

started reaching this location from the northeast direction as expected, from 11 October at 03:00 UTC onwards. This is clear from Figure 5c. The location of the eye of the cyclone at this time was 11.85°N, 88.56°E (nearly 530 km away from BD14). Later, the wave height reached a maximum of 3.96 m on 12 October at 0900 UTC, when the cyclone reached near Gopalpur, due to the combined effect of Southern Ocean swells and cyclone-generated swells. As expected, the wave heights at BD08 were much higher than at BD11, as it was on the right side of the cyclone track.

Figure 6d shows a comparison of measured and forecast wave heights at the Gopalpur location. Error in the forecast wave height at this location was only 14%, which reveals the reliability of the wave forecast system at ESSO-INCOIS. A high degree of correlation of 0.98 between the measured and forecast H_s was obtained at this location. The bias was negligible at this near-shore location, similar to the deep-sea buoys.

In conclusion, the evaluation once again proves that the OSF system at ESSO-INCOIS is fully poised to warn the coastal communities and offshore industries along the entire Indian coastline well in advance. The present study also suggests that the presence of Southern Ocean swells during cyclone events may enhance the complexity of the wave fields.

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Occurrence of native gold and gold–silver alloy in the olivine gabbro of layered cumulate sequence of Naga Hills ophiolite, India

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Occurrence of native gold and gold–silver alloy formed in high-temperature olivine gabbro of a layered cumulate body is reported 2 km northwest of Sutsu. It lies close to a major fault in the central part of Late Cretaceous–Eocene Naga Hills ophiolite (NHO). The amphibole-bearing olivine gabbro is composed of serpentine (MgO-28.91), anorthite (An_{93}), clinopyroxene ($En_{46}Fs_8Wo_{46}$), edenite (Mg# 76), magnesiohornblende (Mg# 78), accessory minerals, viz., chlorite (Mg# 75), epidote, sulphides (chalcopyrite and millerite) and gold. The formation of noble metals in olivine gabbro is related to partitioning of Au into intercumulus sulphides and silicates in magma and their deposition along grain boundaries and fractures. It was carried out by hydrothermal fluids by transportation and concentration of immiscible sulphide phases, and depositing these in suitable locales during final stages of crystallization. Gold mineralization in layered gabbros of cumulate bodies opens a new avenue towards primary source of precious metals in NHO. Alternative secondary source of precious metals in NHO, e.g. (i) basal conglomerate of cover sediments derived from ophiolite (Jopi or Pokhphur Formation), and (ii) placers of arterial Tizu River in Nagaland, may be considered as favourable repository.

Keywords: Anorthite, gold–silver alloy, layered olivine gabbro, ophiolite, native gold.

LATE Cretaceous mafic and ultramafic rocks are known to occur as dismembered ophiolite bodies of varied dimensions along the Trans-Himalayan and the Indo-Myanmar Ranges (IMR). They demarcate the northwestern, northern and eastern margins of the Indian plate¹, along which the Indian plate is subducting under the Eurasian plate since Late Cretaceous². These mafic–ultramafic rocks once constituted a part of the ocean floor of Tethyan Sea (Upper Jurassic)^{3,4}, and were preserved as accretionary wedge or prism on continental margin. Exhumation of such ancient oceanic crust at the eastern Indian plate margin along the hill ranges of Nagaland and Manipur, bordering Myanmar is known as the Naga Hills ophiolite (NHO)¹. The northern and southern edges of the ophiolite belt extend into Myanmar. The NHO is characterized by the presence of ophiolitic melange, olistostrome,

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S-C mylonites, and high-pressure assemblages of glaucophane schists and group-C barroisite eclogite at the western tectonic contact with Disang Flysch¹. Such exotic rock associations are attributed to subduction of the eastern Indian plate against the Burmese microplate.

Ophiolite is a source of a variety of strategic and precious metals like chromium, copper, iron, nickel, cobalt, silver, gold and platinum, as well as non-metallic minerals like talc, asbestos, magnesite and semi-precious gemstones, viz., peridot (olivine), jade (sodic pyroxene) and rodingite (a metasomatic rock). The NHO is known for the occurrence of podiform chromitites and stratiform nickeliferous magnetite in association with cumulate peridotites and serpentinites. The chromitites are host for traces of platinum group elements (PGE) and gold⁵. Although gold is reported previously from placer of Nignthi (Chindwin) River in Manipur⁶, its source remains unknown. Occurrence of primary native gold and gold-silver alloy in layered olivine gabbro of cumulate magmatic sequence of upper mantle has been brought to light in this preliminary study based upon limited EPMA data of silicates and WDS data of ore minerals. Its potential repository on weathering of parent rocks has been discussed for future study.

The Upper Cretaceous–Eocene ophiolite of Naga Hills in the eastern Indian plate margin has drawn attention of geologists in recent years, not only for its tectono-magmatic evolution, but also for its prospect of economic minerals. Inaccessible nature of the terrain, lack of infrastructure and melange-type dismembered ophiolite sheets are major constraints for systematic study and exploitation of even proven prospects. Geologically, the NHO constitutes the northernmost part of the Cenozoic orogenic belt of the IMR. It is bounded in the east by Central Lowland of Myanmar⁷ and in the west by overthrust Tertiary sediments called the ‘Belt of Schuppen’^{8,9}. The orogenic belt extends northward into the eastern syntaxial bend of the Himalaya and southward into the Andaman–Nicobar–Sunda arc system of Southeast Asia.

The NNE–SSW to NE–SE-trending NHO represents 200 km long, narrow, dismembered, steeply inclined imbricated sheets of 2–15 km wide belt, covering an area of about 1200 sq. km within the Indian territory. The NHO is sandwiched between the Upper Cretaceous–Eocene Disang Flysch in the west and accretionary wedge of low-to-medium-grade metamorphics of Nimi Formation¹⁰/Naga Metamorphic¹¹ (Figure 1) of Mesozoic age¹² in the east. These are unconformably overlain by ophiolite-derived sediments as a canopy called Jopi Formation¹⁰, comprising of a sequence of conglomerate, grit, greywacke and polymictic tuff breccia from base upward. The conglomerate contains eroded fragments and unsorted boulders and pebbles of slate, phyllite, peridotite, serpentinite, gabbro, basalt, chert, jasper, greywacke and quartz of bedrocks. The sediments trend NE with low-to-moderate dips and form a broad synclinal core in the

central part of the ophiolite belt¹⁰ (Figure 1). Several cycles of conglomerate–pebble–sandstone–tuff alternations of eroded ophiolite crust are encountered in the shallow basin developed in paralic conditions characterized by presence of invertebrate fossils (gastropods), leaf impression of angiosperms and micro-fossils, and is considered homotaxial with the Barail Group (brackish lagoonal, Upper Eocene–Miocene)¹³ of Assam–Arakan basin.

A complete lithology of alpine ophiolite *sensu stricto* is exposed in NHO, and is represented by peridotite tectonite/serpentinite (also called meta-peridotite with preferred orientation of olivine), layered cumulates (peridotite–olivine gabbro, olivine–hornblende gabbro–norite intersected by pyroxenite, anorthosite and plagiogranite veins), massive isotropic gabbro, minor dolerite, mafic volcanics (olivine basalt, porphyritic basalt, trachy basalt, hyaloclastite, crater facies lava and spilite) and volcanoclastics including ignimbrite of rhyolitic composition^{1,10,14–16}. These are associated with very-low to low-grade metamorphites, belonging to zeolite, chlorite–prehnite and greenschist facies of ocean-floor metamorphism, and high-pressure assemblages of glaucophane schists and barroisite eclogite^{15–18} formed in a subduction zone environment. The rocks have undergone polyphase deformation and metamorphism on exhumation^{19–21}. The pelagic sediments of pelitic–psammitic–calcareous

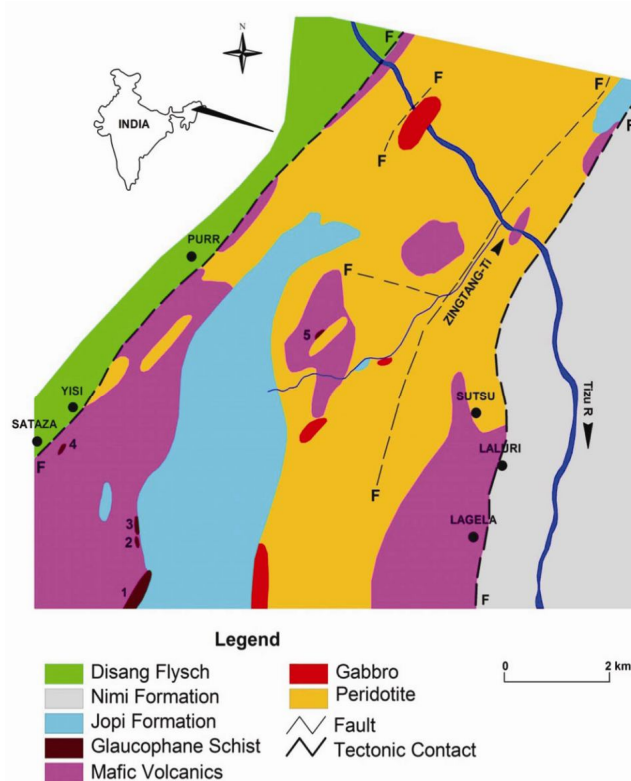


Figure 1. Modified geological map¹⁰ showing occurrence of gabbro and blueschists (numbered 1–5) in Phek district (central part) of the Naga Hills ophiolite. Gold is reported from layered cumulate sequence of olivine gabbro at Zintang-ti rivulet, a tributary of Tizu River.

composition, tuffs and radiolarian cherts are likewise subjected to multiphase deformations and low-grade metamorphism¹.

The mafic cumulates are primarily gabbroid complexes which may be grouped into (i) low-level gabbros displaying layering, and (ii) high-level massive and isotropic gabbros with rare banding. Small, detached lenses or larger bodies of gabbros are encountered between Tizu River gorge in the north to ENE of Zipu and west of Lacham Lake in the central part of ophiolite belt (Figure 1). The cumulate sequences are cross-cut by veins of pyroxenite and plagiogranite. The gabbros occurring in the northern part of the ophiolite belt (e.g. Pang and at cross-sections of Mukoge, Kuboke and Pathe rivulets) show crude layering with peridotite at the base¹⁹. Absence of such features is notable in those occurring far south in Manipur²². The largest body of layered gabbro (dimension 3.0 km in length, 2.5 km in width and 300 m in thickness; Figure 1) is noted east of Moki, is overlain by ophiolite-derived sediments (Jopi Formation). The layered gabbros show progressive fractionation of minerals, giving rise to olivine gabbro, serpentine-bearing hornblende gabbro, norite, gabbro-norite, gabbro and hornblende gabbro¹ on slow cooling. These are characterized by rhythmic, cryptic and cyclic layers^{10,14}, suggesting crystallization in an open system.

In a well-preserved section at Zintang-ti rivulet (Figure 1), cumulate layers of ultramafic and gabbro contain high-temperature minerals formed by cumulus process, possibly at the base of magma chamber (MORB) characterized by the presence of anorthite in olivine gabbro. The basal section of this body comprises harzburgite with occasional lenses of plagiogranite. It grades upward into olivine websterite, olivine clinopyroxenite, websterite and finally olivine gabbro, displaying variable thickness and granularity¹⁰. The upper part of this cumulate sequence is dominated by anorthosite and diorite. The olivine gabbro contains serpentine (after olivine), anorthite (An₉₃), clinopyroxene (En₄₇) and amphiboles, with minor amounts of chlorite, epidote, sulphides and native gold (Tables 1 and 2).

Electron microprobe analysis was carried out at PPOD Division, Geological Survey of India, Bangalore using CAMECA SX-100 by quantitative wavelength-dispersive X-ray spectrometry (WDS). Peak sight software was used for processing the data. The analytical conditions were 15 kV accelerating voltage and 15 nA current with 0.5–1 µm static beam for silicates and oxides, and PM beam current of 20 nA, accelerating voltage of 20 kV with a static beam diameter set to 1 µm for sulphides. The K α signals/emissions were used for Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K and Cr. La emissions were used for Ru, Rh, Pd, Ir, Pt and Au. Lb emissions were used for Ag and Os. Counting time was 10 sec for silicates and oxides, 20 sec for sulphides and precious metals for both peak and background. Natural standards were

used for all elements, except Ti, Cr, Al and 100% metal standards for Ni, Cu, Au, Co, Ag and PGE. Matrix correction was based on PAP. The accuracy of each element was within $\pm 0.5\%$. EPMA analyses were carried out on thin sections of rock samples directly. This allowed preservation of very fine gold particles for investigation. This is reflected in the analysis of some grains due to uneven exposure of the micro-surface.

Limited EPMA data available from the cumulate sequence indicate a progressive decrease in forsterite content of olivine with increase in fractionation¹ from harzburgite (Fo₈₉), lherzolite (Fo₈₅), olivine websterite (Fo₈₄) to olivine gabbro (serpentine with MgO–28.91, FeO^t–3.64; Table 1). Similarly, Cr# values (Cr# = 100Cr/Cr + Al) of chrome spinels in the ultramafic cumulates follow a decreasing trend between harzburgite (47) and lherzolite (39).

It is observed that the meta-peridotites or tectonites contain higher Cr# 80 and Fo₉₃ contents in chrome spinel and olivine respectively (Table 1), compared to the cumulate peridotites (Cr# 39–47, Fo_{89–84}). Such chemical differences may be taken as useful criteria to distinguish the two modes of peridotite generated in different sections of upper mantle.

En contents of clinopyroxenes apparently remain uniform during fractionation between early fractionated harzburgite (En₄₉) and late formed olivine websterite (En₄₈) and olivine gabbro (En₄₇; Table 1). Such behaviour of clinopyroxene is related to mixing of newly formed melt with the host magma, allowing equilibration in open system. However, a subtle change in chemical composition is noted in En : Wo : Fs ratios (Table 1). This is reflected in the calcium contents of plagioclase between olivine gabbro (An₉₃) and anorthosite (An₈₆; Table 1) – late fractionation of plagioclase saturated melt.

The amphiboles derived after pyroxenes are magnesio-hornblende in the lherzolite, olivine gabbro and anorthosite. The olivine gabbro in addition contains edenite (Mg#76), and minor contents of epidote (CaO–19.55, FeO^t–0.19 wt%), sulphides (viz. chalcopyrite and millerite NiS), and native gold (Table 2). A critical assessment of sulphides and gold is made in the following section.

Gold (Au), known as a noble metal, generally occurs with some silver (Ag) and often contains small amounts of copper (Cu), bismuth (Bi), platinum (Pt), arsenic (As) and mercury (Hg)²³. It is a siderophile element and primarily sub-crustal in origin, but in the crustal rocks it is largely associated with post-magmatic products and placers²⁴. Several grains of gold have been noted only in olivine gabbro (sample 155/80) from a layered cumulate magmatic body in Phek district, Nagaland. Gold is associated as intercumulus grains with primary and secondary silicates, and base metal sulphides of chalcopyrite and millerite (NiS; Figure 2a). Though olivine websterite (160/80) from the same body (Table 1) contains sulphides (viz. chalcopyrite and pyrrhotite), it is devoid of gold.

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Table 1. Mineralogical composition of mafic and ultramafic cumulates of Naga Hills ophiolite (wt%)¹

Mineral	Dunite tectonite	Harzburgite cumulate	Lherzolite cumulate	Olivine websterite	Olivine gabbro	Anorthosite
Sample no.	100/79	K-14	131/80	160/890	155/80	T-74
Mg# (olivine)	93.1	89.4	84.6	78	74.5 (chlorite)	
Pyroxene						
En	91.9	48.8	83.1	47.5	46.5	
Fs	7	4.4	15.1	6.5	8	
Wo	1.1	46.9	1.8	46	45.5	
Cr# (chrome spinel)	80.4	47.1	38.9			
Mg# (magnesiohornblende)			85.9		77.8	80.1
Mg# (edenite)					76.1	
An (plagioclase)					93.2	86.1

EPMA data source: table 5.2, Ghose *et al.*¹.

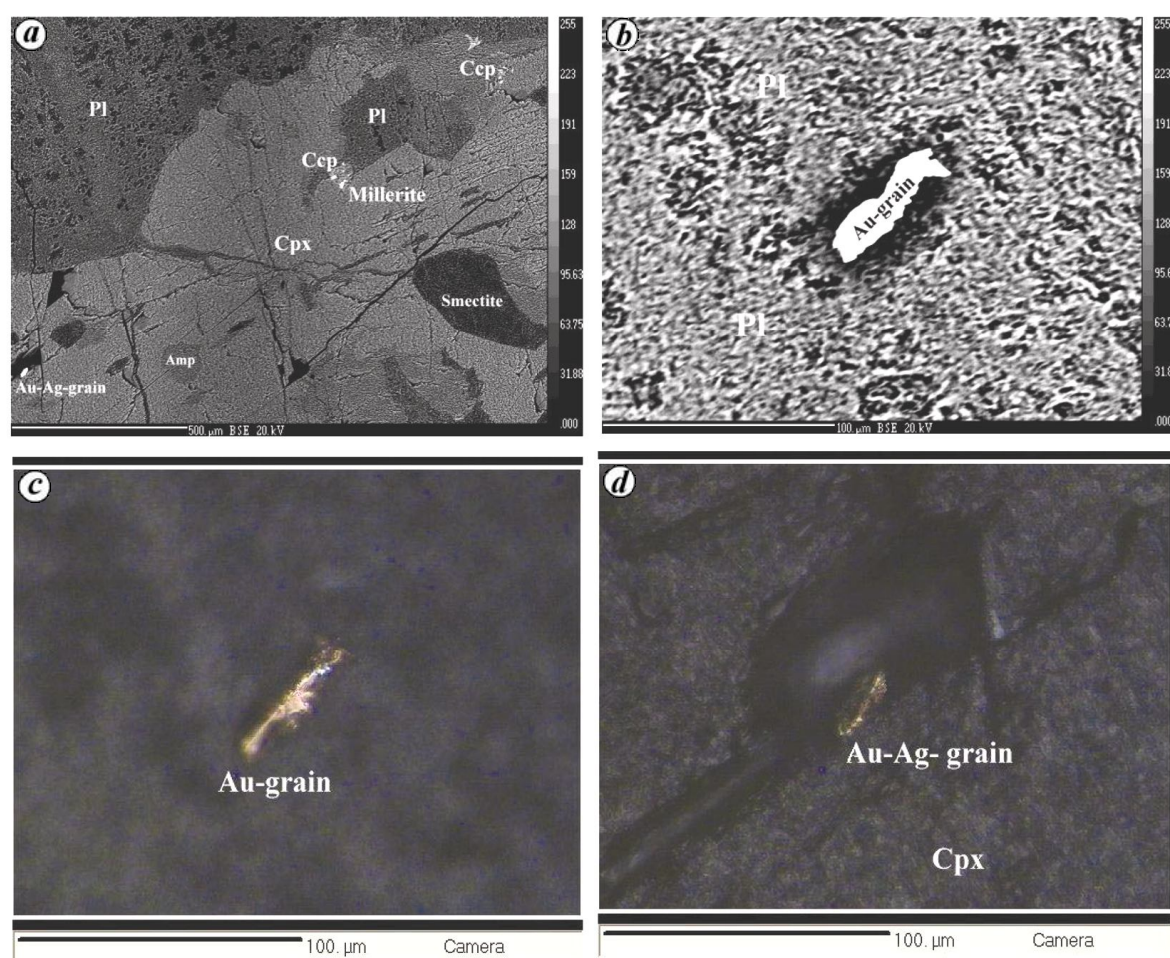


Figure 2. Backscattered electron images of gold grains, sulphides and silicates in olivine gabbro (155/80). *a*, Poikilitic clinopyroxene contains plagioclase, amphibole, gold–silver alloy and sulphide (chalcopyrite and millerite) grains. *b*, Grain of gold occurring in plagioclase, dark shadow around gold is due to uneven polished surface. *c*, An alloy of gold and silver. *d*, Gold–silver alloy along a fracture in clinopyroxene. Pl, Plagioclase; Cpx, Clinopyroxene; Ccp, Chalcopyrite; Au, Gold; Ag, Silver.

Although gold deposits are uncommon in ophiolites, the Upper Cretaceous gold deposit of Zod ophiolite in Small Caucasus is associated with quartz–chalcedony–carbonate veins and stringers, consisting of abundant sulphides and other ore minerals in a shear zone, cutting

across peridotite and gabbro²⁴. Elsewhere, in the Upper Palaeozoic late granitoid plutons in Urals, concentration of gold is noted in Andean-type continental margin, derived from multi-stage partial melting of mantle-derived hornblende gabbro by hydrothermal mineralization²⁵.

Gold and platinum mineralization is dominant in gabbro in the lower part of layered cumulate series of Early Tertiary Kap Edvard Holm complex²⁶. Deposition of the mineralized layer is associated with plagioclase-rich primitive magma which is mixed with evolved magma. This resulted in partitioning of Au into sulphides to develop mineralized layer and subsequently anorthosite layer.

Gold and platinum (PGE) minerals are concentrated in an ultramafic body of the Kruise Fjord gabbro, East Greenland in a narrow zone along the intrusive contact²⁷. The mineralization is associated with pegmatoidal bodies, chromite and sulphide minerals. It is advocated that sub-solidus hydrothermal alteration effectively controlled recrystallization and remobilization of precious metals.

Grains of both native gold and gold–silver alloy, measuring up to 5–20 µm have been detected in olivine gabbro (Figure 2). Unmixed fraction of gold indicates higher value close to native gold. WDS and energy dispersive X-ray spectrometer analyses of gold and sulphides are presented in Table 2 and Figure 2. Gold is associated with chalcopyrite and millerite (Figure 2a). Millerite is a product of incipient weathering of Ni-rich sulphides usually formed at low temperatures²³. The formation of gold in olivine gabbro is due to partitioning of Au into intercumulus sulphides and silicates in magma. Its subsequent deposition along grain boundaries and fractures was carried out by hydrothermal fluids (Figure 2a and d). Presence of millerite, a low-temperature nickel sulphide is a product of hydrothermal fluid of magmatic origin and supports the above contention. Gold mineralization in layered gabbro opens a new avenue for search of primary gold in NHO.

Gold is freed from the associated magmatic minerals in rocks due to weathering or mechanical disintegration and forms secondary concentrations as placer. Concentration of precious metals in the overlying post-ophiolite cover

sediments (Jopi/Phokphur Formation) as a repository of secondary gold, especially in the basal conglomerate is of great significance in this context. Boulders of gabbro in conglomerate, favour ideal repository of noble metals as a result of disintegration of the former. Faulted nature of the contact between the layered gabbro and the cover sediments in the northern (viz., Mukoge rivulet)¹⁹ and central (Moki)¹⁰ parts of the ophiolite belt are favourable sites for exploration and prospecting of noble metals. Similarly, search for placer deposits in the Tizu River and its tributaries flowing across the northern part of ophiolite is also favoured as an alternative prospect of secondary gold.

Table 2. Chemical composition* (wt%) of gold and sulphides in the layered cumulates of NHO

Metal	Olivine gabbro			Olivine websterite	
	Millerite	Chalcopyrite	Gold	Pyrrhotite	Chalcopyrite
<i>n</i>	1	1	3	1	1
Fe	1.21	24.37	0.36	57.53	28.6
Ni	59.53		0.02	1.28	0.13
S	36.36	36.27	0.12	36.68	37.62
Co	1.5	0.04	0.31	0.23	0.04
Cu	0.24	38	0.02		33.08
PGE	0.14				
Ag	0.09	0.03	7.67		
Au			85.9		
Rh	0.01		0.03		
Total	99.08	98.71	94.43	95.72	99.47

*Wave Dispersive X-Ray Spectrometer data by EPMA (Cameca SX-100). *n* = Number of analysis.

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Predatory drilling in Tertiary larger foraminifera from India

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Evidence of predatory drilling in the microspheric tests of Middle Eocene larger foraminifera *Nummulites obtusus* (Sowerby) from western Kutch is reported in this communication from the Indian Tertiary sequences. Evidence in the form of repair structures present in the foraminiferal wall and indicative of post-attack healing, has been described and illustrated. While biological identity of the predator remains enigmatic at the present stage of investigation, this report is likely to throw light on similar instances of predator–prey interaction in previously accounted Tertiary larger foraminiferal assemblages of India.

Keywords: Kutch, larger foraminifera, Middle Eocene, *Nummulites obtusus* (Sowerby), predation.

PREDATION plays a major role in shaping the shallow marine benthonic fauna¹. Benthic foraminifera, a common constituent of the shallow marine bottom community with high preservation potential, are often subjected to bioerosion². All bioeroded foraminifera, however, do not necessarily reflect predatory action, as dead tests are subjected to boring by endoliths or protoplasm scavenging taxa³. As such, the prey–predator interaction involving foraminifera as the prey may not be easy to infer, especially in the fossil record. In this backdrop, unequivocal evidence of predatory drilling can be gathered from the study of foraminiferal specimens surviving one or more sub-lethal attacks to live long enough to heal their damaged tests⁴. Thus, documentation of repair structure in the foraminiferal test wall confirms the prey–predator interaction in either present or fossil foraminiferal assemblages. In this communication, we report the occurrence of repair structures in the microspheric tests of the Middle Eocene larger foraminifera *Nummulites obtusus* (Sowerby) from western Kutch. Perhaps constrained by the limited scope of publication, authors of a previous report⁵ on the predation of Eocene larger foraminifera from Kutch, did not include the detailed account of predation. To our knowledge, there is no other publication on the predation of Tertiary larger foraminifera from India.

So far, interaction among shallow marine benthic biota from the Tertiary basin of Kutch has been sporadically explored. Such studies include the Miocene benthic community in general⁶ and the Miocene mollusks in particular⁷, the Middle Eocene ostracods⁸ and the

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