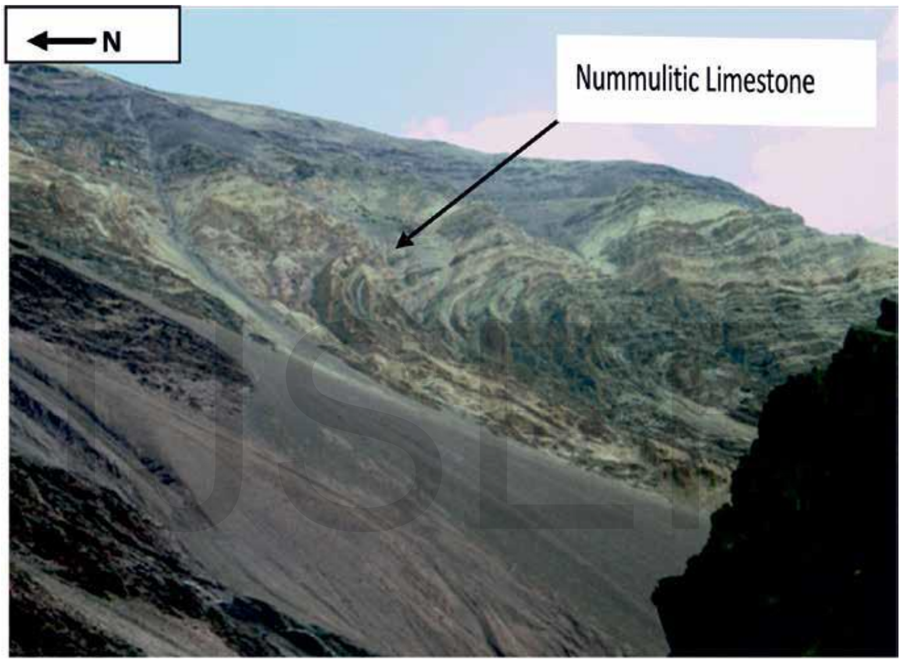
International Journal of Scientific & Engineering Research Volume 11, Issue 9, September-2020
ISSN 2229-5518

Assessing geochemical and biological characteristics of Nummulitic Limestone formation from ITSZ for paleoenvironment interpretation, hinting on the possibility of a PETM boundary

Ananyaa Deepak

Abstract-



Source: Singh IB, Parcha SK, Sahani A etal (2015); Post India-Asia collision sedimentation (Indus Basin) in Ladakh, India

The Cretaceous Eocene successions of the Indus Tsangpo Suture Zone (ITSZ) are the manifestations of the collision between Indian and Asian plate also marking the global Greenhouse warming event at the Paleocene-Eocene Boundary.

The character of global sea level change (or eustacy) during the late Paleocene and early Eocene has direct relevance to the origin of hyperthermals ,invoking a significant drop in sea level and causing substantial changes in biota and geochemistry.

The intent of this project is to prove a link between the aforesaid Paleocene Eocene Thermal Maxima (PETM) event and interpreting the paleo-environment condition using geochemical proxies and foraminiferal assemblage.

The various geochemical analyses thus conducted are suggestive of a highly oxygenated environment under the shallow marine transgressive phase of deposition. The depositional setting, biostratigraphical constrained age along with δ13C values and lower TOC suggested an intense warm period, that might be coeval with PETM event.

The study of foraminiferal assemblage in the sequence reveals initiation of ocean acidification characteristic to PETM.

Contents-

International Journal of Scientific & Engineering Research Volume 11, Issue 9, September-2020
ISSN 2229-5518

INTRODUCTION

The Asian continental margin of the Neotethys Ocean was an active Pacific type active arc-trench system until the Eocene, when it collided with India, to form the ITSZ (Indus Suture Zone, Indus Yarlo Suture Zone, Yarlung Zangbo Suture Zone). In the ITSZ, the northward drift of the Indian Plate during the Early Cretaceous led to subduction of its oceanic crust under the Asian Plate leading to creation of Indus forearc Basin.

Indus Group succession of Ladakh represents the final phase of deposition in the Indus Tsangpo Suture Zone (ITSZ), thus preserving evidence of India-Asia collision.

The Paleogene succession of the Himalayan foreland viz the Indus Sedimentary Basin Rocks (IBSR) harbors a variety of foraminifera useful in deciphering evidences for the changing depositional environments. In particular the nummulitic limestones of Paleogene Tar Formation store within it evidences of the biotic and sea level changes associated with the Paleocene-Eocene transition: marking an episode of rapid global warming 55 million years ago.

In the Ladakh region (type area – Zanskar River Gorge) this IBSR succession is divided into Tar Group (Indus Flysh) and Indus Group (Indus Molasse).

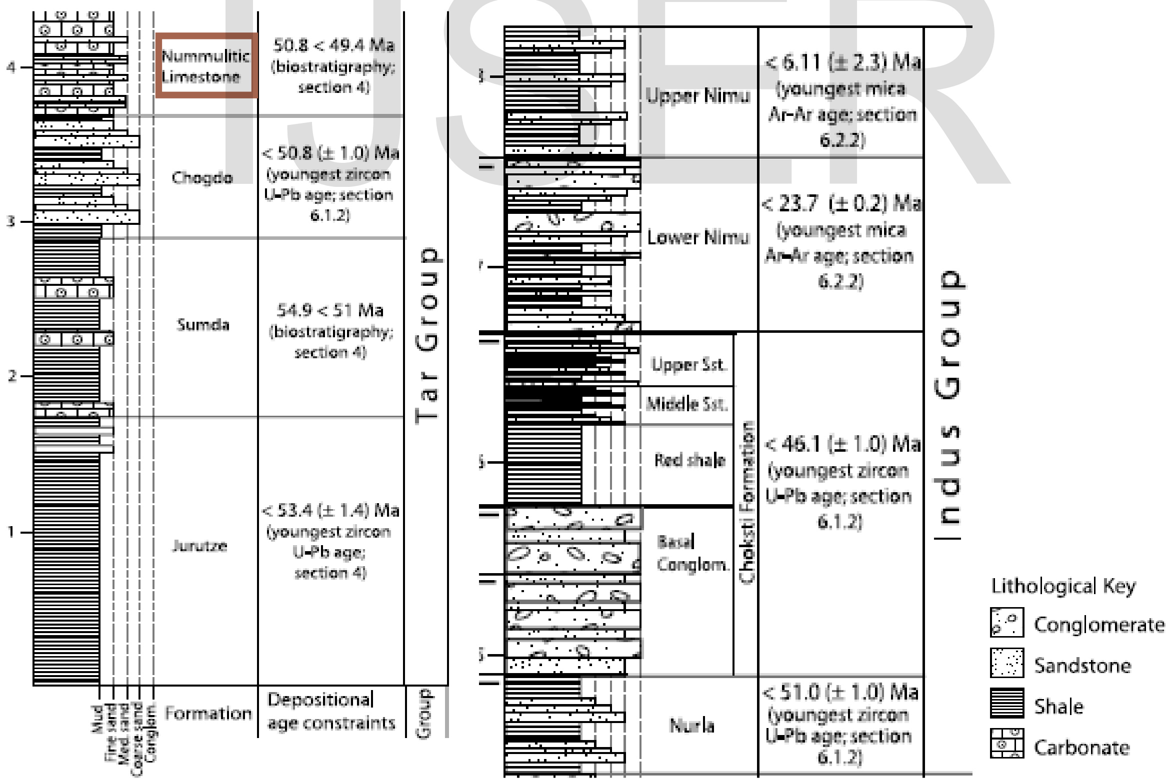


Fig.stratigraphical succession of IBSR

International Journal of Scientific & Engineering Research Volume 11, Issue 9, September-2020
ISSN 2229-5518

The late Paleocene-early Eocene (~56-51 Ma) interval was a critical phase in the history of the Indian-Asia convergence as also for the Cenozoic Climate change and biotic evolution. Among the Paleogene Successions of mighty Himalayas my study are being the Tar Group best exposed in the Zanskar Gorge section.

Nummulitic Limestones are best exposed along this region as a 180m (approx.) thick formation interbedded with *1m thick nummulitid-rich packstones* (Dunham's classification), with coarse sandstone and mudstone (2-3km thick) at its base.

** The Nummulitic Limestone units have been assigned an age of 54.9 Ma (Green et al 2008) based on the benthic nummulitid foraminifers thus lying on the boundary of the PETM event.*

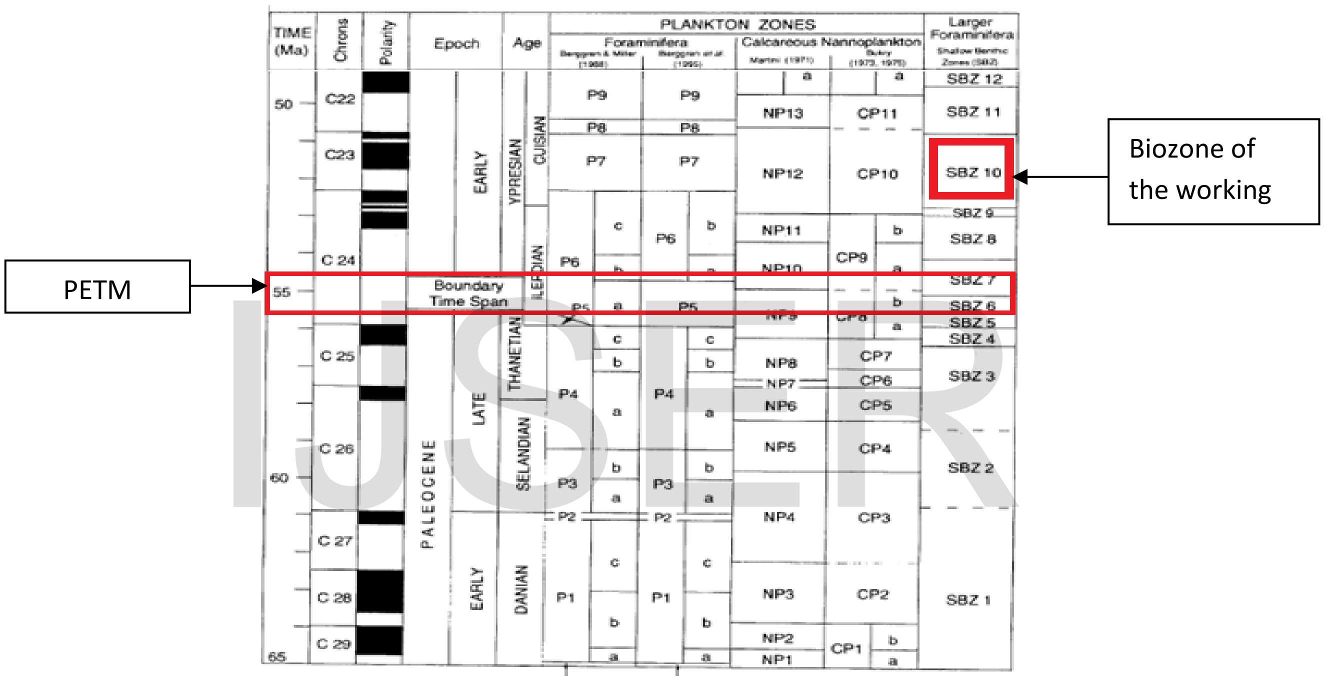


Fig. Correlation between the"SBZ" and the Paleocene Eocene time scale (Berggren et al, 1995)

The PETM is one of the best known examples of a transient climate perturbation associated with brief but intense interval of global warming thus serving as a geological analogue for modern green house driven warming. Manifestations of PETM –

1) Negative shift in bulk Carbonates
2) Lower carbonate content
3) Elevated TOC
4) Lower Si/Al ratios
5) Higher SiO2 and Al2O3

And most significant of all are the biotic changes involving extinction of benthic foraminiferids in shallow marine basins, appearance and diversification of dinoflagellates

<u>Geological setting-</u>

Gondwanaland, the archaic southern supercontinent began disintegrating during the late Jurassic and India broke away from it in the early Cretaceous to set out on a long journey northwards, which resulted in its collision with the Asian plate along the ITSZ and the closure of the Neotehys during the early Eocene. The sediments of Zanskar-Tethyan Zone were deposited at the northern margin of the Indian Plate on the continental shelf and a north facing slope of Neo Tethys (Fuschs and Willems 1990; Upadhyay and Sinha 1998).

Associated with this Indus Suture Zone is Indus sedimentary basin of Ladakh representing the final phase of deposition in the ITSZ , within this basin are classified the - Indus Basin Sedimentary Rocks (IBSR – Henderson et al, 2011) which are essentially successions of terrigenous clastic (sediments derived both from Indian and Asian Plates) and carbonate sedimentary rocks.

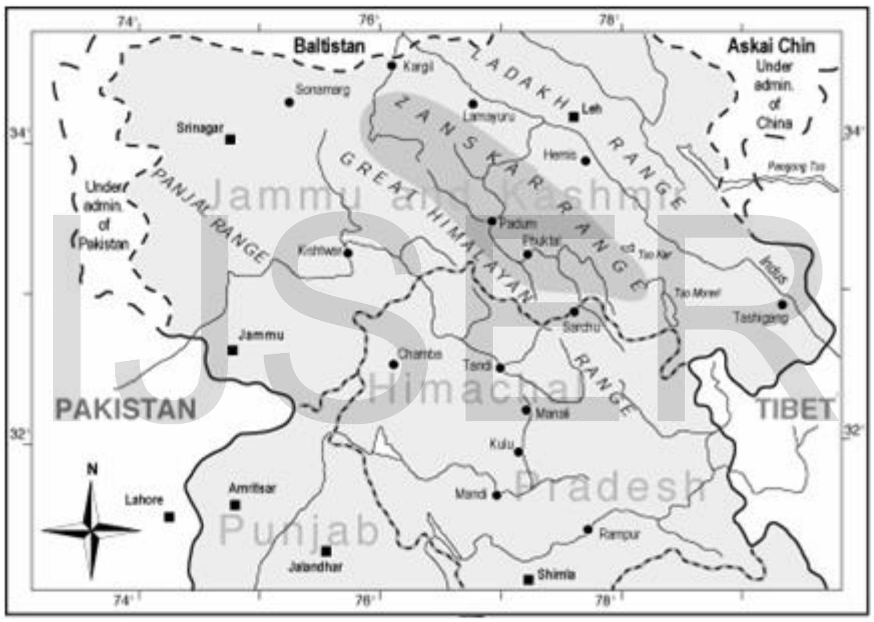


Fig.Map of Jammu and Kashmir

Zanskar Gorge section (2-4 Km south of Choksti), exposes the rock sequences extending from Zanskar range upto Ladakh Batholith. IBSR are well developed in this section exposing both Tar Group and Indus Group.

The Zanskar Range is part of the Tethys Himalaya, an approximately 100-km-wide synclinorium formed by strongly folded and imbricated, weakly metamorphosed sedimentary series. Zanskar covers an area of some 7,000 square kilometres (2,700 sq mi), at an elevation of 3,500-7,000 metres (11,500–23,000 feet).The Zaskar River flows through this range and cuts the deep and narrow Zanskar Gorge.

5

International Journal of Scientific & Engineering Research Volume 11, Issue 9, September-2020
ISSN 2229-5518

Paleocene-Eocene Thermal Maxima (~ 56 Mya)

It is a geologically brief (<20 kyr) hyperthermal period recorded around the Paleocene Eocene Boundary, marking the most significant climate transition of the Cenozoic, characterized by a 5°-8° of temperature hike and major fluctuation of the Earth systems esp. Marine settings. The cause of the initial warming has been attributed to a massive injection of carbon (CO_2 and/or CH_4) into the atmosphere; the source of this carbon has yet to be determined.

The most significant isotopic manifestation of this greenhouse climate conditions is a negative Carbon Isotope Excursion (CIE) averaging approximately −3‰ reflecting geologically rapid input of large amount of isotopically lighter CO2 and or CH4 into the exogenic (ocean-atmosphere) carbon pool i.e at the onset of CIE the ocean absorbed a large amount of Carbon-di-Oxide, reducing its pH and facilitating a sudden rise in CCD. Following the pronounced acidification of the ocean created a biological turmoil causing extinction of 30-40% of benthic foraminifera species.

The PETM provides valuable insights into the carbon cycle, climate system, and biotic responses to environmental change that are relevant to long-term future global changes, however the cause and amount of the PETM carbon emission are still unresolved. Still a few speculated reasons for this transient global warming event include –

- The emplacement of a large cluster of kimberlite pipes at ~56 Ma in the Lac de Gras region of northern Canada may have provided the carbon that triggered early warming in the form of exsolved magmatic CO_2.
- Substantial volcanism and associated continental rifting.
- Intrusions of hot magma into carbon-rich sediments may have triggered the degassing of isotopically light methane in sufficient volumes to cause global warming and the observed isotope anomaly.
- A briefly popular theory held that a ^{12}C-rich comet struck the earth and initiated the warming event.

*None of the above causes are alone sufficient to cause the carbon isotope excursion or warming observed at the PETM.

- Methane clathrates :*biogenic clathrates have a $\delta^{13}C$ signature of −60 ‰ , inorganic clathrates are −40 ‰* (**Dickens *et al*. 1995**, **1997**) also popularly known as methane hydrate trap within their crystal structure of water large amount of methane thus forming a solid similar to ice. As temperature rose, the pressure required to keep this clathrate configuration stable increased, so shallow clathrates dissociated, releasing methane gas to make its way into the atmosphere and later diffused into the surface ocean waters, which mix with the deeper ocean waters over much longer time-scales.

Geochemical and Biological Implications of PETM

6

1. Prominent negative excursion in the carbon isotope composition ($\delta^{13}C$) of carbon-bearing phases *esp in the marine realm, the PETM is characterized by negative δ13Ccar and δ13Corg excursions (*a negative shift in carbon isotope of nearly -2 ‰ for the benthic foraminifera and -4‰ for planktic foraminifera) *and shifts in δ15N to ~0‰ values above the P/E boundary and persisting along the interval suggesting a bloom and high production of atmospheric N2-fixers.*
2. Prominent (>1‰) negative excursion in the $\delta^{18}O$ of foraminifera shells
3. Decrease in carbonate contents could be due to dissolution and/or dilution by increasing detrital input and this carbonate dissolution which marks the PETM in sections from the deep sea had led to ocean acidification.
4. Period was characterized by dominantly reducing sea floor conditions as seen in the Th/U distribution (and the well developed parallel lamination in the pyrite-rich shales)
5. Diminished primary productivity is typified by negative δ 13 C TOC values.
6. Spike in Barium
7. High Ti, K and Zr and decreased Si contents at the P/E boundary indicate high weathering index (CIA), which coincides with significant kaolinite input and suggests intense chemical weathering under humid conditions at the beginning of the PETM.
8. Mineralogically, the PETM is marked by increased detrital input and kaolinite contents due to intense on-land weathering during the hot humid climate.

9. In the terrestrial realm, it led to the diversification of modern mammal species and their migration across the northern continents
10. Shallow-water benthic foraminifera were not more severely affected than deeper dwelling species. True extinction, as opposed to local extinction and/or mass mortality, is generally quite low no matter what the water depth.
11. A significant change in the foraminiferal assemblage occurs from SBZ 5/6 to SBZ 11. The SBZ 5/6 to SBZ 10 interval is characterized by (i) low diversity and dwarfed foraminifera, (ii) rectilinear benthic foraminifera, and (iii) biserial and triserial planktic foraminifera that are known to survive in areas of high runoff, upwelling or otherwise eutrophic conditions.
12. LBF Turnover involving a rapid increase in species diversity, shell size, and adult dimorphism: large benthic foraminifera such as nummulitids and alveolinids were common components of platform carbonates around paleogene especially in the tethyan realm and underwent huge diversification around the Paleocene Eocene Transition.

International Journal of Scientific & Engineering Research Volume 11, Issue 9, September-2020
ISSN 2229-5518

Material and Methods –

The rock sample of the study area was an impure limestone (with intercalated shale of marine origin) embedded with foraminifers obtained in the form of rock chunk or piece broken from the outcrop exposed at the Zanskar Gorge.

Polished Section: the sample was cut and polished using carborundum powder of 600,800 and 1000 mesh sizes to study the –

i) Characteristic minerals, matrix, and textural features
ii) Microfossil assemblages

Geochemistry:

i) Trace element: through ICPMS
ii) REE : analyzed using wet ICPMS technique
iii) Carbon Isotope: organic carbon isotope analysis was carried out using IRMS. For this and TOC analysis firstly inorganic carbonate was removed from the ground sample using 10%HCl. And the isotopic data has been reported against V-PDB.

Picture of the Polished section and Powdered sample

8

1. Reagents

All solutions were prepared using ultra-pure water (18.2 MX), which was obtained from a Milli-Q water purification system. All the Sample were digested by taking 30 mg (-300 mesh) sediment powder by using suprapure Acid (HF, HClO4, HNO3) Four solutions (10, 40, 100, 200 and 300 ppb for all elements) were prepared by 71A and 71B Multi-element Calibration Standard solutions (Inorganic Ventures) as External Calibration..

2. Digestion procedures

The two USGS standard rock powders of Green River Shale,(SGR-1b), Cody Shale(SCo-1), is used for Analysis .

(1) Approximately 30 mg rock powder was weighed in a 50 ml Teflon container.

Cleaned and Rinsed (Dried) vials were used and previously weighed 30 mg of Sample were added to these Teflon vials.

- A mixture of HF & HNO_3 was added (HF : HNO_3 being 2 : 1) along with 1 ml of Perchloric Acid in each Teflon tubes and the temperature was fixed at 120.c for 7 hours
- Then the caps of Teflon tubes were put off to vaporize the sample and to make it dry.
- In next step, 3ml of mixture (HF : HNO_3 being 1:2) and 1 ml Perchloric Acid was added.
- This arrangement was heated for 120.C for 7 hours.
- Samples were dried again
- 2 % Nitric Acid was prepared in a Volumetric Flask (100ml)
- 50 ml of 2% HNO_3 is added to this tube again for better digestion of the sample and for making Final Volume.
    - Nitric acid is used more (comparatively) in this analysis as this acid is used as the matrix for analysis in ICP-MS for the reasons previously stated.

- The digested samples were transferred to the vials for final analysis.
- Sample were repeated with good recovery in this batch that is sample No.V1 .All the data set will be below 5% error with good calibration curve.

International Journal of Scientific & Engineering Research Volume 11, Issue 9, September-2020
ISSN 2229-5518

The rock sample was crushed finely and then treated with acid in order to dissolve the inorganic carbonate.

Placed into a water bath, washed with distilled water and centrifuged 3 times.

Dried, the clumped powder was once again grinded using a mortar and pestle , weighed and filled into vials for analysis

International Journal of Scientific & Engineering Research Volume 11, Issue 9, September-2020
ISSN 2229-5518

IRMS (MAT 253): mass spectrometric methods are used to measure the relative abundance of isotopes in a given sample.

For the analysis of inorganic carbon the rock was drilled using a dental drill to yield a fine powder.

Results and Inferences-

1. Lithology

- Nummulitic Limestones are best exposed along Zanskar Gorge region as a 180m (approx.) thick formation interbedded with *1m thick nummulitid-rich limestones*, with coarse sandstone and mudstone (2-3km thick) at its base.
- The limestone units are sharp based with locally developed pebble layers; with the pebbles comprising of micritic limestone, quartz vein, schists and green mudstones and no granodiorite (i.e no contribution from the magmatic arc system).

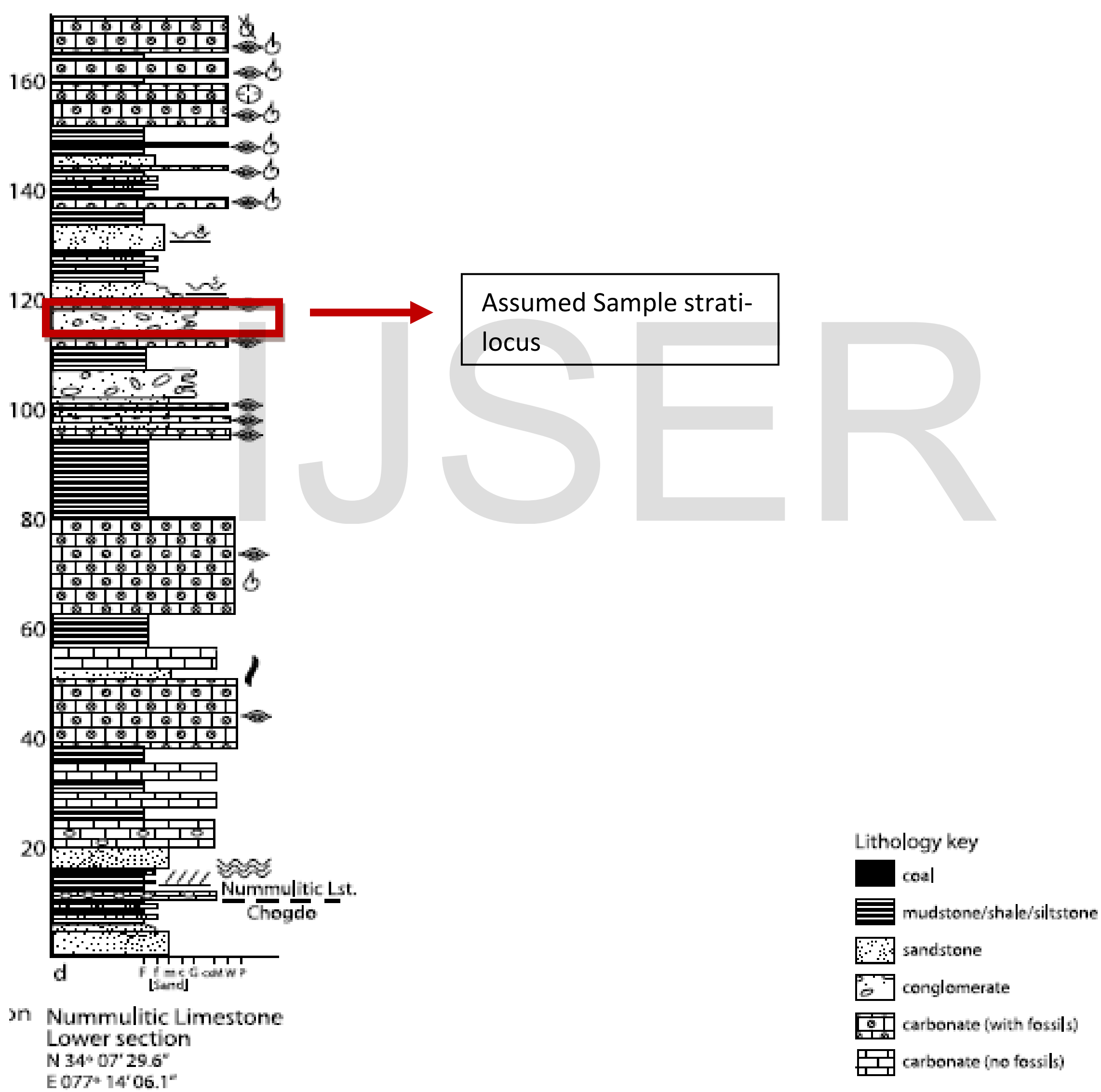


Fig . Measured Stratigraphic log of Nummulitic Limestone measured from along the Zanskar River Gorge. (Henderson et al. 2010)

International Journal of Scientific & Engineering Research Volume 11, Issue 9, September-2020
ISSN 2229-5518

Thin section study –

Folk's Scheme of Classification

A: Allochemical Components (sand sized)

Fossils : tests of carbonate secreting organism in size range 0.02cm-1cm

Oolites and Pellets : absent

Intraclast : reworked fragments

B: Orthochemical Components

Micrite › Sparite

Nomenclature : Biorudite

Dunham's Classification *(Singh IB, Parcha SK, Sahani A etal (2015); Post India-Asia collision sedimentation (Indus Basin) in Ladakh, India : Implications for the evolution of the Northern margin of Indian plate)*

Original components not bound together during deposition

Grain supported framework but contains a matrix of mud

Interpreting the litholgy –

Packstone: wave reworking but inefficient to completely remove the lime mud component.

Pebbly base: episodic storms

Interbedded sandstone: record sand rich shoals or shoreface deposits similar to the sanstone units which intercalate with the time equivalent Nummulitic Limestones of Alpine periphery (Sinclair et al. 1998).

*Thus a suggesting existence of a linearly extending Himalayan-Alpine Belt

These limestones mark the top of the Tar Group and is succeeded by terrigenous clastics of the Nurla Formation, infact these limestones are abruptly overlying the floodplain mudstones of Chogdo Formation (Searle et al.1990) and are *thus interpreted to represent a transgression into an inner, carbonate ramp setting* i.e they accumulated at approximately mean Fair weather wave base (Burchette & Wright 1992).

2. Foraminiferal Assemblage:

Nummulitic Limestones indicate a much shallow water neretic environment of deposition thus harbouring only shallow water but Large Benthic Foraminifers; including some *index taxa* of –

SBZ10: *N. bagelensis, N. atacicus, N. burdigalensis, Lockhartia conditi.*

The Nummulitic Limestone units have been assigned an age of 54.9 Ma (Green et al 2008) based on the benthic nummulitid foraminifers.

Polished Section Study – dissolution observed in larger foraminiferids

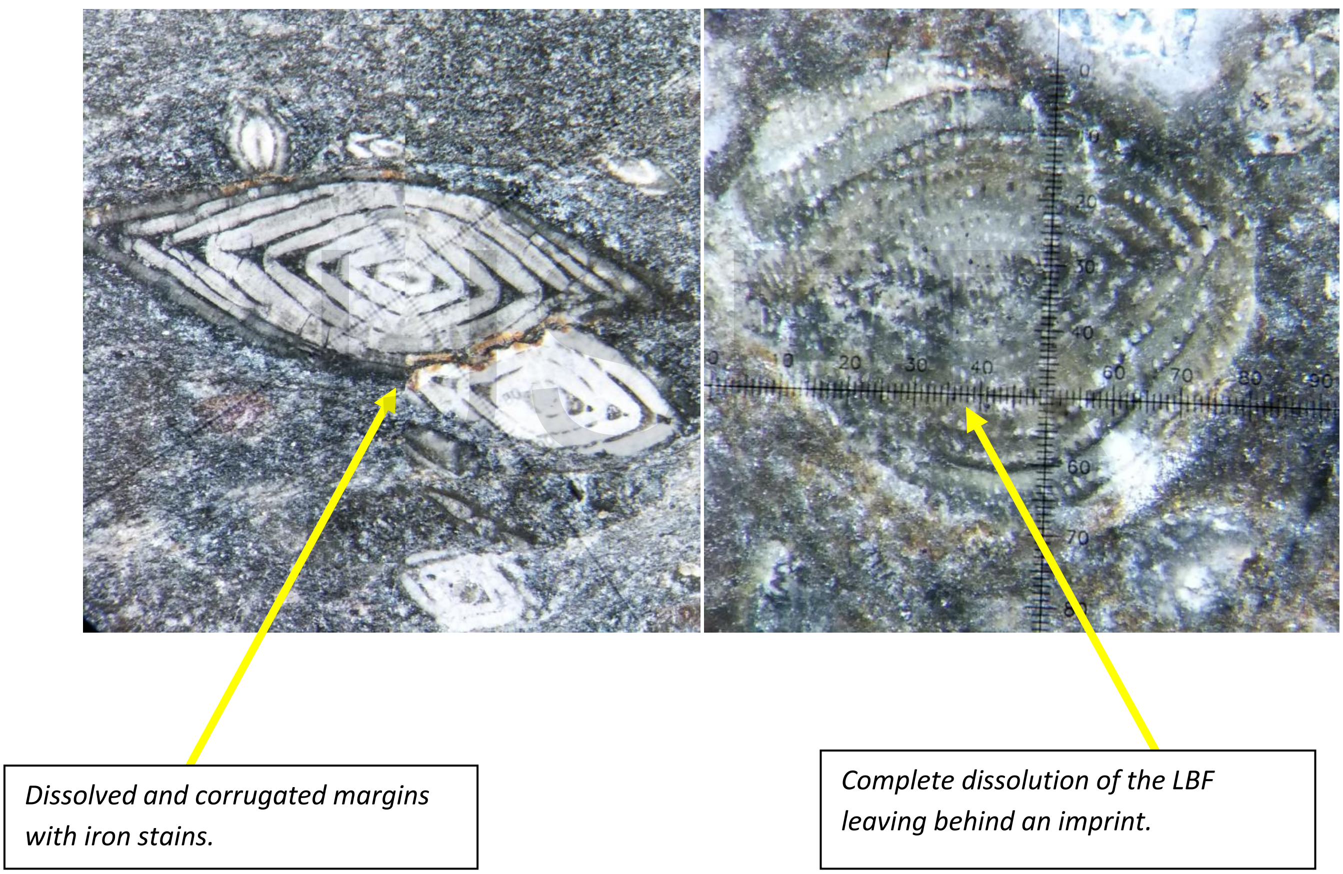


Fig. Polished section showing Nummulite sp.and Alveolina sp.

3. Organic Carbon Isotope excursion and TOC response

Carbon has two stable, naturally-occurring isotopes: ^{12}C (98.89%) and ^{13}C (1.11%). Ratios of these isotopes are reported in ‰ relative to the standard VPDB (Vienna Pee Dee Belemnite).

$$\delta = \left[\frac{\left[\frac{^{13}C}{^{12}C}\right]_{sample}}{\left[\frac{^{13}C}{^{12}C}\right]_{standard}} - 1 \right] \times 1000$$

Organisms preferentially take up light ^{12}C, Therefore, an increase in $\delta^{13}C$ in marine fossils is indicative of an increase in the abundance of vegetation as more ^{12}C is locked up in plants contrary to this a negative $\delta^{13}C$ is indicative of release of huge amount of the light isotope.

Benthic Foraminifers residing on the sea floor secrete their test in carbon isotope equilibrium with surrounding seawater.

A major carbon excursion has been noted for the studied sample of the value = - 23 ‰ and the TOC calculated is 0.19%

Inferences-

**If the values of $\delta^{13}C$ are around -25‰, the source of Carbon is considered to be land plants and if it is around - 23 ‰ the source is organic carbon (Anderson and Arthur 1983; Des Marais, 2001; Sharp, 2017)*

Here $\delta^{13}C$ values are highly depleted indicating a major warming (rise in temperature) and a reduced TOC value of < 1 indicating well oxygenated environment that sustained a rich benthic fauna that homogenized the sediments, also caused oxidation of organic matter and enhanced microbial degradation thence a lower Productivity!

It can be inferred that the extremely negative organic carbon isotopic value is due to addition of C^{12} into the atmosphere and the oceanic system thus increasing the level of CO_2 in atmosphere.

Such low TOC value can be due to increased weathering rate, erosion, runoff (Littke et al. 1991, Schutle et al. 2011). Further the oceanic acidification would have triggered dissolution of the carbonate tests resulting in the reduced productivity.

4. Redox condition (Olayinka S. Togunwa* and Wan H. Abdullah)

To reveal the paleo-redox conditions during sedimentation of the sample various indices were used –

Ni/Co

V/Cr

V/Ni

The relative proportions of **V and Ni** are controlled by the depositional environment. A V/Ni ratio greater than 3 indicates deposition in a reducing environment; V/Ni ratios ranging from 1.9 to 3 or less than 1.9 indicate deposition under sub-oxic conditions and oxic conditions respectively.

Co is usually enriched in comparison with Ni in oxic conditions. . It has been highlighted that values of **Ni/Co** ratio below 5 indicate oxic environment, whereas values above 5 suggest suboxic/dysoxic environment.

Chromium (Cr) is thought to be associated only with the detrital faction and is not directly influenced by redox conditions, and thus high **V/Cr** values (>2) are thought to indicate anoxic conditions and low V/Cr values indicative of an oxic environment.

Ni/Co	0.096773
V/Cr	1.869461
V/Ni (PAAS normalized)	1.156647

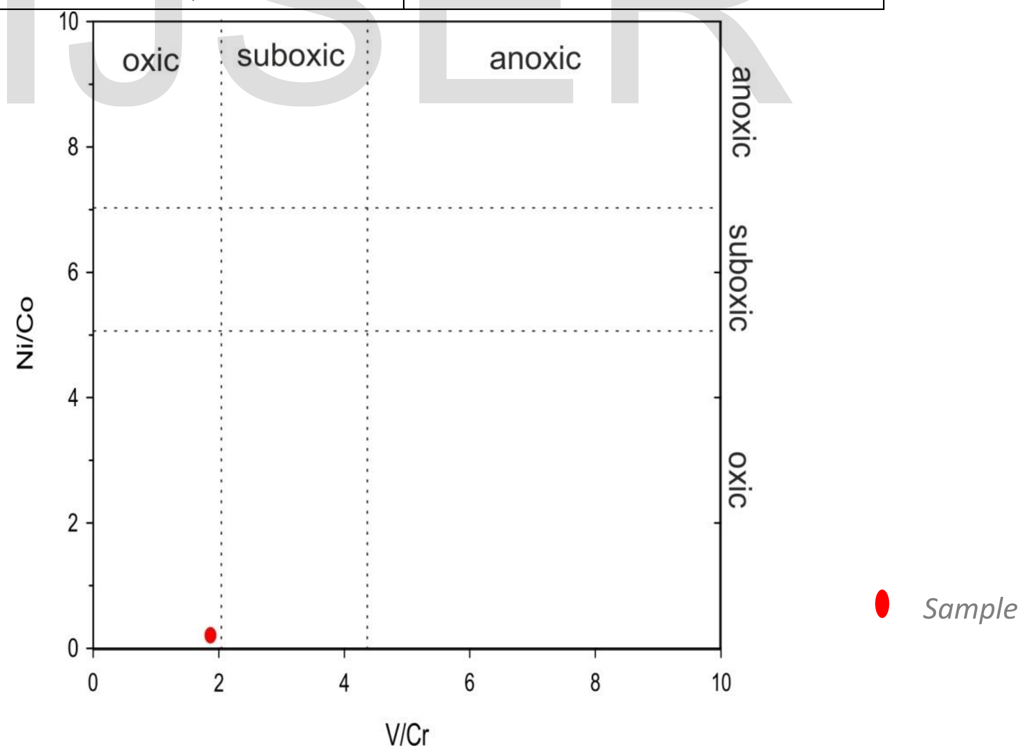


Fig.Cross-plot of Ni/Co versus V/Cr of the analyzed sample showing oxic condition of deposition

*Vanadium is very mobile in nature and is thus vulnerable to loss on weathering therefore U/Th proxy is also considered to determine the paleo-redox condition since both U and Th being relatively immobile and not easily disturbed by the secondary processes. (Jones and Manning 1994)

A U/Th ratio ≤ 0.75 indicates oxic conditions, values > 0.75 to ≤1.25 dysoxic and those > 1.25 anoxic conditions.

U/Th	0.46116

Molybdenum (Mo) can also be used as a proxy for depositional conditions. It was highlighted that Mo concentrations between 5 to 40 ppm can be used as an indicator of anoxic conditions and that less than 5 ppm indicating oxic conditions

Mo	2.813029

Iron (Fe) shows enrichment, it being insoluble in water, is in-corporated in sediments and hence shows enrichment. In general, oxidising and alkaline conditions promote the Fe precipitation, whereas acidic and reducing conditions favour the solution or dissolution of Fe compounds. Therefore, increased percentage of Fe in sample signifies oxic conditions. It is to be noted that Fe is an essential component for plant growth, and provided nutrients for plankton growth during this interval.

The magnesium (Mg) shows a little increase in concentration because it is a slow reacting element. Its reactivity in-creases with oxygen level hence increase of Mg also signifies an in-crease in oxygen level during this period.

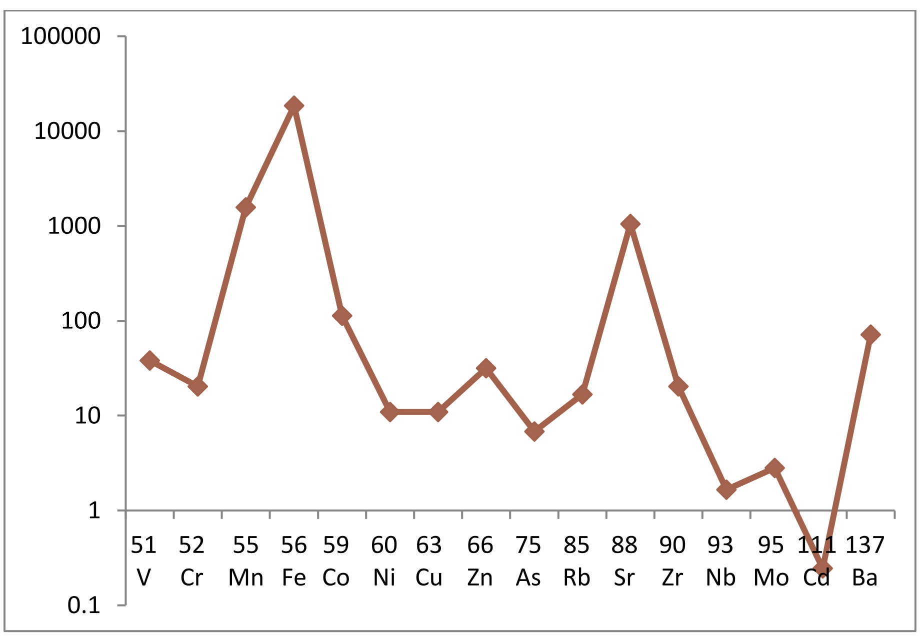
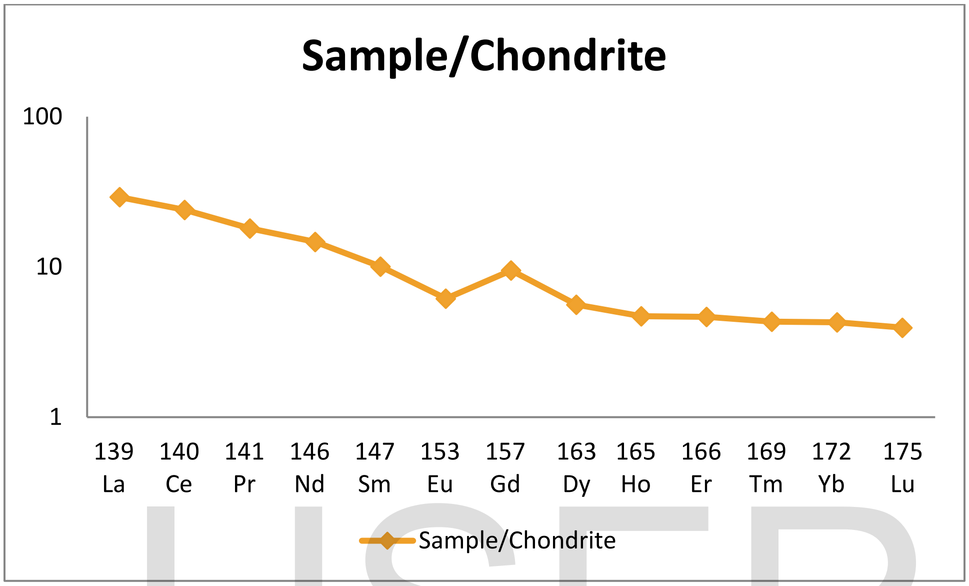


Fig.Trace element plot (ppm levels)

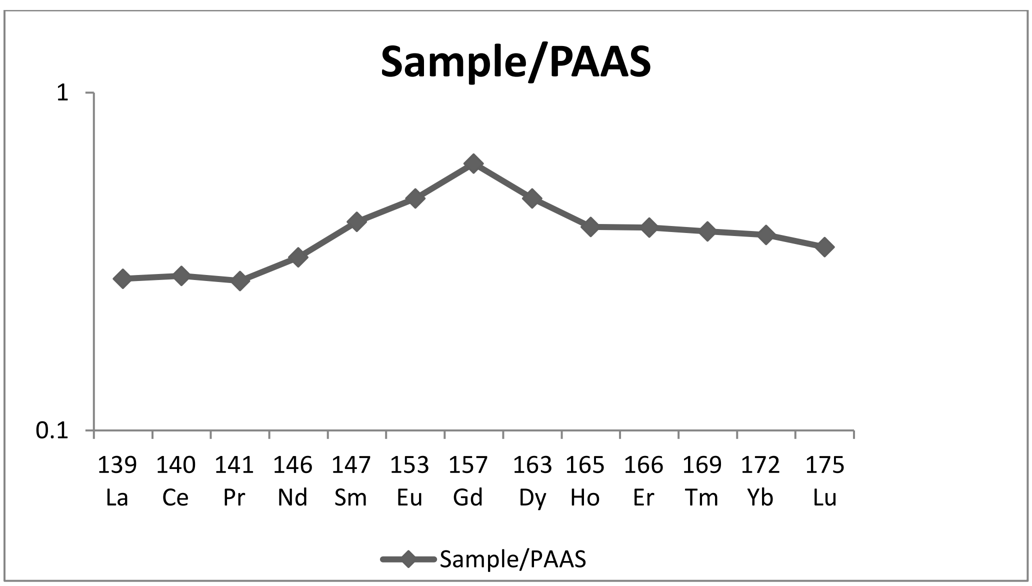
International Journal of Scientific & Engineering Research Volume 11, Issue 9, September-2020
ISSN 2229-5518

5. REE changes

REE have low residence time and low solubility in seawater (Piper, 1974a). REEs are relatively immobile during the post-depositional processes like diagenesis (Chaudhuri and Cullers, 1979) and metamorphism (Muecke et al., 1979).



The chondrite and PAAS normalized REE patterns of the sample are characterized by positive Ce anomaly. They are enriched in LREE and depleted in HREE with negative Eu anomaly.



Anomalies –

1. **Cerium Anomaly:** Ce/ [La*Pr] ½ = 1.0472
2. **Europium Anomaly:** Eu/[Sm*Nd]½ = 0.5066

Positive Ce anomaly in carbonates is considered to be indicative of Transgressive shallow marine phase and a highly oxygenated environment of deposition, probably created due to warming incidences. In oxic conditions Ce is less readily dissolved in sea water and enriched in sediments.

Subsequently a negative Eu anomaly suggests a felsic source.

Apart from a paleo-redox indicator Ce concentration is also a function of the relative proportions of a pure sea water precipitate and clastic contamination. With the Ce anomaly values approaching to 1 depicts increase in clastic contamination.

The studied sample thus suggests that the limestone was precipitated from seawater with some clastic input from the adjacent continent. This conclusion is further affirmed by the negative Eu anomaly.

Gadolinium Anomaly is also encountered which is attributed to the presence of planktons (influenced by carbonate complexation)

6. LBF Turnover

The distribution of larger benthic foraminifera (LBF) during Paleogene is known throughout the Neo-Tethys realm. The appearance of the common species of Nummulites, Assilina, and Alveolina are documented and compared from the Eastern (Sameeni et al. 2009; Ahmad 2010), Central (Sengor 1984; Bellen et al. 1959; Rahaghi 1980; Kalantari 1981; White 1994; Racey 1995 ; Karim and Baziany 2007), and Western Neo-Tethys (Höttinger 1971; Schaub 1966, 1973, 1981; Serra-Kiel et al. 1998).

The larger-foraminifera turnover (LFT) during the Paleocene-Eocene transition constitutes an important step in Paleogene larger-foraminifera evolution, involving a rapid increase in species diversity, shell size, and adult dimorphism.

However the occurrence of the Larger Foraminifera Turnover (LFT) was probably not synchronous in the entire Neo-Tethyan Ocean.

No evident biotic turnover of shallow benthic foraminiferal communities has been noticed in the studied limestone succession; rather it has been found that due to ocean acidification post PETM much of the benthic foraminids have ceased to exist, following proliferation of planktonic species in the succeeding formations (molassic deposits of Indus Group).

Conclusion Drawn-

- Positive Ce anomaly and low TOC indicates highly oxygenated depositional environment for the Nummulitic Limestone Formation
- Chondrite normalized REE pattern indicates a felsic source and fluvial influence.
- The positive Ce anomaly proved transgression and a high negative carbon isotope excursion suggest the deposition event being coeval with Paleocene-Eocene Thermal Maxima event
- CIE values also suggestive of a warming event which led to ocean acidification and shell dissolution of many major LBF.

References-

Singh IB, Parcha SK, Sahani A etal (2015); Post India-Asia collision sedimentation (Indus Basin) in Ladakh, India : Implications for the evolution of the Northern margin of Indian plate

Shukla, M. K., & Sharma, A. (2018). Carbon isotope and REE characteristics of the Paleocene–Eocene shallow marine Subathu formation from the NW Himalaya (India) and their paleo-environmental implications. Geochemistry, 78(3), 314-322

Gupta, S., & Kumar, K. (2019). Precursors of the Paleocene–Eocene Thermal Maximum (PETM) in the Subathu Group, NW sub-Himalaya, India. Journal of Asian Earth Sciences, 169, 21-46

Zachos, J. C., Bohaty, S. M., John, C. M., Mccarren, H., Kelly, D. C., & Nielsen, T. (2007). The Palaeocene–Eocene carbon isotope excursion: Constraints from individual shell planktonic foraminifer records. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1856)

Carozza, D. A., Mysak, L. A., & Schmidt, G. A. (2011). Methane and environmental change during the Paleocene-Eocene thermal maximum (PETM): Modeling the PETM onset as a two-stage event. Geophysical Research Letters, 38(5)

Mcinerney, F. A., & Wing, S. L. (2011). The Paleocene-Eocene Thermal Maximum: A Perturbation of Carbon Cycle, Climate, and Biosphere with Implications for the Future. Annual Review of Earth and Planetary Sciences, 39(1), 489-516

Kishor Kumar (2009). Larger foraminiferal biostratigraphy of lower Paleogene successions of Zanskar Tethyan and Indus-Tsangpo Suture Zones, Ladakh, India in the light of additional data. *Himalayan Geology,* Vol. 30 (1), 2009, pp.45-68