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Ferrolysis induced soil transformation by natural drainage in Vertisols of sub-humid South India

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ABSTRACT

In sub-humid South India, recent studies have shown that black soil areas (Vertisols and vertic Intergrades), located on flat valley bottoms, have been rejuvenated through the incision of streambeds, inducing changes in the pedoclimate and soil transformation. Joint pedological, geochemical and geophysical investigations were performed in order to better understand the ongoing processes and their contribution to the chemistry of local rivers. The seasonal rainfall causes cycles of oxidation and reduction in a perched watertable at the base of the black soil, while the reduced solutions are exported through a loamy sand network. This framework favours a ferrolysis process, which causes low base saturation and protonation of clay, leading to the weathering of 2:1 then 1:1 clay minerals. Maximum weathering conditions occur at the very end of the wet season, just before disappearance of the perched watertable. Therefore, the by-products of soil transformation are partially drained off and calcareous nodules, then further downslope, amorphous silica precipitate upon soil dehydration. The ferrolysed area is fringing the drainage system indicating that its development has been induced by the streambed incision. The distribution of ^{14}C ages of $CaCO_3$ nodules suggests that the ferrolysis process started during the late Holocene, only about 2 kyr B.P. at the studied site and about 5 kyr B.P. at the watershed outlet. The results of this study are applied to an assessment of the physical erosion rate (4.8×10^{-3} m/kyr) since the recent reactivation of the erosion process.

1. Introduction

Vertisols and "black soils" with vertic properties (vertic Intergrades) cover over 335 million ha worldwide (IUSS-ISRIC-FAO, 2006). They are mainly found in lower landscapes such as dry lake bottoms, river basins, lower river terraces, and other lowlands that are periodically wet. Although Vertisols have been reported to form under humid conditions (Nordt et al., 2004, Driese et al., 2005), they occur mainly in tropical and subtropical climates, and in semi-arid to sub-humid climates with distinct wet and dry seasons (Wilding and Tessier, 1988; Balpande et al., 1996; Vaidya and Pal, 2002, Barbiero et al., 2005). Because of the large proportion of smectite-type minerals in the clay fraction, Vertisols and vertic Intergrades have a strong buffering capacity and are resilient to diverse chemical conditions. Smectite minerals also require a base-rich environment for their retention in soil and a high pH to prevent hydrolysis into kaolinite. As a consequence, smectite-rich Vertisols and vertic Intergrades generally persist in areas with high pH and poor drainage.

Ferrolysis is one of many different processes that occur to alter soil. Ferrolysis involves cyclic reduction and oxidation of iron in an open system, which leaches displaced base cations and accelerates mineral weathering (Brinkman, 1970). Introduced by Brinkman, the notion of ferrolysis has been described as a dominant process in many parts of the world to explain the strong textural contrast of soils (and Paleosols, Wright et al., 1991) where bleaching and mottling are predominant features. Although most studies were carried out over thirty years ago (Brinkman et al., 1973; Brinkman, 1977; Brinkman and Wieleman, 1977; Brammer and Brinkman, 1977; Brinkman, 1979), recently several authors have mentioned ferrolysis as a probable process to explain Fe–Mn-oxide segregations, gleying, chloritisation (Singh et al., 1998), textural variation and low pH in soils (Schaefer et al., 2002; O'Geen et al., 2008). Since the eighties, several studies have questioned the incidence of ferrolysis in a number of previously reported sites (Eaqub and Blume, 1982; Boivin et al., 2004). Van Ranst and De Corninck (2002) recently examined soils from Belgium and France that were considered to have formed

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mainly by ferrolysis. Assessment by chemical, mineralogical, morphological, and micromorphological techniques showed that contrasting textures typically attributed to ferrolysis were more likely to have formed by clay translocation (Montagne et al., 2008). Similar findings by Favre et al. (2002) demonstrated that the reduction of structural iron in (2:1) clay during flooding in Vertisols from the Senegal Valley resulted in a significant increase in the CEC value. As a result the ferrous iron produced was not sufficient to saturate the new sites on the complex, thus requiring external iron reduction for the displacement of exchangeable base cations (Boivin et al., 2004). Therefore, recent studies strongly indicate that the role of ferrolysis in soil formation has been overestimated. As such, the boundary conditions necessary for ferrolysis are largely unknown.

Our research team has been conducting parallel pedological, hydrological, geochemical and geophysical investigations on a small experimental watershed (4.1 km²) in sub-humid South India, in order to establish hydro-bio-geochemical balances (Braun et al., 2005). The study involved the assessment of chemical weathering and regolith thickness (Braun et al, 2009), determination of surface and groundwater balance, recharge and modelling, (Legchenko et al., 2006; Descloitres et al., 2008, Maréchal et al., 2009; Ruiz et al., 2010; Parate et al., submitted), physical erosion calculations (Barbiero et al., 2007) and, the appraisal of soil cover dynamics. At the watershed scale, estimates of element exportation are only rarely consistent with long term weathering rate assessments. There exists a need to perform local scale studies of present-day, rapid soil forming processes to fill this knowledge gap. The cover consists mainly of red soil (Chromic Luvisols and small spots of Ferralsols) and black soil (Vertisols and vertic Intergrades). Black soils located in lowlands frequently contain contrasted loamy sand bleached volumes suggestive of soil transformation that is suspected to influence the water chemistry at the outlet of the watershed. In addition, silica-cemented horizons have been observed at several points along the streambed and are likely to be integral components of the soil system. Understanding the processes responsible for these pedological features is key to linking chemical weathering rates with present-day chemical exportation at the watershed scale. The objective of this study is twofold: first, it aims to understand the currently ongoing soil transformation processes and the parameters controlling their development; and second, it intends to assess the consequences of these processes on the chemistry of water flowing out of these black soil areas.

2. Materials and methods

The Western Ghats, parallel to the western coast of the Peninsula in Southern India, form an orographic barrier inducing a climatic gradient. The annual rainfall decreases progressively from roughly 5000 mm in the west, to less than 750 mm at 80 km to the east (Pascal, 1982; Sehgal and Mandal, 1995). The landscape geomorphology changes from convex hills alternating with flat floors to long concave glacis (Gunnell and Bourgeon, 1997; Gunnell, 2000). In connection with the geomorphological changes, we find thin red soils (Chromic Luvisol; IUSS-ISRIC-FAO, 2006) associated with Ferralsols and black soils (Vertisol, vertic Intergrades) in the climatic semi-humid transition area, and further east calcic Luvisol and calcic Vertisol in the semi-arid area (Murthy et al., 1982; Pal and Deshpande, 1987; Bourgeon, 1991; Radhakrishna and Vaidyanadhan, 1994; Jacks and Sharma, 1995; Shiva Prasad et al., 1998; Gunnell, 2000). Along this climatic sequence, the passage in the clay mineralogy from the kaolinite-dominated humid area to the smectite-dominated semi-arid area is achieved progressively via an intermediate area with 2:1 K-clay such as illite and sericite (Bourgeon and Pedro, 1992).

The study was carried out on a 4.1 km² watershed (Fig. 1) located in the conserved Bandipur National Park close to the Mule Hole check post at 11º 44′ N and 76º 27′ E (Karnataka state, Chamrajnagar District). The watershed is located in the sub-humid climatic transition zone, with a mean annual rainfall spread over 20 years of about 1120 mm and annual average temperature of 23 °C. The climate is characterized by recurrent but non-periodic droughts, depending on monsoon flows. The studied area is primarily undulating with gentle slopes, with elevations varying from 800 to 910 m above mean sea level, and incised by a stream network. Streams are temporary flowing for a few hours to a few days after stormy events during the rainy season (June to October). The streambeds are steep-sided up to 4 m down compared to the valley floor. The vegetation consists of a dry deciduous forest (Agarwala, 1985). The area is developed on crystalline rocks of the Precambrian Dharwar supergroup (Moyen et al., 2001) consisting of peninsular gneiss intermingled with mafic and ultramafic rocks of the volcano-sedimentary Sargur Series (Shadakshara Swamy et al., 1995). The peninsular gneiss represents about 83% of the watershed area (Barbiero et al., 2007). Previous observations suggest that both topography and lithology have influenced the formation and distribution of soils in the landscape. Black soils mainly occur in the valley bottom and to a lesser extent are also found at certain zones along the slope and at the crest line (Lacarce, 2005). On the other hand, black soils may be related to the presence of amphibolites, but are not exclusively on amphibolites since they are also frequently observed on gneiss saprolite (Barbiero et al., 2007). The relatively high proportion of smectite clay minerals in black soils causes considerable shrink–swell conditions, which induce crack formation and distinctive structural elements such as wedge-shaped aggregates with smooth- or slikensided surfaces. A previous study showed the relative chronology in the development of the downslope soil cover (Barbiero et al., 2007). This work highlighted that the geomorphology of valley bottoms have been recently reactivated with the development of streambeds. A study on the soil layout at different scales also revealed that thin black soils, unlike thick black soils, have guided the development of the drainage network. Such landscape development was favoured by the presence of saprolite, at less than 2 m deep, and reached by the cracks during the dry season. As a consequence, streambeds meander within the thin black soil, skirting around the thick black soil areas. Recent incisions created by the streambeds are thought to have contributed to changes in the pedoclimate into the black soils, and consequently could have reactivated some soil forming processes. These processes may contribute to the chemistry of the local rivers.

A 5000 m²-black soil area located at the bottom part of the watershed was targeted for the study (Fig. 1). This area was defined using electromagnetic induction, vegetation survey and direct soil observations. It is surrounded and incised by two temporary streams (Fig. 2), the main stream of the watershed and a short tributary, which is less incised, but whose depression consists of successive triangular ponds (Fig. 3a). The black soil area appears as a plateau that is elevated at 2 to 4 m from the bottom of the streambed (Fig. 2).

2.1. Prospecting fieldwork

The prospecting fieldwork was carried out in 3 steps. First, soil transects were studied along the slope from the black soil area to the streambed (transects T, U and V on Fig. 2). Since we observed similar soil organisations, only transect T (30 m) will be presented here. Another 60 m-soil transect was studied along the depression of the streambed (transect S on Fig. 2). The soil pattern was studied in detail along 21 auger holes and 3 excavated pits, which revealed the geometrical relationships between the different horizons (Boulet et al., 1982; Fritsch et al., 1992) identified from basic field observations (Munsell chart colour, texture, structure, macrovoids, presence of coarse elements, intensity of biological activity, etc). Second, dense electromagnetic measurements were carried out along the transect T in an attempt to establish a relationship between the soil layout and the electromagnetic response. Electromagnetic induction using portable instruments is becoming a rapid widespread