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Mineralogical changes during intense chemical weathering of sedimentary rocks in Bangladesh

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Abstract

Bangladesh is situated in a subtropical to tropical climatic zone. A recently weathered crust has developed on sedimentary bedrock (sandstone, siltstone, shale and claystones) of Tertiary–Quaternary age. Weathered samples were collected from 16 sections totaling 68 samples and were analyzed mineralogically. The main primary minerals identified in the weathered crust of sedimentary rocks are quartz, plagioclase, K-feldspar, biotite, muscovite, sparse carbonate and epidote. The secondary minerals are kaolinite, illite, chlorite, gibbsite and goethite. Weathering initiated along the grain boundaries and cleavage planes of the minerals, forming small cloudy materials which were very difficult to identify. In the advanced stage of weathering, these cloudy materials have turned into secondary minerals. In region 1, high rain fall (7100 mm/yr) and monsoonic climate resulted in a kaolinite–gibbsite–goethite suite through the weathering of feldspars and biotite. The occurrence of gibbsite in the relatively elevated lands of Sylhet and Fe-kaolinite throughout the study areas is indicative of a humid–tropical climate during formation of the weathered crust. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Chemical weathering; Sedimentary rocks; Kaolinite; Gibbsite; Bangladesh

1. Introduction

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 (Berg, 1932). The rate and nature of chemical weathering vary widely and are controlled by many variables such as parent rock type, topography, climate and biological activity. The mobilization and redistribution of trace elements during weathering is particularly complicated because these elements are affected by various processes such as dissolution of primary minerals, formation of secondary phases, redox processes, transport of materials, coprecipitation and ion exchange (Harris and Adams, 1966; Nesbitt, 1979; Chesworth et al., 1981; Fritz and Ragland, 1980; Cramer and Nesbitt, 1983; Fritz and Mohr, 1984). Nevertheless, some general statements apply (Middleberg et al., 1988).

During weathering of crystalline rocks, rock-forming minerals are partly dissolved and hydrolysis and hydration take place. New secondary minerals like illite and smectite are the earliest to be formed, followed by halloysite and kaolinite. In the final stage, as leaching intensifies, partial desilicification occurs and kaolinite is converted to gibbsite.

Little et al. (1978) have studied weathering effects on quartz in dune sand in Eastern Australia. These investigators found some extremely weathered quartz grains, and the rate of weathering of quartz grains was very much dependant on their microstructure and original environment of formation. Alteration of feldspars to halloysite, kaolinite, and gibbsite in a deep weathering profile in Peninsular Malaysia has been reported by Eswaran and Bin (1978a,b).

Feldspars in soil reportedly weather directly to an amorphus phase (Fields and Swindale, 1954), to halloysite (Parham, 1969), kaolinite (McCaleb, 1959; Exley, 1976), gibbsite or boehmite (Helgeson et al., 1969; Parham, 1969; Lodding, 1972). Mineral, chemical, and texural changes produced by tropical weathering are reviewed by Delvinge (1965), Nahon (1976, 1991) and Merino et al. (1993) among others.

Banfield and Eggleton (1990) carried out AEM and TEM studies of plagioclase, muscovite, and K-feldspar weathering in New South Wales, Australia. They reported the assemblage of clay minerals produced by weathering of feldspars and muscovite including spherical and tubular

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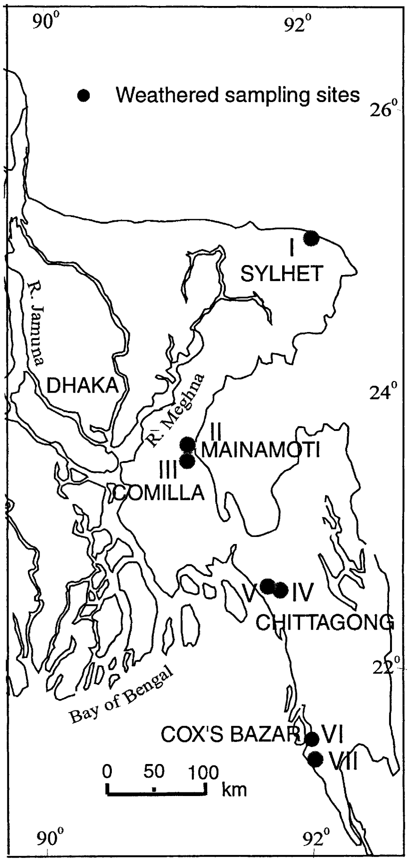


Fig. 1. Location map of Bangladesh showing the sampling sites of weathered samples. Region (I) Barail Group (1 sampling section), Bhuban Formation (2 sampling sections, one each in shale and sandstone); Boka Bil Formation (2 sampling sections), Dupi Tila Formation (1 sampling section); (II) Madhupur Clay Formation (2 sampling sections); (III) Madhapur Clay Formation (2 sampling sections); (IV) Dupi Tila Formation (2 sampling sections); (V) Tipam Sandstone (2 sampling sections); (VI) and (VII) Dupi Tila Formation (1 sampling section from each).

halloysite, and platy kaolinite. Banfield and Eggleton (1988) carried out a TEM study of biotite weathering in New South Wales, Australia and concluded that biotite weathers initially to interstratified biotite/vermiculite, goethite, and kaolinite. In the second stage weathering products are dominated by kaolinite and goethite. Chemical weathering rates of silicate minerals have been reviewed extensively in numerous review papers in volume edited by White and Brantley (1995).

Bhattacharyya et al. (2000) have investigated the genesis of gibbsite in the Ultisols from northeast India, which is very close to the present study area (sampling location 1 Fig. 1) in having similar climatic features. They found that the typical rod-shaped and well crystalized gibbsite formed through the weathering of alluminosilicate minerals. Hill et al. (2000) studied the geochemical evolution of paleolaterite in Northern Ireland where they reported a neo-formed mineral assemblage consisting of hematite, gibbsite, goethite, anatase, meta-halloysite and kaolinite.

The Tertiary–Quaternary sedimentary rocks of Bangladesh are intensely weathered throughout most of the country, particularly in the northwestern, northeastern, eastern and southeastern parts. Most of these areas are characterized by weathered to lateritic red soils. The area lies within the subtropical to tropical humid monsoon climatic zone. We know of no previous studies of weathering that have been carried out in Bangladesh. The present work was undertaken in order to characterize the alteration of primary minerals, formation of secondary minerals, and the nature and environments of the weathering crust.

2. Study area

Bangladesh is located between latitudes 20°43′ and 26°36′N and longitudes 88°3′ and 92°40′E (Fig. 1). Bangladesh occupies the greater part of the Bengal Basin and covers part of the Himalayan piedmont plain and the eastern and southeastern hill ranges of the Sylhet, Chittagong and Chittagong Hill Tracts (Paul and Lian, 1975). The Bengal basin is enclosed to the west, north and east by the Indian shield, the Shillong shield, and the Naga-Lustrai orogenic belt, respectively, and opens to the south into the Bay of Bengal (Sengupta, 1966).

Bangladesh lies within a tropical and subtropical monsoon climatic zone. The monsoon is the main source of precipitation, which begins in May and continues up to October. The climatic features of Bangladesh vary from region to region and season to season. In eastern Bangladesh, precipitation is at a maximum in the northeast and at a minimum in the central region. The mean annual maximum and minimum temperatures of the northeastern district of Sylhet are 35 and 18 °C, respectively, with mean annual rain fall of 7106 mm (Khan, 1978) and average annual humidity of 78% (Statistical Year Book of Bangladesh, 1991). The mean annual maximum and minimum temperatures of the central eastern district of Comilla are 31 and 19 °C, respectively, with annual rainfall of 1629 mm and an average relative humidity of 80%.

The Chittagong and Cox's Bazar districts are situated in the southeastern part of Bangladesh. In the Chittagong district, the annual mean maximum temperature is 31 °C and the mean minimum temperature is 20 °C. Average annual rainfall is 3022 mm and mean annual relative humidity is 76%. The mean annual maximum and minimum temperatures of the Cox's Bazar district are 31 and 21 °C, respectively, with mean annual rainfall of 3633 mm (Samad, 1986) and humidity of 78% (Statistical Year Book of Bangladesh, 1991).

Bangladesh has a thick stratigraphic succession of mostly Tertiary sediments (see Table 1 for Oligocene and younger stratigraphy) and, to a much lesser extent, Quaternary sediments. Sandstone, siltstone, shale and claystone are the main rock types. These rocks are composed mainly of quartz, plagioclase, K-feldspar, biotite, muscovite, kaolinite and illite (Islam, 1996). The detailed stratigraphy of Bangladesh is described by Khan and Mominulla (1980).

Table 1
Stratigraphic sequence in Bangladesh (Source: based on Khan (1980); Zaher and Rahman (1980))

Geologic age	Stable shelf		Bengal foredeep		Lithology
	Group	Formation	Group	Formation	
Holocene		Alluvium		Alluvium	Silt, sand, gravel and clay
		Unconformity		*Unconformity*	
Pleistocene Late Pliocene	Madhupur	Dihing		Madhupur clay	Pebbbly sandstone, sticky clay
		Unconformity		*Unconformity*	
Mid- Pliocene–Early Pliocene		Dupi Tila	Madhupur	Dupi Tila	Sandstone, coarse quartz, pebbles, petrified wood
		Unconformity		*Unconformity*	
Miocene	Surma	Jamalgonj	Tipam	Girujan clay	Claystone with sandstone
				Tipam	Sandstone, coarse-grained, cross-bedded, pebbles of granite, quartzite, shale and lignite. Clay mostly at base
			Surma	Boka Bil	Marine shale, pyritic gray marine fossils;
				Bhuban	Sandy shale, sandstone, breccia interbeds
				Unconformity	
Oligocene	Barail	Bogra	Barail	Jenam	Siltstone, fine-grained sandstone, Carbonaceous shale

Tectonically, the Bengal Basin can be subdivided into a stable area to the west and northwest, and the synclinal Bengal foredeep to the east and southeast. On the stable shelf, between 1 and 8 km of sediments of Permian to recent age have accumulated. By contrast, more than 16 km of mainly Tertiary sediments have accumulated in the more tectonically active Bengal foredeep (Paul and Lian, 1975). The detailed lithostratigraphic units and rock types are described by Ahmed and Zaher (1965), Khan and Muminullah (1980) and Alam et al. (1990).

3. Methods

3.1. Field work

Field work was carried out during February and March, 1991. Sedimentary weathered crusts were collected from 16 sections (68 samples total) along the eastern, northeastern and southeastern parts of Bangladesh and covered most of the lithostratigraphic units (Fig. 1 and Table 1). Sampling was restricted mostly within the upper 3 m of the profile, but in some cases samples were as deep as 15 m. Sampling began from the bottom of the weathered profiles in order to avoid contamination of the samples. The sampling interval within the profiles was a minimum 0.20 m and maximum 8.0 m depending upon the lithological and mineralogical characters.

The weathered material was mainly grey to bluish gray, brown, yellowish brown, fine to medium grained sandstone, siltstone, claystone and shale. The samples were collected along road cuts, natural and other human-made exposures. The original weathered samples were collected as block core by split plastic (PVC) pipe in order to preserve the original lithological structures.

3.2. Laboratory methods

About 250 g of oven dried (at 100 °C for 72 h) bulk samples were broken by a hand crusher primarily to reduce the rock aggregate to monomineralic particles. These samples were divided into seven parts by a mechanical divider. One part was crushed by Vibrating Disk Mills (Herzog, type: Hsm 100 A) and six parts were sieved to obtain size fractions less than 0.06 mm. For clay mineralogical studies, clay size fractions were separated by centrifuge at room temperature. Thin sections were prepared from both the original block sample collected in the PVC pipe and mixed powdered weathered samples for mineralogical analyses using a petrographic microscope and microprobe.

X-ray Diffraction (XRD) analysis was performed on the clay fraction using a SIEMENS D 5000 X-ray diffractometer with Ni filtered CuKα radiation using 40 kV–40 mA at the Institute of Electron Optic, University of Oulu, Finland. The step size was 0.02° and the step time was 1 s with a 1 mm divergence slit, a 0.1 mm detector slit and a 1 mm antiscatter slit. The scan range was 2–40°. Clay fractions were mounted on glass slides in order to obtain a preferred orientation of the clay minerals. The clay fractions (<2 μm) were separated by centrifuging and then placed on the glass slide as a thin layer and allowed to dry at room temperature for analysis. Clay fractions were analyzed five times after heating to temperatures of 20, 230, 450, 550 and 620 °C in order to identify the various clay mineral phases.

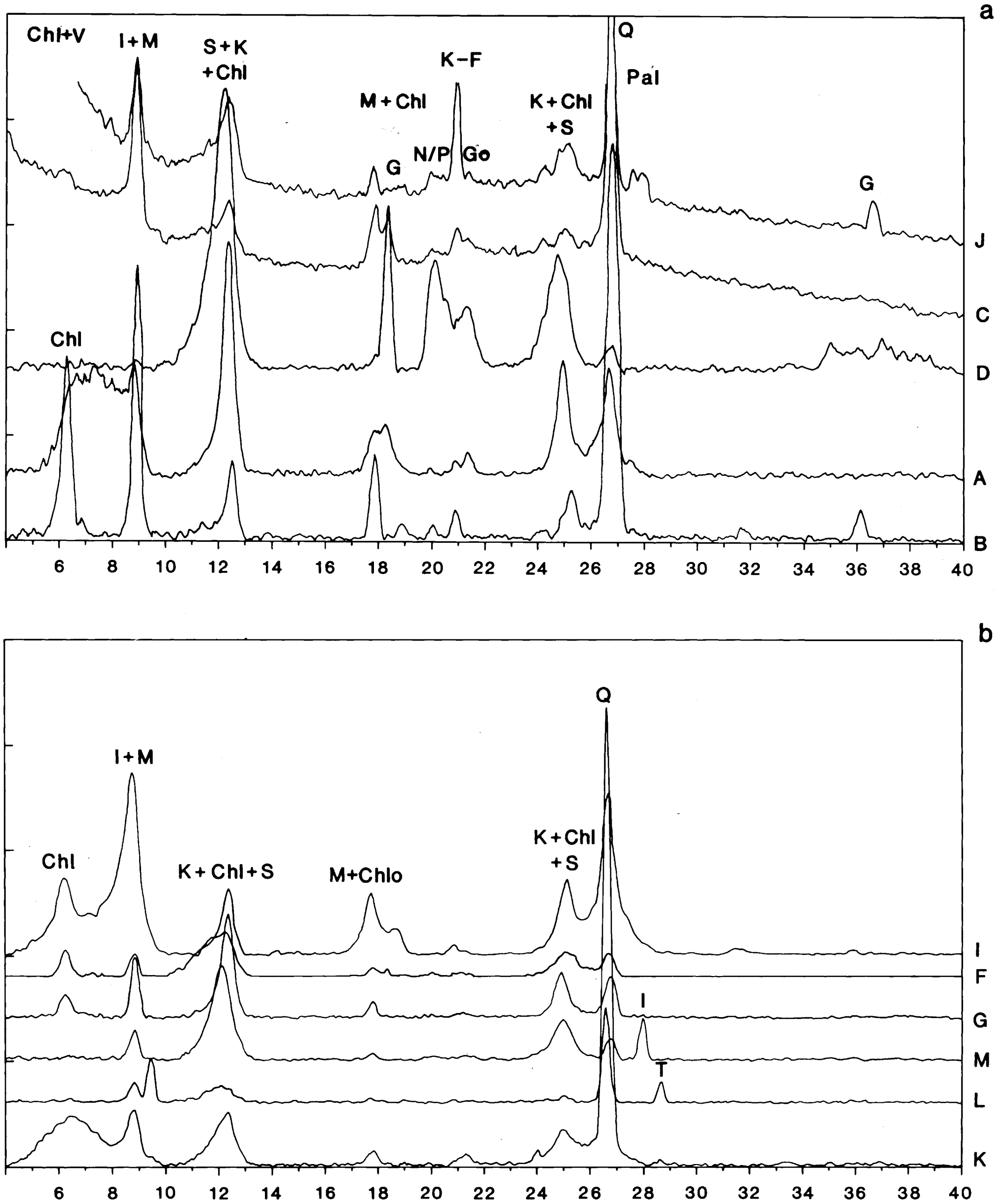


Fig. 2. Characteristic X-ray diffraction diagrams for the oriented, non-heated clay fraction (2 μm). The site locations are (a) from region I, Jaintapur, Sylhet; A: Barail, B: Bhuban, shale, C: Bhuban, sandstone, D: Boka Bil, and J: Dupi Tila; and (b) F: region V (Tipam Sandstone), G: region IV (Dupi Tila), I: region VII (Dupi Tila), K: region II (Madhupur Clay), L: region III (Madhupur Clay), and M: region III (Madhupur Clay). Chl = chlorite, V = vermiculite, I = illite, M = muscovite, S = serpentine, K = kaolinite, G = gibbsite, N/P = nacrite/pyrophyllite, K-F = K-feldspar, Go = goethite, Q = quartz, Pal = palygorskite.

For Electron Microprobe (EPMA) analyses, minerals of the carbon coated polished thin section were analyzed using a JEOL JCXA-733 superprobe instrument at the Institute of Electron Optic, University of Oulu, Finland utilizing Wavelength Dispersive Spectrometry (WDS). A 15 keV accelerating voltage, 15 nA probe current and 10 μm beam diameter were used for analysis. Natural and synthetic minerals were used for standards [MAC No: 2624; Jadeite for Na (MgO) periclase for Mg, aluminum oxide (Al2O3) for Al, wollastonite for Si and Ca, orthoclase for K, etc.]. Thin sections were also studied using a polarizing microscope.

Clay-size fractions were prepared for Transmission Electron Microscopic (TEM) study by dispersing material in alcohol. The samples were placed on a formvar coated TEM grid (150 mesh) and examined with a JEOL, JEM-100 CX II electron microscope at the Institute of Electron Optic, University of Oulu, Finland. A few thin sections of clay-size fractions coated with an Au–Pd conductor (Polaron SEM coating unit E 510) and with carbon were examined morphologically under the JEOL JSM 6400 (with Link EXL, EDS) Scanning Electron Microscope (SEM) at the Institute of Electron Optic, University of Oulu, Finland.

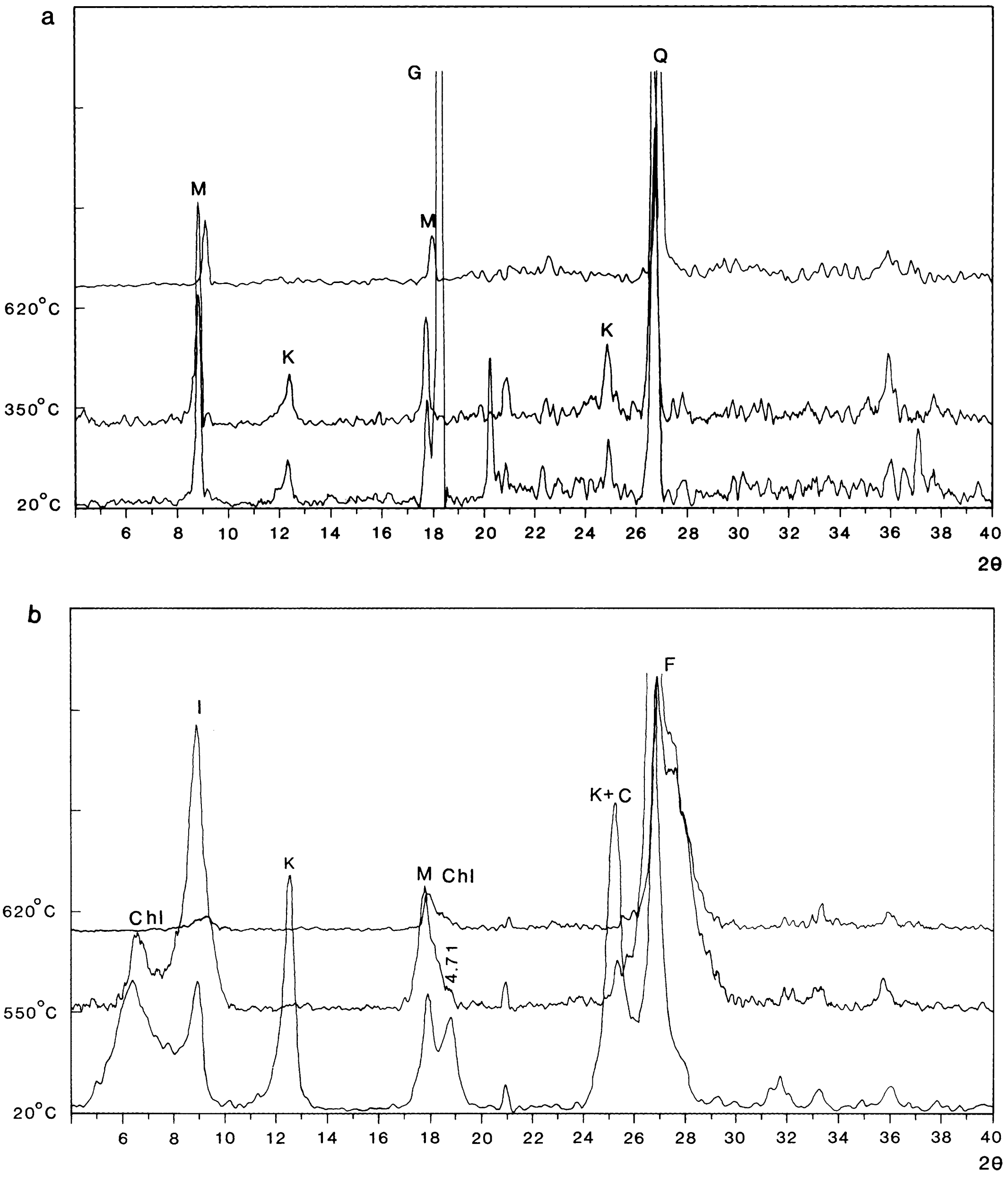


Fig. 3. X-ray diffraction diagrams of oriented clay fraction (2 μm) at differential heat treatment (a) sample from region I (Barail) showing the disappearance of the gibbsite peak after 350 °C while kaolinite peaks remain constant. Prior to 620 °C, however, the kaolinite peaks also disappear (b) sample from region VI (Dupi Tila). Kaolinite peaks disappear after 550 °C whereas, the 14 Å peak decreases followed by an increase of the 10 Å peak confirming the presence of vermiculite. Chl = chlorite, I = illite, M = muscovite, K = kaolinite, G = gibbsite, F = feldspar, Q = quartz.

4. Results

4.1. X-ray diffraction

Quartz and muscovite are the primary minerals indicated by the X-ray data and the main clay minerals are chlorite (clinochlore), serpentine, illite, kaolinite, gibbsite, and rarely, goethite and vermiculite.

Quartz is identified by its typical 3.34 Å peak and muscovite by its typical 10.1 Å symmetrical peak (Fig. 2). Kaolinite is identified by its 7.15 and 3.58 Å peaks which is confirmed after heating to 550 °C where the peaks disappeared (Whittig, 1965) (Fig. 3a). Gibbsite is identified by its 4.85, 4.37, and 2.45 Å peaks (Glen and Nash, 1963; Brown and Brindley, 1980); and is confirmed with heat treatment at 350 °C where the peaks disappear (Glenn and Nash, 1963) (Fig. 3a). Chlorite is identified by its 14.1, 4.68–4.78 and 3.52 Å peaks and is confirmed through heating of the sample to 550 °C where higher order 001 reflections decrease in intensity (Weaver, 1989) (Fig. 3b). Serpentine is identified at 7.25–7.35 Å (10). Illite (with less K_2O) can be identified by broadening of the 001 (10 and 14–17 Å) and 003 (3.33

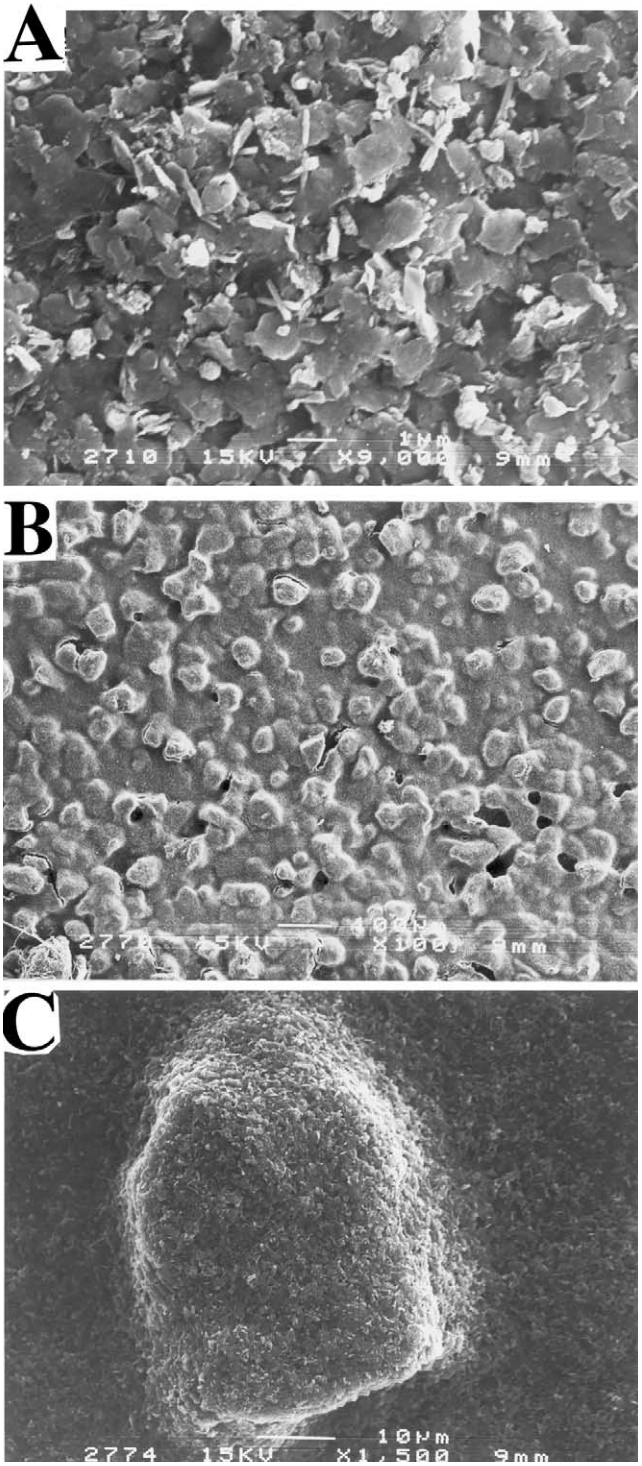


Fig. 4. (A) SEM photograph of a Au–Pd coated oriented clay fraction showing clays from region VII (Dupi Tila) [× 9000] (B) carbon coated oriented clay fractions showing clays [× 100], and (C) carbon coated single kaolinite grain from region VI (Dupi Tila) [× 1500].

and 3.5 Å) on the low angle side and the 002 (5.0 and 4.7 Å) on the high angle side (Weaver, 1989, p. 39) (Fig. 2). Moreover, vermiculite may also be present and can be confirmed through heating, when the 14 Å peak decreases and 10 Å peak increases. Goethite is identified by its 4.15 and 2.67 Å peaks. Palygorskite may be identified by the 4.48 and 3.24 Å peaks (Fig. 2), but the main peak of palygorskite at 10.5 Å is absent. As a result, the XRD data are not sufficient to confirm the presence of palygorskite.

4.2. SEM and TEM

SEM micrographs are shown in Fig. 4. Kaolinite crystallites in mature soils are typically submicron-sized and platy in morphology. Variability in the shape of crystals of the kaolin minerals is almost as great as that of the clay mineral group as a whole. Plates of hexagonal shape are often identified as kaolinite, although other layer-structured minerals may have the same shape. Kaolinite is identified in different sections as flat laths and spherical shapes as observed through the electron microscope in samples from region VII (Fig. 5a). Tabular crystals of chlorite are identified in region VII (Fig. 5b) and the platy form of chlorite in region I (Fig. 5d). The tubular pattern of gibbsite is identified in one sample from region I (Fig. 5c) which is exactly same as the findings (gibbsite) of Calvert et al., 1980 from northeast India.

4.3. Petrographic microscopy

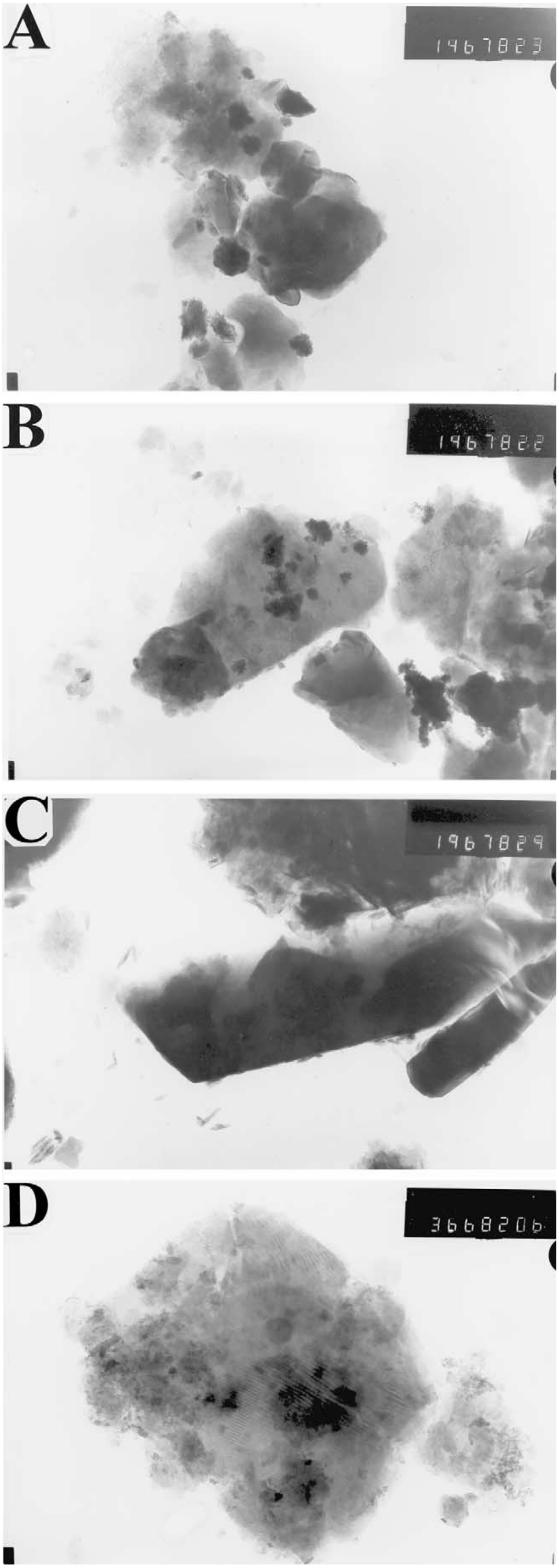
Thin sections of the weathered sandstones, siltstones, shales and claystones contain mainly quartz together with very minor amounts of muscovite, plagioclase feldspar, K-feldspar, biotite, carbonate, epidote, and clay minerals like chlorite and illite. Alteration products were seen frequently in all of the samples but were difficult to identify by petrographic microscope. Photomicrographs are shown in Fig. 6.

4.4. Microprobe (EPMA)

Representative microprobe analyses of illite and its weathering product (Fig. 7) from region IV (Dupi Tila Formation) are given in Table 2. With respect to relatively fresh illite, its weathering product is enriched in Al, Ca and Cr and depleted in Si, Mg, Na, K, F, and Ti which indicates that the weathering product is kaolinite. Note that some of the weathering products are not identified due to exclusion of water and inhomogeneity of the mineral grains. Back scattered electron images (BEI) in Fig. 7a show the alteration of feldspar to illite (inhomogeneous part) and perhaps unaltered quartz inclusions in weathered feldspar.

5. Discussion

The petrographic microscope study shows that the weathering of quartz grains started at the boundaries, fracture planes, and along planes of weakness (Fig. 6a). As the weathering proceeds, the individual grains become extremely etched and highly weathered. Although it is not documented in the present study Little et al. (1978) have



reported highly weathered quartz from their dune sand study in Fraser Island, Australia.

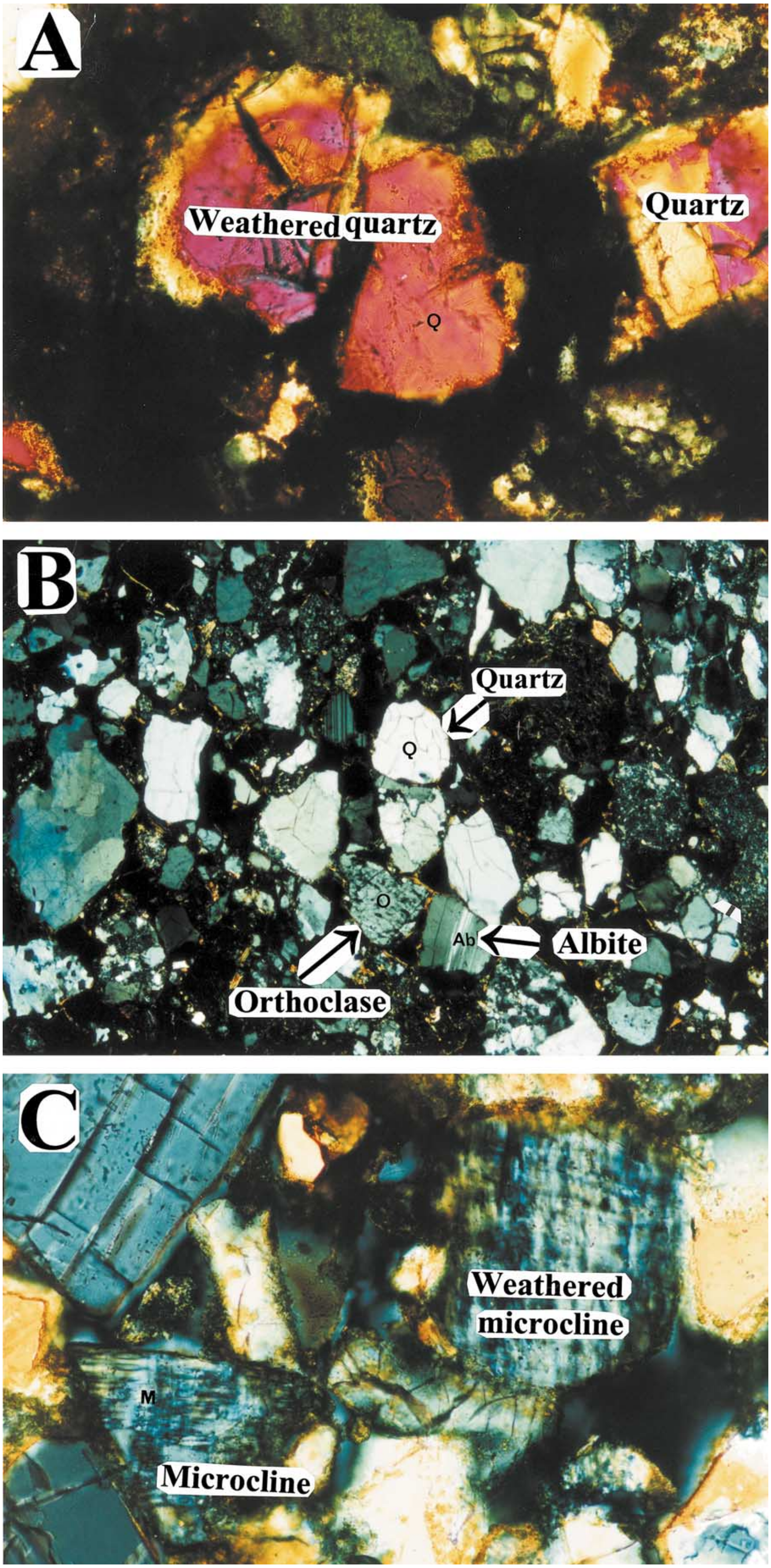
Weathering of K-feldspar also began at the boundaries and cleavage planes forming small cloudy materials (Fig. 6b). In the advanced stage of weathering, these cloudy materials turn into secondary minerals (i.e. kaolinite and illite). Plagioclase, observed under the petrographic microscope, is much more weathered than K-feldspar in all the sections. Its alteration initially starts along the cleavage and fracture planes leaving numerous small cloudy residual feldspars (Fig. 6c). Secondary minerals having a greenish color under crossed-nicols are newly formed illite. BEI (Fig. 7a) has documented the alteration of feldspar to illite. An alternative explanation is that the feldspar contained unaltered quartz inclusions which remained intact and the feldspar altered to illite. Under the petrographic microscope, muscovite grains appear weathered primarily along boundaries and cleavage planes. The typical high interference color of muscovite changes to dark brown at the initial stage. In more advanced stages, this brown colour changes into greenish brown which may be illite as a weathering product. This phenomenon is typical in the weathered samples from region III.

Birkeland (1984) suggested that individual mineral grain morphologies may be a more sensitive indicator of relative differences in weathering than depletion ratio methods because minerals show morphological features associated with weathering (particularly surface etching) long before they are significantly depleted. It has been clearly shown that most silicate minerals do not weather uniformly (Wilson, 1975; Berner and holdren, 1979; Petrovich, 1981); preferential weathering occurs at high energy sites associated with a number of structural features, including twinning planes, dislocations, fracture zones, and area of mechanical abrasion.

Several methods of determining the relative weathering status of mineral grains have been developed using these ideas (e.g. Locke, 1979; Creemens et al., 1992). By observing the morphological features of individual mineral grain caused by weathering in the study areas, we conclude that minerals have been subjected to intense weathering.

Bjorlykke (1998) has reported the formation of kaolinite from feldspar and mica in soils and sediments in the presence of meteoric water drainage. These conditions occur in zones with warm and humid climate, particularly under tropical and subtropical conditions. Kaolinite is formed due to greater leaching in the presence of high rainfall as reported by Ehlmann (1968). Gibbsite is often associated with an advanced state of weathering; however, its direct formation from primary minerals (Eswaran et al.,

Fig. 5. TEM—Photograph of a clay fraction (2 micron) (A) region VII (Dupi Tila) showing spherical kaolinites [× 14 000] (B) chlorite in the same section as A [× 19 000] (C) region I (Barail Group) showing typical gibbsite [× 10 000], and (D) showing chlorite and kaolinite (spherical) from the same section as C [× 19 000].


A
Weathered quartz
Quartz
Q
B
Quartz
Q
O
Ab
Albite
Orthoclase
C
Weathered microcline
M
Microcline

1977), and its resilication to kaolinite—seem to make this mineral an 'outcast' in some of the proposed stability sequences (Calvert et al., 1980). The presence of kaolinite in almost all the samples is indicative of intense weathering. Kaolinite followed by gibbsite in region I (Barail Group) indicates that weathering reached an extreme stage which also agrees with Kronberg et al. (1986). Weaver (1989) noted that if appreciable water is available (not necessarily rainfall) and can move freely (due to high relief, porosity, permeability), virtually any rock or aluminosilicate mineral will alter to a kaolin–gibbsite–Fe oxides suite. Evans (1992) also reported that gibbsite commonly occurs with kaolinite in tropical areas and is believed to be the major end-product of weathering of aluminosilicate minerals. Sherman et al. (1967) reported that in the presence of continuously decomposing rock, an abundance of moisture and good drainage, ionic and amorphous Al are transported by the fluids until they are converted to crystalline gibbsite. The relatively higher elevation and gentle slope of region 1 with more than 7100 mm/yr of precipitation has created conditions favorable for forming a kaolinite–gibbsite–goethite suite through the weathering of feldspars and biotite. Many geologists have emphasized that the development of gibbsite is favorable under an alternating wet and dry climate. In contrast Sherman (1949) suggested that the season and the total amount of rainfall actually governed the development of gibbsite. In region I, which receives the highest rainfall in Bangladesh, the presence of kaolinite, gibbsite and goethite indicate alteration of aluminosilicate (mainly feldspar) minerals during the weathering processes. It is possible that the monsoonic tropical climate has influenced the gibbsite formation.

The increasing trend of Si and Al coupled with decreasing Fe and K in the chemical composition of weathered illite indicates that the weathering product is kaolinite (Table 2). Illite has been altered to kaolinite (Fig. 7c). This character has been observed throughout the sections and is particularly prominent in region III, IV and V. Muller and Bocquier (1985) found that kaolinite replacing mica in the tropics consists of Fe–kaolinites and with increased weathering (upward), becomes more Fe-rich and less crystallized. Kaolinites from Bangladesh, especially those that originated through weathering of illite and hydromica, are also Fe-rich as revealed by EPMA analyses.

Kaolinization of biotite is common under a 'more extreme weathering condition' (Wilson, 1975), particularly in tropical environments (Novikoff et al., 1972; Ojanuga, 1973; Eswaran and Heng, 1976; Eswaran and Bin, 1978a,b; Paven et al., 1981). Gibbsitization of biotite is also a common process in tropical environments according to Novikoff et al. (1972), Gilkes and Shuddhiprakarn (1979a,b) and Bisdom et al. (1982). In a Cape Breton saprolite developed from granite Mckeague et al. (1983) found that feldspar and biotite had weathered to kaolinite, gibbsite and iron oxides. As biotite is affected at the early stage of weathering, the kaolinite, gibbsite, and goethite found in the study area (region 1) could be the product of biotite although no direct evidence has been documented. Vermiculte could be formed through the weathering of biotite.

Rocks in the southern part of Bangladesh (regions IV–VII) contains mostly chlorite and illite. Other areas (e.g. regions II and III) contain kaolinite with chlorite and illite indicating that the chemical weathering active in these areas is rather complex and is similar to that shown by Kronberg and Nesbitt (1981).

Merino et al. (1993) reported that parent rock silicates were extensively replaced by kaolinite and/or by Fe, Al, and Mn oxides (mainly hematite, goethite, gibbsite, and lithiophorite) during tropical weathering. The pseudomorphic replacement of kaolinite and parent-rock silicates by Al and Fe oxides during weathering is not a minor phenomenon. Enormous volumes of rocks (tens of meters of thickness covering about one third of all emerged lands) are today undergoing lateritization. These laterites mostly consists of kaolinite, and Al and Fe oxides. The occurrence of kaolinite, gibbsite, and goethite in the region 1 might indicate the lateritic nature of weathering.

Daniels et al. (1987) reported that gibbsite was apparently generated by rapid dissolution of feldspar in place followed by reprecipitation. Other researchers (e.g. Calvert et al., 1980) have reported that gibbsite forms only at depth as Al is released from feldspars in deep weathering fronts. In surface horizons, kaolinite formation is the primary sink for Al. Whether the primary Al silicates weather directly to gibbsite or through a kaolinite intermediate is governed by the intensity of leaching which is affected by a number of factors such as rainfall, temperature, parent rocks, topography, groundwater table, vegetation, and time (Hsu, 1989).

Our data indicate that gibbsite occurs at all depths in the Sylhet area (region I). The geochemical data (Islam, 1996) shows that Na, Ca, K, and Mg have been depleted by almost 95% compared to fresh bedrock indicating intense leaching and dissolution. As a result, kaolinite appears unstable while gibbsite is common. This phenomena might indicate that gibbsite is transformed through kaolinite which would agree with Daniels et al. (1987).

In general, all of the weathered samples from the study areas contain largely quartz, muscovite, and illite (mainly in clay fraction). Muscovite and illite are relatively resistant to weathering. The most likely source mineral for the formation of pedogenic illite or mica is K- feldspar or plagioclase plus mica.

Fig. 6. Photomicrograph (Petrographic microscope) of samples (A) from region 1 (Barail), Sylhet showing quartz grains affected by intense weathering through boundaries and fracture planes [× 20] (B) from region II (Madhupur clay) showing weathering of albite and orthoclase [× 4], and (C) from region IV [× 20] showing the weathering of microcline.

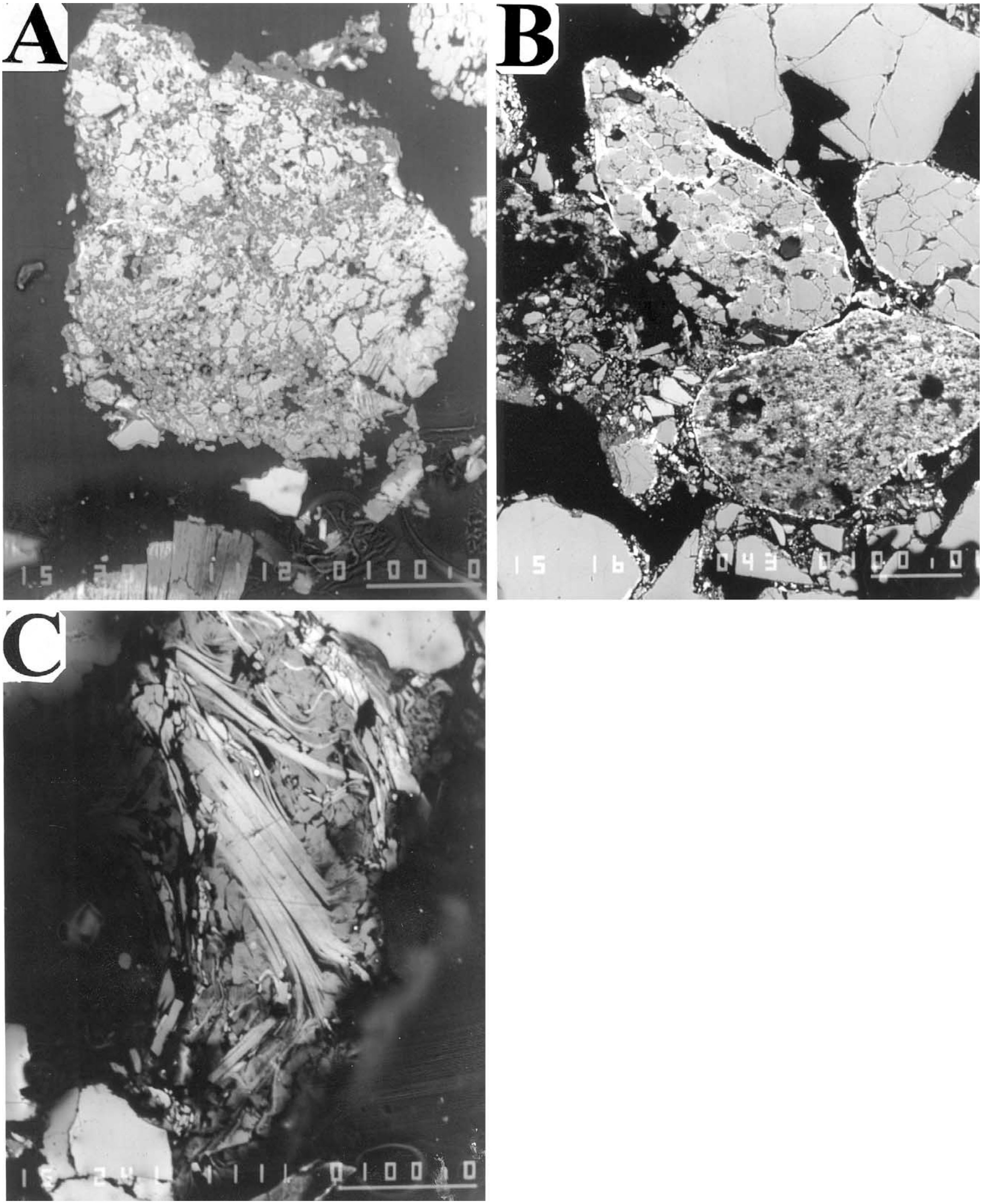


Fig. 7. (A) BEI photograph of a sample from region III (Madhupur Clay) showing the alteration of feldspar to secondary quartz (e.g. solid part) and to illite (e.g. inhomogeneous part) during weathering (B) illite showing initial to extreme stage of weathering in a sample from region VI, and (C) a sample from region IV (Dupi Tila) showing the alteration of illite (e.g. homogeneous fibres) to kaolinite (e.g. inhomogeneous part).

Table 2
Chemical composition of illite and its weathering product

Wt %	Illite[a]	Illite's weathering product
SiO_2	44.26	41.16
Al_2O_3	32.3	33.62
MgO	1.1	0.08
CaO	0	0.05
Na_2O	0.25	0.06
K_2O	6.72	0.31
FeO	1.31	1.05
TiO_2	0.94	0.09
MnO	0	0.04
Cr_2O_3	0.01	0.04
NiO	0	0.09
ZnO	0.03	0.09
V_2O_3	0.12	0
Total	87.04	76.68
	On the basis of 24(O,OH^-)	On the basis of 18(O,OH^-)
Si	6.9	5.22
Al	5.93	4.97
Mg	0.17	–
Ca	–	–
Na	0.06	–
K	1.32	–
Fe	1.16	–
Ti	0.1	–
Mn	–	–
Cr	–	–
Ni	–	–
Zn	–	–
V	–	–

[a] [$K_{0.8}Al_{1.9}(Al_{0.5}Si_{3.5})O_{10}(OH)_2$]) (Garrels, 1984).

6. Conclusions

The variability of alteration of primary minerals during intense weathering throughout the study areas suggest significant variability of the climate in the region. The current climatic conditions of significant increases in precipitation from west to east and from south to north are reflected in the degree of weathering. The minerals have been intensely weathered as revealed by morphological features of individual mineral grains. The presence of kaolinite in almost all the samples is also indicative of intense weathering. Kaolinite is followed by gibbsite in region I (Barail Group) and indicates that weathering had reached an extreme stage, which also agrees with Kronberg et al. (1986).

The major affected minerals during weathering processes are feldspars, biotite and muscovite. Plagioclase feldspar is much more weathered than K-feldspar in all the sections. Feldspar has been altered to illite and illite to kaolinite during intense weathering. In region I, which receives the highest rainfall in Bangladesh, the presence of kaolinite, gibbsite and goethite indicate alteration of aluminosilicate (mainly feldspar) minerals during the weathering processes. It is possible that the monsoonic tropical climate has influenced gibbsite formation. The occurrence of kaolinite, gibbsite, and goethite in the region-I may indicate the lateritic nature of weathering and the influence of a tropical and humid climate in the study area.

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