Paleoclimatic implications of pedogenic carbonates in Holocene soils of the Gangetic Plains, India

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Abstract

This study attempts to reconstruct the Holocene climatic history of the Indo-Gangetic Plains based on micromorphological characteristics and stable isotope composition of calcrites in a soil-chronoassociation between the Ramganga and Rapti rivers. The calcrite from the B2 horizon of older soils (QGH4–QGH5: 6500–13 500 year BP) consists of septarian and irregularly shaped nodules of dense micrite and diffused needles associated with the illuvial clay pedofeatures. Fabric of the calcrites of older soils show inclusion of soil constituents and precipitation of carbonates in between weathered layers of micas. Formation of this calcrite took place during the pedogenesis in an arid to semi-arid climate that also influenced vegetation and C4 type biomass such as Chenopodium and Typha angustata spread in the area. A change to warm and humid phase at 6500 year BP led to dissolution and reprecipitation of the calcrites. This led to the formation of blocky crystals and needles of calcite in voids and coarsening of the fabric in the lower horizons. The vegetation pattern also changed to woodland with Anogeissus and Tecoma spp. The younger soils (<2500 year BP) show secondary carbonate accumulation associated mainly along the voids in lower parts of the profiles. These are relatively coarse textured with little or no inclusion of soil constituents. This coarse grained calcrite results from capillary rise from a fluctuating water table in a sub-humid climate similar to present.

Carbon and oxygen isotope data suggest that the formation of pedogenic carbonate in old soils (QGH4 and QGH5) by evapotranspiration during arid to semi-arid climate. In the upper horizons, the carbonates are depleted in $^{13}$C as their formation was influenced by the sparse vegetation and low soil respiration rate. In the lower horizons, the carbonates show enrichment of $^{13}$C due to its extensive dissolution–reprecipitation during the humid climate. The younger soils showed the enrichment of $^{13}$C in their calcrites and support their formation from fluctuating shallow groundwater table. The oxygen isotope values similar to that of meteoric water of the area indicate calcrite precipitation in equilibrium with the soil water. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Pedogenic carbonate; Paleoclimate; Holocene; Soil-chronoassociation; Soil micromorphology; The Gangetic plains; India

1. Introduction

Earlier works indicate that the Indo-Gangetic Plains, one of the most extensive fluvial plains of the world, consist predominantly of alluvium of lower and upper Pleistocene age (Wadia, 1966; Bhattacharya and Banerjee, 1979). Recent work on soils of the Gangetic Plains has indicated several geomorphic surfaces, that are generally <13 500 year BP old (Mohindra et al., 1992; Srivastava et al., 1994; Kumar et al., 1996; Singh et al., 1998). Five members (QGH1–QGH5, QGH5 being the oldest) of a soil-chronoassociation are now recognised in the...
Indo-Gangetic Plains between the Ramganga and Rapti rivers on the basis of degree of soil development (Fig. 1). Available data on radiocarbon dates, thermoluminescence dates (TL dates) and historical evidence suggest that these five members were formed on surfaces originating at <500, >500, >2500, 8000 and 13 500 year BP, respectively (Srivastava et al., 1994).

Many soil properties/pedogenic features are sensitive to climatic variations. Pedogenic calcium carbonate is also climate specific and can record paleoclimatic signatures. Stable isotope of the carbonates can be used to reconstruct paleoenvironmental change during the soil development (Magaritz et al., 1981; Cerling, 1984; Amundson et al., 1988, 1989; Quade et al., 1989a,b) and the distinct micromorphological features of calcareous soils can be correlated with the specific climates (Rabenhorst et al., 1984).

The Quaternary was marked by severe and frequent climatic changes (Ritter, 1996). The paleoclimatic record has also been documented from sediments in NW and SW parts of India (Singh et al., 1972, 1974, 1990; Hashmi and Nair, 1986; Agarwal, 1992). For example, lacustrine deposits from the Thar Desert in west of the Gangetic Plains suggest that cold and very arid climate at 10 000 year BP changed to a slightly wetter one by 5000 year BP and to an even wetter one by 3800 year BP, but since 3800 year BP drier conditions have generally prevailed (Singh et al., 1972, 1974, 1990). Hashmi and Nair (1986) attributed the high percentages of feldspars in the outer shelf sediments of the Indian peninsula to less weathering during the arid phase from 12 000 to 9000 year BP. From the data on geochemistry, palaeontology, geomorphology and geochronology of the Holocene deposits in the Kashmir Valley, Agarwal (1992) suggested that after the cold dry climate of the Early Holocene there were increase in humidity and temperature at 6000, 1800 and 1000 year BP. Palynological studies from the southwest coast of India showed a marked decrease in mangrove pollens and suggest weakening of monsoon after 11 000 year BP (Van Campo, 1986).

The Holocene climatic change influenced geomorphic and pedogenic processes in soils of the Gangetic Plains (Srivastava et al., 1994, 1998). Climate and neotectonism played a significant role in the evolution of landforms and soils of the area. A cold arid to semi-arid climate prevailed during the Early Holocene as indicated by the formation of smectite and trioctahedral vermiculite at the expense of biotite in soils. The smectite was transformed to interstratified smectite–kaolin (Sm/K) during the later humid climate. The Holocene soils also show accumulation of pedogenic carbonates. In this paper micromorphology and stable isotope of these carbonates are presented to indicate the climatic changes during the Holocene in the Gangetic Plains.

2. Materials and methods

The study area is located between latitudes 26°–29°30’N and longitudes 78°–82°E (Fig. 1). Climate is sub-humid in most of the study area. Monsoonal rainfall occurs mainly between July and August and accounts for the most of the annual mean rainfall (Allahabad 975 mm, Bareilly 1102 mm, Lucknow 940 mm, Faizabad 1008 mm).

A total of 47 soil profiles were studied in different soil-geomorphic units according to the procedure of Soil Survey Staff (1966). Particle size distribution was determined after the removal of organic matter, calcium carbonate and the free iron oxide. Sand (2000–50 μm), silt (50–2 μm) and total clay (<2 μm) were separated according to the procedure of Jackson (1979). For the micromorphological studies, undisturbed soil samples from specific horizons were collected and impregnated with cryslic resin to prepare large (80 mm × 60 mm) thin sections (Jongerius and Heintzberger, 1963). They were described according to Bullock et al. (1985). For the sub-microscopic studies, fresh surfaces of the calcrites were fixed on aluminium stubs with LIET-C conductive cement, coated with gold and were studied by Philips Scanning Electron Microscope (SEM). For stable carbon and oxygen composition, carbonate nodules from the soils profiles were rinsed with distilled water to remove dust and powdery outer
Table 1
Pedogeomorphic features of the soil-chronoassociation (letter symbols for soil-geomorphic units are given in Fig. 1)

<table>
<thead>
<tr>
<th>Member age (year bp)</th>
<th>Geomorphic unit (s)</th>
<th>Horzonation, Thickness of B2 horizon</th>
<th>Development of pedogenic features</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGH1 &lt;500</td>
<td>Flood plains and piedmonts (GFP, RFP, KGPD, GDPD and YSKPD)</td>
<td>A/C</td>
<td>–</td>
<td>Youngest member rarely with weakly developed 15–20 cm B horizon</td>
</tr>
<tr>
<td>QGH2 &gt;500</td>
<td>Young river plains and remnant piedmonts (UKGP, OSKPD and YGP)</td>
<td>A/B/C, 21–57 cm</td>
<td>Weak</td>
<td>Weakly developed soils occur in areas with shallow ground water and high moisture</td>
</tr>
<tr>
<td>QGH3 2500–5000</td>
<td>Old river plains and interfluvés (LKG, OGP, URGHIF and UDGGHIF)</td>
<td>A/B/C, 52–85 cm</td>
<td>Moderate</td>
<td>Moderately developed soils with smooth voids and 60–70 μm thick microlaminated clay pedofeatures.</td>
</tr>
<tr>
<td>QGH4* 8000</td>
<td>Interfluve (LDGGHIF)</td>
<td>A/B/C, 45–100 cm</td>
<td>Strong</td>
<td>Strongly developed soils in lower part of the largest interfluve occurring adjacent to MDGGHIF in the east. Smooth channel voids with 80–100 μm microlaminated clay pedofeatures.</td>
</tr>
<tr>
<td>QGH5 13 500</td>
<td>Interfluve (MDGGHIF and LRGHIF)</td>
<td>A/B/C, 93–97 cm in soils with calcrite and 105–137 cm in soils without calcrite</td>
<td>Very strong</td>
<td>Very strongly developed soils occurring in ancient paleochannels and floodplains in slightly raised (10–20 cm) and shallow areas. Clay pedofeatures 100–150 μm thick and microlaminated.</td>
</tr>
</tbody>
</table>

*After Mohindra et al., 1992.

materials. These were air dried and pulverised to 230 mesh. The fine powdered calcrites were reacted with orthophosphoric acid at 90°C. The resultant CO₂ was analysed in a mass spectrometer at Oil and Natural Gas Commission, Keshav Dev Malvya Institute of Petroleum Exploration, Dehradun, with a machine standard that was calibrated against the NBS-19 standard.

3. Results

3.1. Soils of the area

Soils of the area were described by Srivastava et al. (1994). An integrated approach was used to determine the degree of soil development in 15 soil-geomorphic units. This was based on the thickness of the B horizon, clay accumulation index (Levine and Ciolkosz, 1983), degree of pedality and thickness of the clay pedofeatures. On the basis of relative degree of development soils were grouped into five members of a soil-chronoassociation (QGH1–QGH5, QGH5 being the oldest). Pedogeomorphic features of each member are briefly described in Fig. 1 and Table 1. The physical and chemical properties of the representative pedons from each member are given in Table 2.

3.2. Age of the soils

All the soils in the study area are exposed and have remained so since the start of pedogenesis and thus represent a period of landscape stability and their chronology would be very important to understand the soil-geomorphic evolution of the area. The age of each member was based on relative soil development and radiocarbon, and thermoluminescence (TL) dates and historical evidence (Srivastava et al., 1994, 1998). Radiocarbon dates of the calcrites from the Bk horizon around Lucknow from the Middle Deoha/Ganga–Ghaghar Interfluve (MDGGHIF) of QGH5 member range between 11 000 and 9000 year BP (Rajagopalan, 1992). Two radiocarbon dates of the calcrites from the QGH4 soils from the Lower Deoha/Ganga–Ghaghar Interfluve (LDGGHIF) and Lower Ganga–Yamuna Interfluve (LGYIF) are 6500 and 7000 year BP, respectively (Mohindra et al., 1992; Kumar et al., 1996). Both these dates are from the Bk
soil horizons around Bulandshar from LGYIF and Ballia from LDGGHIF, respectively. The TL dates of the soils from the BC horizon around Sitapur from MDGGHIF and Bulandshar from LGYIF are 13600 and 8300 year BP, respectively (Das, 1993). The TL dates from the BC horizons indicate the time of deposition and approximate maximum age of the soils. Calcrete formation may have taken some time after the start of pedogenesis and thus radiocarbon dates are younger than TL dates.

The characters of the QGH3 soils overlap the QGD3 and QGD4 soils on the adjoining Gandak Megaflan. On the basis of historically recorded position of the Gandak river during its eastward shift of over 80 km in the last 5000 years, Mohindra et al. (1992) assigned the ages of >2500 and >5000 year BP to the QGD3 and QGD4 soils, respectively. Hence, the age of QGH3 soils of the present area can be assigned between 2500 and 5000 year BP. For the soils of the QGH1 and QGH2, tentative ages are given as <500 and >500 year BP, respectively.

3.3. Morphology and distribution of calcretes

The term ‘calcrete’ is now generally accepted and used for a wide range of calcium carbonates in the broadest sense (Netterberg, 1978; Milnes and Hutton, 1983; Milnes, 1992). In the present study the term ‘calcrete’ has been used to denote calcium carbonate accumulation in the soils. The calcretes in these soils are commonly observed as nodules of micrite and sparry calcite in irregular shapes and as coatings along voids, and rarely as disseminated carbonate crystals within the groundmass. The calcretes in younger soils (QGH1–QGH3) show more irregular morphology than in older soils (QGH4 and QGH5) (Table 2). X-ray diffraction analysis of the powdered samples of the calcretes indicates dominance of calcite over quartz, feldspar and phyllosilicates. The peak height ratio of calcite (3.0 Å) and quartz (3.34 Å) is >1 and in younger soils the ratio is greater than that in older soils. Petrographic study of the calcretes of both older and younger soils showed calcite is the major mineral followed by quartz, feldspar and micas. In calcretes of younger soils the proportion of the calcite is greater (90–100%) than in calcretes of older soils (70–80%). Together with micromorphology these features indicate two types of calcrete in the soils.

3.3.1. Type-I calcrete

The Type-I calcrete occurs in strongly developed soils of older members of soil-chronosequence, i.e. in QGH4 and QGH5. Soils of these members occur in upland interfluves with very gentle slopes and deep groundwater table. Septaric and acicular forms of the calcretes are common in the B2 horizon of these soils (Fig. 2a,b). The fabric of the calcrete is defined by dense continuous micrite and diffused needles mixed with soil matrix or as coatings around the coarse particles (Fig. 2c,d). Intense weathering of mica has occurred in these calcretes (Fig. 2e,f). These calcrete features often occur with illuvial clay pedofeatures and sometimes clay coatings also occur on nodules (Fig. 2g). In lower horizons (B3 or C), the calcretes are irregular shaped and contain sparitic and prismatic calcite and dissolution–reprecipitation features (Fig. 2h). Like the calcretes in upper parts, these are also impure due to the assimilation of soils constituents. Coarsening of calcretes in the lower horizons with gradual increase in their proportion suggests their formation by reprecipitation of the carbonates dissolved in the upper horizons.

SEM studies showed them to be poorly crystallized with diffused anhedral to subhedral grains and needles as matrix with inclusion of quartz, feldspar and micas (Fig. 3a,b). These have been cemented with sparry calcite, which occurs as a continuous mass of pure calcite (Fig. 3c). Biotite and muscovite showed curling and opening of the layers with calcite precipitation in between layers (Fig. 3d,e). Pore spaces within calcretes showed precipitation of pure calcite as botryoidal aggregates of blocky crystals and flocks of well-developed needles (Fig. 3f,g). These features increase with depth. On their surfaces and in voids, illuviation of impure clay was observed (Fig. 3h). The fabric corresponds to the ‘alpha type’ pedogenic calcrete developed by abiotic processes (Wright, 1990) and overall degree of carbonate development in these soils ranges from stage I to II (Gile et al., 1966).

3.3.2. Type-II calcrete

The morphology and distribution of Type-II calcretes that occur in soils of QGH1–QGH3 are
### Table 2
Morphological, physical and chemical properties of soils

<table>
<thead>
<tr>
<th>Soil Geomorphic Unit(s)</th>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Colour (moist)</th>
<th>Structure</th>
<th>pH (1:2)</th>
<th>CaCO₃ %</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
<th>Special features</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGH1, &lt;500 year BP, fine to coarse loamy, mixed hyperthermic Typic Ustorthent, Pedon C 16</td>
<td>0–34</td>
<td>Ap</td>
<td>2.5 y 3/2</td>
<td>0</td>
<td>7.9</td>
<td>−</td>
<td>25.7</td>
<td>58.9</td>
<td>15.4</td>
<td>1–3 cm globular and</td>
</tr>
<tr>
<td>GDPD</td>
<td>34–66</td>
<td>C1</td>
<td>2.5 y 4.5/4</td>
<td>1 sbk</td>
<td>8.1</td>
<td>2.4</td>
<td>26.7</td>
<td>59.6</td>
<td>13.7</td>
<td>irregular shaped calcrite</td>
</tr>
<tr>
<td>YSKPD</td>
<td>66–99</td>
<td>C2</td>
<td>2.5 y 5/4</td>
<td>0</td>
<td>8.3</td>
<td>7.4</td>
<td>16.5</td>
<td>74.9</td>
<td>8.6</td>
<td>nodules up to 10% by volume</td>
</tr>
<tr>
<td>RPF, GFP</td>
<td>99–120</td>
<td>C3</td>
<td>2.5 y 5/4</td>
<td>0</td>
<td>8.4</td>
<td>5.6</td>
<td>18.3</td>
<td>71.8</td>
<td>9.9</td>
<td>in C horizons</td>
</tr>
<tr>
<td>QGH2, &gt;500 year BP, Fine to coarse loamy, mixed hyperthermic Typic Ustochrept, Pedon A 2</td>
<td>0–18</td>
<td>Ap</td>
<td>2.5 y 5/3</td>
<td>0</td>
<td>7.8</td>
<td>−</td>
<td>24.8</td>
<td>56.1</td>
<td>19.1</td>
<td>1–2 cm hard irregular shaped</td>
</tr>
<tr>
<td>UKGP,</td>
<td>18–32</td>
<td>Bw1</td>
<td>2.5 y 5/2</td>
<td>1 sbk</td>
<td>7.8</td>
<td>−</td>
<td>19.0</td>
<td>60.3</td>
<td>20.7</td>
<td>calcrite nodules 5 to 10% by volume</td>
</tr>
<tr>
<td>YGP</td>
<td>63–90</td>
<td>Bw3</td>
<td>2.5 y 5/3</td>
<td>1 sbk</td>
<td>8.2</td>
<td>4.6</td>
<td>27.0</td>
<td>53.1</td>
<td>19.9</td>
<td>volume in B3 and C horizons</td>
</tr>
<tr>
<td>OSKPD,</td>
<td>32–63</td>
<td>Bw2</td>
<td>2.5 y 5/2</td>
<td>2 sbk</td>
<td>8.0</td>
<td>−</td>
<td>12.1</td>
<td>62.1</td>
<td>25.8</td>
<td>of some pedons</td>
</tr>
<tr>
<td>90</td>
<td>+</td>
<td>C</td>
<td>2.5 y 5/3</td>
<td>1 sbk</td>
<td>8.3</td>
<td>10.6</td>
<td>39.6</td>
<td>42.1</td>
<td>18.3</td>
<td></td>
</tr>
<tr>
<td>QGH3, 2500 to 5000 year BP, fine to coarse loamy, mixed hyperthermic, Typic Ustochrept, Pedon B 4</td>
<td>0</td>
<td>20</td>
<td>Ap</td>
<td>2.5 y 5/3</td>
<td>1 sbk</td>
<td>8.3</td>
<td>2.4</td>
<td>22.0</td>
<td>61.2</td>
<td>16.8</td>
</tr>
<tr>
<td>LKGP</td>
<td>11–23</td>
<td>A/B</td>
<td>2.5 y 5/4</td>
<td>1 sbk</td>
<td>−</td>
<td>−</td>
<td>8.7</td>
<td>75.5</td>
<td>15.8</td>
<td>shaped calcrite nodules from</td>
</tr>
<tr>
<td>OGP,</td>
<td>23–43</td>
<td>Bt1</td>
<td>2.5 y 4.5/4</td>
<td>2 sbk</td>
<td>−</td>
<td>−</td>
<td>5.8</td>
<td>67.1</td>
<td>27.1</td>
<td>5 to 15% in B2-B3 horizons</td>
</tr>
<tr>
<td>URGHIF</td>
<td>43–67</td>
<td>Bt2</td>
<td>2.5 y 4.5/4</td>
<td>2 sbk</td>
<td>−</td>
<td>−</td>
<td>4.6</td>
<td>66.5</td>
<td>28.9</td>
<td>of many pedons</td>
</tr>
<tr>
<td>UDGGIF</td>
<td>67–93</td>
<td>Bt3</td>
<td>2.5 y 5/4</td>
<td>1 sbk</td>
<td>−</td>
<td>−</td>
<td>5.1</td>
<td>74.5</td>
<td>20.4</td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>+</td>
<td>C</td>
<td>2.5 y 6/4</td>
<td>1 sbk</td>
<td>−</td>
<td>−</td>
<td>17.6</td>
<td>75.9</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>QGH4, 8000 year BP, fine loamy, mixed hyperthermic, Typic Haplustalf, Pedon RC1</td>
<td>0–11</td>
<td>Ap</td>
<td>2.5 y 5/5</td>
<td>0</td>
<td>−</td>
<td>−</td>
<td>10.2</td>
<td>82.3</td>
<td>7.5</td>
<td>2–3 cm fine irregular vein</td>
</tr>
<tr>
<td>11–23</td>
<td>A/B</td>
<td>2.5 y 5/4</td>
<td>1 sbk</td>
<td>−</td>
<td>−</td>
<td>8.7</td>
<td>75.5</td>
<td>15.8</td>
<td>shaped calcrite nodules from</td>
<td></td>
</tr>
<tr>
<td>23–43</td>
<td>Bt1</td>
<td>2.5 y 4.5/4</td>
<td>2 sbk</td>
<td>−</td>
<td>−</td>
<td>5.8</td>
<td>67.1</td>
<td>27.1</td>
<td>5 to 15% in B2-B3 horizons</td>
<td></td>
</tr>
<tr>
<td>LDGGIF</td>
<td>43–67</td>
<td>Bt2</td>
<td>2.5 y 4.5/4</td>
<td>2 sbk</td>
<td>−</td>
<td>−</td>
<td>4.6</td>
<td>66.5</td>
<td>28.9</td>
<td>of many pedons</td>
</tr>
<tr>
<td>67–93</td>
<td>Bt3</td>
<td>2.5 y 5/4</td>
<td>1 sbk</td>
<td>−</td>
<td>−</td>
<td>5.1</td>
<td>74.5</td>
<td>20.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>+</td>
<td>C</td>
<td>2.5 y 6/4</td>
<td>1 sbk</td>
<td>−</td>
<td>−</td>
<td>17.6</td>
<td>75.9</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>QGH5, 13500 year BP, fine loamy, mixed hyperthermic, Typic Haplustalf, Pedon C 7</td>
<td>0–18</td>
<td>Ap</td>
<td>2.5 y 5/4</td>
<td>0</td>
<td>7.9</td>
<td>−</td>
<td>17.6</td>
<td>62.5</td>
<td>19.9</td>
<td>2–3 cm fine irregular vein</td>
</tr>
<tr>
<td>18–38</td>
<td>A/B</td>
<td>2.5 y 4.5/4</td>
<td>1 sbk</td>
<td>7.8</td>
<td>−</td>
<td>10.3</td>
<td>65.6</td>
<td>24.1</td>
<td>shaped nodules in B2</td>
<td></td>
</tr>
<tr>
<td>MDGGIF</td>
<td>38–56</td>
<td>Bt1</td>
<td>2.5 y 4/4</td>
<td>3 sbk</td>
<td>7.9</td>
<td>0.7</td>
<td>8.9</td>
<td>60.8</td>
<td>30.3</td>
<td>horizons of some pedons and</td>
</tr>
<tr>
<td>LRGHIF</td>
<td>56–83</td>
<td>Bt2</td>
<td>2.5 y 4/4</td>
<td>3 sbk</td>
<td>8.2</td>
<td>5.6</td>
<td>9.6</td>
<td>62.5</td>
<td>27.9</td>
<td>throughout the pedon in some</td>
</tr>
<tr>
<td>83–150</td>
<td>Bt3</td>
<td>2.5 y 5/4</td>
<td>2 sbk</td>
<td>8.3</td>
<td>3.3</td>
<td>12.5</td>
<td>61.2</td>
<td>26.3</td>
<td>profiles</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>+</td>
<td>B/C</td>
<td>2.5 y 6/4</td>
<td>1 sbk</td>
<td>8.8</td>
<td>6.6</td>
<td>10.3</td>
<td>70.8</td>
<td>18.9</td>
<td></td>
</tr>
</tbody>
</table>

a Structure: 0 = Apedal, 1 sbk = weak subangular blocky, 2 sbk = moderately subangular blocky, 3 sbk = strongly subangular blocky.

b After Mohindra et al. (1992).

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Fig. 2. Photomicrographs of Type-I calcrite features. All in cross polars. (a) Strongly impregnated septic nodule of micrite. Pedon C5, Bt2 horizon, MDGGIF. (b) Part of an acicular calcrite nodule. Pedon C5, Bt1 horizon, MDGGIF. (c) Strongly impregnated nodules of diffused calcite needles and micrite with inclusion of soil constituents. Pedon C1, Bt2 horizon, MDGGIF. (d) Diffused calcite needles and micritic coatings on skeleton grains. Pedon C1, Bt2 horizon, MDGGIF. (e) Part of an impure micritic nodule, biotite has strongly weathered and exfoliated due to the growth of calcium carbonate. Pedon C5, Bt1 horizon, MDGGIF. (f) Muscovite flakes within calcrite showing bending and opening of the flakes due to the growth of calcium carbonate. Pedon C1, Bt2 horizon, MDGGIF. (g) Illuviated clay pedofeature along the dense micritic nodule (marked by arrow). Pedon C5, Bt2 horizon, MDGGIF. (h) Decalcified soil, microsparatic calcrite dissolved and partially washed out. Pedon C5, BC horizon, MDGGIF.
very different from those of Type-I. They are relatively pure and coarsely crystalline and occur as nodules and hypococatings with prismatic and sparitic calcite (Fig. 4a–c). They are commonly associated with voids, and show very little assimilation of soil mass. Weathering of the primary minerals has not occurred as in Type I calcretes (Fig. 4e). Coarsening of the fabric due to repeated dissolution–precipitation is very common in these calcretes (Fig. 4d,f). SEM studies of these calcretes confirm that they are coarsely crystalline with prismatic and sparry calcite and are also free from soil constituents (Fig. 5a–d).

The QGH1 soils on floodplains (GFP and RFP) and in piedmonts (YSKP and GDPD) show A/C horizon and are weakly to strongly calcareous. Fairly large size (2–3 cm) irregular shaped calcretes are common only in the lower horizons and in thin sections these are marked by nodules of sparite and prismatic calcite and also by the crystallitic b fabric. In QGH2 soils calcrete occurs in Upper Kosi-Gola Plain (UKGP) and Young Ghagha Plain (YGP). They are characterised by sparitic hypococatings and nodules of micrite and sparite. Dissolution features are quite common in them and crystallitic b fabric is extensively developed due to dense fine calcium carbonate in the groundmass. In QGH3 soils calcrete is not very common. Only in northern part of Lower Kosi-Gola Plain (LKGP) and southern part of Upper Deoha/Ganga–Ghagha Interflue (UDGHHIF) they occur in the B3 or C horizons. In thin sections, they are marked by dense and strongly impregnated spartic nodules with dissolution features. Most of these soils occur in Tarai region and are characterized by high moisture regime and shallow groundwater table. High moisture regime in these soils results from the hydrostatic head developed by artesian pressure (Deshpande et al., 1971a). Oxygen isotope composition studies also suggest the contribution of groundwater to the surface in this area (Navada and Rao, 1991).

3.4. Stable isotope composition of calcrete

Carbon and oxygen isotope composition of calcrete can be used to infer genetic processes and reconstruct paleoenvironment and paleoecology (Cerling, 1984). Results of carbon and oxygen isotope analysis of calcretes from the study area are given in Table 3 and Figs. 6 and 7. The oxygen isotope values for both types are very similar but the two separate out in relation to their carbon isotope composition.

Type-I calcretes are generally depleted in $\delta^{13}$C, ranging from −0.6 to −6.9‰ in Middle Deoha/Ganga–Ghagha Interflue (MDGGHHIF), and −1.2 to +1.6‰ in Lower Rapti–Ghagha Interflue (LRGHHIF). The values show a minor increase with depth and lighter $\delta^{13}$C values from the upper horizons are replaced by heavier $\delta^{13}$C values in the lower horizons (Fig. 7). The values are within the range of pedogenic carbonates (Talma and Netterberg, 1983; Cerling, 1984; Quade et al., 1989a; Monger et al., 1998). The Type-II calcretes from the B3 or C horizons of younger soils (QGH1–QGH3) are enriched in $^{13}$C and exhibit a narrow range of $\delta^{13}$C (+0.6 to +1.8‰) and are also marked by extensive dissolution–reprecipitation features.

The oxygen isotope compositions of both types of calcretes are similar and $\delta^{18}$O values range from −6.5 to −10.5‰ with an average of −8.2‰. These low values suggest the input of meteoric water because they correlate well with oxygen composition of river waters ($\delta^{18}$O ranging from −7.7 to −10.5‰) in the study area (Navada and Rao, 1991). Bhattacharyya et al. (1985) also obtained similar values for the Ganga, Yamuna, Ghomti, Ghagha and Gandak rivers of the Gangetic Plains.

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Fig. 3. SEM photomicrographs of Type-I calcretes. (a) Densely occurring anhedral and subhedral calcite crystals and quartz and mica in the groundmass of the calcrete MDGGHHIF Pedon C1, Bt2 horizon. (b) Diffused needles of calcite in the groundmass. Pedon C6, Bt2 horizon, MDGGHHIF. (c) Sparry calcite cement. Pedon C6, Bt2 horizon MDGGHHIF. (d) Strongly altered biotite within the calcrete. Pedon C1, Bt2 horizon, MDGGHHIF. (e) Exfoliated muscovite with precipitation of calcite in between layers. Pedon C6, Bt2 horizon, MDGGHHIF. (f) Botryoidal aggregate of blocky crystals of calcite in a void within the calcrete. Pedon C1, Bt2 horizon, MDGGHHIF. (g) A flock of euhedral needles of calcite in a void within the calcrete. Pedon C1, Bt2 horizon, MDGGHHIF. (h) Illuvial impure clay pedofeature on calcrete. Pedon C5, Bt3 horizon, MDGGHHIF.
Fig. 4. Photomicrographs of Type-II calcrete. All in cross polars. (a) Coarsely crystalline prismatic calcite in a part of the large nodule. Pedon A5, B1 horizon, UKGP. (b) Part of a large calcrete nodule showing microsparitic and prismatic calcite accumulations. Pedon A5, B1 horizon, UKGP. (c) Two generations of prismatic calcite growth. Pedon A5, B3 horizon, UKGP. (d) Skeleton grains within the calcrete are only weakly weathered. Pedon A6, B1 horizon, UKGP. (e) Part of a large calcrete masked by sesquioxide showing coarsening to sparry calcite around dissolution zone. Pedon B14, C horizon, RFP. (f) Part of a large microsparitic calcrete heavily masked by sesquioxide and a few patches of prismatic calcite inside the nodule. Pedon A6, C horizon, UKGP.
Fig. 5. SEM photomicrographs of Type-II calcrete. (a) Well developed crystals of calcite in the microcrystalline groundmass, Pedon A7, B3 horizon, LKGP. (b) Densely packed subhedral calcite grains showing dissolution and coarsening, Pedon B14, C horizon, RFP. (c) Dissolution of rhombohedral calcite grains, Pedon C16, C horizon, GDPD. (d) Formation of sparry calcite and rhombohedral calcite grains. Pedon C16, C horizon, GDPD.

Table 3
Carbon and oxygen isotope composition of calcrete from different soil-geomorphic units

<table>
<thead>
<tr>
<th>Member</th>
<th>Soil geomorphic unit</th>
<th>Pedon</th>
<th>Depth (cm)</th>
<th>Type of calcrete</th>
<th>$\delta^{13}$C %</th>
<th>$\delta^{18}$O %</th>
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<tbody>
<tr>
<td>QGH5</td>
<td>MDGGHIF</td>
<td>B7</td>
<td>38–50</td>
<td>Type I</td>
<td>−2.4</td>
<td>−8.5</td>
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<tr>
<td>Do</td>
<td>MDGGHIF</td>
<td>C6</td>
<td>38–45</td>
<td>Type I</td>
<td>−2.6</td>
<td>−6.5</td>
</tr>
<tr>
<td>Do</td>
<td>MDGGHIF</td>
<td>C6</td>
<td>45–56</td>
<td>Type I</td>
<td>−0.5</td>
<td>−7.8</td>
</tr>
<tr>
<td>Do</td>
<td>MDGGHIF</td>
<td>C6</td>
<td>56–70</td>
<td>Type I</td>
<td>−6.9</td>
<td>−6.1</td>
</tr>
<tr>
<td>Do</td>
<td>MDGGHIF</td>
<td>C6</td>
<td>70–83</td>
<td>Type I</td>
<td>−4.0</td>
<td>−6.9</td>
</tr>
<tr>
<td>Do</td>
<td>MDGGHIF</td>
<td>C6</td>
<td>83–100</td>
<td>Type I</td>
<td>−0.6</td>
<td>−7.6</td>
</tr>
<tr>
<td>Do</td>
<td>MDGGHIF</td>
<td>C7</td>
<td>60–80</td>
<td>Type I</td>
<td>−0.9</td>
<td>−8.4</td>
</tr>
<tr>
<td>Do</td>
<td>LRGHIF</td>
<td>C13</td>
<td>100–120</td>
<td>Type I</td>
<td>−5.6</td>
<td>−8.5</td>
</tr>
<tr>
<td>Do</td>
<td>LRGHIF</td>
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<td>Type I</td>
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<tr>
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<td>LRGHIF</td>
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<td>85–100</td>
<td>Type I</td>
<td>0.7</td>
<td>−8.1</td>
</tr>
<tr>
<td>Do</td>
<td>LRGHIF</td>
<td>C14</td>
<td>100–120</td>
<td>Type I</td>
<td>1.5</td>
<td>−8.0</td>
</tr>
<tr>
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<td>LRGHIF</td>
<td>C14</td>
<td>120–140</td>
<td>Type I</td>
<td>1.6</td>
<td>−7.6</td>
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<tr>
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<td>LRGHIF</td>
<td>C14</td>
<td>140–160</td>
<td>Type I</td>
<td>1.4</td>
<td>−7.6</td>
</tr>
<tr>
<td>Do</td>
<td>LRGHIF</td>
<td>C14</td>
<td>&gt; 160</td>
<td>Type I</td>
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<td>−7.3</td>
</tr>
<tr>
<td>QGH3</td>
<td>LKGP</td>
<td>B4</td>
<td>110–128</td>
<td>Type II</td>
<td>0.7</td>
<td>−9.2</td>
</tr>
<tr>
<td>Do</td>
<td>UDGGHIF</td>
<td>A7</td>
<td>95–135</td>
<td>Type II</td>
<td>1.8</td>
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<tr>
<td>QGH2</td>
<td>UKGP</td>
<td>A5</td>
<td>85–130</td>
<td>Type II</td>
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<td>−7.8</td>
</tr>
<tr>
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<td>UKGP</td>
<td>A6</td>
<td>97–127</td>
<td>Type II</td>
<td>1.6</td>
<td>−8.9</td>
</tr>
<tr>
<td>Do</td>
<td>OSKPD</td>
<td>A15</td>
<td>107–120</td>
<td>Type II</td>
<td>0.6</td>
<td>−8.0</td>
</tr>
<tr>
<td>QGH1</td>
<td>GFP</td>
<td>A14</td>
<td>77–120</td>
<td>Type II</td>
<td>0.3</td>
<td>−10.5</td>
</tr>
<tr>
<td>Do</td>
<td>GFP</td>
<td>B10</td>
<td>70–100</td>
<td>Type II</td>
<td>1.0</td>
<td>−9.6</td>
</tr>
</tbody>
</table>
4. Discussion

The micromorphology of Type-I calcrites, which occur mainly in QGH4 and QGH5 soils, indicate irregularly shaped diffused nodules of dense micrite, calcite needles and sparry calcite cement assimilated with soil constituents and the illuviated clay pedo-features along the walls of the nodules. All these indicate their pedogenic origin. It appears that initially micrite grains were precipitated in the soil groundmass from the soil solution, then it became dense with the formation of sparry calcite cement and diffused needles during the pedogenesis in the same environment. Ca\(^{2+}\) ions in the soil solution before they were precipitated as CaCO\(_3\) influenced the weathering of primary minerals especially biotite within the calcrite than in the adjacent groundmass. The deposition of CaCO\(_3\) (Figs. 2f, 3e) between the layers of muscovite might not have been influenced by Ca\(^{2+}\) ions as the weathering of muscovite is inhibited in presence of biotite (Srivastava et al., 1998). Precipitation of the euhedral blocky and needle shaped crystals of calcite in the pore spaces might have taken place from the supersaturated solutions derived from the dissolved calcrites in the humid environments. Coarsening of the calcrite microfabric in the lower horizons indicates large-scale dissolution and leaching of carbonates in the wet environment. However, some of the carbonates were coated with

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Fig. 6. Plot of \(\delta^{13}C\) and \(\delta^{18}O\) values of calcrites from the Gangetic Plains.

Fig. 7. (a) Plot of \(\delta^{13}C\) values versus depth for Pedon C14, LRGHIF. (b) Plot of \(\delta^{13}C\) values versus depth for pedon C6, MDGGHIF.
thin impure clay on the surfaces. The calcrete micro-fabric corresponds to an alpha calcrete (Wright, 1990). Such calcretes are developed in semi-arid to sub-humid climates (Wright, 1990).

Pedogenic carbonates are generally precipitated when the soil solution becomes supersaturated with calcite due to evapotranspiration and lowering of pCO₂ (Cerling, 1984). Evapotranspiration appears to be the dominant mechanism of soil water loss in the present area with vegetation. The δ¹³C values of the Type-I calcretes are similar to those of modern pedogenic carbonates (Cerling, 1984; Strong et al., 1992; Monger et al., 1998; Nordt et al., 1998). The carbon isotopic composition of soil carbonates is related to vegetation, which may include both C3 and C4 species (Cerling, 1984; Cerling and Wang, 1996). The δ¹³C values of the calcretes from the study area suggest a major fraction of C4 biomass during their formation in soils. This fact is further corroborated from the paleovegetation studies of the study area. The pollen studies of the lake deposits in the study area indicate sparse vegetation and grassland of C4 biomass during the Early Holocene (Gupta, 1978). The pollens were typical of open grassland, with abundant Chenopodium particularly on dry saline land and Typha angustata on lakeshores. This phase of arid climate shifted to humid phase and is characterized by onset of arboreal vegetation such as Anogeissus and Tecoma spp. This suggests that the formation of Type-I calcrete took place in arid to semi-arid climate below 30 cm depth. Extensive dissolution–reprecipitation features and enrichment of ¹³C in these calcretes indicate a wetter pedogenic environment at lower depths. It appears that soil respiration rates were low during the formation of these calcretes. A comparison with the model of Quade et al. (1989a) indicates 0.050–0.025 mmole m⁻² h⁻¹ respiration and large influx of atmospheric CO₂ during the formation of carbonates in upper horizons. In the lower horizons the respiration rates were even lower (0.025 mmole m⁻² h⁻¹ or less) and carbonate formation occurred with the enrichment of ¹³C. The respiration rates are very low in comparison with the terrestrial ecosystem around the world (Singh and Gupta, 1977) and suggest sparse vegetation and large atmospheric component of CO₂ during the formation of these calcretes. The isotopic composition of the calcretes from the area also indicates the effect

of monsoon climate with the enrichment of δ¹³C and depletion of δ¹⁸O in comparison with the normal continental soil carbonates (Cerling, 1984).

Another important consideration is the process controlling ¹³C in the pedogenic carbonates, especially at shallow depths. Although most of the calcretes under study do not have a distinct trend, but show a minor increase in δ¹³C with depth (Fig. 7a,b). This indicates deviation from theoretical models of pedogenic carbonate formation at depths and has paleoclimatic implications (Cerling, 1984; Cerling and Wang, 1996; Nordt et al., 1996). In the present area it was a period of substantial pedogenesis after 13 500 year BP in the stable upland interfluve areas as QGH5 soils show thick (150–200μm) micro-laminated clay pedofeatures and pedogenic carbonate (Srivastava et al., 1994). These features indicate climate mainly controlled ¹³C in these soils, and the calcretes with low δ¹³C were probably formed in arid to semi-arid climate by soil CO₂ loss in an open system during weathering in the upper horizons of the soil profiles (Rabenhorst et al., 1984). The enrichment of ¹³C in the lower horizons appears to have been caused by the repeated dissolution–reprecipitation of calcrete (Pendall et al., 1994; Quade et al., 1989a).

Maximum ages of the QGH5 and QGH4 soils indicated by TL are 13 600 and 8300 year BP, respectively and the corresponding radiocarbon dates are 11 000–9000 and 6500 year BP, respectively. The Type-I calcretes in these soils suggest that the formation of the pedogenic carbonate began in the Early Holocene up to 6500 year BP when amelioration to warm and wet phase took place.

The Type-II calcrete occurs with increasing abundance from the surface to the C horizons in areas with shallow groundwater table and is found in the soils of member QGH1–QGH3. In these soils dissolution and reprecipitation of calcrete with coarse fabric (prismatic calcite) is due to the action of shallow groundwater. Deshpande et al. (1971b) suggested that the calcium carbonate concentration in the soils of this region results from alternating moist and dry conditions with incomplete leaching. The present study suggests that coarsely crystalline calcretes resulted from the fluctuating pore water and the loss of CO₂ from the shallow groundwater. Carbon isotopes are generally enriched in ¹³C by precipitation
and dissolution of the carbonates in shallow confined aquifers as in the present soils (Dever, 1987). This might have enriched $^{13}$C in these carbonates. Groundwater contribution to the surface in the area is indicated by $^{18}$O composition of the rivers and groundwater from the area (Navada and Rao, 1991).

The oxygen isotope composition of the soil carbonates is controlled by pore water derived from precipitation (Cerling, 1984). Hseih et al. (1998) observed that in arid to sub-humid environments, soil water of the surface horizons (0–20 cm) is always enriched in $^{18}$O relative to meteoric water because of mixing between rainfall and antecedent moisture. However, at depth this relationship does not hold well as there has been no difference between $^{18}$O values of soil water and meteoric water. Quade et al. (1989a) also suggested that soil carbonates formed at >30 cm depth reflect average composition of the infiltrating water. In the present study oxygen isotopic composition of both types of carbonates are similar and range from $-6.1$ to $-10.5\%e$. These values correlate well with the river water of the area. Navada and Rao (1991) studied $^{18}$O composition of the Ganges river system and obtained $\delta^{18}$O values ranging from $-7.7$ to $-10.5\%e$. Bhattacharyya et al. (1985) also obtained similar values. The negative values of soil water are typical of low potential evapotranspiration (PET) and high rainfall, and the positive values reflect strong evaporation and dry winter conditions (Hseih et al., 1998). The present study shows that the calcrites are more depleted in $^{18}$O than those reported from arid regions of Rajasthan (mean $\delta^{18}$O = $-4.95\%e$) (Salomons et al., 1978; Andrews et al., 1998). This suggests that the formation of pedogenic calcrite in the study area occurred in an environment of low PET and high rainfall, while strong evaporation and dry winter favoured calcrite formation in Rajasthan.

Pedogenic history of the area clearly demonstrates that the climate has not been stable during the Holocene. The period was marked by the development of impure clay pedofeatures of more than one phase with increased illuviation (Srivastava et al., 1994; Pal et al., 1994). Clay mineral studies of the soils indicate that biotite weathered to trioctahedral vermiculite and smectite during arid to semi-arid climate during the Early Holocene. The smectite was unstable and transformed to Sm/K during the warm and humid phase (Srivastava et al., 1998).

The results of the present study agree well with the paleoclimatic fluctuations inferred from the palynological studies of lake deposits in Rajasthan and south-west coast of India (Singh et al., 1972, 1974; Van Campo, 1986).

5. Conclusions

Results of the present study on the micromorphological characteristics of the calcrites along with their stable isotopic composition of soils belonging to different age groups of the north-central Gangetic Plains correlate well with the types of vegetation specific to both arid and humid climates prevailed during Holocene. This study suggests that the morphology and stable C and O composition of the pedogenic calcrites in the Gangetic Plains were influenced by the climate change and thus these features can be used as paleoclimatic indicators.

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