QUATERNARY RESEARCH **50,** 230–239 (1998)
ARTICLE NO. QR981994

Clay Minerals in Soils as Evidence of Holocene Climatic Change, Central Indo-Gangetic Plains, North-Central India

Pankaj Srivastava[1] and Bramha Parkash

Department of Earth Sciences, University of Roorkee, Roorkee 247667, India

and

Dilip K. Pal

Division of Soil Resource Studies, National Bureau of Soil Survey and Land Use Planning, Nagpur 440010, India

Received September 17, 1997

Clay mineral assemblages of a soil chrono-association comprising five fluvial surface members (QGH1 to QGH5) of the Indo-Gangetic Plains between the Ramganga and Rapti rivers, north-central India, demonstrate that pedogenic interstratified smectite–kaolin (Sm/K) can be considered as a potential indicator for paleoclimatic changes during the Holocene from arid to humid climates. On the basis of available radiocarbon dates, thermoluminescence dates, and historical evidence, tentative ages assigned to QGH1 to QGH5 are <500 yr B.P., >500 yr B.P., >2500 yr B.P., 8000 TL yr B.P., and 13,500 TL yr B.P., respectively. During pedogenesis two major regional climatic cycles are recorded: relatively arid climates between 10,000–6500 yr B.P. and 3800–? yr B.P. were punctuated by a warm and humid climate. Biotite weathered to trioctahedral vermiculite and smectite in the soils during arid conditions, and smectite was unstable and transformed to Sm/K during the warm and humid climatic phase (7400–4150 cal yr B.P.). When the humid climate terminated, vermiculite, smectite, and Sm/K were preserved to the present day. The study suggests that during the development of soils in the Holocene in alluvium of the Indo-Gangetic Plains, climatic fluctuations appear to be more important than realized hitherto. The soils older than 2500 yr B.P. are relict paleosols, but they are polygenetic because of their subsequent alterations.

INTRODUCTION

The Indo-Gangetic Plains of north-central India are among the most extensive fluvial plains in the world. Traditionally the plains are thought to consist of older and younger alluvia. The older alluvium marked by a higher degree of pedogenesis (Bhargava *et al.,* 1981), has been usually assigned a lower Pleistocene age (Wadia, 1966; Bhattacharyya and Banerjee, 1979) or a minimum age of 120,000 yr (Singh, 1988). However, recent soil-geomorphic studies from these plains suggest the presence of more than two soil/surfaces younger than 13,500 TL yr B.P. (Mohindra *et al.*, 1992; Srivastava *et al.*, 1994; Kumar *et al.*, 1996). Based on their degree of development, soils of the central Indo-Gangetic Plains have been grouped into five members (QGH1 to QGH5, QGH5 being the most developed) of a soil chrono-association (Srivastava *et al.*, 1994). On the basis of available limited data on radiocarbon dates, thermoluminescence dates, and historical evidence, tentative ages estimated for QGH1 to QGH5 are <500 yr B.P., >500 yr B.P., >2500 yr B.P., 8000 TL yr B.P., and 13,500 TL yr B.P., respectively.

Studies of the lacustrine deposits from the western part of these plains in the Thar desert suggest that the cold and very dry climate prevalent in ~11,160 cal yr B.P. changed to a slightly wetter climate during 11,160–5730 cal yr B.P., and the period 5730–4150 cal yr B.P. was even wetter (Singh *et al.*, 1972, 1974). This climatic change might have affected all of the Indo-Gangetic Plains. However, climatic changes in these plains have been reported only recently (Srivastava *et al.*, 1994). A cold, arid to semi-arid climate prevailed during the Early Holocene to about 7390 cal yr B.P. in the central and western parts of the plains, favoring pedogenic calcrete development. Later, a warm and humid climate set in, followed by drier conditions that continued until the present (Srivastava *et al.*, 1994). These climatic changes led to the formation of relict soils in the plain (Srivastava *et al.*, 1994).

During the Early Holocene to 7390 cal yr B.P. and also during the latter warmer and wetter period, weathering of minerals and illuviation of clay have been the major pedogenic processes (Srivastava *et al.*, 1994; Kumar *et al.*, 1996). These soils are enriched with fine-grained micas (Bhargava *et al.*, 1981; Pal *et al.*, 1994) and weather to 2:1 expanding clay minerals (Pal *et al.*, 1987a, 1994). There are various processes that are capable of producing different types of clay minerals (Birkeland, 1984). Among these, the formation of clay minerals during pedogenesis is the most fundamental. Precipitation, temperature, and drainage are the principal controls of clay

[1] Present address: Division of Soil Resource Studies, National Bureau of Soil Survey and Land Use Planning, Nagpur 440010, India.

0033-5894/98 $25.00

mineral formation; these factors reflect climate and relief (Blaise, 1989).

This study presents results and the interpretation of clay mineral assemblages in the relict soils of the central part of the plain between the Ramganga and Rapti rivers (Srivastava *et al.*, 1994) and also describes another possible tool for paleoclimatic studies of Quaternary deposits of the Indo-Gangetic Plains.

GENERAL FEATURES OF THE STUDY AREA

The study area is a part of the Indo-Gangetic Plains (Fig. 1a) and includes much of the eastern Upper Ganga Plain and some parts of the Middle Ganga Plain (Singh and Singh, 1971). In general, the modern climate is sub-humid and is mainly controlled by proximity to the Himalayas (Singh and Singh, 1971). The rainfall increases and temperature decreases from the south toward the Himalayas. Four well-marked seasons can be recognized, i.e., hot summer, wet summer, pre-winter transition, and winter. The air temperature rises gradually from February, and rapidly from March onward until May/June, attaining 40°C. The Himalayas exert influence, as the maximum May temperature may remain below 40°C at Gonda (near the Himalayas) but can be well above 40°C in the southern part at Allahabad and Kanpur. The rainy season from the middle of June to late September accounts for over 90% of the total annual rainfall in the area. The monsoon rainfall and annual rainfall decrease westward as well as southward (Gonda, 113 cm; Bahraich, 100 cm; Allahabad, 90 cm) (IMD, 1989).

IDENTIFICATION OF SOIL-GEOMORPHIC UNITS

Visual interpretation of topographic sheets and remote sensed images (Indian Remote Sensing Satellite False Color Composites or FCCs) of the study area was carried out to delineate different landforms. Three major landforms (piedmont, plains associated with rivers, and upland interfluves) were recognized. Within each landform, a number of geomorphic units were identified on the basis of variation in tone, texture, and color on FCCs. Field investigation in each geomorphic unit showed that the soils there were fairly uniform, or varied only over a small range, and it was found that different units had more distinct soil properties. Therefore, these geomorphic units can be referred to as soil-geomorphic units (Fig. 1b). In the field, 47 soil profiles were studied. Master horizons and subhorizons were recognized in the field, and various soil properties such as color, texture, structure, mottling, lime content, and consistency were recorded for each horizon/subhorizon according to Soil Survey Staff (1966). Only 32 pedons showing typical characteristics of the soil-geomorphic units were chosen for detailed laboratory analyses.

ESTABLISHMENT OF SOIL-CHRONO-ASSOCIATION

An integrated approach was used to determine the degree of soil development on fifteen soil-geomorphic units (Fig. 1b). This includes an additional soil-geomorphic unit just adjacent to “MDGGHIF” in the east (Mohindra *et al.*, 1992). This was based on thickness of the B horizons, field characteristics, clay accumulation index (Levine and Ciolkosz, 1983), degree of pedality (Bullock *et al.*, 1985), and thickness and nature of argillans and plasma separations. On the basis of relative degree of development, soils of the units were grouped into five members (QGH1 to QGH5) of a soil chrono-association (Table 1). The soils in the area show systematic variation in their morphology, texture, chemical composition, and micromorphological features, from the least developed soils in QGH1 to the most developed soils in QGH5.

Age control on soil chrono-association is tentative. However, using limited available radiocarbon and thermoluminescence dates, together with historical evidence, some rough estimates can be provided. Radiocarbon dates reported in this paper are the calibrated ones according to the program of Stuives and Reimer (1993). Equivalences are given in Table 2. Radiocarbon dates of the calcretes from the most strongly developed soils, QGH5 (MDGGHIF), reported by Rajagopalan (1988) are between 12920 and 9980 cal yr B.P. Two calcrete dates from QGH4 soils, from LDGGHIF and LGYIF (Lower Ganga-Yamuna Interfluve occurring adjacent to the west of the area) are 7390 cal yr B.P. and 7790 cal yr B.P., respectively (Mohindra *et al.*, 1992; Kumar *et al.*, 1996).

Thermoluminescence (TL) dates of soils from MDGGHIF and LGYIF provided by Das (1993) are 13,600 TL yr B.P. and 8300 TL yr B.P., respectively. TL dates reflect the time of deposition and the start of pedogenesis and can be regarded as the maximum age of the soils. Calcrete formation may have taken some time, and thus the calcrete dates are younger.

QGH3 soils in the present area overlap in characters of the QGD3 and QGD4 soils on the adjoining Gandak Megafan (Mohindra *et al.*, 1992). On the basis of the historically recorded position of the Gandak River during the eastward shift of over 80 km in the last 5000 yr, the QGD3 and QGD4 soils were assigned ages of $>$2500 yr B.P. and $>$5000 yr B.P., respectively, by Mohindra *et al.* (1992). Thus QGH3 soils can be assigned an age of $>$2500 yr B.P.

For the soils of QGH1 and QGH2, tentative ages are given as $<$500 yr B.P. and $>$500 yr B.P., respectively.

MATERIALS AND METHODS

Soils

Four pedons were selected for the mineralogical study, one each from QGH1, QGH2, QGH3, and QGH5, representing soil orders in “Soil Taxonomy” (Soil Survey Staff, 1975): Ustochrept (QGH1 and QGH2) and haplustalf (QGH3 and QGH5) (Table 1).

Analytical Techniques

The soil samples collected from different horizons were analyzed for pH (1:2 soil to water), calcium carbonate, and

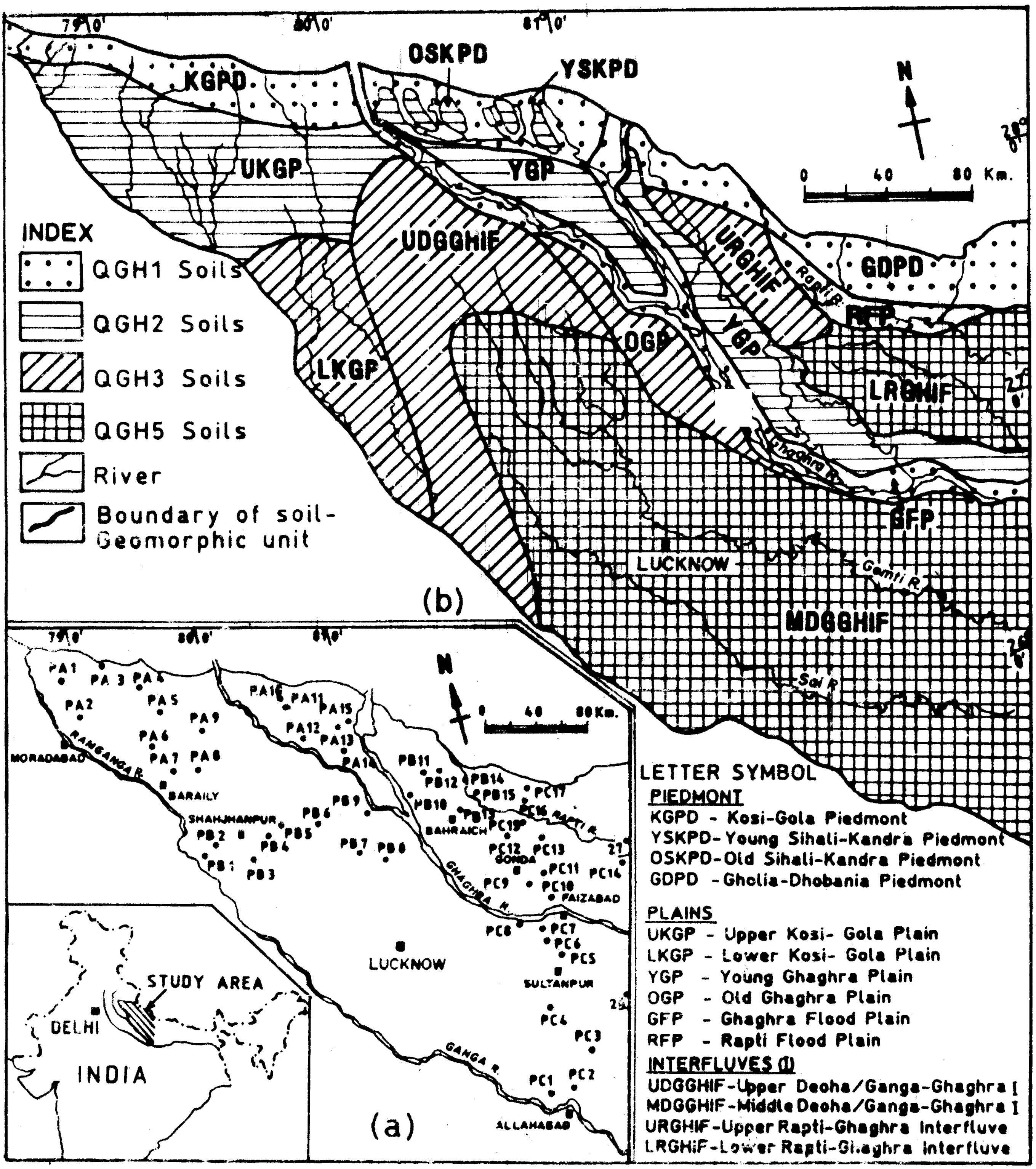

FIG. 1. (a) Location map of the area. PA1–PA15, PB1–PB15, and PC1–PC17 represent soil profile numbers. (b) Soil-geomorphic map of the area.

organic carbon by standard methods (Richards, 1954). Sand (2000–50 μm), silt (50–2 μm), total clay (<2 μm), and fine clay (<0.2 μm) fractions were separated from the samples after dispersion using sodium carbonate according to the size segregation procedure of Jackson (1979).

Oriented silt and clay fractions were subjected to X-ray

TABLE 1
Typical Features of the Members of the Soil Chrono-association

Member	Age (yr B.P.)	Soil, geomorphic units	Soil classification	B horizon thickness (cm)	Structure of B horizon	Texture of B horizon	Color of B horizon	Calcium carbonate (percentage and thickness of calcrete nodules)	Mottiles and Fe–Mn concretions
QGH1	<500	KGPD, YSKPD, GDPD, GFP, and RFP	Coarse loamy lypic ustochrept and fluventic ustochrept	<14	Very weak	Loam to silty loam	5Y 5/2–5/4 2.5Y 4/3–5/4	Nil in some pedons 5–10%, 1–3 cm, confined to A or C horizons of some pedons	Few to common reddish brown motiles increase with depth from A to C horizon
QGH2	>500	UKGP, OSKPD, and YGP	Coarse loamy to fine loamy typic ustochrept	21–57	Weak	Loam to silty loam	2.5Y 5/2–5/4	2–10%, 0.5–1.5 cm, mainly in B-C horizons of some pedons	Common yellowish brown to strong brown, coarse distinct mottles with a few Fe–Mn concretions in C horizons
QGH3	>2500	LKGP, OGP, URGHIF, and UDGGHIF	Coarse loamy to fine loamy typic haplustalf	52–85	Moderate	Silt loam to loam	2.5Y 4/3–5/4 10YR 4/5–5/3	Nil in some pedons 5–20%, 1–2 cm, confined to B3-C horizons of some pedons	Common strong brown, coarse distinct mottles increase with depth with common Fe–Mn concretions in C horizons
QGH4[c]	8000 (TL)	LDGGHIF	Fine loamy typic haplutalf	42–72	Moderate to strong	Silty loam	2.5Y 4/2–5/5	5–15% in B2-B3 horizons of many pedons	Common strong brown, medium coarse distinct mottles with Fe–Mn concretions
QGH5	13500 (TL)	MDGGHIF and LRGHIF	Fine loamy typic haplustalf	93–97[a] 105–137[b]	Strong to very strong	Silty loam to loam	2.5Y 4/3-5.5/4 10YR 6/4-4.5/4	Nil in some pedons, 5–15% confined to B horizons and throughout in some pedons	Strong brown, medium coarse distinct mottles increase with Fe–Mn concretions in lower horizons

[a] Salt-affected.
[b] Non-salt-affected.
[c] After Mohindra *et al.*, (1992).

diffraction (XRD) analysis using a Philips diffractometer and Ni-filtered Cu$K\alpha$ radiation at a scanning speed of $2°2\theta$/min. Samples were saturated with Ca and K, solvated with ethylene glycol, and heated to 110, 300, and 550°C. The identification of minerals was done following the criteria of Jackson (1979). Information about the structure of the clay fractions, the fine clay in particular, was obtained from the 060 reflections of randomly oriented samples (Jackson, 1979). Semi-quantitative estimates of the clay minerals were made following the principles outlined by Gjems (1967) and Kapoor (1972).

Sand-sized biotite, muscovite, and feldspars were picked up under a petrographic microscope, fixed on aluminum stubs with LEIT-C conductive carbon cement, coated with gold, and examined in a Philips SEM.

TABLE 2
Radiocarbon and Calibrated Radiocarbon Ages Pertinent to This Paper

^{14}C yr B.P.	cal yr B.P.
11,000	12,920
10,000	11,120–11,210
9000	9980
7000	7790
6500	7390
5000	5730
3800	4150
2500	2509–2709
500	520

RESULTS

Parent Material Uniformity

Soils of the study area are developed in the alluvium brought by the rivers from the Himalayas. The morphology of the pedons, as

TABLE 3
Physical and Chemical Properties of Soils

Horizon	Depth (cm)	Fine-earth basis: Sand 2000–50 μm (%)	Fine-earth basis: Silt 50–2 μm (%)	Fine-earth basis: Clay <2 μm (%)	Clay-free basis: Sand 2000–50 μm (%)	Clay-free basis: Silt 50–2 μm (%)	Clay-free basis: Sand-silt (%)	pH (1:2 soil to water)	$CaCO_3$ equivalent (%)	Organic carbon (%)
QGH1 (<500 yr B.P.) : Typic Ustochrept : Pedon PA4										
A	0–36	4.2	67.0	28.8	5.9	94.1	0.06	7.8	0.4	0.6
Bw1	36–50	5.4	65.1	29.5	7.7	92.3	0.08	8.0	1.1	0.5
C1	50–73	8.5	63.7	27.8	11.8	88.2	0.13	8.1	Nil	0.4
C2	73–110	24.2	58.0	17.8	29.5	70.5	0.42	8.0	Nil	0.3
QGH2 (>500 <2500 yr B.P.) : Typic Ustochrept : Pedon PA6										
A	0–30	27.4	42.6	30.0	39.1	60.9	0.64	8.1	Nil	0.5
Bw1	30–70	0.2	62.8	37.0	0.3	99.7	0.03	8.2	Nil	0.5
Bw2	70–80	0.2	70.9	28.9	0.3	99.7	0.03	8.2	Nil	0.4
Bw3	80–97	0.5	55.8	43.8	0.8	99.2	0.08	8.4	Nil	0.3
C	97–127	2.9	60.5	36.6	4.6	95.4	0.05	8.5	Nil	0.2
QGH3 (>2500 yr B.P. <8000 TL yr BP) : Typic Haplustalf : Pedon PA7										
Ap	0–26	4.0	80.0	16.0	4.8	95.2	0.05	7.8	Nil	0.6
A/B	26–42	5.4	62.2	32.4	8.0	92.0	0.08	7.8	Nil	0.5
Bt1	42–66	3.0	63.9	33.1	4.5	95.5	0.05	7.7	Nil	0.5
Bt2	66–94	4.2	62.6	33.2	6.3	93.7	0.07	7.9	Nil	0.4
B/C	94–110	2.3	63.0	34.7	3.5	96.5	0.04	8.1	Nil	0.3
C	110–128	5.4	66.6	28.0	7.5	92.5	0.08	8.6	Nil	0.2
QGH5 (13500 TL yr BP) : Typic Haplustalf : Pedon PB7										
Ap	0–18	4.1	64.2	31.7	6.0	94.0	0.06	7.6	Nil	0.6
A/B	18–36	3.7	57.5	38.8	6.0	94.0	0.06	7.7	Nil	0.5
Bt1	36–88	3.4	57.9	38.7	5.5	94.5	0.06	7.7	Nil	0.4
Bt2	88–133	4.6	53.6	41.8	7.9	92.1	0.08	7.9	Nil	0.3
Bt3	133–175	5.9	57.3	36.8	9.3	90.7	0.10	7.9	Nil	0.3
B/C	175–200	6.8	60.4	32.8	10.0	90.0	0.11	7.9	Nil	0.2

well as the depth distribution of sand and silt fractions on a clay-free basis and the sand to silt ratios (Table 3), suggests uniformity of the parent material in general, with the exception that QGH1-C2 and QGH2-A horizons are sandy. Furthermore, the thin sections indicated the presence of a similar group of minerals (quartz, muscovite, biotite, chlorite, and feldspars followed by heavy minerals and rock fragments) within the solum depth, with minor variations in content, and the absence of distinct boundaries between the horizons. Such homogeneity discounts clay enrichment in the B horizons of QGH2 to QGH5 soils caused by sedimentation. In view of the uniformity of the parent material, the clay distribution as a function of depth (Table 3) clearly indicates that these soils are fairly well developed, and the clay enrichment in the B horizons is due to the pedogenic processes (Barshad, 1964; Pal *et al.,* 1994).

Mineralogy of the Silt Fractions

The XRD diagrams of the silt fractions of the soils indicate that, besides quartz, feldspars, and amphibole, 10 and 14 Å minerals are distinctly present in all horizons of the QGH1 and QGH2 soils. Except for amphibole, all other minerals are identical in QGH3 and QGH5 soils (Figs. 2a and 2b). On acid treatment, 14Å minerals disappeared, while 7Å minerals were retained, establishing the trioctahedral character of the 14Å minerals (Kapoor, 1972) and the presence of kaolin, respectively. Persistence of 14Å reflection after heating to 550°C indicated the presence of chlorite, while a decrease in its intensity with concurrent increase in the intensity of 10Å reflection suggested the presence of vermiculite. Incomplete collapse of the 12Å phase to 10Å reflection with heat treatment established the occurrence of chloritic layers in the 10–14Å mixed layer minerals.

Mineralogy of the Clay Fractions

The XRD diagrams of the clay fraction (<2 μm) of the soils are not identical, unlike those of the silt fractions (Figs. 3a and 3b). The clay fraction of QGH1 soils contains mica, 10–14Å mixed-layer minerals, vermiculite, chlorite, kaolin, and quartz,

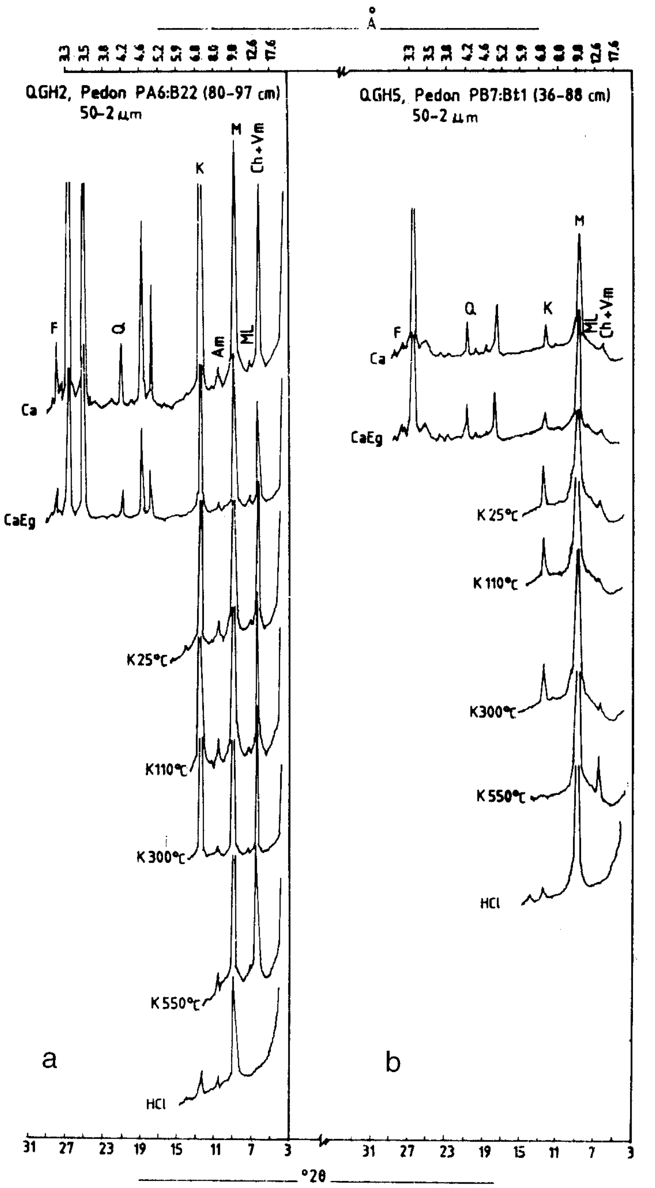

FIG. 2. Representative XRD diagrams of the 50–2 μm fraction of the QGH2 soils (a) and QGH5 soils (b) : Ca–Ca, saturated; CaEg–Ca, saturated and glycolated; K 25°C, K 110°C, K 300°C, and K 550°C–K, saturated and heated; V, vermiculite; Ch, chlorite; K, kaolinite; ML, mixed layer (10–14 Å); Q, quartz; F, feldspars; Am, amphiboles.

whereas the clay fraction of QGH2 soils contains smectite in addition to the above-mentioned minerals. The clay fractions of QGH3 and QGH5 soils contain Sm/K in addition to the clay minerals of the QGH2 soils (Table 4).

The presence of Sm/K is indicated by a plateau at the low-angle region of the 7.3 Å peak of kaolin in the Ca-saturated samples. This peak shifts on glycolation to 8.0 Å (Fig. 3 and 4). The reinforcement of the 10.0 Å peak on K-saturation and subsequent heating (110–550°C) indicates that these kaolins are to some extent interstratified with chloritized smectite. Similar interstratified minerals are the weathering products of smectite in soils of humid tropical climates and are found commonly in ferruginous soils of central and southern peninsular India (Pal *et al.*, 1989; Bhattacharyya *et al.*, 1993) and elsewhere (Wilson and Cradwick, 1972; Buchmann and Grubb, 1991; Churchman *et al.*, 1994; Delvaux and Herbillon, 1995). The presence of Sm/K only in clays of QGH3 and QGH5 soils is thus related to their pedogenesis. The fine clays of these two soils contain smectite and mica in addition to Sm/K, and the content of Sm/K is much higher in QGH5 soils than in QGH3 soils (Table 4). The smectite contracts to 10 Å on K-saturation at ambient temperature (Fig. 4). Hence, this is a low charge vermiculite (smectite) and has hitherto been considered to be an alteration product of biotite in arid

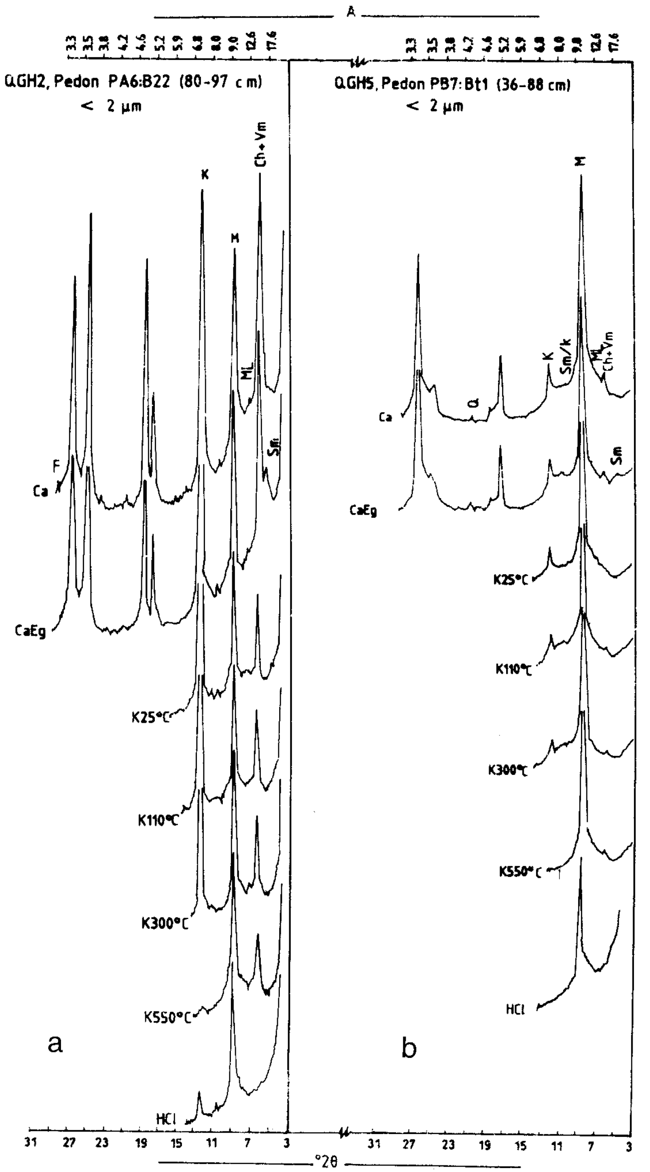

FIG. 3. Representative XRD diagrams of the <2 μm fraction of QGH2 soils (a) and QGH5 soils (b): Ca–Ca, saturated; CaEg–Ca, saturated and glycolated; K 25°C, K 110°C, K 300°C, and K 550°C–K, saturated and heated; S, smectite; V, vermiculite; Ch, chlorite; Sm/K, smectite–kaolin; K, kaolinite; ML, mixed layer (10–14 Å); Q, quartz; F, feldspars.

TABLE 4
Semi-quantitative Estimates of the Clay Minerals

Horizon	Depth (cm)	Clay minerals in <2 μm clay fractions (%)[a]								
		M	ML	Ch	V	S	Sm/K	V + S + Sm/K	K	Q
QGH1 (<500 yr BP) : Typic Ustochrept Pedon PA4										
A	0–36	40	10	30	Tr[b]	Nil	Nil	Tr	20	Tr
Bw1	36–50	30	Tr	35	Tr	Nil	Nil	Tr	35	Tr
C1	50–73	28	15	47	Tr	Nil	Nil	Tr	10	Tr
C2	73–110	45	5	40	Tr	Nil	Nil	Tr	10	Tr
QGH2 (>500 <2500 yr BP) : Typic Ustochrept Pedon PA6										
A	0–30	40	10	18	15	17	Nil	35	Tr	Tr
Bw1	30–70	35	15	10	20	20	Nil	40	Tr	Tr
Bw2	70–80	28	16	10	20	26	Nil	46	Tr	Tr
Bw3	80–97	27	15	10	18	30	Nil	48	Tr	Tr
C	97–127	26	17	14	13	30	Nil	43	Tr	Tr
QGH3 (>2500 yr B.P. <8000 TL yr BP) : Typic Haplustalf Pedon PA7										
Ap	0–26	40	9	6	13	32	Tr	45	Tr	Tr
A/B	26–42	34	12	Tr	13	21	15	49	r	Tr
Bt1	42–66	36	14	Tr	11	25	14	50	Tr	Tr
Bt2	66–94	30	12	Tr	13	25	15	53	5	Tr
B/C	94–110	29	19	Tr	15	10	27	52	Tr	Tr
C	110–128	28	22	5	16	15	14	45	Tr	Tr
QGH5 (13500 TL yr BP) : Typic Haplustalf Pedon PB7										
AP	0–18	52	12	Tr	8	Tr	19	27	9	Tr
A/B	18–36	49	10	Tr	8	Tr	20	28	13	Tr
Bt1	36–88	48	12	Tr	6	Tr	22	28	12	Tr
Bt2	88–133	47	11	Tr	8	Tr	22	30	12	Tr
Bt3	133–175	38	13	Tr	10	Tr	29	39	10	Tr
B/C	175–200	38	11	Tr	11	Tr	25	36	15	Tr

[a] M, mica; Ml, 10–14Å mixed layer minerals; V, vermiculite; Ch, chlorite; S, smectite; Sm/K, smectite–kaolin interstratified mineral; k, kaolin; Q, quartz.
[b] Tr, trace (<5%).

climates (Pal *et al.*, 1989). The presence of Sm/K in soils of the Indo-Gangetic Plains has been very rare (Bhargava *et al.*, 1981; Pal *et al.*, 1987a, 1994). It is, however, present in soils older than >8800 cal yr (Tomar, 1985; Mohindra and Parkash, 1990), representing QGH4 soils of the soil chrono-association described recently by Srivastava *et al.* (1994).

Genesis of Clay Minerals

The presence of mica, chlorite, and kaolin in soil clays of QGH1 indicates that these are inherited from the parent Indo-Gangetic alluvium. With increasing age of the soil from QGH1 to QGH5, clay minerals like smectite and Sm/K are formed due to the pedogenesis.

The XRD diagrams of the silt fractions indicate that mica is the dominant mineral in the soils with 10–14 Å minerals, vermiculite, and chlorite. The ratios of peak heights of the mica 001 and 002 reflections in the silt and clay fractions remain much above unity (Figs. 2 and 3), suggesting the presence of both muscovite and biotite (Pal *et al.*, 1987a). The 10 Å peak of mica is broader and more asymmetrical toward low angles in the clay fractions. The intensity of 14 Å and 10–14 Å minerals is greater in the clay fractions than in the silt fractions. These features indicate the replacement of the interlayer K of mica. The weathering of both biotite and muscovite in terms of interlayer opening (Fig. 5) clearly indicates that in the presence of biotite, the weathering of muscovite is almost inhibited. This suggests that in the early stages of weathering, biotite was weathered to mixed-layer minerals containing vermiculite layers. As more interlayer regions were affected by weathering, there was a progressive formation of trioctahedral vermiculite and smectite (low-charge vermiculite) as evidenced by the presence of 060 reflection at 1.54 Å in the fine fraction of the soils (Fig. 4). Similar transformation of biotite in micaceous soils had earlier been observed by Pal and Deshpande (1987), Pal *et al.* (1989) and Pal *et al.* (1994). This type of biotite

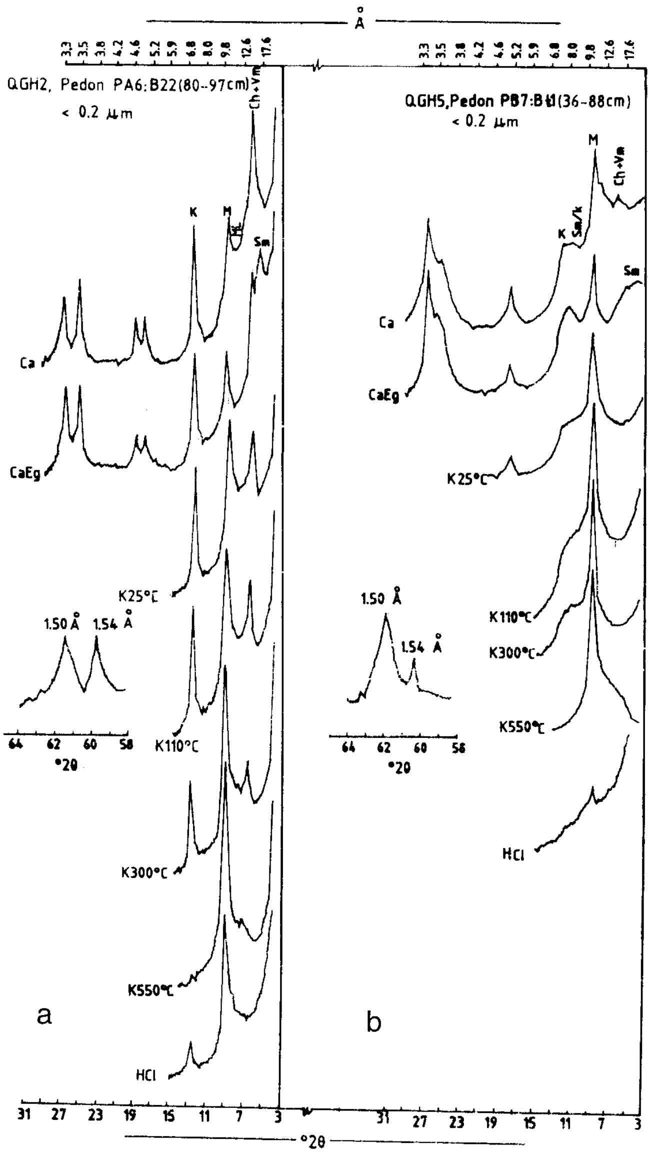

FIG. 4. Representative XRD diagrams of the <2 μm fraction of QGH2 soils (a) and QGH5 soils (b) : Ca–Ca, saturated; CaEg–Ca, saturated and glycolated; K 25°C, K 110°C, K 300°C, and K 550°C–K, saturated and heated; S, smectite; V, vermiculite; Ch, chlorite; Sm/K, smectite–kaolin; K, kaolinite; ML, mixed layer (10–14Å).

weathering has previously been thought to occur only in arid climates (Ismail, 1969; Tardy *et al.,* 1973; Pal *et al.,* 1987a, 1989).

DISCUSSION

The formation of trioctahedral vermiculite and smectite at the expense of biotite mica is feasible in arid climates, while the formation of Sm/K is not. The formation of Sm/K is generally associated in soils developed in humid climates, where it forms an important ephemeral stage during the transformation of smectite to kaolinite (Herbillon *et al.,* 1981; Bhattacharyya *et al.,* 1993). The presence of this mineral in QGH3 and QGH5 soils suggests that these soils are in an advanced stage of weathering as compared to those of QGH1 and QGH2. This is evident from the weathering features of feldspar grains (Fig. 5); the feldspar grains of QGH3 and QGH5 are more weathered than those of QGH1 and QGH2. The ages 12,920–9980 cal yr for QGH5 calcrete and 7390 cal yr for QGH4 calcrete suggest that the period 12920–7390 cal yr B.P. was cold and dry, and soils with pedogenic calcrete and saline epipedons developed in vast regions of the Indo-Gangetic Plains (Srivastava *et al.,* 1994). Formation of trioctahedral vermiculite and smectite at the expense of biotite took place in QGH5 soils during this arid phase of climate. Later, during a warmer and wetter climate with maximum humidity, around 5730–4150 cal yr B.P., dissolution and leaching of the pedogenic calcrete took place (Srivastava *et al.,* 1994). In a warm and wetter climate, the stability of smectite becomes ephemeral and it transforms to Sm/K (Pal *et al.,* 1989). This transformation is evident from QGH3 and QGH5 soils, where the smectite produced during arid phases transformed to Sm/K in subsequent warm and wetter periods. This phase of wetter climate also terminated in the area around 4150 cal yr B.P. as in the Thar desert, where increased salinity and drying of lakes has been inferred around 4150 cal yr B.P. (Singh *et al.,* 1974; Bryson and Swain, 1981; Swain *et al.,* 1983; Dhir *et al.,* 1994). Thus, Sm/K could be preserved to the present, and during the arid climate that followed the elapse of the humid climate, transformation of biotite, into its weathering products like trioctahedral vermiculite and smectite, did continue. This is evident from the presence of these products amidst Sm/K in the fine clay fractions of QGH3 and QGH5 soils.

Clay illuviation occurred during both arid and humid climates. As a result, the clay mica content of QGH2, QGH3, and QGH5 soils decreases with depth (Table 4) (Pal *et al.,* 1994), which is contrary to observations on normal *in situ* soils developed on parent rock (Kapoor, 1972). The fine clay has moved preferentially into the B horizon, thereby causing the observed increase in the proportion of mica in the A horizon, of vermiculite and smectite in the B horizon of QGH2 soils, and of vermiculite, smectite, and Sm/K in QGH3 and QGH5 soils (Table 4). The enhanced illuviation of clay in a wetter and warmer climate has also resulted in the thickness of the argillans increasing with the age of the soils (Srivastava *et al.,* 1994). Thus, the major pedogenic processes in these soils include illuviation of clay, decalcification, and little addition and accumulation of organic matter (Table 3). Such pedogenesis has been common in the Quaternary deposits of the northwestern part of the Indo-Gangetic Plains during the Holocene (Pal *et al.,* 1987b, 1994).

CONCLUSIONS

This study shows that during the Holocene the major pedogenesis of the soils of the central Indo-Gangetic Plains, north-central India, has mainly involved clay illuviation and decal-

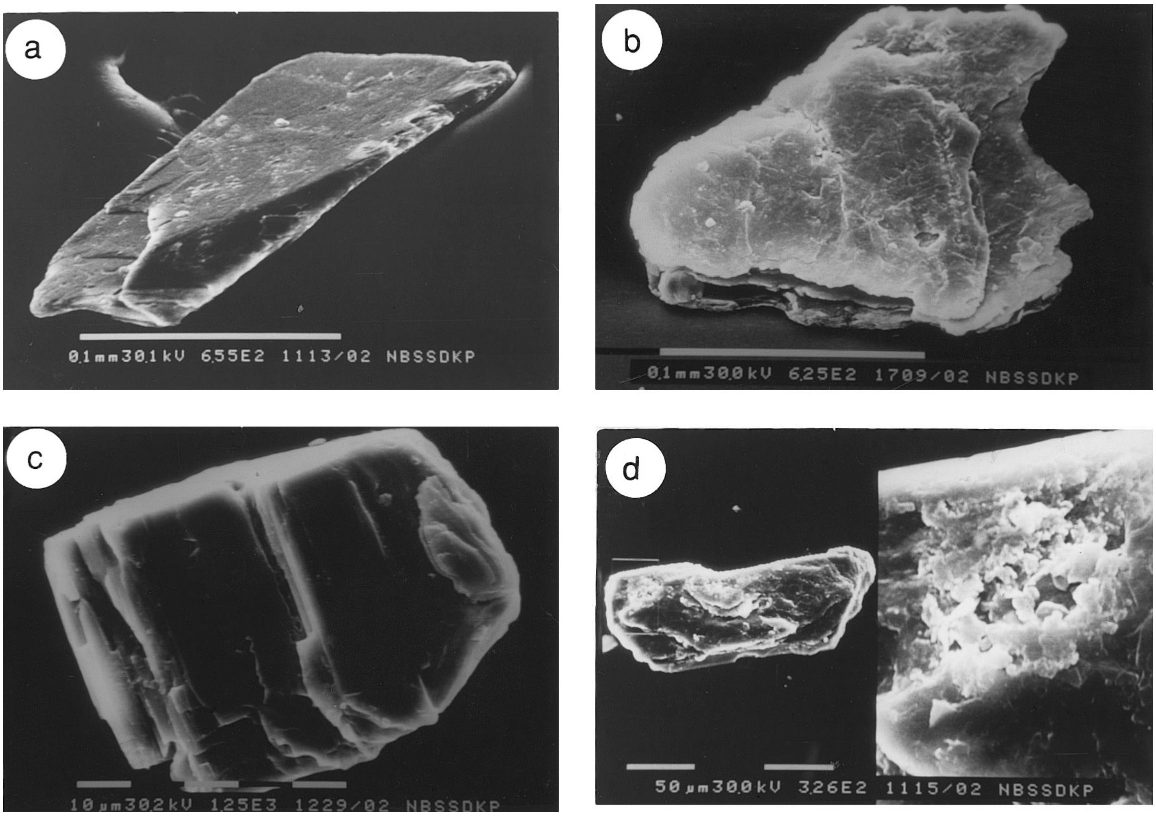

FIG. 5. Representative SEM photographs: (a) muscovite, QGH5 soils, Pedon PB7, B3 Horizon (175–200 cm); (b) biotite QGH5 soils, Pedon PB7, B3 horizon (175–200 cm); (c) plagioclase feldspar, QGH2 soils, Pedon PA6, C horizon (97–127 cm); (d) plagioclase feldspar, QGH5 soils, Pedon PB7, B3 horizon (175–200 cm).

cification. Weathering of biotite was substantial, at first making mixed layers with vermiculite, and then vermiculite and smectite. The clay mineral assemblages of QGH1 have added smectite by QGH2 time, and smectite and Sm/K by QGH3 and QGH5 time.

Despite the fact that equilibria are only apparent and ephemeral, we may conclude that (a) the alluvial soils older than 2500 yr B.P. are relict paleosols (Parsons, 1981), (b) these relict soils have been affected by later climatic change to wetter and warmer conditions as evidenced by the formation of Sm/K at the expense of smectite, and thus qualify to be polygenetic soils (Beckman, 1984; Wright, 1986; Pal *et al.*, 1989), and (c) pedogenic Sm/K that was preserved unaffected within these relict soils can also be helpful for paleoclimatic interpretation.

REFERENCES

Barshad, I. (1964). Chemistry of soil development. *In* "Chemistry of the Soil" (F. E. Bear, Ed.), pp. 1–70. Reinhold, New York.

Beckmann, G. G. (1984). Paleosols, pedoderms, and problems in presenting pedological data. *Australian Geographer* **16,** 15–21.

Bhargava, G. P., Pal, D. K., Kapoor, B. S., and Goswami, S. C. (1981). Characteristics and genesis of some sodic soils in the Indo-Gangetic alluvial plain of Haryana and Uttar Pradesh. *Journal of the Indian Society of Soil Science* **29,** 61–70.

Bhattacharya, A., and Banerjee, S. N. (1979). Quaternary geology and geomorphology of the Ajay-Bhagirathi Valley, Birbhum and Murshidabad districts, West Bengal, India. *Indian Journal of Earth Science* **6,** 91–102.

Bhattacharyya, T., Pal, D. K., and Deshpande, S. B. (1993). Genesis and transformation of minerals in the formation of red (Alfisols) and black (Inceptisols and Vertisols) soils on Deccan basalt in the Western Ghats, India. *Journal of Soil Science* **44,** 159–171.

Birkeland, P. W. (1984). "Soils and Geomorphology." Oxford University Press, New York.

Blaise, B. (1989). Clay-mineral assemblages from Late Quaternary deposits on Vancouver Island, southwestern British Columbia, Canada. *Quaternary Research* **31,** 41–56.

Bryson, R. A., and Swain, A. K. (1981). Holocene variation in monsoon rainfall in Rajasthan. *Quaternary Research* **16,** 135–145.

Buchmann, C., and Grubb, P. L. C. (1991). A kaolin–smectite interstratification sequence from a red and black complex. *Clay Minerals* **26,** 343–358.

Bullock, P., Federoff, N., Jongerius, A., Stoops, G., and Tursina, T. (1985). "Handbook of Soil Thin-Section Description." Waine Research Publications, Wolverhampton.

Churchman, G. J., Slade, P. G., Self, P. G., and Janik, L. J. (1994). Nature of interstratified kaolin-smectites in some Australian soils. *Australian Journal of Soil Research* **32,** 805–822.

Das, P. (1993). Thermoluminescence dating of soils of the western Gangetic Plains. Unpublished M. Tech. thesis, Univ. of Roorkee, 28 pp.

Delvaux, B., and Herbillon, A. J. (1995). Pathways of mixed layer kaolin–smectite formation in soils. *Proceedings 10th International Clay Conference, Adelaide,* 457–461.

Dhir, R. P., Rajaguru, S. N., and Singhvi, A. K. (1994). Desert Quaternary formations and their morphostratigraphy; Implication for the evolutionary history of the Thar. *Journal of the Geological Society of India* **43,** 435–447.

Gjems, O. (1967). Studies on clay minerals and clay mineral formation in soil profiles in Scandinavia. *Meddelelser fra det Norske Skogsforsksvesen* **21,** 303–415.

Herbillon, A. J., Frankart, R., and Vielvoye, L. (1981). Occurrence of interstratified kaolinite–smectite minerals in a red-black soil toposequence. *Clay Minerals* **16,** 195–201.

IMD (1989). “Climate of Uttar Pradesh.” Indian Meteorological Dept., Government of India, Controller of Publication, Delhi.

Ismail, F. T. (1969). Role of ferrous iron oxidation in the alteration of biotite and its effect on the type of clay minerals formed in soils of arid and humid regions. *American Mineralogist* **54,** 1460–1466.

Jackson, M. L. (1979). “Soil Chemical Analysis—Advanced Course.” Published by the author, Madison, WI.

Levine, E. L., and Ciolkosz, E. J. (1983). Soil development in till of various ages in northern Pennsylvania. *Quaternary Research* **19,** 85–95.

Kapoor, B. S. (1972). Weathering of micaceous clays in some Norwegian podzols. *Clay Minerals* **9,** 383–394.

Kumar, S., Parkash, B., Manchanda, M. L., Singhvi, A. K., and Srivastava, P. (1996). Holocene landform and land evaluation of the Western Gangetic Plains: Implications of neotectonics and climate. *Zutschrift fuer Geomorphologie* **103,** 283–312.

Mohindra, R., and Parkash, B. (1990). Clay mineralogy of the Gandak Megafan and Adjoining areas, Middle Gangetic Plains, India. *Sciences Geologiques Bulletin* **43,** 203–212.

Mohindra, R., Parkash, B., and Prasad, J. (1992). Historical geomorphology of the Gandak Megafan, Middle Gangetic Plain, India. *Earth Surface Processes and Landforms* **17,** 643–662.

Pal, D. K., and Deshpande, S. B. (1987). Parent material, mineralogy, and genesis of two benchmark soils of Kashmir Valley. *Journal of the Indian Society of Soil Science* **35,** 690–698.

Pal, D. K., Deshpande, S. B., and Durge, S. L. (1987a). Weathering of biotite in some alluvial soils of different agroclimatic zones. *Clay Research* **6,** 69–75.

Pal, D. K., Deshpande, S. B., and Sehgal, J. L. (1987b). Development of soils of Quaternary deposits of north India. *Indian Journal of Earth Science* **14,** 329–334.

Pal, D. K., Deshpande, S. B., Venugopal, K. R., and Kalbande, A. R. (1989). Formation of di- and trioctahedral smectite as evidence for paleoclimatic changes in southern and central Peninsular India. *Geoderma* **45,** 175–184.

Pal, D. K., Kalbande, A. R., Deshpande, S. B., and Sehgal, J. L. (1994). Evidence of clay illuviation in sodic soils of the Indo-Gangetic plain since the Holocene. *Soil Science* **158,** 465–473.

Parsons, R. B. (1981). “Proposed Soil Stratigraphic Guide.” Progress report of Working Group on Soil Stratigraphy, INQUA/ISSS Paleopedology Commission, 6 pp.

Rajagopalan, G. (1988). Radiocarbon ages of carbonate materials in Gangetic alluvium. *In* “Workshop on Gangetic Plains—‘Terra Incognita.’” Lucknow University, Lucknow.

Richards, L., Ed. (1954). “Diagnosis and Improvement of Saline and Alkaline Soils.” USDA Agriculture Handbook No. 60. U.S. Government Printing Office, Washington, DC.

Singh, I. B. (1988). Geological evolution of Gangetic Plain—What we know and what we do not know? *In* “Workshop on Gangetic Plains—‘Terra Incognita.’” Lucknow University, Lucknow.

Singh, R. L., and Singh, K. N. (1971). Upper Ganga Plain. *In* “India—A Regional Geography” (R. L. Singh, Ed.). National Geographic Society of India, Varanasi.

Singh, G., Joshi, R. D., and Singh, A. B. (1972). Stratigraphic and radiocarbon evidence for the age and development of three salt lake deposits in Rajasthan, India. *Quaternary Research* **2,** 496–505.

Singh, G., Joshi, R. D., Chopra, S. K., and Singh, A. B. (1974). Late Quaternary history of vegetation and climate of the Rajasthan desert, India. *Philosphical Transactions of the Royal Society of London* **267,** 467–501.

Soil Survey Staff (1966). “Soil Survey Manual,” Handbook No. 18. Oxford and IBH, New Delhi.

Soil Survey Staff (1975). “Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys.” Agriculture Handbook No. 436. Soil Conservation Service, U.S. Dept. of Agriculture, Washington, DC.

Srivastava, P., Parkash, B., Sehgal, J. L., and Kumar, S. (1994). Role of neotectonics and climate in development of the Holocene geomorphology and soils of the Gangetic Plains between the Ramganga and Rapti rivers. *Sedimentary Geology* **94,** 119–151.

Stuiver, M., and Reimer, P. (1993). Extended ^{14}C database and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* **35,** 215–230.

Swain, A. M., Kutzbach, J. E., and Hasterntrath, S. (1983). Estimates of Holocene precipitation for Rajasthan, India, based on pollen and lake-level data. *Quarternary Research* **19,** 1–17.

Tardy, Y., Bocquier, G., Paquet, H., and Millot, G. (1973). Formation of clay from granite and its distribution in relation to climate and topography. *Geoderma* **10,** 271–284.

Tomar, K. P. (1985). High-spacing irregularly interstratified layer silicates in the alluvial soil clays of Meerut, India. *Clay Minerals* **20,** 115–124.

Wadia, D. N. (1966). “Geology of India.” McMillan, London.

Wilson, M. J., and Cradwick, P. D. (1972). Occurrence of interstratified kaolinite–montmorillonite in some Scottish soils. *Clay Minerals* **9,** 435–436.

Wright, V. P. (1986). “Paleosols: Their Recognition and Interpretation.” Blackwell, Oxford.