The exokarstic soil record of past environmental changes: Regional expressions

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Abstract
We intend to promote using microfacies analysis how the Quaternary deposits filling karstic cavities that are part of galleries connected by vertical chimneys to the outside surface soils provide an original view on the reactivity of limestone landscapes to short-term environmental changes. Our purpose is illustrated by the early to middle Pleistocene sequences from the Sierra de Atapuerca (Burgos, Spain) and the late-Pleistocene/Holocene sequence of Song Terus (Gunung Sewu hills, Java Island). The micromorphological study and complementary analytical data have allowed subdividing the pedo-sedimentary facies into six types in terms of accumulation and pedogenic processes: (F1) Weakly pedogenised sedimentary facies; (F2) Weakly pedogenised pedo-sedimentary facies; (F3) Excremental pedogenic facies; (F4) Dark organic-rich facies; (F5) Calcitic facies; (F6) Firing facies. They are shown to reflect the range of short-term events that might have severely degraded the soils forming on the limestone landscapes along the course of the Quaternary period in response to various initiating factors, i.e. exceptional abrupt climate changes, wild-fires, volcanic eruptions or cosmic impacts. The rapid fossilisation and the negligible anthropogenic bias explain the excellent preservation of the pedo-sedimentary records in the subsurface karstic galleries. Further study should help to better understand the effects of these ecological crisis on human and animal communities that were occupying in the past the limestone landscapes.

Key Words
Facies, pedo-sediments, surface, fire, events

Introduction

The ongoing studies of deposits that accumulated through the Quaternary period at the foot of rockshelters and karstic cavities of limestone landscapes continue to provide valuable paleoenvironmental data on the past dynamics of terrestrial ecosystems after decades of research (Goldberg and Woodward 2001). The complex spatial variability of facies changes due to local factors and interactions of past animals and humans, which occasionally occupied these natural habitations, on sedimentary processes and pedogenesis is now well controlled by appropriated methodologies (Courty, 2001). Sharp stratigraphic discontinuities due to intensified detritism from the walls and enhanced pedogenesis at the soil surface have been shown to reflect sudden ecological stress generated at a micro-regional level by abrupt climate changes, i.e. .the Dansgaard-Oeschger cycles, the Heinrich events or the severe cooling of the Younger Dyras and 8.2 kyr BP events (Courty Vallverdu, 2001) from caves of Mediterranean regions. At the la Ferrasie rockshelter, a series of dark organic facies that are interbedded within the frost-produced sedimentary deposits have been interpreted to express episodes of soil formation during the Dansgaard/Oeschger climatic cycles of MIS 3 (Bertran *et al*., 2008). Humus development was thus suggested to have occurred in situ from accumulation of organic matter brought into the cavity by wind, water flows, animals, algae, lichens, mosses, thus producing specific humic compounds associated with weak horizonation in contrast to those in 'normal' soils.
Here, we further investigate the originality of the cave soil-like deposits in comparison to soils of the outside surroundings. Our aim is to establish correlation between the range of pedo-sedimentary processes involved in their formation with major changes in the soils formed at the same time on the limestone landscapes in response to climate variability, wildfires, volcanism, or cosmic events.

Materials and methods

Our study is illustrated by two karstic cavities that are part of long gallery network connected to the outside surface by vertical chimneys. The Sierra de Atapuerca (Burgos, Spain) is famous for its oldest direct evidence of hominids in west Europe, ca 1.2 Ma (Carbonell *et al*., 2008). The karstic complex comprises three levels of subhorizontal galleries. The present-day altitudinal continental climate is marked by Atlantic influences. The highly eroded soil cover consisting of Camborthids on reddish decalcified colluvial loam lies abruptly on the unweathered Mesozoic limestone formed of bioclastic grainstone. The deposits represent five distinct phases of filling well dated by radiometric techniques and paleomagnetism from the early Pleistocene to the late Pleistocene (Carbonell *et al*., 2008). They yielded a profusion of archaeological layers

with well preserved assemblage of lithic, bones and human remains that have been for long extensively excavated (Carbonell *et al.,* 1995).
The cave of Song Terus, located in the Gunung Sewu hills (Java Island) is part of a typical karstic landscape in an intertropical environment. The karst started to form during the Early Pleistocene from the Miocene reef coarse bioclastic limestone The highly dissected cone-shaped hills with levels of cavities result from the interaction of the constant regional uplifting due to tectonic activity and intense physical-chemical erosion due to high rainfall (Quinif, Dupuis, 1985). The sequence comprises more than 10 m thick of fluviatile accumulation, overlaid by 5m thick of terra rossa deposits with 3 archaeological layers: at the bottom the Middle Pleistocene Terus layer, the late Pleistocene Tabuhan layers and the Keplek Holocene sequence (in Gallet 2004; Figure 1).
The vertical sequence of the pedo-sedimentary facies and their spatial variability were studied from the sections exposed by the excavation. Continuous columns of undisturbed blocks were collected for thin section preparation. Bulk samples were collected from the distinctive strata, including their lateral variations, for compositional analyses of the coarse and fine components by X-ray diffraction, Raman micro-spectrometry and isotope analysis.

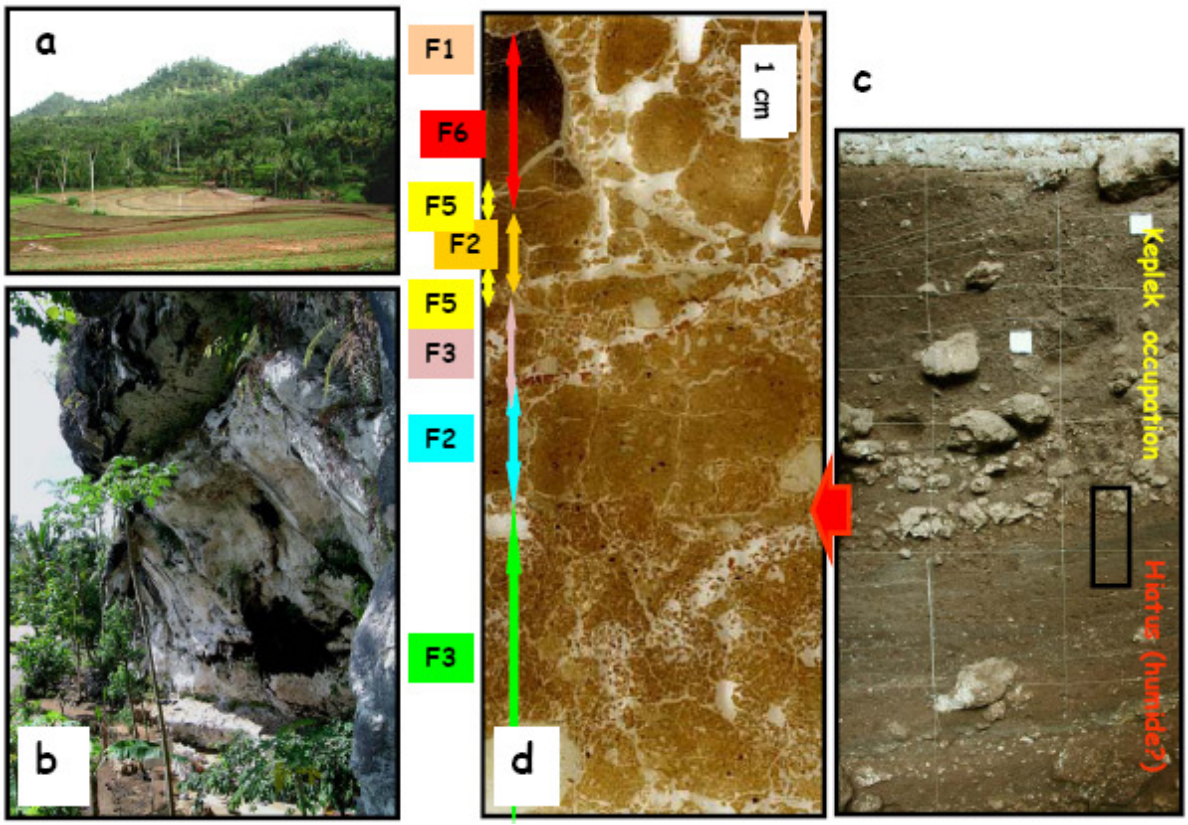

Figure 1. (a) The Gunung Sewu hills and (b) entry of Song Terus cave. (c) Stratigraphy of the upper Holocene layers (Keplek occupation deposits) and the late Pleistocene sequence (no occupation). (d) Photo-scan from thin section showing successive events at the terminal Pleistocene (possibly record of the Younger Dryas) showing the distinctive pedo-sedimentary facies (cf. the text for the description and paleoenvironmental significance) with sharp contact.

Results and discussion

The occurrence of pedological features and their degree of preservation allows classifying the pedo-sedimentary facies into five main categories. (F1) Weakly pedogenised sedimentary facies: massive or laminated, with common sedimentary features, they do not show a distinctive micro-aggregated structure of biogenic origin; pedorelicts are rare; when present limestone fragments have a sharp contact with the decalcified host matrix. Sediments can be of local provenance and/or integrate allochtonous components. These characteristics indicate rapid transfer into the cavities by mass flow of relictual soils covering a highly eroded limestone landscape with a scarce vegetation cover. In the case of allochtonous sediments, i.e. massive tephra at Song Terus, the lack of weathering indicates an arrival in the cavity just following their deposition at the outside soil surface. (F2) Weakly pedogenised pedo-sedimentary facies: generally massive

with rare sedimentary features, they display abundant pedo-relicts largely dominated by textural features and occasional excremental assemblage; the rare limestone fragments have a sharp contact with the decalcified host matrix.
These characteristics indicate rapid transfer into the cavities by mass flow of well developed soils that were extensively covering the limestone landscape; lack of weathered limestone fragments shows that the buried karstic galleries were not directly exposed to deeply penetrating plant roots.
(F3) Excremental pedogenic facies: they present a heterogeneous assemblage formed by the dense to loose packing of disturbed biogenic aggregates and subangular aggregates and rare textural features; the common limestone fragments are fresh to weakly decalcified, often associated to thin calcitic coatings.
These characteristics indicate a formation by disaggregation of the cavity wall that was densely colonized by plant roots issued from the vegetation covering the limestone landscape. The heterogeneity of the assemblage reflects interaction of physical and biochemical processes on the production of aggregates, more likely in response to periodical fluctuations of rainfall.
(F4) Dark organic-rich facies: They share in common a massive to open micro-aggregated structure, the abundance of humified fragments in the decalcified fine mass together with common charred remains, the occurrence of weakly to strongly weathered calcitic features showing amorphous coatings and hypocoatings, and occasionally dusty, finely laminated textural features.
This complex assemblage expresses the succession of two pedogenic phases: (1) the formation of speleothems on the cavity walls and on the ground by dripping of carbonate-saturated water that was slowly percolating through the calcareous soils covering the limestone landscape; (2) the degradation of the speleothems caused by dripping of waters that were enriched in organic acids following their percolation through a thick humic layer. The shift between the two phases suggests a change from a marked seasonal contrast to a globally pronounced humidity with the formation of poorly drained soils in the limestone landscape. The high char content indicates periodical wildfires, possibly during severe drought, that were greatly facilitated by the thick accumulation of biomass in the surrounding landscape. The long maintained humidity during phase 2 appears to have favoured the invasion of the karstic cavities by plant roots and their active corrosion by the organic substances. The record of distinctive wildfire events that are associated to the input at the soil surface of exogenic debris is represented by a distinctive signal in the two cavities.
F4 displays a wide range of sub-facies that expresses the spatial variability of local conditions, i.e. phosphatised organic facies due to high production of phosphate-rich organic substances by cryptogamic vegetation, or finely laminated organic-rich facies resulting from gentle runoff in the cavity at places of intense dripping and pound formation.
(F5) Calcitic facies: They range from thin laminated festoon-like calcitic bands that develop within thin fissures of F4 facies to thick, polyphased laminated calcification, i.e. the speleothems. They result from dripping of carbonate-saturated water with low suspended charge. The low amount of detrital inclusions or pedo-relicts implies that their development was contemporary with the formation of thick calcareous soils on the limestone landscapes and sufficient rainfall for generating a positive hydric balance.
Their thickness and complexity reflects the duration of the accretionary period, and subtle changes in the soil cover in response to climate variability.
(F6) Firing facies that include two sub-types: (F6a) the thick homogenous ashy facies formed of loosely packed phytoliths finely mixed with excremental aggregates (i.e. Song Terus) and (F6b) the dark brown carbonaceous thin facies formed of clay-rich amorphous organic matter with abundant charred remains (Atapuerca). These characteristics reflect sudden firing of considerable amount of biomass from the outside soils rapidly followed by their transportation to the cavities due to subsequent high rainfall. The incorporation of surface horizons indicates that the intense firing of the vegetation and of the humus layers had also severely deteriorated the soil cover.
Figure 1 illustrates a typical series of short-term events from the deposits of Song Terus cave. The unique dark firing facies (F6 on Fig. 1d) occurring just below the Pleistocene/Holocene transition is tentatively interpreted to represent exceptional firing liked to the Younger Dryas boundary events (Kennet *et al*., 2008). This correlation is based on the occurrence of high amount of mineral and organic markers that we suggest to be typical of cosmic airbursts (Courty, Fedoroff, this volume).

Conclusions and perspectives

The study of the Quaternary sequences from these two subsurface karstic galleries provide a challenging perspective in comparison to the classical view that previously concluded to the limited paleoenvironmental interest of exokarstic deposits. The proposed inventory of distinctive pedo-sedimentary facies appears to reflect the range of ecological crises that might have severely affected limestone landscapes in response to

various initiating factors. The short-term pedogenic events that we have identified seem to contrast the well established correlation between long-term soil development during globally stable interglacial periods and formation of speleothems in the underground karst. In fact, the two examples presented show that the record of peculiar situations affecting the outside soils simply benefitted from rapid fossilisation in the subsurface karstic galleries, whereas taphonomic processes, erosion, or human activities might have biased or erased their fingerprints in shelters or wider cavities. A refined timing of the pedo-sedimentary succession will help to better understand how limestone landscapes reacted to the natural stress exerted. Refined absolute dating is also critical to establish regional and long distance correlation, specifically with the distinctive signal of short-term events that is now well extracted from high resolution records on the basis of various proxies. The future, an increasing research effort on the Quaternary filling of subsurface karstic galleries should greatly help to improve our knowledge on the effects of natural hazards on the soil cover on limestone landscapes for key periods of rapid changes and on their regional expressions. The close collaboration with archaeologists and related paleoenvironmental disciplines should greatly contribute to control the bias exerted on the pedo-sedimentary record of the natural events by anthropogenic factors. In addition, the integration of cultural perspectives with the pedo-sedimentary data would help to debate the consequences of the ecological crises on past human and animal communities.

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