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27 Palaeosoils and Relict Soils

Nicolas Fedoroff[1,*,‡], Marie-Agnès Courty[2], Zhengtang Guo[3]

[1] RETIRED FROM AGROTECH, PARIS, FRANCE
[2] CNRS UMR 7194 & IPES, FRANCE AND UNIVERSIDAD ROVIRA Y VIRGILI, TARRAGONA, SPAIN
[3] INSTITUTE OF GEOLOGY AND GEOPHYSICS, CHINESE ACADEMY OF SCIENCES, BEIJING, CHINA

1. Introduction

Soils have played an important role in the history of the Earth history since 3000 million years ago (Retallack 1990; Retallack & Mindszenty, 1994). Primitive soils, which formed by weathering, appeared before vegetation developed (e.g. Driese et al., 2007). Later soils formed in conditions with different atmospheric compositions than those existing at present and with a different impact of cosmic events (e.g. Jones & Bo Lim, 2000).

Definitions of palaeosoils vary widely. For Morrison (1977), palaeosoils are soils of obvious antiquity, whereas Butzer (1971) defines them as ancient soils. For other authors, they are soils formed in a landscape of the past (Ruhe, 1965; Yaalon, 1971), or in a past environment (Yaalon, 1983). In this chapter, the term 'palaeosoil' is restricted to buried soils of any age, whose functioning was totally or partially inhibited by burial. We also apply it to truncated soils, even if just a thin basal stump is preserved. Relict soils are defined as soils belonging to the present-day soil cover but which have characteristics inherited from the past, resulting from different environmental conditions than those occurring today.

The aims and history of palaeopedology differ from those of pedology (Fedoroff & Courty, 2002). Palaeosoils have been approached with different objectives. Many authors (e.g. Kukla & An Zhisheng, 1989) considered palaeosoils as stratigraphic markers in continental sequences, without attempting to analyse them, whereas others considered some layers in such sequences as palaeosoils just because of their colour. Analysis and interpretation of palaesoils with methods used in pedology, including soil micromorphology, began at a relatively late stage (e.g. Fedoroff & Goldberg, 1982). The palaeoenvironmental significance of palaeosoils has also only recently been taken into account (e.g. Fedoroff et al., 1990; Kemp, 1999; Felix-Henningsen & Mauz, 2004; Ferraro et al., 2004). Proxy indicators for

* Corresponding Author:
Tel.: +33 468 591171
E-mail: nicolas.fedoroff@wanadoo.fr

‡ Retired

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defining climatic characteristics under which palaeosoils have developed have been used by some authors (e.g. Wang & Follmer, 1998; Retalllack, 2005a).

Soil micromorphology is at present commonly applied in investigations of palaeosoils and relict soils. Mücher and Morozova (1983) have presented a foundation for the micromorphological description of palaeosoils and related sediments, whereas Fedoroff et al. (1990) drafted keys for the recognition of environmental changes in the past. Most papers deal with Quaternary palaeosoils, especially those formed during the last interglacial, the last glacial cycle and the Holocene (e.g. Kemp et al., 1994; Cremaschi & Trombino, 1998; Kemp, 1998; Srivastava & Parkash, 2002), but pre-Quaternary palaeosoils have also been studied (e.g. Tate & Retallack, 1995; McCarthy et al., 1998; Driese et al., 2007). Micromorphological analyses of palaeosoils often show differences with present-day soil functioning. Elementary attributes of pedogenic facies of the past are similar to present ones, but they can be different by showing a higher degree of development or by the presence of assemblages of pedofeatures unknown in modern soils. Pedofeatures specific of pedogenesis of the past are rare. Micromorphological studies also reveal that almost all palaeosoils were affected by processes of *in situ* reworking, erosion, transport, deposition and allochthonous aggradation (e.g. Retallack, 2005b; Sephton et al., 2005), which are often underestimated or not even recognised by other observations.

Examination in thin sections of well-developed soils, especially those dating back to the Pleistocene, nearly always reveals the presence of relict characteristics (e.g. Fedoroff, 1997). In some relict soils, such as Ferralsols, the history of the soil is almost totally wiped out, but in others, such as calcretes and ferricretes (e.g. Achyuthan & Fedoroff, 2008), the history is preserved to a large extent.

In this chapter, an interdisciplinary approach is used, dealing with analysis of sets of interacting entities and the interactions within those systems (systems analysis). Such an approach is commonly utilised by sedimentary petrologists (e.g. Humbert, 1976a, b).

2. Methodology

2.1 Recognition of Palaeosoils and Relict Soils

The first task when investigating continental sequences is to decide whether the layers defined in the field as palaeosoils are soils that formed *in situ*, transported soil materials (pedosediments), or something else (e.g. McCarthy, 2002). *In situ* soils are characterised in thin sections by a continuous pedogenic facies recognised by at least one of the following features: (i) undisturbed features resulting from soil biological activity, such as passage features and channels with root residues or excrements; (ii) a pedogenic microstructure; (iii) a pedogenic b-fabric; or (iv) one or more types of undisturbed pedofeatures. In contrast, pedosediments are recognised by: (i) an absence of *in situ* biogenic features, but the common presence of tissue and charcoal fragments; (ii) a massive microstructure, and occasionally a structure dominated by packing of rounded aggregates; or (iii) sedimentary features (see also Mücher et al., 2010, this book). Some layers which seem to be free of pedogenic characteristics in the field can show a pedogenic facies in thin sections.

For example, the typic Late Pleistocene loess layers of the Loess Plateau of China consist entirely of passage features and various types of excrements (Guo, 1990). Consequently this examination must be extended to under- and overlying horizons or layers in order to characterise variations in pedogenic facies, identify other possible types of facies, compare groundmass characteristics and identify features related to erosion and aggradation.

Palaeosoils are very rarely preserved as complete and undisturbed profiles. Some discontinuities are easy to identify in the field, such as truncations, stone lines and the superimposition of allochthonous materials on pedogenic horizons. The field diagnosis can be considerably improved by examination in thin section, which can reveal discontinuities in pedofeatures, as well as features due to erosion, *in situ* reworking (see Fig. 15), mass-transportation or minor aggradation (e.g. accumulation of aeolian dust). It also contributes to the determination of which *in situ* horizon or horizons are part of the investigated palaeosoil, on the basis of its pedogenic facies.

Palaeosoils commonly alternate with sediments, as in loess sequences (e.g. Kukla & An Zhisheng, 1989) or in deltas and alluvial plains (Srivastava & Parkash, 2002), creating palaeosoil–sediment sequences termed 'pedocomplexes' (e.g. Morrison, 1977; Feng & Wang, 2005). The palaeosoils can be: (i) juxtaposed, i.e lying in a close vertical succession, without penetration of pedofeatures of the overlying into the underlying palaeosoil; (ii) superimposed, i.e with penetration of pedofeatures of the overlying into the underlying palaeosoil; or (iii) cumulic, i.e palaeosoils in which a type of pedofeature (in general a textural pedofeature) occurs without significant change in a thick homogeneous horizon (Fig. 1) (e.g. Yin & Guo, 2006). An example of a well-studied pedocomplex is the marine

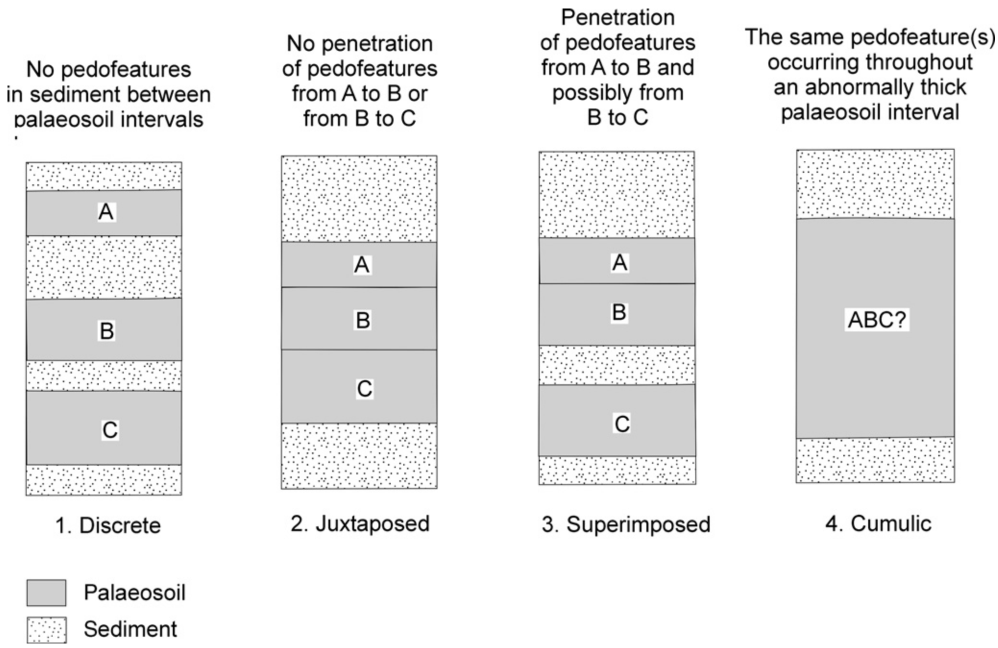

FIG. 1 Possible relationships between palaeosoils and related sediments in palaeosoil–sediment sequences.

isotope stage 5 (MIS 5) pedocomplex, also known as the Eemian pedocomplex, i.e present throughout the loess belt of the northern hemisphere, whose characterisation includes micromorphological analyses (e.g. Fedoroff & Goldberg, 1982; Guo, 1990; Kemp et al., 1995, 1997, 2001; Stremme, 1998; Bronger, 2003; Chen et al., 2003; Chlachula et al., 2004). In the most complete sections, this pedocomplex consists of three juxtaposed palaeosoils, but in some regions they merge into a single soil profile in which no boundaries or transitions are recognised, even in thin sections (e.g. Xifeng loess section, China; Guo, 1990). Pedocomplexes are also frequent in karstic dolines, for which some micromorphological data are available (Boulet et al., 1986; Kühn & Hilgers, 2005).

Relict soils can be subdivided into (i) soils with relict characteristics which cannot be detected in the field; (ii) soils with discrete, randomly distributed inherited pedofeatures; (iii) soils with an ancient truncated base whose age can reach millions of years, covered by partially or entirely allochthonous materials; (iv) totally relict soils, except for the presence of fissures and channels in which water circulates and in which living organisms are active; and (v) soils consisting of micro-fragmented relict soil materials, for example small fragments of ferruginous features as in Ferralsols (Fig. 2).

Relict or inherited characteristics can be (i) discrete pedofeatures characterised by sharp boundaries and by a relict groundmass, embedded in a functioning groundmass; (ii) a disturbed or fragmented pedogenic facies embedded in a different soil material; or (iii) an undisturbed pedogenic facies which is unrelated to present-day soil-forming conditions, for example a platy microstructure due to ice lensing in a deep horizon of a mid-latitude soil. The structure of the parent material can be preserved in the truncated base (isalterite; Delvigne, 1998), or it can be reworked but without major aggradation of allochthonous material (alloterite; Delvigne, 1998). An example of deciphering relict soils can be found in Achyuthan and Fedoroff (2008).

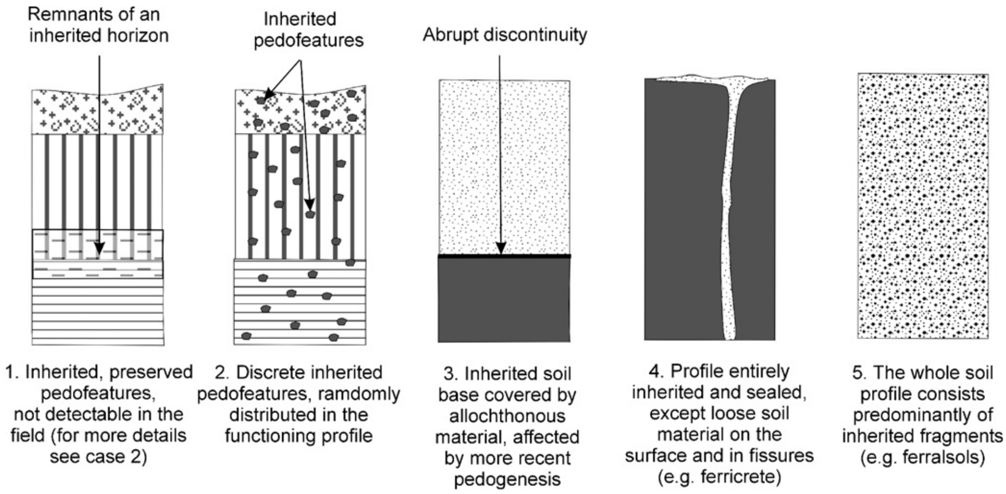

FIG. 2 Types of distribution of inherited attributes in relict soils.

2.2 Reconstruction of History

When reconstructing the history of soils of the past and deciphering their environmental significance, one has to bear in mind a few basic concepts: (i) the evolution of soils at geologic time scales was discontinuous, (ii) the memory of soils is palimpsest-like and (iii) as a consequence of discontinuous soil evolution, pedofeatures and other attributes of soils exposed for long periods are organised according to hierarchies.

2.2.1 Discontinuous Soil Evolution

The theory of biorhexistasy, based on field observations, describes climatic conditions necessary for periods favourable for soil development, called biostasy, separated by episodes of soil erosion, called rhexistasy (Erhart, 1956). The concept of the pedogenic phase, which is derived from the biostasy phase, was formulated later (Fedoroff & Courty, 2002, 2005). A pedogenic phase is defined as a period of soil development induced by an invariant soil-forming process, characterised by a unique pedogenic facies (Fig. 3). For example, a Luvisol with a Bt-horizon characterised by microlaminated clay coatings and infillings or, as illustrated in Fig. 4A, Kastanozem with a completely bioturbated B-horizon characterised by passage features and infillings with excrements, must be considered as a monophase soils. A rhexistasic episode following a pedogenic phase can be characterised by, for example, loess aggradation or *in situ* soil reworking. This is usually followed by a pedogenic phase similar to the preceding phase of soil formation. A cycle consists of a pedogenic phase and a rhexistasic episode (Fig. 3). In Chinese loess, such cycles are repeated many times (Kukla & An Zhisheng, 1989). An example of polyphase evolution is given in Fig. 4B. Cycles also exist in relict soils, for which they are more difficult to identify. They can be impossible to detect, as in most Ferralsols (see Fig. 2). A biostasy period should correspond to a unique pedogenic phase, but biphase and even three-phase palaeosoils without any rhexistasic attribute are quite common. For example, two successive pedogenic phases are recognised in calcareous vertic palaeosoils of Madeira, specifically Vertisol development followed by carbonate enrichment (Goodfriend et al., 1996). Duration and intensity of pedogenic phases can be unequal, some corresponding to extremely strongly developed profiles, for instance relict soils on high terraces of the Rhone valley (Bornand, 1978) and palaeosoils assigned to MIS 14–15 in China (Guo, 1990). In contrast to the latter, palaeosoils of MIS 11, 9 and 7 in China are moderately to weakly developed.

According to the classical model (Jenny, 1941; Yaalon, 1983), soils develop towards a steady state, balanced with existing factors of soil formation. If the evolution of palaeosoils and relict soils is considered to be discontinuous, this concept must be regarded with caution. Some relict soils seem to have reached a steady state, but close investigation at microscopic scales shows that these soils have been affected to some extent by erosion, transport and sediment aggradation during rhexistasic episodes. For instance, the upper horizons of Ferralsols in northeastern Argentina have been affected by complete reworking during episodes of aeolian activity (Iriondo & Kröhling, 1997). The notion of threshold, referring to a fluctuation in soil development resulting from internal factors

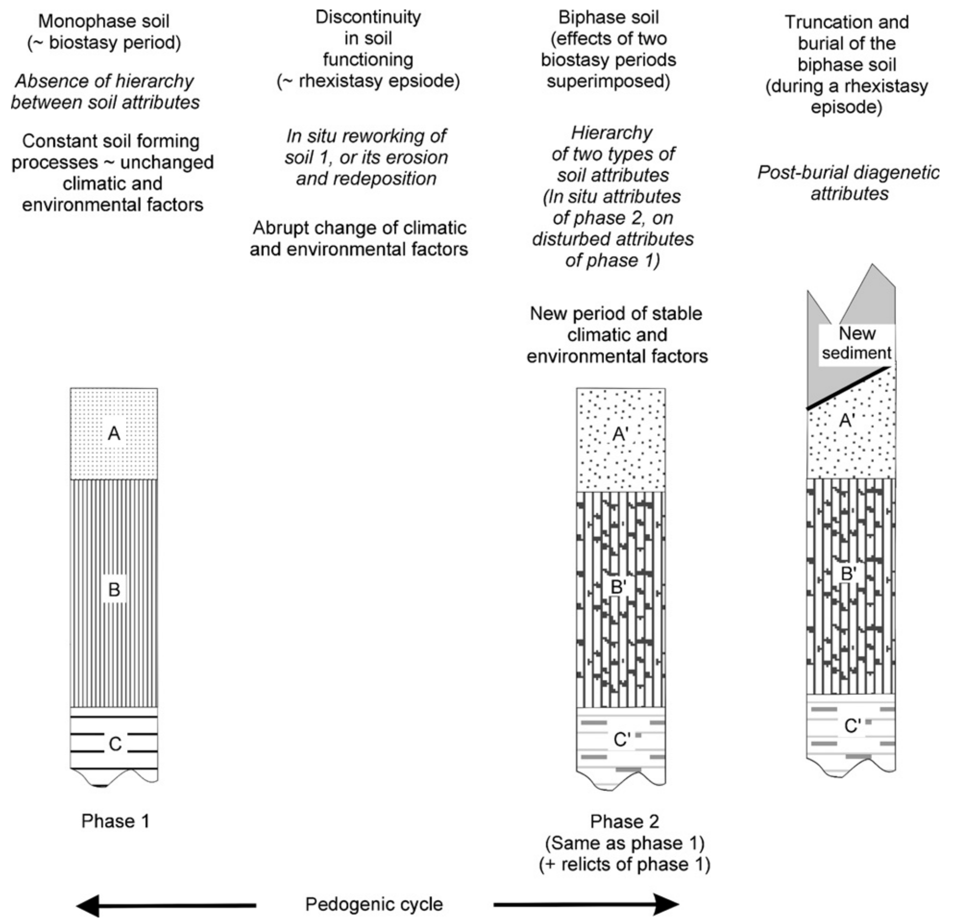

FIG. 3 Principles of soil development over medium and long time spans, applicable to Quaternary palaeosoils.

(e.g. Ewing et al., 2006), must also be considered with caution, as it probably reflects a modification of environmental parameters in some cases.

2.2.2 Soil Memory

Targulian and Sokolova (1996) and Targulian and Goryachkin (2004) defined 'soil memory' as an assemblage of persistent pedogenic solid-phase properties, in the form of a palimpsest-like memory. This concept of soil memory for palaeosoils and relict soils can be enlarged, including the following items (Fedoroff & Courty, 2005):

- assemblage of persistent pedogenic properties, which includes pedofeatures and microstructure; these properties have to be regrouped into pedogenic facies (if more than one is present) and a hierarchy has to be established between them;
- measurement of soil magnetic susceptibility and other magnetic properties; soil magnetic minerals are too fine-grained to be identified by optical microscopy,

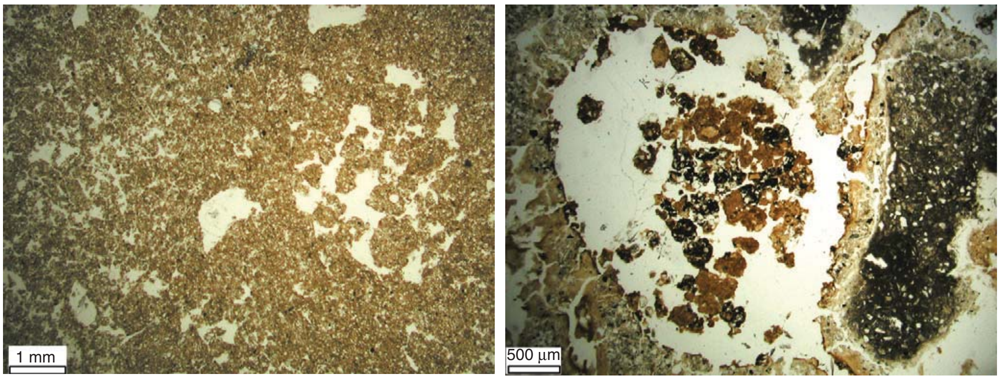

FIG. 4 (A) Monophase palaeosoil, with moderate rubefaction, totally churned by soil fauna, with abundant passage features and aged faecal pellets (Kastanozem, S1 palaeosoil, Loess Plateau, China, Xifeng section) (PPL). The soil is interpreted to have developed during a period with a stable, rather warm, semi-arid climate, under a steppic vegetation (MIS 5). (B) Polyphase soil showing the following hierarchy: (i) monophase micritic carbonate nodule (right); dissolved along its sides; (ii) yellowish-grey clayey illuvial features, partially integrated in the groundmass; (iii) dark brown clay coatings along voids; and (iv) loose infilling with brown clayey aggregates and black aggregates, whereby the latter seem to post-date the former (Pampean soil on loess, Azul area, Argentina) (PPL). The sequence of events is: (i) loess deposition, (ii) calcite accretion in the form of discrete features and (iii) clay illuviation and partial dissolution of the micritic nodule. The brown clayey aggregates probably belong to the clay illuviation phase, whereas the black aggregates are related to an event requiring further investigation.

but they have been observed using electron microscopy (e.g. Perkins, 1996; Grimley & Arruda, 2007); most investigations of magnetic susceptibility of palaeosoils are conducted without using microscopic techniques (e.g. Maher et al, 2003);

- observation of vegetation and fauna remnants such as pollen grains, phytoliths, charcoal fragments, shells and insect cuticles; these remnants have to be separated from the soil mass rather than studied in thin section;
- nature of the coarse mineral fraction (abundance, distribution, sorting, degree of weathering, external morphology) and its variation through the profile; quartz and zircon can be used for detecting depletion and aggradation (e.g. Brimhall et al., 1991);
- identification of possible sedimentary features and features caused by soil reworking (Mücher & Morozova, 1983; Mücher et al., 2010).

The palimpsest-like soil memory refers to the notion that the memory is constantly renewed, even when the soil is buried (e.g. decay of organic components), but that a part of the pedogenic assemblage is preserved through time. Soil micromorphology is the most efficient method for identification and reconstruction of assemblages which are partly erased, degraded or superimposed by secondary constituents. The following principles can be considered:

- The effects of soil functioning, and consequently of environmental events, are maximal at the soil surface and at near-surface levels, and they decrease sharply with depth. In deep horizons the soil memory is incomplete and selective. For example, superimposed silty and clayey coatings and infillings at the top of a Bt-horizon tend to merge progressively into microlaminated features at the bottom of this horizon, and they are replaced by coatings without microlamination in deep C-horizons (Targulian et al. 1974). Consequently the accuracy of the registration of climatic fluctuations tends to decrease with depth.

- The soil memory is renewed rapidly in surface and near-surface horizons, but it is preserved for a long time in deeper horizons, especially in horizons which are out of reach of soil meso-and macrofauna. Ice lens microstructures dating from the Late Pleistocene can be observed in Luvisols on loess at depths of 70–80 cm in the Paris basin (Fedoroff & Courty, 2005).

- The depth of occurrence of a pedofeature within a profile varies with the type of soil-forming processes, climate factors and related soil water regimes. Biogenic processes are concentrated near the soil surface, whereas clay illuviation usually occurs at intermediate depth in B-horizons, and effects of hydrolysis are detected in the weathering zone.

- The resistance of pedofeatures and other soil attributes to ageing is very variable. The most susceptible to ageing are excrement features, followed in order by silty textural features, microlaminated clay coatings or infillings and finally nodules rich in iron oxides (Fedoroff & Courty, 2002). Continuous cemented horizons (duricrusts), such as calcrete, ferricrete, gypcrete and silcrete, have played a specific role in conservation of relict soils because of their resistance to erosion.

Stable and humid climatic phases tend to be overemphasised in the soil memory, whereas the registration of shorter and drier phases can be totally absent. During humid phases, water percolating regularly in great amounts favours illuviation to great depth. For instance, thick well-developed relict Luvisols on Middle Pleistocene terraces in the Rhone valley are characterised by thick red clay coatings and infillings distributed throughout an argillic horizon with a thickness of a few metres, whereas registration of juxtaposed or superimposed later pedological phases is minimal (Bornand, 1978).

In polyphase palaeosoils and relict soils, the memory of the first phase is erased to a variable extent during the following phase. In the first approximation, the degree of memory obliteration is correlated with the duration of soil functioning. Various cases of soil memory preservation are presented in Fig. 2. In that figure, the soil memory is best preserved in case 4, it is not easily detectable in case 1 and the relevant features are too fine for observation by optical microscopy in case 5 (micro-fragmentation).

Micromorphological analysis of the memory of a palaeosoil at the level of a thin section consists of the following steps:

- identifying all pedofeatures and other soil attributes present, using for instance the system of Bullock et al. (1985) and Stoops (2003), separating autochthonous and allochthonous features, grouping them in types, and characterising the assemblage of each type;
- grouping features into pedogenic facies, which correspond to the total of all pedofeatures and other soil attributes occurring simultaneously under constant environmental conditions;

– examining the groundmass in order to detect features caused by erosion or sedimentation;
– establishing a hierarchy between the different pedogenic facies, including erosional and sedimentary features if necessary.

2.2.3 Systems Analysis of Polygenetic Palaeosoils and Soils

Systems analysis can be applied for deciphering and interpreting polygenetic palaeosoils and soils at microscopic levels. The procedure is the following: (i) identify all features (pedogenic as well as sedimentary), (ii) regroup similar features in facies, (iii) order the facies in sequences of events (establishment of a hierarchy; Humbert, 1976a) and (iv) interpret from a pedological–sedimentological viewpoint each facies as well as the transition between facies. In palaeosoils and relict soils, a hierarchy can exist between all types of pedofeatures (e.g. textural and crystallitic, see Fig. 4B) and other attributes such as features resulting from erosion and sediments aggradation. Each type of pedofeature is considered to define a pedogenic phase, a period during which climate parameters are supposed to have been constant. A hierarchy must first be established at the level of the thin section, then extended to the palaeosoil as a whole and eventually to the catena.

In relict soils, establishment of hierarchies requires at first a separation of inherited features from those formed in present-day conditions throughout the profile. Inherited features can then be subdivided into simple and complex (e.g. pisoliths; see Fig. 11), and into *in situ*, reworked and transported. Features resulting from erosion and aggradation of allochthonous materials must be identified. If they are present, their relationships with pedofeatures have to be determined. Pedofeatures can be pre-, syn- or post-erosional and pre-, syn- or post-aggradational.

3. Common Types of Hierarchies

We present here the most common hierarchies of textural, ferruginous and calcitic features and the related facies. Examples of siliceous features and facies can be found in Summerfield (1983), Milnes et al. (1991), Milnes and Thiry (1992), Thiry (1999) and Poetsch (2004). Inherited gypsum crystals and crystal intergrowths, and less frequently barite and celestite occurrences, can be present in palaeosoils and relict soils, but they do not form complex assemblages in which hierarchies can be recognised, except if they are associated with calcitic features.

Partially or totally dissolved gypsum crystals and crystal intergrowths, identified by their preserved external forms are common in palaeosoils of arid and semi-arid regions (Guo, 1990; Sullivan & Koppi, 1993). For more soluble salts, the lifetime of their occurrence is generally too short to be preserved as part of a hierarchy (e.g. Hamdi-Aissa, 2001).

3.1 Textural Features

The following types of occurrences involving one or two kinds of textural features are the most common:

– only one type of textural feature (e.g. microlaminated clay coatings), absence of hierarchy (Fig. 5 case 1); in general some of these features are deformed or burrowed by soil fauna (e.g. small fragments of clay coatings incorporated in excrements), whereby the two processes (illuviation and faunal activity) are synchronous; such a facies characterises monophase soils;
– juxtaposed and concordant features(e.g. parallel lamination in coatings) (Fig. 5 case 2), which implies that two different illuvial phases occurred successively, without erosion or another abrupt event separating stages with different environmental conditions (e.g. replacement of a conifer forest by deciduous vegetation); such a facies characterises biphase soils;
– juxtaposed but discordant features,(e.g. non-parallel lamination in coatings – cross-bedding) (Fig. 5 case 3), which means that a moderate interruption occurred between the different illuvial phases, during a rhexistasic episode; such a facies also characterises biphase soils;
– unrelated features (e.g. different types of clay coatings in different sets of voids) (Fig. 5 case 4), which implies that moderate soil disturbance took place between the two illuvial phases;
– one type of feature occurring in the form of fragments dispersed in the groundmass (clay coatings fragments), whereas an undisturbed feature (clay coatings) covers the sides of voids (Fig. 5 case 5), or coats the fragmented feature, which both mean that Luvisol development was followed by disruption of the Luvisol (e.g. by mass-transportation), followed, in turn, by a new illuvial phase, similar to the first.

Hierarchies of three or more kinds of textural features (Fig. 7A) also occur quite frequently.

The hierarchy of textural features which is established in the horizon appearing in the field as the palaeosoil or its key horizon should be compared with the hierarchy in the under- and overlying horizons or layers (Fig. 6). Relationships between illuvial facies in these horizons or layers, within a single profile, can be for instance:

– Textural features (clay coatings) that are undisturbed in the key horizon (Fig. 6 case 1) occur as fragments in the overlying horizon (Fig. 6 case 2), which means that the palaeosoil was truncated and then covered by reworked pedogenic material derived from the palaeosoil.
– A textural feature (clay coating) both occur in the key horizon and penetrates into the underlying horizon (Fig. 6 case 3), which has to be interpreted as an illuvial phase able to penetrate the underlying horizon.

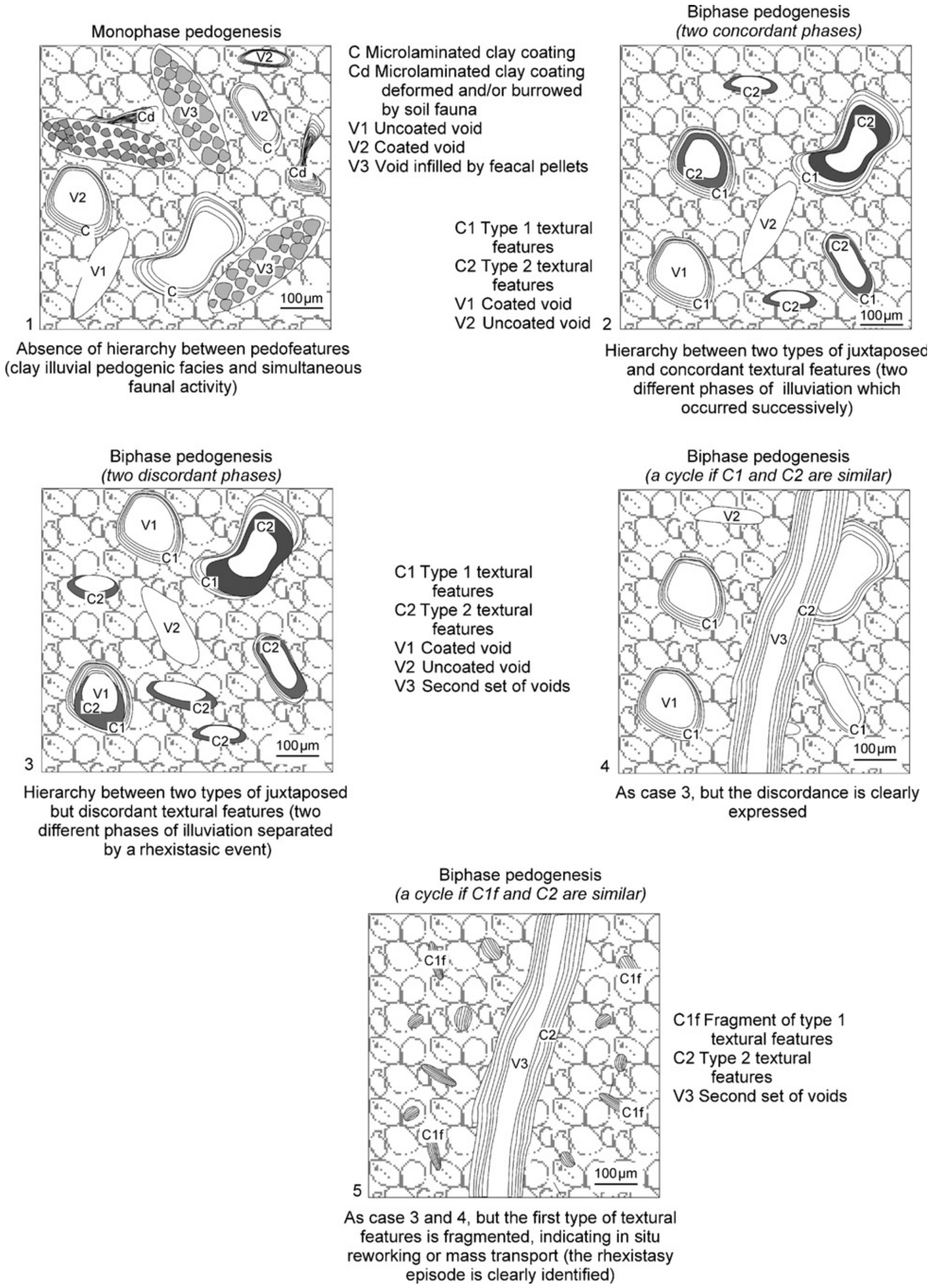

FIG. 5 Types of hierarchy involving one or two sets of textural features, observed for the Bt3-horizon of Luvisols in Western Europe, developed during the Early Holocene (case 1), the Pleistocene–Holocene transition (cases 2 and 3) and the Late Pleistocene (cases 4 and 5).

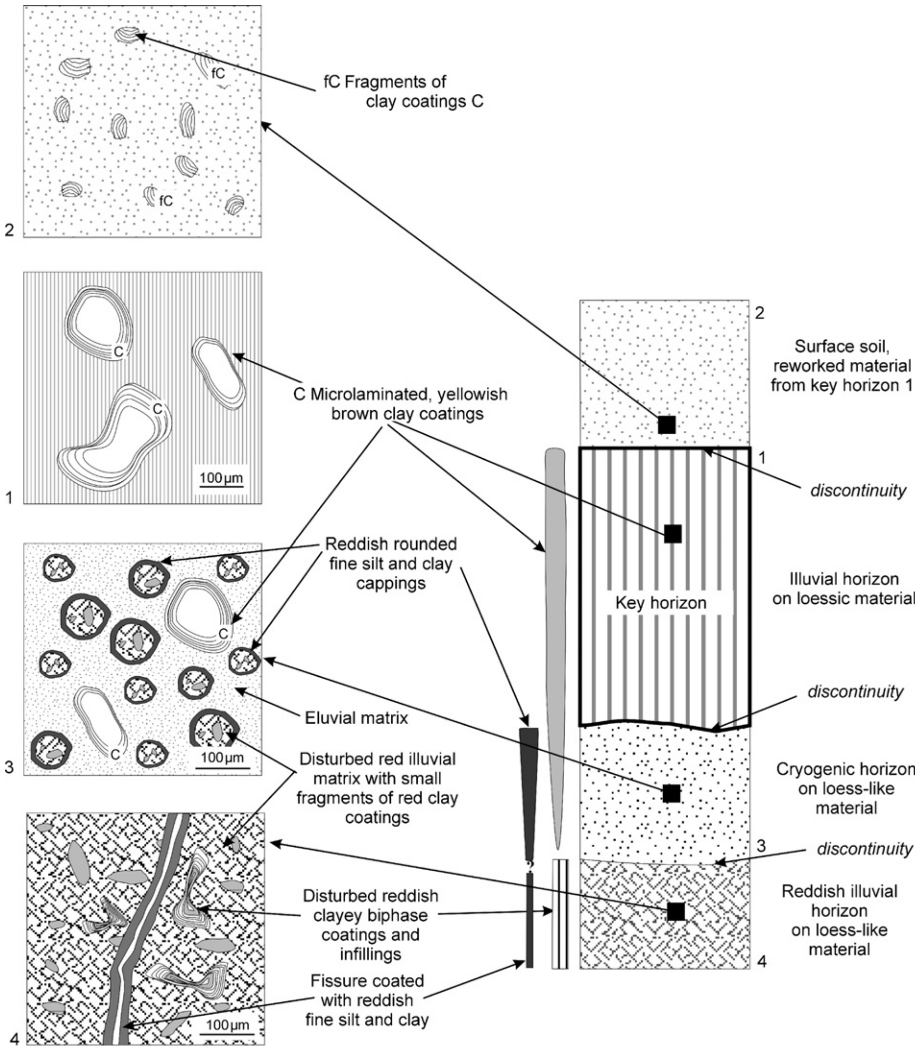

FIG. 6 Example of relationships between illuvial facies in a sequence of superimposed deeply altered loessic materials and palaeosoils (cf. Fig. 1, case 3), as observed for Late Pleistocene sequences in the Po valley, Italy. (See also Cremaschi, 1991).

– Rounded fine silt and clay cappings (Fig. 7B), discordant relative to the clay coatings, are present in the underlying horizon (Fig. 6 case 3); they record a cold phase which has induced permafrost conditions.
– Three or more types of textural features, usually discordant and overlapping, are observed in lower horizons as a result of successive pedogenic phases (Fig. 6 case 4, 7A, 8). Fine silt and clay coatings in fissures occur as an extension in another form of cappings that are present at higher levels, whereas disturbed reddish clayey coatings and infillings belong to two illuvial phases. Such assemblages of textural features

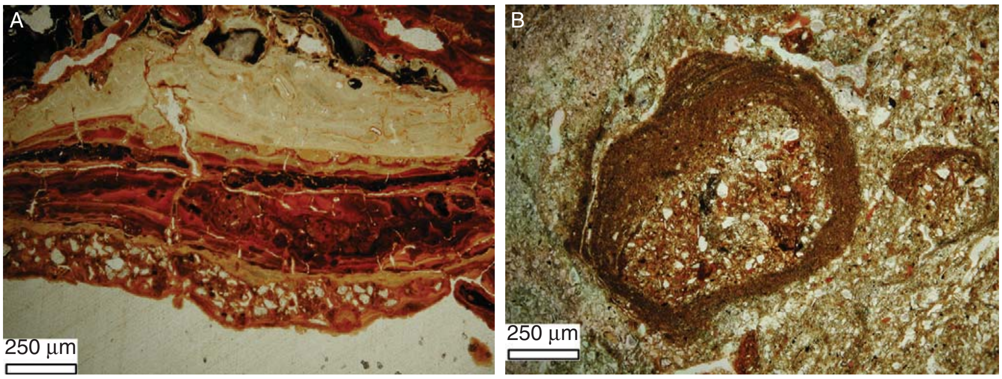

FIG. 7 Hierarchy of textural features. (A) Layered deposit showing the following hierarchy, from the ferruginous nodule to the void: (i) whitish-grey clayey mass; (ii) irregular, red clayey laminae with embedded reddish-brown aggregates; (iii) reddish and whitish microlaminae; (iv) packing of reddish-brown aggregates; and (v) red clay microlaminae (nodular horizon of a laterite profile, Dogon lowlands, Mali) (PPL). The whitish-grey mass corresponds to a high groundwater stand, probably in relation with a humid climate, whereas the following layer indicates a well-drained soil and the third one corresponds to a new phase of high groundwater levels; the reddish-brown aggregates again suggest a well-drained soil, whereas the quartz grains, especially abundant splinters, indicate an aeolian episode; the red clay laminae correspond to a well-drained soil in a stable landscape. (B) Rounded silt capping, around an aggregate embedded in a groundmass affected by clay eluviation, from a layer just above a fragmented argic horizon (see Fig. 15) (Po valley, northern Italy) (PPL). The feature is inherited from a cold episode.

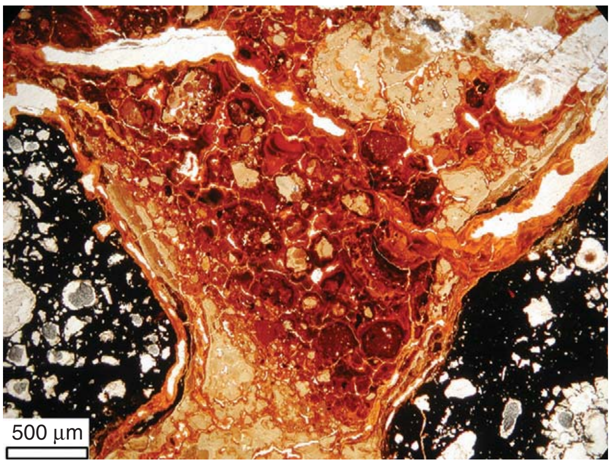

FIG. 8 Hierarchy of ferruginous features. Monophase, homogeneous, black, opaque nodules, with strongly weathered quartz grains (partly dissolved); the material between nodules comprises subrounded aggregates of whitish-grey clayey material and dark red clayey aggregates with silt-sized quartz grains, and it also includes three generations of juxtaposed, cross-bedded clay coatings (Dogon lowlands, Mali) (PPL). The nodules were formed as part of a continuous or semi-continuous ferricrete, during a single phase characterised by a fluctuating water table; the ferricrete was subsequently disjointed and only the nodules were preserved; the sequence of events recorded for the material between nodules, is comparable to the one described for Fig. 7A.

commonly occur in loess that is strongly affected by soil development, for example in northern Italy, where loess aggradation was moderate and where climatic factors were favourable for illuviation even during cold periods (Cremaschi, 1991).

Different textural feature types organised according to a well-expressed hierarchy can merge with greater depth into a single type. Such assemblage can be observed in relict soils developed on deeply karstified limestone (Atalay, 1997; Fedoroff, 1997). One type of textural feature can be present throughout a very thick horizon (e.g. Yin & Guo, 2006).

3.2 Ferruginous Features

Horizons characterised by ferruginous nodules, pisoliths and continuous crusts (ferricretes or laterites), corresponding to ferric, plinthic, petroplinthic and pisoplinthic diagnostic horizons of the World Reference Base (IUSS Working Group WRB, 2006) appear to consist in thin section of a great variety of ferruginous features and facies assembled according to various hierarchies (Delvigne, 1998; Stoops & Marcelino, 2010, this book), which are mainly inherited. The main types are described below.

A first type is iron oxide impregnations of an autochthonous material, which are either continuous, or discontinuous in the form of mottles (Fig. 9 case 1.1). The coarse material can consist of gravel that represents the primary ferricrete (Fig. 9 case 1.2). A hierarchy is usually absent in both types. These forms should be considered as inherited, based on their location in the profile and their relationships with present-day groundwater levels. Discontinuous and continuous cementation result from *in situ* accretion of iron oxides which occurred during a period of high but seasonally fluctuating groundwater rich in chelates (Schwertmann, 1985). Both types have to be considered

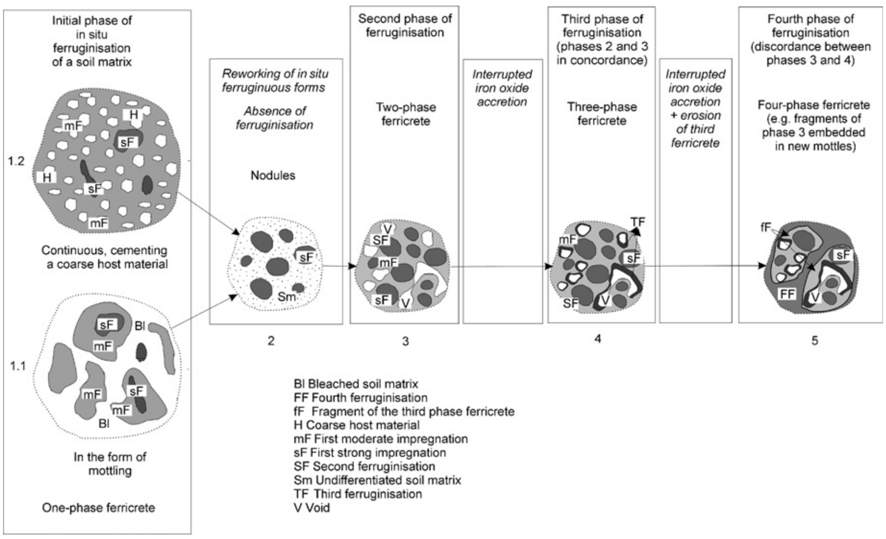

FIG. 9 Schematised sequence of the evolution of a ferricrete. (See also Achyuthan & Fedoroff, 2008).

as monophase plinthite, or as monophase petroplinthite if it is petrified. The host material is supposed to be free from ferruginous grains and gravels.

Ferruginous nodules characterised by sharp boundaries and a random distribution, in a different host material (Fig. 9 case 2), indicates severe reworking or erosion of a plinthitic soil, of which the fine fraction has been reworked or carried away and the mottles have become rounded. In this way, the soil has lost its less resistant parts, while the most resistant constituents were preserved in the form of nodules. The nodules in such a horizon are thus inherited. In nodular facies that formed *in situ*, nodules are uniform in morphology and size; whereas in the case of transported material, the facies consist of nodules of different types and dimensions.

Nodular horizons (Fig. 8) are frequently characterised by two and even more types of nodules between which a precise hierarchy cannot be established. Red, black and brown nodules have been described for a nodular horizon of a relict Plinthosol in Youth Island, Cuba (Gonzalez, 1991). The red nodules impregnate the same clayey material as red mottles that formed *in situ* at the base of the profile. From bottom to top of the profile, reddening of the nodules increases, their boundaries become sharper, their size decreases and their shape becomes rounded. The red nodules undoubtedly belong to the *in situ* profile, or they may have been transported from a similar profile higher on the slope. The black nodules are opaque, masking the impregnated material. They appear to consist of pure oxides, and they contain abundant polyconcave vughs, partly coated with gibbsite crystals. Black nodules do not exist at present in any soils of the study area. Consequently it is assumed that they were formed in Plinthosols, developed during a period with very high rainfall, favouring alteration. These Plinthosols were later completely eroded, whereby the resistant black nodules were preserved and scattered on the soil surface. The brown nodules are in fact pisoliths, as discussed below.

Ferruginous impregnation of the interstitial material of a nodular facies, usually in the form of bridges between the nodules (Fig. 9 case 3), has to be considered as a two-phase ferricrete. A rise of a fluctuating water table in a nodular horizon is responsible of such secondary ferruginous aggradation. Fragments of this type of two-phase ferricrete can be embedded in a new ferruginous impregnation (Fig. 9 case 4), producing a three-phase ferricrete.

Pisoliths, which are common in surface horizons in the tropics (Gonzalez, 1991; Achyuthan & Fedoroff, 2008), consist of a nucleus and a cortex (Delvigne, 1998), which have to be considered as being part of a hierarchy (Fig. 10, 11). The nature of the nucleus varies widely. Examples include (i) nodules originating from mottles present in the mottled clay horizon of the investigated profile (Gonzalez, 1991) (Fig. 10 case 1); (ii) ferruginised fragments of a weathered bedrock, for example, in ferricretes of southeastern Deccan with nuclei of weathered charnockite that occurs in outcrops at a distance of 20 km (Achuythan & Fedoroff, 2008); (iii) fragments of soil horizons; and (iv) charcoal fragments. Charcoal as pisoliths nucleus is quite common (Fig. 11). Gonzalez (1991) mentions them as occurring in considerable abundance in Youth Island, Cuba, and they have also been observed in West Africa (Eschenbrenner, 1987; Delvigne, 1998) and

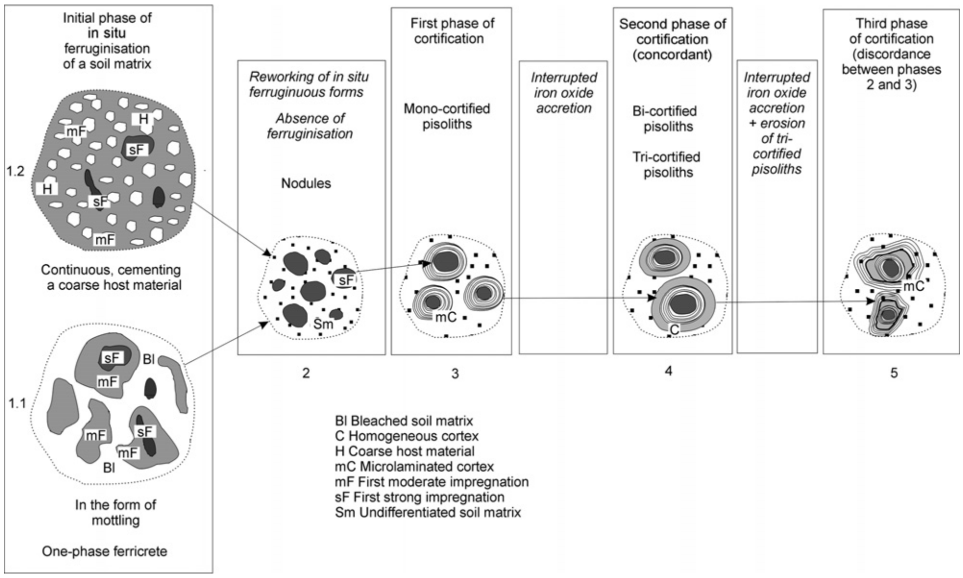

FIG. 10 Schematised sequence of the evolution of pisoliths. (See also Achyuthan & Fedoroff, 2008).

southeastern Deccan (Achuythan & Fedoroff, 2008).These charcoal fragments indicate wildfires which can affect periodically wet zones (Goldammer & Seibert, 1989) and which could correspond to abrupt events (Kennett et al., 2008). The cortex of pisoliths has no relation with the nucleus. It is generally laminated or microlaminated (Fig. 10 case 3, case 4). Clay particles are commonly accreted together with the iron oxides. The cortex frequently consists of two or more types of laminae of different colours, for example red and dark brown, which may be concordant or discordant (Fig. 10 case 4, case 5).

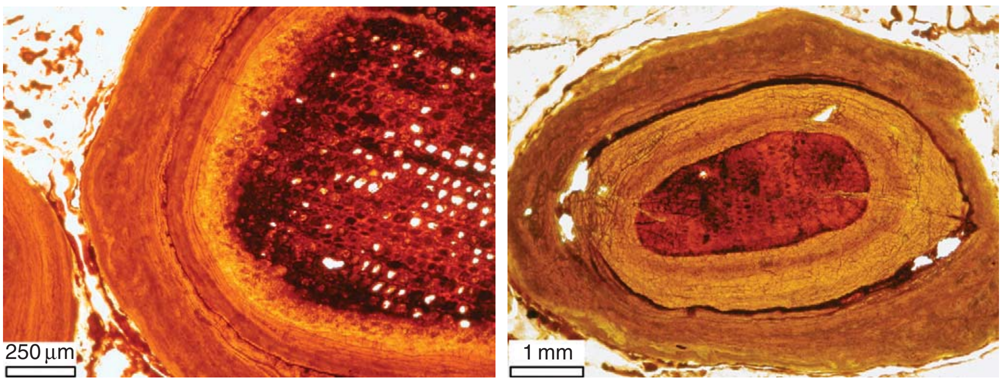

FIG. 11 Ferruginous pisoliths (Youth island, Cuba). (A) Biphase pisolith with a ferruginised charcoal core and a microlaminated cortex, corresponding to two different phases of iron oxide accretion (PPL). (B) Four-phase pisolith, consisting of a red ferruginised charcoal core and a three-member cortex composed of two microlaminated members separated by a dark brown quasi-opaque layer (PPL). The pisolith records four phases of iron oxide accretion, whereby the second and fourth phase appear to be similar.

Cortification probably occurs in a porous surface horizon during a high groundwater stand, whereby ferruginous nodules act as nuclei for bacterial precipitation of iron oxides from water rich in chelates (Emerson & Revsbech, 1994) and clay particles are trapped in the oxides (see also Stoops & Marcelino, 2010, this book). Alternation of red (hematite) and dark brown (goethite) laminae probably results from fluctuations from warm humid to cooler humid periods (Berner, 1969; Bondeulle & Muller, 1988). Cross-bedding indicates erosive episodes during which the soft materials were eroded while the pisoliths were reworked or transported (Fig. 10 case 5). A final phase of ferruginous bridging can cement the pisoliths. Very few radiometric dates have been obtained for the cortex of ferruginous pisoliths, but accretion is probably a slow process (e.g. 0.01–0.02 μm/year; Bernal et al., 2006).

3.3 Calcitic Facies

Buried or relict calcic horizons and petrocalcic horizons (IUSS Working Group WRB, 2006) occur in geological series from the Precambrian (Melezhik et al., 2004; Lewis et al,. 2008) to the Holocene. Petrocalcic horizons or calcretes are described in numerous publications (e.g. Milnes, 1992; Nash & Smith, 2003; McLaren, 2004) (see also Durand et al., 2010, this book). Micromorphological investigations have shown the common complexity of most of these horizons (e.g. Candy et al., 2003). Here we propose a classification of calcitic features and facies based on the concept of hierarchy.

Three main primary types of calcitic features occurring in soils can be distinguished (Fedoroff & Courty, 1994): (i) discrete calcitic features of biogenic origin; (ii) sparitic to micritic crystallisations in the form of nodules of various sizes, merging eventually in continuous horizons in the vadose zone, as a result of evaporation of water saturated with respect to calcite; and (iii) lamellar surface crusts. Like other soil-forming processes, accretion of calcite was discontinuous at geological time scales. Discontinuities result from variations in water table depth, intensity of evaporation, soil water composition and intensity of calcitic dust aggradation. The most common types of hierarchy of calcitic features and facies in palaeosoils and relict soils are as follows (Fig. 12):

– Absence of hierarchy, with the calcitic facies consisting of simple features which can be of biogenic origin and/or consist of sparitic or micritic crystallisations (Fig. 12 case 1). Such facies must be considered as monophase. The common secondary micritisation of primary biogenic forms should be considered as belonging to the same phase as the initial calcitic aggradation (Fedoroff et al., 1994). Such primary facies are common in palaeosoils of the Loess Plateau of China, where discrete biogenic features or nodules of various sizes are monophase (Guo, 1990). The nodules locally merge into continuous monophase calcrete.
– A two-phase hierarchy, consisting of calcitic aggradation followed by partial or total dissolution (Fig. 12 case 2). Calcite dissolution produces various features. The most common are (i) partial diffuse dissolution of a sparitic groundmass expressed by floating detrital grains (e.g. Robinson et al., 2002); (ii) dissolution of a calcitic

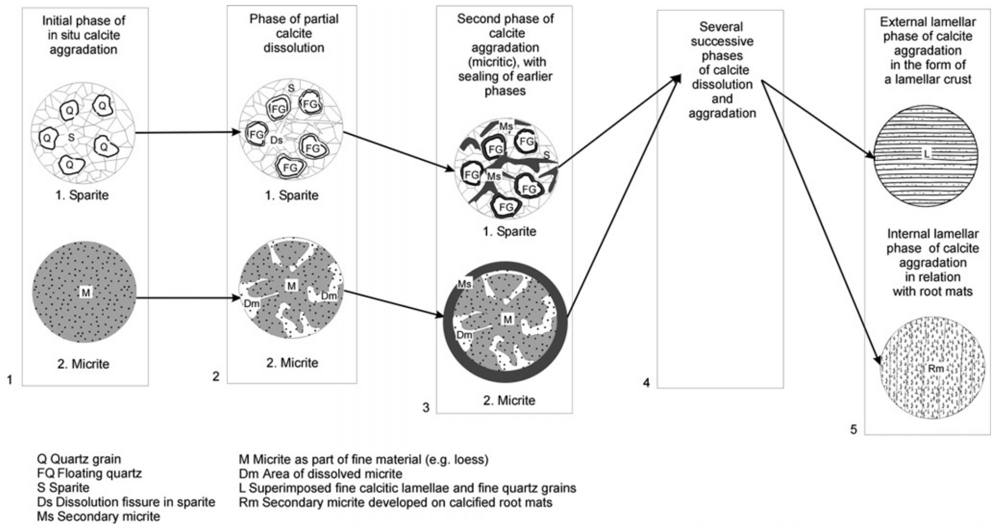

FIG. 12 Schematised sequence of evolution of calcitic facies.

groundmass along fissures, which can be filled by illuvial clay; (iii) scoriaceous hard nodules (Guo, 1990), characterised by dissolution along the edges of the nodule; (iv) partial dissolution of soft nodules, resulting in a less-pronounced crystallitic b-fabric; and (v) complete dissolution of nodules, whereby the external form is preserved (mouldic pores) (Fig. 13). Examples of two-phase features can be found in palaeosoils of the Loess Plateau of China (Guo, 1990).

– A three-phase hierarchy, consisting of a two-phase hierarchy as described above, followed by a new phase of calcitic aggradation, most frequently as micritic calcite

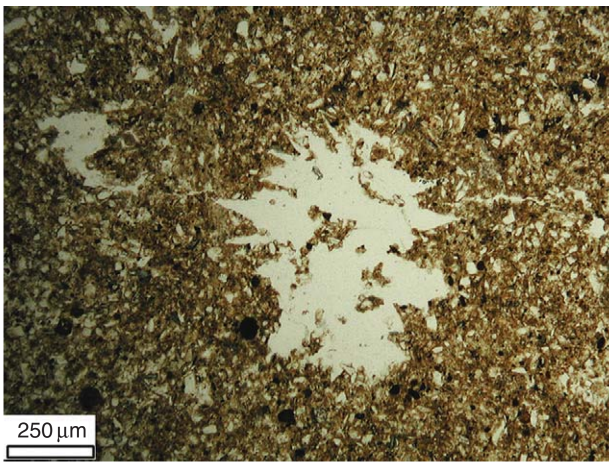

FIG. 13 Mouldic voids, pseudomorphic after gypsum crystal intergrowths, in the upper part of an undisturbed Kastanozem (Loess Plateau of China, Xifeng section) (PPL). The mineral probably crystallised during the transition from MIS 5 to MIS 4 (see Fig. 20), and it was later dissolved.

(Fig. 12 case 3). This new phase can be biogenic (e.g. calcified root mats) or non-biogenic (e.g. sparitic cement).

Polygenetic calcitic assemblages are different from assemblages in ferricretes because after a few phases of calcite aggradation and dissolution, the calcitic groundmass becomes petrified and sealed for water penetration (e.g. Wright et al., 1993; Durand et al., 2006). Further phases of calcification can occur along the top of the horizon and on walls of vertical fissures in the form of lamellar crusts. Each lamella of a surface crust is characterised by a dense, micritic groundmass in which one can recognise residues of cyanobacteria, green algae and fungi (Wright et al., 1996), as well as detrital silt-sized quartz, frequently in the form of splinters (Smalley & Vita-Finzi, 1968). Between the massive calcrete and the lamellar crust, rounded calcitic aggregates are frequently observed. Development of these lamellar crusts can be interpreted to begin with erosion of the friable upper horizon of the calcitic soil down to the petrified horizon, during a rhexistasic episode. Rounded calcitic aggregates are probably remnants of this erosion, which was mainly aeolian. A biogenic surface crust subsequently colonised the eroded soil, protecting it from further erosion. Biogenic filaments trapped aeolian dust from which carbonates were derived and reprecipitated, cementing the crust (Verrecchia et al., 1995). When a lamellae was hardened, a new one developed on top. Lamellar crusts are assumed to have developed during periods that were arid and probably windy (Stahr et al., 2000).

Internal lamellar crusts can be related to climate fluctuations. During a wetter period, the petrified horizon was dissolved along fissures, whereas during the following arid period, calcium carbonate, probably supplied by aeolian dusts, was in excess and precipitated in various forms. The alternation of the wet and arid sequence may be responsible for the lamellar structure (Alonso-Zarza, 1999).

4. Reworked Materials

Soil reworking, soil erosion, transportation and redeposition of soil materials and allochthonous sediment aggradation appear to be underestimated in palaeopedology. Careful analysis of palaeosoils and relict soils in thin sections shows that soil covers of the past were frequently to some extent affected by these processes (e.g. Kemp et al., 2004). Exceptions include palaeosoils buried by man (e.g. soils under burial mounds) and by tephra.

4.1 *In situ* Soil Reworking and Mass Transportation

A continuum exists between *in situ* reworked soils and mass-transported soil materials (Lacerda, 2007) (Fig. 14 case 1). Both are frequently difficult to recognise and distinguish in the field. In thin section, both are recognised by one or more of the following characteristics: (i) a massive microstructure with variable abundance of closed polyconcave vughs, frequently grading to vesicles; (ii) a granular microstructure with rounded to subrounded aggregates which are not of excremental origin; (iii) a more or less

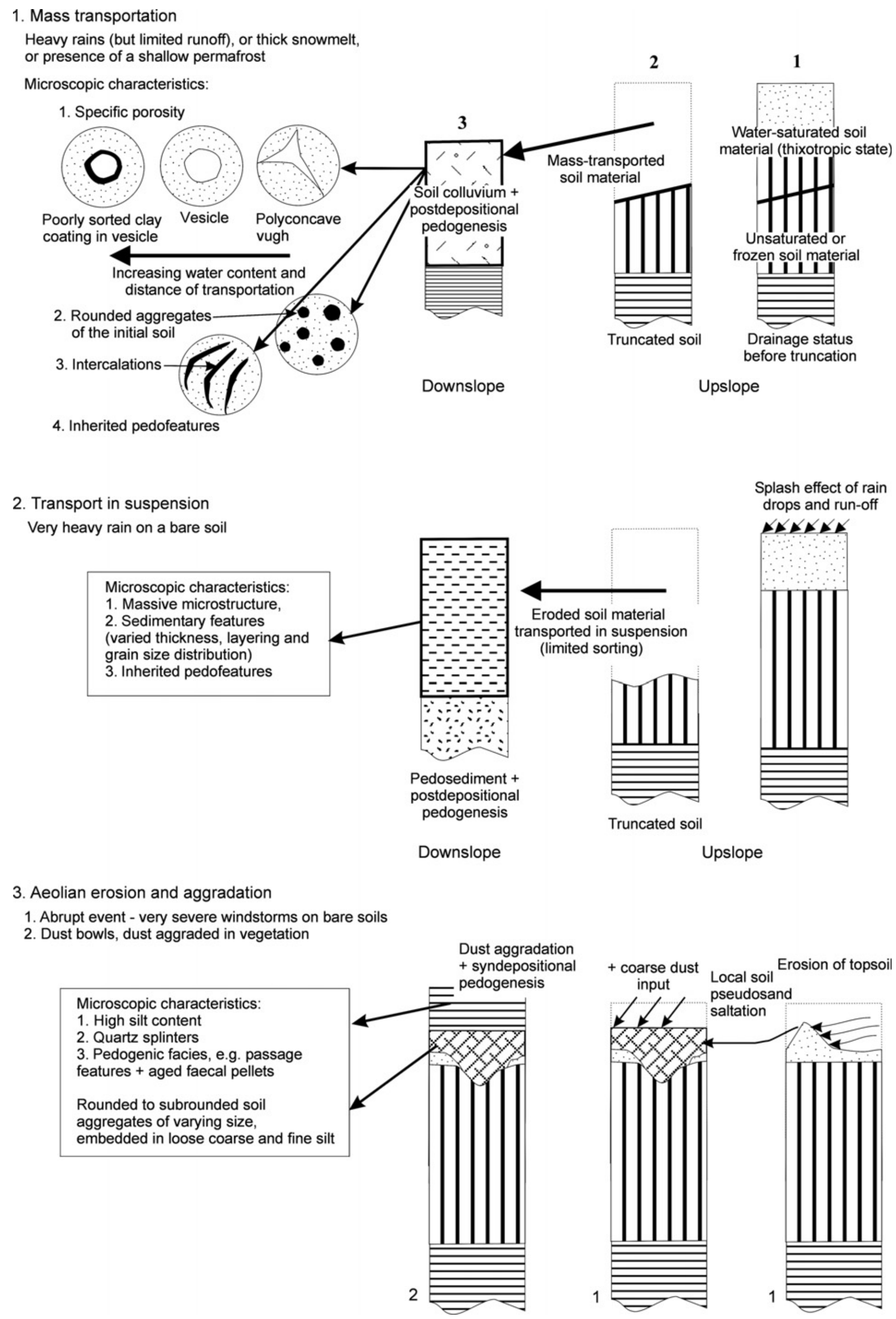

FIG. 14 Macro- and micromorphological characteristics of a mass-transported soil, of soil materials transported in suspension and of a soil affected by aeolian erosion and aggradation.

homogenised groundmass in which the colour of the parent soil is preserved; (iv) the presence of fragmented pedofeatures; and (iv) the presence of clayey to silty clay intercalations or of thin unlaminated clay coatings in vesicules. Ferruginous and calcitic pedofeatures tend be rounded with sharp boundaries. Fragments of clay textural features are angular to subangular, with little or no deformation, the latter resulting in the preservation of their original aspect in XPL (see also Mücher et al., 2010, this book).

Thin section analyses contribute to the identification of the cause of disruption of the parent soil. Soil can be disrupted by water saturation, inducing soil material dispersion and leading to the collapse of the soil structure. Completely dispersed soil material having reached thixotropy is characterised by a homogenised groundmass and by an apedal microstructure, with occluded polyconcave vughs or vesicules. In partially dispersed soil material, rounded aggregates inherited from the parent soil are embedded in dispersed material. The thixotropic state may occur in moving groundwater, in which case textural intercalations would indicate groundwater movement along selected pathways through the groundmass. A thixotropic state also occurs above a permafrost and even above a zone of seasonal deep frost (Fig. 15). Cryoturbation results in structure collapse and local displacements (e.g. Sanborn et al., 2006). Earthquakes can induce structure collapse when the soil or the subsoil is water-saturated (e.g. Wolf et al., 2006). Disruption of palaeosoils can also result from a violent airburst due to the impact of a cosmic bolide (Courty et al., 2008). In thin sections, such disruption can be expressed as loose packing of angular to subangular aggregates of various sizes, initially described as frost-shattered soil (Guo, 1990).

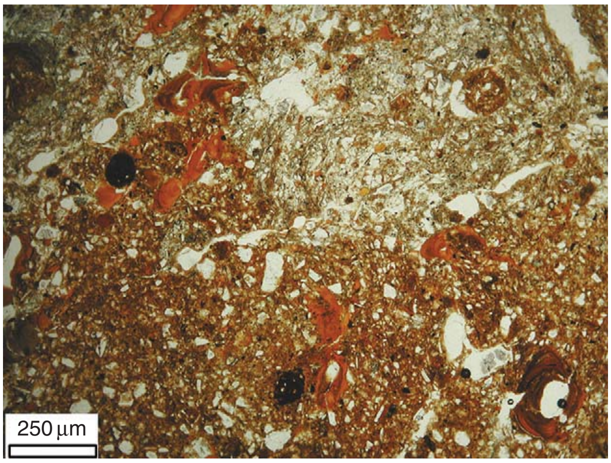

FIG. 15 Disturbed Chromic Luvisol, showing three types of reddish illuvial features: (i) small rounded fragments, randomly distributed in the reddish groundmass; (ii) weakly disturbed large infillings; and (iii) undisturbed clay and fine silt infillings (Po valley, northern Italy) (PPL). The fragmented facies is considered to be the result of deep frost action; illuviation has gone through different phases (i) development of a Chromic Luvisol, of which the small rounded red fragments are remnants; (ii) churning of the Luvisol; (iii) a new illuvial phase, recorded by the weakly disturbed large infillings; and (iv) another illuvial phase, during which silt grains were also translocated.

Mass-transported water-saturated soil material can be distinguished from an *in situ* reworked soil by (i) rounded aggregates belonging either to deep soil horizons or to the parent material (clay balls); (ii) a greater homogenisation of the groundmass in which randomly distributed, sorted fragments of pedofeatures can be present; and (iii) the presence of dusty, poorly oriented clay coatings in vesicles. The latter result from deposition of water-suspended clays in residual voids after the mass-transported material has been stabilised. They indicate mass-transportation in a rather liquid form, as in present-day desert mudflows. Clay balls (Fig. 16) are torn from the dry floor on which the mass-transported material has slid down. If transportation results from collapse, the soil material consists of angular to subangular aggregates derived from various horizons of the eroded soil and in some cases from the underlying material (Rust & Nanson, 1989).

Soil micromorphology has revealed that lower horizons of deep polyphase soils are often characterised by clay fragments (see Fig. 5 case 5), whose abundance varies from scattered occurrences (~1%) to high concentrations in materials composed of an almost pure accumulation of fragments. They exist from mid-latitudes to the tropics. In the Rambouillet forest of the Paris Basin, such horizons are C-horizons of Gleyic Luvisols developed over a thin loess cover that was deposited during various episodes of the last and penultimate glacial cycles. These loess layers, which are strongly affected by several phases of pedogenesis dominated by clay illuviation (Fedoroff, 1968), were either reworked or mass-transported, as a result of deep soil freezing or permafrost conditions during the glacial maximal. Such horizons have also been reported for Red Mediterranean soils (Chromic Luvisols), especially those overlying calcretes (Mücher et al., 1972), and for some tropical soils (e.g. Boulet et al., 1986) (Fig. 17). This suggests that soil covers were periodically destabilised by drastic climatic events, such as a drought followed by

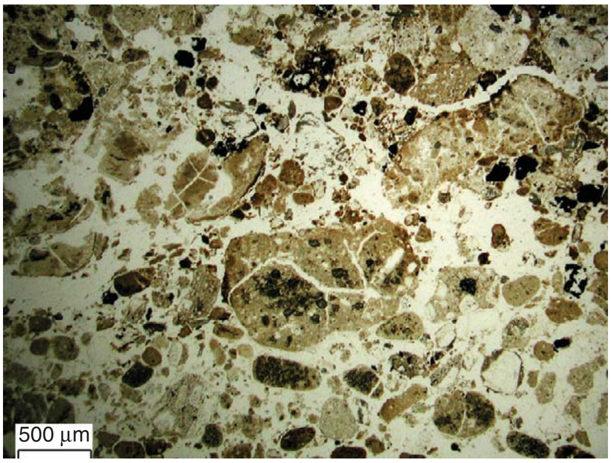

FIG. 16 Pedosediment derived from a Vertisol, in the form of rounded aggregates (clay balls) mixed with volcanic fragments, with associated opaque aggregates (Sangiran dome, Java, Indonesia) (PPL). The clay balls result from heavy rain, affecting a Vertisol fragmented by desiccation; the opaque aggregates are probably heated soil material.

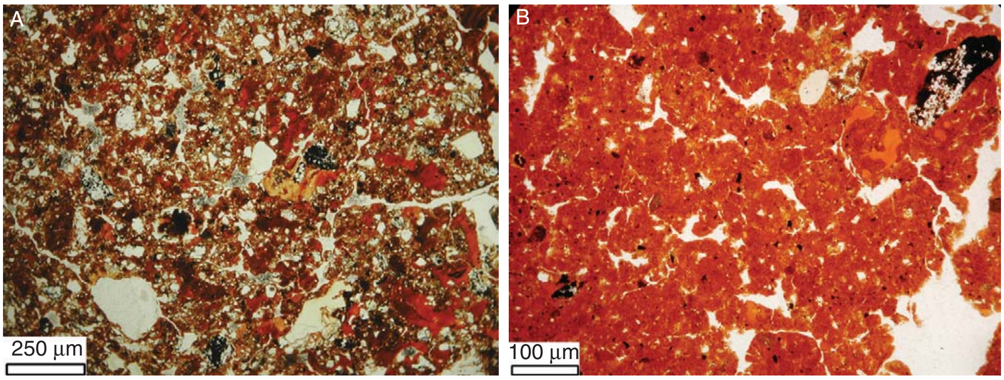

FIG. 17 Disturbed facies, at the bottom of the transition from a weathered zone to a ferralic horizon (Misiones province, Argentina) (PPL). (A) Soil consisting of coalescent aggregates derived from (i) dark red coatings and infillings, (ii) ferruginised weathered basalt and (iii) whitish-grey clayey material. This occurrence of a disturbed facies, in the tropics, cannot be considered as a result of a deep frost, in contrast to occurrences in mid-latitudes (see Fig. 15). (B) Partially homogenised groundmass, comprising (i) aggregates with varying degree of compaction, (ii) an aggregate with red clay infillings, (iii) fragments of ferruginous features, (iv) weathered bedrock fragments and (v) quartz grains, partly in the form of splinters. This facies is considered to be an aeolian soil sediment that originates from ferralic soil developed on weathered basalts (see also Iriondo & Kröhling, 2007); the undisturbed red clay infillings are postdepositional.

heavy rains. Clay-with-flints (argiles à silex), which occurs in patches over a large area in southern England and the Paris basin, consists to a some extent of chalk dissolution residues and mainly of Cenozoic sediments deeply affected by soil-forming processes (Pepper, 1973; Laignel et al., 1998). Pedological aspects of these formations have only rarely been investigated (Stoops & Mathieu, 1970; Thorez et al., 1971).

4.2 Transport in Suspension

Soil materials transported in suspension and deposited as pedosediments are easily distinguished in thin sections from mass-transported materials by a massive microstructure, a groundmass whose colour is close to that of the parent soil and horizontal sedimentary layering with layers of variable thickness and texture (Fig. 14 case 2, 18). Inherited pedofeatures can be present, but in lesser abundance than in mass-transported soil materials. Ferruginous nodules, because of their resistance to both physical desaggregation and chemical weathering, can help in identifying the source of the pedosediment. Flood-suspended particles can penetrate inside coarse deposits within river beds, where they are deposited in packing voids.

4.3 Aeolian Processes

The widespread occurrence of features resulting from aeolian processes shows that wind action on the soil cover is quite common at present and was episodically very strong in the past. These features occur very widely, including occurrences in the humid tropics (e.g. Iriondo & Kröhling, 1997, 2007) (see Fig. 17B). Quartz exoscopy (e.g. Le Ribault, 1977),

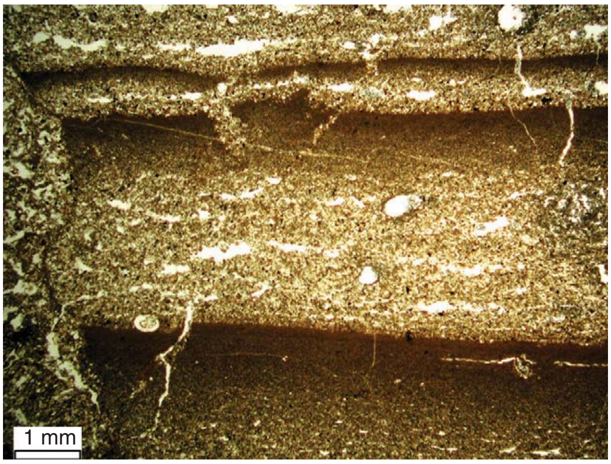

FIG. 18 Layered silt and silty clay crust, crossed by a passage feature (left). The coarser grained layers have elongated horizontal voids, due to ice lensing (Pampean pleniglacial loess, Tortugas quarry, Argentina) (PPL). The crust consists of loess reworked by run-off, deposited in the form of a sedimentary surface crust.

using SEM, is one of the methods that contribute to identifying aeolian episodes in palaeosoils and relict soils.

Well-sorted coarse silt in which quartz splinters are common, is a good indicator for aeolian dust aggradation (Smalley & Vita-Finzi, 1968). Thin section observations have shown that many soil covers in the past were affected by minor dust aggradation that was not sufficiently predominant to create typical loess. Such minor aggradations have been observed for interglacial palaeosoils (e.g. Guo, 1990) and in areas adjacent to loess deposits, but they also exist in areas where loess is absent, such as the humid tropics (e.g. Berger et al., 1994).

Some clay coatings and infillings present in non-Luvisol-related soils have been attributed to aeolian dust (Brimhall & Lewis, 1992), for example abundant thick clay infillings in ferricretes of the Ilgorn Plateau, southwestern Australia. The question of fine dust penetration into soils is not resolved. For instance, it is still unclear how the fine dust from the Sahara that is deposited along the northern side of the Mediterranean Sea is incorporated into soils.

Various forms of calcite, gypsum and more soluble minerals are common in palaeosoils and relict soils of arid to subhumid areas. When occurring as isolated grains, their external morphology can result from aeolian processes, for example rounded grains produced by wind winnowing. After their deposition on the soil surface most of these mineral occurrences are dissolved, followed by transport of ions in solution and by precepitation at depth.

The aeolian origin of lunette dunes is well known (Cooke et al., 1993). They are characterised by packing of rounded aggregates or crystals (e.g. gypsum crystals) that originate from the adjacent wind-deflated sabkha (playa) and whose morphology can be more or less altered by postdepositional soil-forming processes (Hachicha et al., 1987). Lunette-like aeolian features can also exist without being associated with a sabkha. Along the coast of southern Israel, there is a south-to-north sequence from typical loess, over loess containing rounded soil aggregates, to Vertisols (Rognon et al., 1987). In many tropical soils, thin sections reveal characteristics of aeolian origin, for instance the presence of silt-sized quartz grains, some of them in the form of splinters, in Ferralsols developed on large basaltic plateaus in northern Argentina (Iriondo & Kröhling, 1997) (see Fig. 17B). The parent material of the entire soil profile can be aeolian in origin, as in the Sahel of western Africa (Coudé-Gaussen, 1987; McTainsh et al., 1997) and in southern India (Achyuthan & Fedoroff, 2008). The aeolian origin of these relict tropical soils ('sols ferrugineux tropicaux' in western Africa; Bertrand, 1998) is indicated in thin sections by one or more of the following characteristics: (i) homogeneity of the groundmass throughout the profile; (ii) rounded aggregates, more or less altered by postdepositional soil-forming processes; (iii) association of predominantly oxic characteristics with calcitic features; and (iv) inherited rounded ferruginous features that are randomly distributed (Achyuthan & Fedoroff, 2008).

5. Palaeoenvironmental Significance

Many papers have demonstrated a close relationship between climate and soil type, but opinions diverge about climate impact on the evolution of past soil covers. Soil micromorphology has contributed considerably to this debate for Quaternary palaeosoils (e.g. Fedoroff et al., 1990; Kemp, 2001; Kemp et al., 2001; Felix-Henningsen & Mauz, 2004) as well as for older formations (e.g. Driese & Ober, 2005).

Deciphering the environmental significance of palaeosoils and relict soils is usually based on comparison with modern analogues. Some palaeosoils can be interpreted adequately by applying this concept. For instance, Holocene Luvisols can be used as modern analogues for interglacial palaeo-Luvisols, both being characterised by microlaminated clay coatings and infillings. Palaeosoils developed during late Pleistocene interglacials (e.g. MIS 5) in the Chinese Loess Plateau region are typic Luvisols (Guo, 1990).

Palaeosoils and related formations frequently present pedofeature assemblages and facies for which no modern analogues are known. For instance, large channels (a few centimetres in diameter) in soils on loess that developed during glacial cycles in northern Italy are filled, from bottom to top, by: (i) cross-bedded microlaminated clay and fine silt (Fig. 19 case 4.1); (ii) massive coarse clay (Fig. 19 case 4.2); (iii) massive coarse silt with embedded silt-sized fragments of clay-illuvial features, discordantly covering dusty clay (Fig. 19 case 4.3); and (iv) a fine layer of clay and fine silt (Fig. 19 case 4.4). Similar channels were observed in Périgord, southwestern France (Sellami, 1999). The coarse silt with embedded clayey fragments could result from an abrupt event such as a Heinrich event or the Younger Dryas. Fully satisfactory interpretations for such features are still lacking. Cross-bedded microlaminated clay and fine silt coatings occur presently in soils covered by a thick snow cover melting rapidly in spring (Fedoroff et al., 1981).

Collisions with extraterrestrial bolides have been suggested to have had a regional or global impact on soil covers (Bunopas et al., 2001). Ufnar et al. (2001) described features

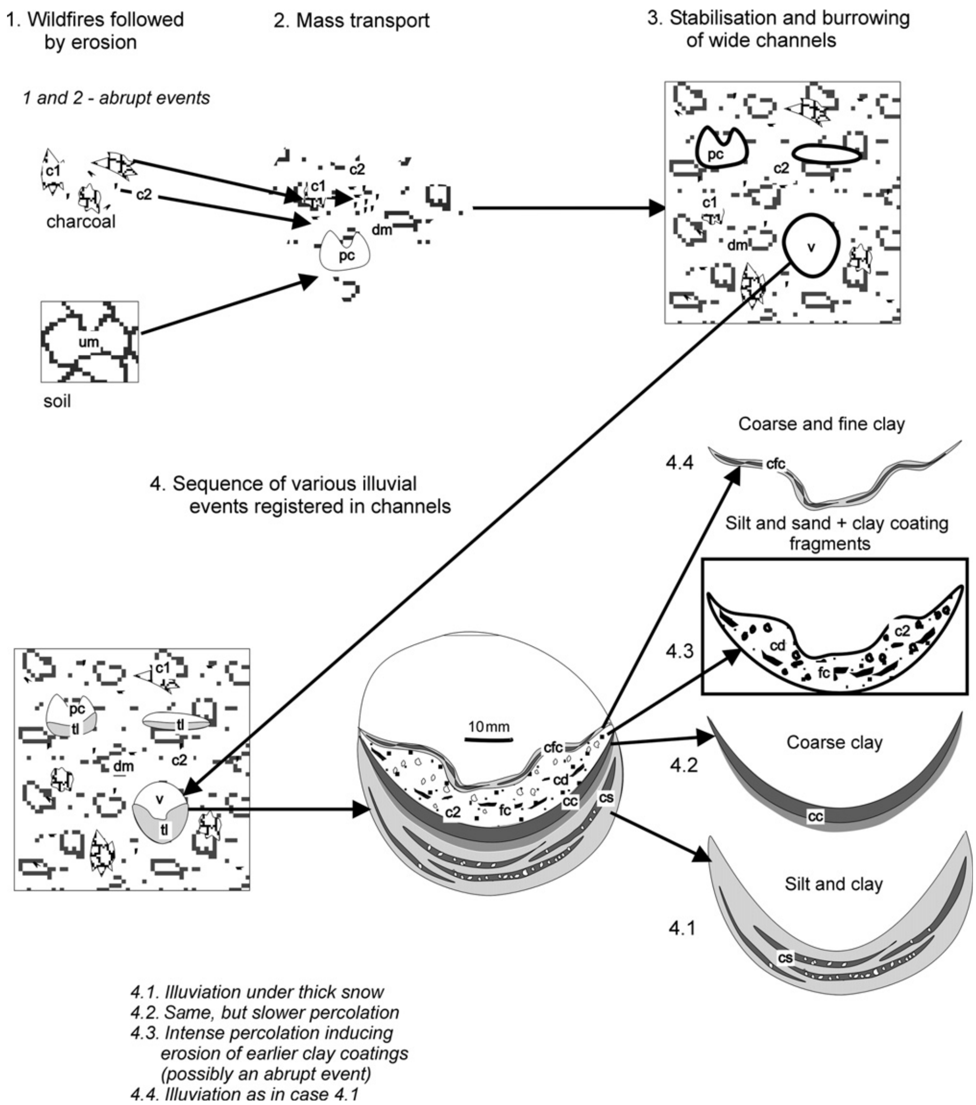

FIG. 19 Example of facies, unknown in presently forming soils, in altered loess deposits of the last glacial cycle (Po valley, Italy).

related to the Cretaceous–Tertiary (K/T) impact in Cretaceous palaeosoils. Courty et al. (2008) using soil micromorphology have proposed a method for deciphering the effects of cosmic impacts on soils. Such impacts in soils are identified by one or more following characteristics: (i) groundmass disruption, (ii) heated fragments, (iii) charcoal fragments and (iv) allochtonuous materials such as microtektites, glass shards and bituminous components. Four tektite-strewn areas resulting from such collisions are known in for the Cenozoic and Quaternary (McCall, 2001), but pedological aspects have not been investigated.

Heated fragments of palaeosoils and *in situ* heated palaeosoils have been recognised, for instance as subangular fragments and ellipsoidal aggregates in Java, where they are related to an occurrence of tektites (Courty et al., 2007) (see Fig. 16). In this study, heating, up to a few hundred degrees Celsius is recognised in thin section by (i) a complete loss of birefringence of the originally smectitic groundmass, (ii) an opaque aspect of the groundmass (Courty et al., 1989) and (iii) compaction of ellipsoidal aggregates probably by heating. In this case, heating is thought to result of a blast of hot air resulting from a meteorite impact. Heat-transformed palaeosoils have also been described for volcanic regions (Usai, 1996).

Charcoal fragments that cannot be the result of human activity are common in palaeosoils (Van Vliet-Lanoë, 1976) and relict soils. Their abundance is underestimated, or their presence is not even recognised, when micromorphological investigations are not carried out. They can be in the form of (i) randomly distributed or aligned fragments in reworked soil material, (ii) nodules consisting of ferruginised charcoal fragments (see Fig. 11) or (iii) silty textural features containing abundant small charcoal fragments. Charcoal fragments are at least partly related to wildfires associated with discontinuities in soil development (rhexistasic episodes). Some extensive wildfires, such as those of the Younger Dryas, may have been caused by cosmic impacts (Kennett et al., 2008).

Layers of tephra are common in palaeosoils and related sediments, but they have only been used as a stratigraphic tool. The impact on soils of major volcanic eruptions such as the 74,000 ka Toba eruption (Rampino & Self, 1993) is unknown.

6. Transitions in Palaeosoil Sequences and Their Significance

Various types of transitions exist in palaeosoil sequences which have to be distinguished from pedogenic horizon transitions. They can be in the form of planar abrupt truncations, or the discontinuity can be irregular, wavy, or in the form of tongues. The transition can also be very progressive, even undetectable in thin sections, although radiometric dates indicate a gap of thousands to hundred thousand of years between levels separated by only a few centimetres. Transitions are frequently emphasised by stonelines, especially in the tropics. In order to interpret the transition in palaeosoil sequences, the under- and overlying layers have to be compared (see Fig. 17). Earthquakes can also be responsible for the presence of discontinuities (e.g. Wolf et al., 2006).

The best-documented example of transition is the passage from the last interglacial pedocomplex to the pleniglacial loess (MIS 5 to MIS 4) as it occurs in the Loess Plateau of China (Guo, 1990; Porter & An Zhisheng, 1995). This transition is characterised in thin sections by a layer with a coarse disrupted assemblage (Fig. 20A), consisting of abundant small

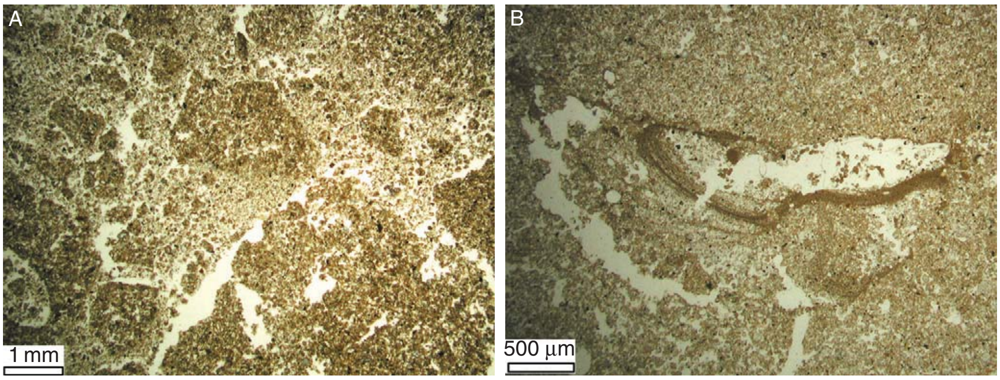

FIG. 20 Facies recognised for the transition from the last interglacial pedocomplex (MIS 5) to the pleniglacial loess (MIS 4) (Loess Plateau of China, Xifeng section). (A) Fragments of a Kastanozem, embedded in a coarse-grained loose calcareous loess, containing rounded aggregates of the Kastanozem (PPL). This facies cannot be due to a deep frost and has been interpreted as the result of an airburst. (B) Blackish brown coating probably corresponding to an episode of wildfires followed by heavy rains (PPL).

rounded aggregates derived from the underlying Kastanozem (see Fig. 4A), randomly embedded in a coarse loessic material rich in detrital calcite grains (Guo, 1990). Below this layer and apparently related to it, infillings composed of blackish-brown massive fine silt rich in small charcoal fragments are recognised (Fig. 20B), as well as mouldic voids after barite or gypsum crystal intergrowths (see Fig. 13). Calcitic features in the form of micritic infillings, micritic hypocoatings and sparitic infillings composed of rounded crystals in channels are present throughout the loess cover, the transition layer and underlying Kastanozem. A grain-size increase occurs within the transition layer and just above in the pleniglacial loess (Porter & An Zhisheng, 1995), together with an increase in mica and heavy mineral content. A tentative reconstruction of the sequence of events, based on the hierarchy of attributes, could be the following: (i) aeolian erosion of the top of the Kastanozem, indicated by small rounded aggregates, associated with coarse loess deposition resulting from exceptional dust storms, more severe than those responsible for the formation of the main loess deposit; (ii) disruption of the top of upper Kastanozem, possibly resulting from an air blast which shattered the soil to some centimetres depth; (iii) an episode of wildfires followed by heavy rains, which is registered by the blackish-brown infillings; (iv) accumulation of gypsum or barite together with coarse loess, followed by dissolution during a wetter episode and by precipitation as crystal intergrowths in the Kastanozem, which were later dissolved during a wetter period of unknown age; (v) development of calcitic features, apparently related to deposition of the main loess deposit, independent from the air blast. A similar type of transition from MIS 5 to MIS 4 in loess and palaeosoil sequences has been observed in the Rhine valley (Rousseau et al., 2002) and in Pampean loess sections (Fig. 21) (Rosario, Argentina). In the latter study, rounded fragments of a Luvisol, probably belonging to the MIS 5 pedocomplex, are embedded in a coarse loess (Kemp et al., 2004).

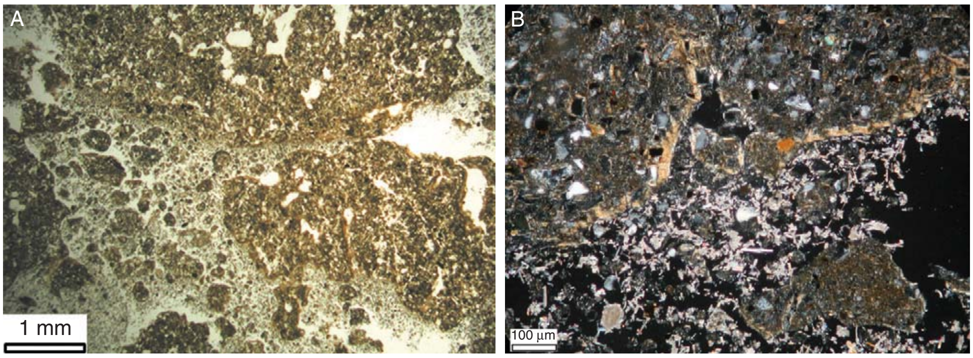

FIG. 21 Facies recognised for the transition from a well developed Luvisol to a pleniglacial loess (Pampean loess, Tortugas quarry, Argentina). (A) Fragments of an argillic horizon characterised by thin pale brown clay coatings, embedded in a coarse-grained loose loess. The facies is comparable to that recognised for the MIS 5 to MIS 4 transition in China, but here the pre-existing soil is a Luvisol (PPL). (B) Detail of the previous showing the occurrence of acicular and rod-shaped calcite crystals (XPL).

7. Reconstruction of The History of Relict Soils

Reconstructing the history of relict soils requires first the identification of present-day pedogenic attributes, then detection of all relict attributes from the soil surface down to the unaltered parent material and finally the establishment of hierarchies between functioning and inherited attributes starting from the bottom of the profile. The palaeoenvironmental significance of each of these events should be considered at the end.

This is illustrated by the example of a Haplic Luvisol developed in loess deposited during MIS 2 in the Paris Basin, which, like many soils of soil covers of mid-latitudes, contains *in situ* relict features (Fig. 22). In this soil, undisturbed relict characteristics are recognised in the B3t- and C-horizons, whereas fragments of clay coatings occur in the B2t-horizon (Fedoroff, 1968). In thin sections (Fig. 22 case 1), the groundmass of the B3t-horizon is a non-calcareous loess with locally zones of ice lensing, crossed by abundant channels. The most common channels (V1) are coated with a dark brown, rather dusty, moderately well-oriented, massive clay coatings, juxtaposed concordantly by yellowish-brown, well-oriented, translucent, microlaminated clay coatings. A few channels (V2) are lined only by massive coatings and others (V3) only by microlaminated coatings. Some channels (V4) are uncoated and others (V5) are filled with excrements which can also be present in V2 and V3 channels. The hierarchy of features is from the groundmass to the middle of channels: (i) zones of ice lensing, (ii) dark brown massive fine silt and clay coatings and (iii) yellowish-brown microlaminated clay coatings. Observations for channels V2, V3 and V4 are apparently not in agreement with this hierarchy. The explanation could be that channels V2 became occluded when sedimentation of yellowish brown translucent clay started, whereas channels V3 developed after the formation of the massive coatings. The history of this horizon could be described as the following

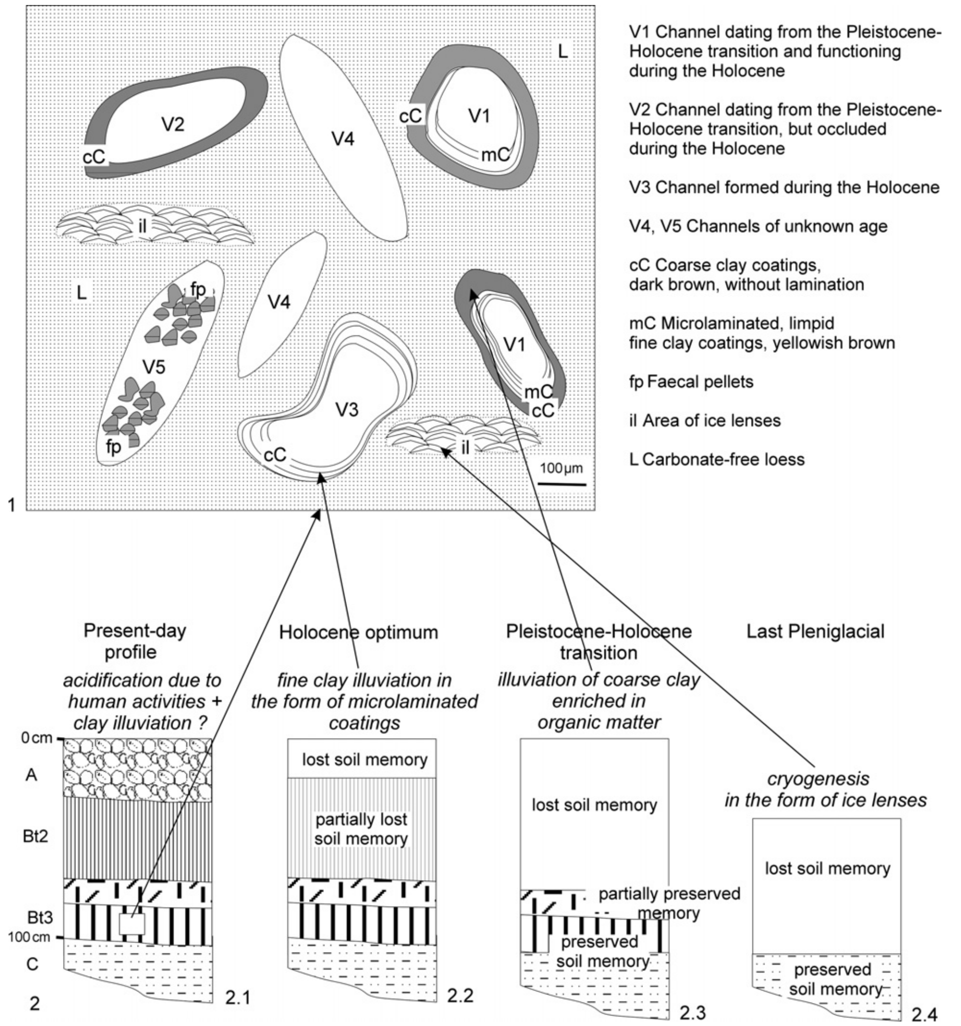

FIG. 22 Reconstruction of the history of a Haplic Luvisol on loess, based on the micromorphology of its B3t-horizon.

sequence of events: (i) development of ice lenses during or immediately after loess aggradation, (ii) a first pedogenic phase characterised by dark brown massive fine silt and clay coatings and (iii) a second pedogenic phase characterised by yellowish-brown microlaminated clay coatings. Ice lenses indicate deep frost affecting a soil saturated with water. The dark brown coatings (cC) indicate a fundamental change in environmental conditions, which switched from an environment with very strong winds and a dusty atmosphere during loess sedimentation to biostasic conditions. The dark brown colour is due to organic matter, which was translocated together with the clay and fine silt. For this period, we can assume that the vegetation was dominated by conifers, a hypothesis based on palynological data for the MIS 2 to 1 transition in northwestern

Europe. The weak sorting of fine silt and clay in these coatings and the absence of layering indicate rapid percolation in spring during snow melt. The microlaminated clay coatings are typical of Luvisols formed during the Holocene. The excrements cannot be included in this hierarchy, being formed during both illuvial phases. Figure 22 (case 2) is an attempt to reconstruct the soil profile at its main stages of development, by extrapolation of results obtained for the B3t-horizon.

8. Dating Palaeosoil Development

Soil micromorphology contributes only indirectly to dating of palaeosoil development. Soil micromorphology cannot replace radiometric dates and stratigraphic correlations, but the lifetime of a polyphase palaeosoil can be estimated from the number and nature of pedogenic phases detected. For instance, in loess–palaeosoil sequences, the illuvial facies developed during the last interglacial (MIS 5e), formed over approximately 10,000 years (e.g. Hearty et al., 2007). The duration of the exposure of palaeosoils interstratified in continental deltaic formations has been estimated from the extent of development of pedofeatures (Srivastava & Parkash, 2002). In this study, passage features and weak iron oxide staining are considered to indicate a few years of exposure, whereas a moderately well-developed illuvial facies is assumed to require a few thousands of years to develop, compared with Early Holocene and MIS 5e illuvial facies. Estimation of the lifetime of relict soils is less certain as they are not included in a stratigraphic sequence and their different facies usually have different ages.

Soil micromorphology can also contribute to dating palaeosoils development by supplying radiometric dating laboratories with samples of specific miccroscopic features instead of bulk samples. Only a few papers combining microscopic analysis and radiometric datings have been published. Courty et al. (1994) integrated geochemical microanalysis and micromorphology to decipher the genesis of calcitic pendants in Spitzbergen, whereas Bernal et al. (2006) proposed a radiometric method for measuring the rate of accretion of ferruginous pisolith cortexes. OSL dating was also utilised in combination with microscopic investigations on an Argentinean loess–palaeosoil sequence by Kemp et al. (2003), while Kühn and Hilgers (2005) used the same approach in southern Taunus (Germany). AMS radiocarbon dating requires only a very small amount of carbon and could be applied to small charcoal fragments that are frequently present in palaeosoils (Carcaillet, 2001).

9. Diagenesis

Diagenesis of recent palaeosoils (Middle Pleistocene to Holocene) usually only concerns biological activity and organic matter (Chichagova, 1995). As soon as a soil is buried, the soil fauna feeding on plant residues disappears. For instance, earthworm populations may disappear, followed by the consumption of earthworm excrements by mites, replacing them with mite excrements. Fresh organic fragments in a buried soil are progressively humified and tend to disappear, whereas charcoal fragments are preserved, especially if they are ferruginised. In much older palaeosoils, buried by less than a few hundred metres and not affected by tectonic movements or thermal activity, microscopic characteristics are weakly altered or unaltered by diagenesis (Retallack, 1991). In lithified palaeosoils, changes are more important, but pedogenic characteristics can still be recognised in thin sections (Retallack & Wright, 1990).

Groundwater can have acted as a major pedogenic factor when it occurred near the soil surface, but it can also induce diagenetic processes in buried soils, similar to near-surface processes (Gibling & Rust, 1992). Development of diagenetic attributes depends on the rate of groundwater circulation, redox conditions and ionic concentration. Textural intercalations can occur at great depth where groundwater moves along faults. Soluble salts may be either dissolved or precipitated. Some iron and manganese oxide impregnations in palaeosoils, unrelated to other pedofeatures, are undoubtedly of diagenetic origin.

Pressure resulting from deep burial combined with circulating groundwater leads to collapse of voids and ultimately to the development of a massive microstructure (Sheldon & Retallack, 2001).

10. Conclusions

Soil micromorphology has largely contributed to deciphering of palaeosoils and relict soils, but its potential is far from exhausted. In the future, systematic coupling of thin section analysis by polarised light microscopy with submicroscopic and microanalytical techniques will boost soil micromorphology in this field (Courty et al., 2008). Also important is an integration of soil micromorphology with magnetic measurements (e.g. Tsatskin et al., 2001, 2006; Maher et al., 2003), radiometric dating (e.g. Bernal et al., 2006) and stable isotope analysis (Courty et., 1994).

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