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Terminal Neoproterozoic (Ediacaran) Chemostratigraphy of the Lesser Himalaya, India

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Abstract : New Ediacaran δ13C chemostratigraphic data from the Garhwal Syncline, Uttarakhand Lesser Himalaya, India, is being reported. A composite δ13C profile for the Krol Formation (Ediacaran System) is prepared based on new data from the Rikhnikhal and Luxmanjhula sections of the Garhwal syncline and previously published δ13C data from Mussoorie Syncline. The Blaini diamictites and the overlying pink cap carbonates are well developed in both the sections representing Neoproterozoic glacial Marinoan/Blainian event. The Lower Krol Formation is shaly limestone and characterized by Vendotaenids. The Blaini pink cap microbial carbonate shows a negative δ13C excursion (-3% ζ%PDB) characteristic of cap carbonates globally. δ13C values rise to + 6 % ζ% PDB in the overlying Krol carbonates. The Krol carbonates are cherty, oolitic, stromatolitic and have yielded well preserved Ediacaran medusoids and frondose forms in the upper silty layers (Krol D Member). A negative δ13C excursion has been recorded just below the Ediacaran–Lower Cambrian boundary. The Ediacaran chemostratigraphy of the Krol Formation (Krolian) from the Lesser Himalaya is identical to the Doushantuo, Lower Dengying and Upper Dengying Formations of the South China. The palaeogeographic reconstruction of the palaeo-continents suggest that around 650-540 Ma, Lesser Himalaya and South China were very close to each other and perhaps part of the same shelf sedimentation. Present Ediacaran chemostratigraphy provides the global correlation of the Ediacaran System.

Keywords: Terminal Neoproterozoic, Ediacaran, Chemostratigraphy, Krol Formation, Garhwal, Lesser Himalaya.

INTRODUCTION

The beginning of the newly established Ediacaran Period is well defined by the Earth's severe paleoclimatic change from Snowball Earth to post-glacial carbonates. The Snowball Earth concept for the Neoproterozoic glaciations suggest that the entire Earth was ice covered around 750 Ma ago.The existence of Rodinia Supercontinent during Meso-Neoproterozoic and its subsequent breakup and reassembly as Gondwana is a widely accepted hypothesis in Precambrian geological history of the Earth. The breakup of the Rodinia resulted in formation of rift basins and passive continental margins around 650 Ma. Major palaeoclimatic events like Neoproterozoic global glaciation (Snowball Earth) followed by global warming have been recorded from different continents including Indian Lesser Himalaya (Blaini -Krol Cryogenian-Ediacaran Period, Figs.1 and 2). The geological map of the Himalaya is after Gansser (Fig.1, 1964), which shows the location of the Lesser Himalaya.The global correlation of these palaeoclimatic events are mostly based on carbonate sedimentary successions and their carbon and sulphur isotopic signatures. The reconstruction of Rodinia supercontinent and the palaeoposition of India (including Lesser Himalaya, Southern China and western Rajasthan) based on palaeomagnetic data strongly suggest that a possible connection of the Lesser Himalayan Meso-Neoproterozoic sedimentary basins; Inner Deoban-Gangolihat belt and outer Blaini-Krol belt) must have existed within the Rodinia. Early Earth possibly witnessed its most extreme climatic fluctuations during the mid/late Neoproterozoic between 750-550 Ma. Palaeoglaciers even reached the equator around 635 Ma covering the whole earth. Evidences from Australia, South China, India, Oman, polar regions of Europe (Svalbard and Oslo), Canada (Newfoundland), USA (Death Valley near California), Africa, Antarctica, South America (Brazil), suggest that there might have been three or more palaeoglacial events during this 200 Ma interval. The global decline of Meso-Neoproterozoic stromatolites, biotic extinctions and discovery of new Ediacaran life after cold climate have been bio, chrono, and chemostratigraphically correlated.Carbon isotopic excursions from all the continents have given the identical results and strongly support the existence of a supercontinent Rodinia during 1100-650 Ma. The basement of the Lesser Himalaya is not exposed. However, sedimentological evolution of the Lesser Himalaya appears to have initiated with the late Palaeoproterozoic rifting event (1800 Ma), followed by a

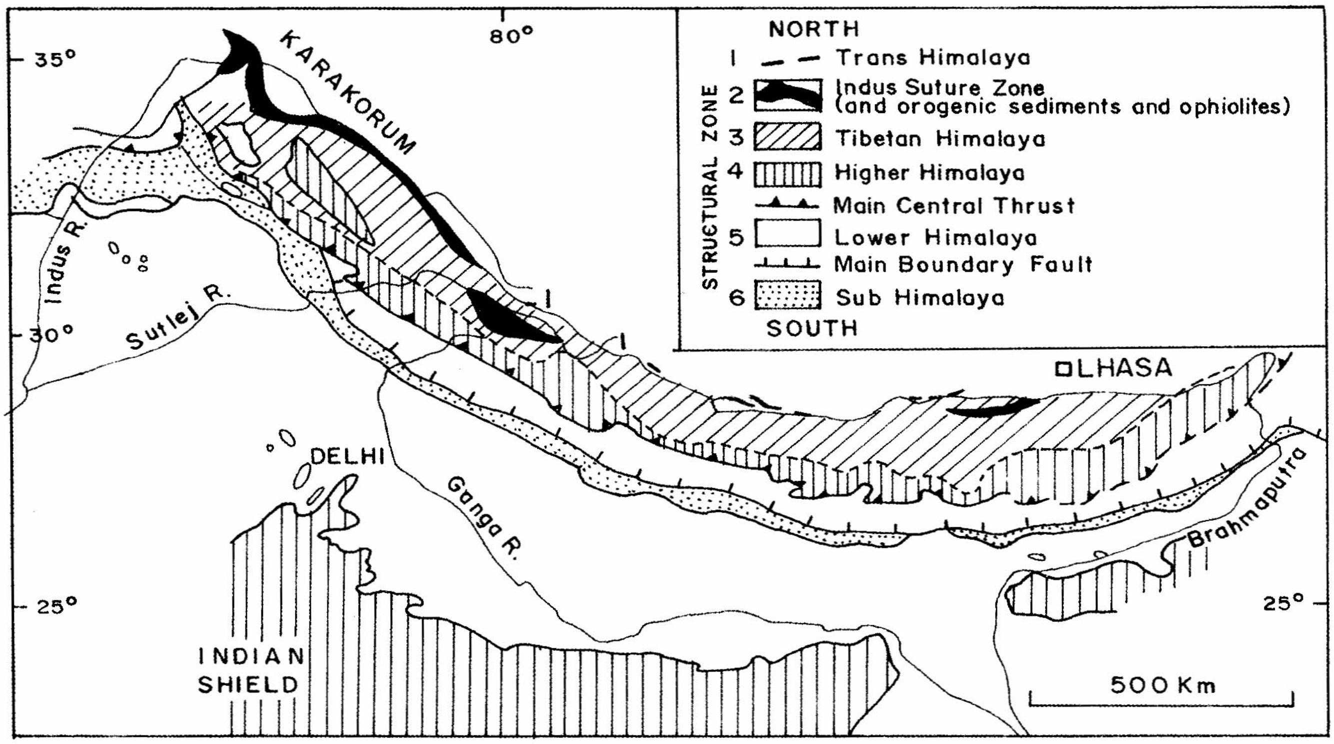

Fig.1. Geological map showing divisions of the Himalaya and the location of the Lesser Himalaya, India, (After Gansser, 1964).

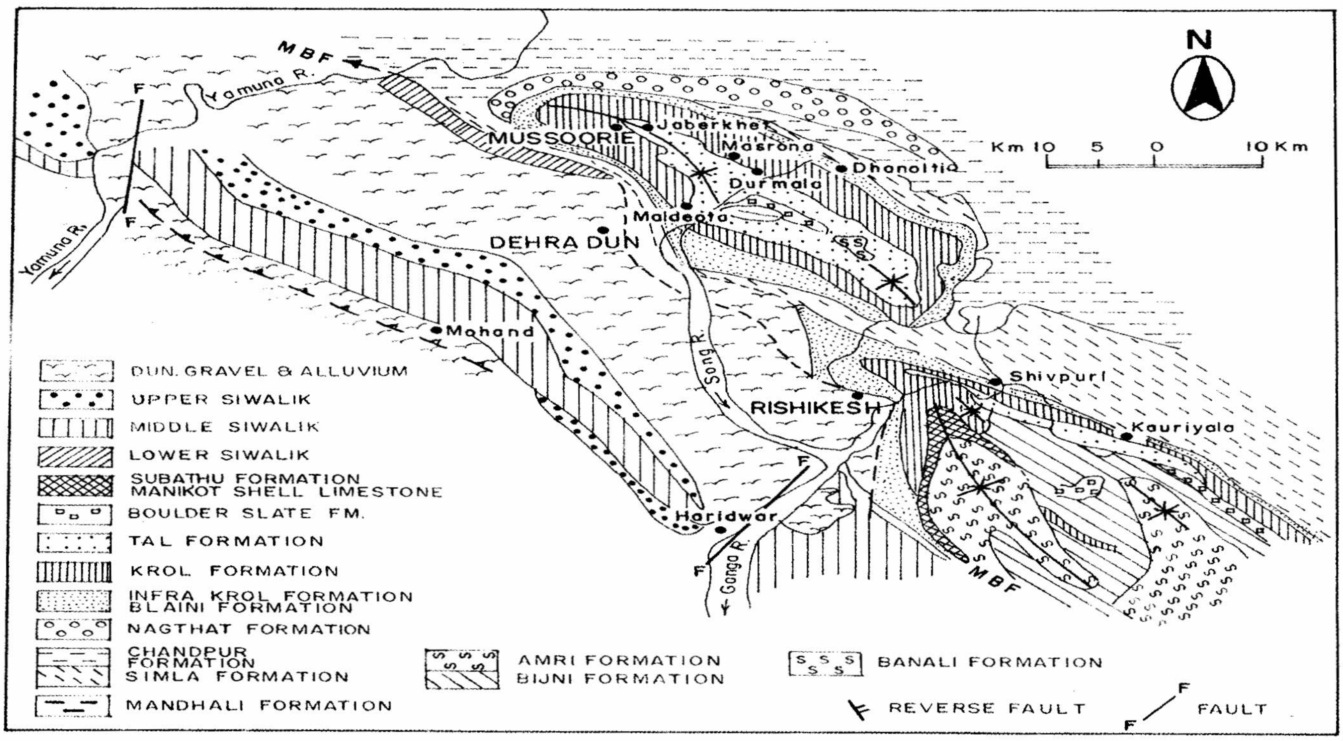

Fig.2. Geological map of the Mussoorie and Garhwal Synclines showing Ediacaran and pre-Ediacaran sediments (After Geological Survey of India).

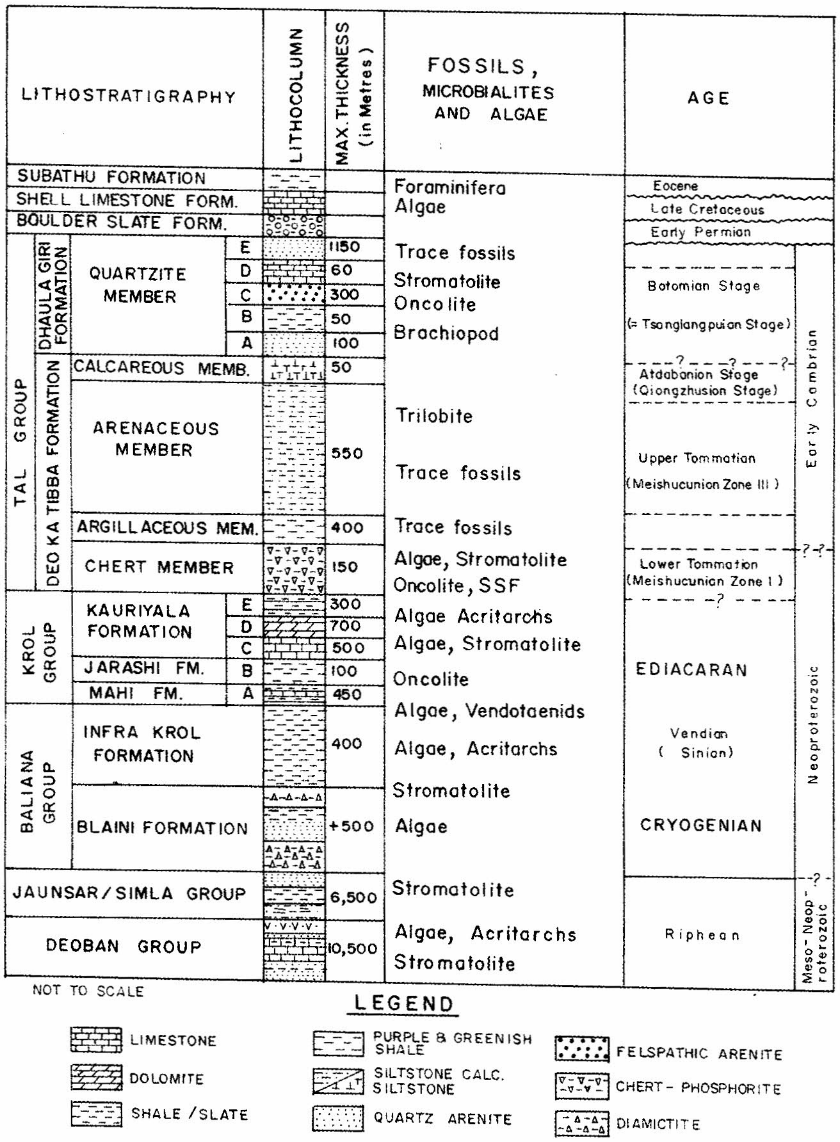

Fig.3. Lithostratigraphy, fossil assemblage and age of the Lesser Himalayan formations.

shelf cycle of tidal flat sedimentation during Mesoproterozoic. The North-Western Lesser Himalaya is characterized by two major sedimentary belts in sequence stratigraphic order. The older sequence is late Palaeoproterozoic to early Neoproterozoic (750 Ma) in age and major lithofacies of this belt are : (i) Volcano-siliciclastic (Rampur-Manikaran-Chamoli-Berinag Quartzite); (ii) Clastic-argillaceous (Sundernagar-Hurla-Rautgara-Rudraprayag-Bhawali Quartizite and volcanics); (iii) Microbial-Stromatolitic carbonate-phosphorite (Shali-Larji-Deoban-Lameri-Pipalkoti-Gangolihat-Dharchula) and (iv) Argillo-calcareous (Sataun,Mandhali-Sor-Thalkedar) in stratigraphic order. The glacial boulder beds have not been reported from the inner belt.

The Deoban-Jaunsar Group in the Lesser Himalaya, underlying the Krol Group, represents preglacial, pre-Ediacaran older carbonate-siliciclastic shallow marine sedimentation (Fig.3). The complete absence of Ediacaran biota, nonglacial sedimentation and characteristic Mesoproterozoic stromatolite taxa and microfossils in black cherts confirm a pre-Ediacaran age. The unconformably overlying Blaini (diamictite) Formation is a Neoproterozoic (Marinoan/ Blainian) glacial deposit corresponding to Snowball Earth palaeo latitude (Cryogenian Period). The overlying pink cap microbial carbonate of the Blaini Formation represents the base of the Terminal Neoproterozoic. The younger carbonate sedimentary succession of the Krol belt is Terminal Proterozoic (Ediacaran, 650-540 Ma) in age and stretching over a distance of 350 km showing major facies variations at Solan-Simla , Nigalidhar, Korgai, Mussoorie, Garhwal and Nainital synclines (Fig.4). The Krol carbonates represent passive continental marginal (carbonate ramp) facies variations as cyclic para sequences like shaly limestone and calcareous shale facies and purple green shales with lenticular bands of limestone and gypsum. Brecciated cherty, oolitic dolomite facies characterized by various types of oolites, bird's eye structure, microbial laminated and stromatolitic build-ups, oncolites indicate that the depositional environment was tidal flat (high energy peritidal).

The Ediacaran microbial mat and metazoan facies of the Krol is finely laminated siltstone, shale and sandy layers with wave ripples. The shaly limestone facies of the Upper Krol grades into the Chert-Phosphorite Facies of the Lower Tal characterized by black chert, shale and phosphorite associated with pyrite, oncolites and stromatolites (Fig.3; Tewari,1984 a,b, 1989, 1998, 2001a, 2002 a,b, 2007). The Precambrian/Cambrian boundary transitional facies shows upwelling and stratification of sea as revealed by carbon isotope excursions of Korl-Tal basin. The other Lower Cambrian facies of the Tal Formation includes bioturbated purple grey siltstone (trace fossil) facies and channel sandstone, orthoquartzite facies of fluvio-deltaic and marine

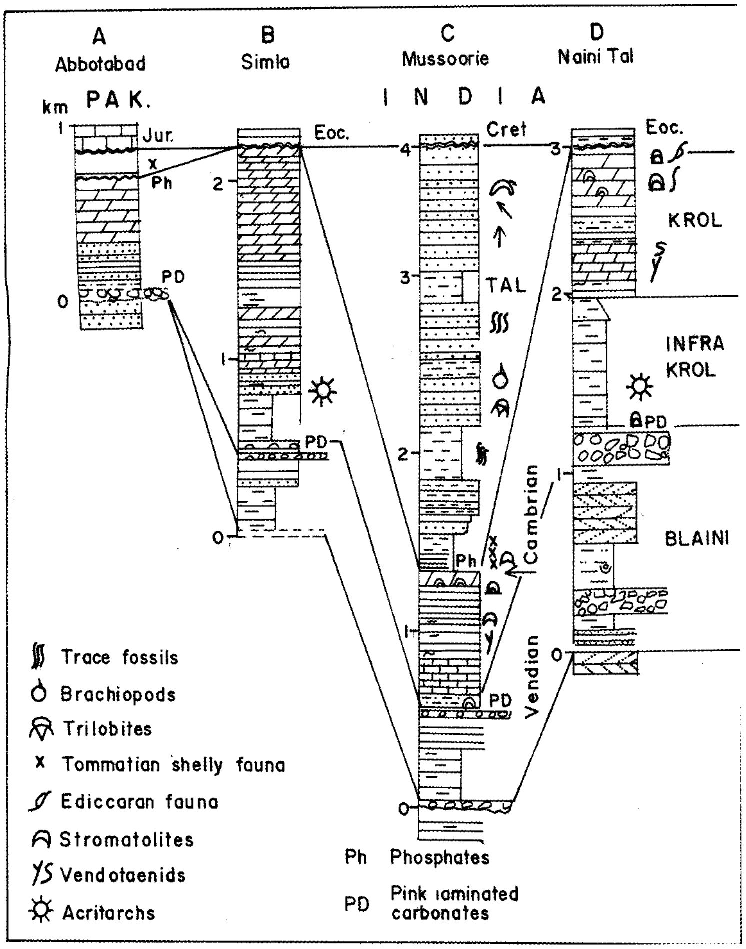

Fig.4. Ediacaran Stratigraphic successions of the Lesser Himalaya from northeast (Nainital, Mussoorie, Simla to Abbotabad, Pakistan) in the northwest.

shelf facies at the top of the sequence. The Krol-Tal basin was possibly obliterated during Lower Cambrian period due to Pan African epeirogenic movements around 550 Ma (by well documented granites of this age, Almora and Mandi granites) in the Lesser Himalayan region. The post-Ediacaran sedimentation of the Lesser Himalaya is represented by chert-phosphorite, siltstone and sandstone facies variation (lagoonal tidal flat environment). The stratigraphic position of the Tal Formation is restricted to only central part (Nigalidhar-Korgai-Mussoorie and Garhwal synclines). The Upper Tal Formation (Quartzite) marks the end of sedimentation and regression of the sea from the Lesser Himalaya.

The Lesser Himalayan sediments are covered by three main Phanerozoic marine transgressions of (i) Permian (ii) Late Cretaceous, and (iii) Late Palaeocene to Eocene age in different areas of the Lesser Himalaya from Jammu in NW to Arunachal Pradesh in NE. Recent sedimentological studies and palaeobiological discoveries from the Buxa-Miri Group sediments, Arunachal Pradesh (Tewari, 2001a,b, 2002a,b, 2003, 2009 a,b, Shukla et al., 2006) suggest that they are equivalents of the Blaini-Krol-Tal sediments and, therefore, quite significant for Proterozoic-Cambrian palaeoclimate and basin evolution in the Eastern Himalaya. The northern margin of the Indian Gondwanaland must have included parts of Tibet and China during Neoproterozoic-Cambrian times forming a megacrustal block (Singh, 1996). It is supported by the close facies relationships and identical biotic and isotopic events from the Sino-Indian region.

EDIACARAN STRATIGRAPHY AND SEDIMENTATION IN THE LESSER HIMALAYA

The Krol Group Peritidal Carbonates, Outer Lesser Himalaya

The Ediacaran Period is recently recognized in the Krol Belt (Krolian) of the NW Lesser Himalaya based on the discovery of a pre-Ediacaran and an Ediacaran biota, carbon isotopic excursions and a Neoproterozoic glacial event.The termination of the Krol algal-stromatolitic carbonate cycle in Terminal Proterozoic and deposition of phosphorite, phosphatic stromatolites of the Tommotian Stage and diversification of small shelly fossils also of Tommotian/Meischucunian Zone 1 age in Lower Tal Formation (Talian) are global events at the Precambrian-Cambrian boundary (Figs.3, 4 and 5).

Terminal Proterozoic Carboanate Sequence of Arunachal Lesser Himalaya

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). The present author has 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, 2007). Recently discovered microbialites, organic walled microfossils, sponge

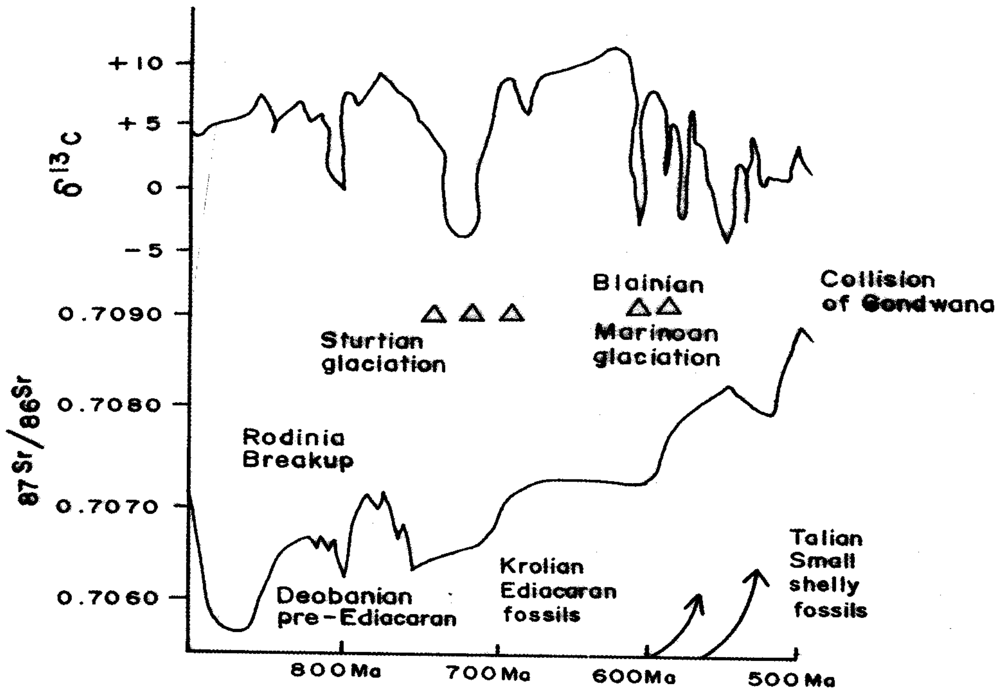

Fig.5. Relationship between breakup of Rodinia, Neoproterozoic glaciations, and variations in carbon and strontium isotope ratios and collision of Gondwana (based on Shields, 1999, Tewari and Sial, 2007).

spicules and carbonate facies (Tewari, 2001 a,b, 2002a, 2003, 2004a , 2009b) from the Menga-Mara section in Subansiri valley indicate a Terminal Proterozoic age for this sequence. 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‰$_{PDB}$. 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; Kumar and Tewari, 1995; Tewari, 1991, 1997, 1998, 2001a, 2002a, 2007; Tewari and Sial, 2007; Bhattacharya et al., 1997; Kaufman et al., 2006). A close relationship of $\delta^{13}C$ enriched carbonate rocks with stromatolite can be attributed to the enhanced bioproductivity.

Breakup of Rodinia Supercontinent and Sedimentological Evolution of the Lesser Himalaya

A supercontinent Rodinia may have existed at the end of the Mesoproterozoic (1000 Ma) up to 750 Ma including the entire continental crust (Li et al., 2003 and the references therein). During Neoproterozoic, Gondwanaland consisted of two separate plates; the Eastern (Australia-Antarctica -India) and the 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; Casnedi, 2002). In South Australia, the Flinders Ranges represent the Adeladian-Cambrian sequence. The Wilpena Pound Quartzite, well known for Ediacaran Period bearing the oldest metazoan fossils underlies the Lower Cambrian archaeocyathan limestone. The presence of Ediacaran metazoans and carbonate stromatolitic platform sedimentation has been reported from the Krol Group of the NW Lesser Himalaya in India (Figs.3 & 4). In the Tethys Himalaya the Phe Formation of Zanskar Range shows the development of Terminal Proterozoic-Cambrian carbonate platform (Tewari, 1998). The S E coast of the present day India might have been connected with East Antarctica (Tewari, 2007). The Himalayan Cambrian sedimentary succession presents particular analogies with the Pacific margin of the Antarctica and Australia. The Cambrian sequences of northern Victoria Land (Antarctica) and South Australia, belonging to the Gondwana, have been correlated with the coeval Tethys

Himalayan sequence. The Tethyan early Cambrian sequence of the Zanskar Range is correlated with Shackleton Limestone Group of Australia and Normanville Group of Southern Australia (Casnedi, 2002). The Terminal Proterozoic-Cambrian sequences in the Himalaya are referred as Blaini (Baliana)-Krol-Tal Group in the Krol belt of Lesser Himalaya (Fig.3), Macchal-Lolab Group in Kashmir, Batal-Kunzam La formations in Spiti, Martoli Group in Kumaon and Buxa-Miri Group in the north eastern Lesser Himalaya (Tewari, 1998, 2002 a,b, 2003, 2007, 2009b, Maithy and Kumar, 2007, Shukla et al., 2006). More recently, Schopf et al. (2008) have discovered permineraralized microbiota from the cherts of the Buxa Dolomite, Sikkim Lesser NE Himalaya. The Laser Raman Spectroscopy and the Confocal Laser Scanning Microscopy have confirmed the presence of three dimensionally preserved biota and kerogen in them. Sedimentation in the Lesser Himalaya was terminated by the Pan African orogeny in the late Cambrian. The recorded Ediacaran biota includes stromatolites, cyanobacteria, acritarchs, algae, sponge spicules, metazoans, metaphytes (Vendotaenids) from the Krol belt of the Himachal and Uttarkhand Lesser Himalaya (Tewari, 1989, 1992, 1993, 1996, 1998, 1999, 2001 (a & b) 2002 (a & b) 2003, 2004; Mathur and Shankar, 1989; Shankar and Mathur, 1997; Kumar, 2000, Kumar et al., 1997, Tiwari et al., 2000, Maithy and Kumar, 2007). The Rodinia supercontinent was broken around 750 Ma and the East Gondwana (India, Australia and Antarctica) separated from West Laurentia. The Baltica, Africa and South America occupied the other side of the Rodinia. The Neoproterozoic rifting, breakup of Rodinia and fragmentation of the Gondwanaland, low-latitude glaciation and global warming events have been recorded from the Lesser Himalaya of India.

The pre-Ediacaran Nonglacial Carbonates of the Lesser Himalaya

The Deoban-Jaunsar Group in the Lesser Himalaya represents pre-Ediacaran pre Neoproterozoic glacial carbonate-siliciclastic sedimentation and the Mesoproterozoic age. is strongly supported by the Lower to Upper Riphean stromatolite assemblages and the associated microbiota. The link between the decrease in microbial carbonate sedimentation, and decline of large Riphean subtidal conical and columnar stromatolites (*Conophyton garganicum, Colonnella columnaris, Kussiella kussiensis* and *Baicalia sp.*) from the inner sedimentary belt (Deoban-Gangolihat, Tewari, 2004, 2007), the first appearance of complex organic walled microfossils and acanthomorphic acritarchs from Blaini-Infrakrol sediments and emergence of Ediacaran soft bodied metazoans *Charniodiscus sp., Cyclomedusa davidi, Kimberella cf quadrata, Zolotytsia biserialis, Conomedusites lobatus, Sekwia sp.* and *Beltanelliformis sp.)*, metaphytes (*Vendotaenia sp. ,Vendotaenia antique, Krolotaenia, Krolotaenia gniloskayi* and *Tyrosotaenia sp.*) from the Krol Formation of the outer NW Lesser Himalaya (Maithy and Kumar, 2007; Tewari, 2004, 2007) is related to the unicellular to multicellular transition during Ediacaran Period. These palaeobiological events are of a global nature and have been documented in Australia, China, Russia (formerly USSR), Canada and Africa (Fedonkin et al., 2007). The base of the Terminal Proterozoic System occurs at the base of a pink microbial limestone in the Blaini Formation and the Precambrian-Cambrian boundary occurs in the Lower Tal Formation. Ediacaran metazoans occur above the Marinoan/Blainian glaciation and below the lowest Cambrian deposits (small shelly fossils of Meischucunian zone I) on all the continents.

The stromatolite assemblage of the Deoban-Gangolihat dolomite is characterized by *Kussiella kussiensi, Colonnella columnaris, Conophyton garganicum* in the lower, *Baicalia, Jacutophyton sp., Baicalia nova, Tungussia* sp. in the middle, and *Jurusania-Gymnosolen -Minjaria-Inzeria* assemblage in the upper part of the sequence (Valdiya, 1969, 1980; Tewari, 1989, 1993, 1996, 1998, 2004; Tewari and Joshi, 1993). The cyanobacterial microbial assemblage of the Deoban chert includes *Huronispora psilata, Glenobotrydion aenigmatis, Myxococcoides minor, Oscillatoriopsis, Obruchevella, Siphonophycus* and *Kildinosphaera* (Tewari 1989, 2003, 2004, 2009b). The diversification of these stromatololites and microbiota had declined in the end of the Mesoproterozoic (Tewari, 1992). The Jaunsar clastic facies does not show any preservation of trace fossils or soft bodied metazoans. The unconformably overlying Blaini Formation is a glacial deposit corresponding to the Snowball Earth palaeolatitute. The pink cap microbial carbonate of the Blaini Formation represents the base of the Terminal Proterozoic, where simple acritarchs Sphaeromorphida and stratified stromatolites have been recorded.

Pre-Neoproterozoi rift-Pre-Blaini Argillaceous-Clastic Nonglacial Sedimentation and Volcanism

In the Uttarakhand Lesser Himalaya, the argillo-arenaceous sedimentation, volcanics and siliciclastic rocks (Mandhali-Chandpur–Nagthat/Simla-Jaunsar-

Saknidhar Group) represent deposition in shallow shelf (tidal flat) and volcanic activity associated with rifting in shallow subsiding basin (Fig.6, Tewari, 1994, 2002a; Valdiya, 1980, 1995). The Blaini glacial diamictites were formed as a result of tectonic-climate interaction during Neoproterozoic rifting (Tewari, 2008, 2009a). The basement of the sedimentary basins of the Lesser Himalaya in India is nowhere exposed. The oldest siliciclastic-volcanic association is known as Berinag- Rampur-Chamoli Quartzite of 1800 Ma age formed in a rift basin (Fig.6). The turbidites-shaly-sandy facies (Rautgara- Chakrata-Damta) are followed by clastic facies of Nagthat-Bhawali Quartzite and interbedded Bhimtal volcanics (Fig.6, Valdiya, 1980, 1995; Tewari, 1994, 2002 a,b). The Chakrata-Damta argillaceous sediments are characterized by sedimentary structures like flute marks, tool marks, ripple marks, graded bedding, slump balls and load casts, etc. indicative of turbidity currents. The regional paleocurrent direction of these Lesser Himalayan sediments is NNW, N, NNE and ENE (Valdiya, 1980, 1995; Tewari 1994). Valdiya (1980, 1995) considere the northern prolongation of the Bundlkhand-Aravalli ridge as the provenance for these sediments of the Lesser Himalaya. The Chakrata-Damta-Saknidhar turbiditic facies sedimentary structures are not seismogenic and can not be related with the paleoseismites formed by earthquakes during early Neoproterozoic period since field evidences strongly support penecontemporoeus deformational structures.

Meso-Neoproterozoic (Stenian–Tonian) Stromatolites in Gangolihat Dolomite and C-Isotopic Variation

The carbon isotope chemostratigraphy of the Meso-Neoproterozoic Gangolihat Dolomite in Pithoragarh area, Kumaon Lesser Himalaya, has been established by Tewari (2007) and Tewari and Sial (2007). The Gangolihat Dolomite in the type area is subdivided into four members, viz. Chhera, Hiunpani, Chandaak and Dhari from base to top in stratigraphic order (Valdiya, 1969, 1980). The $d^{13}C$ 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 $ä^{13}C$ value varies from +0.9 to +1.0‰$_{PDB}$. The positive near zero values indicates 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, Kussiella kussiensis, Baicalia nova, etc.,* Tewari, 1989, 1993) and well developed magnesite lenses within it. The $\delta^{13}C$ value of the stromatolitic-magnesite-dolomite association shows a negative shift in $\delta^{13}C$ (– 0.9 to –1.2‰$_{PDB}$). This negative shift in $\delta^{13}C$ is quite significant and indicates evaporitic/ supratidal environment of deposition. This also suggests that there might have been 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 $\delta^{13}C$ value varies in a narrow range from –0.9 to –1.0‰$_{PDB}$. Therefore, the $\delta^{13}C$ value of Gangolihat Dolomite varies from –1.2 to +1.0‰$_{PDB}$ depicting only one main distinct signature of $\delta^{13}C$ minima. The lower part of the Gangolihat Dolomite, showing mostly positive trend of excursion, may be the result of increased rate of organic matter burial in a shallow carbonate platform. The recorded isotope data represent pristine isotopic signature.

EDIACARAN CARBON ISOTOPE CHEMOSTRATIGRAPHY OF THE KROL BELT, OUTER LESSER HIMALAYA

Carbon and Oxygen Isotopic Variation in the Blaini Pink Cap Carbonate and Krol Carbonate

New additional $\delta^{13}C$ chemostratigraphic data for the Tehri and Pauri Garhwal areas of the Uttarakhand Lesser

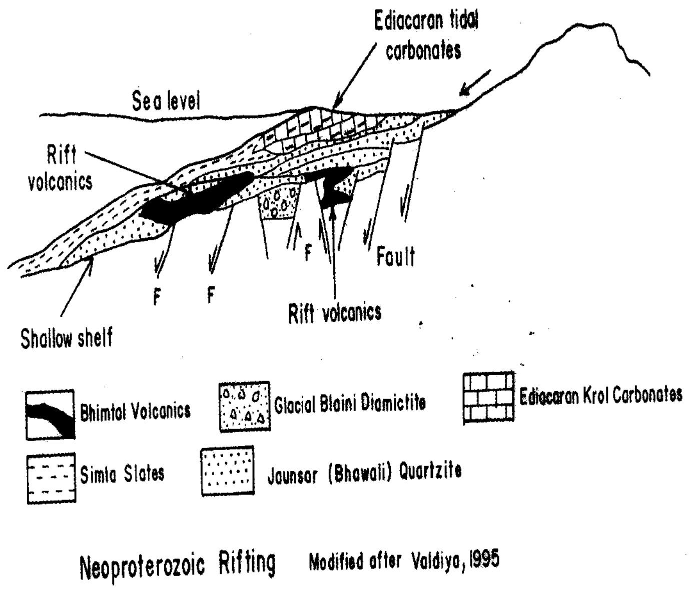

Fig.6. Neoproterozoic rifting in the Lesser Himalaya (modifid after Valdiya, 1995)

Himalaya, India, has been analysed. A composite $\delta^{13}C$ profile for the Krol Formation (Ediacaran System) was prepared based on new data from the Kauriyala, Rikhnikhal and Luxmanjhula sections of the Garhwal syncline and previously published $\delta^{13}C$ data from Mussoorie Syncline. The Blaini diamictites are well developed in both the sections representing Neoproterozoic glacial *Marinoan/Blainian* event (Figs.7, 8, 9, 10). The Blaini pink cap microbial carbonate shows a negative ä^{13}C excursion characteristic of cap carbonates globally (Figs.9, 11, 12, 13). At the Luxmanjhula section, near Rishikesh, the $\delta^{13}C$ values for a stromatolitic pink cap limestone of the Cryogenian Blaini Formation varies from –1.73 to –1.86 $‰_{PDB}$ (Fig.11). Oxygen isotopes range from –9.13 to –11.63$‰_{PDB}$ in carbonates. The Lower Krol Formation is composed of shaly limestone and marl. $\delta^{13}C$ values rise to +4.93$‰_{PDB}$ in the overlying Krol C dolomite in Rikhnikhal area, going up to +6 $‰_{PDB}$ in the Mussoorie Syncline. The Upper Krol carbonates are cherty, oolitic, stromatolitic-oncolitic and zebra fabric is well developed. Krol D/E Member (Figs.14, 15) has yielded well-preserved Ediacaran medusoids and frondose forms in the upper silty layers (Tewari, 2004; Mathur and Shankar, 1989; Maithy and Kumar, 2007). Two carbon isotope trends can be recognized in the Upper Krol dolomites in the Garhwal Syncline. A shift from negative values to positive ones within the Krol E carbonate just below the Krol-Tal contact indicates a period of oxygen deficient bottom waters and an enrichment of 13 C in the shallow water carbonate basin (Fig.16). A marked positive excursion in the Upper part of Krol (+ 2.5 ‰) and sharp decline to (– 4 ‰) in the phosphatic dolomite is very characteristic (Fig.16). The $\delta^{13}C$ carb. and $\delta^{18}O$ curves show excellent co-variance suggesting extensive alteration and modification of the primary isotopic signals (Figs.16, 17).

A negative excursion has been recorded ($\delta^{13}C$ -10.52$‰_{PDB}$) just below the Ediacaran-Lower Cambrian boundary (Fig.16). The Ediacaran C-isotope stratigraphy of the Krol Formation (*Krolian*) of the Lesser Himalaya (Figs.16, 17, 18) is identical to the Doushantuo, Lower Dengying and Upper Dengying Formations of South China and also comparable with the global data.The palaeogeographic reconstruction of the palaeo-continents suggests that around 650-540 Ma, the Lesser Himalaya and the South China were very close to each other. The published palaeogeographic and palaeomagnetic data during this period shows strong evidence for the existence and breakup of Rodinia Supercontinent followed by the Pan African/Pan Indian orogenic event, which reassembled to form Gondwana Supercontinent. The Neoproterozoic is characterized by the 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 and Knoll 1995; Hoffman et al., 1998; Tewari, 1991, 1997; 2007; Kumar and Tewari, 1995; Tewari and Sial, 2007; Kaufman et al., 2006). 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 (Kennedy, 1996; Santos et al., 2000; Tewari, 1999; Kumar et al., 2000; Tewari and Sial, 2007). The concept of glacial advance and the subsequent deglaciation event, an ice covered Neoproterozoic land-mass (Snowball Earth) hypothesis proposed by Hoffman et al. (1998) has been supported by computer simulations with a coupled climate/ice sheet modal. At least two glacial advances occurred with glaciers extending to the equator at sea level (Hoffman et al., 1998; Christie-Blick, 1982). The first phase from 760 to 700 Ma (Sturtian ice age) and the second from 620-580 Ma ago (Varanger/Marinoan ice age, Fig.5). The Blainian ice age of the Lesser Himalaya corresponds to the Marinoan ice age (Tewari, 1999, Fig.5). However, no direct isotopic age is available for the Blaini Formation but the overlying the 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, Uttarakhand. The base of the Terminal Proterozoic is placed at the Blaini pink cap dolomite that overlies the topmost bed of a diamictite (Figs.7, 8, 9, 12, 13). It is now generally agreed that glacigenic beds of East Gondwanaland (Antarctica, Australia and India) are identical and homotaxial to Varanger glacial event (Brookfield, 1994). The depletion (low $\delta^{13}C_{PDB}$ values) in carbon isotope (Fig.11) of pink cap dolomite corresponds to global deglaciation event. This deglaciation has an important implication on evolution of life on the 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

Fig.7. Blaini Diamictite showing different clasts, Rishikesh, Tehri Garhwal Syncline suggesting proximal source for the clasts derived from the underlying rocks. The pink cap limestone is found above the diamictite.

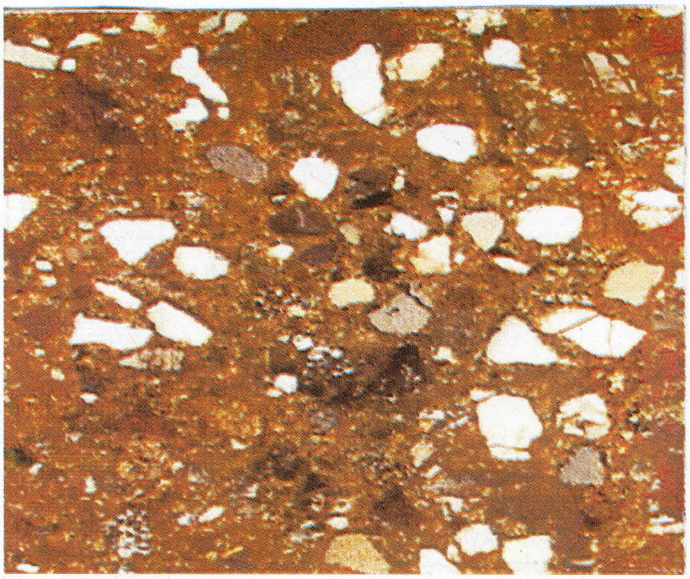

Fig.8. Microphotograph of the Blaini Diamictite, Rikhnikhal area, Pauri Garhwal.

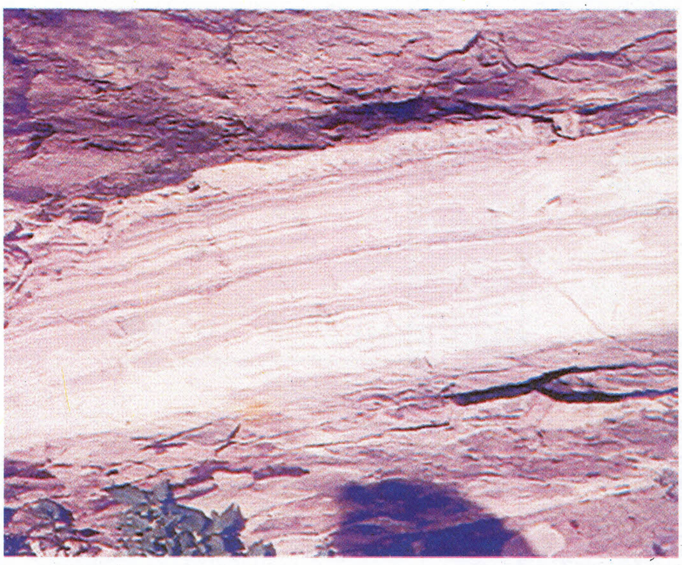

Fig.9. Blaini pink cap carbonate, Mussoorie Syncline, Tehri Garhwal.

calcification of algae below the Precambrian-Cambrian boundary is quite significant in understanding the palaeobiological evolutionary events and palaeoclimate change (Tewari, 1999; 2001b; Tiwari et al., 2000). Isolated hexactinellid and monoaxon sponge spicules (micrometazoans) have been recorded from the Gangolihat Dolomite and the Buxa Dolomite of the Lesser Himalaya (Tiwari et al., 2000; Tewari, 2003, 2009b).

Global Neoproterozoic Paleoclimatic Events and the Outer Lesser Himalaya

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

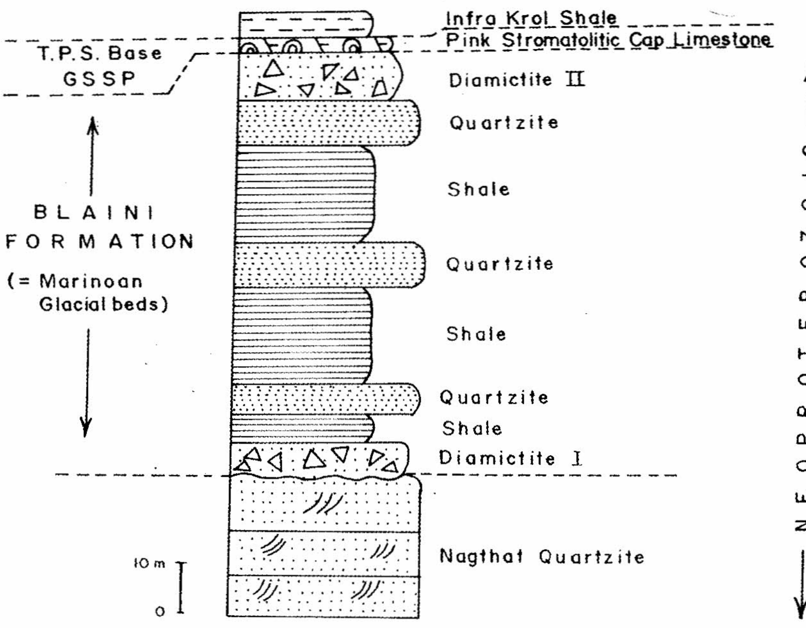

Fig.10. Litholog of the Blaini diamictite.

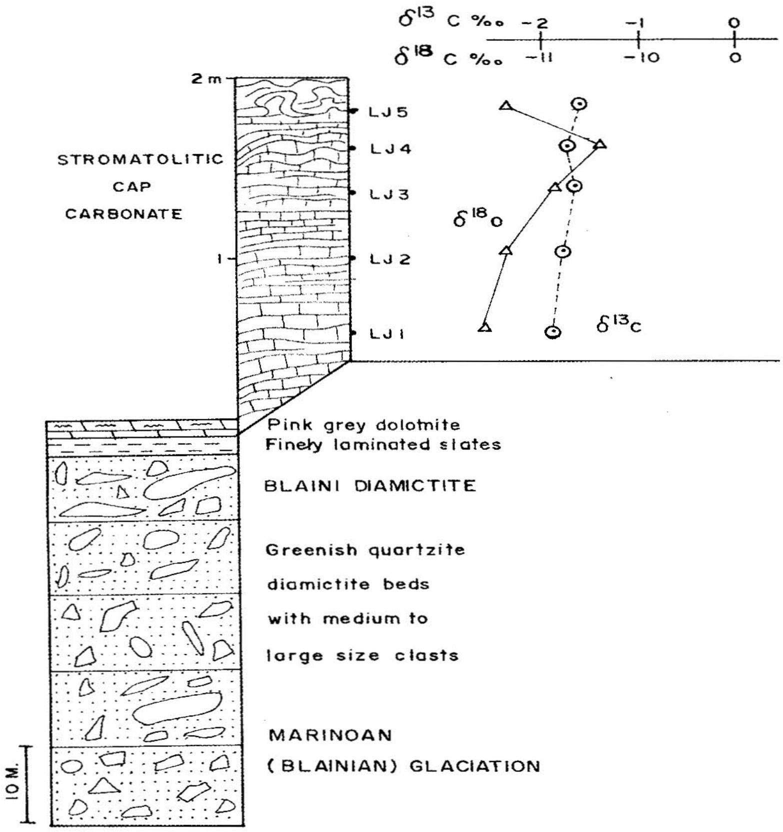

Fig.11. Carbon and oxygen isotope chemostratigraphy of the Blaini pink cap carbonate, Luxmanjhula section, Tehri Garhwal.

Fig.12. Blaini cap carbonate, Baliana type section, Himachal Pradesh (the author pointing to the outcrop).

Fig.13. I.G.C.P.- 512 Neoproterozoic glaciation working-group members in the field workshop, Baliana section, Himachal Pradesh in February, 2010.

Fig.14. Field occurrence of Cherty, oolitic, intraclastic limestone, Garhwal Syncline.

Fig.15. Field occurrence of stromatolitic Upper Krol Dolomite, Garhwal Syncline.

carbonate ($\delta^{13}C$ -2.7‰$_{PDB}$) and the overlying Krol carbonates (very high positive values 6‰$_{PDB}$, Figs.16, 17, 18, Tewari, 1991; Kumar and Tewari, 1995; Tewari and Sial, 2007; Kaufman et al., 2006). It is interpreted that the depleted $\delta^{13}C$ values of the Blaini cap carbonate (deglaciation event) correspond to the Varanger-Blainian event. Isotopically heavy carbonates ($\delta^{13}C$ +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 $\delta^{13}C$ 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.16). These $\delta^{13}C$ records reflect global isotopic and geochemical changes during Neoproterozoic-Early Cambrian oceans of the world (Figs.19, 20, Tewari,1998c). Bhattacharya et al. (1996) have also reported four depletions in $\delta^{13}C$ values from Mussoorie and Garhwal synclines. However, only two

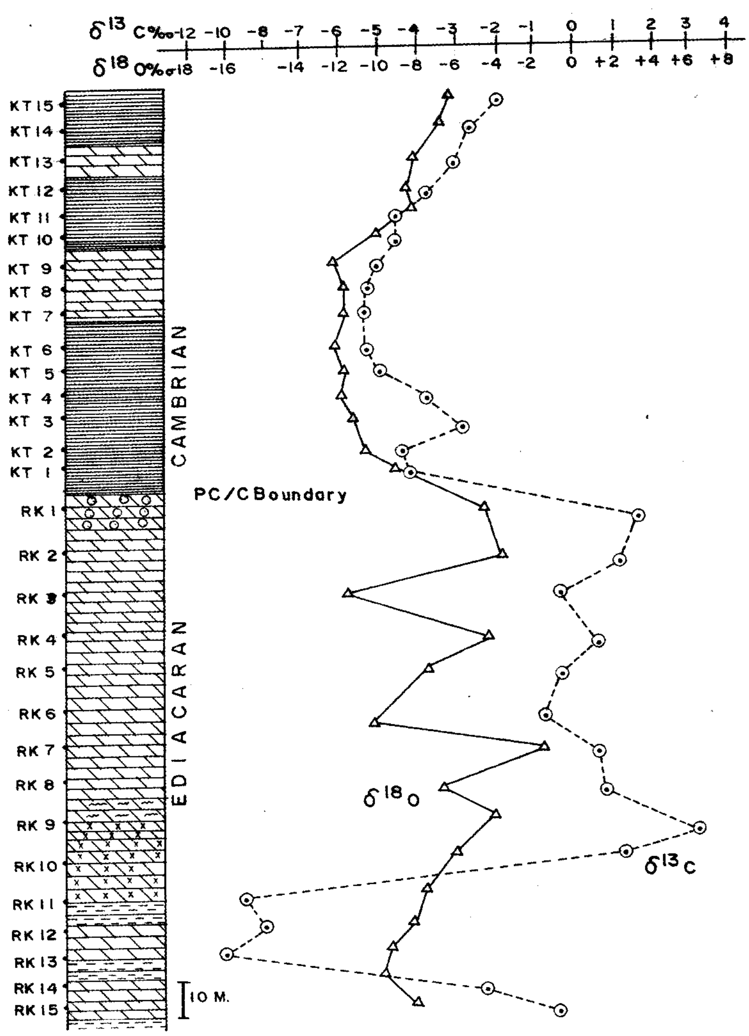

Fig.16. Carbon and oxygen isotope chemostratigraphy of the Krol-Tal formations, Kauriyala section, Tehri Garhwal.

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 $d^{13}C$ values ($d^{13}C$ = -2.2$‰_{PDB}$). The oxygen isotopes ($d^{13}C$ +20.1 to 28.6$‰_{SMOW}$) of the Upper Krol carbonates indicate high oxygen levels associated with Ediacaran diversification (Fig. 18).Major Neoproterozoic and Cambrian palaeoclimatic events, isotopic fluctuations and biotic evolution recorded in Lesser Himalaya are summarized in Fig.21 and Table 1.

Precambrian-Cambrian Boundary Carbon Isotope Chemostratigraphy

Proterozoic and Precambrian/Cambrian boundary biota and events are well recorded in the Blaini Krol-Tal succession of the Uttarakhand Lesser Himalaya (Central sector) in north India. The precise demarcation of the PC/C boundary in the uppermost Krol and the Lower Tal Formation is now more or less established and has been a candidate section for Neoproterozoic III and the Precambrian-Cambrian event stratigraphy (Singh and Rai, 1983; Shankar and Mathur, 1997; Tewari, 1984 a,b, 1989, 1991, 1992, 1993a,b, 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 et al., 1996; Tewari, 1984 a,b; 2001 a; Kumar and Tewari, 1995; Shankar et al., 1997; Tewari, 2007; Tewari and Sial, 2007; Kumar et al., 2000; Maithy and Kumar, 2007). The Lesser Himalaya Neoproterozoic sequence of India is identical to the Yangtze craton of South China block in stratigraphy, biota and chemostratigraphy (Shen and Schidlowski, 2000). The 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 Sturatian glaciation (Santos et al., 2000; Alvarenga et al., 2003) which is similar to the Blainian glaciation (Tewari, 2001a, 2007).

The carbon and oxygen isotopic variation and chemostratigraphy of the Blaini-Krol-Tal succession strongly supports the Precambrian-Cambrian transition lies in the Lower Tal Formation ($d^{13}C$ = -4$‰_{PDB}$). The Krol Belt in the Lesser Himalaya is characterized by positive $d^{13}C$ value (+1 to 6$‰_{PDB}$). The emergence of multicellular Ediacaran life in the Upper Krol is consistent with an increase in atmospheric oxygen which played a major role in metazoan evolution and Cambrian explosion 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 $d^{13}C$ value (-3$‰_{PDB}$) and this Blainian glaciation is correlated with Varanger glacial event. A comparison of the available carbon and oxygen isotope curves from other regions of the Eastern Gondwana land and South China, parts of Siberia and North Africa suggest that the Neoproterozoic-Early Cambrian chemostratigraphy is consistent in the isotopic variation.There is carbon isotopic similarity between Neoproterozoic Bambui Group in Central Brazil, South America and the Krol Formation of the Lesser

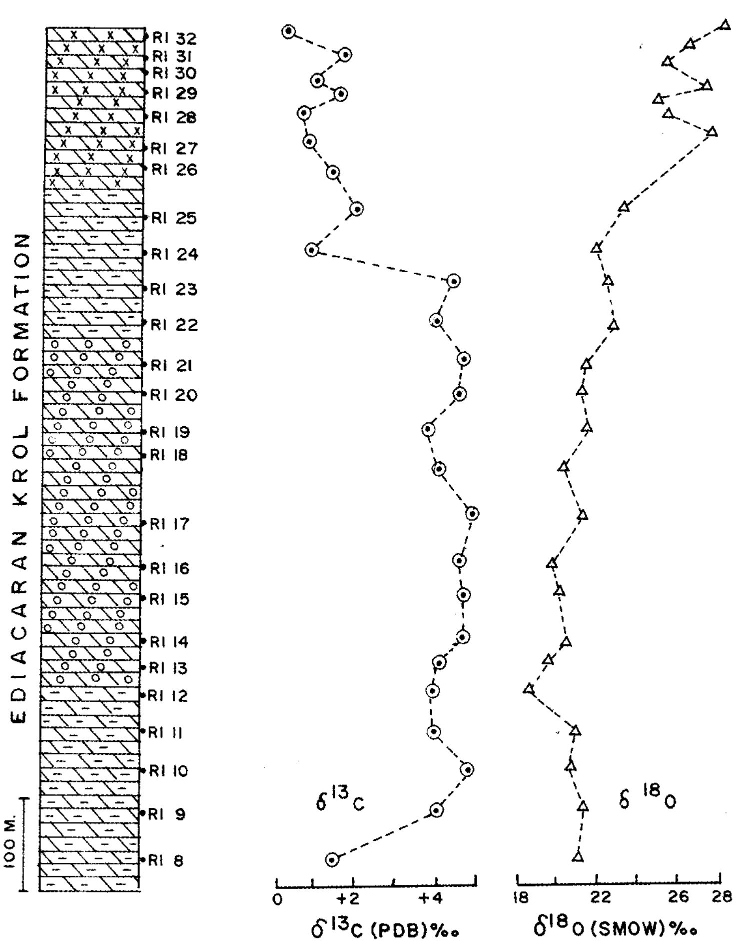

Fig.17. Carbon and oxygen isotope chemostratigraphy of the Ediacaran Krol Formation, Rikhnikhal area, Pauri Garhwal.

Himalaya. In the North Eastern Lesser Himalaya, India, Neoproterozoic sedimentary succession shows well developed carbonate-the Buxa Dolomite - which 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 d^{18}O values fluctuating within a narrow range between –8.9 and –7.2‰$_{PDB}$. 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.

The Neoproterozoic-Early Cambrian chemostratigraphy of the Blaini-Krol-Tal succession strongly supports the Precambrian- Cambrian transition that lies in the Lower Tal Formation (d^{13}C = -4‰$_{PDB}$). The Krol Belt in the Lesser Himalaya (Figs. 16, 17 and 18) 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 ($\delta^{18}O$ = +3.0‰$_{SMOW}$). 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 cap carbonate, Blaini Formation (Tewari, 2001a, 2007). The pink cap carbonate of the Blaini Formation shows negative $\delta^{13}C$ value (-3‰$_{PDB}$) and correlated with Marinoan glacial event. 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. Consistency in the C-isotopic composition during the geological past has been observed in the critical sections world widely.

TRACE ELEMENT, RARE EARTH ELEMENTS, Sr-ISOTOPIC GEOCHEMISTRY OF KROL-TAL CARBONATE-PHOSPHORITE ASSOCIATION (Precambrian-Cambrian Boundary)

Mussoorie–Dhanaulti Section, Mussoorie Syncline

Carbon, Oxygen and Sr isotope data of Krol Tal carbonates from the Mussoorie Syncline is summarized in the Table 2. Stable isotope values lie in 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., 1986). 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, 13C 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

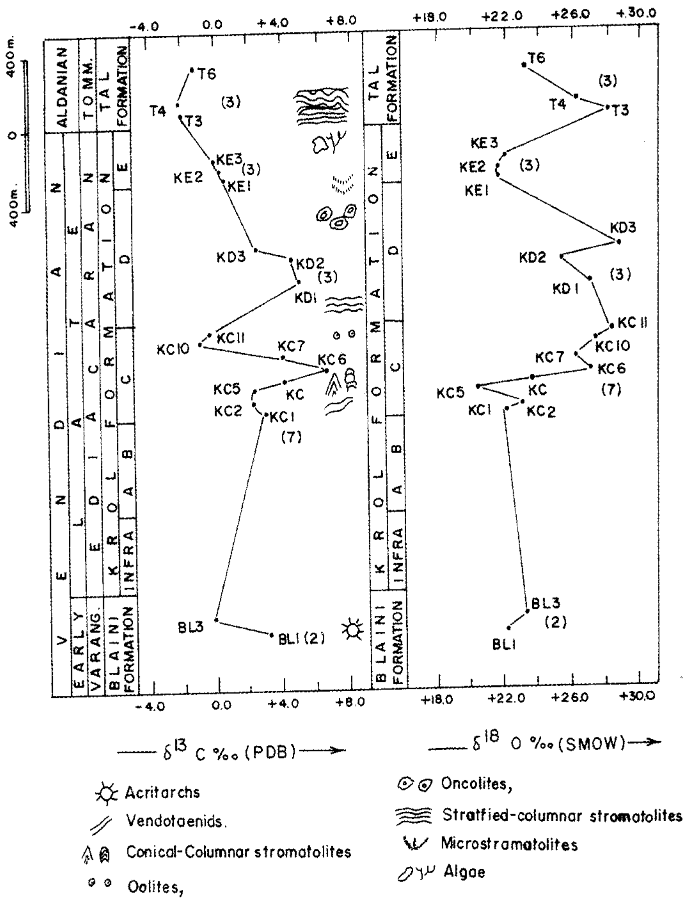

Fig.18. Carbon and oxygen isotope chemostratigraphy of the Ediacaran Krol Formation, Mussoorie Syncline.

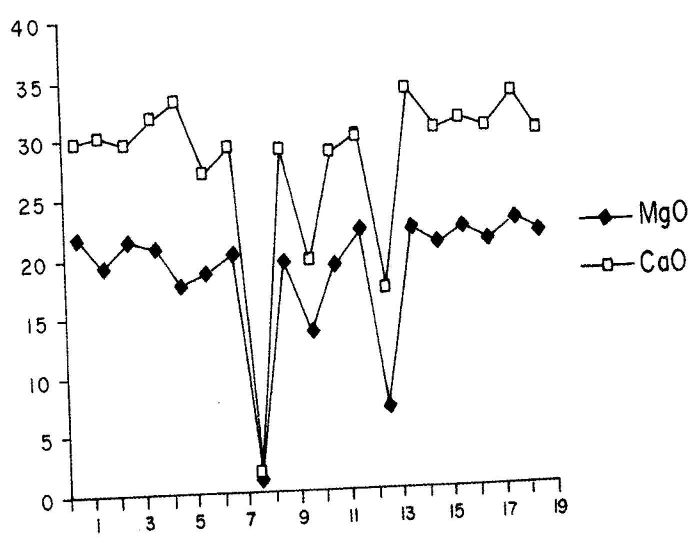

Fig.19. Ca and Mg percentage analysed in an oolitic grain from the Krol dolomite by EPMA.

(Tewari, 1993, 2002a, 2004, 2009b). The Ediacaran metazoans and metaphytes appeared in the Krol Formation (Krolian) which must have originated in highly oxygenated environment (Tewari, 1993, 1998, 2001a, 2002b, 2007).

Strontium ($^{87}Sr/^{86}Sr$) Isotope Geochemistry

$^{87}Sr/^{86}Sr$ data vary from 0.7088 to 0.7151 (Table 2). 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 Ediacaran (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; Burns et al., 1994; Aharon and Liew, 1992). According to the Aharon and Liew (1992) the high Sr-isotope value of >0.7095 for Krol and Tal carbonate may be due to later exchanges with crustal fluids. The Sr isotopic values of the Krol carbonates indicate the composition of the Ediacaran sea water.

Trace Element Geochemistry

Trace element abundances of Blaini-Krol-Tal carbonate rocks are shown in Table 3. All the 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. Sr content shows definite pattern except high content for the lower Tal carbonates.

Major Oxides (Wt%)

Al_2O_3 varies from 0.01 to 0.72%. K_2O varies from 0.01 to 0.017. SiO_2 varies 0.02 to 1% and 74.5% in Black Chert in Precambrian-Cambrian boundary. CaO varies 30.56 to 31.0% in Uppermost Krol and 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 Tal). TiO_2 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).

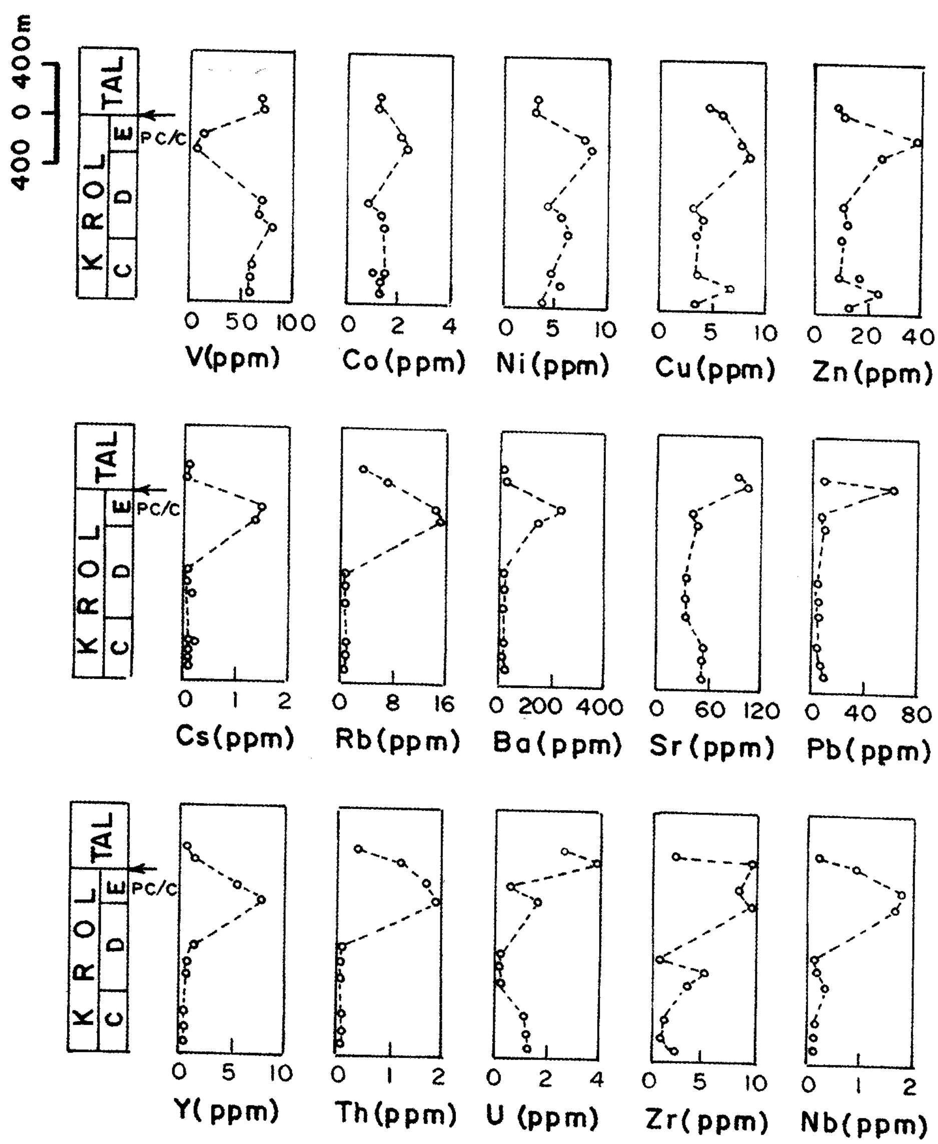

Fig.20. Rare Earth Elemental distribution in Upper Krol-Lower Tal formations (Ediacaran–Lower Cambrian transition) in the Mussoorie Syncline.

Trace Element Distribution (ppm)

Ba varies from 10 to 81 ppm in Upper Krol and 87 ppm in Lower Tal. Cr varies from 10 to 29 ppm (150 ppm in Lower Tal). Sr varies from 32 to 190 ppm (78 ppm in Lower Tal). The strontium is much lower in comparision to 610 ppm given for carbonates of the lithosphere. Cr is having the average value of lithosphere carbonates. Zn varies from 10 to 110 ppm (12 ppm in lower Tal). Cu varies from 3 to 5 ppm (19 ppm in Lower Tal). The average value of Cu is 4 ppm. Co varies from 2 to 24 ppm in Lower Tal which is higher than average value (0.1 ppm). Y varies from 0.32 to 30 ppm (34 ppm in Lower Tal). V varies 4 to 41 ppm in Lower Tal. U varies from 13 to 20 ppm in Krol and 20 ppm in Krol and 20 to 103 ppm in Lower Tal (Table 3).

Rare Earth Elements (REE) Geochemistry

Lanthanum (La) varies from 5 ppm to 70 ppm in Upper Krol and 37 to 101 ppm in Lower Tal. Ce varies from 10 ppm to 105 ppm in Krol and 61 to 89 ppm in Lower Tal. Pr varies from 10 ppm to 14 ppm in Krol and <10 ppm in Lower Tal. Nd varies from <10 ppm to 46 ppm in Krol and 24 ppm to 69ppm in Lower Tal. Sm varies from <10 ppm in Krol to 10 ppm in Lower Tal. Eu varies from <1 ppm to 10 ppm in Krol and 1 ppm to 3.2 ppm in Lower Tal. Gd varies

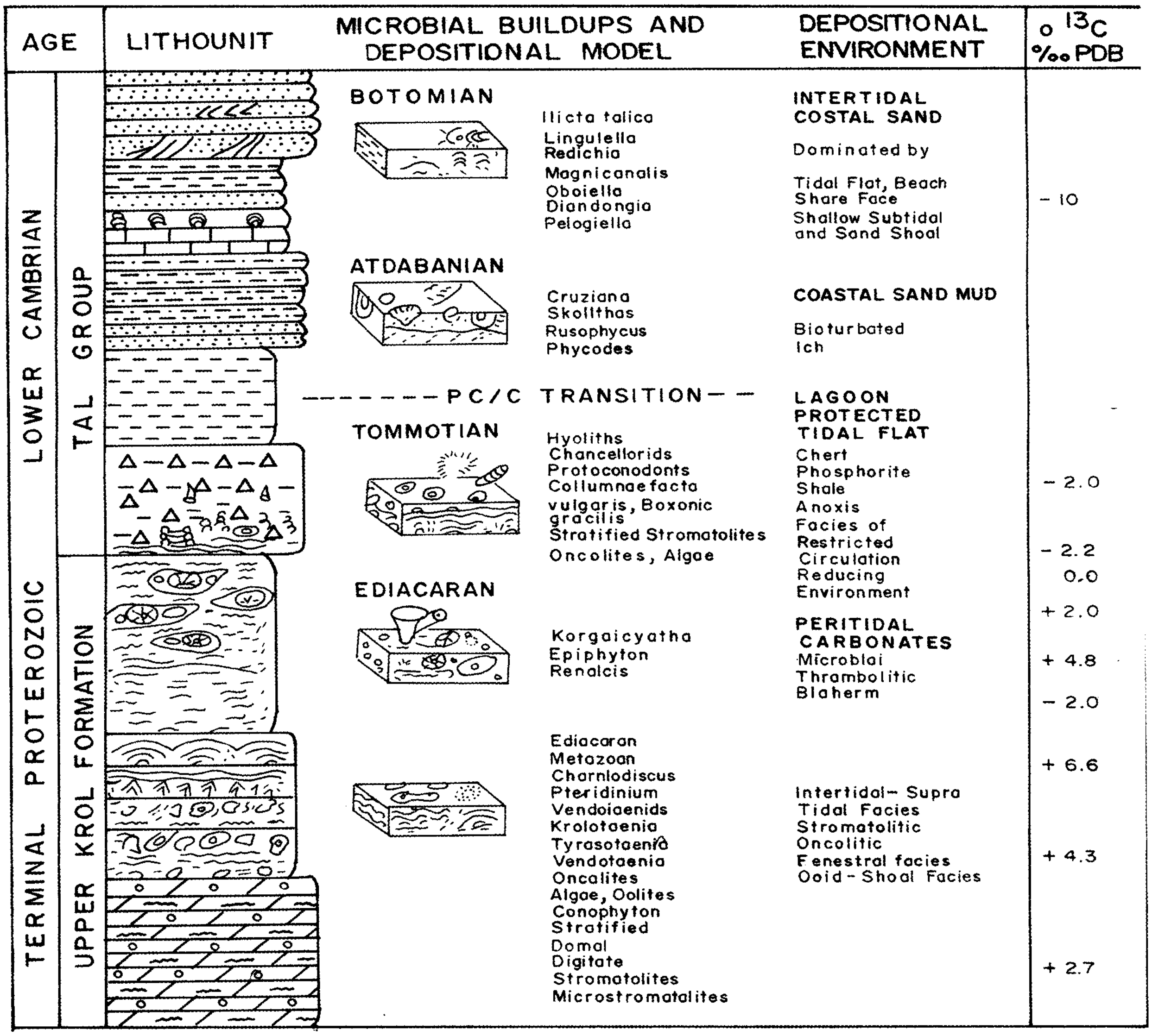

Fig.21. Ediacaran Facies Depositional Model of the Upper Krol Formation.

Table 1. 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, Stromatolites
Ediacaran	Krolian	Warm	Positive	Ediacaran, Vendotaenilids, Algae and Stromatolites
Cryogenian	Blainian	Glacial	Negative (lighter)	Acritarchs, microbialites
Riphean Early Vendian	Deobanian	Warm	Positive (heavier)	Predominantly Stromatolites, Cyanobacteria, Organic walled microfossils, Sponge spicules, Epiphyton algae

Table 2. $\delta^{13}C$, $\delta^{18}O$ and Sr-Isotope data of Krol-Tal carbonates from the Mussoorie Syncline, Uttaranchal.

Sample	Litho units	Rock Type	$\delta^{13}C‰_{PDB}$	$\delta^{18}O‰_{SMOW}$	$^{87}Sr/^{86}Sr$
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	Microbi 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

from <10 ppm in Krol to 14 ppm in Lower Tal. Tb is <5 ppm in both Krol and Lower Tal formation. Dy varies from <2 ppm to 6.5 ppm in Krol and 5 ppm to 17 ppm in Lower Tal. Ho varies from <2 ppm in Krol to 3.5 ppm in Lower Tal. Er varies from <3 ppm to 4 ppm in Krol and 4 ppm to 11 ppm in Lower Tal. Tm varies from 2 ppm in Krol Tal to 3 ppm in Lower Tal. Yb varies from <1 ppm to 3.3 ppm in Krol and 2.8 ppm to 8.6 ppm in Lower Tal. Lu is <1 ppm in both Krol and Lower Tal Formations. Y varies from 1 ppm to 30 ppm in Krol and highly increased from 28 ppm to 242 ppm in Lower Tal. Sc varies from <1 ppm to 13.7 ppm in Krol and 1 ppm to 15 ppm in Lower Tal. Th varies from <10 ppm to 25 ppm in Krol and decrease from 21 pm to <10 ppm in Lower Tal Formation (Fig.20, Tables 4, 5, 6).

The REE variation in Upper Tal stromatolitic carbonates (Lower Cambrian) is also determined. La varies from 10 to 11 ppm, Ce from 16-20 ppm, Pr <10 ppm, Na <10 ppm, Sm <10 ppm, Eu <1 ppm, Gd <10 ppm, Tb <5 ppm, Ho <2 ppm, Er <3 ppm, Tm <2 ppm, Yb <1 to2 ppm, Lu <1 ppm, Y 6.5 to 7.6 ppm, Sc 1.3 to 1.6 ppm, and Th <10 ppm (Fig.20).

In Dhanaulti-Mussoorie profile the concentration of Copper varies from 5 ppm to 50 pm in Krol Dolomite, an increase from 18-52 ppm in Lower Tal (Precambrian-Cambrian boundary) and decrease from 7-11 ppm in Lower Cambrian stromatolitic dolomite of Upper Tal Formation in Mussoorie syncline. Ni is less than 5 ppm in Krol, Highly increased from 5 to 247 ppm in Lower Tal and again less than 5 ppm is reported from Upper Tal. Pb varies from <5 to 14 ppm in Krol, 5 to 30 ppm in Lower Tal again drops to 10-12 ppm in Upper Tal. Zn is generally 6-23 ppm in Krol with a exceptionally high concentration of 270 ppm in one sample (KB_4), varies from 7-89 ppm in Lower Tal and 14-19 ppm in Upper Tal. Co is less than 5 ppm in Krol and Upper Tal but varies from 5 to 23 ppm in Krol, very high concentration of 82-628 ppm in Lower Tal and drops from 59 to 73 ppm in Upper Tal. The concentration of Ba is generally high in all the formations, it varies from 11 ppm to 239 ppm in Upper Tal. Sr varies from 24 ppm to 253 ppm in Krol, 12 ppm to 722 ppm in Lower Tal and 72-74 ppm is recorded from Upper Tal. V varies from less than 10 ppm

Table 3. 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)
GC 3	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

to126 ppm in Krol, highly increased from 39 ppm to 958 ppm in Precambrian-Cambrian transitional beds and a low concentration of 37 ppm is found in Upper Tal. Uranium varies from 12-22 ppm in Krol Dolomite, 16-103 ppm in Lower Tal, Phosphorite and 16-20 ppm in Lower Cambrian stromatolitic dolomite of Upper Tal Formation in Mussoorie. (Fig.20, Tables 4, 5, 6).

Rare earth element (REE) content of Krol-Tal carbonates show high concentration for total LREE and HREE by a factor of 2.3 to 8 for Krol E carbonates. REE patterns show negative Ce and positive Eu anomaly for all the carbonates and these anomalies are less pronounced for Krol E (Tewari, 2002b).

DISCUSSION

Carbon and oxygen isotope data of the whole-rock carbonates from pre-Ediacaran, nonglacial Meso-Neoproterozoic Deoban Group, Lesser Himalaya has been compared with the post glacial cap carbonate, Blaini and Krol peritidal carbonate ramp facies. $\delta^{13}C$ values vary from –3.7 to 6.6‰$_{PDB}$ depicting one main distinct signatures of ^{13}C maxima and minima. $\delta^{18}O$ values vary from +16.8 to 29.4‰$_{SMOW}$ and –1.3 to 12.6‰$_{PDB}$. Two distinct signatures of $\delta^{18}O$ 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

Table 4. 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

Table 5. 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 6. 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

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 $\delta^{13}C$ maxima (6.6‰$_{PDB}$) recorded in Deoban 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 $\delta^{13}C$ 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 carbonate platform. The Deoban carbonates are quite rich in microbiota (organic rich) and a negative ($\delta^{13}C$ –3.7‰$_{PDB}$) to positive $\delta^{13}C$ trend (+2‰ to 4.8‰$_{PDB}$) 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 indicate enhanced organic productivity especially in the *Chuaria cirularis* bearing black shales which have shown a very high $\delta^{13}C$ value (+6.65‰$_{PDB}$). The other published carbon isotope stratigraphy from Africa (Schidlowski et al., 1975), Siberia (Knoll et al., 1995) shows 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 support organic productivity (Tewari, 1989, 2004).The Blaini diamictites and cap carbonate isotope data strongly supports the global Marinoan glaciation followed by the deposition of the warm water Krol carbonate ramp sediments in the Lesser Himalaya. The Krol carbonates are younger than the Deoban-Gangloihat dolomites and show entirely different stromatolitic, microbial and fossil assemblages and C- isotopic signatures separated by Blaini cap carbonate throughout the Lesser Himalaya.

CONCLUSIONS

The present carbon isotope chemostratigraphy (Figs.16, 17) provides additional data from the Garhwal Syncline. A positive excursion in the upper most part of the Krol E (upto + 2.3‰$_{PDB}$) and sharp decline to -4‰$_{PDB}$ in the dolomite associated with phosphorite is quite significant. A broad positive excursion in Krol D/E Ediacaran carbonates sections of Garhwal (Figs.16&17) and Mussoorie Synclines and the gradual decline towards negative values in the Lower Tal Formation (Figs.16 &18) coincides with the global Precambrian-Cambrian boundary isotopic curve. In the Nainital Syncline also, the Chorkhet section which yields Ediacaran fossils has shown normal marine isotopic values. In the far NE Himalaya, the Buxa Dolomite can be correlated with the Krol Formation (Krolian) on the basis of carbon isotopic excursions (positive signatures, Tewari and Sial, 2007; Tewari, 2007). The Lesser Himalayan carbonate sequences of India shows the strong palaeobiological and stable isotopic evidences of rise and fall of Ediacaran (Vendian) biota for global correlation (Figs.22 & 23). The Pan Indian Neoproterozoic Blainian glaciation (Blaini diamictites) is well established in the Lesser Himalaya and correlated with Pokharan boulder beds in

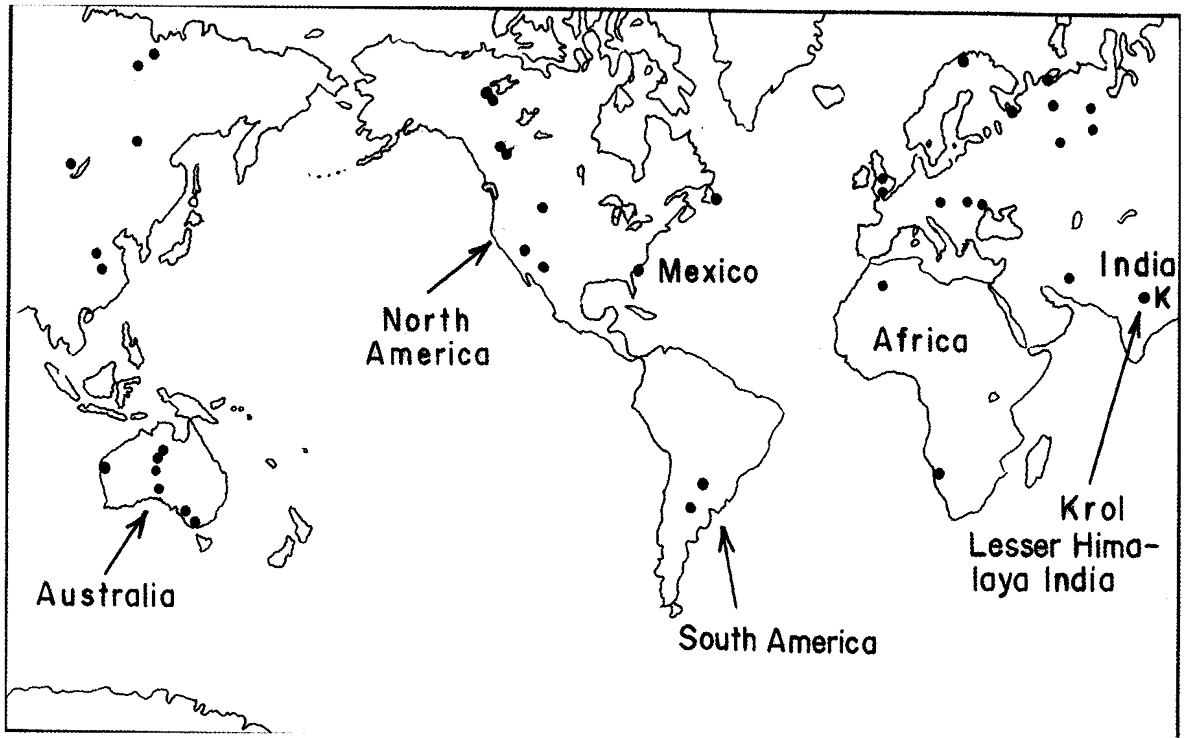

Fig.22. Global distribution of the Ediacaran fossils and the location of the Krol Formation in the Lesser Himalaya, India.

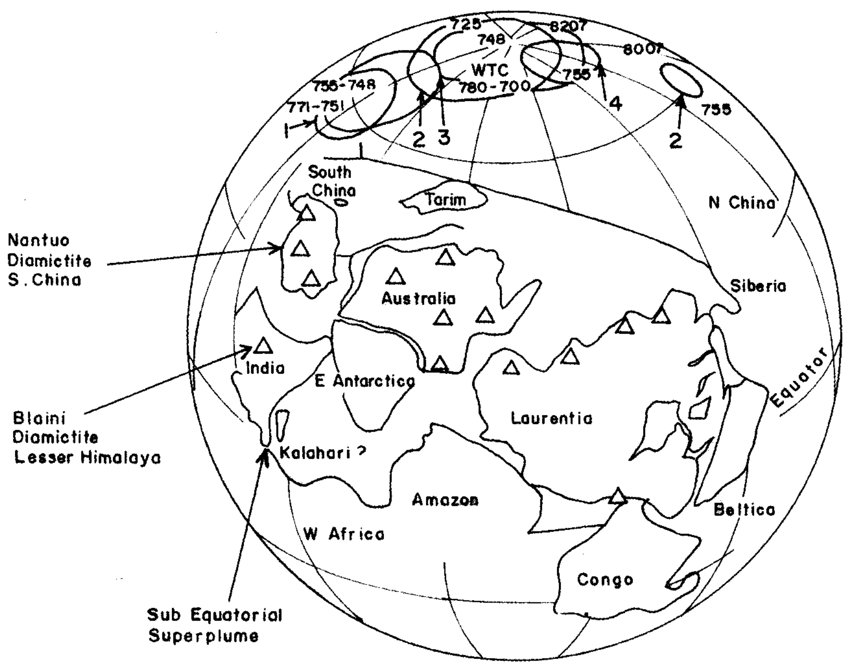

Fig.23. Paleogeographic reconstruction of the Rodinia Supercontinent ca 750 Ma, after Li et al., 2003 (Lesser Himalaya and South China were situated very close to each other.

Rajasthan, Bhimdasa and Manjir diamictites in the Jammu –Kashmir and Himachal Himalaya, Tannaki boulder bed in Hazara, Pakistan in the NW and Shergaon boulder beds in West Kameng Arunachal Lesser Himalaya, NE India (Tewari, 2001 a,b, 2003, 2007, 2008, 2009a; Kochhar, 2007). The Ediacaran-Early Cambrian period must have been a time of continental extension and rifting in the Lesser Himalaya. The Krol carbonates are deposited in the peritidal carbonate ramp- shelf depositional environment (Tewari, 2002a,b, 2008, 2009; Jiang et al., 2003). Continental extension caused breakup of the Rodinia supercontinent and the creation of shallow epicontinental seas at low paleolatitudes in which Blaini-Krol-Tal Cryogenian diamictites, Ediacaran carbonates and Tal phosphorite were deposited. The Lesser Himalayan sedimentation might have terminated due to Pan African orogeny around 500 Ma, which is strongly supported by the occurrence of granites of this age in entire Indian subcontinent.

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Sit quietly, doing nothing, spring comes, and the grass grows itself.

- Zen saying