

The rise and decline of the Ediacaran biota: palaeobiological and stable isotopic evidence from the NW and NE Lesser Himalaya, India

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Abstract: Sediments of Ediacaran age have recently been recognized in the Krol Belt (NW Lesser Himalaya, India) with the discovery of pre-Ediacaran and Ediacaran biotas, carbon isotopic excursions matching the global curve and evidence for one Neoproterozoic glacial event. Other data include evidence for termination of the Krol algal-stromatolitic carbonate cycle in Late Proterozoic and deposition of phosphorite, phosphatic stromatolites similar to Tommotian taxa, and diversification of Small Shelly Fossils (SSF) of Tommotian/Meischucunian Zone 1 in Lower Tal Formation. Recently, Riphean–Ediacaran organic-walled microfossils, stromatolites and sponge spicules (monaxon) have been recovered. The link between the decrease in microbial-induced carbonate sedimentation and the decline of large Riphean stromatolites is recorded in the inner sedimentary belt (Deoban–Gangolihat). The first appearance of complex organic-walled microfossils and acanthomorphic acritarchs is recorded in the Blaini–Infrakrol sediments along with possible Ediacaran soft-bodied metazoans and metaphytes in the Krol Formation. In India, the Late Proterozoic base occurs at the bottom of a pink, microbial limestone in the Blaini Formation, and the Precambrian–Cambrian boundary occurs somewhere in the Lower Tal Formation. Ediacaran metazoans occur above glacial deposits assigned to the Varangian/Marinoan/Blainian and below the first occurrence of SSF (Meischucunian zone I), in the lowermost Cambrian.

Hoffman *et al.* (1998) proposed the term ‘Snowball Earth’ to describe the concept of Neoproterozoic low latitude glaciation. They suggested that oceans became completely frozen. However, not all researchers would agree (e.g. Etienne *et al.* 2006), and others suggest that some ocean waters were free of ice, and that primary biological productivity may have collapsed during this period (e.g. Hyde *et al.* 2000). Indeed, some even infer that continental ice cover was thin and patchy (e.g. Powell *et al.* 1993). Palaeomagnetic data also supports the view that some Neoproterozoic sequences on different continents accumulated at low palaeolatitudes, for instance in Australia (Chumakov & Elston 1989; Brookfield 1994). They also emphasized that if glacial deposits were not present in the Late Proterozoic sections, there would be no reason to question the validity of the low palaeomagnetic inclinations and palaeolatitudes of accumulation.

Jenkins (1981) proposed the concept of an Ediacarian Period as the terminal Precambrian subdivision. This time period was finally officially termed the ‘Ediacaran’ in 2004 (Gradstein *et al.* 2004). The Ediacaran stratotype occurs in the Flinders Ranges of South Australia. The Ediacaran Period corresponds to the Vendian Period in the Russian Platform. A supercontinent, Rodinia, including most of the continental crust may have

existed at the end of the Mesoproterozoic (1000 Ma) up until around 750 Ma. During the Neoproterozoic, Gondwana consisted of two separate plates: the Eastern (Australia–Antarctica–India) and Western (Africa–South America) plates. These plates collided during the Cambro-Ordovician Pan African orogenies, to which the coeval Ross (Antarctica) and Delamerian (Australia) events are related (Dalziel *et al.* 2000). In South Australia, the Flinders Ranges host the Adelaidean–Cambrian sequence. The Wilpena Pound Quartzite, well known for its Ediacaran metazoan fossils, underlies the Lower Cambrian archaeocyathan-bearing limestones.

The presence of Ediacaran metazoans and carbonate stromatolitic platform sedimentation has been reported from the Krol Group of the NW Lesser Himalaya in India. In the Tethys Himalaya, the Phe Formation of Zaskar Range consists of Late Proterozoic–Cambrian carbonate platform deposits (Tewari 1998b). The SE coast of present day India was probably connected with East Antarctica at this time (Fig. 1). The Himalayan Cambrian sedimentary succession closely resembles the deposits of the Pacific margin of Antarctica and Australia. Cambrian sequences of northern Victoria Land (Antarctica) and South Australia, both part of Gondwana, have been correlated with the coeval Tethys Himalayan sequence. The Tethyan Early

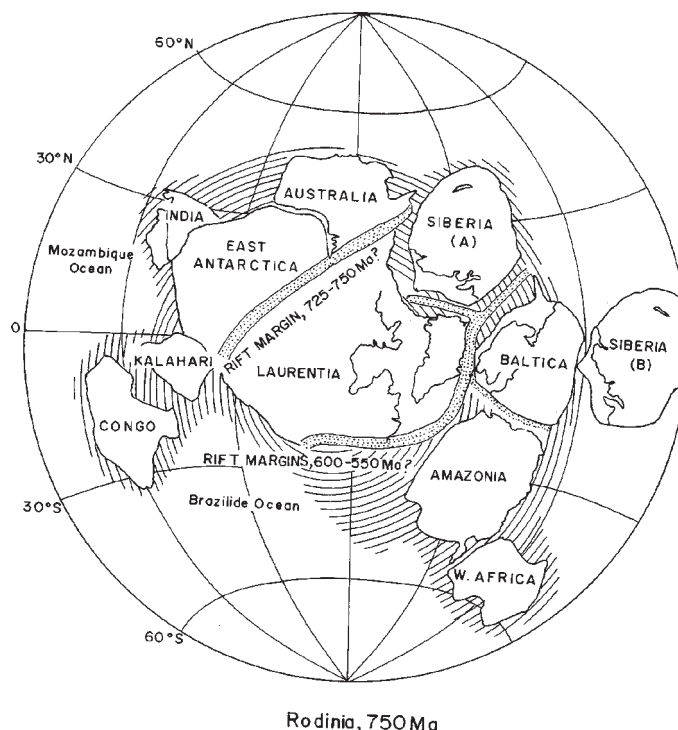


Fig. 1. Rodinia supercontinent (after Powell 1996; Yoshida & Arima 2000).

Cambrian sequence of the Zaskar Range is furthermore linked with the Shackleton Limestone Group of Antarctica and Normanville Group of Southern Australia (Casnedi 2002).

The Terminal Proterozoic–Cambrian sequences in the Himalaya are referred to as Blaini–Krol–Tal groups in the Krol belt of Lesser Himalaya (Figs 2 & 3), the Macchal–Lolab groups in Kashmir, the Batal–Kunzam La formations in Spiti, the Martoli Group in Kumaon and Buxa–Miri groups in the NE Lesser Himalaya (Tewari 1998a, b, c, 2002a, b, 2003). Sedimentation in the Lesser Himalaya was terminated by the Pan African Orogeny in the Late Cambrian. The Ediacaran biota recorded in these sequences includes stromatolites, cyanobacteria, acritarchs, algae, sponges and other metazoans, metaphytes (vendotaenids) from the Krol Belt of the Himachal and Uttaranchal Lesser Himalaya (Tewari 1989, 1993, 1994, 1996, 1998a, b, 1999a, b, 2001a, b, 2002a, b, 2003, 2004b; Mathur & Shanker 1989; Shanker *et al.* 1997; Kumar *et al.* 1997, 2000; Tewari *et al.* 2000).

The Deoban–Jaunsar groups in the Lesser Himalaya represents pre–Ediacaran carbonate–siliciclastic sedimentation, and a Mesoproterozoic age is strongly supported by the presence of Early to Late Riphean stromatolite assemblages, and associated microbiota (Table 1).

The stromatolite assemblage characteristic of the Deoban–Gangolihat dolomite includes *Kussiella kussiensi*, *Colonnella columnaris*, *Conophyton garganicum* in the lower part, *Baicalia chandakia*, *Jacutophyton* sp., *Baicalia nova*, *Tungussia* sp. in the middle part and *Jurusania–Gymnosolen–Minjaria–Inzeria* assemblage in the upper part of the sequence (Valdiya 1969, 1980; Tewari 1989, 1996; Fig. 5). Cyanobacteria found in the Deoban Chert include *Huronispora psilata*, *Glenobotrydion aenigmatis*, *Myxococcoides minor*, *Oscillatorioopsis*, *Obruchevella*, *Siphonophycus* and *Kildinosphaera* (Tewari 1989, 2003). Biodiversity of stromatolites and microbiota declined at the end of the Mesoproterozoic. The Jaunsar clastic facies contains no preservation of trace fossils or soft-bodied metazoans. The unconformably overlying Blaini Formation is a glacial unit. The pink cap microbial carbonate of the Blaini Formation may represent the base of the Late Proterozoic (base of the Ediacaran) where simple acritarchs such as the Sphaeromorphida and stratified stromatolites occur.

Rodinia began to fragment around 750 Ma, and East Gondwana (India, Australia and Antarctica) separated from West Laurentia. Baltica, Africa and South America were positioned on the other side of Rodinia. Neoproterozoic rifting, breakup of Rodinia and fragmentation of Gondwana, low-latitude

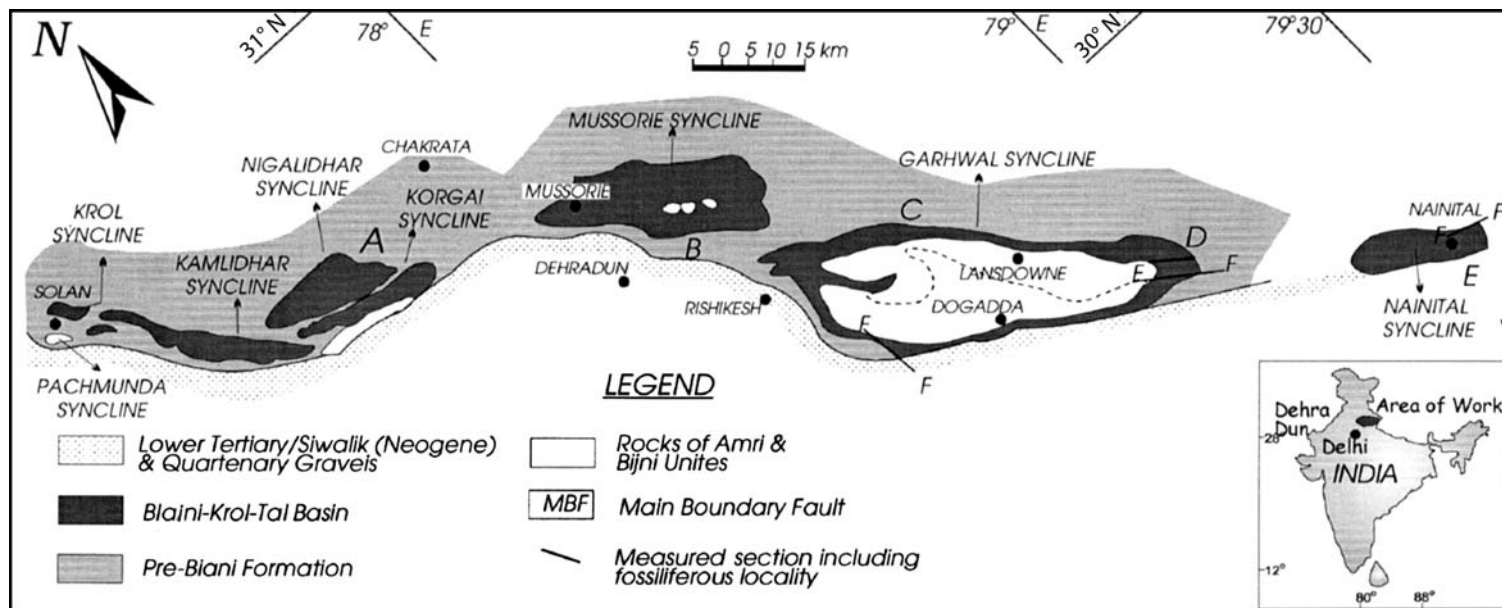


Fig. 2. Geological map of the Blaini-Krol-Tal basin, Lesser Himalaya, India (after Geological Survey of India).

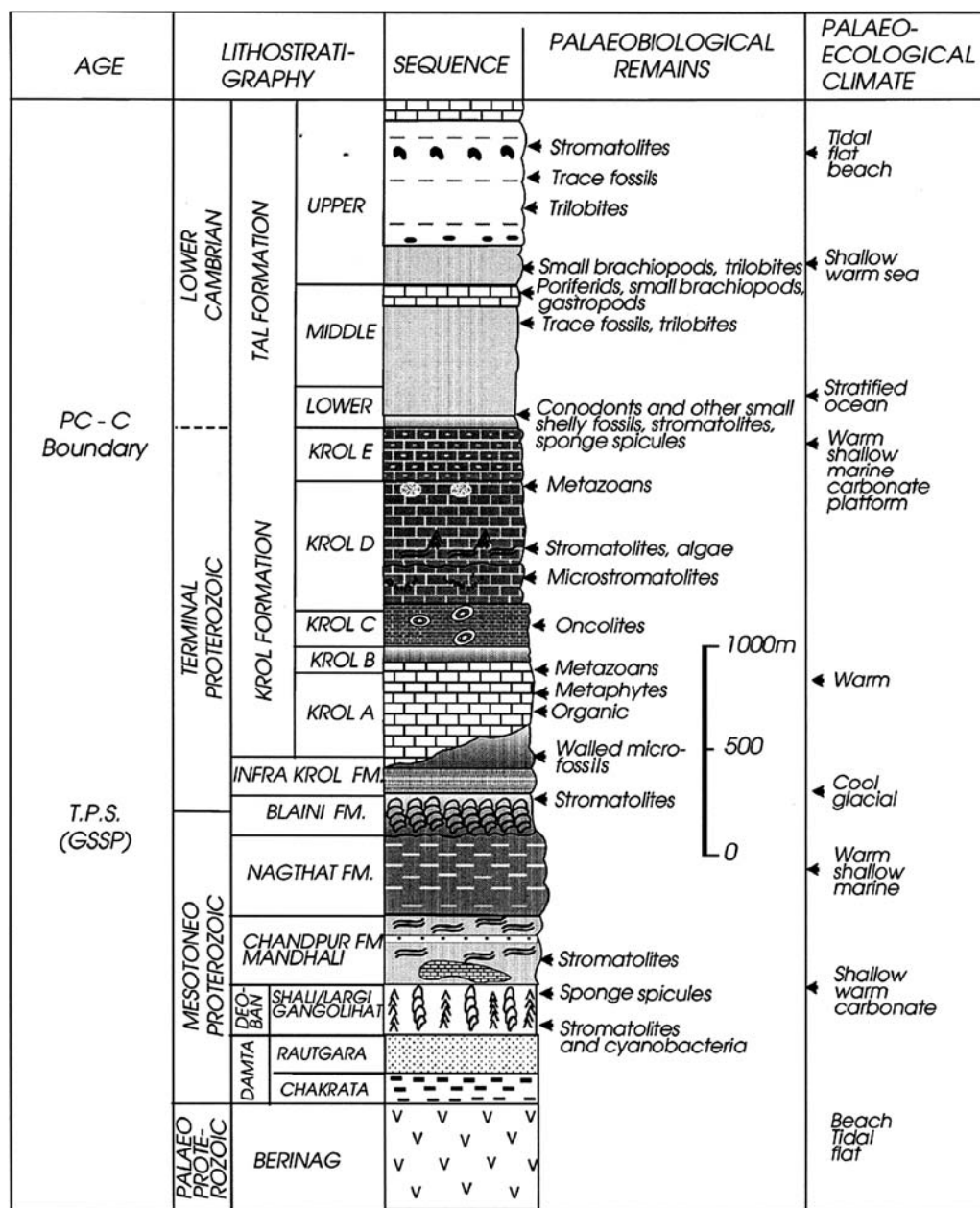


Fig. 3. Lithostratigraphic column, palaeobiological remains and palaeoclimatic events in the Lesser Himalaya, India.

glaciation and global warming events have all been recorded from the Lesser Himalaya of India. Carbon and oxygen isotopic variation and chemostratigraphy of the Blaini-Krol-Tal succession strongly suggests that the Lower Tal Formation ($\delta^{13}\text{C} = -4\text{‰}$ PDB) is of Late Neoproterozoic to Cambrian age. In contrast, sediments of the Krol belt in the

Lesser Himalaya are characterized by positive $\delta^{13}\text{C}$ values (+1 to 6‰ PDB). The presence of multicellular fossils in the Upper Krol is consistent with a possible increase in atmospheric oxygen.

The base of the Late Proterozoic in the Lesser Himalaya occurs in the Blaini Formation. A pink cap carbonate in the Blaini Formation registers a

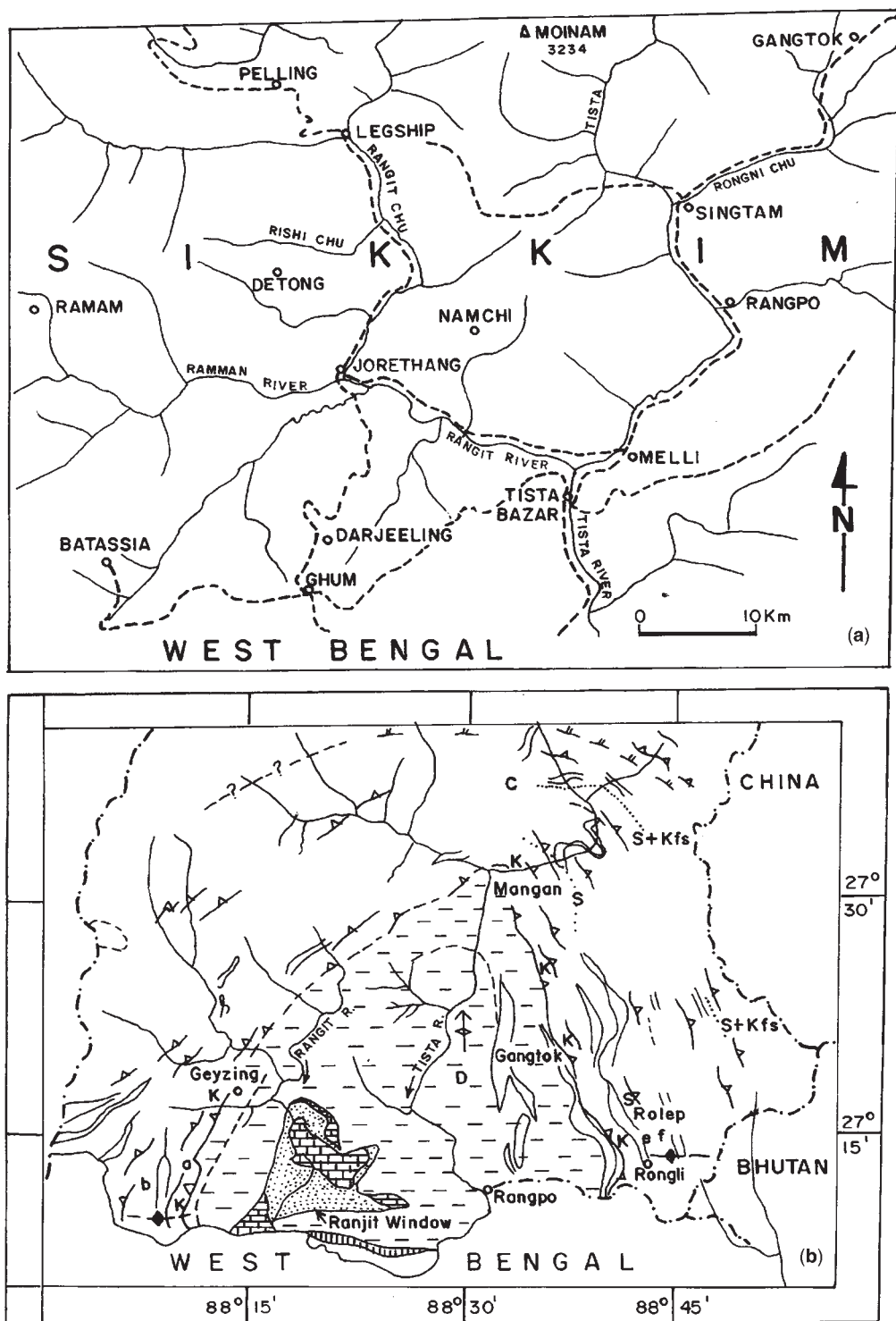


Fig. 4. Location and geological map of the Ranjit Window (RW), Sikkim, NE Lesser Himalaya, India.

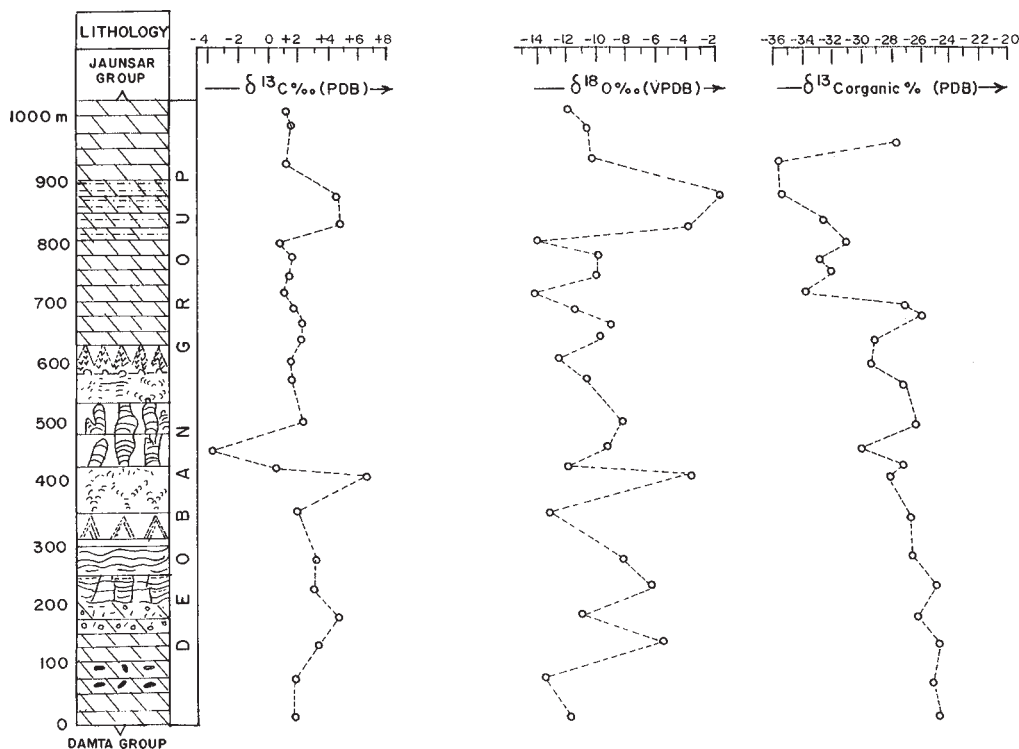


Fig. 5. Carbon isotope chemostratigraphy of the Deoban Group (Meso-Neoproterozoic) Garhwal, Lesser Himalaya, India.

negative $\delta^{13}\text{C}$ value (-3‰ PDB) and caps glacial sediments that are possibly representative of the Varanger glacial event. Comparison of the available carbon and oxygen isotope curves from other regions of Eastern Gondwana and South China, parts of Siberia and North Africa suggests that the Neoproterozoic–Early Cambrian chemostratigraphy is consistent in isotopic variation, with carbon isotopic signatures similar between Neoproterozoic sediments of the Bambui Group, Central Brazil and the Krol Formation of the Lesser Himalaya, India. In the northeastern Lesser Himalaya of India, the Neoproterozoic sedimentary successions show well developed carbonates, the Buxa Dolomite, with positive C-isotope ratios ($\delta^{13}\text{C} = +3.7$ to $+5.4\text{‰}$ PDB). The O-isotopic data also demonstrate $\delta^{18}\text{O}$ values fluctuating within a narrow range between -8.9 and -7.2‰ PDB corresponding with global Late Proterozoic C-isotopic evolution, followed by oscillations during the Precambrian–Cambrian transition in the Lesser Himalaya of Eastern Gondwana.

The break-up of Rodinia, East Gondwana and the Lesser Himalayas

The Rodinia supercontinent (Fig. 1) began to fracture around 750 Ma. East Gondwana (India, Australia and Antarctica) separated from West Laurentia (Powell *et al.* 1993). Baltica, Africa and South America occupied the other side of Rodinia. However, the existence of a Neoproterozoic supercontinent Rodinia is still hypothetical (Yoshida & Arima 2000) and recent geochronological and palaeomagnetic records of South America and Africa show that these cratonic fragments may not have been part of Rodinia (Cordani *et al.* 2003). The Neoproterozoic evidence for the rifting apart of Rodinia and the fragmentation of Gondwana low-latitude glaciation and global warming events have been recorded from the Lesser Himalaya of India (Tewari 2002a). Carbon and oxygen isotopic variation and chemostratigraphy of the Lesser Himalayan carbonate formations evidently reflect global palaeoclimatic and palaeobiological events (Tewari 2001a, b, c, 2002a, b, 2003, 2004b; Figs 6,

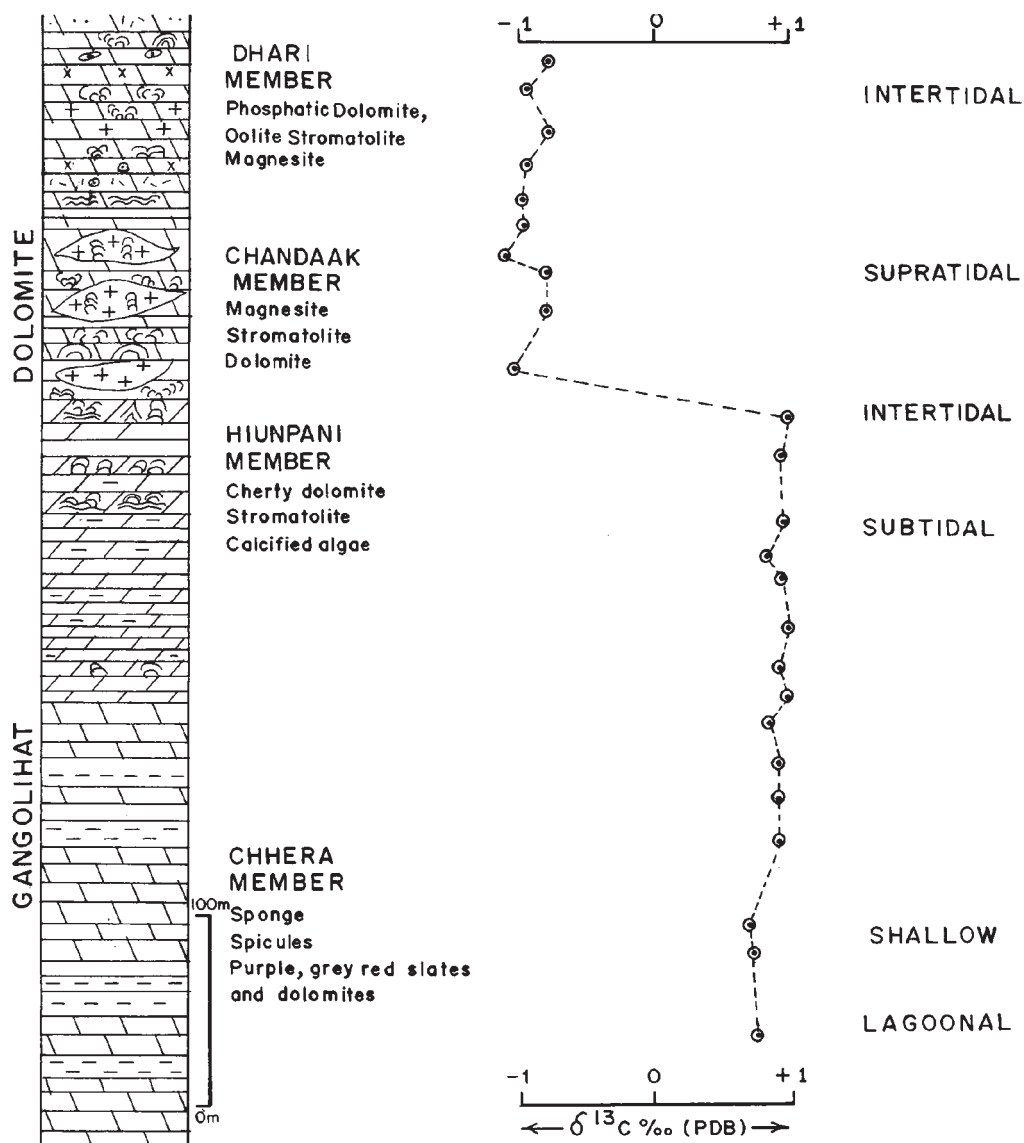


Fig. 6. Carbon isotope chemostratigraphy of the Gangolihat Dolomite (Meso-Neoproterozoic), Kumaun, Lesser Himalaya, India.

7 and 8). The concept of using C-isotope variation as a global correlator is based upon the assumption that C-isotopic ratios fluctuate in response to changes in the net rate of organic burial, climate variations and availability of atmospheric oxygen.

Terminal Proterozoic glacial deposits have been recorded from most continents, suggesting that palaeoclimatic change on Earth over the last

650 Ma is directly related to atmospheric CO_2 fluctuations (Jacobson & Kaufman 1999; Tewari 2001a, 2003). The 'Snowball Earth' model suggests that during global glaciation there may be a short-lived change in the C-isotopic ratios of the ocean because of elimination of marine life (not all researchers ascribe to this model, (e.g. Etienne *et al.* 2006). Hence, the $\delta^{13}\text{C}$ in marine carbonates

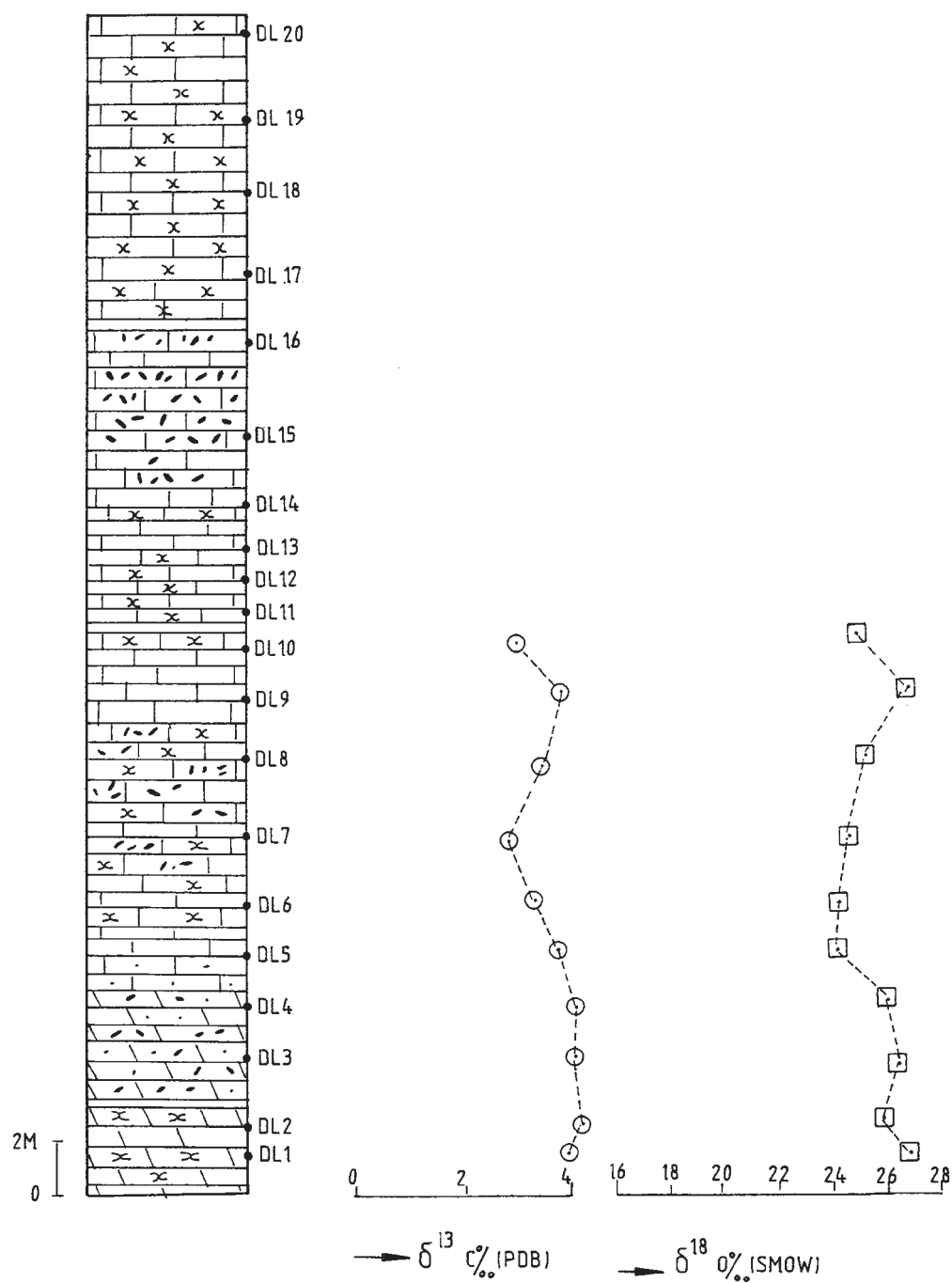


Fig. 7. C-isotope chemostratigraphy of the Uttarkashi Limestone, Garhwal, Lesser Himalaya, India.

will drastically decrease to $-6 \pm 1\%$ (PDB) (Jacobsen 2001). The deglaciation event is recorded in the C-isotope variation from a pink cap carbonate indicating the end of the Terminal Proterozoic glaciation (Tewari 2001a, 2003). Kaufman *et al.* (1997) reported $\delta^{13}\text{C}$ values in cap carbonates varying globally from 0 to -5% PDB. The $\delta^{13}\text{C}$ values of the pink Blaini Limestone also vary from 0 to 3% PDB, consistent with the global record. Major palaeoclimatic changes, carbon isotopic fluctuations, biotic extinction-evolutionary events, sea level changes during the Late Proterozoic that are recorded from the Lesser Himalaya, India, are discussed in some detail in this paper.

Secular variations in carbon isotopes, palaeobiological and biogeochemical cycles

Palaeobiological activities on Earth started around 3800 million years ago with carbon as the main element in organic matter (Schidlowski *et al.* 1975; Eichmann & Schidlowski 1975). The ratio of stable C-isotopes reflects the effect of biological activity in the carbon cycle. Isotopic fractionation of c. 25% between the two carbon species (terrestrial or carbonate carbon, and organic or reduced carbon) has been recorded from rocks c. 3500 Ma old (Eichmann & Schidlowski 1975; Schidlowski *et al.* 1975, 1983). Carbon isotope stratigraphies of Proterozoic and Early Cambrian sequences have been established in recent years from many different parts of the world (e.g. Knoll *et al.* 1995; Santos *et al.* 2000). Carbon isotope excursions through the Neoproterozoic and across the Precambrian–Cambrian boundary have been interpreted to explain evolutionary diversification and extinction events, palaeoenvironmental and palaeoceanic conditions, changes in sea water chemistry and extraterrestrial impacts, and have been used to set up a chemostratigraphy for this time period (see reviews of Brasier *et al.* 1990, 1996; Brasier 1992; Knoll *et al.* 1995; Ripperdan 1994; Tucker 1986).

Ediacaran carbon-isotope chemostratigraphy and trace element geochemistry of the Blaini–Krol–Tal sequence, Lesser Himalaya

The Neoproterozoic is characterized by global occurrence of thick tidal flat carbonate-siliciclastic sequences and glacial cycles. Carbon and oxygen isotopic variations in these sequences have been used as palaeoclimatic indicators. Neoproterozoic carbonates have been studied worldwide for

variations in oxygen and carbon isotope ratios, with special reference to inorganic and organic carbon reservoirs (Schidlowski *et al.* 1976; Aharon *et al.* 1987; Brasier *et al.* 1996; Kaufmann & Knoll 1995; Hoffman *et al.* 1998; Tewari 1991, 1997; Kumar & Tewari 1995). Low (-3% to -5%) $\delta^{13}\text{C}$ PDB values have been reported from reddish-pinkish dolomites (cap carbonates) associated with Neoproterozoic deglaciation around the globe, including the Blaini Formation (Bhattacharya *et al.* 1997; Tewari 1999a, b; Kumar *et al.* 2000; Santos *et al.* 2000; Alvarenga *et al.* 2003).

The carbon isotope chemostratigraphy of the Blaini pink microbial/stromatolitic cap carbonate shows negative values ($\delta^{13}\text{C} -2.7\%$ PDB), and the overlying Krol carbonates indicate very high positive values ($+6\%$ PDB, Fig. 9, Tewari 1991; Kumar & Tewari 1995). Isotopically heavy carbonates ($\delta^{13}\text{C} +6.6\%$ PDB) were deposited in the Upper Krol D stromatolitic facies representing enhanced organic burial. This strong positive isotopic shift is followed by a decrease in $\delta^{13}\text{C}$ from $+2\%$ to c. 0% in Krol E carbonates. There is a negative shift in $\delta^{13}\text{C}$ (-2.2% to -4% PDB) just below the Lower Cambrian (Fig. 9). These $\delta^{13}\text{C}$ records are in concert with global isotopic variations in Neoproterozoic–Early Cambrian oceans of the world (Tewari 1998c). Bhattacharya *et al.* (1997) have also reported four depletions in $\delta^{13}\text{C}$ values from Mussoorie and Garhwal synclines. However, only two peaks are of global significance, the first corresponding to what appears to be the end of the Varanger glaciation of Late Neoproterozoic age. The Blaini pink limestone in the Nainital syncline also shows depleted $\delta^{13}\text{C}$ values ($\delta^{13}\text{C} = -2.2\%$ PDB). The oxygen isotopes ($\delta^{18}\text{O} +20.1$ to 28.6% SMOW) of the Upper Krol carbonates indicate high oxygen levels associated with possible Ediacaran diversification (Fig. 9). Major Neoproterozoic and Cambrian palaeoclimatic events, isotopic fluctuations and biotic evolution recorded in Lesser Himalaya are summarized in Table 2.

Carbon, oxygen and strontium isotopes, trace and rare earth element data are known from the Dhanaulti–Durmala section of the Mussoorie Syncline (Fig. 2; Table 3). The Precambrian–Cambrian boundary has been placed in the Lower Tal Formation (Aharon *et al.* 1987; Shanker & Mathur 1992; Tewari 1984, 1996, 1999a). The contact between the uppermost Krol Formation (Krol E) and the lower Tal Formation (chert-phosphorite member) is well exposed at Durmala Phosphorite Mine, where phosphorite is being commercially mined. An Early Cambrian stromatolite assemblage including *Collumnaefacta vulgaris*, *Boxonia gracilis*, *Colleniella*, *Aldania mussoorica*

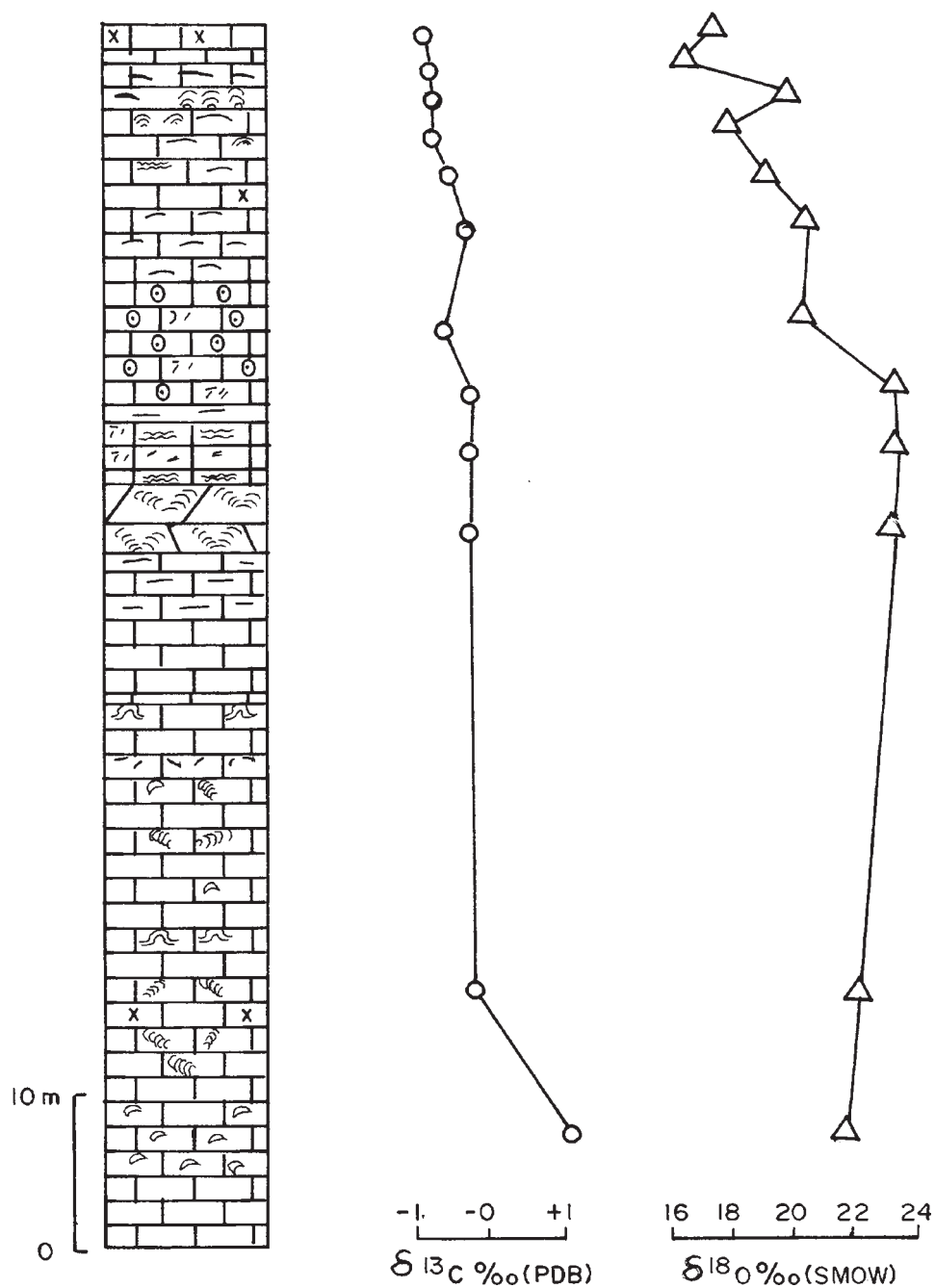


Fig. 8. C-isotope chemostratigraphy of the Lameri Limestone, Garhwal, Lesser Himalaya, India.

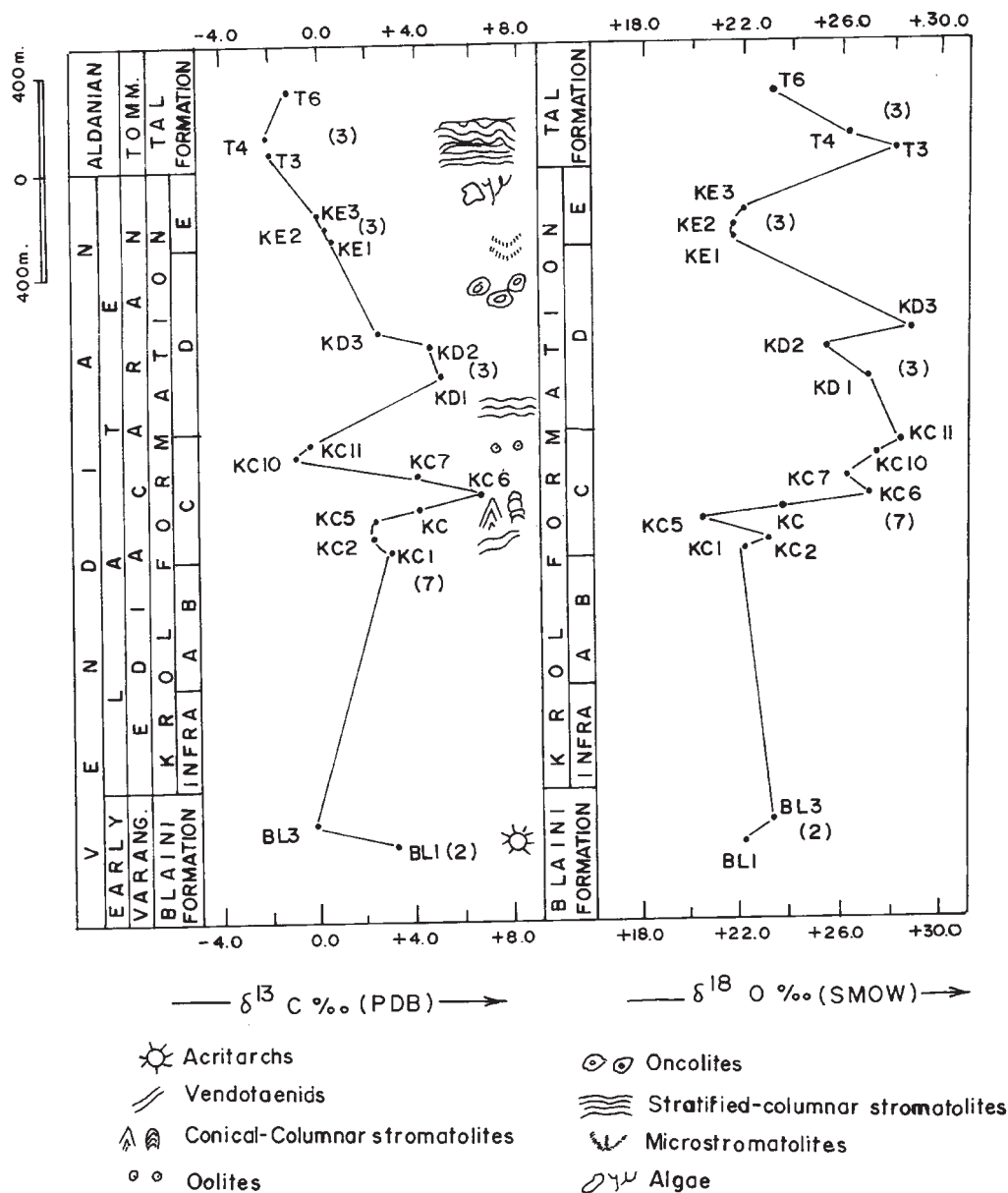


Fig. 9. C-isotope chemostratigraphy of the Blaini-Krol-Tal (Terminal Proterozoic-Lower Cambrian) succession of the Lesser Himalaya, India.

and oncolites are recorded from this locality (Tewari 1984, 1989, 1993, 1996). Small Shelly Fossils of Tommotian (Early Cambrian) age are also reported from phosphatic deposits in the Lower Tal Formation (Brasier & Singh 1989; Brasier *et al.* 1996). Laser Raman spectroscopy of the Mussoorie Tal Phosphorite indicates the presence of amino acids.

The underlying Krol carbonates are tidal flat deposits including stromatolites, and fenestral facies are well developed (Tewari 1984, 2001a, 2002a, b). Carbon, oxygen and strontium isotope data from the Krol Tal carbonates in the Mussoorie syncline are summarized in Table 4. Stable isotope values range from -2.9 to +6.5‰ PDB for $\delta^{13}\text{C}$ and +20.1 to +28.6‰ SMOW for $\delta^{18}\text{O}$

Table 1. *C- and O-isotope analyses for Deoban carbonates*

Sample No.	Description of sample	$\delta^{13}\text{C}\text{‰}_{\text{PDB}}$	$\delta^{18}\text{O}\text{‰}_{\text{SMOW}}$
25. D25	Light grey laminated dolomite (altitude 10 000 feet)	1.1	19.1
24. D24	Light grey laminated dolomite (altitude 10 000 feet)	1.4	20.6
23. D23	Light grey dolomite (altitude 9000 feet)	1.1	20.9
22. D22	Finely laminated calcareous silty layers	4.3	29.4
21. D21	Alternating thin dolomite and silty layers	4.8	27.3
20. D20	Light grey dolomite after 100 feet interval	0.9	16.8
19. D19	Light grey dolomite after 100 feet interval	1.3	21.1
18. D18	Light grey dolomite after 100 feet interval	1.2	21.0
17. D17	Light grey dolomite after 100 feet interval	0.9	16.8
16. D16	Light grey dolomite after 100 feet interval	1.5	19.6
15. D15	Light grey dolomite after 100 feet interval	2.1	21.9
14. D14	Light grey dolomite foot path to Deoban summit	2.0	21.1
13. D13	Dark bluish grey dolomite with elongated conical <i>Georginia</i> sp. and <i>Conophyton</i> sp. structures	1.4	18.5
12. D12	Dark bluish grey dolomite with <i>Tungussia</i> sp	1.4	20.4
11. D11	Dark bluish grey dolomite with <i>Jurusania</i> sp. and <i>Minjaria</i> sp. biostrome, 100 m below Deoban Forest Rest House (DFRH)	2.0	22.6
10. D10	Dark bluish grey dolomite with <i>Jurusania</i> sp. and <i>Minjaria</i> sp. biostrome, 100 m below DFRH	-3.7	21.5
9. D9	Dark black (organic) silty shale (similar to D8)	0.3	18.9
8. D8	Greyish black shale with <i>Chuarina circularis</i> megascopic acritarch between stromatolitic buildups, 500 m west of DFRH. Locality as D7	6.6	27.2
7. D7	Dark bluish dolomite with <i>Baicalia nova</i> biostrome, 500 m west of DFRH (altitude 9232 feet)	1.7	17.8
6. D6	Light grey dolomite with <i>Stratifera</i> sp. 1 km from bifurcation	3.0	22.7
5. D5	Light grey dolomite with large <i>Kussiella kussiensis</i> biostrome and small <i>Conophyton</i> sp. biostrome, DFRH road, 100 m from bifurcation	2.9	24.5
4. D4	Oolitic-intraclastic, coated carbonate grains near bifurcation to Deoban Forest Rest House (DFRH) mule path, Deoban 3 km	4.6	19.9
3. D3	Dark bluish (organic) cherty laminated dolomite (microbiota-bearing), Chakrata–Deoban road, 1.3 km	3.2	25.4
2. D2	Dark bluish dolomite with chert lenses and layers (microbiota), Chakrata–Deoban road, 1.2 km	1.8	17.3
1. D1	Grey dolomite, lowermost Deoban road section 1 km near the contact with Chakrata slates (Damta Group)	1.4	19.2

Table 2. *Major palaeoclimatic and biotic changes across Neoproterozoic–Cambrian Transition in the Lesser Himalaya, India (Tewari 2001a)*

Age/Stage	Period	Climate	$\delta^{13}\text{C}$ values	Fossils
Cambrian	Talian	Warm	Changing (-ve to +ve)	Brachiopods, trilobites, trace fossils, small shelly fossils, sponge spicules, stromatolite
Ediacaran	Krolian	Warm	Positive	Ediacaran, vendotaenilids, algae and stromatolites
Varangian	Blainian	Glacial	Negative (lighter)	Acritarchs, microbialites
Riphean–Early Vendian	Deobanian	Warm	Positive (heavier)	Predominantly stromatolites, cyanobacteria, organic walled microfossils, sponge spicules, epiphyton algae

Table 3. $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and Sr-Isotope data of Krol–Tal carbonates from the Mussoorie Syncline, Uttarakhand

Sample	Lithological units	Rock type	$\delta^{13}\text{C}_{\text{‰PDB}}$	$\delta^{18}\text{O}_{\text{‰SMOW}}$	$^{87}\text{Sr}/^{86}\text{Sr}$
T6	Tal	Oncolitic	−1.2	23.1	N.D.
T4	Tal	Stromatolitic	−2.5	27.3	0.7092
T3	Tal	Phosphatic & dolomite	−2.9	27.8	0.7098
KE3	Krol E	Shaly dolomite	0.1	21.9	N.D.
KE2	Krol E	Shaly dolomite	0.0	21.8	0.7151
KE1	Krol E	Shaly dolomite	0.5	22.2	0.7151
KD3	Krol D	Shaly dolomite (micritic)	2.4	28.6	0.7094
KD2	Krol D	Microbial mat dolomite	4.6	25.8	0.7091
KD1	Krol D	Shaly dolomite	4.8	28.5	0.7091
KC11	Krol C	Shaly dolomite	0.3	28.2	N.D.
KC10	Krol C	Cherty dolomite	1.0	27.3	N.D.
KC7	Krol C	Cherty dolomite	2.9	26.0	N.D.
KC6.1	Krol C	Oolitic dolomite	2.4	24.3	0.7110
KC6	Krol C	Cherty banded limestone	6.5	27.4	0.7094
KC5.1	Krol C	Oolitic limestone	2.4	24.5	0.7104
KC5	Krol C	Fine grained limestone	2.2	20.4	N.D.
KC	Krol C	Bhatta limestone (micritic)	2.1	20.1	0.7088
KC2	Krol C	Oolitic limestone	2.1	23.2	0.7122
KC1	Krol C	Brecciated limestone	2.8	21.9	N.D.
BL3	Blaini	Pink dolomite (fine grained)	−0.4	23.3	N.D.
BL1	Blaini	Pink laminated dolomite	2.9	22.1	N.D.

N.D. not determined.

respectively; $\delta^{13}\text{C}$ values are generally positive for Krol C and D, carbonates reaching a $\delta^{13}\text{C}$ maximum of 6.5‰ PDB. Krol E carbonates have near zero $\delta^{13}\text{C}$ values. Tal carbonates show negative $\delta^{13}\text{C}$ values with a $\delta^{13}\text{C}$ minimum of −2.9‰ PDB. The petrographic study of these carbonates indicates that they preserve primary fabric-like oolites, microbial laminites and micrite. The isotopic signatures are considered unaltered and primary (Aharon *et al.* 1987). Hence, the positive $\delta^{13}\text{C}$ values relative to PDB represent high rates of organic carbon burial whereas negative $\delta^{13}\text{C}$ values and $\delta^{13}\text{C}$ maxima of 6.5‰ PDB for Krol D dolomite represent increased organic carbon burial. Conversely, ^{13}C minima of −2.9‰ PDB of Lower Tal Formation indicate low rate of organic carbon burial. Possible Ediacaran metazoans and metaphytes are recorded in the Krol Formation (Tewari 1993, 1998b, 2001a, 2002b).

$^{87}\text{Sr}/^{86}\text{Sr}$ data in the Krol sequence vary from 0.7088 to 0.7151 (Table 4). The lowest value of 0.7088 was obtained from the Middle Krol C limestone. Krol C is a cement grade limestone in the Mussoorie Syncline, which has a Sr content of 659 ppm. Veizer *et al.* (1983) and Burns *et al.* (1994) have shown that the seawater $^{87}\text{Sr}/^{86}\text{Sr}$ value was *c.* 0.707, during what appears to be the Varanger glaciation, and rapidly rose to 0.709 during Late Ediacaran (to near present day sea water value). The Sr-isotope value of 0.7088 for

the Upper Krol carbonates of the Mussoorie syncline may be taken as a near pristine sea water value, confirming that Late Proterozoic sea water values reached to *c.* 0.709 and corroborating with the earlier findings (Veizer *et al.* 1983; Burns *et al.* 1994; Aharon & Liew 1992). According to Aharon & Liew (1992), the high Sr-isotope value of >0.7095 for Krol and Tal carbonate may be due to exchanges with crustal fluids.

Trace element abundances of Blaini–Krol–Tal carbonate rocks are shown in Table 4. All samples from Krol E have high concentration of transition metals (Co, Ni, Cu and Zn), lithophile elements (Cs, Rb, Ba and Pb) and high field strength-cations (Y, Th, U, Zr and Nb), but are depleted in vanadium (Table 5). The strontium content is high for the Lower Tal carbonates. Major oxides, trace elements, and rare earth concentrations are summarized in Table 3.

Oxides include Al_2O_3 , which varies from 0.01% to 0.72%, K_2O which varies from 0.01% to 0.017, SiO_2 which varies from 0.02% to 1%, and 74.5% in the black chert straddling the Precambrian–Cambrian boundary. CaO varies from 30.56% to 31.0% in the uppermost Krol and is 9.6% in Lower Tal. MgO varies from 20.97% to 21.0% (0.84% in lower Tal). Na_2O varies from 0.033% to 0.34% (0.03% in Lower Tal). Fe_2O_3 (total) varies from 0.042% to 0.16% (10% in Lower Tal). P_2O_5 varies from 0.015% to 0.039% (4.0% in Lower

Table 4. Trace element distribution in Blaini–Krol–Tal carbonates of the Mussoorie Syncline

Sample No.	Cu (ppm)	Ni (ppm)	Pb (ppm)	Zn (ppm)	Co (ppm)	Cr (ppm)	Ba (ppm)	Sr (ppm)	V (ppm)	U (ppm)
GC3	11	<5	12	18	5	73	239	74	36	20
GC2	7	<5	10	14	5	59	228	72	37	17
GC1	10	<5	10	19	5	68	191	73	37	16
KP3	18	28	<5	<5	<5	328	133	50	115	20
KP1	20	38	<5	43	<5	331	146	28	111	19
TIM	19	76	23	<5	10	114	1654	12	240	56
KCM	42	52	30	66	18	105	292	39	142	20
KT2	47	16	8	51	16	106	437	66	352	19
KT1	52	88	15	55	18	102	430	69	304	19
TC2	21	29	13	44	15	106	362	45	76	16
TC1	14	9	<5	20	5	82	238	60	39	16
TD2	50	205	21	34	23	112	1878	61	478	42
TD1	45	92	22	16	5	112	223	722	585	103
TD1	45	247	23	89	15	105	1609	25	274	62
MP2	98	5	29	82	5	628	981	78	958	20
MP1	10	14	<5	7	<5	<5	1496	291	49	19
KER1	13	<5	<5	23	<5	31	501	63	34	12
VKD2	<5	<5	<5	<5	<5	11	17	36	<10	17
KD1	15	<5	<5	22	<5	17	4419	253	15	17
KC9	12	<5	<5	13	<5	92	273	40	126	19
KC8	13	<5	14	13	<5	89	254	39	113	15
KC6	<5	<5	<5	<5	<5	23	11	78	<10	17
KC3	<5	<5	<5	14	<5	12	32	64	<10	22
KC1	7	<5	<5	6	<5	141	24	45	<10	15
KB4	50	16	14	270	8	94	220	24	55	15
KB2	5	5	5	17	5	36	70	58	13	13
KB1	6	5	5	17	5	27	91	55	17	20

Table 5. REE, Y, Sc and Th distribution in the Blaini and Krol carbonates of the Mussoorie Syncline

REE (ppm)	KD1	VKD2	KC1	KC6	KC9	KC8	KC3	KB1	KB2	KB4
La	<5	<5	<5	<5	70	70	<5	10	9	30
Ce	<10	<10	<10	<10	105	103	<10	17	13	57
Pr	<10	<10	<10	<10	14	11	<10	<10	<10	<10
Nd	<10	<10	<10	<10	45	46	<10	<10	<10	20
Sm	<10	<10	<10	<10	11	10	<10	<10	<10	<10
Eu	<10	<1	<1	<1	<1	<1	<1	<1	<1	1.2
Gd	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Tb	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Dy	<2	<2	<2	<2	5	4	<2	<2	<2	6.5
Ho	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Er	<3	<3	<3	<3	4	3.5	<3	<3	<3	<3
Tm	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Yb	2.3	<1	<1	<1	2.8	2.7	<1	1.0	<1	3.3
Lu	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Y	8.3	2.5	3.2	<1	24	22.3	<1	8	7	30
Sc	<1	<1	<1	<1	13.5	13.7	<1	2.8	2.0	7.9
Th	<10	<10	<10	<0	25	22	<10	<10	<10	13

Tal). TiO₂ varies from 0.001% to 0.022% (0.008% in Lower Tal). MnO varies from 0.004% to 0.035% (0.44% in Lower Tal) (Tables 6 and 7).

Carbon and oxygen isotope chemostratigraphy and palaeobiology of the Buxa Dolomite, NE Lesser Himalaya

Acharyya (1974) subdivided the Buxa Group into two units in the type area based on carbonate content and colour. Namely: (1) the lower Sinchula Formation overlain by (2) the Jainti Formation. The Buxa Group is exposed in Nakshal Khola and in the Jaldhaka river section in the easternmost part of

the Darjeeling foothills, eastern Himalaya (Fig. 4). It is also recognized in the Sikkim Himalaya in the Ranjit Window (Raina 1976; Tewari 2004a). In western Arunachal, the Buxa Group is subdivided into two units separated by a pebbly diamictite bed (Shergaon pebble bed). However, the tectonostratigraphic position of the Buxa Group is still not certain in the Arunachal Lesser Himalaya. (Tandon *et al.* 1979; Tewari 1998a, b, 2002a, b, 2003).

The base of this Late Proterozoic carbonate sequence is represented by glaciomarine-fluvial diamictite-pebble beds. Other sedimentary facies include microbial buildups, oncolites, oolites, fenestral-textured sediments and microstromatolites, suggestive of shallow marine tidal flat

Table 6. REE distribution in Lower Tal (Precambrian–Cambrian boundary) Formation, Mussoorie Syncline

REE (ppm)	TD-1	TD-1	TD-2	TC-2	TC-1	KT-2	MP-2
La	101	53	43	46	40	37	48
Ce	65	85	72	89	79	64	61
Pr	<10	<10	<10	<10	<10	<10	<10
Nd	69	40	31	31	24	31	38
Sm	<10	<10	<10	<10	<10	<10	<10
Eu	3.2	1.1	1.2	1.1	1.0	1.1	2.3
Gd	14	<10	<10	<10	<10	<10	<10
Tb	<5	<5	<5	<5	<5	<5	<5
Dy	17	5	5	6	5	5	10
Ho	3.5	<2	<2	<2	<2	<2	<2
Er	11	4	5	5	4	5	5
Tm	<2	3	2	<2	<2	3	2
Yb	8.6	4.5	4.5	3.8	2.8	3.3	6.8
Lu	<1	<1	<1	<1	<1	<1	<1
Y	242	29	31	29	28	29	105
Sc	<1	15	13	11	6	13	4
Th	<10	21	19	21	18	17	10

Table 7. REE distribution in Lower Tal Formation, Mussoorie Syncline

S. No.	Sample No.	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y	Sc	Th
1	KER-1	14	26	<10	12	<10	<1	<10	<5	2	<2	<3	<2	1.6	>1	14.6	4.6	>10
2	GC-1	<10	17	<10	<10	<10	<1	<10	<5	<2	<2	<3	<2	<1	>1	6.6	1.3	>10
3	GC-2	10	16	<10	<10	<10	<1	<10	<5	<2	<2	<3	<2	<1	>1	6.5	1.3	>10
4	GC-3	11	20	<10	<10	<10	<1	<10	<5	<2	<2	<3	<2	1.2	>1	7.6	1.6	>10
5	MP-1	11	17	<10	>10	<10	1.7	<10	<5	2	<2	<3	<2	1.1	>1	8.7	1	>10
6	KCM	53	86	<10	40	<10	1.3	11	<5	7	<2	4	<2	4.1	>1	32	17.8	24
7	KT-1	36	66	<10	26	<10	1.0	<10	<5	5	<2	4	<2	3.7	>1	30	13.2	17
8	TIM	42	81	<10	32	<10	1.0	<10	<5	4	<2	4	<2	4.5	>1	26	9.7	16
9	KP-3	12	16	<10	10	<10	1.0	<10	<5	5	<2	<3	<2	1.8	>1	36	1.7	>10
10	KP-1	<10	<10	<10	10	<10	<1	<10	<5	<2	<2	<3	<2	<1	>1	13.6	1.5	>10

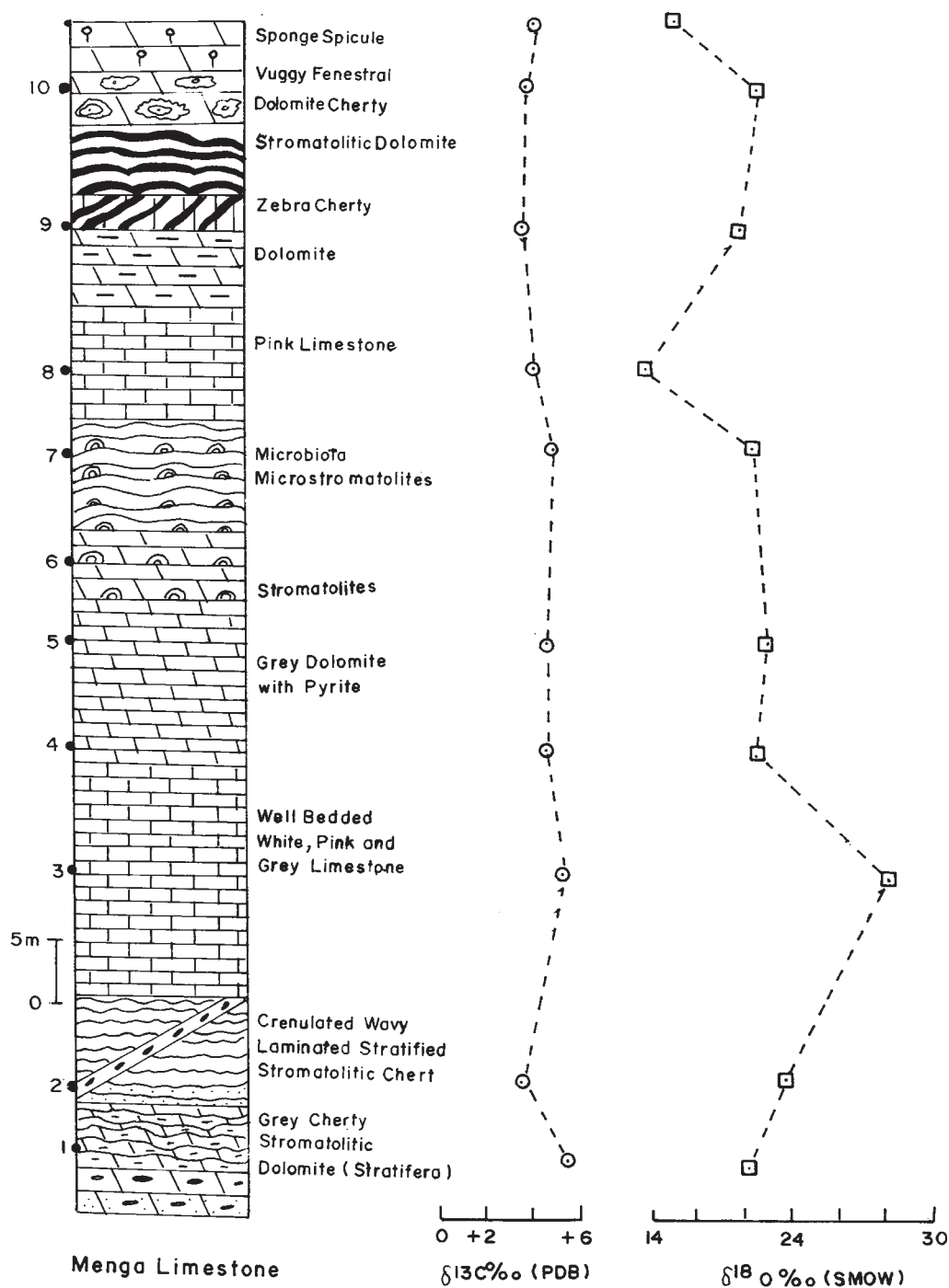


Fig. 10. C-isotope chemostratigraphy of the Menga (Buxa) Limestone (Terminal Proterozoic), Arunachal, Lesser Himalaya, Northeastern Himalaya (East Gondwana).

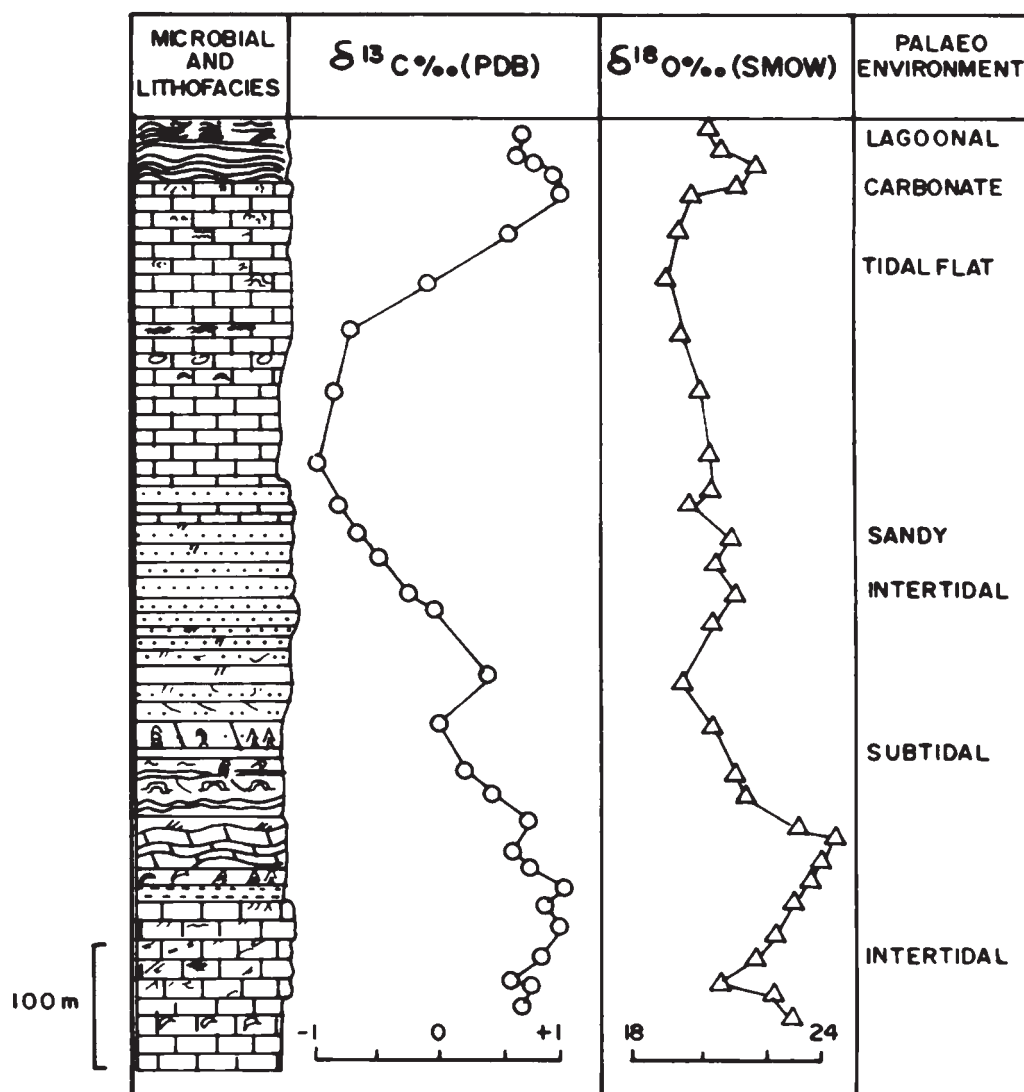


Fig. 11. C-isotope chemostratigraphy of the Buxa Dolomite, Ranjit Window (Meso-Neoproterozoic), Sikkim, NE Lesser Himalaya, Northeastern Himalaya (East Gondwana).

depositional environments for the Chillipam, Rupa, Dedza, Menga and Panging limestones. Acharyya (1974) interpreted the Buxa Dolomite as shallow subtidal to intertidal deposits. Fossils include organic-walled microfossils, vase-shaped microfossils and micro metazoans, in addition to stromatolites, all suggestive of a Late Proterozoic age (Figs 13 and 14). Positive C-isotopic values (+3.7 to +5.4‰ PDB) of the Buxa Limestone (Fig. 10) relate to known global palaeobiological events. High positive values of $\delta^{13}\text{C}$ from +2.8‰ PDB to +4.2‰ PDB characterize the Chillipam Dolomite

and the Dedza Dolomite in the West Kameng of the Arunachal Lesser Himalaya ($\delta^{13}\text{C} = +5.8‰$ PDB). Additional microbiota have been recorded from the Subansiri area of the Arunachal Lesser Himalaya (Tewari 2005).

The stable carbon and oxygen isotope data from the Buxa Dolomite (Meso-Neoproterozoic) cropping out in the Ranjit river valley, western Sikkim, NE Lesser Himalaya, India (Figs 4 and 11). The Buxa Dolomite comprises stromatolitic dolomite, cherty dolomite, intraclastic-oolitic dolomite, and minor siliciclastic sediments (Fig. 11).

The stromatolite assemblage and the recently discovered microbiota from the Buxa Dolomite in Ranjit window, Sikkim Lesser Himalaya suggest a Meso-Neoproterozoic age (Tewari 2003, 2004a, b). The $\delta^{13}\text{C}$ (PDB) varies in a narrow range from -1.4‰ to $+1.0\text{‰}$ (Fig. 11) Oxygen isotope values grade from 19‰ to 23.9‰ ($\delta^{18}\text{O}$ SMOW). The lower part of the Buxa Dolomite showing a mostly positive trend may be the result of an increased rate of organic matter burial in a shallow carbonate platform. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of the Buxa Dolomite are summarized in Table 8.

The recorded stromatolite assemblage includes: *Kussiella kussiensis*, *Clonnella columnaris*, *Conophyton garganicum*, *Baicalia* sp., *Tungussia* sp., *Jurusania* sp., *Gymnosolen* sp., *Minjaria* sp., *Kalpanaella* n. sp., *Nucliella*, *Colleniella*, *Conistratifer*, *Aldania* sp. and *Collumnaefacta* sp. (Tewari 2004a). The microbial assemblage from cherts includes *Obruchevella* sp., *Eomycetopsis* sp., *Myxococcoides* sp., *Huronispora* sp., *Melanocyrrillium* sp. etc (Tewari 2004b).

Based on isotope data combined with sedimentological and palaeobiological data, the Buxa Dolomite appears to have been deposited on a carbonate

platform, well connected with the ocean, the environment favourable for the formation of microbialites and cyanobacterial microbial mats, indicating that the environment of deposition was shallow marine (peritidal/subtidal to intertidal).

Discussion and conclusions

The Ediacaran radiation of metazoan and metaphytic multicellular life seems to have occurred after a change from 'Snowball Earth' to global warming in the Neoproterozoic period (Fig. 12). A major global decline of Mesoproterozoic stromatolites, planktonic acritarchs and other prokaryotic biota has been recorded on Earth, related to Neoproterozoic glaciation (Hoffman *et al.* 1998; Tewari 1993). Radiation of new acanthomorphic acritarchs, stromatolites, multicellular brown algae, vendotaenids, *Tyrosotaenia*, *Krolotaenia* and Ediacaran metazoans like *Cyclomedusa*, *Charniodiscus*, *Dickinsonia*, *Spriggina* and *Pteridinium* was recorded widely, and possibly in the Krol Group of the Lesser Himalaya (Fig. 3) (Knoll & Walter 1992; Kaufman & Knoll 1995; Mathur & Shanker 1989; Shanker *et al.* 1997; Tewari 1993, 1999a, b; Kaufman *et al.* 1997). Ediacaran animals originated prior to the main Varanger glaciation and diversified. The Cambrian explosion of shelled organisms is recorded in the Tal Group of rocks of the Lesser Himalaya (Fig. 12) and in the Tethyan sequences of Spiti-Zaskar and Uttaraanchal Himalaya (Kumar *et al.* 1997; Tewari 1998b). Tewari (2001b) has reported Late Proterozoic organisms and microstromatolites in the Menga (Buxa) Limestone of the northeastern Himalaya. In this sequence, there is a well-developed diamictite, stromatolitic carbonate sequence (Buxa Dolomite/Chillipam Formation) exposed in the West Kameng district of the Arunachal Lesser Himalaya, similar to the Blaini diamictite and Krol Formation in sedimentary facies and microbial buildups (Tewari 2003). The Precambrian–Cambrian boundary may exist in this section (Tewari 1998a).

The Buxa Dolomite of the Northeastern Himalaya of Bhutan, Sikkim, Darjeeling and Arunachal Pradesh has been traditionally correlated with the Mesoproterozoic (Riphean) Shali–Deoban–Gangolihat carbonate belt of the NW Himalaya, on the basis of lithological similarities and stromatolite content (Valdiya 1969, 1980; Tewari 2003). Acharyya (1974), to the contrary, considered the Buxa Dolomite to be older than Late Palaeozoic but younger than the Shali–Deoban stromatolitic carbonates. This paper suggests correlation of Buxa, Chillipam and Dedza dolomites of the northeast Himalaya to the Late Neoproterozoic on the basis of microstromatolites/stromatolites,

Table 8. $\delta^{13}\text{C}_{\text{PDB}}$ and $\delta^{18}\text{O}_{\text{PDB}}$ of the Buxa Dolomite, Ranjit Window, Sikkim, NE Lesser Himalaya

Sample	$\delta^{18}\text{O}_{\text{SMOW}}$	$\delta^{18}\text{O}_{\text{‰PDB}}$	$\delta^{13}\text{C}_{\text{‰PDB}}$
TR30	19.7	−10.8	−0.1
TR29	20.1	−10.5	−0.9
TR28	21.8	−8.7	−0.1
TR27	21.1	−9.5	0.1
TR26	19.4	−11.1	0.4
TR24	19.0	−11.5	−0.1
TR23	19.5	−11.1	−0.1
TR22	20.6	−10.0	0.1
TR20	22.8	−7.9	−0.9
TR19	20.6	−10.0	−1.4
TR18	19.8	−10.8	−0.9
TR17	21.8	−8.8	−0.8
TR16	21.4	−9.2	−0.7
TR15	21.6	−9.0	−0.7
TR13	19.5	−11.1	0.3
TR12	20.9	−9.7	−0.4
TR11	21.8	−8.8	0.1
TR10	22.9	−7.7	0.6
TR9	23.9	−6.7	0.5
TR8	23.9	−6.8	0.6
TR7	23.5	−7.1	0.9
TR6	23.4	−7.3	0.9
TR5	22.6	−8.0	1.0
TR4	22.2	−8.4	1.0
TR3	20.8	−9.7	0.5
TR2	22.8	−7.8	0.7
TR1	23.0	−7.6	0.7

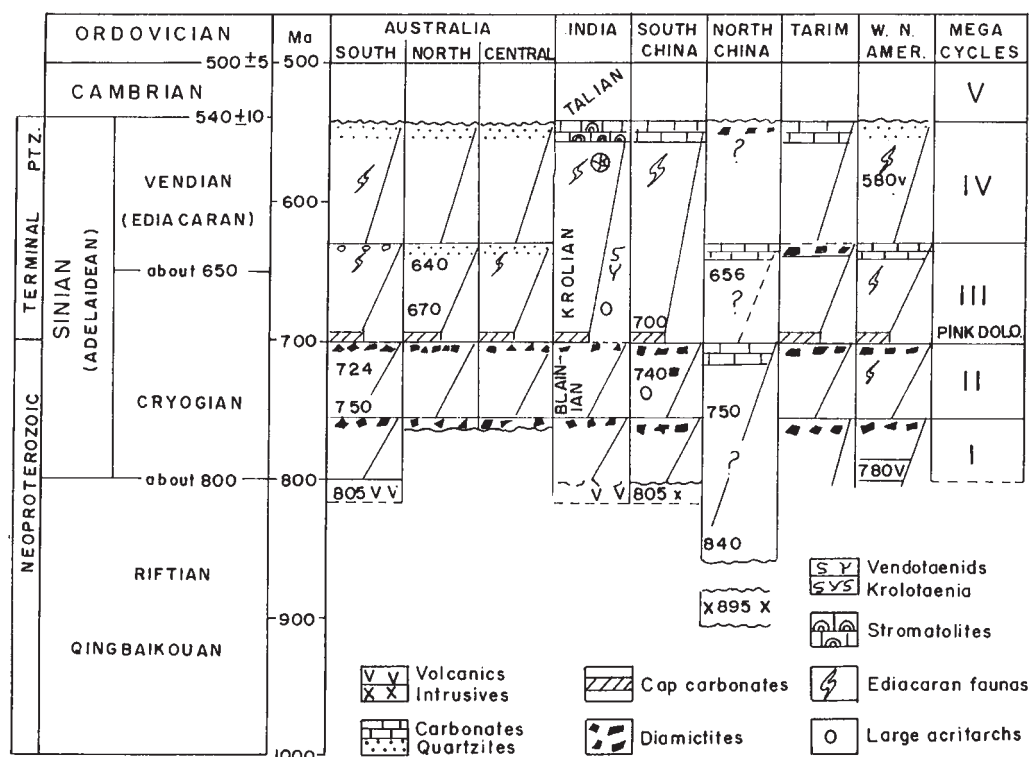


Fig. 12. Global correlation of the Blainian-Krolian and Talian (Neoproterozoic to Lower Cambrian) stages of the Lesser Himalaya, India, East Gondwana, (after Brookfield 1994 with slight modification).

microbiota and carbon isotope stratigraphy (Tewari & Sial 2003, 2004). Recently discovered microbialites, organic walled microfossils, sponge spicules and extensive carbonates (Tewari 2001a, b, c, 2002a, 2003, 2004a) (Fig. 10) from the Menga-Mara section in Subansiri Valley indicate a Late Proterozoic age for this sequence. Ten representative samples (MM1 to MM10, Fig. 10) of dolomite were analysed for C- and O-isotopes. The C-isotopic ratios are significantly positive and quite consistent with $\delta^{13}\text{C}$ (carbonate carbon) values varying from +3.7 to +5.4‰ PDB. $\delta^{18}\text{O}$ values fluctuate between -8.9 and -7.2‰ PDB. The consistency of the carbon isotopic record from the Buxa Dolomite indicates that the isotopic data are representative and the signatures are unaltered. The significantly positive C-isotopic results are in concert with global Late Proterozoic isotopic patterns (Aharon *et al.* 1987; Kumar & Tewari 1995; Tewari 1991, 1997, 1998c, 2001a, 2002a; Tewari & Sial 2004; Bhattacharya *et al.* 1996). A close relationship of $\delta^{13}\text{C}$ enriched carbonate rocks with peaks in stromatolite diversity and

biomass can be attributed to the enhanced bioproductivity.

The Late Proterozoic–Early Cambrian sequence of the Uttaranchal Central Lesser Himalaya has been studied in detail for C-isotope chemostratigraphy (Aharon *et al.* 1987; Tewari 1991, 1997, 2001a, b; Kumar & Tewari 1995; Tewari & Sial 2004; Bhattacharya *et al.* 1996)—the first such attempt in the northeastern Himalaya. The Buxa Dolomite positive isotopic excursions are strikingly similar to those of the Krol Formation (Krolian) of the Uttaranchal (Central Lesser) Himalaya. It is interesting that the Doushantuo carbonates of the Yangtze Platform, Southern China (Shen & Schidlowski 2000) display high positive $\delta^{13}\text{C}$ values similar to the Krol–Buxa belt. The Krol–Buxa–Doushantuo carbonates were deposited after a Neoproterozoic glaciation (Tewari 2001b, c, 2002a, 2003) and have very similar sedimentary facies, biota, and carbon-isotope chemostratigraphy (Tewari 2001a, b, 2002). The Lesser Himalayan sequences of India show similar palaeobiological and stable isotopic patterns to other Ediacaran

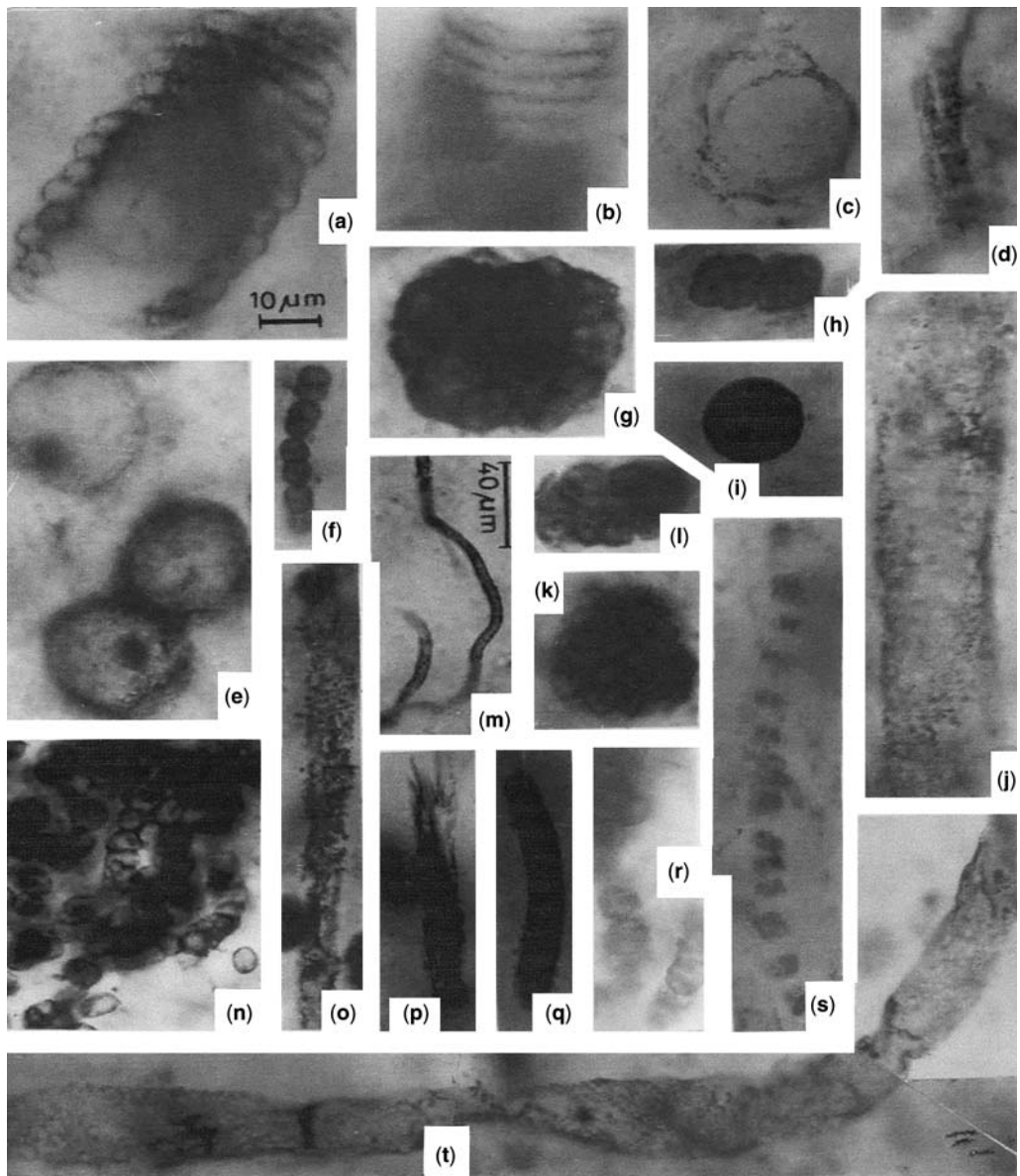


Fig. 13. Neoproterozoic microfossils from the Buxa Dolomite, NE Himalaya. (a–b) *Obruchevelia parva* Reitlinger 1959, BSIP Slide No. 13; (c) *Volyniella valdaica* (Shepeleva 1967), BSIP Slide No. 13; (d) *Palaeolynghya catenata* Hermann 1974, *emend* Butterfield *et al.* 1994, BSIP Slide No. 13; (e) *Glenobotrydion aenigmatis* Schopf 1968, BSIP Slide No. 13; (f) *Vetronostocale equale* sp. nov., BSIP Slide No. 13; (g) *Palaeoanacystes suketensis* Zhang 1984, BSIP Slide No. 13; (h and i) *Paratetrarhynchus giganteus* Zhang 1984, BSIP Slide No. 13; (j) *Oscillatoropsis robusta* Mendelson & Schopf 1980, BSIP Slide No. 13; (k) *Syphonophycus typicum* Hermann 1974, BSIP Slide No. 11; (m) *Myxococcoides minor* Schopf 1968, BSIP Slide No. 13; (n) *Eosynechococcus rugosum* (Maithy) Hofmann & Jackson 1994, BSIP Slide No. 13; (o) *Siphonophycus rugosum* (Maithy) Hofmann & Jackson 1994, BSIP Slide No. 13; (p) *Polythrycoides lineatus* German 1974 *emend* Timofeev *et al.* 1976, BSIP Slide No. 13; (q and r) *Vetronostocale amoenum* Schopf and Blacic, *emend* Xu & Awramik 2001, BSIP Slide No. 13; (s) *Oscillatoropsis breviconvexa* Schopf & Blacic 1971, BSIP Slide No. 13; (t) *Oscillatoropsis rhomboidalis* Sivertseva 1989, BSIP Slide No. 13.

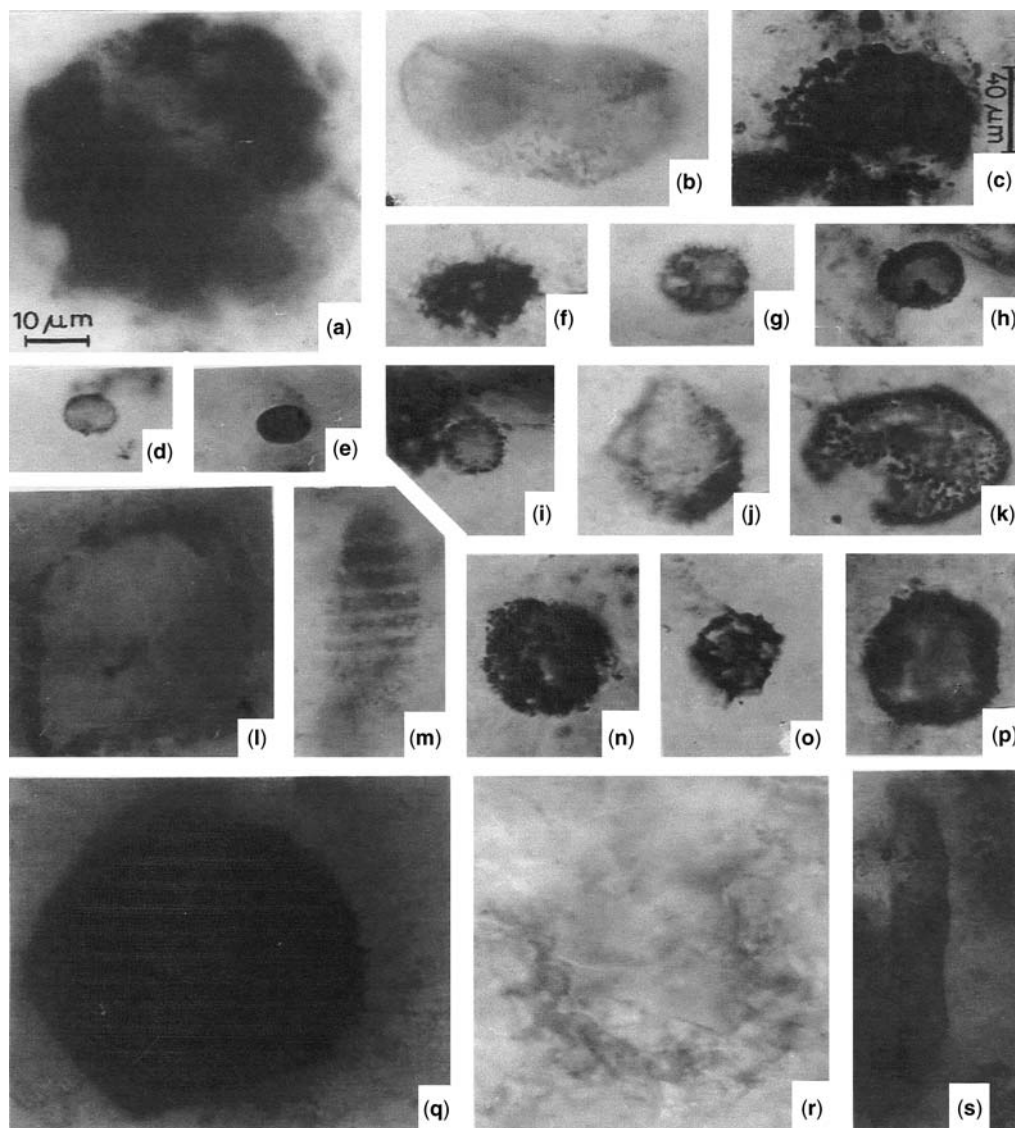


Fig. 14. Neoproterozoic microfossils from the Buxa Dolomite, NE Himalaya. (a) *Trachyhystrichosphaera aimica* Hermann 1981, BSIP Slide No. 13; (b) *Lophosphaeridium rarum* Timofeev 1959, BSIP Slide No. 13; (c) *Vandalosphaeridium reticulatum* Vidal 1981, BSIP Slide No. 13; (d) *Margominuscula rugosa* Naumova 1960, BSIP Slide No. 13; (e) *Margominuscula simplex* Pychova 1973, BSIP Slide No. 13; (f) *Archaeohystrichosphaeridium semireticulatum* Timofeev 1959, BSIP Slide No. 13; (g) *Micrhystridium lanatum* Volkova 1969, BSIP Slide No. 13; (h) *Granomarginata vetula* Saluja *et al.* 1972, BSIP Slide No. 13; (i) *Micrhystridium ampliatum* Wang 1985, BSIP Slide No. 13; (j) *Melanocyrrillium hexodiadema* (Bloesser) *cf* *Angochitina milanensis*, BSIP Slide No. 13; (k) *Lophosphaeridium jansoniusii* Saluja *et al.* 1971b, BSIP Slide No. 13; (l) *Leiosphaeridia visingsa* Zang in Zang & Walter 1995, BSIP Slide No. 13; (m) *Navifusa segmentatus* Prasad & Asher 2001, BSIP Slide No. 13; (n) *Trachysphaeridium robustum* Yin & Li 1978, BSIP Slide No. 13; (o) *Archaeohystrichosphaeridium cellulare* Timofeev 1959, BSIP Slide No. 13; (p) *Polythrycoides lineatus* German 1974 *emend.* Timofeev *et al.* 1976, BSIP Slide No. 13; (q) *Vetronostocale amoenum* Schopf and Blacic, *emend.* Xu & Awramik 2001, BSIP Slide No. 13; (r) *Vetronostocale amoenum* Schopf & Blacic, *emend.* Xu & Awramik 2001, BSIP Slide No. 13; (s) *Oscillatorioopsis brevicconvexa* Schopf & Blacic 1971, BSIP Slide No. 13.

sequences; further detailed investigation shows promise of correlation worldwide.

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