Soil reactions to extreme environmental stress: lessons from the past records

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Abstract
Two paleosol sequences of the Late (South France) and Middle Pleistocene (South China) were investigated using a high resolution approach associated with SEM-EDS and XRD analysis on selected grains. This approach has enabled us to distinguish the repetitive succession of an initial pedogenic phase, ending by a soil disruption in response to an abrupt event. In South France, the sequence is terminated by a cryogenic episode associated with poor drainage as indicated by the hydromorphic characters that are superimposed on the earlier pedogenic events. In South China, the disruption episode is associated with the presence of macro and micro-tektites which leads to interpret this disruption as due to a cosmic airburst. The clear signatures of exceptional events in these Pleistocene paleosols have at present no analogue in modern soils. Their considerable high amplitude in comparison to the gentle stress that is generated by the global warming suggests that paleosols are of limited use for predicting effects on soils of the ongoing atmospheric change.

Key Words
Hierarchy of features, pedo-sedimentary sequences, extreme events, uniformitarism refutation.

Introduction
Intense research effort on high resolution marine, ice, lacustrine and loess sequences has considerably changed our perception of the Earth recent history. By combining a suite of multi-proxies, interdisciplinary studies have identified the occurrence throughout the last glacial cycle, as well as during the Holocene , and most probably during the former glacial and interglacial cycles, of recurrent abrupt climate forcing with centennial, even decennial, time-scale variability (Alley *et al.* 2003, Alley and Ágústsdóttir 2005). These cyclical and rapid climatic changes, known as the Dansgaard-Oeschger cycles, Heinrich events, or the Younger Dryas for the last glacial period, are now well established to have been global however with variable regional expressions depending on local settings (Broecker 1994). Stormy crisis preceding the initiation of loess deposition have took place within short periods (Rousseau *et al.* 2002). Surprisingly, the signatures of these short climate crises have not drawn much interest in paleopedology. The research conducted on paleosols have not seriously revisited the principles of linearity and of uniformitarism applied to soil development. Gaps in soils are still suggested to reflect thresholds independently from external factors.

However already in 1956, Erhart distinguished periods of stability favourable to soil development (biostasy) alternating with episodes of instability marked by soil erosion (rhexistasy). Haesaerts and Mestdagh (2000) have precisely deciphered in paleosols the succession of glacial/interglacial episodes stages that have developed through Europe during OIS 5. Porter and An (1995) have easily identified the signal of Heinrich events in the Chinese loess deposited during glacial periods, while Courty and Vallverdu (2001) identified the soil features resulting of abrupt events in exokarstic cavities of the Western Mediterranean region which trapped the soil cover extensively eroded during these exceptional crises. Similarly, Courty *et al.* (2008) have identified in various regions the widespread disruption of soil-landscapes at 4 kyr BP in response to extreme conditions. Our aim is at first to illustrate the record in paleosols and soils of abrupt events based on two key-studies. Then arguing for the irrelevance to apply the principle of uniformitarism to paleosols, we question the real potential of soil archives for predicting the effects of the global warming on soil development.

Methodological approach and key-studies
The methodology that we have developed (Courty *et al.* 2008) is aimed to provide a precise estimate of the integrity of the soil record with respect to its paleoenvironmental relevance. We combine the survey of serial trenches that provide sequences of paleosols and intercalated sediments across landscape units with the detailed investigation with of linked assemblages of artefacts, bones and rock clasts. This approach allows to

view the developmental stages of paleosols within the general frame of landscape evolution. The well preserved paleosurfaces, provide access to distinctive events along the course of this historical frame. Laboratory analysis are at first performed on test samples obtained from strategic positions. Micromorphological study of a few thin sections are combined to SEM-EDS and XRD analysis on distinctive components picked up by hand under the binocular microscope after extraction from the soil matrix by water-sieving. Results from the tests help to select the best preserved records for performing a complete analytical characterization by adjusting high resolution sampling to the set of pedo-sedimentary entities deciphered in the field. Samples for absolute dating are collected from controlled situations. The interpretative phase consists of the following stages: (i) identification of the pedological and sedimentary features; (ii) establishment of a chronostratigraphical frame giving the successive pedological phases and sedimentary episodes on the basis of hierarchies between all the identified features; (iii) exploration of the genetic linkages between the host soil matrix and the included elements, e.g. human artefacts or allogenic components linked to cosmic (i.e. tektite) or volcanic (i.e. tephra) events. A great attention is given to distinguish *in situ* formed soils, disturbed, but still in situ soils, transported soil materials (pedo-sediments), and true sediments that are not affected by pedogenesis.

The first key-study is located in southern western France at the transition of the Landes to the Chalosse regions near Saint-Gein. The sections are on a water divide. The surface soil, a Gleyic podzol, is developed in Late Pleistocene sands that are overlying a sequence of superimposed paleosols consisting of truncated Glossalbic Luvisols. The upper argic horizon is yellowish brown whereas the lower one is dark red. The lower yellowish brown argic horizon is locally strongly impregnated by manganese oxides. The dark red argic horizon lies over Tortonian clays which present the morphology of a reworked, bright red, aquic argic horizon. Abundant Mousterian artefacts are embedded in the matrix of the upper yellowish brown argic horizon. This sequence was compared at first to a younger sequence of paleosols situated nearby at Pujo-le-Plan in which Mesolithic artefacts are present at the base of the Landes sands just above the glossic soil. The second sequence used for comparison is also located near-by on a high terrace of Adour near the village of Cazères-sur-Adour. Acheulean industry was found in the upper yellowish brown argic horizon. The present day climate of the area is mild and humid with 990 mm of annual precipitation.

The second key study is located in the Bose basin in Guangxi province (south China) where the present-day climate is of tropical monsoonal type. The investigated paleosol sequence is developed on the fourth terrace (T4) of the Younjiang river. Six meters of Cumuli Gleyic Acrisols are sandwiched between cobble conglomerate and a recent soil cover (Qiuzhen and Guo 2006). Extensive excavation have demonstrated the association over several tens of kilometre of *in situ* tektites with delicate forms together with Acheulean-like stone tools and charcoal fragments in the T4 paleosol unit (Yamei *et al* 2000). The 803 $\pm$ 3 ka ^{40}Ar/^{30}Ar age of tektites is in agreement with their attribution to the Australasian strewnfield assumed to represent the dispersion area of melted by-products from a major cosmic impact (Lee and Wei 2000).

Results

At Saint-Gein, the argic ground masses viewed at microscopic scales consist of an undifferentiated mass that contain deformed and fragmented clay coatings and infillings while some voids are coated by a new set of clay coatings and infillings. The glosses are depleted iron oxides while in the centre voids are infilled by poorly sorted, bleached clays in the form of intercalations. A hierarchy between glosses has been recognised. In the Saint-Gein area, in each paleosol the following stages have be recognized: (i) a phase of clay illuviation corresponding to a period of stability (a biostasy phase), (ii) an episode of soil disruption characterized by deformation and fragmentation of illuviated features, however the distribution of human artefacts is preserved to a large extent which means a severe but *in-situ* disruption, (iii) formation of an hexagonal network of ice wedges, (iv) replacement of ice wedges by a slow migration of reduced water enriched with iron oxide depleted clays, (v) sediment accretion. We assume that the stage of severe soil disruption corresponds to an abrupt event, probably an airburst. It was followed by a cold episode responsible for the ice-wedges. The soil disruption destroyed most of the existing porosity making the disrupted argic horizon impermeable which induced during the next period of stability seasonal waterlogging (water could circulate only in ice wedges). A new cycle starts with an accretion of glacial sediments.

In Bose, the 6 m thick Cumuli Gleyic Acrisol does not display any horizonation, although a polyphased organisation is observed at microscopic scales. In the layer containing tektites the organisation is the following: (i) a reddish, disrupted, ground mass, in which fragments of clay coating and charcoal micro-fragments can be distinguished, (ii) irregular bleached zones, (iii) compound coatings showing an irregular alternation of microlaminated clays, dark fine silt layers and infillings generally located in the bleached zones. SEM-EDS and XRD analysis on discrete components revealed the presence of: (i) tektites micro-fragments, (ii) clasts of marine mud with foraminifera and radiolarian, (iii) clusters of aliphatic polymers, (iv) angular quartz, translucent glass shards, actinolite and zircon grains, (v) droplet coating on sand grains formed of native metals (iron, chromium, nickel, copper and zinc). The following stages of development can be proposed for the tektite layer: (i) an episode of soil disruption characterised by fragments of clay coatings synchronous to the incorporation of allogenic components, (ii) seasonal waterlogging characterized by bleached zones, a consequence of soil disruption, (iii) a phase of irregular illuviation.

Discussion and conclusion

The disruption of the soil fabric appears as the most striking character resulting from extreme events. The two key-studies illustrate the in situ disruption of the soil components, although lateral displacement in the form of a mud flow is also possible. In Bose (China), the occurrence of macro and microtektites in the disrupted soil matrix provides strong evidence for relating the disruption phase to a surface airburst in relation with a cosmic event. The subsequent waterlogging suggests an immediate rainfall increase. Our first case study shows an excellent record of periodical extreme events in a paleosol sequences that can be paralleled to the ones usually identified in ice, ocean and lake floors. Soils are the most accurate recipient with ice of extreme events because they are directly exposed to atmospheric changes and thus concentrate space debris, just simply filtered by the atmosphere. Refined investigation in the future on the periodicity of these extreme manifestations, specifically on the loess/paleosol sequence of the Loess Plateau of China, should greatly help to further elucidate their exact role on atmospheric perturbations and the linked environmental changes. Their identification emphasizes the discontinuous dimension of soil development through time that contrasts from the long accepted view of steady and gradual soil evolution.

The lack of an appropriate field-analytical methodology for detecting the unequivocal fingerprints of extreme events explain why paleopedology has been for so long mislead by the concept of uniformity (Gould 1987). A more dynamic perspective of soil development can be achieved by decoupling the genesis of paleosols into a succession of phases and cycles by applying the concept of the hierarchy of features (Fedoroff and Courty 2002). This approach incites to distinguish four types of paleosols:

1. The cyclical paleosols that display a paleosol and the overlying sediment. The rapid accretion of sediments (most frequently loess) as the result of an extreme event lead to complete burial of the paleosol. The sequence can be monophased, bi or triphased, as well illustrated by the Chinese loess/paleosol record.
2. The accretion of sediments was not sufficient to instantaneously bury the paleosol as illustrated by the St-Gein paleosol. Two and more phases of pedogenesis, e.g. clay illuviation, are overlapping and separated by unconformities.
3.The paleosol that appears in the field as an undifferentiated paleosol complex shows under microscope pedogenic features that are typical of extreme events as in the case of Bose; however their intense disruption at the time of formation has partly erased the soil record of short-term cyclicity.
4. The paleosol that is in general a relict soil, e.g. ferralsols, in which the presently available tools do not permit to identify in the field and also in laboratory, any hierarchy of features.

Although the triggering processes yet remain to be further elucidated, the recent recognition in paleosols of evidences linked to extreme events once more emphasizes how conceptual models progress from stimulating objectives.The assumption that paleosols can be used for predicting the future soil evolution due to the predicted global warming is questionable. The progressive temperature elevation of the modern area is weak in contrast to the nearly instantaneous drastic temperature changes of the past, up to 10°c in a few years, e.g. at the Younger Dryas. Furthermore, the subtle effects of the atmospheric changes linked to industrial activities are not accompanied by the range of severe manifestations that occurred in the past at the time of extreme events, i.e. airburst, extended wildfires. Moreover, the predominant effect of human impact on present day soils makes comparison with soils of the past more difficult. Soil characteristics resulting of soil biological activity and organic matter evolution can be used as references for the future when considering Holocene soils. These characteristics have however to be handled with great care because past faunal activity is estimated only by excrements and eventual preserved animal remnants, while the soil organic matter, even in buried soils, is ageing rapidly. Exchangeable cations (Pal *et al*. 2009) and soluble salts (Hamdi-Aissa, 2004) might be good indicators for tracing the evolution in soils of the recent past simply because of their high reactivity to the soil water regime.

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