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Weathering and Mineralogical Alteration of Granitic Rocks in Southern Purulia District, West Bengal, India

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Abstract

Geologically, Purulia district of West Bengal is dominated primarily by granite gneiss rocks. Proterozic hard granite gneiss and migmatite are the principal rock types found in Manbazar while Proterozic soft, flaky phyllite and mica schist belonging to the Singhbhum Group, composed of quartz, muscovite and biotite mica, are the dominant rocks in Banduan area. The present study examines the geochemical alteration of rocks and minerals and transport of weathering end products at Manbazar and Banduan sample sites in relation to spatial variability in geological setting and differential response of rocks to weathering-denudation processes. Variations in geochemical and mineralogical characteristics were measured through weathering sequences exposed near Manbazar and Banduan in Purulia district. Altogether 14 weathered rock samples were collected from 3 weathering profiles and were analyzed mineralogically by X-Ray diffraction (XRD) technique. The major primary minerals identified in the weathering crust of granitic rocks are quartz, muscovite, feldspar and biotite. The dominant secondary minerals are kaolinite, montmorillonite and illite. Quartz is found in all the sequences of weathering crust for its poor susceptibility to chemical weathering. The occurrence of Phyllosilicate clay minerals in all the weathering facies in the study area is indicative of an intensive weathering under tropical humid climate leading to the development of weathered crust.

Keywords: Geochemical alteration, x-ray diffraction, primary minerals, phyllosilicates, weathering crust.

Introduction

The study of geochemical weathering in different weathering crusts is a subject of great geomorphological interest, because it is an important source of information on the condition of landscape evolution, especially in humid tropical areas. Chemical weathering and physical erosion are act together to generate soils and sculpt landscapes. They are also interdependent. Chemical weathering is responsible for alteration of chemical composition and/or structural organization of minerals and weathering of rocks and thereby makes rocks prone to physical weathering. On the other hand, physical disintegration makes more mineral surface available for chemical attack[1]. Chemical weathering of rocks is one of the major processes that modify the earth's surface and is one of the vital processes in the geochemical cycling of elements[2]. Widely variable the rate and nature of chemical weathering are controlled by several factors of which the most important are climatic condition, rock type, surface topography, and time[3]. During weathering the mobilization and reorganization of trace elements are affected by various processes such as dissolution of primary minerals, formation of secondary phases, coprecipitation, ion exchange and transport of materials[4-6]. However, in 1988 Middleberg et al.[7], some general statements apply.

Weathering of rocks alters their physical, chemical or mineralogical properties, and in often poorly understood ways, creating difficulties for engineering in these materials. The spatial and temporal contexts have been chosen as a framework for assessment of the importance of chemical weathering for the formation of bedrock morphology by chemical weathering[8]. During weathering of granitic rocks and rock-forming minerals are partly dissolved by some chemical weathering processes like hydrolysis and hydration. New secondary minerals like illite and montmorillonite are the earliest to be formed, followed by biotite and kaolinite. As leaching intensifies, partial desilicification occurs and many clay minerals can be converted to oxides. Little et al. have studied the effects of weathering on quartz in dune sand in Eastern Australia. These investigators found some quartz gains which are extremely weathered and indicated the rate of weathering of quartz gains, which was very much dependent on their microstructure and original environment of formation[9]. In a deep weathering profile the geochemical alteration of feldspars to halloysite, keolinite, and gibbsite in Peninsular Malaysia has been reported by Eswaran and Bin (1978 a,b)[10,11].

Weathering is closely related to dynamics of geomorphology, as it both drives and reflects morphogenesis[12]. The type and degree of weathering of in situ materials (saprolite and soils) are indicative of the environmental conditions and the intensity of development of surficial materials. With the changing environmental condition, properties related to previous weathering conditions are usually preserved[13]. Petrographic and mineralogical analyses are useful tools for the understanding of the factors controlling the weathering of crystalline rocks and their influence on the typical development of weathered landforms. Thus, relations between the parent rock materials and secondary clay minerals can assist in determining different degrees of weathering. Extensive efforts have been directed at determining the feedback mechanisms and rates of weathering of the most common minerals present in crystalline protoliths[14]. Bhattacharyya et al. have investigated the origin of gibbsite in the ultisols from northeast India. They found that the typical rod-shaped and well crystallized gibbsite formed through the weathering of alluminosilicate minerals[15]. Hill et al. studied the geochemical alteration of paleolaterite in Northern Ireland where they reported an assemblage of neo-formed mineral consisting of gibbsite, hematite, meta-halloysite and kaolinite[16].

Pre Cambrian to Archacan granite gneiss and mica schiest rocks of Purulia district, are intensely weathered. The area lies within the tropical to subtropical monsoon warm humid climatic region. The present study was undertaken in order to characterize the alteration of primary minerals, formation of secondary minerals and the nature and environments of the weathering crust.

Study area: The study area, Purulia district is located in the western most part of West Bengal (Figure-1), belonging to the eastern plateau region of India. It is surrounded by Paschim Medinipur, Bankura and Burdwan districts of West Bengal and Dhanbad, Bokaro, Hazaribagh, East and West Singhbhum of Jharkhand state. The Purulia district extends between 22° 42′ 19″ N and 23° 42′ 00″ N latitudes and 85° 49′ 19′ E and 86° 54′ 25″ E longitudes covering an area of 6259 sq. km. Climatically, the area is subtropical and sub-humid, with hot wet summers and cool dry winters characterized by annual mean temperature of 25.6° C and mean summer and mean winter temperature of 29.0° C and 21.3°C, respectively. The monsoon is the main source of precipitation, which starts in May and continues up to October. It has an annual average precipitation of 1393 mm. About 82% of the annual rainfall occurs during the monsoon which lasts roughly from June to September.

Regionally the area is a part of Chotanagpur Gneissic Complex of Eastern Indian Peninsular Shied, lying to the north of Singhbhum Craton. China clay occurrences of Purulia district are invariably associated with granitic rocks and metasediments of the Chhotanagpur Gneissic Complex of Precambrian age. Dunn and Dey first described the complex as largely a product of replacement origin[17]. The area is mostly covered by soil and represents undulating topography with moderate to gentle slopes. Purulia has a thick Stratigraphic succession of mostly Archacan granite gneiss (table-1) and to a much lesser extent, Quaternary semi consolidated sediments, Permo Carboniferous sandstone shale, Pre Cambrian massive granites and quartzite and with Recent alluvium sediments deposition (figure-2). Mineralogically these rocks are composed mainly of quartz, feldspar, muscovite, biotite, illite and kaolinite.

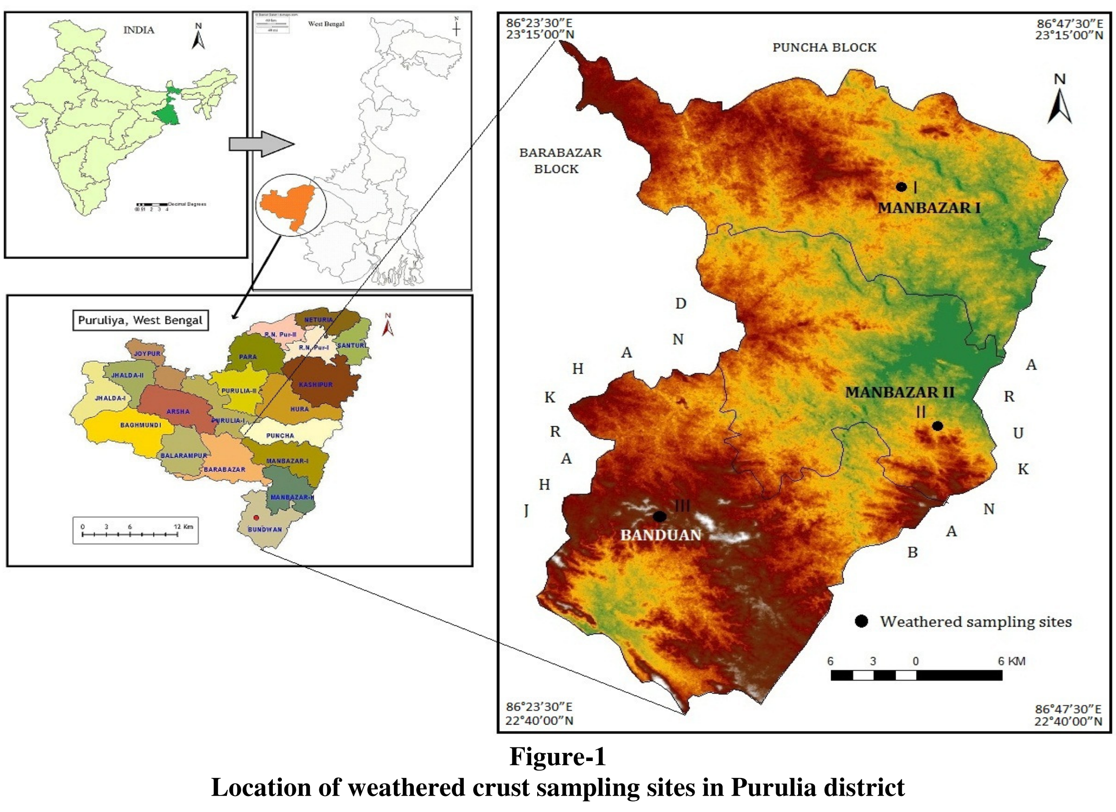

Figure-1
Location of weathered crust sampling sites in Purulia district

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Table-1
Stratigraphic succession in Purulia district (Adapted from Geological Survey of India)

Formation	Age	Lithology	Hydrogeology
Recent Alluvium	Recent	Semi consolidated sediments consisting of conglomerates, lateritic and gravel beds	Aquifer is shallow and unconfined. Yield is 5000, to 7000 lph
Sijua Formation	Quaternary	Semi consolidated sediments consisting of gravel bed and conglomerate	Aquifer is shallow and unconfined. Yield is 5000, to 7000 lph
Gondwana Rocks	Permo Carboniferous	Sandstone shale and coal seams	Sandstone act as minor aquifer Secondary aquifer developed with the fracture zone and cracks and fissures. Average yield is 8000 to 10000 lph
Quartzite and Pegmatite Granite	Pre Cambrian	Massive Granites and pegmatite and quartzite veins	Secondary aquifer developed at the capping and on the weathered resideum. Cracks and fissures developed in the rocks act as a minor store of groundwater. Aquifer is shallow and unconfined. Yield is 500, to 700 lph
Meta Volcanics	Archacan	Rock types belong to Chhotanagpur gneissic complex. Granite gneiss with quartz veins and pegmatite veins.	Secondary aquifer developed at the capping and on the weathered resideum. Cracks and fissures developed in the rocks act as a minor store of ground water. Aquifer is shallow and unconfined. Yield is 500, to 7000 lph
Metabasic Rocks			
Phyllite and Mica Schiest			
Granite Gneiss			
Calc Granulites			
Mica Schiest		Muscovite and biotite schiest, highly foliated	

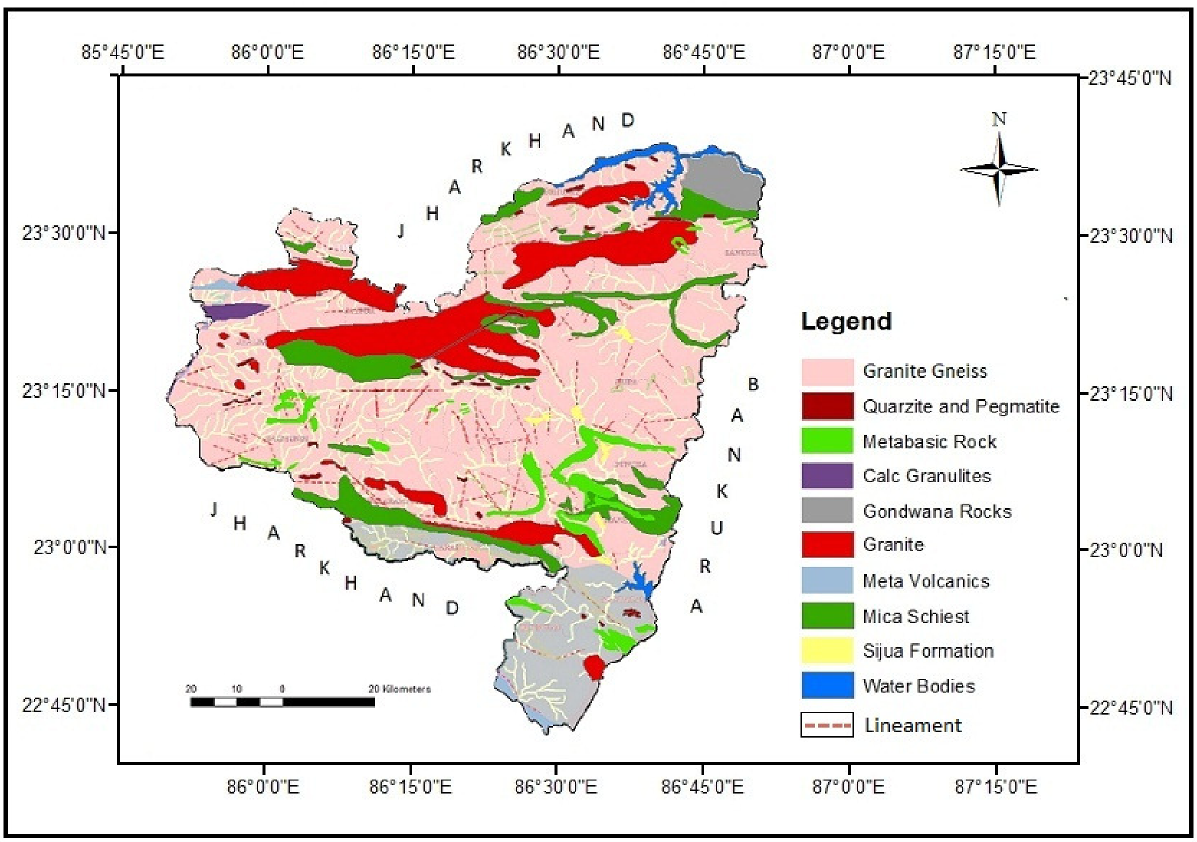
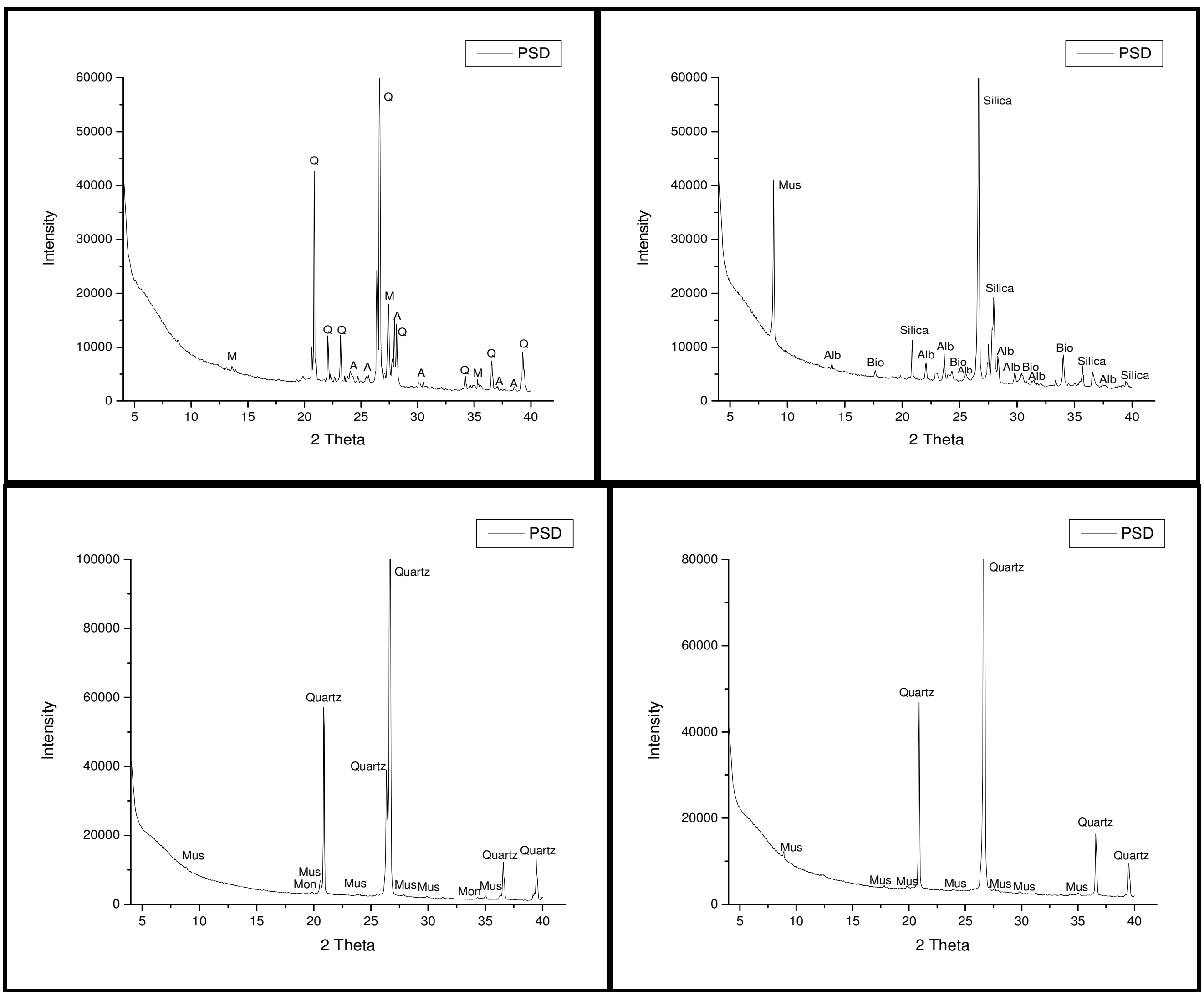


Figure-2
Geological map of Purulia district (source: G.S.I.)

Material and Methods

Field work: Geological, pedological and geomorphological techniques were integrated in the analysis of weathering crust in 3 sample sites of Purulia district with the goal of understanding the weathering processes as a whole. Field work was carried out during March and April, 2013. Granitic weathering crusts were collected from 3 sections (14 samples total) of 3 different C.D. blocks namely, Manbazar-I, Manbazar-II and Banduan situated in the South-eastern part of Purulia district (Figure 1). Sampling was restricted mostly within the exposed layers of the respective weathering profile. The samples from weathered crust were collected along road cuts, natural and other man-made exposures. Sampling began from the bottom of the weathered profiles and the sampling interval within the profiles was determined depending upon the lithological and mineralogical characters. The weathered materials derived from hard bedrocks were mainly grey to redish grey or brown to yellowish brown in colour. This fine to medium grain size materials occur in association with altered siltstone, claystone and shale in the profile.

Laboratory work: About 150-200 gm of dried bulk samples was broken by a small hammer and hand crusher primarily to reduce the rock aggregate to smaller particles and finally to get the powder samples. To determine the mineralogical composition of different weathering facies, X-Ray Diffraction (XRD) analysis was performed on the powder samples using X-Ray Diffractometer PW-17291710 at the department of Chemistry, Indian Institute of Technology, Kharagpur. The step size was °2Th (0.05°) and the step time was 1 sec with fixed 1 mm divergence silt in 25°C temperature. The scan range was 2°-40°. Sample fractions were mounted on a glass slides in order to obtain an ideal orientation of sample minerals. Geochemical alteration was deduced from the mineralogical composition as observed in the micro-morphological analysis.



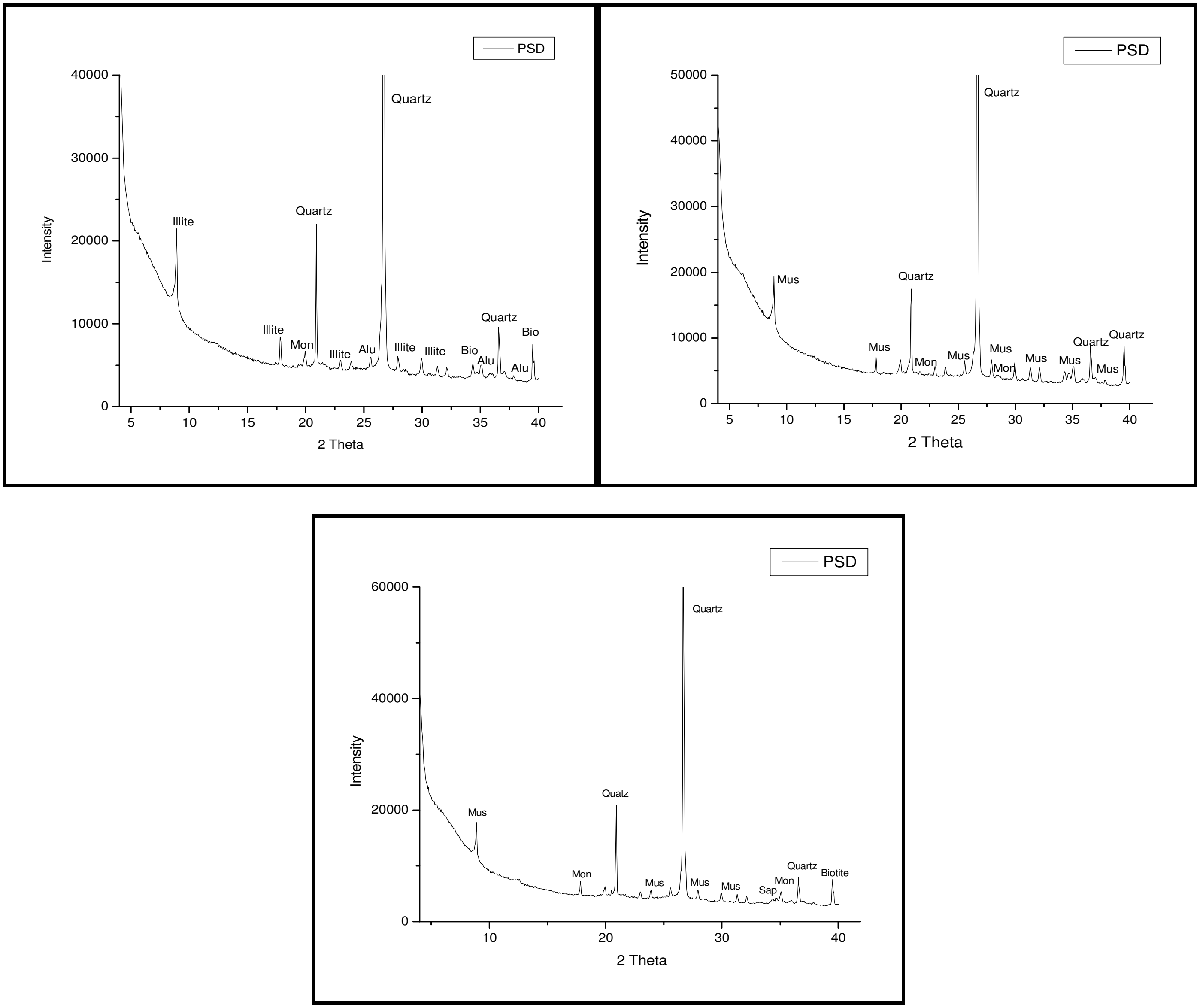


Figure-3

Characteristics of X-ray diffraction diagram for mineral identification. The site location are M-I 1: Manbazar-I upper; M-I 2: Manbazar-I lower; M-II 1: Manbazar-II upper; M-II 2: Manbazar-II lower; B 1: Banduan upper; B 2 Banduan middle; B 3: Banduan lower. In XRD graph M = montmorillonite, A = albite, Q = quartz, Mon = montmorillonite, Mus = muscovite, Bio = biotite, Alu = alumina

Results and Discussion

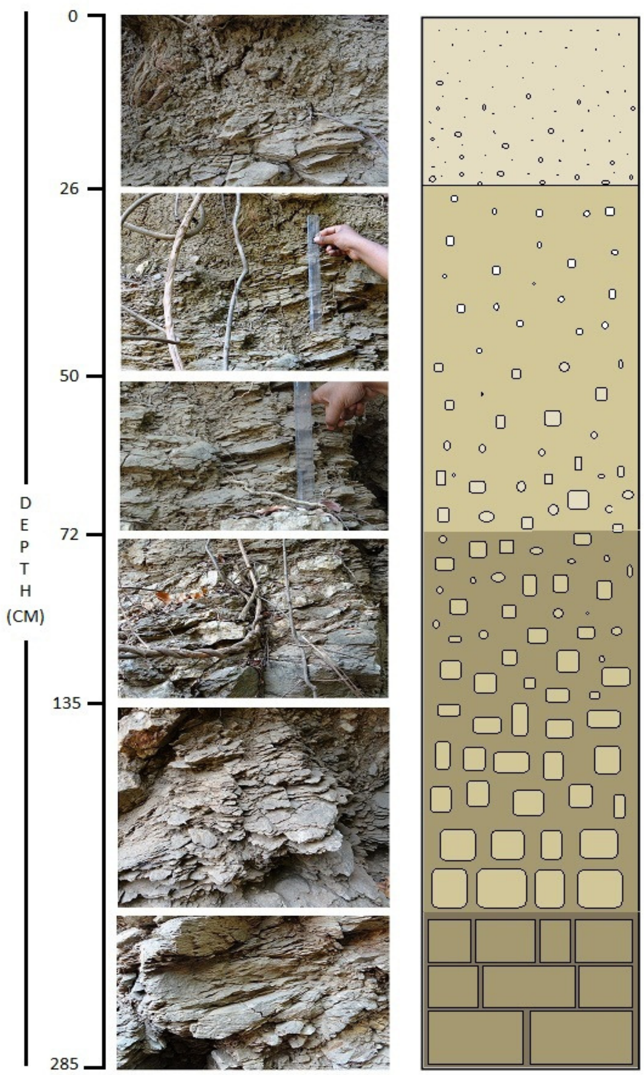
Quartz and muscovite are the primary minerals indentified by the XRD data and the most important clay minerals are kaolinite, montmorillonite, illite, alumina or gibbsite and saponite. Quartz is identified by its typical 3.34 Å peak. Gibbsite is identified by its 2.45 Å peak. Illite can be identified by 10 Å and 13.7 Å peaks.

The weathering profile of granite gneiss sampled at approximately 6 km southeast of Banduan, Purulia, provides a complete weathering sequence from fresh to complete weathered rock. This exposure is a part of Chhotanagpur gneissic complex and consists of granite gneiss with quartz veins and mica schist. Figure 4 is a summary log of one of the quarry profiles. The profile can be divided into four weathering grades based on visual characteristics modified as defined by the New Zealand Geomechanics Society standards[18]. fresh (F) unweathered parent rock shows no evidence of weathering; slightly weathered (SW) rock has discolored discontinuity surfaces; moderately weathered (MW) rock is discolored with some soil materials; highly weathered (HW) rock containing more than 60% soil materials but may contain core stones.

Sampling locations were selected to obtain a range of materials through the profile.

The Petrographic analysis by XRD shows that muscovite, silica, albite and biotite are the main primary minerals which have composed the bed rock of Manbazar-I profile and smaller quartz grains, albite and montmorillonite are main minerals found in the saprolite of the same profile. In the Manbazar-II profile, quartz and muscovite are identified as primary minerals in the parent materials and in the upper layer of this weathered profile quartz and muscovite are identified to occur in the form of smaller particles and montmorillonite could be identified as the dominant secondary clay mineral. In the Banduan weathered profile muscovite, quartz, saponite and biotite are identified as the dominant primary minerals in the base rock and quartz, muscovite and montmorillonite in the saprolite. In the upper layer of this profile quartz, biotite, illite, alumina, montmorillonite are identified as the main minerals of secondary origin.

Discussion: Purulia District comes under the sub tropical region and characterized by the monsoon climate. Therefore, in Purulia the average temperature of about 25-35°C and rainfall of about 150 cm in rainy season are the favorable conditions for moderate physical weathering and moderate to strong chemical weathering. So the rock fragmentation by physical weathering and mineralogical alteration by chemical weathering simultaneously act to generate soil and differential landforms (Figure-5 and 6) in the study area. The processes of geochemical alterations throughout the weathering crust are more or less similar in all of the sample profiles.



Highly weathered materials contain more than 70% insoluble secondary clay minerals (Montmorillonite) and resistant minerals (Quartz, Muscovite), grey to radish brown with fine component comprised of clay minerals.

Moderately weathered rock contains secondary clay minerals and other soluble minerals such as Biotite, Illite, alumina, Montmorillonite, and quartz. Dark grey to brown, moderately strong, contain 60% clay minerals.

Slightly weathered, dark grey and loose bedrock with plate like structure contain lesser amount of clay.

Unweathered Parent Rock, dark grey and very strong bed rock, contains Quartz and muscovite.

Figure-4
Banduan weathering profile description

Table-2
Weathering potential index of different minerals

Group	Mineral	Formula	Weathering potential index
Silicates	Serpentine	$Mg_3\,Si\,O_5\,(OH)_4$	-
	Biotite (mica)	$K\,(Mg, Fe)_3\,(Al\,Si_3\,O_{10})\,(OH)_2$	22
	Albite (sodic plagioclase)	$Na\,(AlSi_3\,O_8)$	13
	Orthoclase (potassium feldspar)	$K\,(Al\,Si_3\,O_8)$	12
	Quartz	$Si\,O_2$	0
	Muscovite (mica)	$K\,Al_2\,(Al\,Si_3\,O_{10})\,(OH)_2$	- 10.7
Clays	Montmorillonite (Na or Ca)	$Na_{0.5}\,Al_{1.5}\,Mg_{0.5}\,Si_4\,O_{10}\,(OH)_2$	-
	Illite	$K\,Al_2\,(Al\,Si_3)\,O_{10}\,(OH)_2$	-
	Vermiculite		-
	Kaolinite (+ halloysite)	$Al_2\,Si_2\,O_5\,(OH)_4$	- 67

Source: adapted from Chorley, et.al. 1984

Figure-5
Geochemical alteration in different sequence of weathering crust at Manbazar-I sample site

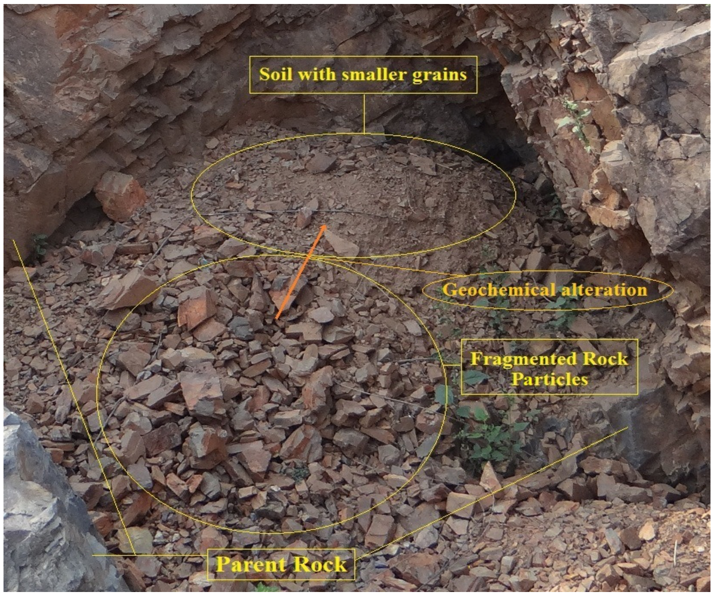


Figure-6
Physical and chemical weathering are together to generate soil (Manbazar-II sample site)

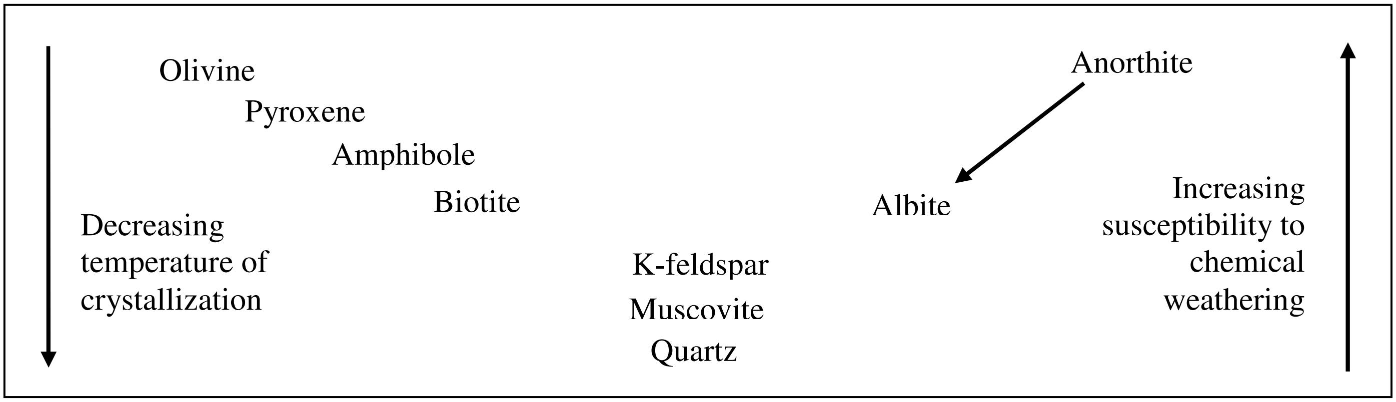


Figure-7
Bowmen's reaction series and mineral susceptibility to chemical weathering

Rainfall is an important factor to influence chemical weathering. It controls the moisture supply for chemical reactions and for the removal of soluble constituents of the minerals[19]. Minerals are well leached through constant downward movement of percolating rain water. Availability of the sufficient water in saprolite has been responsible for permanent saturation of the stable minerals and increased potentiality of mineralogical alteration of parent rock. Under these situations, the chemical weathering tends to ensue rapidly through loss of soluble constituents and the residue becomes progressively enriched with minerals than are left over.

The petrographic analyses by X-ray diffraction reveal that quartz, feldspar, muscovite and biotite are the main primary minerals in all sample profiles and those minerals are observed mainly in unweathered bedrock of each profile. On the other hand kaolinite, montmorillonite and illite are indentified as the main secondary minerals which are found to occur in the upper layers of the weathering profile. At the same time, smaller grain of some primary minerals like, quartz and muscovite are present throughout profile. According to Bowmen's reaction series, quartz and muscovite has poor susceptibility to chemical weathering (figure-7) or very less potential for weathering (table-2). Because the susceptibility of silicates minerals to weathering depends on the number and weakness of the cation links (K^+, Na^+, Mg^{2+}, Ca^{2+}, Fe^{2+}, Fe^{3+}, Al^{3+}) between the silicate tetrahedras and in quartz this tetrahedra are completely interlocked[20]. Because of this quartz (SiO_2) is present throughout the weathered profiles in the study area. In some cases K^+ ion is leached out from muscovite [$K\ Al_2\ (Al\ Si_3\ O_{10})\ (OH)_2$] and partly retained to kaolinite [$Al_2\ Si_2\ O_5\ (OH)_4$] (Figure-9). In potassium feldspar (orthoclase) the structure of silica tetrahedra is tight enough seriously to reduce the escape of K^+ ions; in albite the silicon tetrahedra structure is weakened by replacement of Si^{4+} ions by Al^{3+} ions; in biotite mica sheets the silica tetrahedra are sandwiched between Al^{3+}, Mg^{2+}, Fe^{2+} and K^+ ions[20]. Therefore, K^+, Na^+, Mg^{2+}, Ca^{2+}, Fe^{2+}, Fe^{3+}, Al^{3+} ions of feldspar, albite and biotite are released in lower saprolite and chemically altered to secondary silicates like kaolinite, montmorillonite, vermiculite or illite. Islam et al. (2002) has reported that plagioclase feldspar gets more intensively weathered than K-feldspar[21]. During intense weathering feldspar in the studied profiles has been altered to illite and illite to kaolinite. The weathering of trioctahedral biotite to dioctahedral kaolinite indicates might be an extreme example of change in composition between reactant and produced phyllosilicates[22]. They have also stated that solution-precipitation was the major process of the alteration of feldspar to clay minerals where as biotite was epitactically replaced by kaolinite. The usual sequence from complex to simple minerals is as follows:
Feldspar → montmorillonite → kaolinite → gibbsite
The weathering of feldspar may thus be represented by:

$$2K\ Al\ Si_3O_8 + 2H_2O + CO_2 \rightarrow Al_2\ Si_2\ O_5\ (OH)_4 + K_2\ CO_3 + 4SiO_2$$
Feldspar Kaolinite

Feldspar → Illite → Kaolinite[21]

$$6K\ (Al\ Si_3\ O_8) + 4H_2O + 4CO_3 \rightarrow K_2\ Al_4\ (Si_6\ Al_2\ O_{20})\ (OH)_4 + 12SiO_2 + 4K^+ + 4HCO_3^-$$
Orthoclase Illite solution

And continued leaching may form kaolinite:
$$2K\ Al_5\ Si_7\ O_{20}\ (OH)_4 + 2H_2O + 2CO_3 + 13H_2O \rightarrow 5Al_2\ Si_2\ O_5\ (OH)_4 + 4H_4SiO_4 + 2K^+\ 2HCO_3^-$$
Illite Kaolinite

According to Bethke, chemical reaction produces gibbsite from feldspar and adds Na^+, K^+ and dissolves SiO_2 in the top layer of the saprolite, according to the reactions as follows[23].

$$Na\ Al\ Si_3\ O_8 + CO_2 + 2H_2O \rightarrow Al\ (OH)_3 + Na^+ + 3SiO_2 + HCO_3^-$$
Albite Gibbsite
$$K\ Al\ Si_3\ O_8 + CO_2 + 2H_2O \rightarrow Al\ (OH)_3 + K+ + 3SiO_2 + HCO_3-$$
K-feldspar Gibbsite

At the same time, fragmented quartz at the same place dissolves congruently, adding additional silica to solution.

$$SiO_2 \rightarrow SiO_2$$
Quartz dissolves quartz

As result of these reactions, abundance of silica in saprolite increased. Because of this in the solution secondary clay minerals becomes saturated and precipitates and the mineral replaces gibbsite as the sink for alumina. The reactions are given below,

$$Na\,Al\,Si_3\,O_8 + CO_2 + 3\,H_2O \rightarrow Al_2\,Si_2\,O_5\,(OH)_4 + Na^+ + 2\,SiO_2 + HCO_3^-$$
Albite Kaolinite

$$K\,Al\,Si_3\,O_8 + CO_2 + 3\,H_2O \rightarrow Al_2\,Si_2\,O_5\,(OH)_4 + Na^+ + 2\,SiO_2 + HCO_3^-$$
K-feldspar Kaolinite

Figure-8
Weathering profile of Manbazar-II

During the early stage of geochemical alteration, etching takes place along surfaces and boundaries of particles as well as along the fracture planes of the minerals. Quartz persists throughout the saprolite because quartz is less susceptible to chemical weathering (figure-7) and is not chemically altered. So fragmented (physical weathering) smaller quartz grains are found to occur in the upper layer of all weathered crusts in the study area. At the extreme stage of weathering, silicate clay minerals are altered to secondary clay minerals[4]. In the presence of meteoric water kaolinite formed from feldspar and mica in saprolite[24]. These situations occur in the areas with hot and humid climate, particularly under tropical and subtropical climatic environment. Ehlmann has reported that, kaolinite is originated due to intensive leaching in presence of greater precipitation[25]. Wilson has reported that formation of secondary clay minerals such as kaolinite from biotite is common under a 'more extreme weathering condition', particularly in tropical to subtropical environments[26-28]. Within a single biotite grain, oxidation, cation ejection, K-exchange, and development of secondary minerals simultaneously occur[29]. As biotite and feldspar are affected at the early stage of weathering, the secondary clay minerals such as kaolinite, montmorillonite and illite are found to occur in the study area. It could be possible that kaolinite is formed through the biotite via vermiculite (figure-9) and the sequence is given below:

Biotite → vermiculite → montmorillonite → kaolinite

Weathering of muscovite produces dioctahedral montmorillonite and regular mixed-layer mica-montmorillonite which suggests that the transformation into kaolinite may take the following course[30]:

The presence of kaolinite and montmorillonite in all saprolite indicates an intense weathering stage in which vermiculite has been decomposed to kaolinite. Many earth scientists have emphasized that the development or formation of secondary clay minerals like kaolinite, gibbsite, illite from primary minerals such as feldspar, muscovite, biotite are favorable under an alternating wet and dry climatic condition which is also a climatic characteristics of the area under study. Weaver reported that the alteration of biotite to vermiculite advances in the humid tropics to weather directly in to kaolinite or halloysite[37]. However, similar statements apply by Torrent and Benyas[38]. The presence of montmorillonite in dominance over kaolinite and large size fragmented rock materials in the upper saprolite of Manbazar-I and II profiles (figure-8) indicates that chemical alteration and soil formation processes are yet to advance to reach an equilibrium weathering condition.

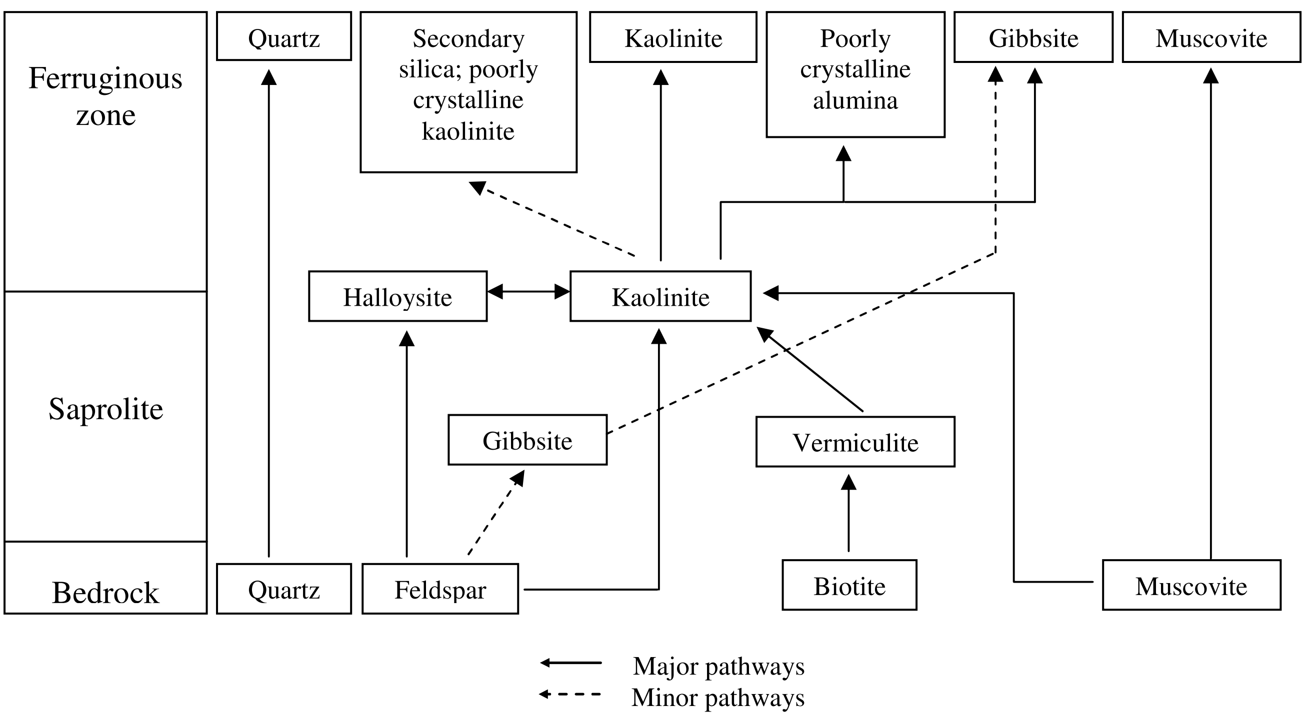


Figure-9
Pathways of formation of secondary minerals in weathering profiles (modified from Anand and Paine 2002; and compiled from Gilkes et al. 1973; Anand and Gilkes 1984a, b, c; Singh and Gilkes 1991)[31-36]

Muscovite → Muscovite/montmorillonite → Montmorillonite → Kaolinite

$$2K_2 Al_4 (Si_6 Al_2) O_{20} (OH)_4 + 6H_2O + 4 H^+ \rightarrow 3Al Si_4 O_{10} (OH)_8 + 4K^+$$

Muscovite Kaolinite

Conclusion

The present study shows that in the early stage of weathering, physical process initially disintegrated the parent rocks as seen in all weathering sequences, followed by the progressive development of secondary minerals which reduce the strength of materials. The variability of geochemical or mineralogical alteration of primary minerals to secondary clay minerals is conspicuous. This study shows that studied part of Purulia district underwent intense chemical weathering in relation to physical disintegration. The present climatic condition of relatively wider range in temperature and abundant rainfall throughout the study area are reflected in the degree of weathering. Sufficient supply of water favours alteration of alluminosilicate minerals to secondary clay minerals. The presence of secondary Phyllosilicate clay minerals such as montmorillonite and kaolinite in all the weathering crusts is indicative of intense chemical weathering and also indicates that weathering had passed through an early stage but yet to reach an extreme stage of equilibrium.

Feldspar, biotite and muscovite are the major primary minerals which are affected during weathering. Feldspar and biotite are much more altered than muscovite in all the profiles. Feldspar has been altered to kaolinite followed by the gibbsite and illite by chemical weathering. Biotite has been altered to montmorillonite and kaolinite followed by vermiculite during intense weathering. So the abundance of secondary clay minerals in granite gneiss saprolite may indicate a set of weathering processes that promote laterization operative under a tropical to subtropical humid climate of the study area.

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