vity of 7682 kg/cubic m. In this study, the weight of the Delhi Iron Pillar has been estimated accurately taking into account current information about the pillar. This can be compared with published literature[2] estimates, which generally mention the weight of the pillar as 6 t. It is clear that the results of this study are in agreement with the published data. The main advantage with the current approach is that the computer model of the Delhi Iron Pillar can be utilized for a wide variety of purposes, e.g. modelling the thermomechanical deformation of an object, a subject that will be taken up in the future.

The CATIA V5R16 software was used to prepare component drawings of the Delhi Iron Pillar. Based on estimated dimensions, the weight of various components of the pillar was determined. The total weight of the pillar has been precisely estimated as 6511 kg, which is comparable to estimates available in the literature. This study also explains how computer modelling can be usefully employed to determine precise weights of historical objects.

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Berthierine-rich ooidal ironstone from the Late Palaeocene–Middle Eocene Subathu Formation, Dogadda area, NW Himalaya and its stratigraphic significance

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Berthierine-rich ooidal ironstone occurs within carbonaceous shale in the lower part of the Late Palaeocene–Middle Eocene Subathu Formation in Dogadda, Uttarakhand Himalaya. Berthierine/chamosite occurs both as ooids and as matrix. Ooids are spherical with 1–2 mm diameter and have concentric layer structure around a nucleus. Quartz is coarse-grained and occurs as embayed grains. Carbonate phase is absent in the ooids. Berthierine and chamosite assemblage indicates a temperature of ~130–160°C of burial diagenesis for Dogadda ironstone. The lithological association, distinct mineralogy and texture suggest that the mineralogy of the Dogadda ooidal ironstone is *in situ*, formed in a shallow-marine environment under conditions of low net sediment accumulation. Dogadda ooidal ironstones, along with coeval ash beds in the foreland basin are useful in stratigraphic correlation.

Keywords: Berthierine, ooidal ironstone, Palaeocene–Eocene, Subathu Formation.

MUCH attention is being paid in recent years in examining the Maastrichtian to Early Eocene sedimentary sequences the world over, as this interval encompasses events of global significance such as Mid-Maastrichtian deep ocean circulation reversals, the Cretaceous–Tertiary (K/T) boundary mass extinction, Palaeocene–Eocene Thermal Maximum (PETM), extensive Cenozoic volcanism, and collision of the Indian plate with Eurasia. In this context, the Subathu Formation in the foothills of NW Himalaya, by virtue of its stratigraphic age (Late Palaeocene–Middle Eocene), shallow marine sediments and/or conditions, abundant fauna with excellent preservation, along with ample outcrops of almost complete and continuous sequence (Figure 1), forms an ideal field laboratory to obtain insights into events of global and regional importance. During the course of a systematic investigation on the lithological make-up of the Subathu Formation in Dogadda area, Uttarakhand, aimed to trace mineralogical variation across Late Palaeocene–Eocene transition in a shallow marine setting, the author found a prominent unit of berthierine-rich ooidal ironstone in the lower part of the Subathu Formation. The stratigraphic position of the

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berthierine-rich ooidal ironstone at Dogadda is significant, since ash beds (tonsteins) have been found in similar stratigraphic level at Kamli (Himachal Pradesh), ~ 200 km northwest of Dogadda[1].

Berthierine is an iron-rich, aluminous, 1 : 1-type layer silicate with a basal spacing of 7 Å, belonging to the serpentine subgroup and forms at low Eh conditions, in open reducing conditions like estuarine or prodeltaic environments[2]. Several recent studies have outlined the relationship of berthierine-rich ooidal ironstones to unconformities and condensed deposits[3–5]. Therefore, study of ironstones containing authigenic clay minerals is useful for interpreting depositional environment as well as developing sequence stratigraphy. Although a few occurrences of oolitic ironstone have been reported from the Himalaya, none has been fully documented to date[6,7]. This communication presents the geological occurrence, mineralogy, and textures of the ooidal ironstone at Dogadda, describes ooid formation and highlights its stratigraphic and tectonic significance.

The ooidal ironstone was identified on the basis of observations from relatively unweathered outcrops exposed due to highway construction, polished slabs and standard thin-section petrography. A total of ten bulk samples of the ooidal ironstone were collected from freshly cleared exposures across the unit. Representative sample portions were used for making 40 thin and 20 polished sections for microscopic studies. The mineralogy, mode of occurrence and textural features of phyllosilicate minerals were examined by means of transmitted and reflected light microscopy and X-ray diffraction (XRD) analyses of uncovered thin sections, bulk sample powder as well as hand-picked mineral separate. XRD analyses on ten powder samples were done with Cu$K\alpha$ radiation in an angular range (2θ) from 5° to 70°. XRD patterns reveal that both 7 Å berthierine and 14 Å chamosite are present in the ironstone. The organic content of the ooidal ironstone was determined as the loss of weight upon ignition at 650°C.

The study area is near Dogadda village, on the bank of River Khoh along the Main Boundary Thrust in Pauri Garhwal District, Uttarakhand, India (Figure 1). The Kakara–Subathu formations are exposed near Dogadda village on the Kotdwar–Dogadda Road.

The Kakara–Subathu formations are mixed carbonate–siliciclastic successions, characterized by alternating shale and limestone produced during transgressive and regressive cycles. The Kakara–Subathu sediments are underlain by Tal quartzite and overlain by Dagshai–Kasauli succession of brackish to freshwater deposits[8,9]. The Kakara Formation comprises fossiliferous limestone, shale and oolitic limestone. It is overlain by the Subathu Formation, which consists of carbonaceous shale with coal bands, ooidal ironstone, and grey, green and red shale with thin lenses of limestone and sandstone. Based on faunal assemblages, the age of the Kakara–Subathu Formation is assigned to Late Palaeocene to Middle Eocene[9]. In Dogadda area, the Kakara–Subathu transition is characterized by deposition of ferruginous ooidal ironstone. Based on field and detailed petrographic data, the present study describes the origin of this ironstone.

Ooidal ironstone occurs as a distinct unit in the lower part of the Subathu Formation in Dogadda area (Figures 2 and 3). It is bounded by carbonaceous shale and has sharp lower and upper contacts. Carbonaceous shales are dark grey, non-calcareous and poorly consolidated. Lignitic fragments are scattered in the carbonaceous shales and ironstones. The ooidal ironstone is about 3 m thick, dark

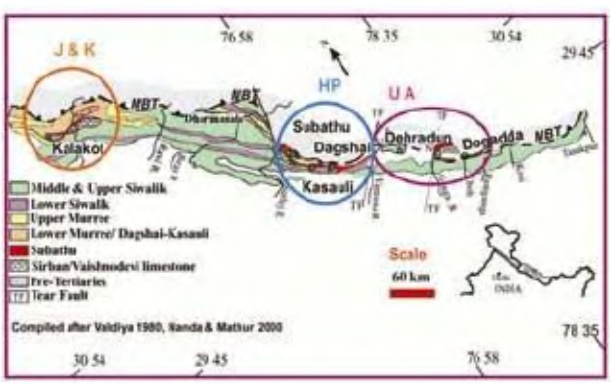

Figure 1. Geological map showing the occurrence of Subathu Formation in NW Himalaya[8,21]. J&K, Jammu and Kashmir; HP, Himachal Pradesh; UA, Uttarakhand.

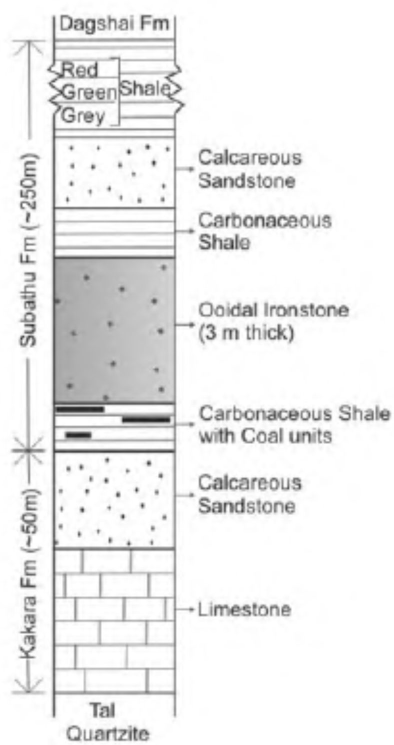

Figure 2. Lithological log of lower part of Subathu Formation exposed along the Kotdwar–Dogadda Road showing stratigraphic position of ooidal ironstone.

grey to black, massive, dense, fine-grained, highly indurated (hard) and non-calcareous. It consists predominantly of iron-rich clay minerals, berthierine and chamosite. Other minerals are quartz, pyrite, chert and iron hydroxides.

Berthierine and chamosite are in microcrystalline form and occur both as ooids as well as in groundmass. Berthierine and chamosite are brown to colourless and show weak pleochroism and 'Maltese cross-extinction'. Berthierine is identified by characteristic XRD peaks at 7.06, 4.27, 3.51 and 1.55 Å, while chamosite is identified by its characteristic peak at 14.0 Å (Figure 4). Berthierine and chamosite are observed in the same sample powders. Quartz content of the ironstone is variable, some portions being quartz-poor, while others are quartz-rich. Quartz is coarse-grained (1–4 mm), poorly sorted, angular-to-subangular with corroded surface and embayed margins (Figure 5 *a*). It is monocrystalline, shows mild undulose extinction, and contains inclusions (Figure 5 *b*). Pyrite occurs as irregular globules (1–3 cm dia) enveloping berthierine/chamosite ooids and its occurrence is restricted to a (10–15 cm) narrow zone, in quartz-poor portions of the ironstone. The total organic matter of the ironstone varies from 6.0 to 8.9 wt%.

The ooids constitute ~15 to 20 volume % of the ironstone and are well preserved. The ooids are steel grey, spherical and have relatively uniform size, from 1 to 2 mm. Berthierine/chamosite ooids occur disseminated within berthierine matrix and also as clusters in pyrite matrix. Berthierine ooids in pyrite matrix are closely spaced without any grain boundary suturing among the ooids (Figure 6). Berthierine predates pyrite formation and shows no textural evidence of the latter replacing the former.

Internally, the ooids are made up of alternating light and dark, thin and nearly continuous concentric layers of berthierine; the number of concentric layers varies from 2 to 6 (Figure 7 *a*). The thickness of concentric layers is variable within and among ooids. All the ooids, irrespec-

Figure 3. Field photograph of Dogadda ooidal ironston. Dip is almost vertical. Note generally structureless character of the ironstone. (Person shown for scale.)

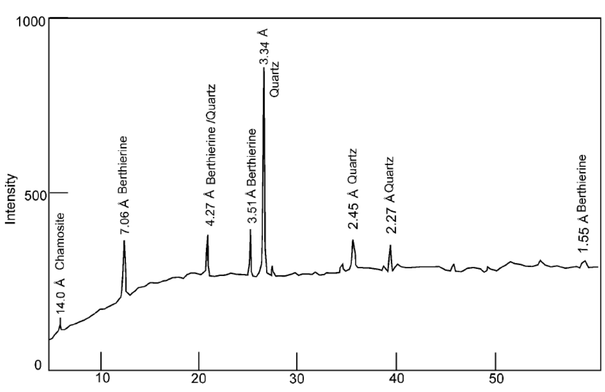

Figure 4. X-ray diffraction pattern of Dogadda ooidal ironstone powder sample showing reflections for chamosite, berthierine and quartz.

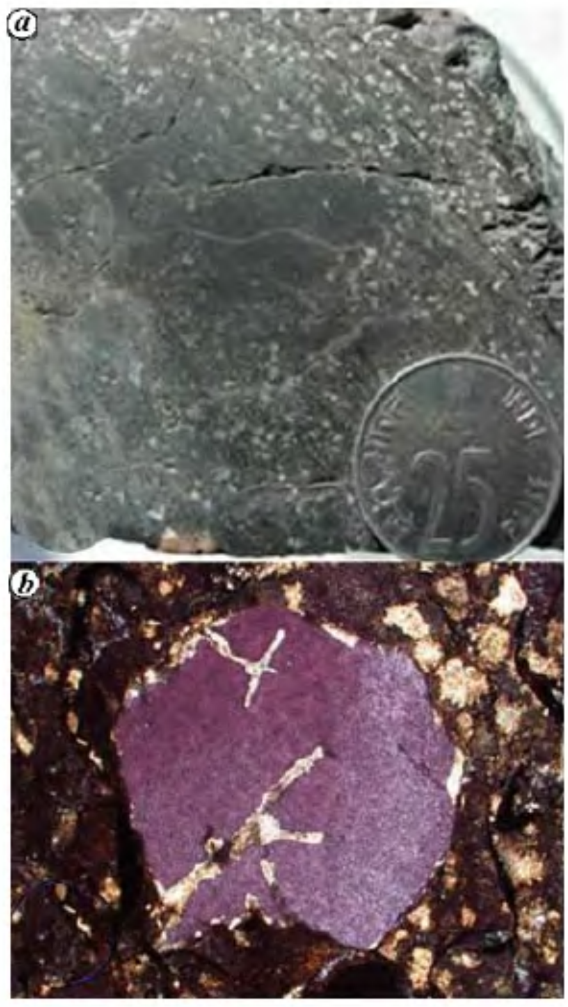

Figure 5. Photographs of Dogadda ooidal ironstone showing morphology of quartz grains. ***a***, Polished hand specimen showing poorly sorted, silt-and-sand size angular quartz grains (light grey) within a matrix of fine-grained berthierine (dark grey). ***b***, Photomicrograph of a quartz grain showing monocrystalline nature, mild undulose extinction, and embayed margins. Crossed nicols, width of the quartz grain is 2.5 mm.

tive of their size, invariably have an outer cortex of amorphous silica with smooth tapered width (Figure 7 *b*).

Interestingly, quartz grains, albeit ubiquitous in ooidal ironstone, do not serve as nuclei. The nuclei of the ooids are dominantly of berthierine itself. There is no discernible shape of the nucleus; many are rounded, and some are irregular. Contact between the nucleus and cortex, and the cortex and matrix is sharp and distinct. Several ooids have cracks that radiate from the centre (Figure 7 *a*). In some ooids, part of the outer silica cortex is torn-off. Ooid cortices are exquisitely preserved and lack relict carbonate phase.

Based on petrographic criteria, two distinct types of ooids have been observed in the Dogadda ooidal ironstone. Type-1 ooid is characterized by well-developed, concentrically laminated inner cortices of berthierine/chamosite around a small nucleus of berthierine itself (Figure 7 *a*). Type-2 ooid is characterized by a large nucleus of berthierine/chamosite without concentric lamination (Figure 7 *a*). Both types of ooids have silica as outer cortex.

Though the textural features of ooids from the Dogadda ironstone are similar to those described from Phanerozoic oolitic ironstones[4,10,11], their spherical shape differs significantly from oblate ellipsoid shape of Phanerozoic ooids. Phanerozoic ooids have length : width ratios[12] between 5 : 1 and 10 : 1, whereas Dogadda ooids are almost 1 : 1. The shape as well as internal structure of the ooids in the Dogadda ironstone are strikingly similar to those of modern iron ooids discovered in a shallow-marine setting, offshore a volcanic island in Indonesia[12]. However, the presence of a prominent outer cortex of silica with tapered width is a unique feature of the ooids of the Dogadda ironstone, and such a feature is not reported for ooidal ironstones anywhere in the world.

The presence of both berthierine and chamosite in the Dogadda ironstone is of special interest given that berthierine is considered to be a diagenetic precursor to chamosite[2]. The temperature of complete transformation of berthierine ranges from ~130°C to 160°C, with lower temperatures generally being favoured[13–15].

Rare and restricted occurrence of pyrite in the Dogadda ironstone suggests that sulphate reduction was a negligible process during ironstone formation. Where it is present it post-dates berthierine, indicating that sulphate reduction may have been a later process. The high total organic content (6.0–8.9 wt%) observed in Dogadda ironstone may reflect slow sedimentation rates and limited dilution by clastic detritus.

Origin of ferrous clay minerals (berthierine and chamosite) in ooidal ironstone deposits has been the subject of intense debate[16]. This mineral assemblage is not common in marine sediments, where pyrite and siderite are the common iron minerals. Several mechanisms have been proposed for the formation of iron-rich ooids. They are: (1) iron-rich ooids formed during the pedogenic processes and subsequently transported into the sea[17]; (2) ooids that are primary marine, formed on shallow, clastic-starved shelves subjected to frequent reworking[11,16], and (3) large-scale replacement of ooidal limestones by iron-rich pore waters[18].

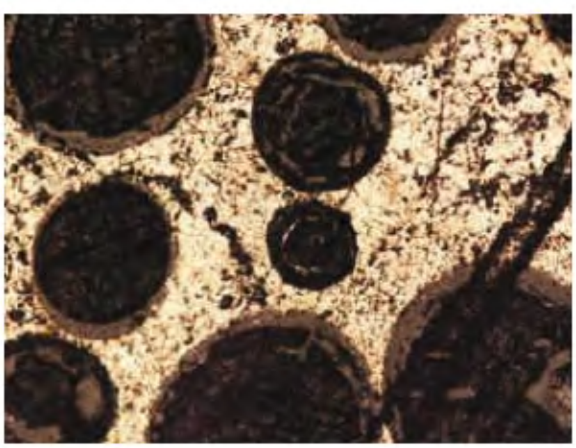

Figure 6. Photomicrograph of polished thin section of Dogadda ooidal ironstone showing spherical berthierine ooids in pyrite matrix with sharp contact. Reflected light, crossed nicols, ooids = 1–2 mm.

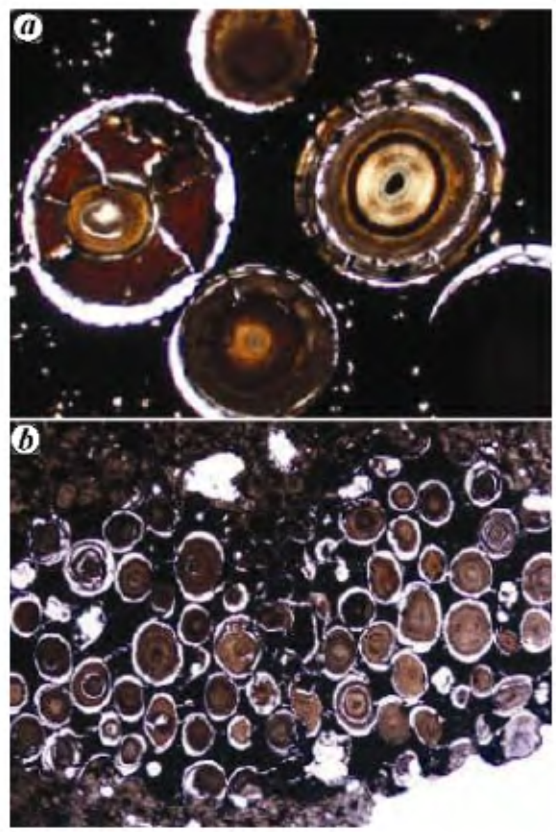

Figure 7. Overview of ooids from Dogadda ironstone. ***a***, Photomicrograph of thin section showing well-developed spherical ooids with several concentric lamina around a small nucleus (upper right) and without concentric lamina (upper and lower right). Note radial cracks in the cortex (left). Plane-polarized light, ooids = 1–2 mm. ***b***, Photomicrograph of thin section showing ooids with prominent outer cortex of silica. Plane polarized light, ooids = 1–2 mm.

Petrographic features of the Dogadda ooidal ironstone, particularly the symmetrical shape, high sorting and absence of broken ooids rule out their transported origin. In addition, preservation of delicate textural features of the ooids would not be likely if they were transported from a distant source. Exquisitely preserved ooid cortices and the absence of relict carbonate phase indicate a non-replacement, primary origin. Therefore, the textures observed in the Dogadda ooidal ironstone indicate authigenic formation of berthierine ooids.

Some researchers believe that the concentric fabric of ooids is a primary structure produced by mechanical accretion of clay particles, which may be either primary berthierine or kaolinite[10,19]. Several recent studies of other ooidal ironstone deposits elsewhere in the world, have proposed that ooidal ironstone was a result of specific sedimentary processes like low sedimentation rate[11]. The Dogadda ironstone with its ferrous mineral assemblage, well-sorted, well-rounded texture of the ooids, higher content of organic matter, and scarcity of detrital material relative to the underlying sandstone suggests shallow-marine environment (prodeltaic to estuarine) with reduced clastic input.

Based on mineral stability relations, it has been shown that berthierine is stable under anoxic conditions with very low sulphide activities[20]. The petrographic evidence that berthierine predates pyrite in the Dogadda ironstone indicates that it precipitated during early sub-oxic diagenetic conditions, below the sediment–water interface in which iron reduction was the dominant process in the oxidation of organic matter. The kaolinitic ash beds present at similar stratigraphic level in the basin may have provided the Fe, Al and Si required for berthierine formation.

The geological setting, mineral assemblage and textural characteristics of the Dogadda ooidal ironstone indicate that it was deposited in a shallow-marine environment during periods of reduced clastic sediment influx. Berthirine and chamosite assemblage in the Dogadda ooidal ironstone suggests a temperature of ~130–160°C of burial diagenesis and/or metamorphic grade, consistent with the sub-bituminous rank of coal units in the sequence. The textural relation of berthierine and pyrite in the Dogadda ironstone indicates that sulphate reduction was a later process, and berthierine was formed during early sub-oxic diagenesis, where iron reduction was the dominant process of organic matter reduction. The ooidal ironstones and coeval ash beds of the Subathu Formation represent excellent marker horizons for stratigraphic correlation.

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