SOILS OR SEDIMENTS?

The role of Roger Langohr's process-oriented approach in understanding carbonate-related palaeosols of the stratigraphic record

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ABSTRACT
This paper is a summary of palaeopedologically-oriented research on and the interpretation of subaerial exposure-related features in cyclically organised shallow marine carbonates. We point out that the structure of soil profiles in such environments cannot be interpreted simply in terms of pedogenesis. Apparent soil-thickness is not necessarily proportional with soil-maturity and clays and secondary carbonates are not always direct indicators of climate, either.

KEYWORDS
carbonate palaeosols, soil-maturity, climate signal, Late Triassic, Hungary

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1. Prelude

My friendship with Roger Langohr was promoted by Judit Deák and dates back to the early '90s of the past century. Being a bauxite geologist, I arrived on the Soil Science scene from the field of ferrallitic weathering. I wanted to use the Cretaceous bauxites I was studying to understand Cretaceous climates. However, soon I realised that beyond the generalisation of the Cretaceous Greenhouse, undoubtedly favourable for bauxite formation, there are other factors controlling soil development, with *time* being the most important of them all. So I became interested in soil science and wanted to learn more about non-bauxitic palaeosols, possibly contemporaneous with my bauxites. At this time, Greg Retallack published his book about palaeosols (Retallack, 1990). Not knowing about Roger Langohr's Soil Science School, I decided to go to the US and spent nine months with Greg Retallack in Oregon. I learned a great deal, both in the field and in the laboratory, however, I also had fierce disputes, even quarrels with Greg because I did not share his rather rigid attitude towards palaeosol-classification. He would mechanically apply the categories of the US Soil Taxonomy (obviously constructed for recent soils) and would do so not only concerning suborder, but sometimes even on a subgroup level. However - despite these quarrels - as a result of Greg's experience and enthusiasm and the beauty of those colourful Central Oregonian palaeosols, I happened to fall in love with palaeopedology forever.

When I returned from the States, I became involved in a Tertiary palaeosol project in Nigeria's Kerri Kerri basin. There, I had to face the complexities of pedogenesis in an alluvial environment, where, unlike in the US, soils developed on strongly pre-weathered ferrallitic materials and the whole sequence was first subject to shallow-burial diagenesis, then uplifted and eventually re-exposed. In other words, a superimposition of too many processes. At that point, I almost gave up working with palaeosols.

That was the point in time when I got into contact with Roger Langohr's Soil Science Group.

Despite all the previous frustrations, I launched a curriculum on Palaeopedogy in Budapest in 1993. To fill the gaps in my knowledge, I began to regularly invite foreign scientists and included their lectures and short courses in this new curriculum. In addition to Paul V. Wright from Reading (UK) and Jacques Thorez from Liège (Belgium), there was Prof. Georges Stoops from Ghent (Belgium) who gave an unforgettable course on Soil Micromorphology, and, thanks to Judit (my former MSc student), suddenly and unexpectedly Roger Langohr also turned up. They were working on a project on European loess-related palaeosols for which they visited Hungarian loess sections. I happily volunteered to assist and got acquainted with Roger in the field. That was a true revelation. Roger's attitude towards palaeosols was exactly what I was missing throughout my stay in the US. His approach was truly process-oriented and his way of thinking was exactly that of a geologist. He had a clear concept of time and knew how temporal changes of the environment could or could not be reflected in changes in soil properties. He always stuck to the facts and knew precisely how physics and chemistry (including colloid chemistry) controlled those processes, the results of which can be seen in the soil. As he always said: "*the soil is a book and with the right approach, we might be able to read it and thus understand the story written in it*".

Equipped with Roger's ideas and understanding the advantages of the process-oriented approach, I began to examine a well-studied, but still ambivalent group of palaeosols: those intercalated in cyclic carbonate depositional sequences.

2. Introduction

The study of palaeosols associated with cyclically organised, shallow-marine carbonates dates back to the 19th century. For a long time, they were considered indicators of sub-aerial exposure at the base of individual cyclothems (= Fischer's Lofer-cycles). This exposure was suggested to be the result of astronomically controlled, eustatic sea level oscillations (e.g. Schwarzacher, 1954; Fischer, 1964; and others). Only in the 1980s, their potential to assess the duration of subaerial episodes was realised (e.g. Goldhammer and Elmore, 1984). Through an analogy with modern soils, the degree of development (a soil-maturity index) of pedogenically modified surfaces seemed to be promising. Soil thickness was used first as a measure of maturity, however, several detailed studies revealed that there were other features that could be taken into account when trying to establish a rank exposure index for carbonate palaeosols (Smosna and Warschauer, 1981; Goldhammer and Elmore, 1984; Goldhammer et al., 1990; Strasser, 1991 and others). D'Argenio and Ferreri (1991) found a straightforward relationship between cyclothem packaging, the maturity of palaeosols, and the degree of development of other exposure-related features. The climate signal, potentially recorded by the mineralogy of palaeosols, has also been used by sedimentologists to support climate reconstructions. There was general consent about predominantly argillaceous palaeosols being signs of a humid climate (precipitation>>evaporation), whereas predominantly calcareous ones ('calcretes' for the geologist) pointing to aridity/semi aridity (precipitation<<evaporation) throughout their exposure period (e.g. Wright 1994). More and more detailed studies, however, revealed

that the analogy with modern soils had to be applied with extreme caution. These palaeosols, occurring in cyclically organised shallow-marine carbonate sequences, proved to be much more like sediments than just plain old soils and the climate signal, supposedly preserved by their mineralogy, turned out to be less straightforward than previously expected (Muhs et al., 1990; Foos, 1991). As to the time signal, recalling the irregularities of the sea-level curve, Wright (1996) suggested that even when, theoretically, accepting that each cyclothem represents ~20 kyrs (the Milanković-frequency), the duration of the effective exposure of the sediment surface at cycle-bases could not be more than ~1000 yrs or less. Additionally, he put forward the idea of apparent palaeosol development sometimes being the result of the amalgamation of several successive soil-forming events and suggested that some of these cycle-bound palaeosols could be polygenetic, sometimes even recording climatic change during their development.

3. A case study

3.1. STUDY AREA

Back in the late '90s, two cyclically organised Late Triassic (Rhaetian) carbonate platform sequences of the Gerecse Hills (Transdanubia, Hungary) were selected for a detailed study (Mindszenty and Deák F.J., 1999; Deák, F.J. et al. 2002).

The Kecskekő profile, exposed in a still active quarry close to the village of Lábatlan, was ~41 meters thick and comprised 19 cyclothems and related palaeosols (Fig.1). Vöröshíd, next to the village of Tardosbánya, was ~30 meters thick comprising 16 cyclothems and related palaeosols. The top of both profiles was truncated by submarine bioerosion and the contact surfaces overlain with a hiatus, by Lower Jurassic (Liassic) pelagic sediments. The latest Rhaetian and the earliest Liassic are missing from the succession (Fülöp, 1975; Haas, 2001). No palaeosols could be detected on this contact surface. According to Vörös and Galácz (1998) and Győri (2014), the contact can be qualified as a typical drowning unconformity. However, Győri (2014) presented isotopic geochemical evidence strongly supporting the idea that final drowning might have been preceded by a short subaerial episode.

3.2. AIMS OF THE STUDY

The aim of this research was a high-resolution micropetrographic investigation to:

- contribute to the understanding of the controls of apparent soil maturity in the carbonate depositional environment;
- see whether in the studied palaeosol sequence the climate-signal is separable from the time signal;
- see whether the distribution of soil types in the vertical profile could be interpreted in terms of climate change within the time period presented by the studied sections.

3.3. METHODS

The methods used were:

- detailed field descriptions of the recognised cyclothems and the related palaeosol horizons;
- cm-scale sampling and detailed micropetrographic analysis of 140 thin sections taken from the palaeosol horizons and the enclosing carbonates;
- establishment of palaeosol types;
- qualitative XRD and DTA to check the mineralogy of the clay- and carbonate fractions associated with the exposure surfaces.

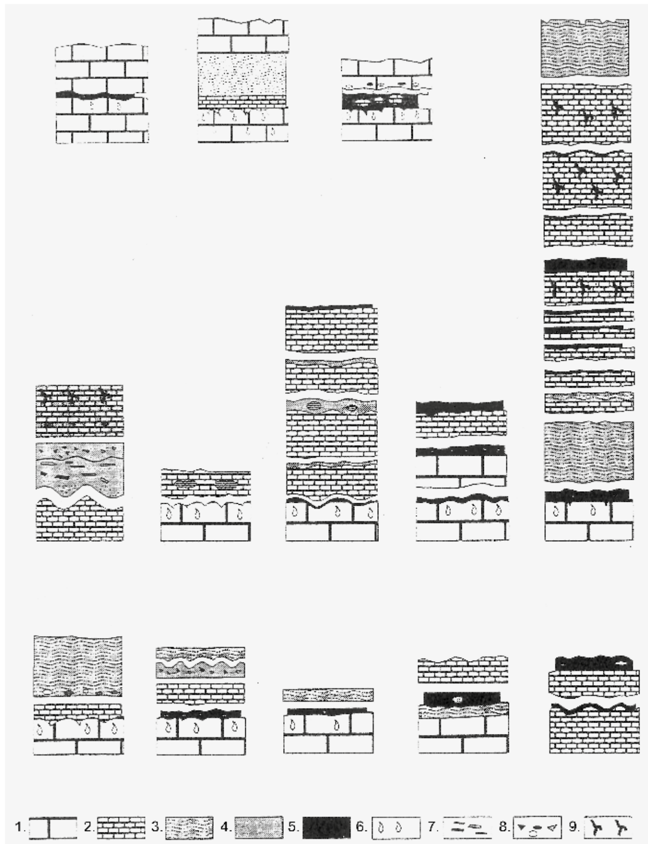

Figure 1. Schematic representation of carbonate-palaeosol profiles recording several exposure events (marked by interruption of the columns) of the Late Triassic Kecskekő (Gerecse Hills, Transdanubia, Hungary), after Mindszenty and Deák 1999.

Legend: 1) subtidal (marine) limestone, 2) mud pond deposit, 3) partially 'calcretised/dolocretised' microbial mat, 4) calcrete/dolocrete, 5) clay 6) microkarst, 7) laminated calcrete/dolocrete, 8) limestone, calcrete, dolocrete fragments, black pebbles 9) rhizolith.

3.4. RESULTS AND DISCUSSION

Soil maturity

The conventional approach based on destratification, clay accumulation, soil colour, and soil-thickness proved to be inadequate to assess the degree of development of the studied palaeosols.

Clay thickness could not be correlated with microkarst features in the substrate, supposedly formed simultaneously with pedogenesis. All clay horizons were rich in silt size detrital minerals (quartz and mica), even though other evidence suggested that there was no substantial erosion to provide for such a voluminous dissolution residue. Therefore, in full accordance with Wright (1994), it was possible to confirm that the clay content is not pedogenic, but airborne. Instead of representing the intensity/duration of pedogenesis, it is rather the measure of dust-deposition that perhaps indirectly provides some hints on the duration of the exposure, as during a longer time span more dust can be deposited.

Soil colour proved to be the most ambivalent. Definite and widespread signs of hydromorphy, apparently arising from early diagenetic overprint during incipient burial, were widely observed in the studied sections. This resulted in the transformation of ferric to ferrous iron and the formation of finely disseminated pyrite, suggesting microbial decomposition of former organic matter in brackish or marine porewaters. Most palaeosols in the sequence are therefore greenish to greyish in colour. However, some of them somehow managed to preserve their original(?) reddish tint, though they apparently were affected by the same burial diagenetic history as the green ones. The only way to solve the problem of this apparent contradiction was to apply the famous 'process-oriented' approach learned from Roger.

We know that soil colour depends on the oxidation state of Fe in the soil. The presence of ferric iron, normally associated with good drainage, results in red soils. However, when reddish coloured Fe^{3+}-oxides are present in a mineralogically unstable form (like e.g. ferrihydrite) they will – as a result of the hydrological change associated with the rise of sea-level – readily react with reducing porewaters and because of the $Fe^{3+} \rightarrow Fe^{2+}$ conversion, the soil colour will change to grey or green.

Good drainage combined with long-enough exposure may result in the mineralogical stabilisation of Fe-oxides during the subaerial period, and in this case, as the result of prolonged exposure, a red colour may survive even in shallow burial.

Poor drainage results in hydromorphy and hydromorphic soils that are relatively rich in organic matter and poor in Fe^{3+}, their colour is originally grey or green and this colour of course survives during shallow burial.

Whether palaeosols are well-drained red or hydromorphic grey/green in a cyclic carbonate sequence depends on how far below the platform top the relative sea level drops and how fast it rises again. The reason for this is that the eventual redoximorphic overprint of an originally red (well-drained) palaeosol under conditions of a rising sea level is ultimately controlled by the degree of mineralogical stability of Fe-oxides in the soil, which is controlled by the duration of exposure. Unstable Fe-minerals react with hydrological change, while those already stabilised by the time of re-submergence preserve their original structure and colour during early and also during a later shallow burial diagenesis.

Soil thickness as an indicator of maturity is also ambivalent and, therefore, received special attention. By definition, soil thickness includes the topsoil and the underlying pedogenic altered, homogenised, or horizonated substrate. In a carbonate depositional environment this includes all karst features formed simultaneously with pedogenesis. Due to the repeated and profuse phreatic-lens related micro-karst pervading the whole sequence, it is difficult, if not impossible, to distinguish between micro-karst features that belong exclusively to one or the other of the superimposed palaeosol levels.

Micropetrography revealed that the thickest exposure horizons are not the most mature ones. Rather, they consist of a series of moderately to very weakly developed palaeosols formed on the surface of muddy supratidal pond-type sediments and they represent stacked ephemeral exposure surfaces. This way, instead of representing a single long-lasting soil-forming episode, the thickest exposure horizons record a long-lasting period during which the groundwater table was more-or-less coincident with the sediment surface. Furthermore, due to the oscillations of the groundwater table, a system of alternating supratidal pond-type sedimentation and pedogenic alterations could be maintained for a long time. This particular set of conditions resulted in the (observed) almost continuous inter/supratidal aggradation. Similar successions of weakly developed palaeosols that occur in Devonian alluvial environments are called 'cumulates' by Wright and Marriott (1996). They are close equivalents to Roger Langohr's 'soil-sedimentary complex', introduced for Quaternary palaeosols. They form when the sedimentary increments added to a soil profile are thinner than the horizons of the developing profile would be. In this way, the sediment becomes digested by pedogenesis and the profile gradually migrates upward.

3.5. SOIL TYPES AND THE CLIMATE SIGNAL

Based on mineralogy, macro-, and micropetrography, the following major groups of palaeosols could be distinguished in the investigated sequences.

Simple clayey

Generally, greenish/grey clay that overlays eroded subtidal carbonate facies, characterised by minor microkarst and covered by subtidal facies. The clay lacks both pedofeatures and/or limestone fragments. Laterally it may pass into stylolites (pressure solution features related to burial diagenesis).

Interpretation: single exposure of short duration. Supposed origin of clay: airborne dust settled on the exposed surface; no particular climatic significance.

Simple, calcareous

A thin layer of supratidal pond-type sediment covers the subtidal substrate. It is overlain by vaguely laminated calcrete, with or without thin clay intercalations and sometimes well-developed root molds. The subtidal substrate is affected by minor to moderate microkarst, often with pendant cement.

Interpretation: moderate length of exposure, brought about by a single oscillation of the sea level, but not accompanied by significant dust-transport. Climate: probably semi-arid, evaporation>precipitation.

Simple, mixed (clay + calcrete)

Brecciated, clayey with cm-size hard carbonate clasts, black pebbles, root molds and a thin calcrete cap on top. It is accompanied by moderately to well-developed microkarst, often with distinct cm-scale karst topography.

Interpretation: relatively long exposure (possibly comprising more than one high frequency sea level oscillation), accompanied by considerable air-born dust deposition, promoted by abundant rainfall; prolonged humidity. Climate signal: ambiguous (humid rather than arid).

Composite, mixed (clay < sediment < calcrete)

Thin clay blanket followed by laminated, brecciated, or massive calcrete with intraformational erosion surfaces. Karstification of the substrate variegated. ('Composite' is used in the sense of Wright (1992) i.e. '*merging superimposed soil profiles*').

Interpretation: Long exposure, possibly comprising several high frequency sea level oscillations, or interruption of the ephemeral low-supratidal pedogenesis by autocyclic events (e.g. storm-tides). Climate signal: ambiguous.

Cumulate mixed (clay < sediment > calcrete)

Predominantly calcareous with micritisation/melanisation, intraclasts, calcrete clasts, root molds, wispy clay-seams and microkarst ('cumulate' is used in the sense of Wright and Marriott, 1996). It rests on moderately karstified subtidal lithologies, first blanketed by a thin clay film. On the top, there is a thin clay-film beneath the covering subtidal sediments. It is interesting that calcretes and karst features are not mutually exclusive in this type of profiles, either in space or in time.

Interpretation: slowly aggrading soil-sediment complex brought about by the stacking of repeated ephemeral episodes of supratidal to high-intertidal sedimentation and pedogenic alteration, suggesting long-lasting development in close-to-sea level position. They are thought to be the result of a delicate balance between steady platform-subsidence and (several) high frequency sea level oscillations superimposed on a likewise steady, lower-order fall of sea level. The obviously changing clay content may be the result of episodically changing dust-supply. Alternation of more calcretised and more intact, clayey sublayers may reflect either high frequency climate-oscillations

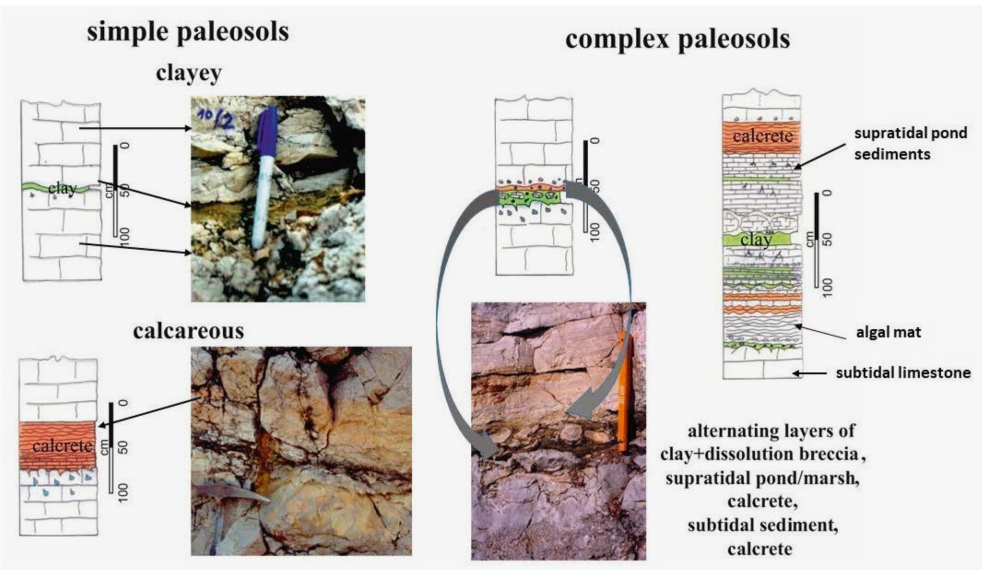

Figure 2. Selected examples of carbonate-related palaeosol-types recognised in the Gerecse Hills Triassic (Transdanubian Range, Hungary).

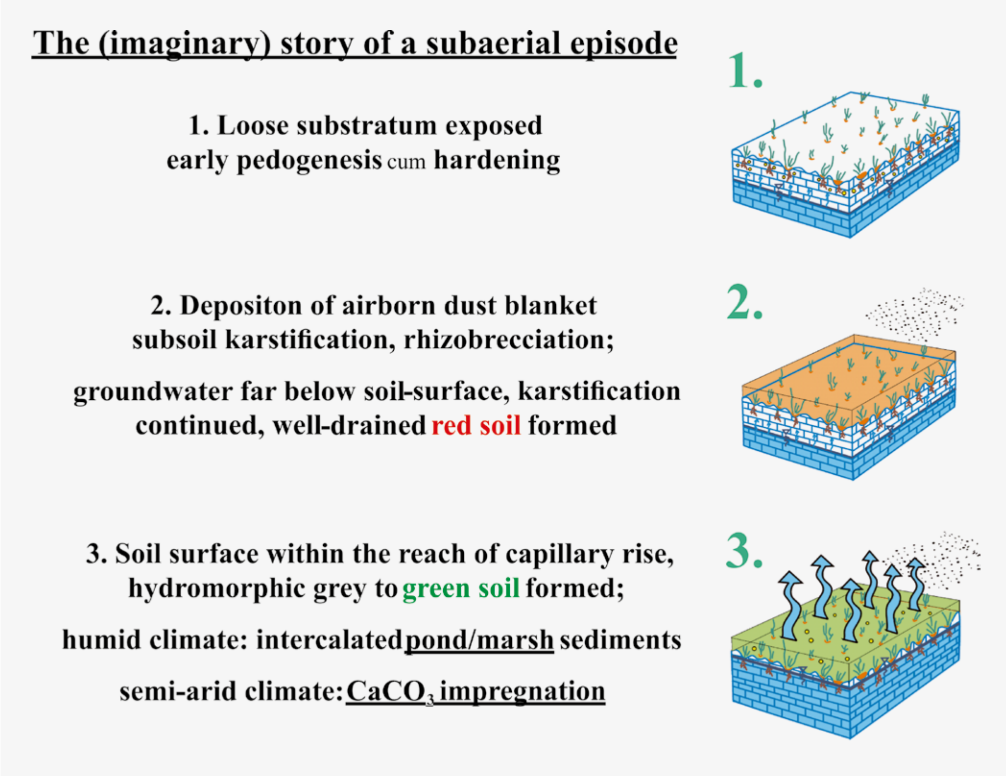

Figure 3. Illustration showing the imaginary story of a subaerial episode in the peri-tidal carbonate depositional environment.

between the humid and arid extremes during the suspected long interval, or it could record the changes of the soil-moisture regime (a combined effect of climate and a changing sea level). Climate signal: ambiguous.

Steady co-occurrence in these cycle-bound palaeosols of calcretes and clays *cum* karst, considered antithetic in terms of climate, obviously require an unorthodox explanation.

It is suggested here, that the calcrete-clay-calcrete succession, accompanied by micro-karst, observed in most of the studied palaeosols is not the result of climate change (arid-humid-arid) during the subaerial episode (as proposed by Vanstone, 1996). Instead, it may simply be the result of the change of the soil moisture-regime caused by the oscillation of the groundwater table concomitant with sea level change. When the water table is high enough for groundwater to reach the surface by capillary action and the climate is at least seasonally arid (= amphipercolative system of Yaalon, 1983), evaporation may easily provide elements for the formation of laminar calcretes, particularly when that groundwater is slightly saline (as it is in a coastal position when the sea level is high). On the other hand, when the groundwater table is far down (i.e. at times of a sea level low stand), moderate karstification may, indeed, occur in the fresh-water vadose-zone.

4. Conclusions

In a shallow-water carbonate-platform environment

1. the apparent thickness of palaeosols is not necessarily time-proportional;

2. the clay content is not proportional to soil maturity and cannot be taken as a direct indication of a humid climate. Most of the clay is not pedogenic in origin, but probably wind-born;

3. the secondary carbonate enrichment is not necessarily a sign of high aridity. It may just be an indication of a slight seasonal surplus of evaporation in a soil/sedimentary environment, where any porosity is filled with saline groundwater;

4. the structure of the soil profiles cannot be interpreted simply in terms of pedogenesis. Most of the palaeosols of the intertidal to low-supratidal carbonate environments, particularly the composite and cumulate ones, include a great deal of sedimentary aggradation, and are equivalents of R. Langohr's soil-sedimentary complex.

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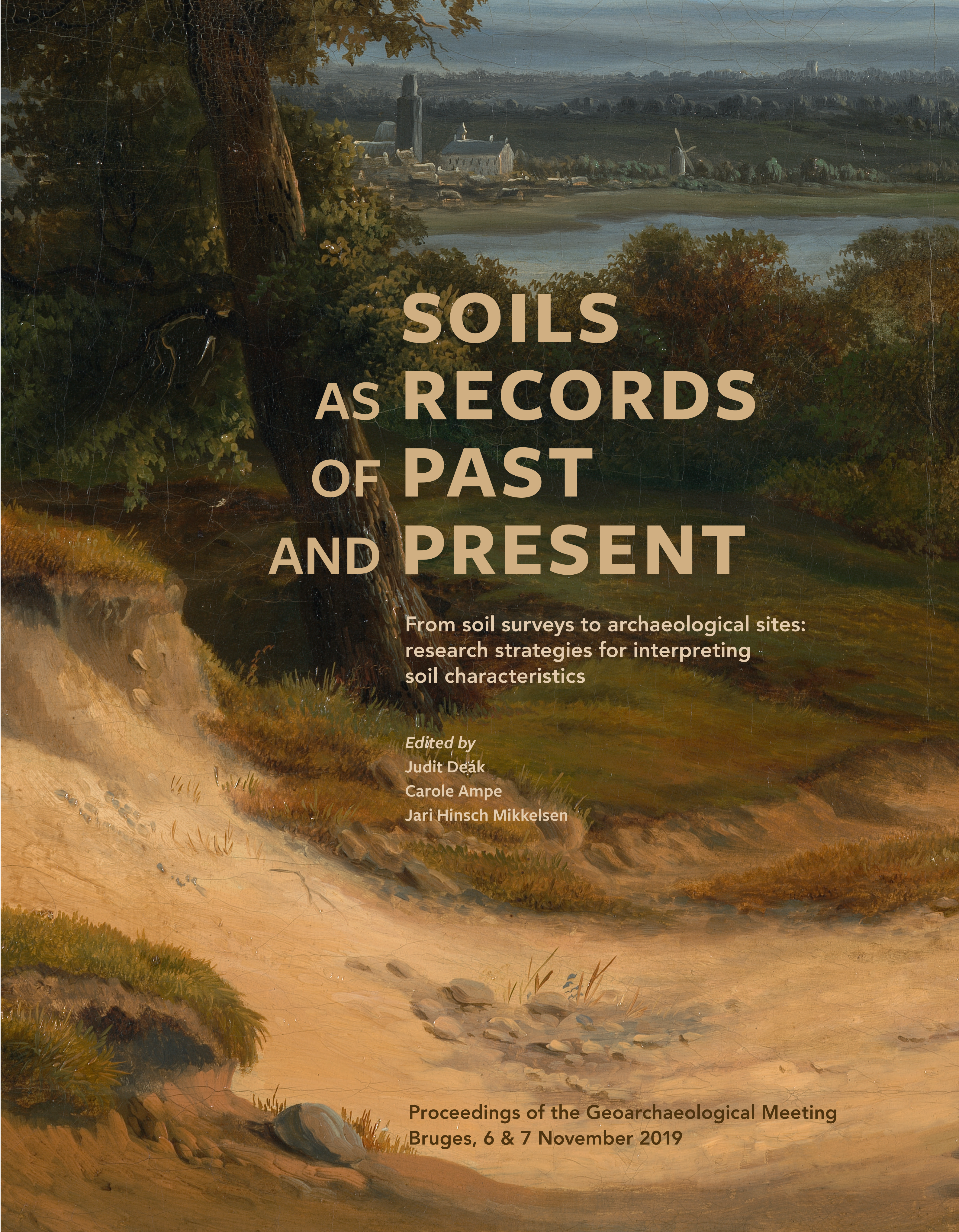

SOILS AS RECORDS OF PAST AND PRESENT

From soil surveys to archaeological sites: research strategies for interpreting soil characteristics

Edited by
Judit Deák
Carole Ampe
Jari Hinsch Mikkelsen

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