In summary, assuming very low $P_{H_2O}$ and some effect of Fe$_2$O$_3$, a more reasonable, albeit rough, estimate would be $P \approx 7$ kbar and $T \approx 1000^\circ$C obtained by combining the $P$–$T$ diagrams in Aranovich and Podlesskii\(^1\) and in Aranovich and Berman\(^1\). For comparison, other investigators have estimated peak conditions of $P$ from 6.5 to 9 kbar, $T$ from 900 to over $1000^\circ$C for ultrahigh-temperature metamorphism in the Eastern Ghats belt\(^13\)–16,22.

In conclusion, we were unable to confirm the presence of any mineral rich in Be at Ayyanna Agraharam and Venugopalapuram, two of the localities reported to be enriched in this rare element, as well as Ga and B\(^7\). Had gallium been present in the gneiss, it would have been concentrated in hycynite, but Ga was below detection in this mineral (Table 4). A small amount of Ga (0.56 wt% Ga$_2$O$_3$) was found in the Fe–Mg–Ti–Al oxide hýcyanite, a minor constituent of a magnetite-rich rock associated with the gneisses at Venugopalapuram. Boron-enrichment was also found at Venugopalapuram, but not in surinamite. Instead, we discovered a new locality for a prismatic containing 2.85–3.04 wt% B$_2$O$_3$ and 160–170 ppm Be, which indicates the presence of a boron-enriched layer in the gneisses. This Fe–Mg–Al borosilicate has been found at two other localities in the Eastern Ghats belt\(^2\). The quartzfeldspathic gneisses reported to contain surinamite were found to have hypersthene instead. Compositions of hypersthene, garnet, cordierite and oxide minerals in the gneisses indicate crystallization under relatively high oxygen fugacity, very low water activity, ultrahigh temperature and moderate pressure.


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Discovery of coesite from Indian Himalaya: A record of ultra-high pressure metamorphism in Indian Continental Crust

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Coesite inclusions have been identified from eclogite in the Tso-Morari crystalline complex of Ladakh (India) by petrography and Raman spectroscopy. This is the first location from where coesite has been identified as inclusion in garnet in the Himalayan belt. The occurrence of coesite supports ultra-high pressure metamorphic event in the Indus Suture Zone. Coesite occurs as inclusions in garnet in which radial cracks are developed, whereas quartz pseudomorph after coesite occurs in the close association with garnet and omphacite. The preliminary $P$–$T$ estimate revealed coesite formed at the minimum pressure of 28 kbars at 700–800$^\circ$C. The preservation of metastable coesite in eclogite is strongly regulated by $P$–$T$–$t$ path during its uplift and retrograde metamorphism. This finding also indicates that the Indian plate subducted at a steeper angle of paleo-subduction plane from Pakistan to the Ladakh region of India.

SPENCER\(^1\) reported the first eclogite in the Himalaya in 1993, from Pakistan. Eclogite has also been identified in a few areas by Guilhot et al.\(^2\) and Sachan et al.\(^2\). In comparison to the Alps, Caledonides and Dabieshan

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(China), eclogites are a rare commodity in the Himalaya. Here, we present a detailed account of new evidences for ultra-high pressure metamorphism in Indian Himalaya, on the basis of petrography and Raman spectroscopy.

This ultra-high pressure segment of the Indian continental crust may return to the surface from a depth of >64 km. This challenges the conventional understanding of petrotectonic process in the formation of the Himalaya and raises new questions about the uplift mechanism, exhumation rate and cooling history of ultra-high pressure metamorphism (UHPM) rock. This discovery will change our understanding of the history of the Himalayan building.

The Tso-Morari crystalline complex occurs as a dome and is located between the Indus Suture Zone to the north by Zhidat detachment fault and Zanskar sedimentary unit in the south. The Tso-Morari dome appears as an internal crystalline massif like other norther Himalayan massif (Gurla Mandata and Kangar, in South Tibet. The crystalline complex is divided into three principal tectono-stratigraphic units, the Puga Formation, the Taglang La Formation and Polokong La and Rusphu granitoids. The Puga Formation is composed of Cambro-Ordovician gneisses of sillimanite–kyanite grade.

The eclogite occurs in the form of lenses and irregular bodies, dark and light in colour with size ranging from 1 to 40 m. These eclogite bodies are wrapped by sillimanite–kyanite grade of gneisses of Puga Formation.

Garnet contains minute inclusions of omphacite, amphibole and phengite. The amphiboles are sodic in nature, in which glaucophane is predominant and mostly associated with omphacites. Garnet shows well-developed major element zoning with increasing Mg and decreasing Ca and Fe/Mn from core to rim, which provide evidence for increasing temperature and pressure during crystallization. Phengite occurs mostly in the matrix and also inclusion in garnet.

The garnet porphyroblasts have some lensoid inclusion containing subhedral and rounded coesite rimmed by palisade quartz aggregate with radial fractures in the host grain (Figure 1a and b). Coesite is a high-pressure polymorph of SiO$_2$ and 30–80 µm in size, characterized by its distinctly higher relief and lower birefringence as compared with quartz and is confirmed by Raman microprobe spectroscopy by recognition of the characteristic Raman shift.

Quartz is euhedral, monocrystalline and ranges in size from 30 to 100 µm. In some others eclogite samples polycrystalline quartz is observed, which clearly reflects the presence of coesite.

The coesite-bearing eclogite pyroxenes have 60 mol% jadeite, 38 mol% diopside and 2 mol% aegerine. Garnet has an almandine-rich composition. The core has high Mn and low Mg, whereas the rim has the highest Mg.

The mineral assemblage we observed is as follows: Garnet + Omphacite + Phengite + Coesite.

From the observed mineral assemblage, the minimum $P$–$T$ that can be envisaged (by the presence of coesite) is 28 kbars at 700–800°C, which is in accordance with other studies. The presence of coesite inclusions in garnet with the coexisting assemblage of omphacite and phengite is used as the minimum $P$–$T$ indicator. The higher estimate of $P$–$T$ value is possible when graphite/diamond is present. Till date, we did not observe any mineral assemblage in the coesite-bearing rocks having constituents of graphite or diamond as stable phase.

The Raman spectra were obtained using JASCO, NRS Laser Raman spectrometer at the Department of Earth and Planetary Sciences at Tokyo Institute of Technology, Tokyo. The inclusion of coesite can yield the principal Raman band displaced at 523.1 cm$^{-1}$ (Figure 2) and the lower intensity coesite band at 118.6, 272.6 and 428.5 cm$^{-1}$. These Raman bands are displaced to a higher side by 0.64 cm$^{-1}$. The Raman spectra were
Figure 2. Representative Raman spectra for coesite inclusions within the garnet showing characteristic peaks for coesite.

compared with those of monomineralitic coesites from Kokchetav, Sulu, Dabie, Dora Maar and UGR Norway\textsuperscript{12,15–19}. The displacement of coesite bands to higher frequency (523.1 cm\textsuperscript{-1}) as well as weaker bands of coesite occur due to increase in confining pressure, as suggested by the experimental work of Hemley\textsuperscript{20} and Parkinson\textsuperscript{21} for untransformed and metastable coesite.

The discovery of coesite from the Tso-Morari crystallines is strong evidence that this part of the Indian plate in NW Himalaya has been subducted to more than >84 km depth. This is three times the known thickness of the continental crust. The occurrence of such high-pressure rock in the NW Himalayan belt (both in Pakistan\textsuperscript{22} and India) could be tentatively explained by a steeper dip of the palaeo-subduction planes or the acute angle of subducting plane\textsuperscript{23}.

The depth deduced from the present study is two times greater than the previous estimated depth of peak eclogitization. The previously estimated $P$–$T$ conditions by Guillot et al.\textsuperscript{2} and Sachan et al.\textsuperscript{3} of eclogitization in the Tso-Morari area indicate maximum depth of subduction around 65 km. This means that the previous estimated $P$–$T$ conditions of eclogitization are not really showing peak $P$–$T$ conditions of eclogitization. In fact they are pre-peak $P$–$T$ conditions. The metastable preservation of coesite may be entirely due to the buoyancy of relatively low density in comparison to mantle subducted Indian–Continental crust hosting the eclogite.

In the western part of the Himalayan belt, the geological data indicate that continental subduction plane is steeper with subductions of at least 150 km below Pamir–Hindukush\textsuperscript{24,25}. This model is much more consistent with the model of Chemenda et al.\textsuperscript{23}. The latest discovery of ultra-high pressure (UHP) mineral in this part of the Himalayan belt also supports the conclusion that palaeo subduction plane of the Indian plate is very steep.

The geochronological dating for UHP eclogite is not yet known from the Tso-Morari crystalline complex in Ladakh India as well as from Pakistan. This UHP eclogite lies within the lenses of post-peak retrograded eclogite whose age is 55 Ma\textsuperscript{26}. The discovery of coesite and occurrence of eclogite in the Indian continental crust will enhance further petrologic, geochronological and tectonic investigations in this region.

Heavy sediment influx during early Holocene: Inference from clay mineral studies in a core from the Western Bay of Bengal

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Clay mineral studies were carried out in a 650 cm long sediment core collected at a depth of 2200 m from the north-western Bay of Bengal. Illite is the predominant mineral, followed by montmorillonite and chlorite. Illite concentration varies from 49 to 65% from the core top to 380 cm and further down, increases to 85%. Montmorillonite content ranges from 22 to 36% above 380 cm, with a maximum in the upper 20 cm. Lowest values of montmorillonite (3–8%) are observed below 380 cm. Chlorite values range from 12.8 to 29%. Kaolinite is present in traces.

The changes in mineral composition at 380 cm in the core are interpreted to be a transitional period of Pleistocene–Holocene. This is substantiated by the lithological, foraminiferal and geochemical studies of the core. Very high content of illite below 380 cm of the core reflects glacial weathering products of crystalline metamorphic/sedimentary rocks of Himalayas carried by Ganges–Brahmaputra rivers during the late Pleistocene, when the sea level was low. Increase of montmorillonite and kaolinite during the Holocene indicates that the Ganges–Brahmaputra province sediments were diluted with sediments from the peninsular rivers draining metamorphic gneisses, schists, Deccan Traps and Quaternary sediments. This distribution can be explained by circulation pattern and tectonics in the Ganges delta during early Holocene.

The top 380-cm thick sediment deposition during Holocene is attributed to heavy sediment influx during Mid Termination (MT) (12,500–10,000 years BP), due to increased precipitation and run-off resulting from high intensity monsoonal regime.

CLAY minerals are a powerful source for the interpretation of marine depositional processes and their study also reflects weathering conditions imparted on the rock particles that were found in the source terrain1,2. For example, well-crystallized smectite and kaolinite were used to elucidate depositional origin on the eastern Nile cone3. Chlorite and kaolinite also have been used as valuable indicators of continental sources and differential depositional sites in the eastern Atlantic sediments off North America4. The Bay of Bengal covers about 2.2 million sq km and is one of the highest terrigenous input sites of the world ocean. The fan is reported to be about 2800–3000 km long, 830–1430 km wide and 16 km thick, beneath the northern Bay of Bengal. Though the shelf sediments on the east coast of India were studied in detail for clay minerals, very few studies5–9 were carried out in the deeper Bay of Bengal especially in the Bengal Fan. Chauhan et al.10 reported clay minerals in a core from the eastern Bay of Bengal and suggested peninsular river source to the Holocene sediments. Chaudhri7 has encountered only Holocene sediments derived from the Himalayas, in cores of 303 cm length from the middle Bengal fan region. Chowdary et al.8 ruled out the peninsular river source to the middle fan during mid-Holocene. In contrast, Shastri et al.9 concluded that the transportation of sediments is from shelf to slope to deeper western Bengal Fan. In view of the above, we plan to address to the provenance of the sediments in a sediment core from the western Bengal Fan. In this paper, we report clay mineralogy and provide an explanation for the heavy sediment deposition during the Holocene. A sediment core of 650 cm length was collected during the 42nd cruise of ORV Sagard Kanya at a water depth of 2200 m (lat. 16°00’N and long. 87°05’E) (Figure 1). Subsampling of the core was done onboard, mainly at 10 cm interval and also wherever a change in colour was observed. For clay mineral analysis in all 14 subsamples were selected. Less than 2 μm fractions of the sediment were separated10 and rendered free of CaCO3 and organic matter, by treating with acetic acid and hydrogen peroxide, respectively. Oriented clay slides were prepared and scanned from 3 to 30° 2θ at 2° 20min−1 with a Philips X-ray diffractometer, using nickel filtered CuKα radiation. These samples were again rescanned after treatment with ethylene glycol for 1 h at 100°C for confirmation of montmorillonite11. The

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