Chapter 11
Later Proterozoic and Early Cambrian in the Himalaya

11.1 Tectonic Layout

The Late Proterozoic to Early Cambrian sedimentary formations of the Purana spectrum occur in three lithotectonic zones of the Himalaya province (Fig. 11.1; Table 11.1). The windows and half windows carved by rivers in the thrust sheets of epimetamorphic and mesometamorphic rocks expose Proterozoic sedimentary succession. The larger part of this succession belongs to the Upper Mesoproterozoic–Neoproterozoic period, extending up to the Early Cambrian. In the central sector of the Himalaya province, the outer Lesser Himalayan part was uprooted and thrust 4–23 km southward during the Tertiary revolution, forming parautochthonous Krol Belt. This belt is made up of preponderant Neoproterozoic to Early Cambrian rocks. The third zone encompasses the transition from the Great Himalaya to the Tethys subprovince and embodies rocks of the Neoproterozoic and Early Cambrian times.

It may be recapitulated that the Proterozoic rocks of the Himalaya represent a thick and extensive deposit on the distal part of the passive continental margin of the Indian plate. Experiencing occasional tectonic unrest in the early stage, the lower part of this succession comprises argilloarenaceous sediments of the time extending from Late Palaeoproterozoic to Early Mesoproterozoic. They have been discussed in Chap. 10. These sediments pass upwards to preponderant calcareous and argillocalcareous sediments laid down in shallow-shelf platforms and lagoons under tectonically tranquil conditions. Except for intrusion of basic sills and dykes, there were no tectonothermal events of consequence to leave imprints in the geological record of the Lesser Himalaya in the Late Proterozoic era.

However, as the Neoproterozoic era closed, the situation changed. The change was drastic in some sectors. As the direction of earth's spin axis changed during the Vendian–Cambrian period, there was shifting of continental plates followed by

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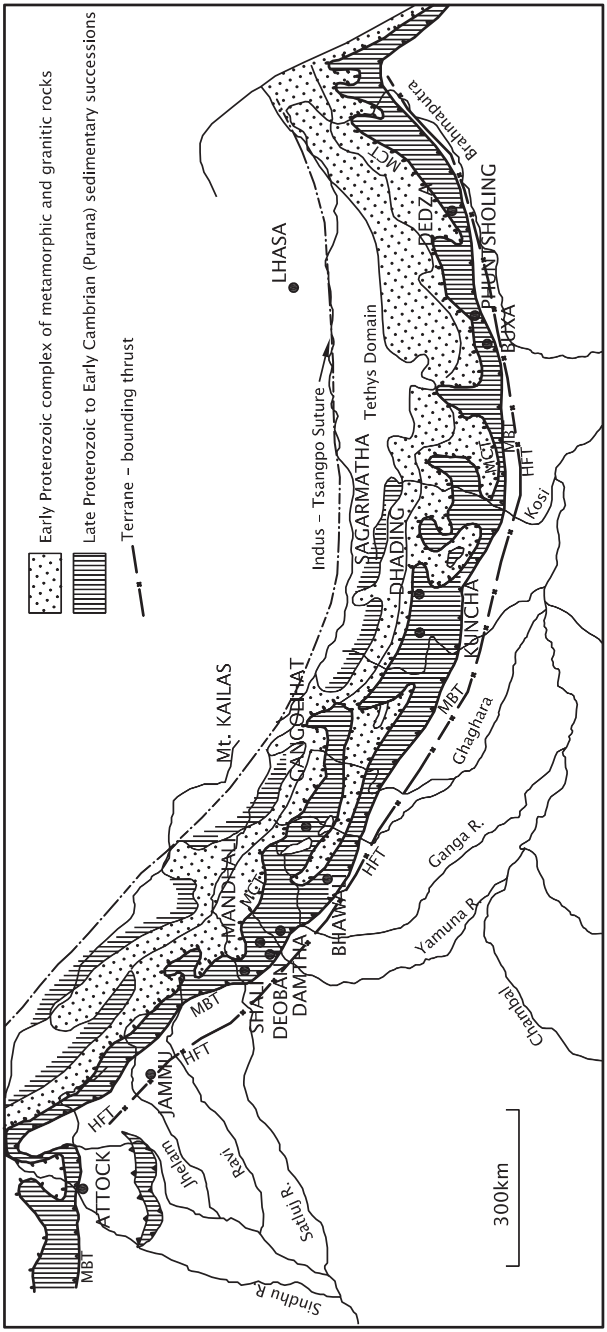

HFT– Himalayan Frontal Thrust; MBT – Main Boundary Thrust; MCT– Main Central Thrust

Fig. 11.1 Sketch map shows the Purana succession in the Himalaya province. The upper part of the succession belongs to the Late Proterozoic–Lower Cambrian time (Valdiya 1995)

Table 11.1 Later Proterozoic and Early Cambrian succession in different sectors of the Himalaya (Valdiya 1998a)

Age	Northern Pakistan	Jammu–Kashmir	Himachal Pradesh	Outer Lesser Himalaya in Himachal-Kumaun	Kumaun	Nepal	Sikkim–Bhutan	Arunachal Pradesh
Early Cambrian	Jhelam Fm.	Sincha Fm./Zilant Fm. (I)		Tal (O)		?		
Late Proterozoic	Hazira Fm. Salt Range Fm.	Baila Fm. Gamir Fm. (O)	Basantpur (I)	Krol (O)	Mandhali (I)	Robang (I) Malekhu (I) Benighat (I)		Saleri
	Shahkot/Sirban Limestone	Jammu Limestone (O)	Shali (I)	Blaini (O)	Deoban (I)	Dhading (I)	Buxa (O)	Dedza
Early Proterozoic	Hazara Slate/Attock Slate	Ramban Fm. (O) Dogra Slates (I)	Sundernagar (O)	Jaunsar (O)	Damtha (I)	Kuncha (I)	Phuntsholing (O)	Bichom

I Inner (northern) belt, *O* Outer (southern) belt, *Fm.* Formation, *Ls.* Limestone, *Lr.* Lower their rifting and eventual separation between 850 and 750 Ma (Sankaran 2004). These geodynamic developments resulted in shifts of climate zones, disruption of ecosystems and isolation of organic communities, leading to diversification of life on earth. The period of tectonic turmoil and attendant developments in the Lesser Himalayan terrane is manifested in the variable sedimentary sequences, their rapid facies variation and the appearance of life in varied forms in the newly developed ecological niches.

11.2 Carbonate Sedimentation: Autochthonous Zone

11.2.1 Deoban Lithostratigraphy

Overlying the siliciclastic assemblage of the Ramban–Sundernagar–Damtha–Kuncha–Phuntsholing groups (Figs. 11.2 and 11.4), the carbonates form an extensive succession of cherty dolomites intercalated with bands and beds of blue limestones and grey slates. R.D. Oldham in 1883 recognized and named this succession as the *Deoban Limestone* after the Deoban peak north of Chakrata. It extends south-east (Fig. 11.1) into Kumaun and is described as the *Gangolihat Dolomite* in the Pithoragarh district (Valdiya 1962a, 1980b). The most notable and characteristics feature of the Deoban are algal bioherms made up of columnar-branching stromatolites (Misra and Valdiya 1961; Valdiya 1969). The carbonates comprise, in addition to predominant chemically precipitated dolomite and limestone of a wide variety, minor detrital calcarenites (pelletal, oolitic) and calcrudites (intraformational conglomerate) associated with stromatolitic bioherms. The stromatolites have a wide variety of shape and size, predominantly columnar branching in nature. An outstanding feature of the Gangolihat Dolomite is the occurrence of large and small lentiform deposits of crystalline magnesite between the Kali and Mandakini rivers (Misra and Valdiya 1961; Valdiya 1962a, 1968, 1980b). Associated with talc and steatite, the magnesite deposits have considerable economic importance. There are sporadic disseminations, pockets and veins of copper and lead sulphides in magnesite and associated dolomites. The Deoban extends north-west and is known as the *Shali* in Himachal Pradesh, the *Jammu Limestone* in the Vaishnodevi massif in Riasi district, and the *Sirban* or *Shahkot* in northern Pakistan. Towards east, the equivalents of the Deoban have been described as the *Dhading* in Nepal, the *Buxa* in the Darjiling–Sikkim–Bhutan sector and the *Dedza* in western Arunachal Pradesh (Table 11.1).

Distribution of zircon ages and whole-rock neodymium isotope composition demonstrates that the Gangolihat Dolomite in Uttarakhand is correlative with Rohtas Formation of Semri Group of nearly 1600 Ma depositional age in the Vindhyan Basin (Cawood et al. 2007). This implies that the whole Damtha–Gangolihat succession of the Lesser Himalaya belongs to the Palaeoproterozoic time span. Significantly, the detrital zircon age distribution for the sedimentary

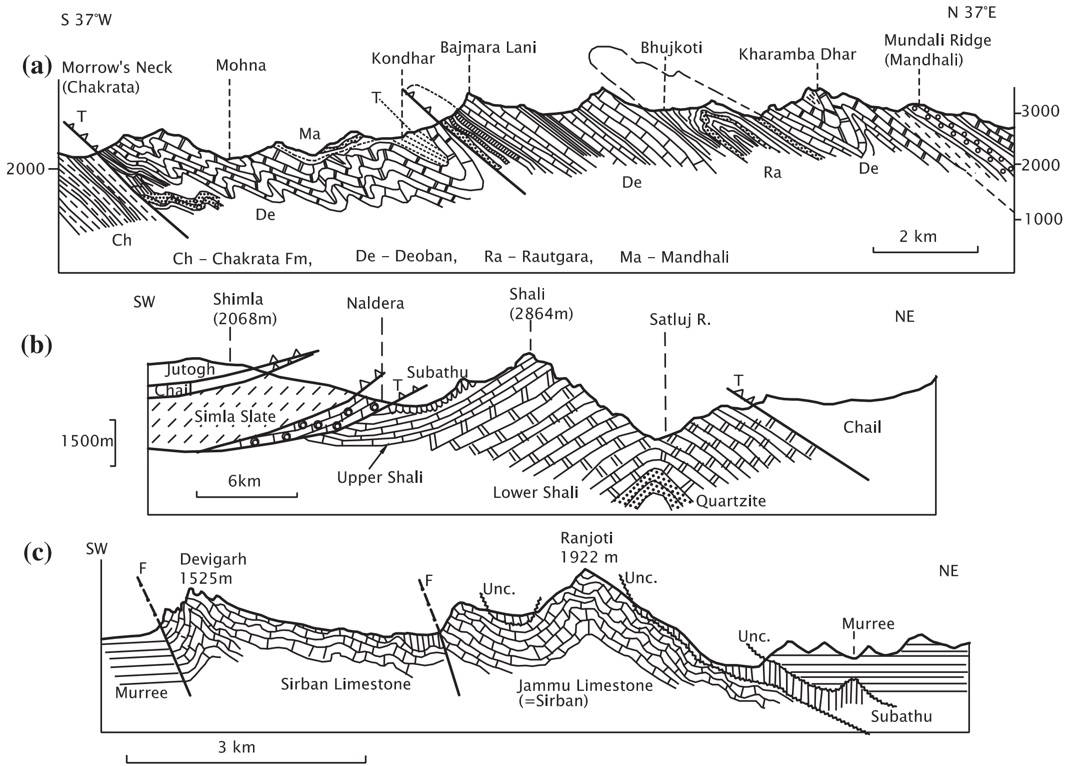

Fig. 11.2 Cross sections showing the stratigraphic positions of the Late Proterozoic carbonate formations in the Lesser Himalaya. **a** Deoban Limestone in western Uttarakhand (After Valdiya 1980b). **b** Shali Formation in eastern Himachal Pradesh (After West 1939). **c** Jammu Limestone in Ranjoti Peak in the Riasi district, Jammu (After Wadia 1937)

succession of the cratonic in northern India is remarkably similar to the distributions in the depositional coeval sedimentary rocks of the Lesser Himalaya, suggesting that both the regions shared similar detrital sources and that they are not separated (Cawood et al. 2007). This is exactly what was proposed long ago by Krishnan and Swaminathan (1959) and Valdiya (1964, 1970, 1976).

These findings negate the postulation that the Gangolihat Dolomite belongs to the Neoproterozoic on the basis of presence of microscopic features described as hexactinellid and monaxon sponge spicules (Tiwari 2008; Tiwari and Pant 2009).

11.2.2 Life in the Deoban Time

South of Rawalpindi in the Shahkot Limestone (≡Sirban) of the Gandgarh Range, R.D. Oldham had noticed "pseudo-organic structures resembling closely chambered heads", which he linked in 1883 to the structures discernible in the Deoban. The Deoban features were identified as cyanobacterial stromatolites (Misra and Valdiya 1961; Valdiya 1962a, 1969). The dominant type is the columnar-branching *Baicalia* of Middle Riphean (1350 ± 50 to 950 ± 50 Ma). The other types are *Minjaria*, *Kussiella* and *Maslowviella*, the first one being a typical Upper Riphean (950 ± 50 to 680 ± 50 Ma) form. On the basis of collective testimony of the stromatolites, the Deoban (Gangolihat) is placed in the transitional period between Middle Riphean and Upper Riphean, that is around 1100–900 Ma (Valdiya 1969, 1980b). At Chhera near Pithoragarh and near Ultrora south-west of Kapkot in the Pithoragarh district, an uppermost horizon of the Gangolihat has yielded isolated hexactinellid and monaxon sponge spicules of Lower Vendian age (Tiwari et al. 2000), implying that the temporal range of the Gangolihat carbonate formation extends up to Lower Vendian in the Neoproterozoic. The Shali in the Satluj Valley is, likewise, characterized by such stromatolites as *Colonella*, *Conophyton*, *Tungussia*, *Newlandia* and *Kussiiela* (Sinha 1977). The Jammu Limestone has an assemblage of *Colonella*, *Conophyton* and *Baicalia* (Raha and Sastry 1973; Raha and Das 1989). Coccoid and crustose cyanobacterial mats entombed in cherts of the Jammu Dolomite around Bidda indicate warm shallow hypersaline marine water in which these stromatolites proliferated (Venkatachala and Kumar 1997). Galena occurring in the top quartzite bed at Garan and Sarsenda give a Pb/Pb age of 967 Ma (Raha et al. 1978).

The Buxa Dolomites at Chillipam, Rupa and Dedza in the Kameng district and at Menga in the Subansiri Valley in Arunachal Pradesh show development of stromatolites characterized by vase-shaped microfossils suggesting Terminal Proterozoic–Lower Cambrian transition, and, significantly, δ^{13}C value in the Menga Dolomites ranges from +3.7 to +5.45 ‰ PDB and δ^{18}C value from −8.9 to −7.2 ‰ PBD (Tewari 2003).

11.2.3 Depositional Environment

Benthic algae flourished in abundance in the clear warm waters and formed stromatolites, building bioherms and biostromes. The formation of algal reef created protected environment like enclosed lagoons in the intertidal zones. Agitated waves and tides lashing the bioherms produced pelletal and oolite calcarenite and flat-pebble conglomerate consistently associated with the stromatolites (Valdiya 1980b). Locally in the enclosed lagoons of the subtidal zone developed conditions propitious for increase in phosphorous content, leading eventually to partial phosphatization of stromatolites and associated dolomites (Valdiya 1972). As the climate grew warmer and evaporation exceeded supply of water, concentration of $MgCO_3$ in the shallow barred basin increased, and magnesite was formed by late synsedimentary diagenetic replacement (Valdiya 1968). A good portion of magnesium might have been contributed by blue-green algae themselves which held footholds here and there.

11.2.4 Vendian Time: Mandhali Sediments

The dominant carbonate sediments of the Deoban gave way to a very thick argillocalcareous succession known as the *Mandhali Formation* (Figs. 11.2, 11.3 and 11.4). Locally dominated by euxinic facies, the assemblage consists of shale and slate interbedded with marlites and argillaceous limestones and large and small lenticular horizons of limestones and cherty-dolomitic limestones or dolomites. Locally, there are lense-shaped units of diamictites occurring at several levels. Occurring in the shallow water quiet environment of argillites, the diamictites represent debris flows, presumably triggered by tectonic disturbances. The tectonic disturbances were precursors of the impending tectonic upheaval that eventually terminated protracted Proterozoic sedimentation.

This variable succession was described by R.D. Oldham as *Mandhali* after a place Mundali in the Deoban massif. In Kumaun, Heim and Gansser in 1939 included the sequence in the upper part of what they called Calc Zones of Tejam and Badolisera. The Mandhali is a succession of olivegreen, grey and black carbonaceous and locally pyritic shale, interbedded with variegated marble and marlite. The basal conglomerate at Mundali is made up of clasts derived from the Deoban and the older Rautgara and embedded in the matrix of black limestones and shales. Elsewhere, the transition from the Deoban to the Mandhali is gradational. In the larger Mandhali spectrum, three units have been identified in Kumaun—the calcareous slates interbedded with argillaceous limestone and marlite with carbonaceous shales making the *Sor Slate*, the large lentiform horizon of dolomitic limestone constituting the *Thalkedar Limestone* (Valdiya 1962a), and the upper succession of grey-brown slates interbedded with fine-grained sandstone and siltstone forming the *Patet Slate* in the Pipalkoti–Tejam zone in the inner Lesser Himalaya (Kumar et al. 1976).

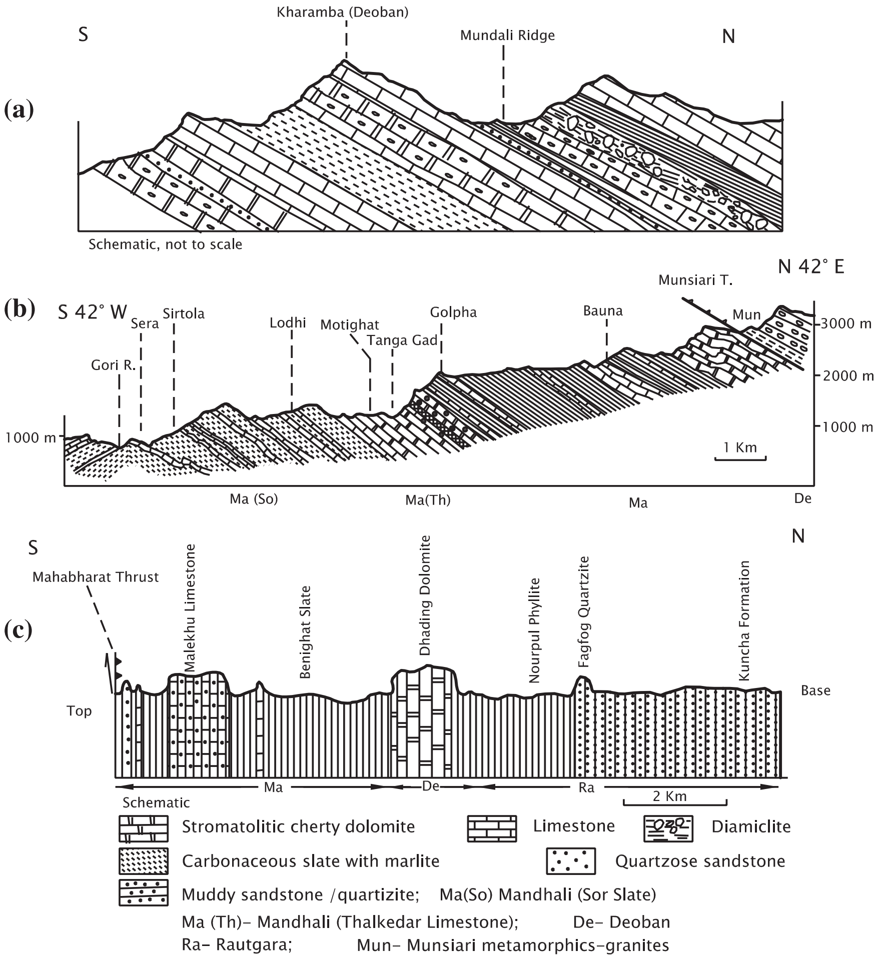

Fig. 11.3 Cross sections showing the stratigraphic positions and lithology of the Mandhali in different transects. **a** Type area Bawar in western Uttarakhand (After Valdiya 1980b). **b** Tanga Valley, Tejam zone, in Kumaun (After Valdiya 1980b). **c** Toppled column of Upper Nawakot in central Nepal (After Stocklin 1980)

The Mandhali extends into Himachal Pradesh as the *Basantpur Formation* which is thrust southwards (Srikantia and Sharma 1976). In northern Pakistan, the equivalent is known as the *Hazira Formation* and in the Gandgarh–Cherat–Attock Ranges described as the *Uttchkhattak* (Tahirkheli 1970; Yeats and Hussain 1987).

In Nepal, the Kali Gandaki, Budhi Gandaki and Trisuli rivers have exposed 5000-m-thick succession of the *Upper Nawakot* comprising the *Benighat Slate*, the *Malekhu Limestone* and the *Robang Formation* (Stocklin 1980), lithologically comparable and correlatable with the Sor, the Thalkedar and the Patet. The Upper Nawakot Formations are units of Kumaun. In western Arunachal Pradesh, the Mandhali is represented by the *Saleri* (Das et al. 1976).

11.2.5 Life During the Vendian Transition

The Naldera Limestone of the Mandhali succession in Himachal Pradesh contains Late Precambrian *Osagia tenuilamellata* (Nalivkin 1966). The carbonate contains a suite of Upper Riphean to Vendian stromatolites, including *Jusussania Irregularia*, *Stratifera*, *Tungussia*, *Acaceilla* and *Inzeria* (Valdiya 1969) and *Jurusania* (Sinha 1977, 1989) very similar to those of the Thalkedar Limestone in Kumaun. This age assignment of the Thalkedar at Naldera places the younger Patet in the Late Vendian to Early Cambrian. Significantly, at Lameri, near Rudraprayag in the Alaknanda Valley, carbonaceous shale overlying the equivalent of Thalkedar Limestone yielded acritarchs of very Early Palaeozoic affinity (Agarwal 1974). In the Deoban mountain top, a tectonic slice representing the Mandhali contains *Illictica*, a Lower Cambrian stromatolite (Sinha 1977). Interestingly in Paristan in south-eastern Kashmir, the *Zilant* Formation (made up of chert, black shale with limestone cap) is characterized by Lower Cambrian microfossils (Raina et al. 1988). Overlying the Abbotabad Formation, the *Hazira* is made up of 150-m-thick ferruginous siltstone–shale with ferromanganese ores, phosphorites with barytes and thickly bedded reddish brown siltstones (Shah and Moon 2004). In the Hazira were found Lower Cambrian archiasters and calyptomids (Fuchs and Moestler 1972).

On the other side towards east, the upper succession of the south-easterly extension of the Tejam in western Nepal has been consistently described as Tal (of the parautochthonous Krol Belt) by Fuchs (1967, 1975, 1977; Fuchs and Frank 1970). In northcentral Nepal in the Kathmandu–Sagarmatha section, the sparry magnesite associated with carbonates—presumably the Thalkedar equivalent—exposed on the slope of the Magar-ko-danda revealed sporocysts' palaeobasidiospores of Late Proterozoic to Early Cambrian age (Brunel et al. 1985).

It seems that the upper part of the Mandhali extends into the Lower Cambrian time.

11.2.6 Mandhali Environment of Deposition

The Mandhali sediments (Fig. 11.4) were deposited in shallow water littoral environment. Under humid climate condition, development of semi-isolated basins due to the reefs built by prolifically growing algae promoted sedimentation in oxygen-deficient condition (Valdiya 1980b). The abundant carbonaceous shales and limestones testify to the existence of euxinic or anoxic environments in the Mandhali time. In northern Pakistan, geochemical analysis of the Hazira demonstrates

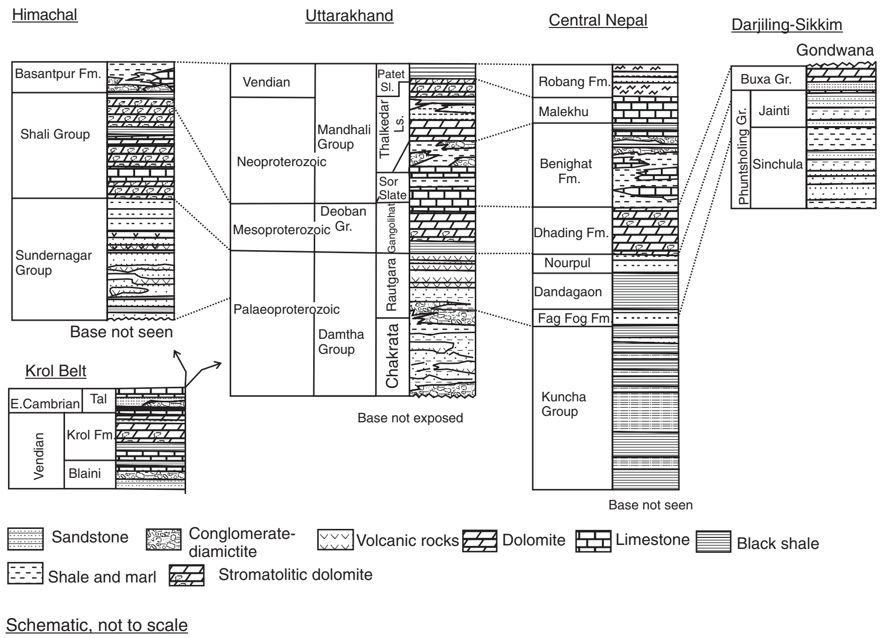

Fig. 11.4 Lithological columns of the Lesser Himalayan sedimentary succession in Larji window in the Beas Valley and the Dhauladhar Range (combined); Yamuna and Kali sections (combined) in Kumaun Himalaya; Trisuli–Mahabharat section in west central Nepal; and Sikkim–Bhutan in the east

"a line of descent from LREE to HREE with a small positive Ce-anomaly", the petrochemical characters suggesting the formation in shallow water on the continental shelf environment due to upwelling of anoxic deep-seated water (Shah and Moon 2004).

The Mandhali represents a time of tectonic disquiet manifested in submarine mass movements and formation of diamictites. These events, as already stated, were precursors to the orogenic upheaval that eventually brought about cessation of sedimentation all over in the Lesser Himalaya subprovince.

11.3 Parautochthonous Krol Belt

11.3.1 Tectonic Setting

As stated at the outset, the second zone of Proterozoic sedimentary rocks occurs in the southern part of the central sector of the Himalayan arc. Extending for 300 km from Solan in Himachal Pradesh to Nainital in Uttarakhand, the Krol Belt is named after the mountain peak south of Shimla by J.B. Auden in 1934. It comprises a chain of five en echelon basins (Figs. 11.4 and 11.5) constituting a doubly plunging synclinorium defined by the Krol Thrust (Auden 1934, 1937; Hukku et al. 1974; Fuchs and Sinha 1974; Pande 1974; Valdiya 1980a, 1981, 1988). Thrusting along the Krol Thrust is responsible for 4–23 km of horizontal southward dislocation of the Krol Belt succession. The Krol Nappe in its southern flank is split by a multiplicity of faults and is truncated against the Siwalik terrane by the Main Boundary Thrust.

11.3.2 Lithostratigraphy

The Krol Nappe is made up of two groups of sedimentary rocks (Fig. 11.5)—the *Jaunsar Group* comprising the *Chandpur* and the *Nagthat* formations, and the *Mussoorie Group* consisting of the *Blaini*, the *Infrakrol,* the *Krol* and the *Tal* formations.

The *Chandpur* in the Bhumiadhar section of the Nainital Hills comprises lithicwacke and sublitharenite laterally grading into siltstone and shale that are characterized by ubiquitous limonite stain. Lenticular horizon of diamictite is intimately associated with greywackes (Valdiya 1988). The Chandpur sediments were deposited in a storm-dominated progradational shelf affected by a major transgression (Pant and Goswami 2002). In Himachal Pradesh, the tectonic situation has been variously interpreted by different workers. North of the Krol Hill syncline, the lower part of the Shimla Hill syncline is made up of a succession of the *Simla Slates* and the *Jagas Quartzite* (Pilgrim and West 1928), under the thrust sheets of epimetamorphic Chail and mesometamorphic Jutogh rocks. The Simla Slates is a shaly flysch facies consisting of greywackes and pelites. Characterized by such sedimentary features as graded bedding, load cast, ball-and-pillow structure, longitudinal microridges with transverse wrinkles, torose load cast, furrow and groove casts, flute cast and small-scale ripple cross-lamination (Valdiya 1980b), the Simla sediments were deposited by the north-westward-flowing turbidity currents in the distal part of the basin that was simultaneously swept by indigenous bottom currents flowing consistently in the easterly direction across the basin slope (Valdiya 1970). It seems that the detritus was derived from the northern edge of the then high Aravali Mobile Belt of the Peninsular India. Another view is that the Simla Slate represents a prograding muddy delta built by collapse of a carbonate shelf that formed in the basal part of the succession (Kumar and Brookfield 1987). Floods from distributaries and shelf storms caused very rapid deposition, mostly above wave base.

Over the Simla Slates, the *Jagas* is an attenuated horizon of pink and white quartzarenite with subordinate purple and maroon phyllites. In the Krol Belt, the Chandpur is overlain by a thick succession of the *Nagthat Formation* made up of white, fawn, pink and purple quartzite interbedded with subordinate variegated slates and locally associated with shoe-string-like body of oligomictic conglomerate. Three lithofacies are identifiable in the Nagthat succession in Mussoorie Hills: (i) cross-bedded (tabular and trough types) sandstones with lenses of conglomerate and erosional surfaces, (ii) medium-grained siliciclastics characterized

(a)

(b)

(c)

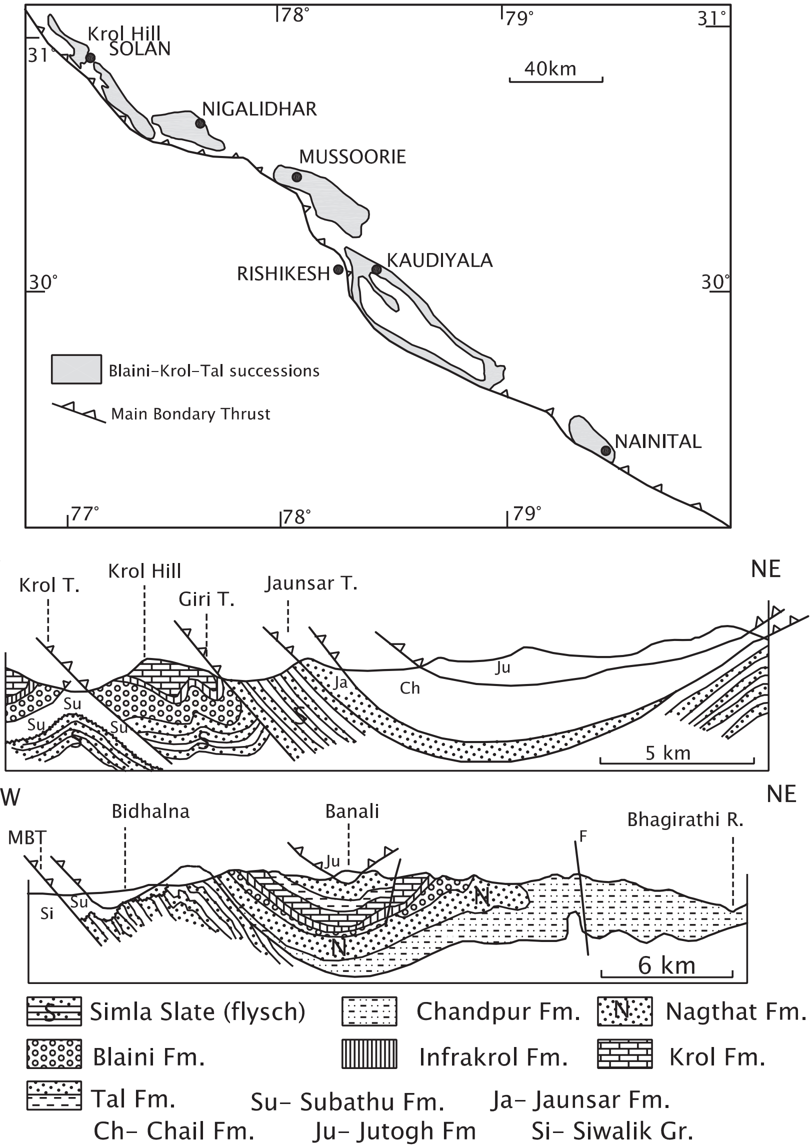

Fig. 11.5 **a** Krol Belt is a doubly plunging synclinorium comprising a chain of five basins. **b** Section shows the structure of the Krol Belt in Himachal Pradesh (After Auden 1934). **c** Lithostratigraphy and structure in the Mussoorie Hills (After Auden 1937)

by alternation of subarkose and quartzwacke showing herringbone-type cross-lamination and (iii) fine-grained siliciclastics showing parallel to cross-lamination in silty sandstone and shale (Ghosh 1991a, b). The multistoried sedimentary complex of the Nagthat is a shoreface to proximal inner shelf deposit representing a prograding delta developed under dominant influence of tides and occasional storms. In the Nainital Hills, the Nagthat succession is a deposit laid down by currents that flowed in the NE, E and SW directions along shallow shore in the Nainital part of the basin (Valdiya 1988). Lateral and vertical distributions of various lithofacies demonstrate deposition in a progradational barrier-island system in subtidal upper shoreface and channels, subtidal longshore bars, foreshore beachface, tidal channels, intertidal sandflat channel and mixed flat environments (Shukla and Pant 1996; Pant and Shukla 1999).

The *Blaini Formation* begins with polymictic conglomerate intimately associated with greenish brown sandstone, calcareous sandstone, purple shale and deep pink or red dolomitic limestone. While the purple siltstones are characterized by flutecasts and small-scale cross-stratifications, the pink limestone locally exhibits algal mats. Rounded, subrounded clasts of quartzites, phyllites and marble are embedded in sandy matrix of the conglomerates characterized by imbrication of clasts, pointing to NNE direction of palaeocurrents in the Kilberry–Pangot belt of the Nainital Hills (Valdiya 1988). The Blaini diamictites are believed to be glacial tillites (Gaur and Dave 1971; Bhargava 1972; Niyogi and Bhattacharya 1971; Jain and Varadaraj 1978) as first suggested by R.D. Oldham in 1883. The tillites can be related to the global event within the period 900–540 Ma. The warmer climate that followed resulted in the melting of ice in a very short geological time, giving rise abruptly to precipitation of ferruginous red and pink dolomitic limestones. In the Nainital Hills, imbrication of rounded to subrounded clasts in Blaini sandstones and sedimentary features like cross-bedding indicate that the sediment deposition took place in a supratidal to intertidal environment under warmer climate condition (Tangri and Singh 1982; Valdiya 1988). The NE, NNW and less common SE and SW palaeocurrent directions indicate dominant tidal dispersal, in addition to longshore currents at an earlier stage (Pant and Goswami 2003). The other view is that the diamictites were produced by submarine slides in an environment of tectonic instability (Rupke 1968, 1974; Valdiya 1980b). The uppermost unit of the Blaini Formation, known as *InfraKrol*, is a succession of ashgrey and black carbonaceous shales, locally containing pyrite and nodules of phosphate. In the InfraKrol time, it was deposition as tidal-flat sediments in the lagoonal environment characterized by euxinic conditions.

The InfraKrol is succeeded by the *Krol Formation*. A sequence stratigraphic study backed up by carbon isotope analysis (Fig. 11.6) reveals existence of a regional stratigraphic discontinuity marked by less than 60-m-deep incised valleys and irregular relief, regional flooding surfaces and subaerial dissolution and weathering calcrete and breccia filling fissures and cavities, all through the 300-km expanse of the Krol Belt (Jiang et al. 2002, 2003). The Krol consists of calcareous limestone with minor gypsum in some places and carbonaceous shale at the base (*Krol A*). This is overlain by red and purple ferruginous shale interbedded with biohermal stromatolitic dolomite (*Krol B*). Still higher up, massive dark grey and blue dolomite characterized by pervasive brecciation and such structures as fenestral, shrinkage and pinch-and-swell structures and cross-bedding in

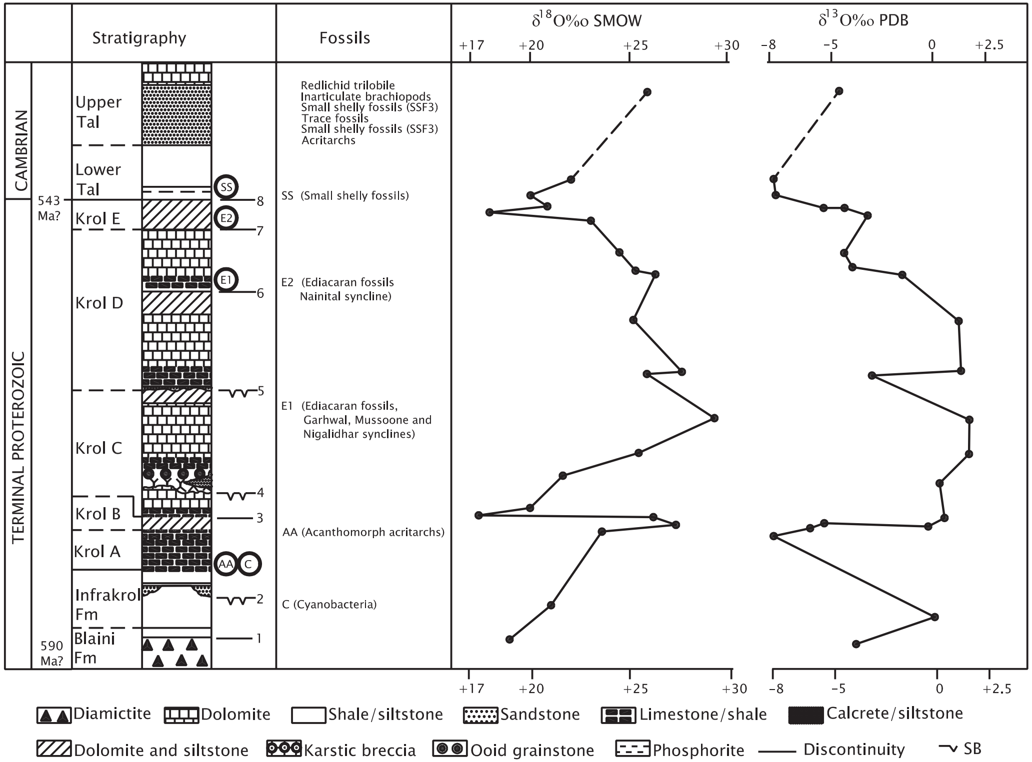

Fig. 11.6 Lithological succession of the InfraKrol–Krol and Tal formations showing reported fossil finds, interpreted stratigraphic discontinuities and carbon isotope excursion (Jiang et al. 2002; Mathur et al. 1997)

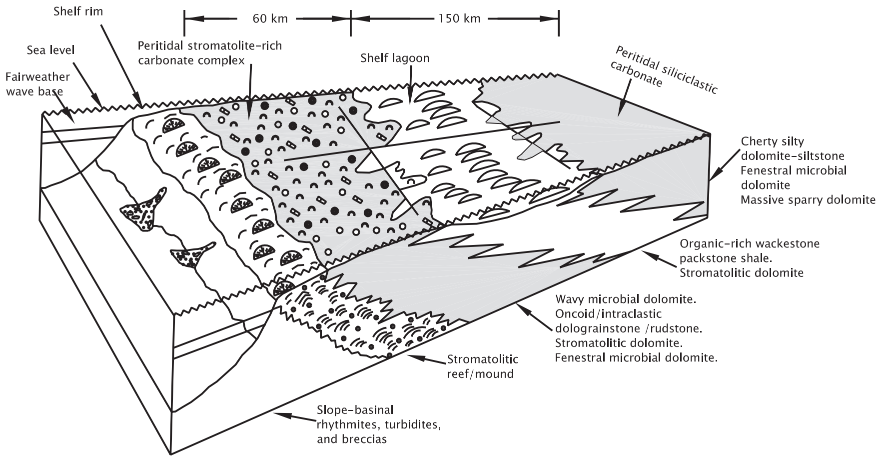

Fig. 11.7 Model portraying the geometry and facies distribution of a peritidal shelf of the Krol platform (After Jiang et al. 2003)

calcarenite form the *Krol C*. This unit is succeeded by a horizon made up of rhythmic alternation of thinly bedded black shale with marlite and carbonaceous limestone showing convolution and pinch-and-swell structure (*Krol D*). The uppermost horizon (*Krol E*), well-developed in the Sherwood College campus in the Nainital Hill, is a sequence of cherty dolomite which is locally phosphatic. The dolomite is characterized by short columnar branching, domal, plumose, oncidal and laminated stromatolites, associated with pelletal and oolitic calcarenite (Fuchs and Sinha 1974). The Krol carbonates were deposited in shallow lagoons along the coast—behind barrier beaches, which later changed to tidal flats (Awasthi 1970; Niyogi and Bhattacharya 1971; Kharkwal and Bagati 1974), which were evaporitic in parts during the mid-Krol time (Gundu Rao 1970). It seems that the intertidal conditions of the Middle Krol (Fig. 11.7) time became lagoonal towards the later period when formation of bioherms gave rise to pockets of restricted water circulation and resulted in the development of euxinic condition in the peritidal belt (Valdiya 1988).

The *Tal Formation* (Auden 1934; Bhargava 1975; Shanker 1975; Valdiya 1988) is made up of two members. The lower member comprises carbonaceous–pyritic black shale with subordinate black limestone showing stromatolites and penecontemporaneous deformation structures. Characterized by phosphatic nodules and lamine, it becomes a prominent chert–phosphorite horizon in the Mussoorie Hills. The upper member is made up of ripple-marked sandstone–siltstone interbedded with purple brown and grey shales. Towards the end of the Krol time, the chemistry of sea water had changed. The carbon isotopes show marked negative excursion, and there was concentration of such trace elements such as Ba, Cu, Zn, Ni, U and V and increase in the contents of phosphorous and organic carbon across the Krol–Tal boundary (Banerjee et al. 1997). The Tal Basin was shallow, and algal reefs caused restriction in the circulation of water, so that lagoons and enclosed embayments had anoxic environment in the back-shelf side (Valdiya 1980a, b). Possibly, basin upwellings moved the organic-rich anoxic water to the coastal flats, leading to widespread episodic deposition of black shale, organic-rich chert and dark grey phosphorite It may be pointed out that chemostratigraphy of the Blaini–Krol–Tal succession demonstrates that the Neoproterozoic–Cambrian transition lying in the Lower Tal is characterized by δ^{13}C—4 % PDB (Tewari and Sial 2007).

11.3.3 Lithostratigraphical Comparison of Krol Belt and Autochthonous Zone

It is apparent that the Jaunsar Group made up of Chandpur and Nagthat formations of the Krol Nappe is comparable in lithology with the Damtha Group comprising Late Palaeoproterozoic to Mesoproterozoic Chakrata and Rautgara formations of the autochthonous zone. In the autochthonous zone, the Damtha succession is overlain by Deoban and Mandhali formations of the Tejam Group, while in the Krol Belt, the Jaunsar Group made up of the Chandpur and the Nagthal is succeeded by Mussoorie Group of the Krol Belt which is made up of the Blaini–Krol–Tal succession. The testimonies of stromatolites, acritarchs and other microbiota favour placing the Mandhali in the temporal range of Upper Vendian (680–570 Ma) to Lower Cambrian (542–513 Ma). The Tal is characterized by definite Lower Cambrian fauna. It seems that the autochthonous Tejam Group of the Deoban and Mandhali formations, correlatable with the parautochthonous to allochthonous Mussoorie Group of the Blaini, Krol and Tal formations, is a Neoproterozoic to Lower Cambrian succession.

11.3.4 Life in the InfraKrol–Krol Time

The chert nodules and shales of the InfraKrol in the Nainital and Nigalidhar areas contain prokaryotic and eucaryotic organic-walled and multicellular microfossils comprising cyanobacterial filaments, coccoids, large acanthomorphic acritarchs and thallophytic algae (Tiwari and Azmi 1992; Tiwari and Knoll 1994; Tiwari 1996; 1999; Tiwari and Pant 2004). The Krol stromatolites have been identified as *Stratifera*, *Irregularia* and *Conophyton* of Vendian/Yudomian age (Tewari 1984). In the uppermost horizon—including the Sherwood Member in the Nainital Hills—the occurrence of small shelly fossils such as *Caleoloids typicalis*, *Olivooides alveus*, *Spiellus columnorus* and *Anabarites trisulitos* (Bhatt and Mathur 1990; Bhatt 1996) indicates the first appearance of preservable life forms.

11.3.5 Appearance of Shelly Fauna in Tal

The marked negative excursion of carbon isotope ratio ranging from −8.4 ‰ to −2.6 ‰ together with high proportion of organic carbon buried in the phosphorite and black shale in the basal Tal was accompanied by the first appearance of small shelly fossils in the Nigalidhar, Mussoorie and Nainital subbasin (Azmi 1983; Azmi and Pancholi 1983; Bhatt et al. 1983; Brasier and Singh 1987; Bhatt and Mathur 1990; Bhatt 1996). The appearance of the shelly fauna heralded the coming of a variety of organism that had preservable body parts, such as conodonts; trilobites *Redlichia noetlingi;* and brachiopods *Obolus*, *Obolella and Lingulella* (Rai and Singh 1983; Kumar et al. 1983; Tripathi et al. 1984; Joshi et al. 1989; Bhargava et al. 1998), hexactinellid and siliceous sponge spicules (Mazumdar and Banerjee 1998) and a variety of microscopic biota (Tiwari and Azmi 1992; Tiwari 1996). The trilobites and brachiopods place the Tal Formation in the Lower Cambrian (Tommotian) epoch.

Far west in the Salt Range, the Early Cambrian trilobite *Neobolus* suddenly appeared in shales overlying the magnesian sandstone of the Jhelam Formation (Tahirkheli 1982; Gee 1989).

11.3.6 Sudden Diversification

It is obvious that towards the end of the Neoproterozoic suddenly around 550 Ma, the cyanobacteria-dominated sea was swarmed by diverse type of complex multicellular life forms, including sponges, trilobites and brachiopods. And they evolved rapidly, culminating in what has been described as *Cambrian Explosion of Life* or *Evolutionary Big Bang*. There was maximum diversification globally during 550–543 Ma interval (Shields 1999).

This biological event of great moment is attributed to burst of voluminous methane and/or emplacement of flood basalts, particularly in submarine environment which provided nutrients and materials for building of preservable skeletons of the organisms. There must have been climate shift that changed the regional ecosystems and created, among other things, isolated communities of organisms. This isolation prompted natural selection and diversification of life. There is also a suggestion that increase in oxygen level (by 5–15 % of the present level) that took place in the Neoproterozoic may have sparked a biological revolution.

11.4 Transition in the Salt Range

Along the north-western flank of the Sindhu Basin, a Neoproterozoic succession known as the *Salt Range Formation*—earlier described as the Saline Series (Gee 1989)—forms the hills of the Salt Range (Fig. 11.8). The 800–2000-m-thick

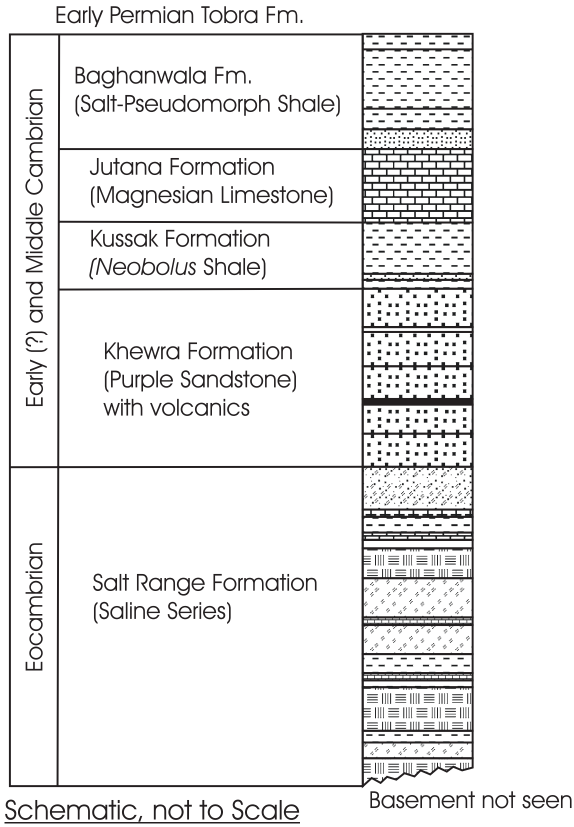

Fig. 11.8 Lithology shows the transition from Neoproterozoic to Lower Cambrian in the Salt Range (After Gee 1989)

alternation of gypsum and red clay is capped by ultrapotassic porphyritic lava known as the *Khewra Traps*. It occurs widely—under the cover of the alluvial deposits of the Sindhu River including the foredeeps in front of Kohat–Potwar and Sulaiman ranges (Kazmi and Qasim Jan 1997). The Salt Range evaporite formation is succeeded without break by the *Jhelam succession* (Tahirkheli 1982) of magnesian sandstone and shale, the latter characterized by Lower Cambrian *Neobolus* (Gee 1989). The Jhelam Formation marks the end of the Purana sedimentation.

11.4.1 Time of Desiccation

Evaporites occur widely in north-west India at the terminal stage of the Neoproterozoic era—the Ropri–Mandi belt in Himachal Pradesh (Srikantia and Sharma 1972), in the Sincha area in the Ramban belt in Kashmir (Virdi 1990), the

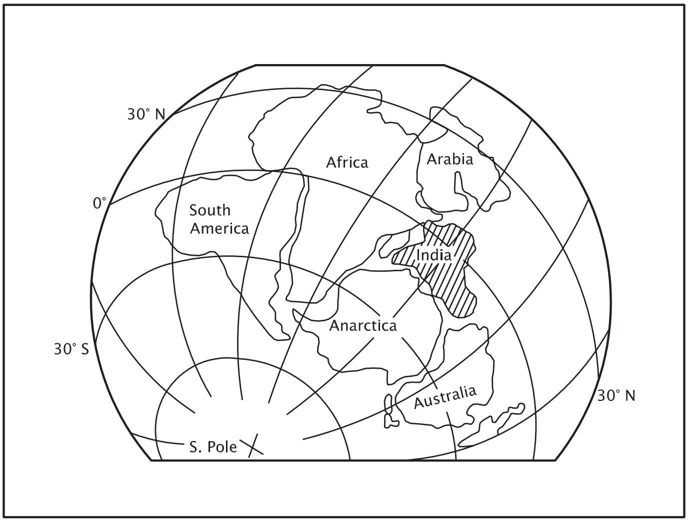

Fig. 11.9 India was close to the equator towards the end of Neoproterozoic and beginning of the Early Cambrian when quite a part of the subcontinent was affected by dessication (After Virdi 1990)

Salt Range in Pakistan (Gee 1989) and the Hanseran belt in Marwar (Dasgupta et al. 1988). These occurrences imply desiccation just before the advent of the Phanerozoic era that was full of life. In the Vindhyan Basin of the Peninsular India, evaporitic condition had begun a little earlier as evident from salt pseudomorph in shales of the Upper Bhander (Misra 1969). The desiccation occurred in the period 570–525 Ma when India was near the equator (Fig. 11.9). It was but natural that in some parts of the continental marginal sea where evaporation exceeded precipitation, there was concentration of salts in the waters of barred basin.

11.5 Proterozoic–Lower Cambrian Transition in Tethys Domain

Overlying the crystalline complex of the Great Himalaya, the 10–12-km-thick sedimentary succession of the Tethys domain occurs in a number of basins (Fig. 12.1). Putting a boundary between the crystalline basement and the covering sedimentary pile is beset with difficulty in view of transitional passage in some areas and tectonic detachment or faulting in other sectors (Berthelsen 1951, 1953).

In Himachal Pradesh, the high-grade metamorphics of the Vaikrita Group are transitionally succeeded by metamorphosed muddy flysch described by H.H. Hayden in 1904 as the *Haimanta* or as the *Batal* by S.V. Srikantia in 1981. The transition zone Batal gives way gradationally through greywacke–slate assemblage the *Kunzumla* (Bhargava 1991) to what Hayden had called the Parahio series. The *Parahio Formation* consisting of more than 1350 m of dominantly siliciclastic sediments is characterized by numerous medium-scale shallowing cycles in deltaic lobes (Myrow et al. 2006). The palaeocurrents suggest northward prograding fluvial–deltaic depositional system. The Parahio is characterized by Early Cambrian trilobite *Olenus*. In north-eastern Kumaun, Heim and Gansser (1939) showed the Vaikrita passing gradually into slightly metamorphosed *Martoli* flysch. In the flyschoid maroon phyllite rhymically alternating with siltstone, representing the north-western extension of the Martoli Fm of Kumaun and south-eastern continuation of the Kunzumla Formation of Himachal Pradesh, well-preserved trace fossils produced by trilobites such as *Cruziana*, *Dimorphicnus and Rusophycus* along with worm tracks have been found at Lal Devata Temple in the Jadhganga Valley, NNW of Gangotri (Upadhyay and Parcha 2012). In the Tsarap Valley in Ladakh, the Zanskar Crystallines are overlain by mildly trace metamorphosed argillites and siltstones of the *Phe Formation* (Nanda and Singh 1976; Baud et al. 1984; Gaetani et al. 1985; Fuchs 1987). The Phe is a succession of massive to laminated wacke–sandstone that are locally micaceous and conglomeratic greywacke characterized by clay galls, groove cast, flute casts, load cast convolutions and scour marks. The horizon contains trace fossils including *Cruziana* (Srikantia 1981; Bhargava and Srikantia 1985). The Kunzumla/Phe (Lower Haimanta) bears strong lithological resemblance with the Salkhala of Kashmir. The *Salkhala* in the Pir Panjal Range (Thakur et al. 1990) is made up of metamorphic rocks which imperceptibly grade into the flysch assemblage described as the *Dogra Slate* by Wadia (1934). The Dogra Slate comprises argillites and wacke–sandstones with lenticular beds of diamictites (*Machhal*) giving way up to the Cambrian Formation the *Lolab* in the Hundwara–Kupwara belt and the *Nutunus* in the Liddar Valley (Shah 1982, 1991) and Redlichid trilobites (Shah et al. 1980). In the Pohru Valley, the Precambrian–Cambrian boundary sequence contains sponge spicule with an assemblage of small shelly fossils (Tiwari 1997).

In Nepal, the Annapurna Gneiss of the Vaikrita complex is succeeded with a sharp break by an attenuated horizon of phyllites, greywackes and acidic tuff of the *Sanctuary Formation* (Colchen et al. 1986). Similar is the situation in the Dolpho–Dhaulagiri massif (Fuchs 1967). In the Marsyangdi Valley, the augen gneiss of the Great Himalayan complex gives way to the geochemically similar *Larjung Formation*, made up of the carbonates in the Chame–Mustog belt and the latter overlain by the Ordovician Nilgiri Limestone (Upreti 1999). In the TangChu–WachuLa area in Bhutan, the high-grade Thimpu is succeeded by the low-grade Chekha Formation, and the latter passes upwards through metamorphosed amygdaloidal andesite–dacite volcanics (Singhi) and quartzarenite–conglomerate sequence (*Deshichiling*) to fine-grained quartzite–slate succession (*Maneting*) containing Early Cambrian trace fossils in the lower part and brachiopod *Lingulella* and Lower Cambrian trilobites in the upper part (Tangri et al. 2003).

11.6 Chaung Magyi Group

Overlying the basement of the Mogok complex, the *Chaung Magyi* is a 3000-m-thick succession of mildly metamorphosed flysch (Fig. 10.13. It has been assigned to the Late Proterozoic period (Searle and Haq 1964). Between the Shan States and the Salween River in the east, the Chaung Magyi rocks form about 2000-m-high mountain ranges trending N–S. Its arched up parts occur as inliers within the terrane of the Plateau Limestone. In the Ye-ngan area in Southern Shan States, the Chaung Magyi comprises in the lower part a sequence of greywacke, felspathic subgreywacke, mudstone and shale. There are intercalation of dolomite and green limestone. The siliciclastics are characterized by graded bedding, flute and groove casts, giving way upwards to cross-bedded sandstone and shale with burrows, indicating deposition in the delta-top and delta-slope under shallow water (Garson et al. 1976).

11.7 Pan-African Tectonism

11.7.1 Manifestation

After life had diversified in various forms, and proliferated in the Himalaya province, and sedimentation had continued in environments varying from open shelf to anoxic lagoons, there was a tectonic upheaval. The tectonic movements resulted in wholesale cessation of sedimentation in the entire Lesser Himalaya subprovince and in the whole of Peninsular India and caused pronounced interruption in basin-filling in the Tethys domain (Valdiya 1993a, 1995). This interlude of non-deposition varied in temporal span from sector to sector. The tectonism manifested itself in (i) deformation of rocks, including tilting and folding; (ii) widespread granitic activity; and (iii) cessation of sedimentation in the Lesser Himalaya and its interruption in the Tethys domain.

11.7.2 Deformation

In the Rohtang Pass in Himachal Pradesh, the Vaikrita rocks under the Tethyan sedimentary pile show NE–SW trending folds and NE/ENE–SW/WSW-oriented upwarps associated with Shyarma Fault—the fault that exercised control on emplacement of sediments and transverse pattern of their facies variation (Bhargava 1991). About 20 km south of Muth in the Pin Valley, the pre-Ordovician rocks below an unconformity are deformed into mesoscopic upright folds with their axial planes dipping 30°NW (Grassemann et al. 1997). A well-marked unconformity between the Kunzumla (Haimanta) and the younger Thango conglomerate in the Zanskar–Lahaul region argue strongly for the tectonic upheaval and attendant marine regression in the Cambro–Ordovician interval.

Manifestation of Early Palaeozoic tectonism was, in addition to moderate- to high-grade metamorphism, a large-scale southward thrusting as witnessed in the Kathmandu sector where there was folding of garnet-grade metamorphic rocks and offsetting along faults *prior to* the emplacement of the 476.3 ± 3.4 m.y. old Palung Granite (Stocklin and Bhattarai 1979; Stocklin 1980). In the Kinnar Kailas area in eastern Himachal Pradesh, the 488-million-year-old Kinnar Kailas Granite intrudes the regionally folded kyanite–sillimanite schist (Marquer et al. 2000). In the Zanskar area in the Tethyan strata, the Middle Ordovician conglomerate contains sediments representing a foreland basin of a thrust belt that was active during the Late Cambrian through Middle Ordovcian time (Garzanti et al. 1986). And in the Koraikhola in far-western Nepal, a 30-m-thick conglomerate sequence at Damagad comprises clasts of *pre-Ordovician metamorphic rocks* along with 530–480 Ma detrital zircon in the sediments (Gehrels et al. 2006).

Along the border of Uttarakhand–Himachal Pradesh, in the Tons Valley, the Proterozoic sedimentary succession rests as pile of sheets upon the Middle Cambrian Chilar Formation which also occurs as tectonic slices within the thrust sheets (Bhargava et al. 2011). Taken in conjunction with the existence of a distinct unconformity between the Cambrian and the overlying Ordovician in the Tethys domain, Early Palaeozoic metamorphism and widespread emplacement of Early Palaeozoic granites, there is a strong case for Late Cambrian deformation in the Lesser Himalaya (Bhargava et al. 2011).

11.7.3 Volcanism

Volcanic explosion and eruption in many areas were precursors to the tectonic upheaval that overtook the Himalaya in the Cambro–Ordovician time. In Pakistan, the Salt Range Formation is capped by a thin sheet of ultrapotassic porphyritic lavas described as the *Khewra Traps* (Jan and Faruqi 1995). The Khewra underlies the Cambrian fossil-bearing Jhelam Formation. In the Suran Valley in Punch district (Kashmir) between the Dogra Slate and the Tanawal of the Cambrian spectrum, ichnofossil-bearing slates are interbedded with dominant spilitic lavas, tuffs and associated keratophyre dykes which constitute the *Bafliaz Volcanics* (Wakhaloo and Shah 1968; Sharma and Gupta 1972). To the south-east in the Spiti Basin, the greywackes and slates of the Kunzumla are interbedded with basaltic tuffs (Fuchs 1982, 1987). In Kinnaur in north-eastern Himachal Pradesh, the Hilap succession contains acid tuffs (Bhargava and Bassi 1998; Bhargava 2000). In the Kali Valley in north-eastern Kumaun, chlorite schist and K-bentonite representing an altered basic tuffs occur in the lower part of the Garbyang Formation (that succeeds the flyschoid Martoli–Ralam sequence) (Gansser 1964). In the Annapurna massif in Nepal, acid tuffs and lavas occur in the *Yellow Formation* (≡Larjung) of the probable Cambrian age (Colchen et al. 1986). Between the Precambrian Chekha and Late Precambrian Deshichiling in the Black Mountain in Bhutan occurs nearly a hundred metre thick horizon (the Singhi) of amygdaloidal andesite and dacite interbedded with quartzarenite (Tangri and Pande 1995a, b) (Table 11.2, Fig. 11.10).

11.7.4 Granitic Activity

Strikingly leucocratic, the 500 ± 25 million-year-old granites occur extensively in the upper part of the low- and medium-grade metamorphic nappes of the Lesser Himalaya, in the lower part of the high-grade metamorphic rocks of the Vaikrita, and in the domal upwarp in the proximity of the Indus–Tsangpo Suture (Fig. 11.10; Table 11.2). The suture represents the junction of India and Asia. These granites belong to the 10,000-km-long girdle of the Cambro–Ordovician granites embracing Afghanistan, the Himalaya, Australia, and Antarctica (Le Fort et al. 1986)—the landmass that once formed a supercontinent. The granites are products of anatexis of the continental crust that was rifted and attenuated. The thermal events were not restricted to the Himalaya province, the south-western part of Rajasthan also witnessed the granitic activity during nearly the same period, as testified by the 510 ± 10 Ma Sendra Granite (Gangopadhyay and Lahiri 1984). In the distant Kerala, the 550 ± 15 Ma Ponmudi Charnockite (Choudhary et al. 1992), representing widespread charnockite emplacement in the Southern Granulite Terrane, shows that even South India did not escape the Pan-African granitic activity.

The Cambro–Ordovician peraluminous granites are identical in petrological and geochemical characters all through the expanse of the Himalaya—quartz + felspar + plagioclase + biotite + muscovite ± garnet ± tourmaline ± cordierite ± andalusite ± sillimanite. Granitic bodies of all sizes, including batholithic dimension such as the *Badarinath Granite* in Uttarakhand, occur extensively in the Vaikrita succession, particularly in the upper part. They have thrown out a network of dykes and veins of adamellite, aplite and pegmatite. There was a large-scale permissive layer-by-layer injection of granitic melt formed at depth of 15–20 km due to differential melting of high-grade metamorphics (Powar 1972). This resulted in the formation of migmatites on an extensive scale around granitic bodies (Valdiya and Goel 1983; Valdiya et al. 1999). The anatectic origin of granite is borne out by sillimanite, garnet and cordierite present in the granites and is corroborated by high strontium ratios of 0.743–0.784. The highly variable strontium ratios and the low REE imply involvement of a variety of metasediments in the differential melting of rocks that gave rise to the granitic melt. In the Nanga Parbat massif in the north-western part of the Himadri domain, there was wholesale granitization of the high-grade metamorphic rocks (Misch 1949;

Table 11.2 Rb–Sr whole-rock isochron dates from granites from the Chail, the Jutogh and the Haimanta formations and the Tso–Morari Crystallines (Modified after Islam et al. 1999)

Locality	Tectonic unit	Age (Ma)	Initial Sr isotope ratio	Authors
Almora	Almora (≡Jutogh)	560 ± 20	0.710 ± 0.001	Trivedi et al. (1984)
Ranikhet	Almora	485 ± 55	0.735 ± 0.009	Pandey et al. (1981)
Champawat	Almora	565 ± 22		Trivedi et al. (1984)
Chaur	Jutogh	530 ± 40	0.7326	Kwatra (1986)
Kulu	Jutogh	518 ± 8	0.719	Mehta (1977)
Mandi	Chail (Salkhala)	545 ± 12		Mehta (1977)
Mandi	Chail	500 ± 100/ 518 ± 100/ 545 ± 12		Jaeger et al. (1971)
Dalhousie	Chail	472 ± 50/ 456 ± 50		Bhanot et al. (1974)
Manikaran	Chail/Jutogh	467 ± 45	0.719	Bhanot et al. (1979)
Lahaul	Haimanta	495 ± 16		
Jispa	Lower Haimanta	512 ± 16	0.720	Frank et al. (1977)
Akpa-Rakcham	Haimanta	477 ± 29	0.7201	Kwatra (1986)
Rohtang	Central crystallines	601 ± 19/ 581 ± 9	0.711	Mehta (1977)
Kade	Tso Morari Gneiss	472 ± 9/–6 460 ± 8		Stutz and Thoni (1987)
Nanga Parbat	Shengus Gneiss	400–500 (U–Pb, zircons)		Zeitler et al. (1989)
Kazinag	Salkhala	477 ± 24		Trivedi et al. (1985)
Kagan	Salkhala	470 ± 11	0.7216 ± 0.0023	Trivedi et al. (1985)
Mansehra	Tanol (Chail/Haimanta)	516 ± 16	0.7189	Le Fort et al. (1980)
Nimaling	Tanglang La of Tso–Morari Crystallines	460 ± 8		Stutz and Thony (1987)
Polokong La	Tso–Morari Crystallines	487 ± 25	0.7154 ± 0.0067	Trivedi et al. (1986)
Korzok	Tso–Morari Crystallines	487 ± 14	0.7113 ± 0.0036	Trivedi et al. (1986)
Palung		486 ± 10	}	
Dudh Kosi		550 ± 32	}	
Kangmar		485 ± 6/ 484 ± 14/ 435 ± 37	}	References in Lefort et al. (1986)
Thimpu		508 ± 15		

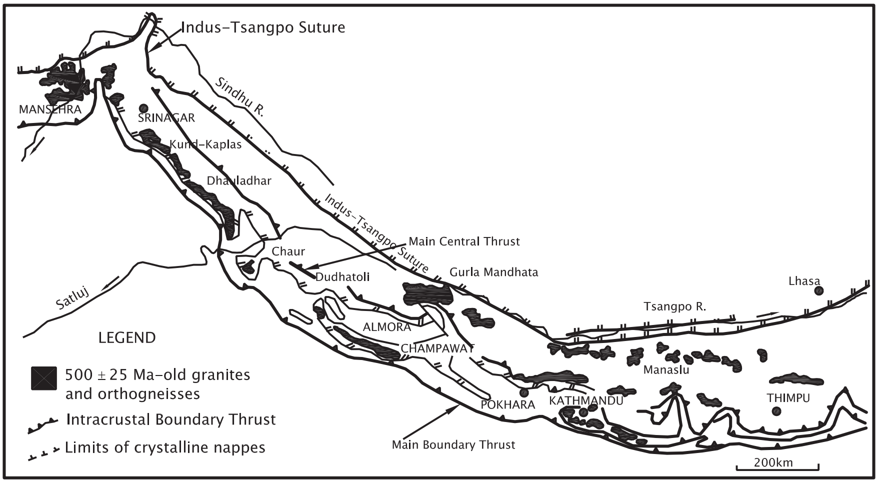

Fig. 11.10 Cambro–Ordovician (500 ± 25 Ma) granites in the Himalaya province occurring preponderantly in the epimetamorphic nappes of the Lesser Himalaya, the lower part of the Vaikrita, and in the northern upward edge of the Indian plate along the India–Asia junction (Based on Le Fort et al. 1986)

Shams 1983). In eastern Himachal Pradesh, the *Kinnar Kailas Granite* is a discordant body penetrating the Vaikrita metamorphic rocks that were affected by four phases of deformation. The granite contains xenoliths of paragneiss characterized by deformational features developed under amphibolite facies conditions (Marquer et al. 2000). This fact has profound implication—the first three phases of deformation suffered by the Vaikrita occurred prior to the emplacement of the 488-million-year-old Kinnar Kailas Granite. Thus, there was pre-Cambrian deformation in the Himachal Himalaya. U–Th–Pb dating of zircon and monazite crystals establishes the age of Kade Granite in the Himadri domain at 472 ± 9/−6 Ma (Pognante et al. 1990). The Nyimaling Granite in the TsoMorari complex is dated by Rb–Sr method at 460 ± 8 Ma (Stutz 1988). In the Tethyan terrane, the Puga gneiss at Kiagarla is 499 ± 8 Ma old and the granites of the Polokongkla and Tso–Morari areas in the setting of the Puga gneisses and schists have yielded U–Pb zircon age of 479 ± 2 Ma (Rameshwar Rao and Rai 2002). The age data together with similarity of petrochemical compositions of the gneisses and granites imply their derivation from similar or the same magma generated by partial melting of crustal-derived pelitic rocks.

The calcalkaline Hant Granite in north-west Kashmir, syntectonically emplaced in the Salkhala and the Dogra Slate, crystallized from anatectic magma generated in the Precambrian continental crust (Rameshwar Rao et al. 1990). The 553 ± 2 Ma Kund Kaplas Granite (Miller et al. 2001) and the intrusive peraluminous Dalhousie Granite in the Chail are depleted in REE (Sr, Zr, Th, P) and somewhat enriched in U (Mukherjee et al. 1998). The crustally derived 477 ± 29 and

453 ± 9 Ma Akpa-Rakcham Granite in the Satluj Valley is characterized by higher Sr, Ba, Zr, Ni, Th and Y and total REE contents pronounced Eu anomaly, and low Rb content and lower Rb/Sr ratio (Islam and Gururajan 2003; Singh and Kumar 2005). Hornfels is formed around the Dalash Granite in the Satluj Valley due to contact metamorphism and at the base of the Mandi–Karsog Granite (Gururajan and Islam 1991; Islam and Gururajan 2003). Compositionally, the *Champawat Granodiorite* is a quartzdiorite–granodorite–adamellite–granite suite, it evolved in an environment charged with moisture or water, and was subsequently involved in the folding of the host rocks (Valdiya 1962b). The granodiorite–granite assemblage is characterized by enrichment of Y, Zr, Th, U, Nb, La, Ce, Pr and Nd (Singh et al. 1991). The Rb–Sr whole-rock isochron age of the Champawat pluton is 560 ± 20 Ma (Trivedi et al. 1984; Trivedi 1990). The age of the *Chaur Granite* is 526 ± 46 Ma or near about (Kwatra et al. 1986; Singh 2003). The Champawat Granodiorite within the mesometamorphic succession of the Dadeldhura Range in far-western Nepal has yielded concordant U–Pb zircon age of 492 ± 6 Ma, while the associated augen gneiss of granitic composition gave U–Pb zircon age of 478 ± 10 Ma (Upreti 1996; DeCelles 2000, 2001). The biotite–quartz-rich Champawat Granodiorite body is intruded by sills, dykes and veins of leucocratic adamellite, aplogranite and pegmatite which are compositionally and texturally indistinguishable from the granite plutons intruding the Chail Nappe in the Dhauladhar and Pir Panjal Ranges. The Mandi, Dalhousie and Kazinag granites have been dated, respectively, 545 ± 12 Ma (Mehta 1977), 456 ± 50 and 477 ± 24 Ma (Bhanot et al. 1980). The origin of the *Mandi Granite* is attributed to partial melting of heterogeneous crustal material under water-deficient condition (Gupta 2001).

In northern Pakistan, the polymetamorphic Tanol assemblage enveloped by the Salkhala is intruded along the contact by granitic bodies (Shams 1983). One of them, the *Mansehra Granite,* is dated 516 ± 16 Ma (Lefort et al. 1980). It is derived from old crustal material. The *Ambela Granite* and the Lower *Swat Granite*, showing alkaline affinity (Ahmad and Ahmad 1974; Shams 1980a, b; Jan et al. 1983; Kempe and Jan 1970; Kempe 1983), belong to the same generation of granites—the 500 ± 25 m year old Cambro–Ordovician granites.

In the east, the Palung (485 ± 20 Ma), the Dudhkosi (550 ± 32 Ma), (Decelles et al. 2000), the *Thimpu Granite* (508 ± 15 Ma) and the *Bomdila Granite* (530 ± 75 Ma) (Dikshatulu et al. 1995) represent this event of global significance.

SHRIMP U–Pb zircon dates of peralkaline Lesser Himalayan granites in the Kathmandu region with xenoliths showing deformation structures truncated by host granite and their signature inherited detrital zircon ages ranging from Archaean to Palaeozoic (~500 Ma)—with prominent peaks of Late Proterozoic and Neoproterozoic ages—there is little doubt that the Himalaya was strongly affected by Cambro–Ordovician Pan-African orogeny (Cawood et al. 2007) as earlier suggested among others by Valdiya (1995).

These are the few of the many anatectic granites showing distinctive petrochemical characteristics of the Pan-African granites.

11.8 Mineralization

The Neoproterozoic rocks of the Lesser Himalaya are very valuable in terms of mineral deposits of economic value and genetic significance. Among the important mineral deposits, those of magnesite, talc, phosphorite, barytes and copper sulphides are quite important.

The Gangolihat Dolomite is the mineralised facies of the Deoban. It is characterized by lentiform deposits of coarsely crystalline to spathic *magnesite* interbedded with cherty dolomite and dolomitic–stromatolitic limestones. Locally, the relationship is discordant, marked by interdigitation of magnesite and dolomite. Generally, the contact is sharp. The thickness of the deposits vary from a fraction of a metre to as much as 30 m (the average 5–25) and the length ranges from less than a kilometre to several kilometres. The deposits occur at a definite stratigraphic level in the Deoban succession that is mineralized between Kali and Mandakini rivers in Uttarakhand. The important deposits are located at Jhirauli in the Almora district and Chandaak in the Pithoragarh district.

The origin of magnesite is attributed to hydrothermal metasomatism of dolomites, the magnesian solution supposedly derived from basic intrusives being the agent of transformation (Nautiyal 1953; Nath and Wakhaloo 1962). The other view is that synsedimentary diagenetic volume-for-volume replacement of dolomite sediment gave rise to the magnesite deposits (Misra and Valdiya 1961; Valdiya 1968, 1980b). Interestingly, the Kumaun magnesite deposits strongly resemble in shape and textural character of the magnesite deposits of Asturettes in the Spanish Pyrenees. The Asturette magnesite was formed by diagenesis at ~150 °C in the basin which had high primary concentration of Mg-rich sedimentary carbonate, resulting in the transformation into magnesite with minor ulterior metamorphic remobilization (Velasco et al. 1987). In Kumaun, the algae that built the stromatolite structures must have played a vital role in the genesis of magnesium carbonate, particularly in creating an environment conducive to the concentration of $MgCO_3$ in barred basins (Valdiya 1968). There is also a suggestion that magnesite was initially precipitated as nesquehonite and later converted to magnesite (Tewari 1973). South-east of the Jhiroli magnesite mine in Almora district, the Bauri magnesite deposit shows correlation between salinity and temperature, indicating formation of magnesite through diagenetic replacements of dolomite at 90–160 °C (Sharma and Joshi 1997). Significantly, not only the magnesite and dolomite minerals show the same range of oxygen isotope ratios, but also are characterized by fluid inclusion of nearly the same characters. The magnesite deposits in the Chamba district in western Himachal Pradesh, localized below the Chamba Thrust between Jiuni in Bharmauer and Bindrabani in the Pangi Valley, are supposedly products of reaction of hot (200–275 °C) saline waters with dolomite and limestone, a process prompted by the tectonics of the Chamba Thrust (Singh and Sharma 1997).

Intimately associated with magnesite occur lentils, pockets and veins of *talc and steatite*, and the latter intercalated with dolomite in a bedded form. They are extensively mined. The origin of talc is attributed to reaction during mild metamorphism of $MgCO_3$ with silica that occurs abundantly in magnesite and dolomite. The reaction was promoted by CO_2-rich groundwaters (Valdiya 1968). In the Rema area, irregular patches and pockets of talc within magnesite were formed at the expense of magnesite by silica as borne out by the common presence of fluid inclusions in talc, magnesite and dolomite associated with it. The fluids within inclusions are $H_2O + NaCl + KCl + MgCl_2CaCl_2$—representing the fluids of the sedimentary basin (Sharma et al. 2008).

The lower part of the Tal Formation in south-eastern Himachal Pradesh and the Mussoorie Hills in Uttarakhand is made up of *phosphorite* with chert, black limestone and carbonaceous shale (Shanker 1975). The thickness of the deposit varies from less than a metre to over 150 m in some places. Phosphorite of Maldeota, Chamsari, Paritibba and Chaunpa–Kumali occurs predominantly in a laminated or platy form and less commonly as granular (pelletal and nodular) deposits. The finely laminated phosphorite laterally grades into cherty limestones, implying their formation due to concentration of phosphorous brought up by upwelling currents (Patwardhan and Ahluwalia 1973).

Copper and lead sulphides occur as disseminations, small veins and lentils in dolomites and magnesite of the Gangolihat facies of the Deoban Formation. In Kumaun, the sulphide mineralization shows preference for contact between the Gangolihat Dolomites and overthrust Berinag quartzites (Valdiya 1980b). There seem to be a stratigraphic control on the base metal localization and their syngenetic remobilisation in structurally weak zones. South-west of Bageshwar, in the Sisakhani–Chhanapani–Bhaldeo belt, lead sulphide (galena) occurs in *en echelon* bodies of cherty dolomite, magnesite and talc, as dissemination, minute veins and tiny streaks or patches. The model Pb–Pb age of the lead sulphide mineralization is 1550–1700 Ma (Sarkar 2000). In the Jammu Limestone, the sphalerite mineralization is confined to two carbonate units, the mineral initially occurring as a stratabound deposit later altered and remobilised by hydrothermal solution (Sharma and Nayak 1991). Near Askot in the Pithoragarh district, deposits of copper sulphide (along with other sulphides) in the basic schists within the Berinag are being mined.

In eastern Arunachal Pradesh, in the NNE–SSW trending Siang Group, the iron formation is associated with muscovite–quartz schist and brecciated quartzite in a 30-km-long and 30-m-wide belt and the *sulphides* associated with the *uranium minerals* occur as disseminations, stringers, veins and vug fillings along fractures in sericite–quartzites and garnetiferous amphibolite (Bisht et al. 2005). The sulphide–uranium mineralization is attributed to hydrothermal solutions, possibly derived from the Cambro–Ordovician granites of the terrane.

The Krol–Tal contact in the Mussoorie Hills and the Nigalidhar belt contain pockets of *barytes* in the phosphorite zone. In the Nigalidhar Hills in south-east Himachal Pradesh, the barytes deposits occur below the phosphorite zone. It occurs as veinlets, nodules, lentils and stringers in limestones. Near Khairasen in the Nayar Valley, the barytes deposit is 500 m long and 1–1.5 m thick in the basal part of the Nagthat quartzite (Sharma et al. 2003). In the Jammu Limestone, barytes occurs as veins, nodules and stringers in cherty and dolomitic limestones, and in the brecciated carbonates of the Jangalgali, Kherikot and Sersandhu areas. The origin of these stratabound deposits is attributed to synsedimentary processes.

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