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Neoproterozoic–Early Cambrian isotopic variation and chemostratigraphy of the Lesser Himalaya, India, Eastern Gondwana

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Abstract

The Rodinia supercontinent had fragmented by 750 Ma and East Gondwana (India, Australia and Antarctica) separated from West Laurentia. Baltica, Africa and South America occupied other side of the Rodinia. Neoproterozoic rifting, breakup of Rodinia low latitude glaciation and global warming events have been recorded from the Lesser Himalaya of India. Chemostratigraphy of the Blaini–Krol–Tal succession indicates Precambrian–Cambrian transition lies in the Lower Tal Formation ($\delta^{13}C = -4‰$ PDB). The Krol belt in the Lesser Himalaya is characterized by positive $\delta^{13}C$ values (+1 to 6‰ PDB). The appearance of multicelluler Ediacaran life in the Upper Krol is consistent with hypothesis that increase in atmospheric oxygen played a major role in metazoan evolution and Cambrian diversification of life on Earth. The base of the Terminal Proterozoic System in the Lesser Himalaya is established in the Blaini Formation. The pink cap carbonate of the Blaini Formation shows negative $\delta^{13}C$ value (−3‰ PDB) and this Blainian glaciation is correlated with Marinoan glacial event other regions of the Eastern Gondwana and South China, parts of Siberia and North Africa. Neoproterozic–Early Cambrian chemostratigraphy in the Lesser Himalaya is consistent in the isotopic variation where there is carbon isotopic similarity between Neoproterozoic Bambui Group in Central Brazil, South America and the Krol Formation of the Lesser Himalaya, India. In the northeastern Lesser Himalaya, India the Neoproterozoic sedimentary succession shows well developed carbonate the Buxa Dolomite shows significantly positive C-isotope ratios ($\delta^{13}C = +3.7$ to +5.4‰ PDB). The O-isotopic data also shows remarkable consistency with the $\delta^{18}O$ values fluctuating within a narrow range between −8.9 and −7.2‰ VPDB. These isotopic results from the Eastern Lesser Himalaya correspond to the Terminal Proterozoic C-isotopic evolution, followed by oscillations during the Precambrian–Cambrian transition in the Lesser Himalaya in Eastern Gondwana.
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Keywords: Neoproterozoic; Carbon and oxygen isotopes; Chemostratigraphy; Lesser Himalaya, Gondwana, India

1. Introduction

Himalayan mountain chain was formed as a result of collision of Indian Plate with Asian Plate. The fossil evidences of early evolution of life are well preserved in the Lesser Himalayan Proterozoic sedimentary basins

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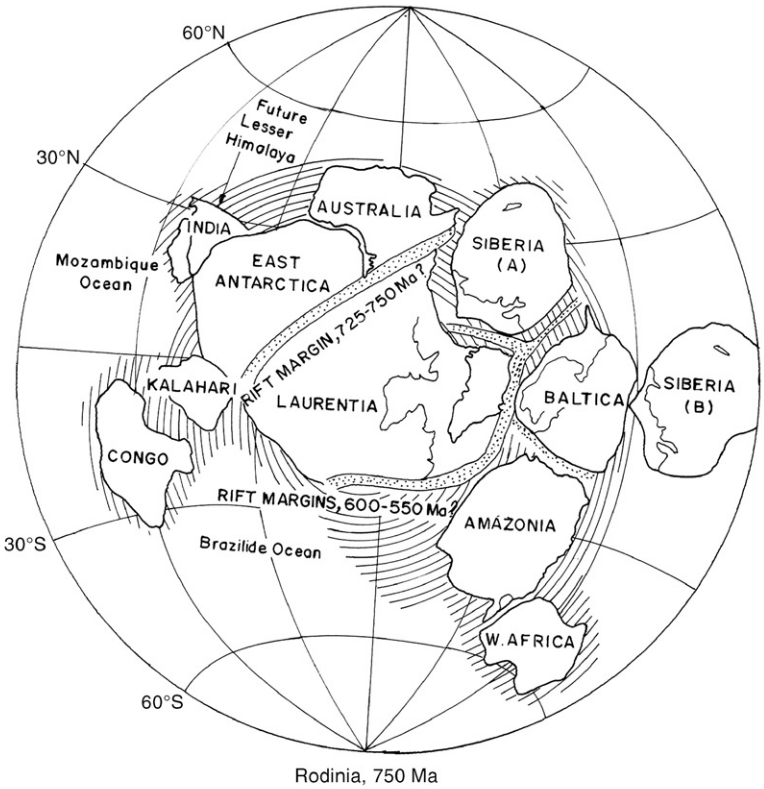

Fig. 1. Rodinia supercontinent (Cited after Powell et al., 1993; Yoshida and Arima, 2000).

from NW and NE region of India. The newly established Ediacaran Period (650–540 Ma) confirmably overlying the Cryogenian Period represents the evolution of the soft bodied animal on earth just after the Neoproterozoic glacial event. The record of Vendian/Ediacaran biota from the Lesser Himalaya (Krol belt in India), Doushantuo and Dengying Formations of China and other parts of Rodinia strongly supports that palaeogeographically these sedimentary basins were very close to each other. The Blaini diamictites in the NE Arunachal Himalaya and the Sinian diamictites of the Chinese region are correlated with the global Marinoan glaciation. During Terminal Neoproterozoic time (Tewari, 2001a,b,c, 2002a,b, 2003, 2004a,b). Major palaeobiological and carbon isotopic changes occurred in the Indian Lesser Himalaya and the Yangtze Platform of southern China leading to rapid evolution and diversification of multicellular life (Tewari, 2003, 2004a,b). Large acanthomorphic acritarchs, calcareous algae, Vendotaenids, sponges (micrometazoans) and Ediacaran soft bodied animals appeared in the Infra Krol–Krol Formation of India and Doushantuo Formation of Southern China. This major event was followed by Cambrian Explosion of life (animals with hard parts and small shelly fossils) found in the Lower Tal Formation of the Lesser Himalaya which corresponds to the Phosphatic Meischucunian Zone I of China. The carbon isotope chemostratigraphy of the Krol and Buxa Formations from the Lesser Himalaya and the Doushantuo Formation from the Yangtze Platform indicate very high positive carbon isotope values (Tewari, 2003; Shen and Schidlowski, 2000). Recently a detailed sedimentological study has been done in the Krol belt by Ganqing et al. (2002, 2003). This Ediacaran event is also global and has significance in early organic evolution of life on Earth (Narbonne, 1998).

A Late Neoproterozoic (Ediacaran, 0.6–0.54 Ma) supercontinent assembly was defined as Rodinia, however later it also included the older rocks that came together at 1.0 Ga (Veevers, 2004 and the references therein). The Rodinia supercontinent (Fig. 1) brokeup around 750 Ma and the East Gondwana (India, Australia and Antartica) separated from West Laurentia (Powell et al., 1993). The Baltika, Africa and South America occupied the other side of the Rodinia. However, the existence of Neoproterozoic super continent Rodinia is still hypothetical (Yoshida and Arima, 2000) and the recent geochronological and palaeomagnetic record of South America and Africa shows that these cratonic fragments may not have been part of Rodinia

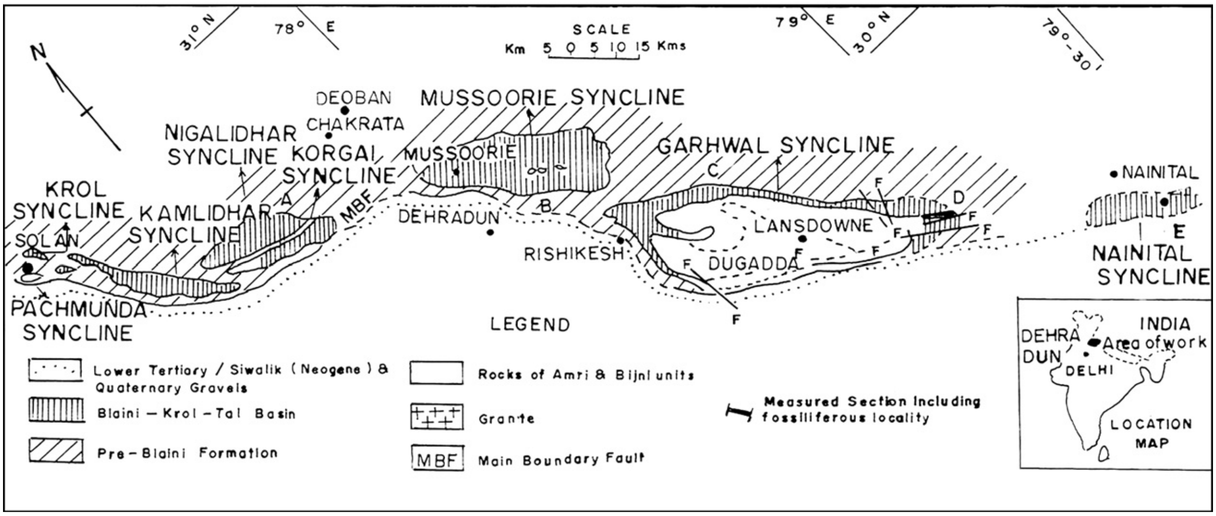

Fig. 2. Geological map of the Blaini–Krol–Tal basin, Lesser Himalaya, India (after Geological Survey of India).

(Cordani et al., 2003; Casnedi, 2002). The Neoproterozoic rifting, breakup of Rodinia and fragmentation of the Gondwanaland, low-latitude glaciation and global warming events have been recorded and recently reviewed from the Lesser Himalaya of India (Tewari, 2002a; Veevers, 2004).The Carbon and oxygen isotopic variation and chemostratigraphy of the Lesser Himalayan carbonate formations reflect global palaeoclimatic and palaeobiological events (Tewari, 2001a,b,c). The Neoproterozoic –Early Cambrian chemostratigraphy of the Blaini–Krol–Tal succession strongly supports the Precambrian–Cambrian transition lies in the Lower Tal Formation ($\delta^{13}C=-4‰_{PDB}$). The Krol belt in the Lesser Himalaya (Fig. 2) is characterized by positive $\delta^{13}C$ value (+1 to $6‰_{PDB}$). The emergence of multicellular Ediacaran life in the Upper Krol is consistent with an increase in atmospheric oxygen ($\delta^{18}O=-2.2‰_{VPDB}$). The oxygen isotope supports that oxygen played a major role in metazoan evolution and Cambrian explosion. The base of the Terminal Proterozoic System in the Lesser Himalaya is established in the Blaini Formation (Tewari, 2001a). The pink cap carbonate of the Blaini Formation shows negative $\delta^{13}C$ value ($-3‰_{PDB}$) and correlated with Marinoan glacial event.(Knoll et al., 2004). A comparison of the available carbon and oxygen isotope curves from other regions of the Eastern Gondwanaland and South China, parts of Siberia and North Africa suggest that the Neoproterozoic–Early Cambrian chemostratigraphy is consistent in the isotopic variation (Shen and Schidlowski, 2000). There is carbon isotopic similarity between Neoproterozoic Bambui Group in Central Brazil, South America (Santos et al., 2000; Alvarenga et al., 2003) and the Blaini–Krol Formation of the Lesser Himalaya India. (Fig. 3) Consistency in the C-isotopic composition during the geological past has been observed in the critical sections world wide. Schidlowski et al. (1976) and Schidlowski (2000) developed a well constrained carbon isotopic evolution curve. The concept of C-isotope chemostratigraphy is based upon the assumption that C-isotopic ratios fluctuate with time, largely in response to the changes in net rate of organic burial and climate variations (availability of atmospheric oxygen).

In the NE Lesser Himalaya, India Neoproterozoic sedimentary succession shows well developed carbonate sequence — the Buxa Dolomite (Fig. 4). The recent discovery of microbialites and organic walled microfossils (Tewari, 2002a) confirm Terminal Neoproterozoic age for the Buxa (Menga) Dolomite. The C-isotopic ratios are significantly positive and quite consistent with the $\delta^{13}C$ (carbonate carbon) value ranging from +3.7 to $+5.4‰_{PDB}$ in the Buxa Dolomite. The O-isotopic data also shows remarkable consistency with the $\delta^{18}O$ values fluctuating within a narrow range between −8.9 and $-7.2‰_{PDB}$.The significantly positive C-isotopic evolution, followed by oscillations during the Precambrian–Cambrian transition in the Lesser Himalaya.

Terminal Proterozoic glaciogenic deposits have been recorded from all the continents. They were formed by breakup of Rodinia supercontinent. Recent carbon isotopic studies of Phanerozoic and Terminal Proterozoic glaciogenic deposits in general has suggested that palaeoclimate changes on Earth over the last 650 Ma is directly related to atmospheric CO_2 fluctuations (Jacobson and Kaufman, 1999; Tewari, 2001a, 2003; Tewari and Sial, 2003). The snowball Earth model

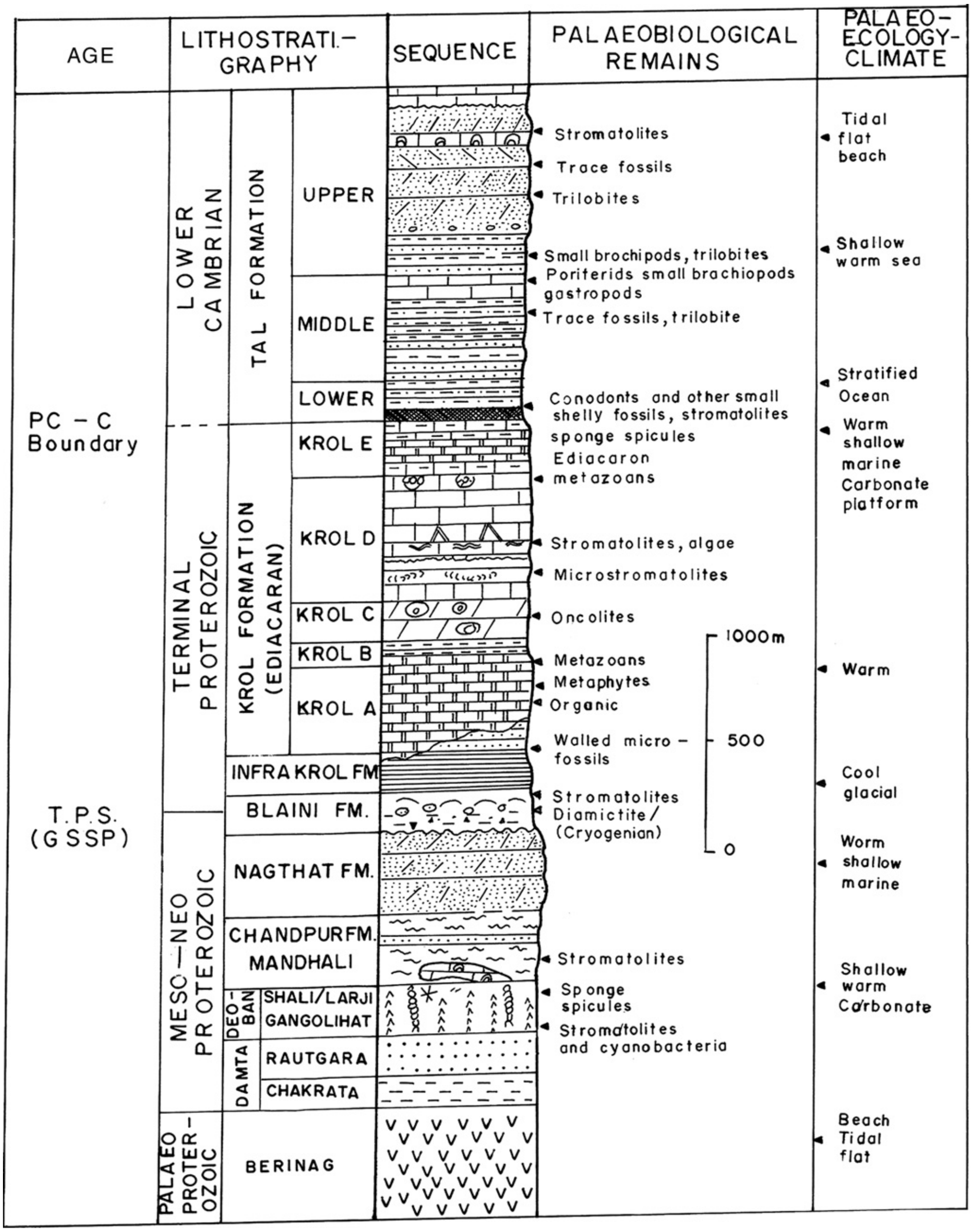

Fig. 3. Lithostratigraphic column, palaeobiological remains and palaeoclimatic events in the Lesser Himalaya, India.

suggests that during global glaciation there may be a short lived change in the carbon isotopic ratios of the ocean because of elimination of marine life. Hence the $\delta^{13}C$ in marine carbonates will drastically decrease to $-6\pm1‰$ ($_{PDB}$) (Bartley et al., 2001). The deglaciation event is also well recorded in the carbon isotope variation from pink cap carbonate indicating end of the Terminal Proterozoic glaciation (Tewari, 2001a, 2003). Kaufman et al. (1997) have observed $\delta^{13}C$ values in cap carbonates globally range from 0 to $-5‰_{(PDB)}$. The $\delta^{13}C$ values of the pink Blaini Limestone also range from 0 to $-3‰_{(PDB)}$ confirming the global event. The major palaeoclimatic changes, carbon isotopic fluctuations, biotic extinction–evolutionary events, sea level changes recorded from the Lesser Himalaya, India has been discussed in the present paper in detail.

Palaeobiological activities on earth had started around 3800 Ma ago and carbon is the main element in organic matter (Schidlowski et al., 1975; Eichman and Schidlowski, 1975). The ratio of stable carbon

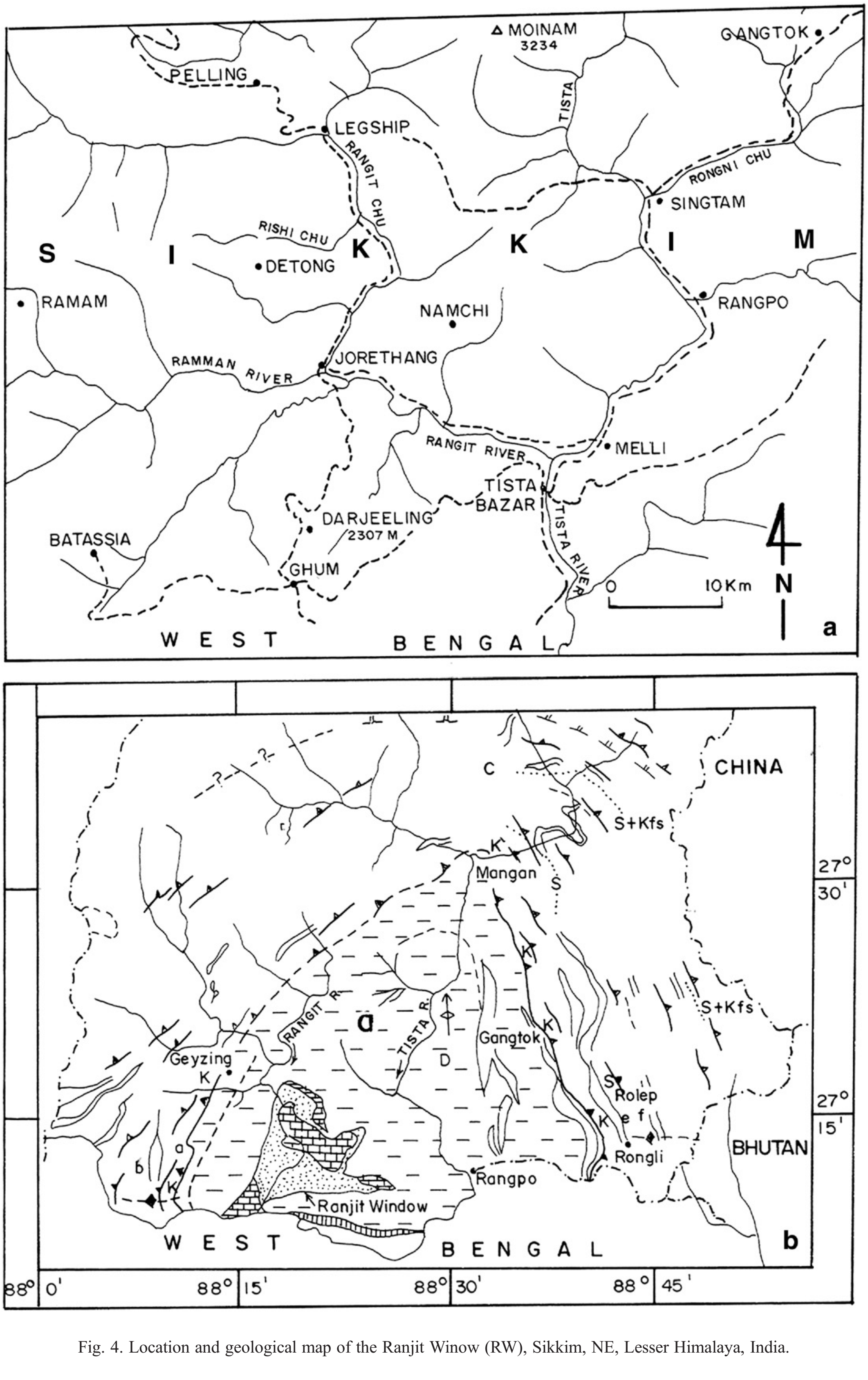

Fig. 4. Location and geological map of the Ranjit Winow (RW), Sikkim, NE, Lesser Himalaya, India.

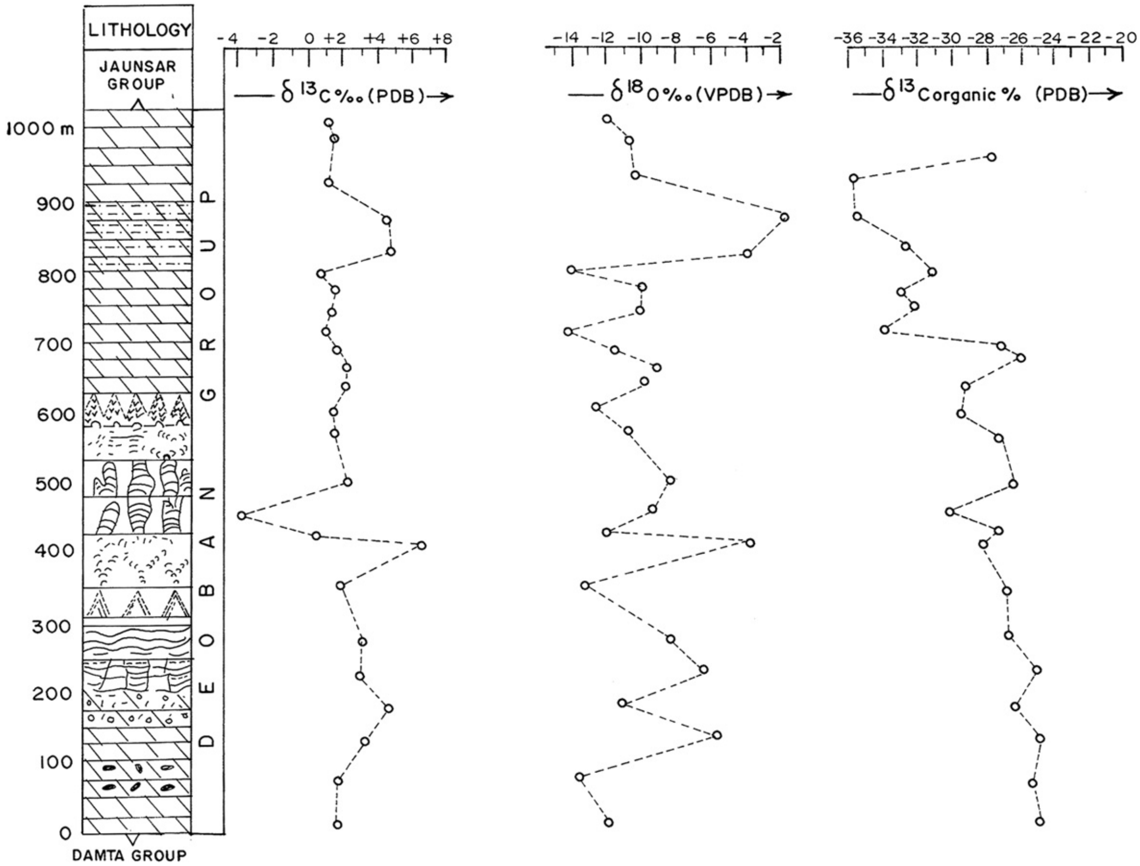

Fig. 5. Carbon isotope chemostratigraphy of the Deoban Group (Meso-Neoproterozoic) Garhwal, Lesser Himalaya, India.

isotopes reflects the effect of biological activity in the carbon cycle. Isotopic fractionation of about 25% between the two carbon species (terrestrial or carbonate carbon and organic or reduced carbon) has been recorded from the rocks about 3500 Ma old (Eichman and Schidlowski, 1975; Schidlowski et al., 1975). Carbon isotope stratigraphies of Proterozoic and Early Cambrian sequences have been established in recent years from different parts of the world. For example, Siberian platform (Magaritz et al., 1986; Knoll et al., 1995), Morocco (Tucker, 1986), Greenland–Spitsbergan (Fairchild and Spiro, 1987), China (Hsu et al., 1985; Lambert et al., 1987; Brasier et al., 1990), Krol–Tal sequence of the Lesser Himalaya (Aharon et al., 1987; Brasier et al., 1990; Tewari, 1991; Kumar and Tewari, 1995; Aharon and Liew, 1992; Banerjee et al., 1997), Iran (Brasier et al., 1990), Namibia (Kaufman et al., 1991, 1993) and from Brazil (Santos et al., 2000). Analysis of global Proterozoic and Cambrian boundary sequences by Ripperdan (1994) suggest that all these localities preserve the secular variations in the carbon isotope composition of the global ocean system. The carbon isotope excursions across the Precambrian and Cambrian boundary has been interpreted to explain evolutionary diversification and extinction events, palaeoenvironmental and palaeooceanic conditions, changes in sea water chemistry, extraterrestrial impacts and to establish chemostratigraphy (see reviews of Brasier et al., 1990; Brasier, 1992; Ripperdan, 1994; Brasier et al., 1996). Tucker (1986) also made an attempt to explain the formation of rifted basins and passive continental margin in the Late Precambrian–Cambrian transition affecting the isotopic composition of seawater. Most of the isotope data for Proterozoic successions has been published from Late Riphean and Vendian (1000 to 545 Ma) or Neoproterozoic basins (Schidlowski et al., 1983; Knoll et al., 1995). Detailed carbon and oxygen isotopic analysis of Precambrian sedimentary carbonates between 1600 to 850 Ma done by Schidlowski, Eichmann and Junge (1975) have $\delta^{13}C$ values of 0±2‰. The $\delta^{13}C$ variation within narrow limits from 1600 Ma to 850 Ma ago is quite

Table 1
C and O isotope analyses for Deoban carbonates

Sample no.	Description of sample	$\delta^{13}C‰_{PDB}$	$\delta^{18}O‰_{VPDB}$
25. D25	Light grey laminated dolomite.	1.1	−11.5
24. D24	Light grey laminated dolomite .	1.4	−10.0
23. D23	Light grey dolomite.	1.1	−9.8
22. D22	Finely laminated calcareous silty layers.	4.3	−2.0
21. D21	Alternating thin dolomite and silty layers.	4.8	−3.4
20. D20	Light grey dolomite	0.9	−13.2
19. D19	Light grey dolomite.	1.3	−9.5
18. D18	Light grey dolomite.	1.2	−9.6
17. D17	Light grey dolomite.	0.9	−13.2
16. D16	Light grey dolomite.	1.5	−11.0
15. D15	Light grey dolomite.	2.1	−8.8
14. D14	Light grey dolomite.	2.0	−9.5
13. D13	Dark bluish grey-dolomite with elongated conical *Georginia* sp. and *Conophyton* sp. structures.	1.4	−12.0
12. D12	Dark bluish grey dolomite with *Tungussia* sp.	1.4	−10.0
11. D11	Dark bluish grey dolomite with *Jurusania* sp. And *Minjaria* sp. biostrome.	2.0	−8.0
10. D10	Dark bluish grey dolomite with *Jurusania* sp. And *Minjaria* sp. biostrome.	−3.7	−9.5
9. D9	Dark black (organic) silty shale with thin dolomite layer	0.3	−11.2
8. D8	Greyish black shale with *Chuaria circularis* megascopic acritarch between stromatlitic buildups.	6.6	−3.0
7. D7	Dark bluish dolomite with Baicalia nova biostrome.	1.7	−12.4
6. D6	Light grey dolomite with *Stratifera* sp.	3.0	−7.9
5. D5	Light grey dolomite with large *Kussiella kussiensis* biostrome and small *Conophyton* sp. biostrome.	2.9	−6.2
4. D4	Oolitic–intraclastic dolomite.	4.6	−10.8
3. D3	Dark bluish (organic) cherty laminated dolomite (microbiota bearing).	3.2	−5.0
2. D2	Dark bluish dolomite with chert lenses and layers (microbiota).	1.8	−12.8
1. D1	Grey dolomite, lowermost Deoban.	1.4	−11.5

interesting in palaeobiological and biogeochemical changes.

A high-resolution carbon isotope stratigraphy and depositional environment has been established for Neoproterozoic (Lower to Middle Riphean) Deoban carbonates. A carbon isotope relationship between stromatolites, phytoplankton and sea water (photosynthetic process) has also been studied for Mesoproterozoic carbonates. In this paper C and O isotopic data from an important Meso-Neoproterozoic sequences of Deoban Group, Garhwal Lesser Himalaya, India generated at Max Planck Institute for Chemistry at Mainz in Germany by one of the authors (VCT) is given. The paper incorporates the C and O isotopic data from the Blaini–Krol–Tal sequence and the Buxa Dolomite of the Indian Lesser Himalaya analysed at (Lower to Upper NEG Riphean)-LABISE, Pernambuco, Brazil.

2. Geology

The Deoban type area near Chakrata (Fig. 2) was systematically sampled for carbon and oxygen isotope analysis on stromatolitic, oolitic and cherty dolomite facies of Deoban Group. Deoban Group comprises an approximately 1000 m thick succession of carbonate rocks (stromatolitic dolomite, cherty dolomite rich in microbiota and oolites) with thin beds of grey and black shales, slates and thinly laminated calcareous silty layers in the upper part (Fig. 5). Detailed litholog showing the lithology, types of microbial buildups and sample locations was prepared in the field (Fig. 5). The description of samples selected for carbon and oxygen isotope analysis is given in Table 1. Deoban Group (Meso to Neoproterozoic/Lower to Upper Riphean) in age in the type area (Tewari, 1993a, 1996) is overlying the Damta Group (Chakrata Slates) of Lower Riphean age and followed by a shallow marine sequence of argillo-siliciclastic deposit known as Jaunsar Group (=Simla Group) of Upper Riphean age which in turn is unconformably overlain by Blaini Group of Early Vendian (Cryogenian) age (Tewari, 1996, 2004a,b).

Fine grained carbonates, oolites and shales containing acritarch *Chuaria circularis* were analysed for present study. Whole rock samples were analysed but petrographically the carbonates and oolites are not much altered diagenetically and good preservation of original fabric and texture was found in thin section study (Tewari, 1994). Tewari and Joshi (1993) have done detailed study of microstructures of stromatolites from Deoban Group and recorded well preserved microfabric representing original microbial texture. Petrographically controlled samples were analysed in

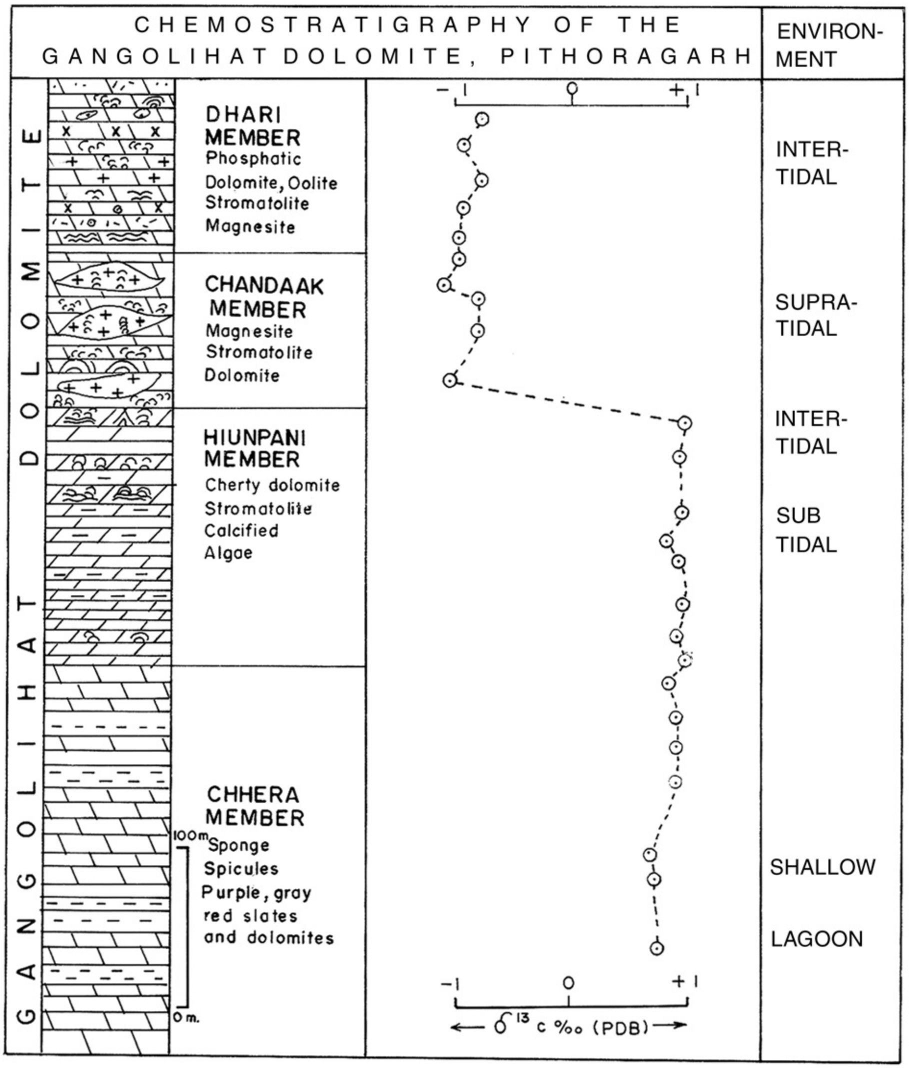

Fig. 6. Carbon isotope chemostratigraphy of the Gangolihat Dolomite (Meso-Neoproterozoic) Kumaun Lesser Himalaya, India.

the present study and care taken for selection of samples while avoiding coarse grained carbonates, recrystallisation veins and other diagenetic features. The ooids show primary fabric and no later calcite/dolomite cement has been observed. Thus, the $\delta^{13}C$ values of the carbonates represent pristine signatures and isotopic composition of the Deoban sea during Meso-Neoproterozoic time. The carbon- and oxygen-isotope values obtained for 25 samples of the Deoban carbonates are shown in Fig. 5 and Table 1. Very light to quite heavy (−20 to +10‰) $\delta^{13}C$ values may result due to the presence of organic matter and diagenesis in the carbonate rocks, however in the present isotopic analysis $\delta^{13}C$ range from −3.7 to 6.6‰$_{PDB}$ and mostly between 0 to 2‰$_{PDB}$. Thus, the $\delta^{13}C$ values of the dolomite analysed are considered to be very close to the Proterozoic $\delta^{13}C$ values recorded by Schidlowski et al. (1975, 1983) and represent original marine values.

The Deoban carbonates are tidal flat (shallow marine) deposits (Tewari, 1994, 1996) and the facies analysis of the Deoban Group (subtidal to ooid shoals and protected intertidal flats) is similar to the modern tidal flat (Sabkha) deposits which have near marine $\delta^{13}C$ values.

2.1. Blaini–Infrakrol–Krol–Tal succession, Uttaranchal Lesser Himalaya

The Neoproterozoic Blaini Formation is a glacial–glaciomarine diamictite-sandy tidal flat lithostratigraphic unit at the base of the Krol belt in the Lesser Himalaya (Figs. 2 and 3). The Blaini diamictite in Mussoorie,

Table 2
Distribution of major oxides and Sr (ppm) in the Gangolihat dolomite–magnesite deposit, Pithoragarh, Kumaun Himalaya

S.no.	Sample no.	Na_2O %	MgO %	Al_2O_3 %	SiO_2 %	P_2O_5 %	K_2O %	CaO %	TiO_2 %	MnO %	Fe_2O_3 %	Sum %	Sr ppm
1	CCH3	0.061	22.97	3.28	12.18	0.027	0.03	21.98	0.110	0.113	1.67	62.42	28
2	CCH5	0.168	15.04	11.33	29.22	0.072	2.47	22.03	0.206	0.286	1.69	82.53	40
3	CCH9	0.001	17.53	BDL	0.81	0.090	1.87	24.88	0.164	0.296	1.58	46.59	83
4	CCH13	0.030	18.72	1.37	7.61	0.064	1.08	26.43	0.140	0.271	1.63	57.35	21
5	CCH14	0.028	19.17	1.26	7.24	0.060	1.02	26.14	0.140	0.284	1.63	56.98	23
6	CCH15	0.036	18.36	1.68	8.97	0.057	1.26	26.31	0.121	0.287	1.58	58.67	29
7	CCH18	0.029	18.32	1.53	14.66	0.023	0.00	25.46	0.024	0.172	1.54	61.77	48
8	CCH19	0.038	33.13	0.80	8.76	0.017	0.01	9.68	0.030	0.088	5.96	58.51	BDL
9	CCH20	0.023	38.42	0.04	BDL	−0.001	0.05	9.51	0.057	0.085	9.27	57.38	BDL
10	CCH21	0.047	29.50	1.52	22.28	0.005	−0.00	9.67	0.031	0.071	3.85	66.96	BDL
11	CCH23	0.026	39.21	0.09	BDL	−0.002	0.00	9.47	0.036	0.092	8.78	57.39	BDL
12	CCH24	0.024	38.71	0.08	BDL	−0.001	0.01	9.51	0.046	0.105	8.53	56.76	BDL
13	CCH25	0.026	36.95	0.19	1.15	0.000	−0.00	9.57	0.026	0.090	7.74	55.74	BDL
14	CCH26	0.025	37.90	0.12	0.19	−0.000	0.03	9.51	0.038	0.092	8.63	56.53	BDL
15	CCH27	0.025	39.00	0.07	BDL	0.009	0.03	9.50	0.044	0.105	8.67	57.20	BDL
16	CCH30	0.051	29.45	1.85	15.74	0.006	0.02	11.96	0.041	0.070	3.48	62.67	BDL
17	CCH31	0.134	19.70	8.50	30.21	0.028	0.01	20.29	0.084	0.096	1.29	80.34	18
18	CCH32	0.057	16.31	3.71	30.58	0.022	0.01	23.27	0.024	0.118	1.14	75.25	36

BDL: Below Determination Level.

Garhwal and Nainital synclines overlies the Nagthat Siliciclastic with an erosional unconformity (Figs. 2 and 3). The first glacier advance (Blainian glaciation) corresponds to Marinoan event took over the shallow tidal sea of Nagthat times in the Krol belt. The second ice advance (Upper diamictite) was capped by pink microbial dolomite. Infrakrol shales and quartzites overlie the Terminal Blaini Formation.

The Terminal Proterozoic Lower Krol (Krol A) is essentially a sequence of thinly laminated shales and siltstones with wave dominated shallow marine sedimentary structures like wavy bedding, ripple bedding, ripple drift lamination etc. The palaeobiological records include sheet mega algae, *Vendotaenia*, *V. antiqua*, *Krolotaenia*, *K. gnilovskayi* (Tewari, 1993a,b) and possible metazoan form *Chuaria*, *Beltanelliformis* from Nainital and Nigalidhar synclines (Tewari, 1991, 1996). The organic walled microfossils (OWM's) are found in the black bedded and chert nodules from Infrakrol–Krol A succession of Nainital and Solan areas include *Eomycetopsis*, *Siphonophycus*, *Obruchevella*, *Animikiea*, *Myxococcoides*, *Huronispora*, *Eosphaera* and *Melanocyrillium* (VSM's) (Kumar and Rai, 1992; Tiwari and Knoll, 1994).

The Middle Krol (B) Formation is represented by red and green shales with bands of limestones. The palaeobiological information is scarce from Krol B except doubtful algae. The Upper part of the Krol Formation (C, D, E Member) has yielded rich and diverse assemblage of Vendian/Ediacaran stromatolites, algae, trace fossils, vendotaenids and impressions of soft bodied medusoids and frond like forms of Ediacaran age (Mathur and Shanker, 1989; Tewari, 1989, 1991, 1993a, 1996, 2004a,b). The Upper Krol carbonates are microbially formed peritidal deposits. Krol C is a high energy carbonate shoal (dominantly oolitic) deposits with minor development of *ministromatolites* and *oncolites*. (Tewari and Quershy, 1985). Krol D is characterized by the development of stromatolites bioherms, biolaminated deposits, small microbial reefs with dominantly thrombolitic clotted fabric formed by *Renalcis cyanobacteria* (Tewari and Joshi, 1993). The Vendian taxa of stromatolites recorded in the Upper Krol formation of Nainital and Mussoorie synclines include *Paniscollenia*, *Linella*, *Tungussia*, *Stratifera*, *Irregularia*, *Nucleiella*, *Linocollenia*, *Minicolumella* (microstromatolites), *Yugmaphyton*, *Valdiyaphyton* and *Aldania* (Tewari, 1989, 1991, 1993a, 1998a,b). A detailed study of the microstructures of these stromatolites have shown that the *Vermiform* microstructure appeared for the first time in the Krol stromatolites (Tewari and Joshi, 1993).

The shales, shaly dolomites and siltstones of Krol E represent the uppermost lithounit of the Krol sedimentary cycle. Ediacaran fossils like *Cyclomedusa*, *Pteridinium*, *Kimberella*, *Zolotytsia*, *Charniodiscus*, *Irridinites*, *Beltanelliformis* trace fossils like *Gordia*, *G. meanderi* and vendotaenid algae *Tyrasotaenia* is recorded from the upper part of the Krol Formation in the Nainital, Garhwal, Mussoorie, Korgai and Nigalidhar synclines (Tewari, 1989, 1991, 1993a,b, 1996; Shanker et al., 1997). These impressions are well preserved in the

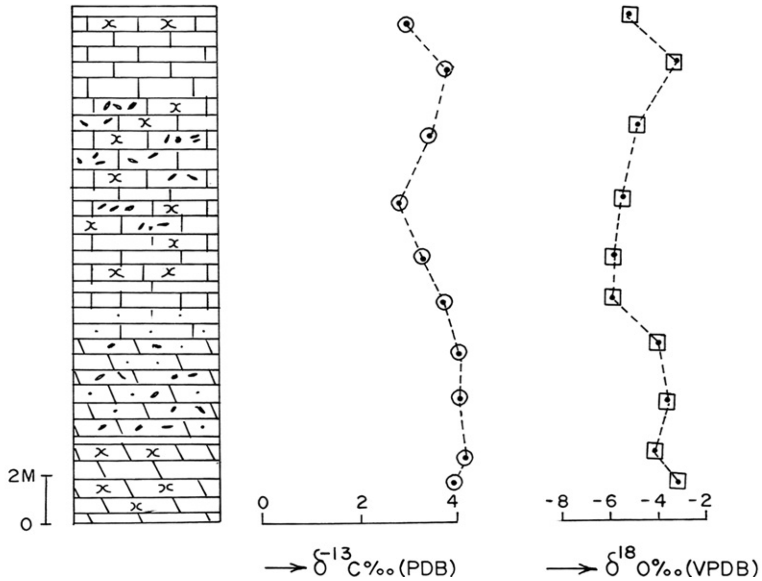

Fig. 7. Carbon isotope chemostratigraphy of the Uttarkashi Limestone, Garhwal Lesser Himalaya, India.

thinly bedded greyish, pink and black shales which are also characterized by the presence of fine laminations, rhythmites and lenticular bedding indicating subtidal to intertidal depositional environment for these beds. On the basis of occurrence of Ediacaran fossils a Terminal Proterozoic (Neoproterozoic III/Ediacaran) age is now assigned to the Krol Formation of the Lesser Himalaya (Tewari, 1991, 1993a, 1996, 2004a,b). The *Ediacaran System* is represented by Krol Formation (*Krolian Period*) which overlies the Blaini Formation; Marinoan glacial beds (Tewari, 1991, 1996, 2004a,b). Neoproterozoic biota and isotopic signatures have been recorded from Deoban Group (Tewari, 1996, 1997). There is a strong possibility of occurrence of Ediacaran fossils in the Buxa sediments of the eastern Himalaya, similar to the Krol Formation of the Central Himalaya. Ediacaran medusoids have been recently recorded from Garbyang Formation of the Tethys Himalaya in Kumaun (Tewari, 1997, 1998a). Precambrian–Cambrian boundary is also demarcated in the Garbyang Formation (Tewari, 1997).

The Krol Formation underlies the Lower Tal Formation which has yielded Early Cambrian diversified small shelly fossils of Tommotian/Meischucunian Zone I of China (Brasier and Singh, 1989). The Chert Phosphorite Member of the Lower Tal Formation from Mussoorie Syncline contains *Protohertzina*, *Circotheca*, *Trapezotheca*, *Anabarites*, *Sachites* etc. found at the base of the Cambrian. The microgastropods, brachiopods, trilobites and abundant trace fossils of Lower Cambrian age have been recorded from the Middle and Upper Tal Formation (Singh and Rai, 1983; Rai and Singh, 1983). The Lower Cambrian brachiopods *Obolella* sp., *Lingulella* sp. and the stromatolite forms *Ilicta talica*, *Columnaefacta korgaiensis*, *Aldania birpica* and macrooncolites have been reported from the thin bands of the limestones and shales within Phulchatti Quartzite which is the youngest unit of the Tal Formation (Tewari, 1989, 1993a; Tewari and Mathur, 2003). The Tal stromatolite taxa (Lower Cambrian) are characterized by the presence of patchy and vermiform to grumous microstructures. There is change in microstructure from vermiform in the Krol (Vendian) to the grumous in the Lower Tal stromatolites.

2.2. Gangolihat Dolomite, Kumaon Lesser Himalaya

The Meso-Neoproterozoic Gangolihat Dolomite of the Lesser Himalaya is well known for its rich economic deposits of magnesite in the Uttaranchal state (Valdiya, 1969, 1980; Tewari, 1994). The thickness of Gangolihat Dolomite is about 700 m (Fig. 6). The magnesite deposits are lenticular in shape and mainly confined to Chandaak Member (100 m). The yellowish-grey magnesite is crystalline phosphatic magnesite with light grey dolomite. The topmost Dhari Member of the Gangolihat Dolomite (110 m) is characterized by stromatolitic–phosphatic dolomite, calcarenite, intraformational conglomerate, cherty-oolitic dolomite and grey magnesite. The chemical analysis of the selected magnesite and dolomite samples from the Chhera–Chandak section of the Pithoragarh is given in the Table 2. *Epiphyton* algae

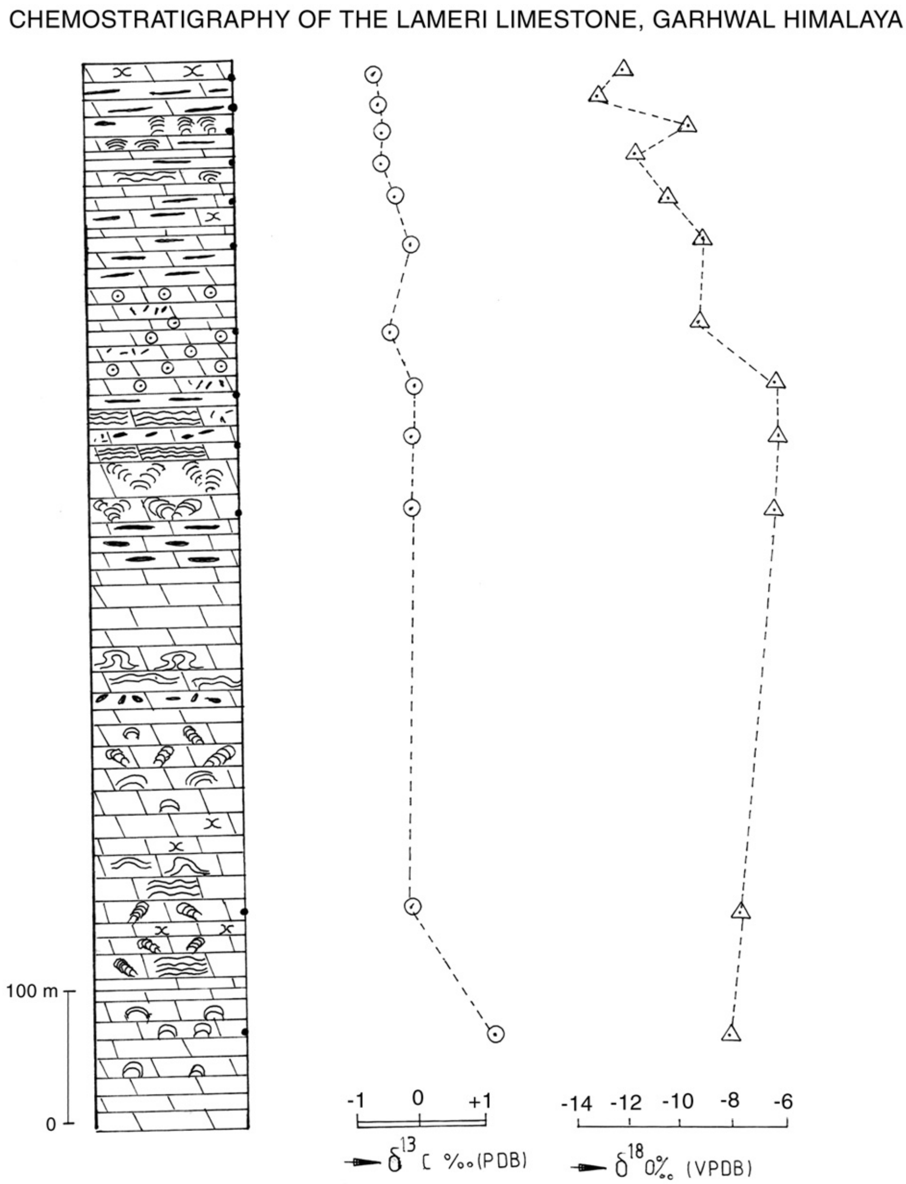

Fig. 8. Carbon isotope chemostratigraphy of the Lameri Limestone, Garhwal Lesser Himalaya, India.

and amino acids phenylalanine, tryptophan and phosphorylcholine have been discovered from the Gangolihat Dolomite, using Laser Raman spectroscopy (Tewari, 2002b). Sponge spicules and organic walled microfossils have been recently reported from the Gangolihat Dolomite (Tiwari et al., 2000).

The magnesite deposits at Jhiroli and Chandaak areas of the Kumaon Lesser Himalaya were formed in shallow hypersaline lagoonal conditions (Tewari, 1994).During the genesis of magnesite the coastal lagoon was connected with open sea and highly variable conditions like evaporitic (increased salinity) conditions were prevailing in the depositional basin. Cyanobacteria and other microbial communities were thriving on the tidal flats and Riphean stromatolites were formed. Similar to the Deoban Group the magnesite associated with stromatolites is due to palaeobiological activity. The magnesite was formed by cyanobacteria under evaporitic conditions in restricted shallow basin. The Deoban–Gangolihat carbonates were deposited on shallow shelf (subtidal to supratidal) environment. (Tewari, 2002a). The Uttarkashi Limestone (Fig. 7) and the Lameri Limestone (Fig. 8) represents smaller outcrops of Deoban–Gangolihat carbonate belt in the Garhwal Lesser Himalaya.

2.3. Menga (Buxa) Limestone, Arunachal Lesser Himalaya

The Menga Limestone is well developed in the Upper Subansiri district, Arunachal Pradesh, Lesser Himalaya. A litholog showing sedimentary facies of the Menga Limestone, exposed about 2 km from Menga village on Menga–Mara road is given in Fig. 10. The geology of the Sipi–Mara window in the Siang district from where microstromatolites and organic walled microfossils have been recorded (Tewari, 2001a,b,c, 2003). The sedimentary rocks are divided into three formations, namely the Menga Limestone (microstromatolite and microbiota bearing), the Sipi Shale and the Raje Quartzite. The Daporijo Gneiss overrides the Menga Limestone. It is mainly banded in nature and exposed in Daporijo–Sipi section. The Menga Limestone is best along the Daporijo–Taliha road (Fig. 10) and occupies the core of the window. It is light to dark grey, cherty, oolitic, intraclastic, stromatolitic dolomite, siliceous dolomite and pink Limestone. It occurs in the form of lenticular bodies, and small patches of dolomite are seen within the Limestone. The Menga limestone is cement grade with CaO ranging from 53 to 55% and MgO from 0.49 to 21.45%. The Laser Raman Spectroscopy of the Menga microstromatolitic facies shows a Raman shift around 625 cm^{-1}, 725 cm^{-1}, and 1082 cm^{-1}. These spectral bands correspond to phenylalanine, tryptophan and phosphorylcholine. The Menga Limestone is overlain by black shales, phyllites and siltstones of the Sipi Shale, which in turn is followed by the Raje Quartzite, a sequence of pink quartzite, diamictite and conglomerate. Palaeobiological activity in the Menga Limestone (microstromatolites, sponge spicules, cyanobacteria etc.) has been recorded by Tewari (2001a,b, 2002a,b, 2003 and Tewari and Sharma, 2005) and suggested Terminal Proterozoic age.

2.4. Buxa Dolomite, Ranjit Window, Sikkim Lesser Himalaya

A very thick sequence of the Buxa Dolomite (800 m) is exposed in the Ranjit Valley, West Sikkim, NE Lesser Himalaya. (Fig. 4). Microbial (stromatolitic) buildups are well developed in the Buxa Dolomite and show a variety of morphological diversity from bottom to top of the sequence. The important buildups recognized are 1. Grey Dolomite with *Colonella columnaris*, *Kussiella kussiensis* and *Conophytopn garganicus*. The cross bedded intraformational pebbles, intraclastic–oolitic dolomite and sandy-oolitic dolomite is intimately associated with this buildup. This buildup was formed in the high energy subtidal and intertidal environment. 2. Dark grey cherty intraclastic–oolitic dolomite with microbial mats and stratified buildups (*Stratifera*) and *Nucleiella* structures. The buildup was formed in subtidal environment. 3. A thick microbial buildup with diversified assemblage (*Jurusania*, *Coloniella*, *Minjaria*, *Gymnosolen*, *Tungussia*, *Jacutophuton*, *Baicalia*, *Aldania*, domal, *Nucliella* and linked conical-stratified and columnar stratified forms). This buildup represents peritidal depositional environment. 4. A cyclic buildup of digitate microbialites, intraformational pebbles, crenulated microbialites and columnar and domal forms is developed. There is cyclicity in the introformational pebbles and microbialites. This buildup is a product of high energy intertidal depositional environment. 5. Shaly dolomite buildup with large domal columnar and *Nucleiella* forms. The intraformational pebbles are found associated with shaly dolomite. Five cycles of columnar and domal buildups have been recorded. (Fig. 11). All these microbial buildups of the Buxa Dolomite recorded between Reshi and Tatapani in Ranjit river section suggest a shallow marine (high energy tidal flat) depositional environment. The microbialite (stromatolitic) assemblage of the Buxa Dolomite suggest a Lower Riphean to Upper Riphean–Vendian (Meso-Neoproterozoic) age. (Tewari, 2004a,b; Tewari and Sharma, 2004, 2005).

3. Analytical method

Finely powdered sample (10 mg) of carbonates and shales (n=25) were treated with anhydrous (100%) phosphoric acid at 25 °C for two days according to the method described by Craig (1957). The resulting carbondioxide gas was subjected to mass spectrometric analysis. VG Isogas PRISM isotope ratio mass spectrometer of the Max Planck Institute of Chemistry (Biogeochemistry Department) Mainz, Germany was used for the determination of C and O isotopic compositions. Results are reported as δ^{13}C values relative to the PDB standard with

$$\delta^{13}C = \frac{(13C/12C)\text{sample}-(13C/12C)\text{standard} \times 1000(\%)\text{PDB}}{(13C/12C)\text{standard}}$$

All values are corrected for Craig correction (Craig, 1957). For determination of organic (reduced) carbon 0.5 gm powder organic carbon rich material, 1.0 gm of moderately organic rich and 2.0 gm of material low in organic matter was used. Carbonate carbon was removed with diluted (1:4) phosphoric acid at 50 °C. The material was then reacted with CaO as oxidizing agent at 900 °C under vacuum. Carbon and Oxygen isotope ratios were obtained after reacting the samples with 100% H_3PO_4 at 25 °C for 12 h for calcite and for 3 days for dolomite. The released CO_2 has been analysed by a SIRA triple collector dual inlet, VG Isotech mass spectrometer at the NEG-LABISE, University of Pernambuco Brazil by A.N. Sial.

4. Results

4.1. Carbon and oxygen isotope chemostratigraphy of the Deoban Group

The results of C and O isotope measurements on Deoban carbonate are shown in Table 1. The carbon and oxygen isotope stratigraphy of the Deoban Group is presented in Fig. 5. The number of samples analysed (25) from 1000 m thick Deoban Group are representative for isotope stratigraphy. However, the important microbial buildups, organic rich shales and light grey dolomite (bulk lithology of the Deoban Group) has been investigated which covers the important facies of Deoban Group from base to top in the type area. As a whole, the isotopic composition of the dolomites seems to be fairly uniform throughout the Deoban Group except in black organic shales where isotopically lighter ($\delta^{13}C=0.2$ to $-3.7‰_{PDB}$) values have been recorded due to organic matter. The heaviest carbon ($\delta^{13}C=+6.6‰_{PDB}$) has been recorded in thin limestone associated with grayish black shale and acritarch *C. circularis* between the stromatolitic buildups, 500 m west of the DFRH.

Following major carbon isotopic trends have been recorded from the Deoban Group.

(i) Low positive values (+1.4 to +1.8‰) for the first 100 m of grey dolomite at the lower part of the Deoban Group.
(ii) High positive values (+3.2 to +4.6‰) for next 100 m of dark bluish black (organic) dolomite and oolitic dolomite.
(iii) A gradual low positive values (+2.9 to 3.0‰) for next 100 m for microbial buildups of *K. kussiensis*, small *Conophyton* sp. and *Stratifera* sp.
(iv) Low positive value (+1.7‰) for *Baicalia nova* microbial buildups for next 25 m.
(v) Highest positive value (+6.6‰) for grayish black shale with acritarch *C. circularis* for next 25 m.
(vi) Drastic drop in the positive value from +6.6 to 0.28‰ for dark black silty shales for next 50 m.
(vii) A shift from positive value to moderately negative value (−3.7‰) for dark bluish grey dolomite with *Jurusania* sp. which become again positive within 100 m thickness (+2‰).
(viii) Low positive values (+0.9 to 2.1‰) persist for about next 300 m for light grey dolomites.
(ix) High positive values (+4.3 to +4.8‰) for the next 100 m for light grey laminated dolomite with silty layers.
(x) Low positive values (+1.1 to 1.4‰) for the last 100 m (uppermost part) of the Deoban Group.

The $\delta^{18}O_{VPDB}$ values of the Deoban Group varies from −2 to −12.8 (Fig. 5) Since $\delta^{18}O$ signature of a marine carbonates precipitate is a reflection of the isotopic composition of seawater and the temperature and the values may change for biogenic carbonates (Tucker, 1986). $\delta^{18}O$ of Deoban Group is mostly in the range of −12.8 to −5‰ (VPDB) in the lower 400 m. The increase in $\delta^{18}O$ (−3‰) has been recorded in the limestone with grayish black shales *C. circularis* acritarchs. $\delta^{18}O$ of bluish grey dolomite and light grey dolomite varies in a narrow range of −8 to −11.2‰ in the next 400 m. This steady value shift to −2‰ in finely laminated limestone and calcareous silty layers for 100 m. $\delta^{18}O$ value of light grey laminated dolomite in the upper part of Deoban Group (100 m) varies from −9.8 to −11.5‰. $\delta^{18}O_{VPDB}$ values of the Deoban Group are highly negative (mostly −1.8 to 12.8% VPDB). The organic carbon ($\delta^{13}C_{org.}$) isotope value varies from $-25.4‰_{PDB}$ to $-36.8‰_{PDB}$ and shown in Fig. 5. This biogenic carbon is quite significant for stromatolitic Deoban limestone.

5. Carbon isotope chemostratigraphy of the Gangolihat Dolomite, Kumaon Lesser Himalaya

The carbon isotope chemostratigraphy of the Meso-Neoproterozoic Gangolihat Dolomite in Pithoragarh area, Kumaon Lesser Himalaya has been established (Fig. 6). The Gangolihat Dolomite in the type area is subdivided into four members namely Chhera, Hiunpani, Chandaak and Dhari from base to top in stratigraphic order (Valdiya, 1969). The distribution of major oxides and strontium in the Gangolihat Dolomite is shown in the Table 2.

The $\delta^{13}C$ value of the basal Gangolihat Dolomite (Chhera Member) vary from +0.8 to $+1.0‰_{PDB}$ and indicate shallow marine (tidal flat) depositional environment. The Hiunpani Member is a cherty stromatolitic dolomite and the $\delta^{13}C$ value vary from +0.9 to $+1.0‰_{PDB}$. The positive near zero values indicate that the environment of deposition is shallow marine (subtidal–intertidal zone). The Chandaak Member of the Gangolihat Dolomite is characterized by prolific development of the microbialites (*Colonnella columnaris*, *K. kussiensis, Baicalia nova* etc.) and well developed magnesite lenses within it. The δ^{13}C value of the stromatolitic-magnesite–dolomite association show a negative shift in δ^{13}C (+0.9 to −1.2‰$_{PDB}$). This negative shift in δ^{13}C is quite significant and indicate evaporitic/supratidal environment of deposition. This also suggests that there may be a change in the benthic microbial community which helped in the formation of magnesite in the Gangolihat Dolomite. The youngest member of the Gangolihat Dolomite (Dhari Member) is a cherty stromatolitic dolomite and the δ^{13}C value vary in a narrow range from −0.9 to −1.0‰$_{PDB}$. Therefore, the δ^{13}C value of Gangolihat Dolomite vary from −1.2 to +1.0‰$_{PDB}$ depicting only one main distinct signature of δ^{13}C minima (Fig. 6). The lower part of the Gangolihat Dolomite showing mostly positive trend (Fig. 6) of excursion and may be the result of increased rate of organic matter burial in a shallow carbonate platform. The recorded isotope data represent pristine isotopic signature.

The Uttarkashi Limestone, Dichli Dolomite and Lameri–Pipalkoti Limestone in Garhwal Lesser Himalaya is part of the Deoban–Gangolihat belt. The carbon isotope chemostratigraphy of this part has also been attempted for regional correlation of the larger Deoban–Gangolihat basin of the Uttaranchal Lesser Himalaya. The δ^{13}C of the Uttarkashi Limestone (Fig. 7) range between +3.4‰$_{PDB}$ and +4.3‰$_{PDB}$. The $\delta^{18}O_{VPDB}$ range from −6.2‰ to −3.4‰ (Fig. 7). The C and O isotope values of the Lameri Limestone are within a narrow range (δ^{13}C close to 0‰$_{PDB}$) and $\delta^{18}O_{VPDB}$ varies from −12.8‰ to −7.9‰ (Fig. 8).

6. Neoproterozoic carbon isotope chemostratigraphy of the East Gondwana

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; Tewari, 1991; Kaufman and Knoll, 1995; Kumar and Tewari, 1995; Brasier et al., 1996; Tewari, 1997; Hoffman et al., 1998; Tewari and Sial, 2003). Low (−3‰ to −5‰) $\delta^{13}C_{PDB}$ values have been reported from reddish-pinkish dolomite (cap carbonate) associated with Neoproterozoic deglaciation in North America, Brazil, Africa, Australia, China, and the Blaini Formation of the Lesser Himalaya, India (Tewari, 1999a,b; Santos et al., 2000; Kumar et al., 2000; Tewari and Sial, 2003). The concept of glacial advance and the subsequent deglaciation event, an ice covered Neoproterozoic land mass (snow ball earth) hypothesis proposed by Hoffman et al. (1998) has been supported by computer simulations with a coupled climate/ice sheet modal (Hyde et al., 2000). At least two glacial advances occurred with glaciers extending to the equator at sea level (Christic-Blick, 1982; Hoffman et al., 1998). The first phase from 760 to 700 Ma (Sturtian ice age) and the second from 620–580 Ma ago (Varanger/Marinoan ice age). The Blainian ice age of Lesser Himalaya corresponds to the Varanger ice age (Tewari, 1999a,b). However no direct isotopic age is available for the Blanin Formation but the overlying Krol–Tal Formations have yielded definite Terminal Proterozoic–Lower Cambrian fossils in Krol belt (Fig. 3). The Terminal Proterozoic succession of Blaini–Krol–Tal sequence is well exposed at Maldeota in the Mussoorie syncline, Uttaranchal. This section, recently has been proposed as a candidate for the Global Stratotype Section and Point (GSSP) by Tewari (1999a; Terminal Proterozoic System, 12th Circular, February 2000a, page 9–19; 2000b). The base of the Terminal Proterozoic is placed at the Blaini pink cap dolomite that overlies the topmost bed of a diamictite (Fig. 3). It is now generally agreed that glacigenic beds of East Gondwanaland (Antarctica, Australia and India) are identical and homotaxial to Marinoan glacial event. The depletion (low $\delta^{13}C_{PDB}$ values) in carbon isotope (Fig. 9) of pink cap dolomite corresponds to global deglaciation event. This deglaciation has an important implication on evolution of life on Earth. The occurrence of acanthomorphic acritarchs from the Infra Krol sediments followed by a radiation of Ediacaran metaphyte–metazoan multicellular life in Krol sediments and calcification of algae below the Precambrian–Cambrian boundary is quite significant in understanding the palaeobiological evolutionary events and palaeoclimate change (Tewari, 1999a,b, 2001b). Isolated hexactinellid and monoaxon sponge spicules (micrometazoans) have been recorded from the Gangolihat Dolomite and the Buxa Dolomite of the Lesser Himalaya (Tewari, 2003).

6.1. Chemostratigraphy of Blaini–Krol–Tal sequence, Lesser Himalaya

The palaeoclimatic change from snowball Earth to global warming is well reflected in carbon isotope excursions obtained from the Blaini pink microbial/

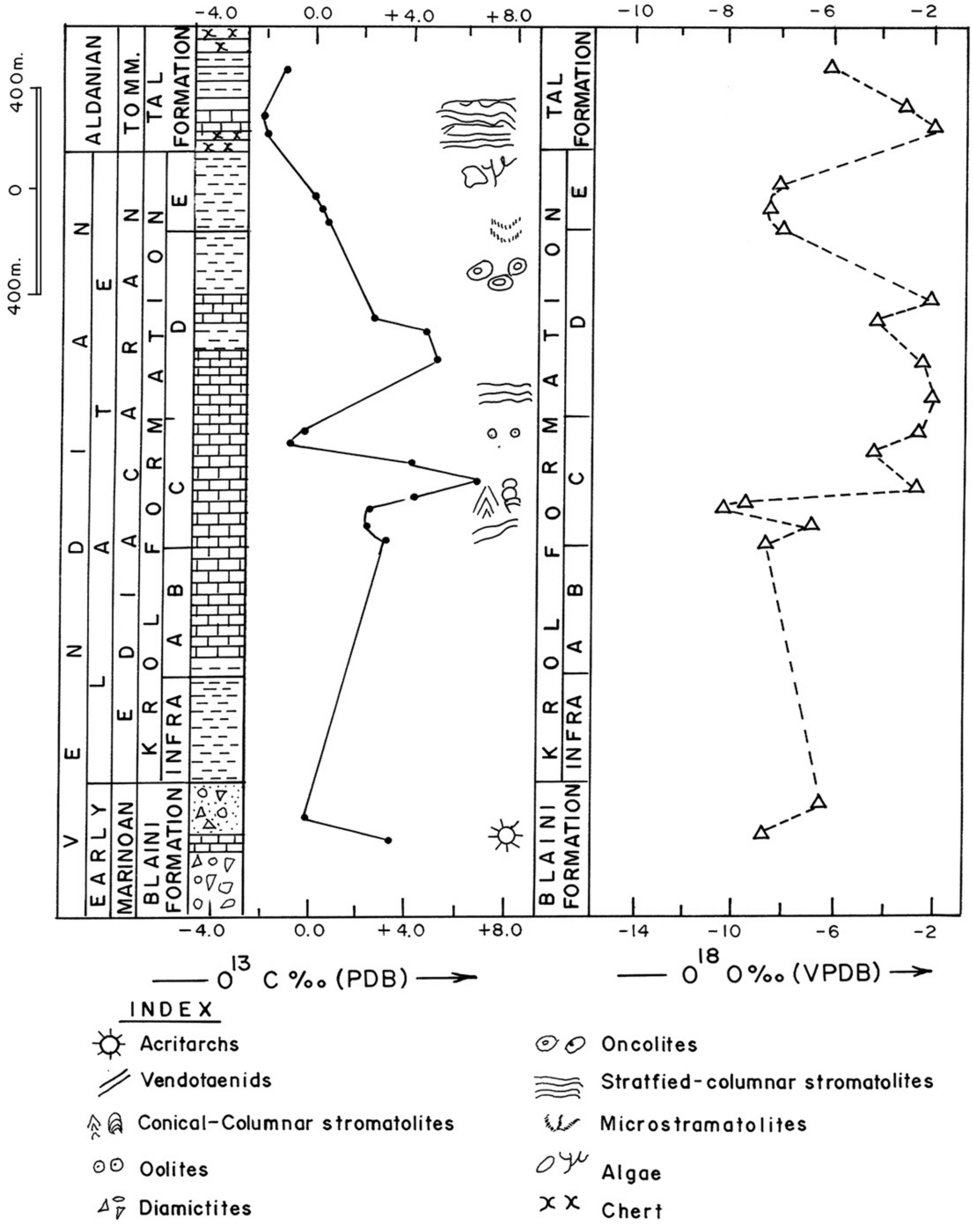

Fig. 9. Carbon isotope chemostratigraphy of the Blaini–Krol–Tal (Terminal Proterozoic–Lower Cambrian) succession of the Lesser Himalaya, India.

stromatolitic cap carbonate (δ^{13}C −2.7‰$_{PDB}$) and the overlying Krol carbonates (very high positive values 6‰$_{PDB}$, Fig. 9, Tewari, 1991; Kumar and Tewari, 1995; Tewari and Sial, 2003). It is interpreted that the depleted δ^{13}C values of the Blaini cap carbonate (deglaciation event) correspond to the Marinoan/Blainian event. Isotopically heavy carbonates (δ^{13}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

Table 3
Major palaeoclimatic and biotic changes across Neoproterozoic–Cambrian Transition in the Lesser Himalaya, India (Tewari, 2001a)

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

$\delta^{13}C$ from +2‰ to near zero in Krol E carbonates. There is a negative shift in $\delta^{13}C$ (−2.2‰ to −4‰$_{PDB}$) just below the Lower Cambrian or Precambrian–Cambrian boundary (Fig. 9). These $\delta^{13}C$ records reflect global isotopic variations in Neoproterozoic–Early Cambrian oceans of the world (Tewari, 1998c). Bhattacharya et al. (1997) have also reported four depletions in $\delta^{13}C$ values from Mussoorie and Garhwal synclines. However only two peaks, the first corresponding to the end of the Varanger glaciation and the below Precambrian–Cambrian boundary are of global significance. The Blaini pink limestone in the Nainital syncline also shows depleted $\delta^{13}C$ values ($\delta^{13}C$=−2.2‰$_{PDB}$). The oxygen isotopes ($\delta^{18}O_{VPDB}$ −10.4 to −2.1‰$_{VPDB}$) of the Upper Krol carbonates indicate high oxygen levels associated with Ediacaran diversification. (Fig. 9).

Major Neoproterozoic and Cambrian palaeoclimatic events, isotopic fluctuations and biotic evolution recorded in Lesser Himalaya is summarized in Table 3.

Proterozoic and Precambrian/Cambrian boundary biota and events are well recorded in the Blaini Krol–Tal succession of the Uttaranchal lesser Himalaya (Central sector) in north India (Fig. 3). The precise demarcation of the PC/C boundary in the uppermost Krol and the Lower Tal Formation is now more or less established and is a candidate section for Neoproterozoic III and the Precambrian–Cambrian event stratigraphy. (Singh and Rai, 1983; Shanker et al., 1997; Tewari, 1984a,b, 1989, 1991, 1993a, 1996, 2001a,b,c). The Krol–Tal PC/C boundary section has the maximum potential for global correlation based on palaeontological and carbon isotopic changes across the PC/C boundary (Aharon et al., 1987; Brasier and Singh, 1989; Kumar and Tewari, 1995; Kumar et al., 2000; Tewari, 2001a). The Lesser Himalaya Neoproterozoic sequence of India are identical to the Yangtze craton of South China block in stratigraphy, biota and chemostratigraphy. (Shen and Schidlowski, 2000). The

Table 4
$\delta^{13}C$, $\delta^{18}O$ and Sr-Isotope data of Krol–Tal carbonates from the Mussoorie Syncline, Uttaranchal

Sample	Litho units	Rock type	$\delta^{13}C$‰$_{PDB}$	$\delta^{18}O$‰$_{VPDB}$	$^{87}Sr/^{86}Sr$
T6	Tal	Oncolitic	−1.2	−7.53	N.D.
T4	Tal	Stromatolitic	−2.5	−3.45	0.7092
T3	Tal	Phosphatic and dolomite	−2.9	−2.97	0.7098
KE3	Krol E	Shaly dolomite	0.1	−8.69	N.D.
KE2	Krol E	Shaly dolomite	0.0	−8.79	0.7151
KE1	Krol E	Shaly dolomite	0.5	−8.40	0.7151
KD3	Krol D	Shaly dolomite (micritic)	2.4	−2.19	0.7094
KD2	Krol D	Microbi mat dolomite	4.6	−4.91	0.7091
KD1	Krol D	Shaly dolomite	4.8	−2.29	0.7091
KC11	Krol C	Shaly dolomite	0.3	−2.58	N.D.
KC10	Krol C	Cherty dolomite	1.0	−3.65	N.D.
KC7	Krol C	Cherty dolomite	2.9	−4.71	N.D.
KC6.1	Krol C	Oolitic dolomite	2.4	−6.36	0.7110
KC6	Krol C	Cherty banded limestone	6.5	−3.36	0.7094
KC5.1	Krol C	Oolitic limestone	2.4	−6.17	0.7104
KC5	Krol C	Fine grained limestone	2.2	−10.14	N.D.
KC	Krol C	Bhatta Limestone (micritic)	2.1	−10.43	0.7088
KC2	Krol C	Oolitic limestone	2.1	−7.43	0.7122
KC1	Krol C	Brecciated limestone	2.8	−8.69	N.D.
BL3	Blaini	Pink dolomite (fine grained)	−0.4	−7.33	N.D.
BL1	Blaini	Pink laminated dolomite	2.9	−8.49	N.D.

N.D.: Not Determined.

Neoproterozoic Bambui and Paranoa groups of Central Brazil are correlated with the Blaini–Krol–Tal succession of the Lesser Himalaya. The negative Carbon isotope values reported from the base of the Bambui Group is related to the Sturtian glaciation (Santos et al., 2000; Alvarenga et al., 2003) similar to the Blainian glaciation (Tewari, 2001a).

6.2. Isotopic and trace element geochemistry of Krol–Tal carbonate–phosphorite association (Precambrian–Cambrian Boundary)

Carbon, oxygen and strontium isotopes, trace and rare earth element data are reported from the Dhanaulti–Durmala section of the Mussoorie syncline (Fig. 2); Table 4. The Precambrian–Cambrian boundary lies in the Lower Tal Formation (Aharon et al., 1987; Shanker and Mathur, 1992; Tewari, 1996, 1999a). The contact between the uppermost Krol Formation (Krol E) and the Lower Tal Formation (Chert–Phsophorite Member) is well exposed at Durmala Phosphorite Mine where phosphorite is being commercially mined. Lower Cambrian stromatolite assemblage *Collumnaefacta vulgaris*, *Boxonia gracilis*, *Colleniella*, *Aldania mussoorica* and oncolites were recorded from this locality (Tewari, 1984a,b, 1989, 1993a, 1996). Small shelly fossils of Tommotian (Early Cambrian) age have been reported from phosphatic deposits of Lower Tal Formation (Brasier and Singh, 1989; Brasier et al., 1996). The Laser Raman spectroscopy of the Mussoorie Tal Phosphorite shows the presence of amino acids. The underlying Krol carbonates are tidal flat deposits and stromatolites and fenestral facies are well developed (Tewari, 2001a, 2002a,b). Carbon Oxygen and Sr isotope data of Krol–Tal carbonates from the Mussoorie syncline is summarized in Table 4. Stable isotope values lie in a range of -2.9 to $+6.5‰_{PDB}$ for $\delta^{13}C$ and $+20.1$ to $+28.6‰_{SMOW}$ for $\delta^{18}O$ respectively. $\delta^{13}C$ values are generally positive for Krol C and D carbonates reaching a $\delta^{13}C$ maxima of $6.5‰_{PDB}$. Krol E carbonates have near zero $\delta^{13}C$ values. Tal carbonates show negative $\delta^{13}C$ values with a $\delta^{13}C$ minimum of $-2.9‰_{PDB}$. The petrographic study of these carbonates shows that they preserve primary fabric like oolites, microbial laminites and micrite. The isotopic signatures are unaltered and primary (Aharon et al., 1987). The positive $\delta^{13}C$ values relative to PDB represent high rates of organic carbon burial whereas negative $\delta^{13}C$ values and $\delta^{13}C$ 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. Krol carbonates are related to the unicellular to multicellular evolutionary stages of life (Tewari, 1993a, 2001a,c, 2002a,b). The Ediacaran metazoans and metaphytes appeared in the Krol Formation (Krolian) which must have originated in highly oxygenated environment. (Tewari, 1993a, 1998a, b,c, 2001a, 2002b).

6.3. Strontium ($^{87}Sr/^{86}Sr$) isotope chemistry

$^{87}Sr/^{86}Sr$ data vary from 0.7088 to 0.7151 (Table 4). The lowest value of 0.7088 has been obtained from Middle Krol C limestone. Krol C is a cement grade limestone in Mussoorie syncline which has Sr content of 659 ppm. Veizer et al. (1983) and Burns et al. (1994) have shown that the sea water $^{87}Sr/^{86}Sr$ value was ≈ 0.707 during the Varanger glaciation and rapidly rose to 0.709 during Late Vendian (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 near pristine sea water value. The preliminary Sr-isotope results from Mussoorie syncline confirm that Terminal Proterozoic sea water values reached to ≈ 0.709 and corroborates with the earlier findings (Veizer et al., 1983; Aharon and Liew, 1992; Burns et al., 1994). According to the Aharon and Liew (1992) the high Sr-isotope value of >0.7095 for Krol and Tal carbonate may be due to latter exchanges with crustal fluids.

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

Acharyya (1974) subdivided the Buxa Group into two units in the type area namely, the Lower Sinchula Formation and the Upper Jainti Formation based on carbonate content and colour. The Buxa Group is exposed in Nakshal Khola and in Jaldhaka river section in the eastern most part of the Darjiling foothills, eastern Himalaya. (Fig. 4). It is also recognized in the Sikkim Himalaya in the Ranjit Window (Raina, 1976; Tewari, 2004a,b). In western Arunachal, Buxa Group is subdivided into two units separated by a pebble diamictite bed (Shergaon pebble bed). However, the tectonostratigraphic position of the Buxa Group is still disputable in the Arunachal Lesser Himalaya. (Tandon et al., 1979; Tewari, 1998b, 2002a, 2003). The base of the Terminal Proterozoic carbonate sequence of the Buxa Group is recognized by the Neoproterozoic glaciomarine–fluvial diamictite-pebble beds. The other sedimentary facies, microbial buildups, oncolites, oolites, fenestral texture, digitate and microstromatolites suggest shallow marine tidal flat depositional

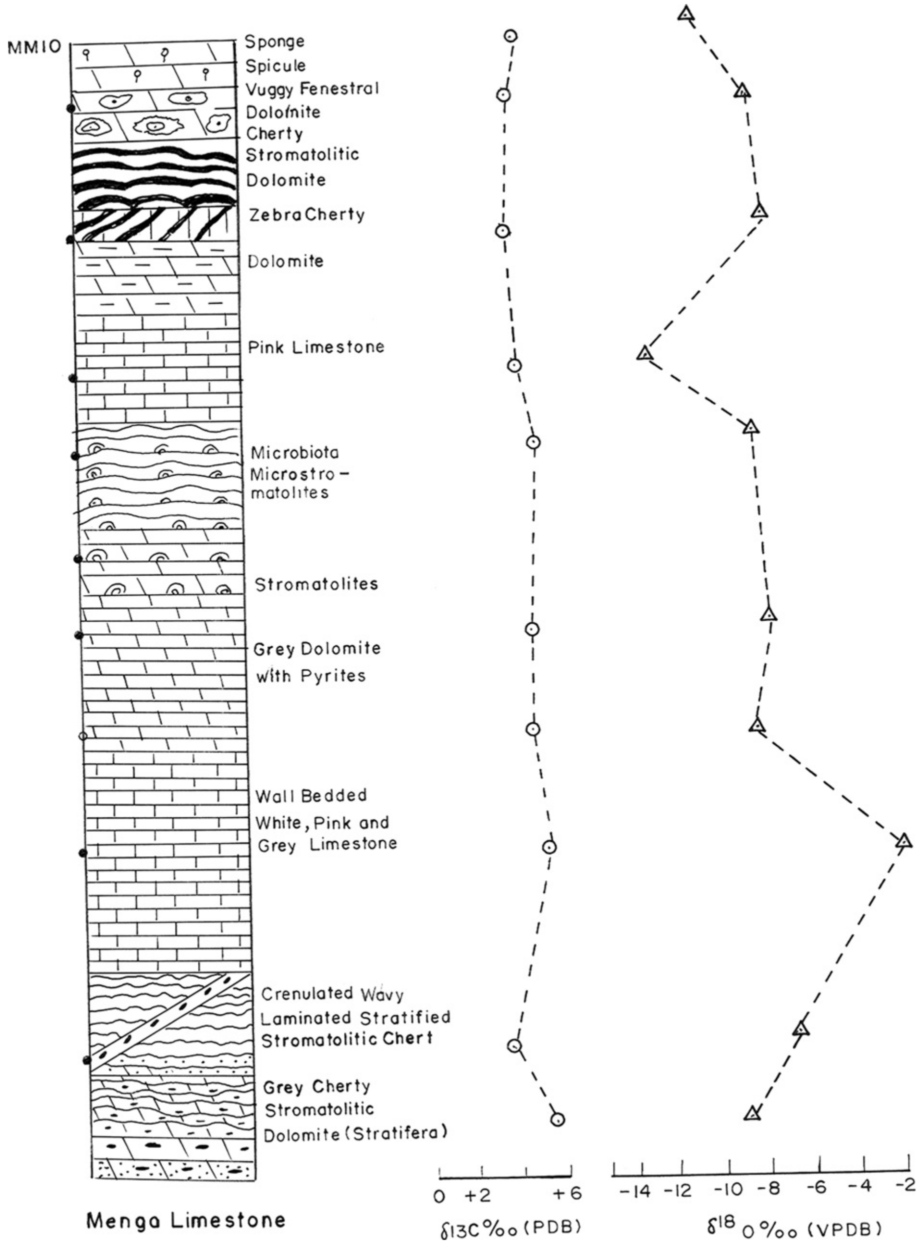

Fig. 10. Carbon isotope chemostratigraphy of the Menga (Buxa) Limestone (Terminal Proterozoic), Arunachal Lesser Himalaya, Northeastern Himalaya (East Gondwana).

environment for the Buxa (Chillipam, Rupa, Dedza, Menga and Panging Limestone) Group. Acharyya (1974) has also interpreted that the Buxa Dolomite was deposited in a shallow subtidal to intertidal environment. The palaeobiological remains like organic walled microfossils, vase shaped microfossils and micro metazoans apart from stromatolites and microstromatolites suggest a Terminal Proterozoic (Vendian) age for the Buxa Dolomite (Tewari, 2004a,b; Shukla et al., 2006). The significantly positive C-isotopic values (+3.7 to +5.4‰$_{PDB}$) of the Menga (Buxa) Limestone (Fig. 10) correspond to the global palaeobiological events. Higher positive values of δ^{13}C from +2.8‰$_{PDB}$ to +4.2‰$_{PDB}$ have been obtained from the Chillipam Dolomite. Significantly positive (δ^{13}C=+5.8‰$_{PDB}$) values were recorded from the Dedza Dolomite in the West Kameng of the Arunachal Lesser Himalaya. The Precambrian–Cambrian boundary may lie between the

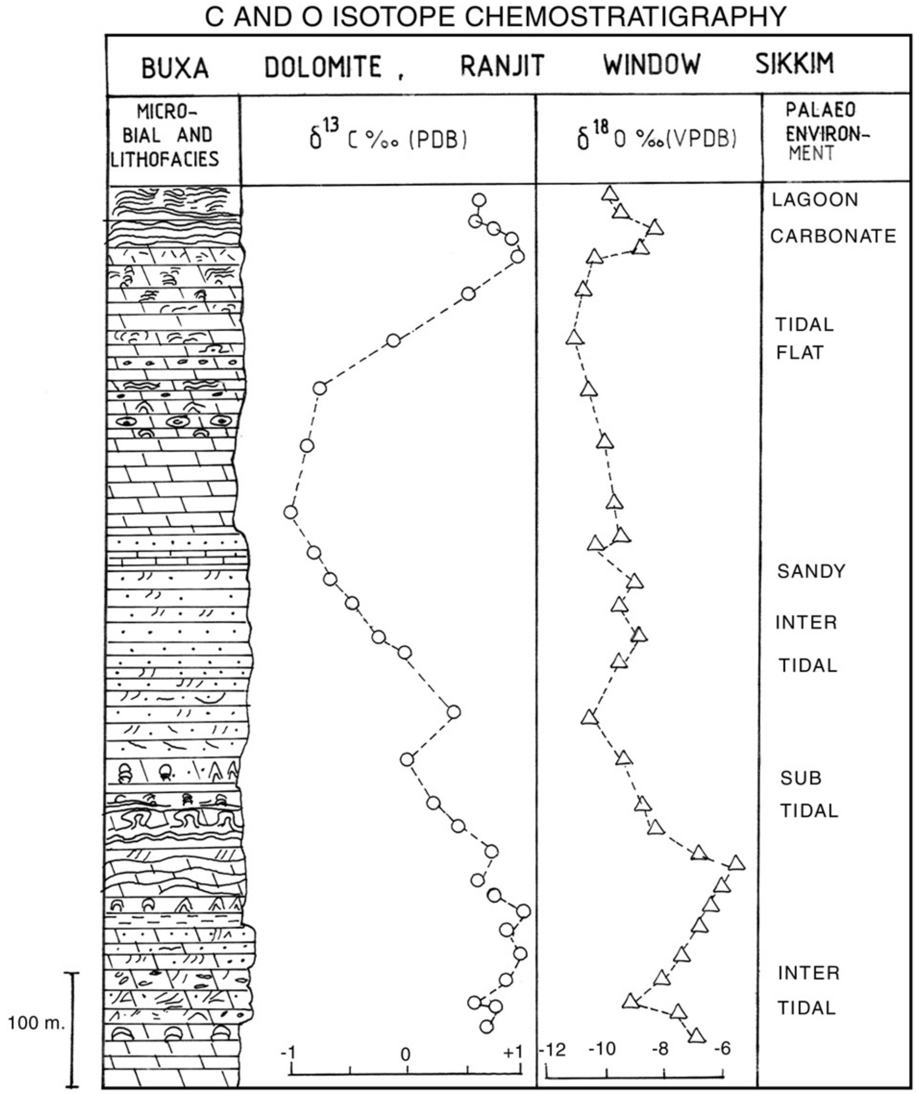

Fig. 11. Carbon isotope chemostratigraphy of the Buxa Dolomite, Ranjit Window (Meso-Neoproterozoic), Sikkim Lesser Himalaya, Northeastern Himalaya (East Gondwana).

Buxa Group and the Miri Quartzite in the northeastern Himalaya.

The stable carbon and oxygen isotope data has been generated from the Buxa Dolomite (Meso-Neoproterozoic) well developed 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, 2004a,b) δ^{13}C (PDB) in the Buxa Dolomite vary in a narrow range from −1.4 to +1.0‰. (Fig. 11) Oxygen isotope $\delta^{18}O_{VPDB}$ values grade from −11% to −6.7‰ ($\delta^{18}O_{VPDB}$). The lower part of the Buxa Dolomite showing mostly positive trend of excursion and may be result of increased rate of organic matter burial in a shallow carbonate platform. We interpret based on our isotope data combined with sedimentological and palaeobiological studies that Buxa Dolomite was deposited in a carbonate platform well connected with the ocean. The environment was highly favourable for the luxuriant growth of the microbialites and the cyanobacterial microbial communities were flourishing in the photic zone. The presence of stromatolitic build-ups and microorganisms indicate that the environment of deposition was shallow marine (peritidal/subtidal to

Table 5
$\delta^{13}C_{PDB}$ and $\delta^{18}O_{VPDB}$ of the Buxa Dolomite, Ranjit Window, Sikkim, NE Lesser Himalaya

Sample	δ^{18}O‰$_{VPDB}$	δ^{13}C‰$_{PDB}$
TR30	−10.8	−0.1
TR29	−10.5	−0.9
TR28	−8.7	−0.1
TR27	−9.5	0.1
TR26	−11.1	0.4
TR24	−11.5	−0.1
TR23	−11.1	−0.1
TR22	−10.0	0.1
TR20	−7.9	−0.9
TR19	−10.0	−1.4
TR18	−10.8	−0.9
TR17	−8.8	−0.8
TR16	−9.2	−0.7
TR15	−9.0	−0.7
TR13	−11.1	0.3
TR12	−9.7	−0.4
TR11	−8.8	0.1
TR10	−7.7	0.6
TR9	−6.7	0.5
TR8	−6.8	0.6
TR7	−7.1	0.9
TR6	−7.3	0.9
TR5	−8.0	1.0
TR4	−8.4	1.0
TR3	−9.7	0.5
TR2	−7.8	0.7
TR1	−7.6	0.7

intertidal). The δ^{13}C and δ^{18}O values of the Buxa Dolomite are summarized in Table 5.

8. Discussion and conclusions

Carbon and oxygen isotope data of whole rock carbonates from Meso-Neoproterozoic Deoban Group, Lesser Himalaya has been investigated. δ^{13}C values vary from −3.7 to 6.6‰$_{PDB}$ depicting one main distinct signature of ^{13}C maxima and minima. δ^{18}O values vary from −2.0% to −13.2‰$_{(VPDB)}$. Two distinct signatures of δ^{18}O maxima–minima have been recorded. The recorded isotope data represent pristine isotopic signature. The Deoban Group carbonates are mostly stromatolitic and microbial in nature and the deposition of these carbonates indicate increased productivity of stromatolitic microbial communities which preferentially fixes ^{12}C in the form of organic carbon (C_{org}) resulting ^{13}C enrichment in carbonate carbon. The δ^{13}C maxima (6.6‰) recorded in Deoban limestone associated with organic shales, thus relate to overall increase in sedimentary carbon ($C_{carb.}+C_{org.}$) budget, increased availability of carbon dioxide in the environment and possibly warmer climates and alkaline pH conditions. The δ^{13}C values of the Deoban carbonates showing mostly positive trend of excursion could be the result of increased rate of organic matter burial in a shallow stromatolitic carbonate platform. The Deoban carbonates are quite rich in microbiota (organic rich) like presence of cyanobacterial microfossils *Huronispora psilata*, *Glenobotrydion aenigmatis*, *Myxococcoides minor*, *Oscillatoriopsis*, *Obruchevella*, *Siphonophycus* and acritarch *Kildinosphaera* (Tewari, 1989 and the references therein). A negative (δ^{13}C −3.7‰$_{PDB}$) to positive δ^{13}C trend (+2‰ to 4.8‰) may reflect a gradual increase in the biomass productivity. Since highly diversified microbiota is recorded from the Deoban cherts, dolomite and black shales as the increase in organic productivity will lead to preferential extraction of ^{12}C resulting in a ^{13}C enrichment of sea water. The organic (reduced) carbon ($^{13}C_{org}$) results of Deoban carbonates the organic productivity especially *Chuaria cirularis* bearing black shales with thin bands of limestone have shown a very high δ^{13}C value (+6.65‰$_{PDB}$). The other published carbon isotope stratigraphy from Africa (Schidlowski et al., 1975) and Siberia (Knoll et al., 1995) show a similar trend of carbon and oxygen excursions from Mesoproterozoic carbonates. The organic carbon is biologically produced and highly reduced in Deoban carbonates. The prolific growth of stromatolites and benthic microbial community supports organic productivity.

The magnesite deposits of the Gangolihat Dolomite at Jhiroli and Chandaak areas of the Kumaon Lesser Himalaya were formed in shallow hypersaline lagoonal conditions (Tewari, 1994). During the genesis of magnesite the coastal lagoon was connected with open sea and highly variable conditions like evaporitic (increased salinity) conditions were prevailing in the depositional basin. Cyanobacteria and other microbial communities were thriving on the tidal flats and stromatolites were formed. The magnesite associated with stromatolites is due to palaeobiological activity. The magnesite was formed by cyanobacteria under evaporitic conditions in restricted shallow basin. The Deoban–Gangolihat carbonates were deposited on shallow shelf (subtidal to supratidal) environment. (Tewari, 2002a). The organic walled microfossils have been reported from the Deoban bedded and stromatolitic chert (Tewari, 1989) and Gangolihat Dolomite (Tiwari et al., 2000). The carbon and oxygen isotope chemostratigraphy has been established for the Deoban Limestone (Fig. 5) and the Gangolihat Dolomite (Fig. 6). δ^{13}C values vary from −3.7 to +6.6‰$_{PDB}$ for carbon and δ^{18}O values very from −2.0% to

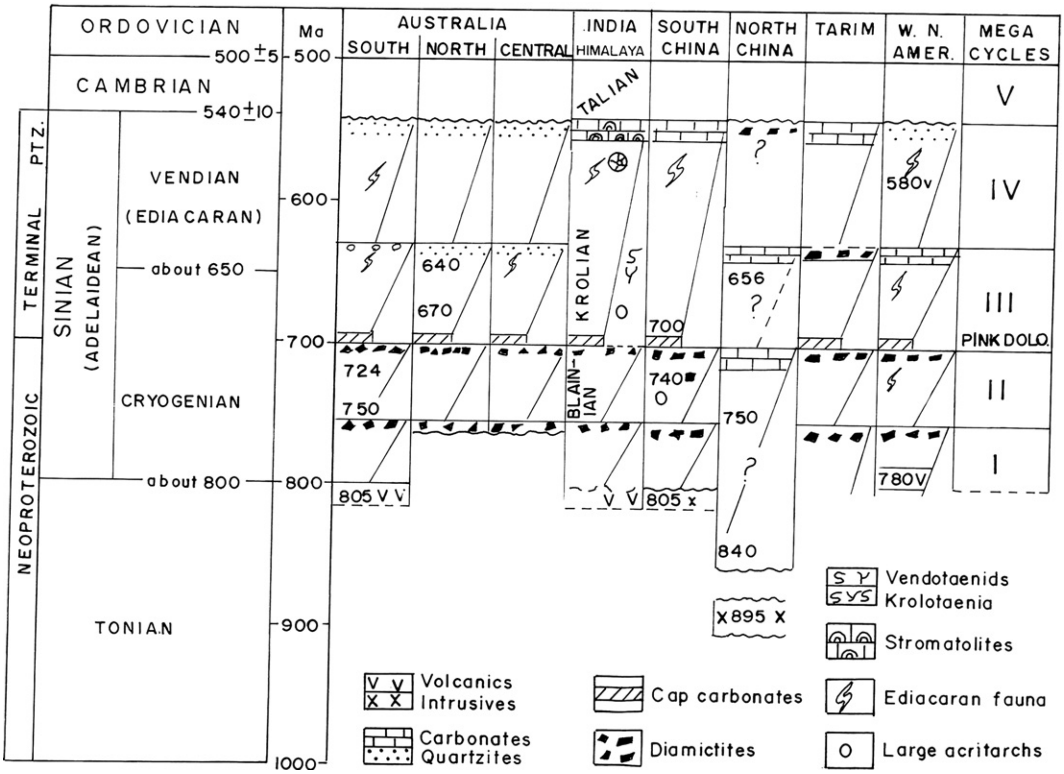

Fig. 12. Global correlation of the *Blainian–Krolian and Talian* (Neoproterozoic to Lower Cambrian) stages of the Lesser Himalaya, India, East Gondwana, (cited after Brookfield, 1994 with slight modification).

−13.2‰$_{VPDB}$ for oxygen isotope. The organic (reduced) carbon δ^{13}Corg varies from −25.4‰$_{PDB}$ to −36.8‰$_{PDB}$ and indicate organic productivity (Fig. 5).

Hoffman et al. (1998) proposed the concept of Neoproterozoic low latitude glaciation as "Snowball Earth". The oceans became completely frozen and primary biological productivity collapsed during this period. They inferred that continental ice cover was thin and patchy. The palaeomagnetic data also supports that Neoproterzoic sequence on different continents accumulated at low palaeolatitudes (Chumakov and Elson, 1989; Brookfield, 1994). They also emphasized that if glacial deposits are not present in the Late Proterozoic sections, no reason would exist to question the validity of the low palaeomagnetic inclinations and low palaeolatitudes of accumulation.

Neoproterozoic Blaini Formation constitutes an important glacial–glaciomaine diamictite-sandy tidalflat lithostratigraphic unit. The Blaini diamictite (first lower glacier advance) in Mussoorie–Garhwal and Nainital synclines overlies the Nagthat siliciclastic with an erosional unconformity (Fig. 2). The first ice advance (Marinoan) tookover the shallow tidal sea of Nagthat times in the entire Lesser Himalaya. The second ice advance (Upper diamictite) was capped by pink microbial (stromatolitic) dolomite with depleted δ^{13}C values and marks the base of the Terminal Proterozoic System. (Tewari, 1999a, 2001a,b,c 2002a, 2004a,b).

The Ediacaran radiation of metazoan and metaphytic multicellular life has taken place after the major palaeoclimatic change from snowball Earth (ice house) to global warming (greenhouse) during Neoproterozoic period (Fig. 12). A major global decline of Mesoproterozoic stromatolites, planktonic acritarches and other prokaryotic biota has been recorded on Earth related to Neoproterozoic glaciation (Tewari, 1993a; Hoffman et al., 1998). Radiation of new acanthomorphic acritarchs, stromatolites, multicellular brown algae Vendotaenids, *Tyrosotaenia*, *Krolotaenia* and Ediacaran metazoans like *Cyclomedusa*, *Charniodiscus*, *Dickinsonia*, *Spriggina*, *Pteridinium* etc. was recorded from Australia, Krol Group (*Krolian*) of the Lesser Himalaya India (Fig. 3), China, Europe, Africa, Siberia and Canada (Mathur and Shanker, 1989; Knoll and Walter, 1992; Tewari, 1993a; Kaufman and Knoll, 1995; Kaufman et al., 1997; Shanker et al., 1997; Tewari, 1999a,b, Tewari, 2004a,b). Ediacaran animals originated before the main Marinoan Ice Age and began to diversify after this glacial event and there after rapidly radiated (Fig. 12). The worldwide occurrence of Ediacaran fossils including Lesser Himalaya corresponds to post Marinoan glacial event. Cambrian explosion of highly evolved life is well recorded from the Tal Group of rocks (*Talian*) of the Lesser Himalaya (Fig. 12) and the Tethyan sequences of Spiti–Zanskar and Uttaranchal Himalaya (Kumar et al., 1997; Tewari, 1998b). Tewari (2001b) has discovered Terminal Proterozoic biota and microstromatolites from the Menga (Buxa) Limestone of the northeastern Himalaya. A well developed diamictite, stromatolitic carbonate sequence (Buxa Dolomite/Chillipam Formation) is exposed in the West Kameng district and Subansiri valley of the Arunachal Lesser Himalaya. This sedimentary succession is quite similar to the Blaini diamictite and Krol Formation in sedimentary facies, microbial buildups and depositional environment (Tewari, 2003). Precambrian–Cambrian boundary may exist in this section (Tewari, 1998a). The Marinoan (*Blainian*) glaciation, appearance of Ediacaran metazoans and negative $\delta^{13}C$ values in pink cap limestone has been described from the Paraguay belt in western Brazil, South America (Santos et al., 2000). The global correlation of the pink cap dolomite of the Blaini Formation is shown in Fig. 12.

The Buxa Dolomite of the northeastern Himalaya of Bhutan, Sikkim, Darjiling and Arunachal Pradesh is traditionally correlated with the Mesoproterozoic (Riphean) Shali–Deoban–Gangolihat carbonate belt of the NW Himalaya by earlier workers on the basis of lithological similarities and stromatolites in the Buxa Dolomite (Valdiya, 1969,1980; Tewari, 2003 and references therein). Acharyya (1974) instead considered Buxa Dolomite to be older than Late Palaeozoic Gondwana but younger than Shali–Deoban stromatolitic carbonates. The present authors have correlated the Menga (Buxa), Chillipam and Dedza Dolomite of the North eastern Himalaya on the basis of microstromatolites/stromatolites, microbiota and carbon isotope stratigraphy indicative of Terminal Neoproterozoic age (Tewari and Sial, 2003).

Recently discovered microbialites, organic walled microfossils, sponge spicules and carbonate facies (Tewari, 2001a,b,c, 2002a, 2003, 2004a,b, Fig. 10) from the Menga–Mara section in Subansiri valley indicate a Terminal Proterozoic age for this sequence. Ten representative samples (Fig. 10) of dolomite were analysed for C and O isotopes. The carbon isotopic ratios are significantly positive and quite consistent with $\delta^{13}C$ (carbonate carbon) values ranging from +3.7 to +5.4‰$_{PDB}$. The O-isotopic data also shows remarkable consistency with the $\delta^{18}O$ value fluctuating with in a narrow range between −8.9 and −7.2‰$_{VPDB}$. The consistency of the carbon isotopic record of the Buxa Dolomite shows that the isotopic data is representative and the signatures are pristine. The significantly positive C-isotopic results correspond to the Terminal Proterozoic C-isotopic evolution (Aharon et al., 1987; Tewari, 1991; Kumar and Tewari, 1995; Bhattacharya et al., 1997; Tewari, 1997, 1998a,b,c, 2001a, 2002a; Tewari and Sial, 2003). A close relationship of $\delta^{13}C$ enriched carbonate rocks with stromatolite can be attributed to the enhanced bioproductivity.

The Terminal Proterozoic–Lower Cambrian sequence of the Uttaranchal Central Lesser Himalaya have been studied in detail for C-isotope chemostratigraphy (Aharon et al., 1987; Tewari, 1991; Kumar and Tewari, 1995; Bhattacharya et al., 1997; Tewari, 1997, 2001a,b; Tewari and Sial, 2003). The present isotope chemostratigraphy is the first such attempt in the north eastern Himalaya. The Buxa Dolomite can be correlated with the Krol Formation (Krolian) of the Uttaranachal (Central Lesser) Himalaya on the basis of carbon isotopic excursions (positive signatures). It is interesting that the Doushantuo carbonates of the Yangtze Platform, Southern China (Shen and Schidlowski, 2000) display high positive $\delta^{13}C$ values similar to the Krol–Buxa belt. The Krol–Buxa–Doushantuo carbonates were deposited after Neoproterozoic (Blainian) global glaciation (Tewari, 2001b,c, 2002a, 2003) and are identical in sedimentary facies, biota, depositional environment, age and carbon-isotope chemostratigraphy (Tewari, 2001a,b, 2002a,b). Therefore, the Lesser Himalayan sequences of India shows the strong palaeobiological and stable isotope chemostratigraphic evidences of preEdiacaran life and rise and fall of Ediacaran (Vendian) biota for global correlation.

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