OBSERVATION ON CEMENTATION (DIAGENESIS) AND LITHIFICATION OF THE SIWALIK SANDSTONES AROUND KOTDWARA REGION

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Sandstones of the Siwalik Sequence (around the Kotdwara region) made up largely of silicate minerals apparently display the process of cementation during which the mineral matter was crystallized in intergranular pores of the framework. The variety and mode of cementation is strongly influenced by the texture, or framework of sandstones made up mainly by the mixture of sand and clay/silt particles : quartz grain dominated (quartz arenite), quartz grain cemented by a fair amount of clay-silt matrix (quartz wacke). Calcareous sandstones (Lower Sequence) fairly indicate diagenetic displacive precipitation of calcareous material in matrix of framework and modification of the associated clastic, granular mineral contents. In addition to cementation (diagenesis), other closely related processes demonstrated in sandy rocks of the sequence include: mineral authigenesis, intergranular welding and recrystallization.

INTRODUCTON

THE OUTCROP sections of the Siwalik Sequence (Cainozoic) are well displayed along a motor road situated between Kotdwara and Dogadda of the Garhwal Sub-Himalayan region. The sedimentary sequence occurs between the Ramganga and Ganga rivers, and the studied sections, I to VI (Fig. 1), are located in the area confined between the coordinates 29° 43′ 0″ N and 29° 45′ 40″ N (Lat.) and 78° 34′ 24″ E and 78° 37′ 30″ E (Long.). In this area these fresh-water molasse deposits of the Himalayan foot-hills are well stratified, with beds dipping from 30° to 55° E.N.E. and N.E. and are thrusted. The sediments have been studied as Lower and Upper Sequence (term used in a relative sense) at six sections, I to VI, in the area (Nautiyal 1977).

The Lower Sequence of the Siwalik sediments consists predominantly of fine to very fine grained sandstones (light to medium gray, greenish gray, light olive gray) with interbeds of siltstones (medium light gray to greenish gray, grayish red) and shales (grayish red). The arenaceous rocks are thin to moderately thick-bedded, with very fine grained sandstone commonly appearing with light to dark gray banded aspect. They commonly display fine planar cross-lamination and current lineation.

The Upper Sequence comprise mainly of fine to rarely medium grained sandstones (with same colour as in Lower Sequence) interbedded with siltstone (grayish red, greenish gray) and shale (greenish gray) beds. The arenaceous rocks occasionally display 'salt-and-pepper' texture and in places appear friable due to dissolution of cementing material. They are commonly thick-bedded, prominently mega cross-

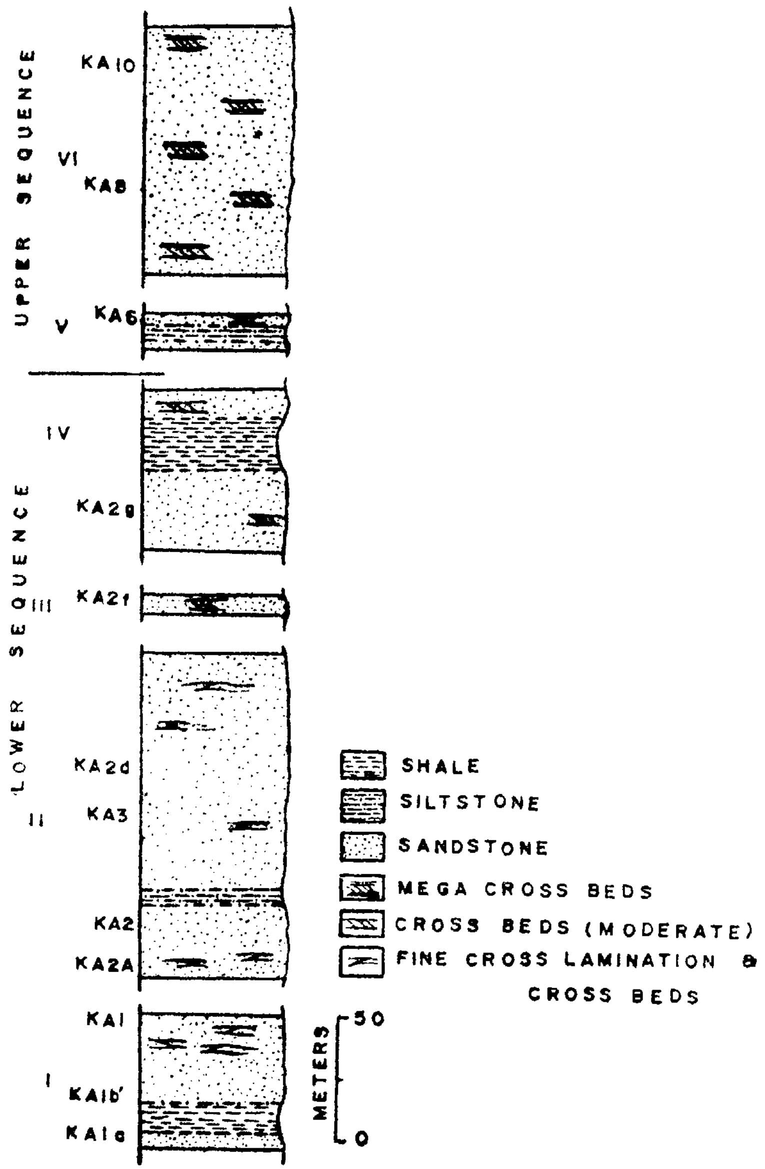

FIG. 1. Generalised lithostratigraphic column of the Siwalik Sequence showing six studied sections, I—VI (Nautiyal 1977), of the area between Kotdwara and Dogadda, Garhwal Sub-Himalaya (KA1*a* to KA 10, represent sample number of rock stratigraphic units referred in explanation of Plates I & II).

bedded and rarely plane laminated. Lithologically, sandstones of the Siwalik Sequence correspond to the wackes and arenites in Gilbert's classification.

A large number of geoscientists have discussed the process of cementation and lithification in sedimentary rocks along with the properties of the cementing material (van Hise 1904; Grabau 1913; Twenhofel 1932; Pettijohn 1957; Siever 1959; Carozzi 1960; Krumbein & Sloss 1963; Friedman 1965; Fairbridge 1967; Rittenhouse 1971). The effects of these processes were observed in various sandstone types from different geological formations and have been petrographically studied in detail by many workers (Giles 1932; Waldschmidt 1941; Davies 1947; Gilbert 1949; Taylor 1950; Gaither 1953; Heald 1956; Dapples 1962, 1967, 1971,1972; Waugh 1970). In this regard the Siwalik sandstones of the Himalayan foot-hills region have been paid

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PLATE I: (a) Quartz wacke (KA1). Displaced precipitation and replacement of feldsar, quartz and clay by calcite. Figure shows partly replacement (along grain margin) of plagioclase and quartz grains (Q) by very fine crystalline calcite. Corroded surface of former mineral is occupied by fine inclusions of cryptocrystalline calcite appearing as minute crystals and lath-like. Plagioclase feldspar (oligoclase ?) and quartz grains are cemented (noncoherent) by fine film of clay (right upper corner in figure). Calcite is mixed with recrystallized clay (sericite and chlorite) in matrix (left lower corner). Example illustrates incompatible calcite cement (spar and cryptocrystalline calcite) is in early stage of displaced precipitation and replacement of clastic grains and matrix, where by expansion of calcite (during crystallization) it fractures into feldspar (see figure) and quartz. Crossed nicols. (× 710)

(b) Quartz wacke (KA1). Replacement of quartz grains, chlorite and chert by calcite. Quartz grains partly replaced by calcite crystals (L, lath-like in figure) through crystallization and expansion. Clay recrystallized into chert (B, beaded appearance in figure) and chlorite (dark part in between beads). in equilibrium phase, are partly replaced by fine calcite crystals, (C, top and left side in figure). Crossed nicols. (× 710).

(c) Quartz arenite (KA3). Incompatible cement (calcite) expands former detrital quartz arenite framework principally of quartz grains (gray). Cement is polycrystalline mosaic of spar ccaite (white) with some tendency to replace quartz by its expansion and dissolution of original quartz grains, thus appearing as skeletal remains in some places. Calcite cement behaves as matrix isolating and surrounding quartz grains formerly in contact, thus latter appearing as 'floats' in calcareous matrix. Crossed nicols. (× 710).

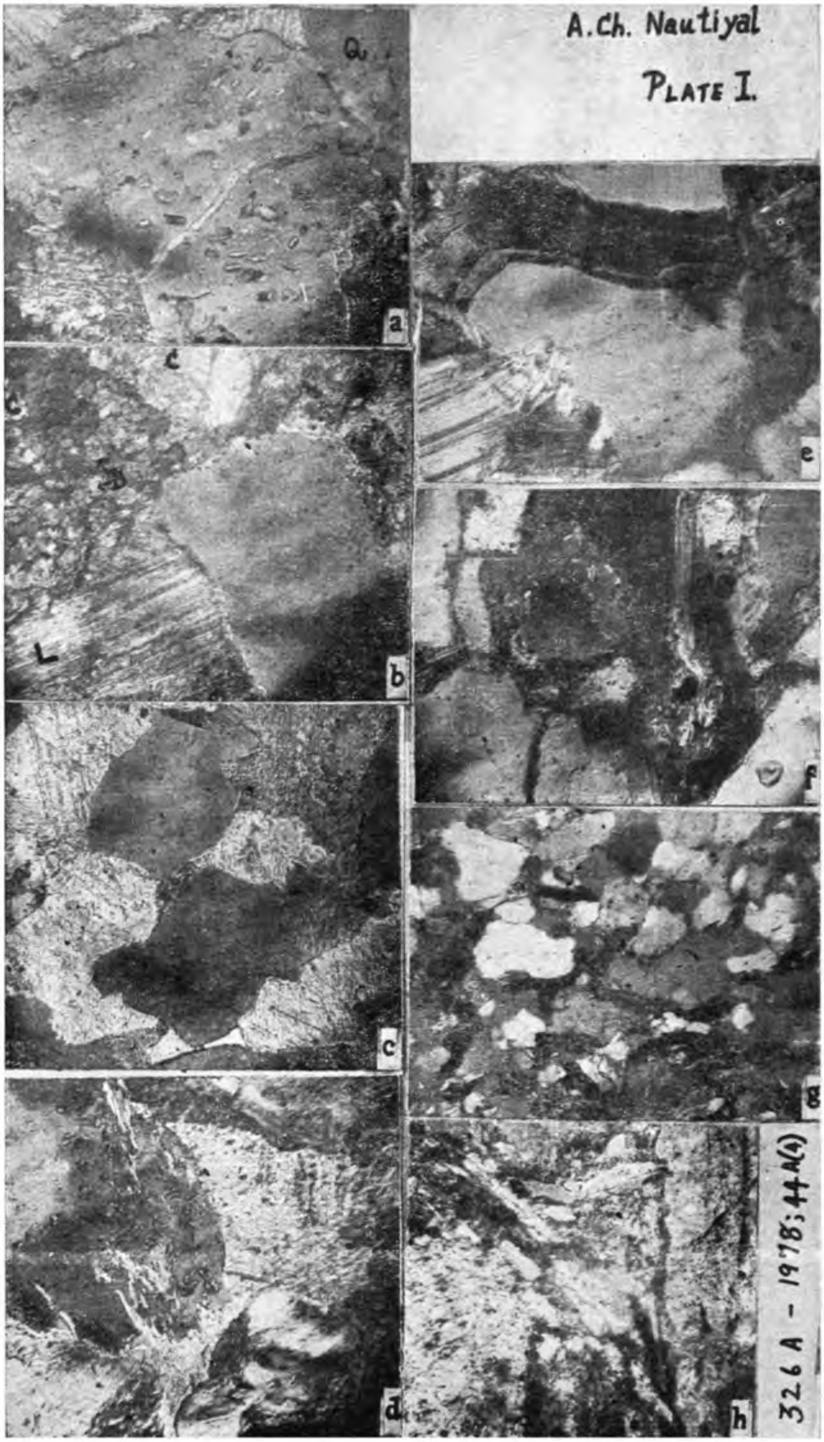
(d) Quartz arenite (KA3). Displacive precipitation and replacement of polygranular quartz fragment and matrix. Sand-sized polygranular quartz fragment (light and medium gruy) is partly corroded and replaced by calcite (appearing as white 'threads in figure). Replacement proceeds predominantly through the contact boundary of microcrystalline quartz in the fragment. Crossed nicols. (× 710).

(e) Quartz wacke (KA2A). Quartz grains and mica flakes showing effects of diagenetic compaction. Detrital muscovite flakes caught around quartz grains producing curved strained and crushing (see left side) effects on the former during diagenetic compaction of sediment. Quart in triple grain contact partly covered by clay matrix (lower right in figure) moved over the former during compaction of sediment. Crossed nicols. (× 710).

(f) Quartz wacke (KA 1*a*). Clay bond in quartz wacke framework. Clay bond in quartz wacke framework demonstrating poor association of loose mixture of partially recrystallized clay (chlorite and sericite; with silt particles, left centre) partly squeezed between quartz grains (gray) (left and lower side). A corroded quartz grain at margin (near centre in figure) and fine chlorite needles with some clay demonstrate partial intercrystalline intergrowth. Some chlorite needles can be observed inside quartz, and epidote inclusion in a quartz grain (lower right in figure). Crossed nicols. (× 710).

(g) Quartz arenite (KA2*g*). Quartz grains mostly in bilateral junctions with mica flakes of preferred orientation. Quartz to quartz weld in early stage of development between quartz grains—such welded self boundaries are non-coherent with quartz grains are aligned detrital mica (biotite, muscovite) flakes in matrix imparting a banded aspect to the rock. Cross nicols. (×240).

(h) Quartz wacke (KA2A). Movement and alignment of recrystallized matrix. Demonstrating movement and alignment (towards lower right corner in figure) of partly recrystallized clay material (mixture of extremely fine grains of quartz, sericite, chlorite, and some clay). Alignment of fine muscovite laths and is lt isapparent. Part of shale fragment on right side. Crossed nicols. (×710).


A.Ch. Nautiyal
PLATE I.
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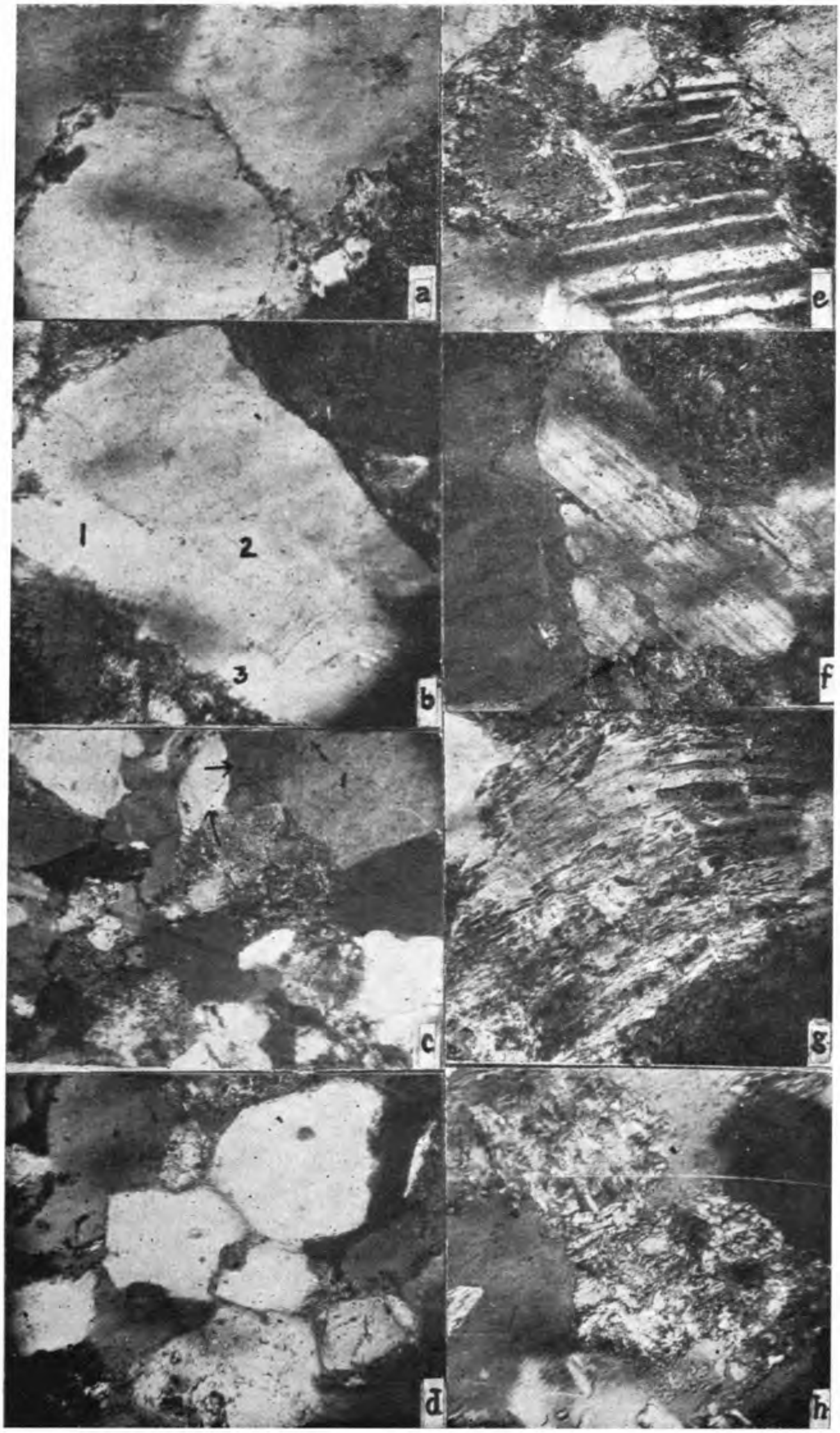
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some attention so far (Krynine 1937; Raju 1967; Johnson & Vondra 1972). Indeed these sandstones around the Kotdwara region reveal some interesting effects of the above mentioned diagenetic changes which have been described in this paper (Plate I : a-h, Plate II ; a-h). Some of the diagenetic changes, that are well illustrated in the two photo plates, may be helpful to the sedimentologists engaged in the petrographic study of the Siwalik sediments.

PLATE II (a) Quartz wacke (KA10). Overgrowth on quartz and welded self boundary between grains. Outline of detrital quartz grain (left side) is marked by ferruginous—clay coating. Welded self boundary between overgrowths in two grains (in figure) is noncoherent. Illustrated example suggests early stages of crystallization in progression of texture in quartz wacke with less clay matrix. Crossed nicols. (×710).

(b) Quartz wacke (KA10). Compound grain of quartz (light and medium gray) developed in quartz wacke. Outlines of original three quartz grains (1-3) and their boundaries poorly visible in figures, but compatible siliceous mineral weld is generally complete and boundaries between grains are partly coherent, thus forming a compound grain. Triple grains in compound grain show slight variation in optical orientation. Boundaries between compound grain and other detrital grain (e. g. dark gray quartz grain, right upper corner in figure) are poorly welded with argillaceous cement and noncoherent. Some angularity in compound grain introduced due to overgrowth. This example illustrates early development of compound grains with coherent self boundaries. Crossed nicols. (×710).

(c) Quartz wacke (KA6). Quartz grains in bilateral and triple-grain junctions. Quartz grains show bilateral (right side in figure) and triple-grain (left side) junctions—such welded self boundaries between quartz grains in most places are noncoherent. In some places coherent self boundary is demonstrated by quartz overgrowth (acting as compatible cement) on quartz grain (see arrows.) This example illustrates quartz to quartz weld in early stage of development between quartz during cementation of quartz wacke. Crossed nicols. (×240).

(d) Quartz wacke (KA2). Noncoherent self boundaries development shown between originally detrital quartz grains in wacke framework. Incomplete development of triple-grain junction is demonstrated by grains at center. Also, quartz has recrystallized to develop bilateral junctions. In places quartz display no recognizable boundary between original grain and recrystallized part (upper and lower parts, left side in figure), illustrating advanced locomorphic stage of diagenesis. Crossed nicols. (× 710).

(e) Quartz wacke (KA8). Altering plagioclase (oligoclase ?) and contact of quartz with noncoherent boundary. Plagioclase partly altered to sericite and partly replaced by cryptocrystalline calcite along twin lamellae. Corrosion of gray quartz grains (left side) by cryptocrystalline calcite. Segregation of muscovite and sericite around quartz (left side) illustrates micaceous minerals related to the phyllomorphic stage in wacke framework. Small amount of microcrystalline chert occurs in micaceous portion. Boundary between plagioclase feldspar and quartz grains is noncoherent. Crossed nicols. (× 710).

(f) Quartz wacke (KA1*b*). Quartz grains in bilateral junction (noncoherent) and also in contact with plagioclase feldspar in wacke framework. Showing quartz grains in bilateral junction (left side), contact boundary between quartz grains and plagioclase feldspar (oligoclase ?) is of ferruginous clay (noncoherent). Plagioclase partly altered to sericite and partly replaced by cryptocrystalline calcite along cleavages and twin lamellae. Crossed nicols. (×710).

(g) Quartz arenite (KA2*f*). Strain effects on plagioclase (oligoclase ?) caught between quartz grains. Plagioclase feldspar, caught between quartz grains, became curved and microfractured during diagenetic compaction of sediment. Contact boundary between plagioclase and quartz is noncoherent. Plagioclase partly altered to sericite and partially replaced by calcite. Crossed nicols. (×710)

(h) Quartz wacke (KA2*d*). Complex equilibrium of muscovite, chlorite and some micorcrystalline chert. Intergrowth of muscovite, chlorite and microcrystalline chert (two areas, right side in figure). Corroded grains of gray quartz (left side) with intergrowth of chlorite (fine needle like) at margin. Quartz grains show no recognisable boundary between original grain and recrystallized part (upper right side)—example illustrating advanced locomorphic stage of diagenesis. Crossed nicols. (× 710).

In general, cementation in sediments is of considerable interest and significance to the geologists working with engineering projects, groundwater operations, and petroleum or natural gas exploration, etc. Cementation, as a part of diagenetic process, includes introduction and deposition of some substance (inorganic or organic material) in the pore spaces of a sediment, binding the grains and particles together, which leads to the final stage in the formation of the sedimentary rock. "Diagenesis refers primarily to the reactions which take place within a sediment between one mineral and another or between one or several minerals and the interstitial or supernatant fluids" (Pettijohn 1957, p. 648).

Generally, frameworks of sandstones are either dominated by sand grains are rich in matrix material. Frameworks with sand grains in contact are reported as *arenites,* whereas individual sand grains isolated by the claysilt matrix are recognised as *wackes.* And boh these kinds of frameworks, occurring in some sandstones, have been referred as *subwackes* (Dapples 1972). However, separation line between the former two sand groups depends largely on the percentages of agrillaceous matrix present in rocks (Folk 1951; Gilbert 1954; and Dapples 1972). In this study, a *wacke* (Plate I : f) is defined as consisting of more than 10 percent argillaceous matrix, whereas other sandstones having less than that value are recognized as *arenites* (Plate I: g) (Dott 1964). These two sandstone types of the Siwalik Sequence around the Kotdwara area display the following stages of cementation (diagenesis) and lithification.

DIAGENESIS IN SIWALIK SEDIMENTS

Clay Bond with Quartz Grains

Quartz grains held together by fine clay minerals (Plate I : f) are considered as primary bonds and represent initial stages of the process of lithification in wacke frameworks of the Lower Sequence. At places, clay minerals are partly recrystallized into chlorite, and siderite. However, their firm bond relationship is achieved by compression strength existing between them. Dapples (1972) indicated that the same may be enhanced with the addition of small amounts of water, up to certain limit of highest value of strength. Beyond this limit the additional influx of water to the framework becomes catastrophic to the bond relationship. On the contrary, this surplus liquid water may be lost through air—drying, thus enhancing the compression strength of clay—sand bond, and gradually it leads to cementation and lithification of the sediment.

In Plate I : f, clay bond in quartz wacke framework demonstrates poor association of loose mixture of partially recrystallized clay (chlorite and sericite) with silt particles partly squeezed between gray quartz grains (left and lower side in figure). In addition, quartz grains at margin occur in partial intercrystalline intergrowth with secondary, fine chlorite needles and some clay contents (Plate I : f). This sort of quartz—clay mineral intergrowth represents one of the diagenetic modifications and assists in the process of cementation of rock.

Incompatible Mineral Cement

(a) *Carbonates demonstrating crystallization*—Quartz grains in some arenites and wackes occur cemented with calcareous material (mostly calcite). The latter acts as incompatible cement (Dapples 1972) and demonstrates a considerable range of variations. The interstitial spaces of the rock become occupied with calcite, which is more or less crystallized, but which does not show single optical orientation. In such case the quartz grains appear scattered in a calcite cement and so may be of primary origin. Such example rarely occurs in the Siwalik Sequence.

Aside to the above mentioned process, quartz and other clastic grains in the Siwalik arenites and wackes (Lower Sequence) are scattered due to displacive precipitation and crystallization of calcite in the matrix (Plate I ; a-d). The depositional framework is expanded in those regions where the circulating fluids (calcareous) through the sediments have reached a supersaturation of that material (Dapples 1972). In such case calcite forces quartz grains apart during the crystallization and as a result the latter appear as 'floats' in a calcite cement (Plate I ; c).

(b) *Quartz grains displaying corrosion*—In addition to the displacive precipitation of calcareous material, quartz and other associated (feldspar) grains in wackes and arenites of the Siwalik Sequence are commonly corroded by incompatible calcite cement during replacement (Plat I ; a-d). The process starts with infiltration of calcitic material in a rock and subsequently converting to its framework to more calcareous in nature at the expense (dissolution) of siliceous grains. These grains eventually appear as skeletal individuals after dissolution of a considerable amount of siliceous material. In figure a of Plate I, a grain of plagioclase feldspar (oligoclase ?) has been corroded by the introduction of calcite cement in minute spaces which appears as minute grains or lath-like. In addition, quartz grains and sand-sized quartz fragments are also corroded at the margin and very fine spaces (or 'threads') so developed are occupied by calcite cement (Plate I ; d).

(c) *Chert in crystallization relationship*—Quartz wackes of the Lower Sequence demonstrate microcrystalline chert in the clay matrix. Generally, clay cells of wackes and arenites are partially recrystallized to very fine grained sericite, chlorite, quartz and occasionally to microcrystalline chert. Dapples (1972) also considered the development of microcrystalline chert due to recrystallization and neoformation of new clay minerals from the detrital clay matrix in subwackes.

However, microcrystalline chert in the Siwalik sediments occurs either in association with micaceous part of matrix (Plate II : e) or establishes a complex equilibrium relationship while in connection with muscovite and chlorite (Plate II ; h). It seems to be in a complete equilibrium phase wherever in association with chlorite (Plate I ; b). Since chert occurs in minor amounts in the rocks, it does not seem to be a dominant element of the cementing material.

(d) *Mica from clay minerals*—In some Siwalik wackes concentration of clay contents leads to the reconstitution of clay minerals which further crystallize to form micas and the process constitutes the *phyllomorphic stage*. During this process, micaceous minerals like muscovite and chlorite are commonly recrystallized from clay minerals (Plate II ; e-h) and often either the former minerals or only the latter (chlorite) is intergrown with chert (Plate II : h).

Compatible Mineral Cement

Quartz arenites and some quartz wackes of the Siwalik Sequence commonly display compatible mineral cement (Dapples 1972) by quartz grains and quartz cement (Plate II : c). In addition, coherent and noncoherent grain boundaries are also well illustrated and developed between the quartz grains in the arenaceous rocks.

An example of monocrystalline quartz, as mentioned above (Plate II ; c), apparently illustrates compatible cement. In the figure, two grains of monocrystalline quartz display coherent self boundary made by quartz over-growth (acting as compatible cement) on quartz grain (Plate II : c, see arrows). In other examples (Plate I : g & Plate II ; a-c, d-g) two quartz grains demonstrate incomplete welded (noncoherent) boundary, although the weld is fairly strong. The slightly curved contact between quartz grains in apparently visible in crossed nicols (Plate II: a, c, f), and suggests that the lattice configurations are discordantly arranged between the two mineral grains.

Boundary of Grains' Contact

Sedimentary rocks consist of grains and fine particles of varying sizes, forms and different composition. The grains may be distributed, arranged and cemented loosely or tightly. Intergranular porosity occurs very commonly in sandstones, but the same may be destroyed by the crystallization of authigenic cementing matter in the pore spaces, converting rocks to become non-porous and impermeable. On the contrary, porosity in sandstone is drastically reduced by very tight packing of grains. Furthermore, the grains may be converted to partial solution, under considerable pressure in deep burial conditions, destroying the form of primary grain contact boundaries. The rock may eventually be welded to form an aggregate, thus retaining partial granular texture.

Pressure solution acting at the contact of quartz grains commonly does not result in deformation or fracturation of rocks. It develops into sutured contacts and microstylolites. Presence of relatively high percentage of such contacts between grains, with accompanied long and concavo-convex contacts, indicates increase in pressure upon rocks (Carozzi 1960). Such grain contacts are commonly not visible in the Siwalik sediments. In contrast, boundaries that are rarely associated with pressure solution are almost straight line (Plate II : c), or appear slightly curved, especially in grains provided with overgrowths (Plat II ; a), and commonly occur in the Upper Sequence.

In some clastic grains, straight line boundaries are originated as a result of recrystallization. In frameworks where two or more detrital grains, held with compatible welds and demonstrate self boundaries, appear in close optical orientation and produce a compound grain. Such example is commonly illustrated by the quartz wackes of the Upper Sequence (Plate II : b).

Diagenetic Compaction of Sandstones

The Siwalik sandstones (quartz arenite, quartz wacke) in the Lower Sequence occasionally show effects of strong pressure and diagenetic compaction where mica, feldspar and rock fragment are influenced considerably (Plate I: e, f, g; Plate II ; g). In such example biotite, muscovite flakes are distorted and micas are broken along cleavages (Plate I : e). In addition, tension and pressure craks are developed in feldspars and their twin lamellae are offset partially (Plate II ; g).

CONCLUSION

The Siwalik sandstones (quartz arenite, quartz wacke) around the Kotdwara area display some interesting phases of cementation (diagenesis) and lithification. These processes modify the rock frameworks. Displaced precipitation of calcareous material in the frameworks of quartz arenites is very commonly found in the Lower Sequence, whereas the quartz wackes of the Upper Sequence dominantly demonstrate overgrowth on quartz grains and their welded self boundaries.

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