21	M—22	M—23	M—25	U—10
Quartz		41.73	43.79	27.16	15.66	31.14	26.17	32.24	30.44	26.08	25.03
Feldspar		7.60	11.50	13.80	11.74	26.22	30.33	23.76	28.56	28.42	20.39
Calcite		25.50	26.98	35.43	44.75	7.13	8.12	3.37	5.26	3.20	2.00
Muscovite		Tr	—	1.10	0.90	2.12	2.80	3.26	1.14	5.15	2.60
Biotite		—	Tr	3.30	1.80	3.18	3.09	4.10	5.20	4.50	5.05
Hornblende		—	—	0.45	3.49	6.65	9.11	3.79	6.18	5.19	Tr
Epidote		—	Tr	3.59	1.80	2.31	1.15	3.16	2.20	2.04	Tr
R	Granite	—	—	—	4.89	3.66	6.10	4.32	7.15	12.09	13.27
O	Schist	—	—	—	9.23	11.37	8.15	14.85	8.00	6.39	10.78
C	Limestone/Fissil	9.63	6.50	9.90	—	1.44	1.50	1.84	—	—	—
K	Sandstone	—	—	—	—	—	2.25	1.36	4.00	2.00	11.17
S	Shale	0.50	—	1.24	—	3.47	—	—	—	—	8.25
	Ore	7.95	11.10	3.95	0.40	1.25	1.00	1.15	Tr	2.00	1.25
	Garnet	—	—	—	Tr	—	Tr	Tr	1.50	2.00	Tr
	Chlorite	—	—	Tr	1.60	Tr	Tr	1.68	—	Tr	Tr
	Clay minerals	—	—	—	3.44	—	—	Tr	Tr	Tr	Tr
	Tourmaline	Tr	Tr	Tr	—	Tr	—	—	—	—	—
	Kyanite	—	—	—	—	—	—	—	Tr	Tr	—
	Staurolite	—	—	—	—	Tr	—	0.70	Tr	—	—
	Zircon	Tr	—	—	—	—	—	Tr	Tr	Tr	Tr
	Pyroxene	—	—	—	Tr	—	Tr	Tr	—	Tr	—
	Siderite	7.01	Tr	—	—	—	—	—	—	Tr	—
	Glauconite	Tr	Tr	Tr	—	—	—	—	—	—	—
	Apatite	—	—	—	Tr	—	—	—	Tr	Tr	—
	Sillimanite	—	—	—	—	Tr	—	—	—	—	—

The feldspar grains in the Lower Siwalik are devoid of inclusions. The zircon inclusion in feldspar grains first appear at the base of the Middle Siwalik and become a common feature upward in the stratigraphic sequence (Pl. 2b). Beside

Considerable variation in the type and proportions of minerals is observed across the sequence. The sandstone in the Lower Siwalik consists of a limited

PLATE 1

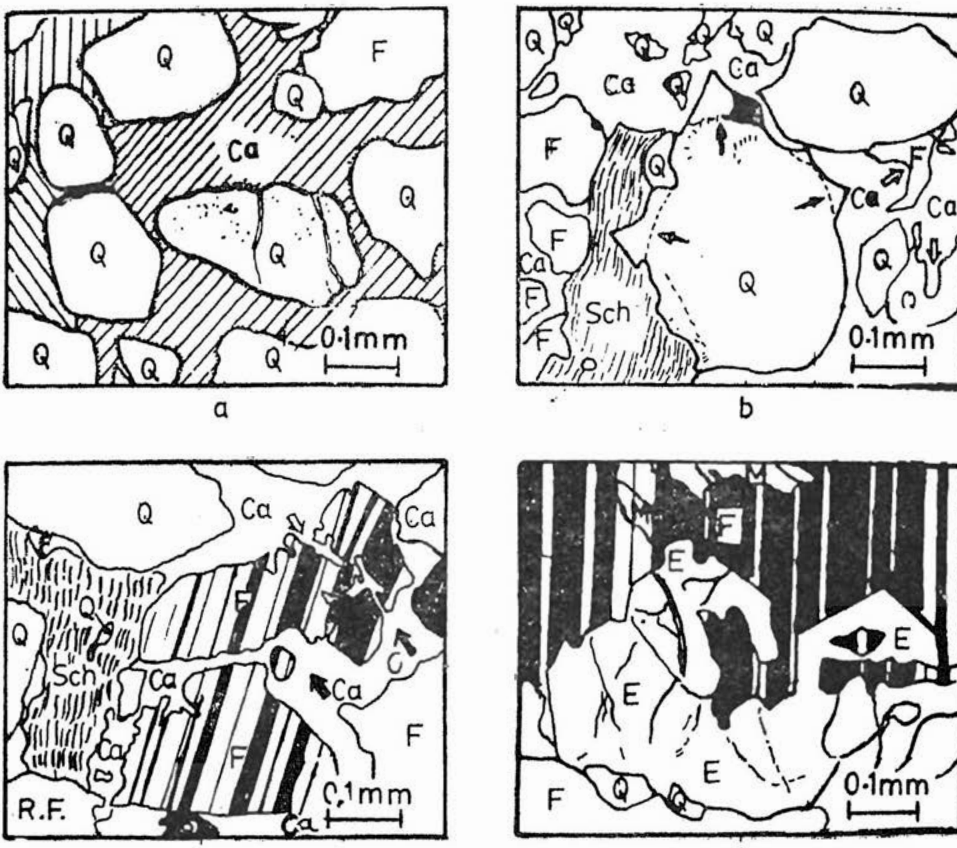

Plate 1 All plates sketched from photomicrographs (Key. Ca, Calcite; F, Feldspar; Hb, Hornblende; M, Muscovite; Or, Ore; Opx, Orthopyroxene; Po, Pore space; Q, Quartz; R.F., Rock fragments; Sch, Schist; Se, Sericite).

a. Poikilotophic texture developed by growth of a large single crystal of calcite (note continuity of twin lamellae). As a result of crystal growth, grains which were originally in a framework have been displaced. Detrital grains are surrounded by iron oxide and clay rims. (Fine-grained, Lower Siwalik, L-1).

b. A well-developed quartz overgrowth which displaces calcite cement around detritus quartz, but on left side it penetrates into a chlorite mica schist. In this sketch replacement of quartz and feldspar by calcite can be observed on the right side. (Medium-grained, Middle Siwalik, M-21).

c. Plagioclase grain partly replaced by calcite cement. Replacement is irregular except locally along the twin lamellae. (Medium grained, Middle Siwalik, M-17).

d. A coarse plagioclase grain containing inclusions of subhedral epidote and muscovite. (Coarse-grained, Middle Siwaik, M-13).

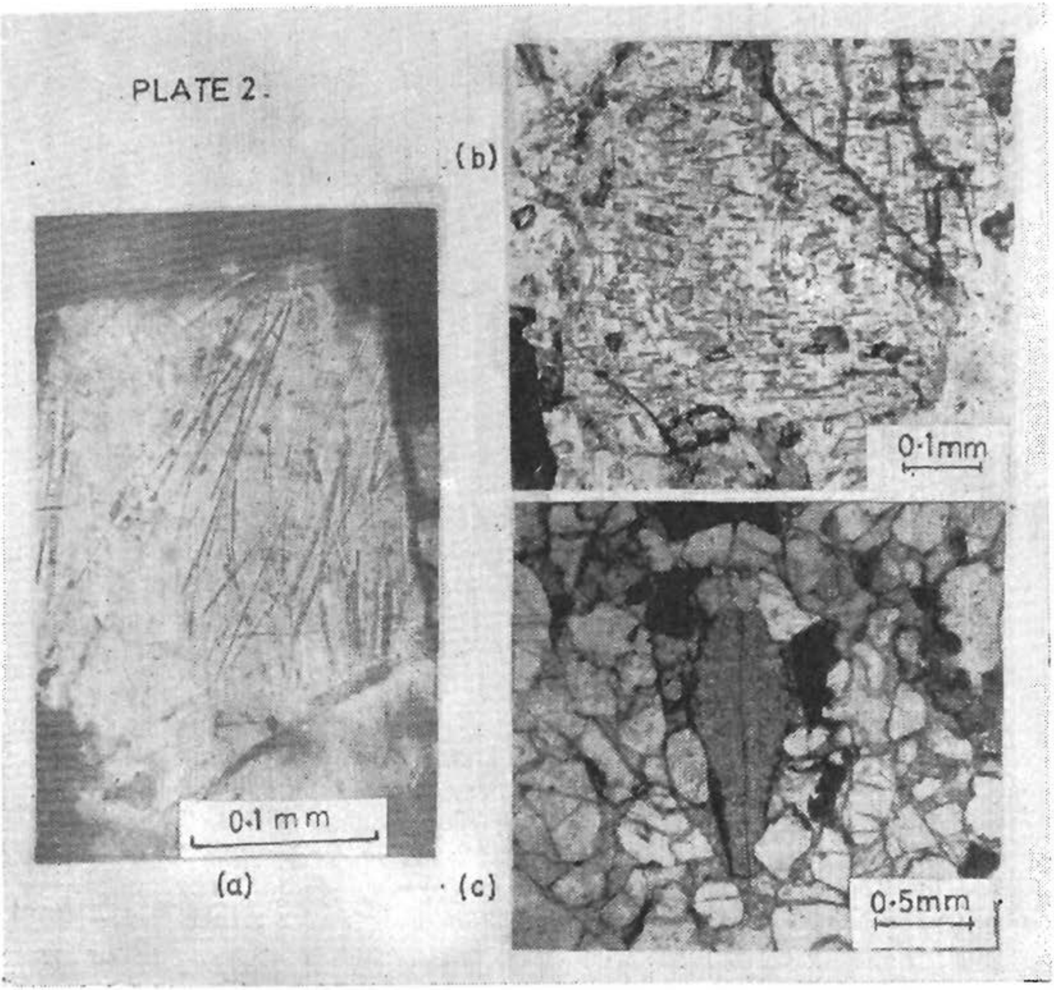

Plate 2a. Photomicrograph showing sillimanite inclusions in quartz grain, Middle Siwalik, M-19. (Crossed Nicols).

b. Photomicrograph showing abundant zircon with minor epidote inclusions in a plagioclase grain, Middle Siwalik, M-25. (Open Nicols).

c. A complete reworked fossil (discocyclina) preserved in the sandstone. The high relief fractured grains are those of quartz coated by clay rims, Lower Siwalik L 4 (plane light).

assemblage, mostly comprising of quartz, carbonate (detrital and cement), feldspar, and ore. Of these quartz, carbonate, and limestone fragments decrease whereas zircon, other inclusions in feldspar of the Middle and Upper Siwalik are epidote, muscovite, apatite and ore (Pl. 1d).

Carbonate. The Lower Siwalik sandstone contains appreciable amount of carbonate minerals (up to 44.75%). The calcite may be both syn- as well as post-depositional. In the basal sandstone some patches of poikilotopic calcite have developed by the growth of large single crystal which enclose numerous detrital grains, as reflected by the continuity of twin lamellae (Pl. 1a).

Unlike the Lower Siwalik, the Middle and Upper Siwalik sandstones contain only subordinate amounts of carbonate minerals. However, hard bands in the Middle Siwalik contain up to 30% of calcite, partially or completely replacing the plagioclase grains, (Pl. 1c). The post-depositional solution activity may be responsible for the recrystallization of this calciet.

Mica. Subordinate amounts of muscovite and biotite are present in the sandstones of all the stratigraphic levels, except for the basal part of the Lower Siwalik. Mostly they occur in tabular grains, with well-rounded edges and larger in grain size than the other grains. Occasionally, the biotite flakes are spillayed out at the ends and contain hematite concentration in cleavages. Preferred orientation of mica has been noted in some mica-rich layers in sandstone. Elsewhere these are bent around the adjacent detrital grains probably indicating advanced stage of compaction (Pl. 3a).

Hornblende. The Middle Siwalik sandstone is marked by the introduction of hornblende in the mineral assemblage, increasing upward in the sequence. The normally prismatic crystals are frayed at the ends due to dissolution (Pl. 3b). The hornblende grains are comparatively fresh in the upper part of the sequence, whereas in the basal parts of the Middle Siwalik they tend to decompose into chlorite.

Rock Fragments. Detrital rock fragments, making 6 to 24%, cover a wide range of varieties. All the three units, i.e. Lower, Middle and Upper Siwalik, contain different sets of rock fragments. In the Lower Siwalik, limestone and reworked fossil fragments are dominant. Complete fossils of discocyclina and lepidocyclina have been observed in one section from the Lower Siwalik sandstone (Pl. 2c). This clearly suggests that the unconformably underlying Eocene limestones have been one of the major contributors of the Lower Siwalik detritus.

Amongst the rock fragments of the Middle Siwalik sandstone, schists are most common. They include greenschist, graphitic-schist, quartz-mica-schist, amphibolite-schist, and kaolinite-sericite-schist. Other rock fragments include those of granite, sandstone, shale and carbonaceous material. Few epidote and epidote-chlorite-rich, fine-grained rock fragments may be of volcanic nature. The Upper Siwalik sandstone contains comparatively greater amounts of rock fragments, most of them being of sandstone compositon (Table 1). This means that the detrital material for the Upper Siwalik owes to the reworking of Middle and Lower Siwalik.

Epidote. Both detrital as well as authigenic epidote occurs in the Siwalik sandstone, normally in minor proportions (up to 3.5%). The detrital epidote grains are generally subrounded or irregular, etched, spotted and surrounded by clay rims, whereas the authigenic crystals are mostly subhederal and considerably fresh. In one section an authigenic epidote crystal has been observed to be penetrating a nearby fossil fragment (Pl. 3c). Elsewhere epidote occurs either as inclusion or an alteration product of hornblende and greenschist.

Glauconite. Traces of glauconite occur in the basal sandstone of the Lower Siwalik near the limestone contact. The glauconite grains are both rounded as well as irregular, normally filling the pore spaces. The roundness does not necessarily

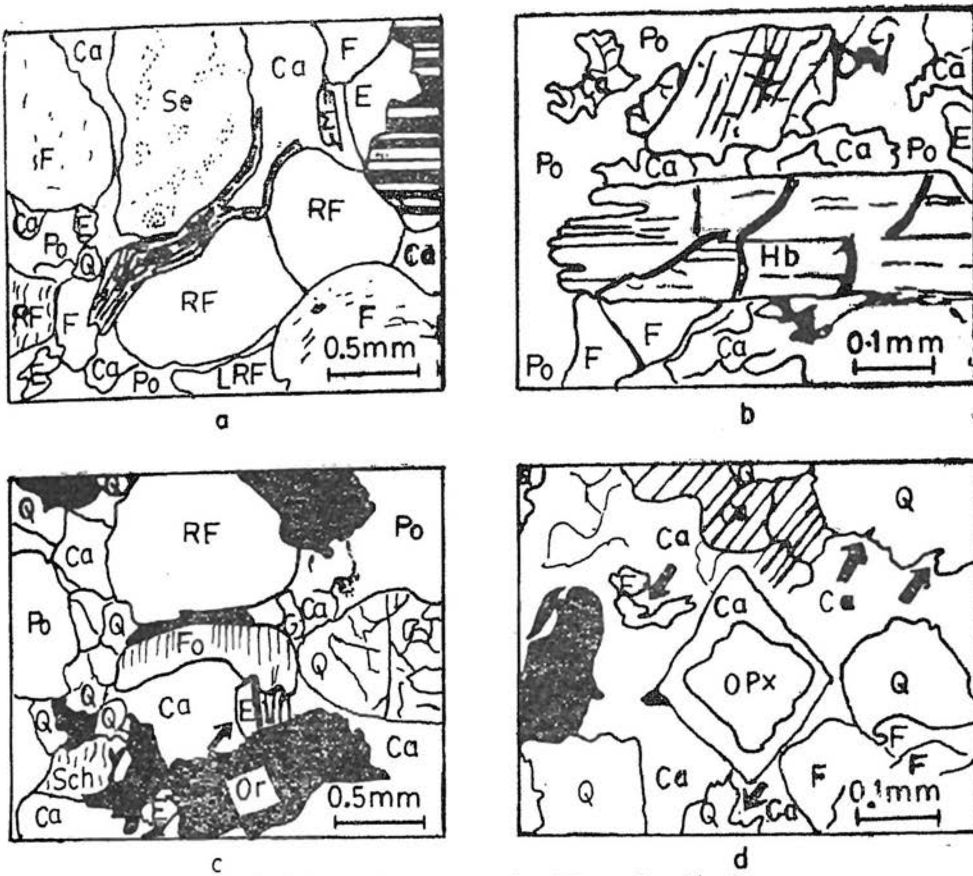

Plate 3 All plates sketched from photomicrographs. (Key : See Pl. 1).

a. A muscovite flake between detrital grains is bent due to compaction. A feldspar grain is completely sericitized (top) while an adjacent feldspar grain is partly changed into sericite (left top). (Medium-grained, Middle Siwalik, M-13).

b. A fresh prismatic crystal of hornblende, frayed at the end due to dissolution. (Medium-grained, Middle Siwalik, M-14).

c. Authigenic epidote crystals (arrow) penetrate into nearby fossil fragment during upward growth. Note irregular shape of the hematite replacing calcite cement. (Coarse-grained, Lower Siwalik, L-3).

d. Recrystallized calcite rhomb enclosing a detrital orthopyroxene. This section also shows corrosion effect of calcite on feldspar and quartz grains as indicated by arrows. (Hard concretion of Middle Siwalik, M-17).

imply the effect of abrasion, but may be due to aggregation of pellets, whereas that in irregular shape may be due to compactional deformation, as the glauconite pellets are considerably soft. The glauconite may owe its origin to reworking of marine rocks or it might have been altered from biotite.

Miscellaneous. As already mentioned, the Middle and Upper Siwalik are characterized by a wide range of mineral varieties. Most of them, though only in minor proportion (usually ~ 1%), are of considerable importance as they provide very useful clues regarding the provenance. Such minerals include garnet, tourmaline, pyroxene, kyanite and staurolite. Garnet is colourless or light pink, commonly subhedral to euhedral and medium-grained. Tourmaline in the Lower Siwalik sandstone is comparatively more rounded, whereas in the Middle Siwalik it is subangular to subhedral. Orthopyroxene is surrounded by recrystallized calcite rhomb in one thin section, M–17 (Pl. 3d).

Cement. The calcite makes the major part of cementing material which in addition consists of iron oxides, silica and clay minerals. The sandstone of the Lower Siwalik, which is rich in calcite cement, is more hard and compact as compared to that of Middle Siwalik, which is loosely cemented and friable. A few calcite-cemented hard bands also occur in the Middle Siwalik.

Besides calcite, the Lower Siwalik sandstones also contain hematite coating around the detrital grains, mostly in the form of irregular patches. Quartz overgrowth on the detrital quartz is common in the Middle Siwalik.

CHEMISTRY

Chemical analyses of representative samples of Siwalik sandstone for major elements are given in Table 2. SiO_2 has been determined by the gravimetric method, P_2O_5 and TiO_2 by the colorimetric method while the rest of the oxides were determined by the atomic absorption spectrophotometer.

By plotting the ratios of SiO_2/Al_2O_3 and the ratio of Na_2O/K_2O in the chemical classification scheme of Pettijohn *et al.* (1972) in Fig. 4 the representative samples fall into two categories. The basal part of the section represented by the samples L2 to L8 is characterized by higher SiO_2/Al_2O_3 values and fall in the category of lithic arenites (mature). The average ratio of SiO_2/Al_2O_3 for the upper part of the stratigraphic section represented by the samples M1 to M13–a is lower, characteristic of graywackes (immature).

It is clear from Table 2 that there is a decrease in SiO_2, CaO and increase of Al_2O_3 from bottom to the top of the section. Except for the two samples (L2 and L5) the rest of the samples contain Na_2O exceeding the K_2O. The sample M2 contains 7.67% of Fe_2O_3 and 3.29% of MgO while the rest of the samples contain less than 4.61% Fe_2O_3 and 3.29% MgO.

The variations in the proportions of major oxides across the sequence are appropriate to those of modal composition. There is a higher amount of quartz and lesser amount of alkali feldspar in the lower Siwalik, compatible to higher quantity of SiO_2 (average 68.60) and lower Al_2O_3 (average 6.31) and K_2O (average 0.85). Similarly the lower Siwalik sandstone contains higher amounts of CaO (average 13.23%) which is in concordance with the higher amounts of calcite. The greater amounts of Fe_2O_3 and MgO present in the Middle and Upper Siwalik suggest greater amounts of ferromagnesian minerals.

DEPOSITIONAL ENVIRONMENTS AND PROVENANCE

Several of the sedimentary features and lithological characteristics, e.g., frequent occurrence of cross-bedding, ripple-marks, logs of vertebrate fossils and woods, and the association of pebble- and cobble-sized fragments with sand size detritus are suggestive of shallow nature of the basin of deposition for the Siwalik rocks of the study area. This is further supported by the presence of slumps in the current-bedded rocks (Packham, 1954). Two other clues with regard to the depo-

TABLE 2. REPRESENTATIVE CHEMICAL ANALYSES OF THE SIWALIK SANDSTONE

	Lower	Siwalik			Middle				Siwalik				
	L2	L5	L7	L8	M1	M2	M3	M4	M5	M9-a	M12	M12-a	M13-a
SiO_2	70.93	69.83	67.75	65.90	64.73	64.47	64.41	62.41	62.21	63.18	64.42	65.57	63.71
TiO_2	0.01	0.30	0.22	0.34	0.21	0.10	0.30	0.02	0.02	0.01	0.20	0.10	0.13
Al_2O_3	7.02	8.47	6.14	5.59	13.41	8.60	12.31	12.00	14.54	13.31	13.31	10.91	14.31
Fe_2O_3	2.61	1.96	1.52	1.70	2.25	7.67	2.40	2.90	2.73	1.88	2.34	2.57	2.25
MnO	0.03	0.03	0.06	0.22	0.08	0.14	0.09	0.08	0.13	0.07	0.04	0.04	0.05
MgO	0.00	0.00	0.38	0.00	1.02	3.29	0.79	1.42	0.74	0.71	0.70	1.27	0.21
CaO	13.42	11.71	14.52	13.29	7.31	6.99	7.72	7.67	8.71	8.47	7.89	7.38	6.21
Na_2O	0.00	0.00	2.23	1.73	1.61	1.32	2.35	2.25	2.65	2.51	1.44	2.19	3.42
K_2O	0.35	0.72	1.21	1.12	1.60	0.84	1.96	1.75	1.49	1.65	0.99	1.28	2.04
P_2O_5	0.09	0.15	0.11	0.09	0.04	0.03	0.00	0.05	0.04	0.04	0.02	0.00	0.00
H_2O	0.23	0.38	0.29	0.31	0.37	0.39	0.31	0.59	0.21	0.17	0.20	0.55	0.15
Ign. loss	5.00	5.01	6.31	7.54	3.21	5.10	5.02	4.99	4.21	4.23	3.98	5.12	4.61
Total :	99.69	98.56	100.74	97.84	95.84	99.15	97.66	96.13	97.68	96.23	95.53	96.98	97.09
SiO_2/Al_2O_3	10.04	8.47	11.03	11.79	4.83	7.51	5.23	5.18	4.28	4.75	4.84	6.01	4.45
Log SiO_2/Al_2O_3	1.00	0.93	1.04	1.07	0.68	0.88	0.72	0.71	0.63	0.68	0.68	0.78	0.65
Log Na_2O/K_2O	0.00	0.00	0.27	0.19	—	0.20	0.08	0.11	0.25	0.18	0.16	0.23	0.22

sitional environments come from (i) the presence of thin beds of conglomerates in the sandstone, and (ii) occurrence of thinly-laminated black shale in the middle part of the sequence. These lithological characteristics favour channel lag or braided stream deposition under swampy conditions. The huge thickness of the Siwalik is however, incompatible with the shallow water depositional environments. This can only be explained if considered that deposition took place in a shallow, fast sinking basin under the conditions of rapid erosion, short transportation and quick deposition.

The presence of thick (up to 20m) well-developed vertical accretion units implies the relatively prolonged existence of a flood plain environment, which is a feature of a meandering stream. However, the greater lateral extent (< 10 km) of lateral accretion deposits suggests that streams were not confined to narrow meander belt. Similar diversion from Allen's (1965) model has also been noted by Johnson and Vondra (1972) and Visser and Johnson (1978) in Potwar Plateau.

The detailed field and laboratory investigation, discussed in the foregoing pages, suggest different source rocks for the Lower, Middle and Upper Siwalik.

LOWER SIWALIK

The basal sandstone of the sequence is characterized by a mature nature, as reflected in moderate to good sorting and roundness, subrounded tourmaline and low feldspar content. This aspect indicates either a long transportation of the detrital constituent or reworking of a pre-existing sandstone. Another important feature of this sandstone is the presence of considerable proportions of calcite and limestone fragments and, in one section, Eocene index fossils (Discocyclina and lepidocyclina (Pl. 2c). This probably means a considerable contribution by the unconformably underlying Sakesar Limestone of Eocene age. Reworking from a marine source rocks is further evidenced by the traces of glauconite occurring in the very basal part of the sequence.

A notable absence amongst the detrital constituents of the Lower Siwalik in the study area is that of minerals of metamorphic parentage. Contrary to this, the Lower Siwalik of Himachal Punjab re-entrant, and Nahan-Kalsi (Uttar Predesh) in India are reported to be containing garnet and staurolite (Raju, 1962). Such a facies change reflects a major difference in the unrooting history of the rocks of the two source areas. This may also cast doubts about Pascoe's (1919) and Pilgrim's (1919) concept of Indo-Brahma River or Siwalik River. This concept has already been disreputed on the basis of geological (Krishnan and Aiyangar, 1940; Gill, 1951) as well as zoological (Prashad, 1941) evidences.

MIDDLE SIWALIK

In contrast to the Lower Siwalik, the Middle Siwalik sandstone is characterized by angular to subangular grains, moderate to poor sorting and comparatively greater number of mineral species. In general, mineral grains (especial those of pyroxene) are comparatively fresher. These factors suggest a derivatic from a rapidly uplifting source, under the conditions of greater mechanical disintegration and comparatively little transportation.

A sound concordance has been found between the mineral assemblage of the Middle Siwalik in the study area and that of Himachal-Punjab re-entrant and Utter Pradesh reported by Raju and Dehadrai (1962). A consistent feature of this unit from Nepal to Jammu, as well as that of the studied area, seems to be the presence of garnet, kyanite, and staurolite, i.e. minerals of metamorphic affinity. This indicates revolutionary changes in the source area by that time, i.e. considerable enhancement in the rate of uplift resulting in the unroofing of high-grade metamorphic crystallines to the north of the basin of deposition (Chaudhri, 1972)

Quartz and feldspar grains with zircon inclusions appear at the base of the Middle Siwalik and become a common feature upward. Some of the quartz and feldspar grains are almost loaded with zircon. As zircon is a radioactive mineral, so there may be a relationship between this aspect of the Middle Siwalik and the uranium mineralization, present in the same stratigraphic level. Due to lack of sufficient data, we are not in a position to further emphasise this point, but think that more work on the petrography of this unit will help to understand the uranium mineralization in sandstone and nature of uranim-bearing source rocks.

The upper parts of the Middle Siwalik are characterized by a little higher proportion of rock fragments (15–24%), mainly of schists and gneisses, but toward the top of the unit, mainly granites. There is a proportional increase in the contents of hornblende, mica and composite quartz with that of rock fragments. The composite nature of the quartz suggests a possible derivation from metamorphic rocks (Bokman, 1952; Blatt, 1967), however, there are contrary views too, which assign composite quartz to primary source rocks (Blatt and Christie, 1963) or to the coarser size of the detritus (Conolly, 1965).

Hard-concretions, which are common in the Middle Siwalik, show no mineralogical variation except for higher proportions of calcite (20–30%). Strong corrsion effect of calcite on detrital grains may suggest subsurface solutional effects.

Amongst other mineralogical characteristics of the Middle Siwalik, there is a considerable increase in feldspar content as compared to the Lower Siwalik. Of the feldspars, orthoclase plus microcline dominate over plagioclase. These factors, together with granitic rock fragments, suggest increasing contribution from granitic source rocks, in addition to metamorphics. It is logical to expect that after the removal of a thick cover of sedimentary and low grade metamorphics. crystalline and deep-seated metamorphic rocks were exposed to denudation during the deposition of the Middle Siwalik.

UPPER SIWALIK

Rocks of the Middle and Lower Siwalik were the main contributor during the deposition of Upper Siwalik. This evidence is supported by (i) the clast of the conglomerate beds, that is mainly intrabasinal, (ii) a little higher proportion of sandstone rock fragments. Keller (1977), Johnson *et al.,* (1972), Parkash *et al.,* (1980) and Tandon (1971) also noted that rock fragments of sandstone increase toward the top of the section in the Potwar Plateau and India. This fact can be interpreted as involvement of foredeep sediments due to the uplifting Himalayan orogeny.

Acknowledgements. M. Attaullah Khan is thanked for useful discussion and suggestions. M. Majid, M. Rafiq are highly acknowledged for their help during thin sections study and M. Qasim Jan for constructively reading the manuscript. Aziz Qureshi and M. Banaras are thanked for field guidance and drafting of various figures, respectively. The National Centre of Excellence in Geology provided funds and facilities.

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