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ORIGINAL PAPER

Morphological and microstructural characteristics of bauxite developed over a part of Precambrian Iron Ore Group of rocks, Sundergarh District, Eastern India

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Abstract Bauxite occurring as a blanket over volcanics of Precambrian Iron Ore Group in Kusumdih and Jaldih of Sundergarh district, Odisha, Eastern India exhibits four types of morphology viz. pisolitic, disseminated, spotted and massive. The volcanics/tuffs are altered to shale and is predominantly constituted of kaolinite. Microstructures documented in different morphologies of bauxite are collomorphous, framework, chain, stalactitic, reticulate, vesicle filled and foliated-platy types. Gibbsite, diaspore and kaolinite exhibit the abovementioned morphological and microstructural features. The morphological and microstructural characteristics are interpreted in terms of genetic evolution of aluminous minerals of bauxite in such a setup. Gibbsite and diaspore are formed through solution and precipitation/recrystallisation from kaolinite booklets present in parent tuffaceous shales. Some diaspores were formed at the expense of gibbsites. Small well-ordered kaolinites are of authigenic nature. Kaolinite formed inside a localized closed system containing supersaturated solution exhibits growth spirals. The textural and morphological diversities of the bauxite, abundance of well-ordered bauxite minerals and the absence of any iron/silica phase along with limited occurrence of primary kaolinite together suggest that the deposit has attained a high degree of bauxitisation in weathering environment at surface temperature.

Keywords Bauxite · Microstructure · Scanning electron microscopy · Morphology

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Introduction

It is equivocally accepted over the world that any rock containing more than 15% Al_2O_3 can be converted to bauxite through residual concentration under tropical to sub-tropical climatic condition. In India, bauxite has developed over all most all kinds of rocks, for example (1) khondalites (east coast bauxite, Odisha, Andhra Pradesh; Raman 1978; Reddy et al. 2015), (2) Deccan Traps (Muthuraman and Murthy 1985; Sahasrabudhe 1978; Gujarat, Suss et al. 1988; Jadav et al. 2012), (3) charnockites (Shevaroy and Kollimalai hills, Tamil Nadu; Subramanian and Mani 1979; Mukherjee 1984), (4) crystalline rocks (Kerala and Karnatak; Radhakrishna 1965; Viswanathaiah et al. 1974; Balasubramaniam 1978), (5) Vindhyan sandstone/shale (Chhattisgarh, Rao and Krishnamurthy 1979; Murthy et al. 1979; Swarup 1973), (6) iron ore volcanic (Koira, Odisha, Mohapatra et al. 1989; Rao and Sahu 1984), (7) limestone (Jammu and Kasmir, Mohan 1979), etc. A large number of literatures pertaining to the detailed geology, mineralogy, geochemistry and reserve potential of most of the bauxite deposits, excepting the ore developed over the iron ore volcanics of the Precambrian age, are available. However, limited researchers have reported on the bauxite developed over volcanics/tuffs (Mohapatra et al. 1989; Rao and Sahu 1984). The present study aims at characterising the bauxite developed over iron ore volcanics, exposed near Kusumdih and Jaldih of Sundergarh district, Odisha. Since these deposits are awaiting mining, only different varieties of bauxite/lateritic bauxite samples were collected and studied in respect of their morphology, microstructure and mineralogy and results are reported in this communication.

Geological setup

Precambrian Iron Ore Group of rocks occurs in the form of horse shoe-shaped synclinorium (Fig. 1) in the Bonai-Keonjhar belt, Odisha, Eastern India. Thick piles of volcanic rocks (basalt, tuff) are associated with these rocks. The area is well known for occurrence of iron and manganese mineralisation. Large volumes of altered volcanics/tuffs and tuffaceous shales are present in different locations such as below, inside and above the Fe/Mn ore bodies (Mohapatra et al. 1989). The bauxite in Kusumdih and Jaldih, Sundergarh district, Odisha occurs over the peneplain basement of volcanics/tuffs/volcaniclastic shales belonging to the Lower Shale Formation (Mohapatra et al. (1991)) of Iron Ore Supergroup of Precambrian age (Fig. 1). The stratigraphic succession of the study area is given in Table 1. The Kusumdih and Jaldih, located in the western limb of horse shoe synclinorium, lie within about 8 km and attain an average elevation of about 600 m above MSL, while the valleys in between the plateaus are at an elevation of about 500 m above MSL. Thus, it is evident that the relief, during active formation of bauxite ore bodies, had lowland topography. The laterite forms a thin capping on the plateaus within which bauxite occurs as tabular bodies or impersistent lenses or pockets. The bauxite profile, as envisaged from the scarp face, is found to comprise of three zones, which from surface downwards are as follows: (a) the upper laterite, (b) ferruginous bauxite/bauxite and (c) the lower clay zone with relicts of basement rock. The contacts between the three zones are gradational with occasional tongues of ore zones protruding into the other. In the laterite zone, the cap is ferruginous which grades upward into thick aluminous laterite of ~1 m thickness. The bauxite zone extends for 0.5 to 1 km in length and occurs in the form of sub-horizontal sheets with a variable thickness. It is a compact, cream, light grey in colour and largely shows pisolitic or massive form. The average thickness of bauxite is around 2 to 5 m in Kusumdih and 2 to 3 m in Jaldih. A zone of low-grade bauxite occurs both above and below the major bauxite zone. Though the gradation of laterite/bauxite into underlying rocks is not traceable, the presence of shale and clay pebbles in laterite zone suggests their basement to be made of volcaniclastic shale. The

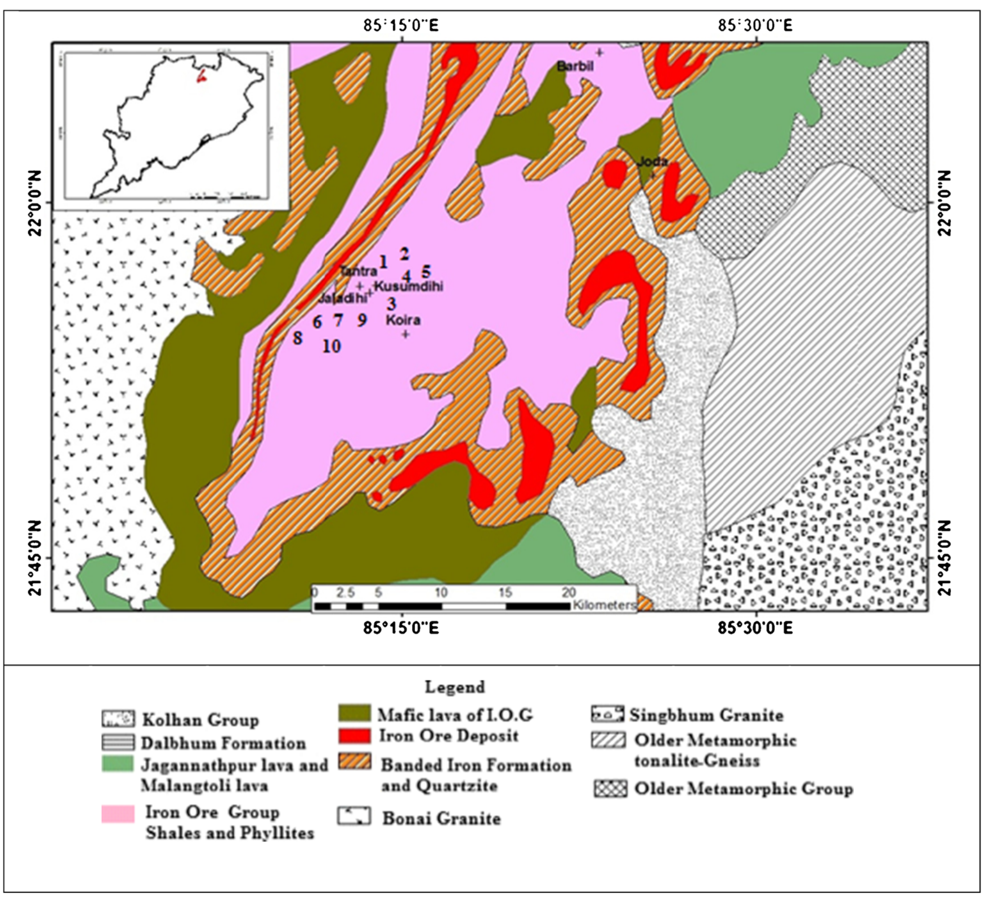

Fig. 1 Geological map of the Horse shoe synclinorium showing the bauxite deposits

Table 1 Geological succession of bauxite developed over iron ore volcanics in Odisha

Age	Formation	Rock type
Tertiary to Quaternary	Laterite	Laterite with associated bauxite and clays
Pre-Cambrian	Upper shale formation	Yellow, white, maroon shale, purple, black brown grey shale (manganiferous)
	Younger intrusive (basalt and dolerite)	
	Banded iron formation	Lateritic ore, blue dust, friable ore,
		Massive, laminated/shaly ore
		Purple shale
		Banded Hematite Jasper/quartzite
		Banded/hematite shale
	Disconformity	
	Lower shale Formation	Banded brown, grey/black shale
		Variegated tuffaceous shale
	Lower volcanic formation	Lava-tuff assemblages
	Older metamorphic Group	

saprolite zone above the basement rock is concealed in the scarp section though stray boulders at the foot hills represent some of these rocks. Similarly, the basement rock is not exposed below the bauxite since no mining activities has been undertaken, though pebbles/boulders of tuffaceous rocks are seen all round the plateau.

It may be interpreted from the foregoing geological setting that the bauxite is formed by in situ chemical weathering of volcanics/tuffs due to enrichment of alumina.

Analytical methods

Ten different bauxite samples representing various morphological types were collected from different scarp faces of Kusumdih and Jaldih. The microstructural peculiarities of the bauxite samples both in their fractured and polished surfaces were investigated by JSM 6510 Scanning Electron Microscope (JEOL make) at IMMT, Bhubaneswar. Samples in polished sections coated with carbon by a vacuum evaporator were prepared. The working voltage was kept between 5 and 15 kV with variable beam current (40–100 nA). Secondary electron images of the areas under consideration were recorded in the form of micrographs. The micrographs were taken at variable magnification (200 to 1000 μ). X-ray diffraction technique was used to identify the major mineral phases in each of the morphological varieties of bauxite using a Philips X-Ray Diffractometer (PW-1710,) where CuK_α radiation operating at 40 kV and 20 nA was employed and the characteristic reflection peaks were matched with JCPDS data book.

Results

Morphology

The bauxite developed over the iron ore shales exhibits four morphological features such as pisolitic, disseminated, massive and spotted (Fig. 2). The laterite capping over bauxite appears in reddish yellow coloured and spongy forms.

The pisolitic bauxite of the studied area is reddish to reddish brown in colour, consisting dominantly of pellet shaped pisolites/oolites. Similar type of pisolitic texture has been reported by Rao and Krishnamurthy (1979) in bauxite developed over Deccan basalt from Amarkantak area, Chhatisgarh, India. The pisolites are embedded within aluminous matrix and range up to 2 cm in diameter (Fig. 2a). The pisolitic type shows both aluminous pisolites and iron pisolites with a core of hematite/clay. The pisolites are seen in all shapes like rounded, elliptical, angular and broken fragments. The disseminated type of bauxite has a buff colour with mottled appearance and consists of iron shreds. Disseminations of dusts, in red and black colour, are enclosed within aluminous matrix (Fig. 2b). Massive type appears cream white in colour, compact, hard with occasional dusts of ooloids (Fig. 2c). The spotted type is flesh red in colour and is non-pisolitic, often bearing small cavities filled with white/buff-coloured materials having a spotted appearance (Fig. 2d).

Microstructure

Aluminium oxide and aluminium silicate minerals in various types of bauxite are studied under scanning electron microscope (SEM). The first SEM study on bauxites was reported

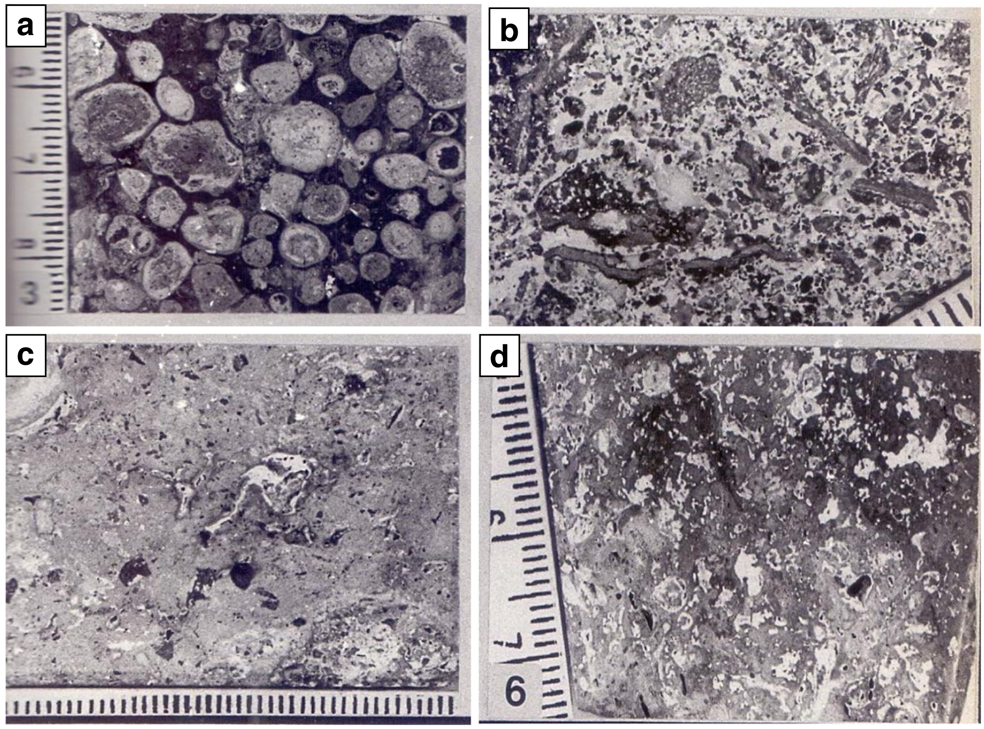

Fig. 2 **a** Pisolitic bauxite showing growth of well-developed oolites and pisolites. **b** Dissemination of dusts of iron shrads in clayey matrix. **c** Massive type bauxite showing dense structure with occasional patches of powdery material. **d** Spotted bauxite having small cavities filled with aluminous matrix

by Lahondy-Sarc et al. (1972). Bardossy et al. (1978), Balasubramaniam et al. (1980), Mukherjee (1984), Authier-Martin et al. (2001), Yu et al. (2014), Bhukte and Chaddha (2014) and Ling et al. (2015) are amongst the other principal workers in this field. The present work focuses on morphological and microstructural analysis of the bauxite ore and aims to establish the presence of different minerals in it so that its genetic evolution can be traced. The different types of microstructures recorded are collomorphous, framework, chain, stalactitic, reticulate, vesicle-filled and foliated-platy types. The loose framework texture is seen in two types: disseminated and spotted. The details of the microstructures are described below:

1. *Collomorphous*—This texture is characterised by cryptocrystalline bands and patches of aluminous mineral and has high porosity. It is the commonly observed texture in both the bauxite deposits (Fig. 3a) and resembles the 'Gel-like texture' reported by Valeton (1970). Similar texture in bauxite capping over Deccan basalt is reported by Rao and Krishnamurthy (1979) who termed it as collomorphous-pelitomorphous texture. The precipitation of hydrous, aluminous material as colloidal bands resulted in the formation of collomorphous texture. The colloidal growth is attributed to the variation of rhythmic differentiation of Fe^{3+} and Al^{3+} from the hydroxyl gel (Nia 1971). The presence of stringers of gibbsite within the cavities suggests that the mobilised alumina might have moved through them, got deposited and later developed into fine crystals of gibbsite which often shows lamellar twinning.
2. *Vesicular/vesicle-filled*—Vesicles of variable shape (circular, oblong, elliptical and irregular) and size are commonly present in Jaldih bauxites. Due to leaching action of the circulating solution, certain constituents of the original rock are removed resulting in the formation of vesicular texture. Vesicles are often partially filled up (vesicle-filled) with aluminous or ferruginous material brought in solution. They are found to be internally rimmed by concentric stringers and layers of gibbsite crystals (Fig. 3b). Rims composed of concentric layers represent sequential depositions of aluminous material from remobilised alumina-rich circulating solution under excellent leaching conditions.
3. *Loose framework*—Considerable degree of pore spaces and loose packing of the constituent amorphous-cryptocrystalline mineral phases characterise this texture. The crystallites (aluminous phase) are loosely stacked together and show less degree of porosity as compared to purely spongy types. Loosely stacked and well ordered gibbsite crystals of variable length (4 to 20 μ) occurring in irregular clusters in and around cavities within the spongy matrix constitute the spotted/disseminated texture of bauxite (Fig. 3c). The presence of this texture along with spongy matrix indicates the availability of free passages for easy circulation of water/solution and thereby facilitating good leaching condition.

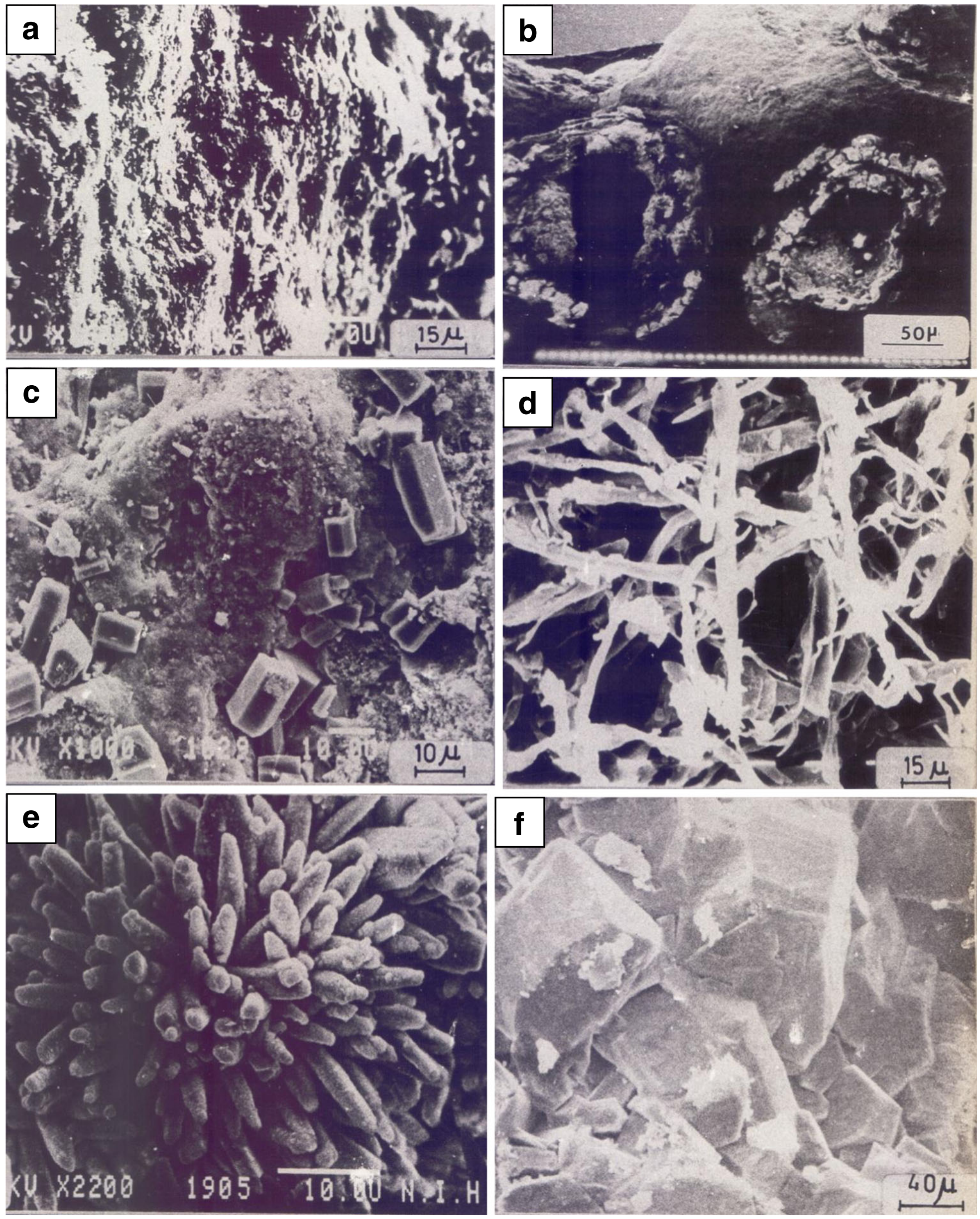

Fig. 3 **a** Collomorphous microtexture showing cryptocrystalline colloform bands of hydrous alumina phase and high degree of pore spaces. **b** Vesicles partially filled up and concentrically rimmed by layers/stringers of secondary gibbsite crystals growing into the cavities. **c** Loose framework crystalline-disseminated microtexture showing partially agglomerated pseudo-hexagonal gibbsite crystals in irregular clusters in the cavities. The *matrix* shows loose framework spongy texture. **d** Reticulate texture showing anastomosing network of gibbsite rods. **e** Stalactitic microtexture with radiating arrangement of gibbsite pendants. **f** Tight framework type consisting of well-ordered gibbsite crystals of monoclinic tabular habit. The large crystal to the top-right shows polysynthetic twinning

4. *Chain*—Well-formed gibbsite crystals (varying in length between 13 and 38 μ) of prismatic habit joined together end to end and constitute a chain type texture in the cavities (Fig. 3c). It is developed due to marginal fusion of well-ordered pseudo-hexagonal gibbsite crystals.
5. *Reticulate*—This intricate network texture comprising gibbsite rods of crisscross anastomising nature is illustrated in Fig. 3d. It suggests secondary precipitation of aluminous material in several phases within a porous substrate.
6. *Stalactitic*—This is an illustrative microtexture exhibited by Jaldih bauxite. It consists of long icicle like pendants which are grown downwards from the roof as radiation clusters exhibiting the fanciful shape of a flower (Fig. 3e). Each stalactitic unit tappers away from the base and consists of enveloping encrustations of cryptocrystalline gibbsite.
7. *Tight framework*—Well-developed monoclinic crystals of gibbsite showing tabular habit are stacked together and exhibit compact and somewhat crystalline webby fabric (Fig. 3f). This texture indicates a high degree of recrystallisation. Similar texture has been reported by Mukherjee (1984) in Salem bauxite of Tamilnadu, India.
8. *Foliated—platy*—Aggregates of kaolinite crystals present in Kusumdih bauxite show this texture. It is either recorded as loosely packed coarse and highly foliated books (average size 500 μ) as shown in Fig. 4a or as six-sided small flakes (12 to 45 μ) stacked together

one above the other (Fig. 4b, c). The matrix in both the cases exhibit loose framework type of texture.

Micromorphology

The aluminous minerals recognised from their characteristic micromorphology in the bauxite are gibbsite, diaspore and kaolinite. The identification of these minerals was later supported by their respective XRD analyses. The bauxite samples examined under SEM brought out the micromorphological details of gibbsite associated with diaspore and kaolinite.

Gibbsite

Gibbsite occurring in various forms and textures are described in detail by Authier-Martin et al. (2001) and Reddy et al. (2015). In the study area, gibbsite is the most dominant phase, which occurs as (i) well-formed monoclinic crystals of pseudo-hexagonal habit (length between 5 and 40 μ) in disseminated (Fig. 3c), agglomerated and chain form; (ii) tabular euhedrals stacked together forming a tight framework texture (Fig. 3f); (iii) radiating pendants (avg. 15 μ length) growing in a spheroidal-stalactitic form (Fig. 3e); (iv) surface encrustation, occasionally with fibrous-scaly microstructures (Fig. 4d); and (v) minute, ill-defined grains mostly in different mineral matrices. Both undeveloped and well-crystallised pseudo-hexagonal gibbsite in lateritic bauxite deposits are reported by Bhukte and Chaddha (2014) in the coastal Andhra Pradesh. The well-developed gibbsite crystals are the results of the complete bauxitisation process. A gradational increase in the crystallinity of bauxitic minerals is discernible from spotted to massive types. The ill-defined minute gibbsite crystals are most abundant in spotted to disseminated types; the pisolitic type comprises larger proportions of columnar crystals, while larger tabular crystals are mostly recorded in the massive types.

Well-ordered gibbsite crystals often show twinning. Some crystals exhibit polysynthetic twinning (Fig. 3f), and some others show knee-bend twinning along the pyramidal face (compositional plane). The morphological characteristics of gibbsite from different lateritic bauxite deposits of Guyana, Australia, Brazil and Jamaica are reported by Authier-Martin (2001). However, the gibbsite from the study area shows similarity with the Brazilian type rather than the other three.

Diaspore

Diaspores, the other aluminous mineral, recorded in minor proportions in massive types, occur as (i) acicular crystals (av. 50 μ length) in the form of parallel bunches (Fig. 4e) and (ii) vertically striated crystals (about 50 μ length) of prismatic habit associated with kaolinite plates (Fig. 4f). Diaspore crystals elongated along *C*-axis show the development of macropinacoidal (100), prism (110 and 110) and macrodome (101) faces; (iii) isolated prismatic crystal (av. 30 μ length) exhibiting interpenetration twinning in which the twinning plane is the pyramid and the crystals cross each other at 60°/120°. Diaspore having short prismatic or platy shapes is also reported from central Guizhou province, Southwest China (Ling et al. 2015).

Kaolinite

Kaolinite is the only silicate mineral observed under electron microscope. Further, kaolinite was recorded only in limited sample. It generally occurs as (i) loosely packed foliated books (Fig. 4a) in spotted bauxite (av. 500 μ size), (ii) well-developed six-sided, tightly packed small flakes associated either with tabular gibbsite in pisolitic types (Fig. 4b) or with prismatic diaspore in massive types (Fig. 4f; 10 to 45 μ); and (iii) hexagonal-shaped growth spirals with edges parallel to the external edges of the crystals (Fig. 4c). Wide spacing and monomolecular step heights are observed on the basal plane of these kaolinite booklets which occur as independent individuals within a hydrous aluminous phase. Six such growth steps with spacing width varying between 0.4 and 1 μm are discernible on the surface of kaolinite in one sample of bauxite.

Mineralogy

Mineralogical variations in different morphologies of Kusumdih bauxite is observed from their respective XRD (Fig. 5) and micromorphological pattern under electron microscope. Major minerals present in the lateritic zone are gibbsite and hematite. Irrespective of morpho-types, gibbsite dominates in the bauxite zone along with minor amounts of boehmites and diaspores. Minor amounts of brookite are observed along the entire profile, whereas anatase is recorded only in the laterite and bauxite zones. The saprolite sample is also rich in gibbsite along with subordinate amounts of kaolinite and albite.

Discussion

The topography of the above landscape during the formation of laterites and of their lateral facies differentiation into bauxite is reconstructed in lack of mining and sub-surface geology. The surface of the volcanics/tuffs from which these laterites derived was nearly plane. The laterite-bauxite layer, about 2–

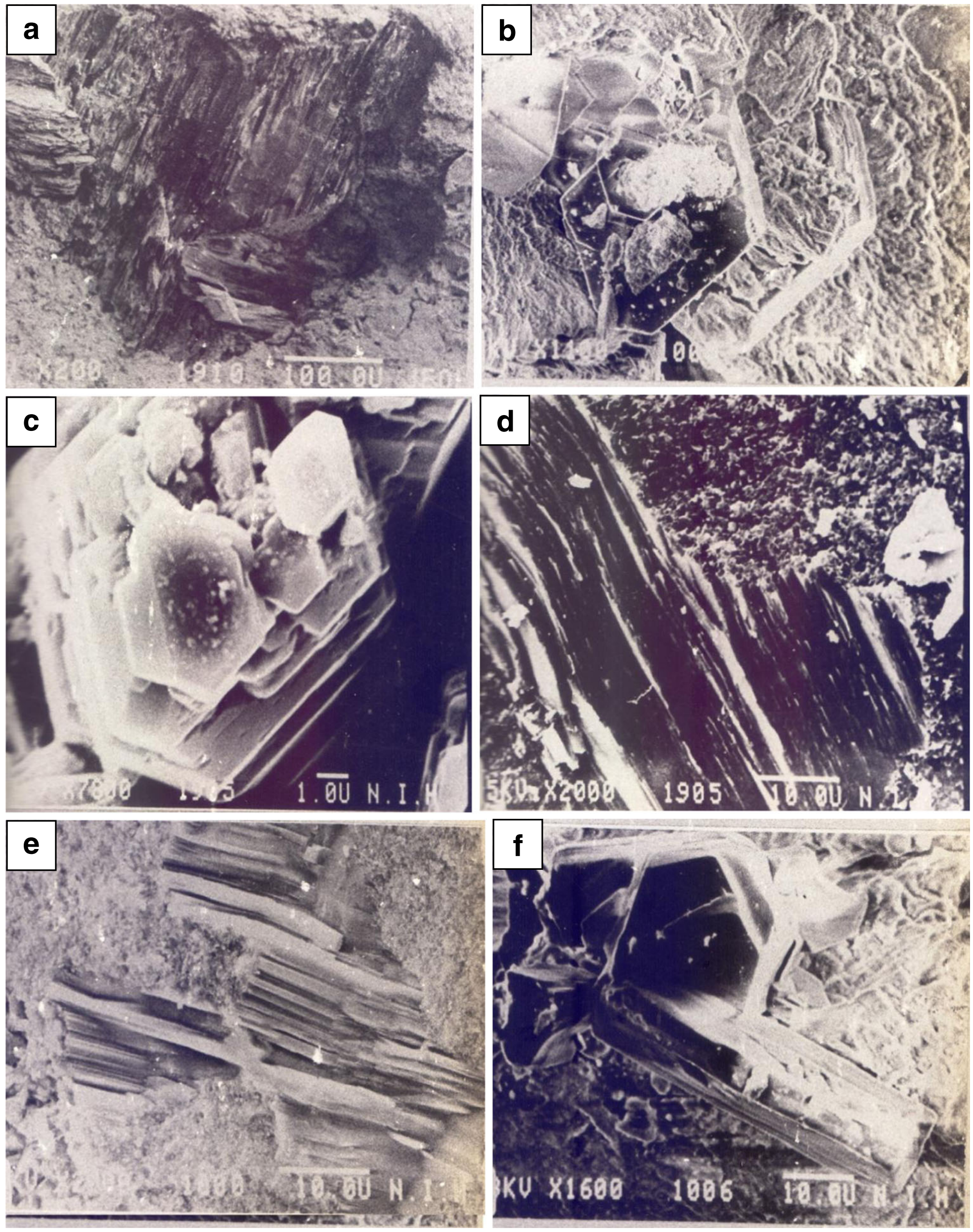

Fig. 4 **a** A coarsely crystalline and loose book of kaolinite being transformed to cryptocrystalline hydrous aluminous phase showing loose framework texture. **b** Six-sided small flakes of kaolinite, authigenically growing from gibbsite matrix of loose framework texture. To the left top, a well developed twinned gibbsite crystal is seen. **c** Tightly packed six-sided kaolinite booklet, showing multistep growth spirals elongated hexagonally and showing comparatively wide centrally increasing spacing width. **d** Fibrous scaly gibbsite in a loose framework spongy matrix. **e** Stack of acicular diaspore crystallising from hydrous alumina phase in the matrix showing loose framework texture. **f** A euhedral prismatic crystal of diaspore (vertically striated on prism face) growing at the expense of a hexagonal kaolinite crystal. The matrix is that of loose framework texture composed of fine alumina phase

7 m thick, is intersected by shallow equidimensional valleys. Thus, it is evident that the relief, during the active formation of the bauxite ore bodies in Jaldih and Kusundih are only slightly dissected and had a lowland topography.

During Tertiary to Quaternary period, in a tropical to subtropical climate, the volcanics/tuffs had undergone intense chemical leaching resulting lateral/vertical facies change giving rise to laterite and bauxite with a vertical well-developed profile as given below:

Fe-Si rich zone in upper part
Al-rich zone in the middle part
Al-Si rich zone in the lower part

During the process of lateritization/bauxitization, a lot of change took place; some elements like Si, Fe, Mg are leached out. Enrichment of Al is not only due to its residual concentration but also caused by sequential Al-migration, both laterally and downwardly, as evident from pisolitic morphology dominating over the plateau

Complex textural variations along with the presence of well-ordered gibbsite and diaspore crystals was related to very active drainage system, which was governed not only by high rate of leaching but also by concordant Al precipitation. The loose framework, reticulate and vesicle-filled textures are indicative of good leaching conditions which facilitate desilicification of the parent rock material (tuffaceous shale)

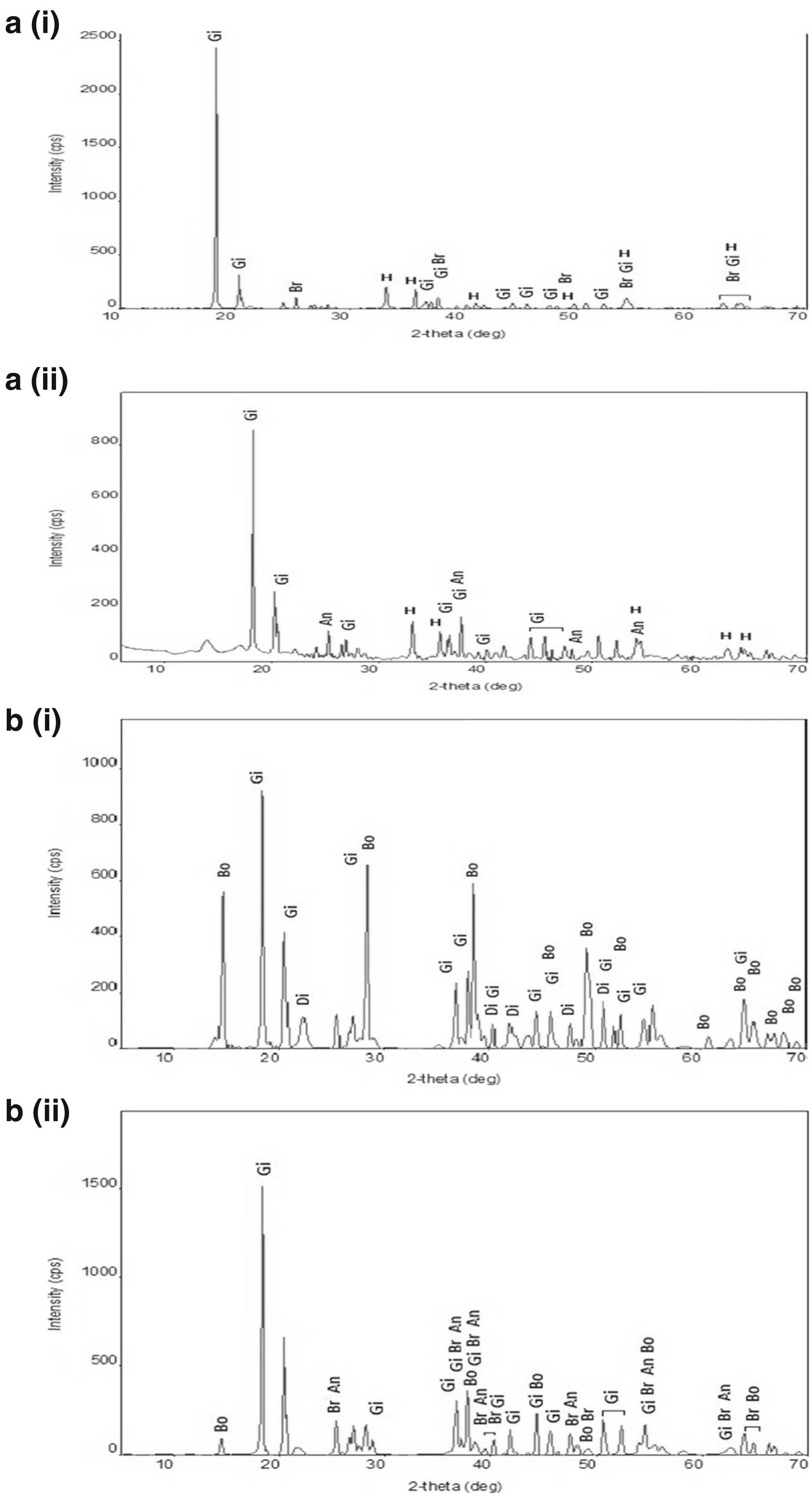

Fig. 5 XRD pattern of different lithotypes in a mine section of bauxite. **a** (*i*, *ii*) lateritic zone, **b** (*i*, *ii*) bauxite zone and **c** (*i*, *ii*) saprolite zone

to a larger extent. The complimentary precipitation of aluminous hydroxide from alumina-charged solution into the colloidal state is well documented by collomorphous and stalactitic textures. The reticulate type indicates secondary and colloidal precipitations of aluminous hydroxides in several phases over a porous substrate. Perfectly developed gibbsite

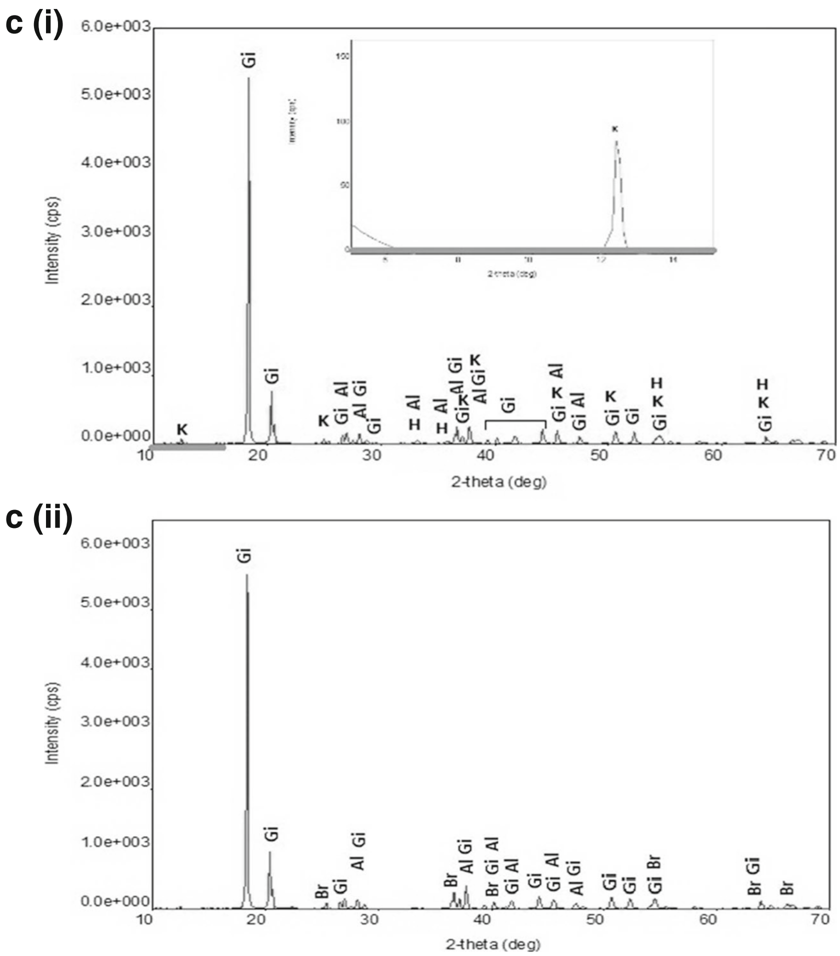

Fig. 5 (continued)

crystals along with tight framework microtextures indicate towards a high degree of recrystallisation in the weathering zone.

The mineral-textural variations, the presence of well-ordered gibbsite and diaspore crystals along with the absence of iron minerals or crystalline silica reflect, in general, the high-grade nature of this bauxite. This is also corroborated by chemical analytical data of bauxite (average value Al_2O_3–65%; SiO_2–1.00%; Fe_2O_3–2.00%).

Gibbsite crystallises from gels as 'cryptocrystalline aggregates' and directly from solutions as crystals of variable size to accumulate in pores and joints. Development of crystalline gibbsite from the Az Zabirah bauxite profile of Saudi Arabia is also reported. Diaspore is likely to have originated both by the recrystallization of gibbsite and by precipitation from alumina-rich solutions filling joints and cavities (Ling et al. 2015).

Although the required temperature for transition of trihydrate (gibbsite) to monohydrate (diaspore) ranges above 450 °C in the laboratory, the authors support Schoen and Roberson's view (Schoen and Roberson 1970) that the presence of salt in the soil profile may facilitate dehydration at low temperature. Further, electron micrographic observation by Keller (1970) of coarse diaspore's crystallization from clay deposits in Missouri, USA in a weathering environment strengthens a similar claim by the author of coarse diaspore crystallization from kaolinite at surface temperature. Figure 4f demonstrates such development of prismatic diaspore crystal from kaolinite.

Kaolinite-forming loosely packed and highly foliated coarse books (500 μ size) of irregular shape (Fig. 4a) within the matrix of aluminous hydroxide are a direct evidence of its in situ transformation to gibbsite. However, the small, tightly packed, six-sided kaolinite booklets (about 45 μ size) occurring with gibbsite are of authigenic nature and generate from the reaction between the downward-descending silica solution and microcrystalline gibbsite. Similar reaction has also been reported by Lucas et al. (1983) in elucidating the origin of bauxite at Eufavula, Alabama, USA. Liu et al. (2010) have also discussed the formation of kaolinite via silica's replacement of alumina in diaspore during the epigenetic process. Formation of epigenetic kaolinite through silicification of boehmite by the circulation of SiO_2-rich solution into its fractures and microcracks has been reported by Mameli et al. (2007) from Nurra, West Sardinia, Italy. De Kimpe et al. (1964) have, however, shown that gibbsite breaks down to boehmite under suitable acid medium in a scenario where the latter reacts with depolymerised silica solution to yield kaolinite. This mechanism accounts for the absence of crystallised boehmite in our bauxite sample. The growth of multistep spirals in kaolinite is attributed to the well known spiral mechanism of precipitation occurring from supersaturated solution (Sungawa and Yutake 1975). Their development in tightly packed kaolinite booklet also indicates that they did not grow in the open space, but in a closed system, under quiet environment. However, the scarce occurrence of such spirals suggests the limited presence of the above environment.

The presence of varied textures and well-ordered, crystalline aluminous minerals along with limited occurrence of primary clay and the absence of any silica/iron minerals in bauxite at different places of Sundergarh district, Odisha, Eastern India together indicate that the deposit has attained a maturity in bauxitisation under weathering condition at surface temperature.

Conclusions

Morphological, microstructural and mineralogical characteristics of bauxite developed over volcanics/tuffs in a part of Precambrian Iron Ore Group of rocks, Sundergarh District, Odisha, Eastern India are reported. The bauxite in general shows four types of morphology, namely, pisolitic, disseminated, massive and spotted. Common microstructures documented are collomorphous, vesicle-filled, loose-framework, chain, reticulate, stalactitic, tight-framework and foliated platy. These are refractory-grade bauxites and comprise well-developed gibbsite and diaspore crystals. Kaolinite booklets, rarely present in the bauxite zone, are of authigenic nature. The thin saprolite zone at the bottom of the bauxite contains gibbsite and kaolinite. The morphology, microstructure, mineralogy and well-ordered crystallinity reveal the development of bauxite over iron ore volcaniclastic shale and its attainment of high degree of maturity.

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