Response of pedogenesis to Holocene climate change in Southern Arabia

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Abstract

Pedostratigraphic and soil morphological data show a well-preserved and wide spread palaeosol at the southwestern margin of the Ar-Rub' al-Khali, Ma'rib, Yemen. The marker horizon of the buried soils is considered as a new proxy of Holocene climate change that is characterised by alternation of e.g. low and high precipitation. The humic palaeosol mainly represented by Ahb and ABb horizons indicates soil development in a more humid climate during the Early Holocene in Southern Arabia as compared to overlying sediments (cover sediments). These cover sediments are obviously a result of increasing aridity from 5800 to 5950 yrs BP on. The early Holocene palaeosol is characterised by AMS ^{14}C, soil chemical and geochemical data. The pedogenic status quo of this palaeosol is a very important proxy for the interpretation of regional palaeoclimate fluctuations and of the southward shift of the ITCZ in Southern Arabia.

Key Words

Holocene palaeosol, pedogenesis, ITCZ, AMS radiocarbon data, Yemen

Introduction

Holocene climate change on the Arabian Peninsula is characterised by well-known fluctuations of both moisture and aridity (Mayewski *et al.,* 2004). Particularly the variability of the monsoonal climate and the shift of the Intertropical Convergence Zone (ITCZ) were in focus of recent research on dune activities (Bray and Stokes, 2004), playa like sediments (Fuchs and Buerkert, 2008), faunal assemblages of interdunal deposits (Radies *et al.,* 2005) and the geochemistry of lacustrine sediments (Parker *et al*., 2006) in southeastern Arabia. High resolution palaeoclimate information is available from speleothem records in Oman (Fleitmann *et al*., 2007) and from Socotra (Shakun *et al*., 2007) as well as from marine sediment records in the Northern Arabian Sea (Sirocko *et al*., 1993). In southwestern Arabia data of lacustrine response to a period of increased precipitation between 12 ka and 7.5 ka BP come from sediments of palaeolakes in the Ramlat al-Saba'tayn (Lezine *et al.,* 2007) and from Lake Mundafan situated more northerly in the Ar-Rub' al-Khali (McClure, 1976). Longer lasting lacustrine phases may correlate with geomorphodynamic stable phases and, therefore, with phases of soil development.

Early to Mid Holocene palaeosols in the central Yemen Highlands, Yemen (see Figure 1) were dated to the period from 7300 to 4290 cal yrs BP (Wilkinson, 1997; Davies, 2002).

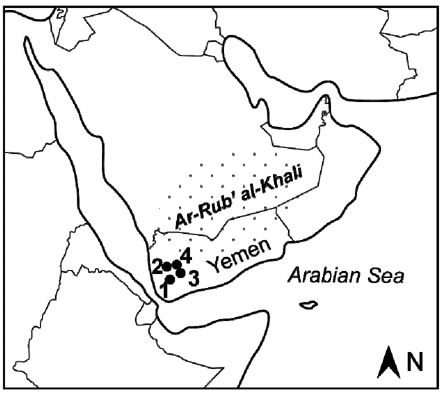

Figure 1. Location of soil investigation sites in Yemen (1 Wilkinson, 1997, Davies, 2002; 2 De Maigret *et al*., 1989; Brinkmann, 1996; 4 this paper).

A palaeosol in Wadi At-Thaylah (Khawlan), dated at 5700 to 5500 cal yrs BC (De Maigret *et al*., 1989), indicates pedogenesis in the eastern Yemen highlands during the moist Early Holocene. Palaeosols with comparable ages were found in Wadi Al-Jubah area, southeast of Ma'rib, dated at 6400 to 5500 cal yrs BC (e.g. Brinkmann, 1996).

In the context of archaeopedological research buried palaeosols dated to the Early Holocene were recently found around Ma'rib at the southwestern margin of the Ar'Rub al-Khali (Pietsch *et al*., 2010; Kühn *et al*., 2010).

Methods

Soil description followed the FAO Guidelines (FAO, 2006). Soils were classified after WRB (IUSS-Working Group WRB 2007). Layer identification followed Ollier and Pain (1996) and substrate classification Pietsch and Lucke (2008). Soil analysis was carried out after Blume *et al*. (2000). Major and trace elements were measured by XRF (Zschornack, 2007). Existence of allophane was proved by NaF method (Fieldes and Perrott, 1966). Colours have been classified by Munsell colour charts (2000). For selected soil physical and chemical data refer to Table 1. Radiocarbon data were obtained by AMS from humic acid and minute gastropods. Little carbon-reservoir effects of those molluscs yield reliable ^{14}C ages and are therefore suitable for constraining the ages of sediments in which they occur (Pigati *et al*., 2004).

Results

In the surrounding of Ma'rib Oasis a buried palaeosol with Ahb (sometimes ABb) horizon is widely spread. The palaeosol - visible as a humic marker horizon - represents an old land surface and is covered by a stratified cover sand with an average thickness of 40 cm and no sign of soil formation. At most sites a desert pavement is developed and embedded in a vesicular Av horizon on top of the cover sediment (cf. McFadden *et al.,* 1998). The Av horizon is 5 to 10 cm thick and occurs on many sites around the oasis of Ma'rib. The stones of the desert pavement have a blackish desert varnish on the upper side and are lighter coloured at the lower side. In the Ahb or ABb horizon below the cover sediment rhizolithes occur, which are described as former root channels, often calcified and holding organic remnants (Klappa, 1980). Yet they do not have visible signs of secondary calcifications and fall apart by soft pressure in our study areas. Some of the soil horizons reveal even a structure after these root pseudomorphs implying a dense vegetation cover or a long period of vegetation. Similar root pseudomorphs were described so far only within irrigation sediments of the Sabaean time (Brunner, 1982).

AMS ^{14}C- data

Buried soils have been dated at 8000 to 4500 cal yrs BC (ERL, Hv). Radiocarbon ages of humic acid correlate well with ^{14}C-ages of mollusc shells, mainly of *Pupoides coenopticus* and *Zootecus insularis*. The potential for incorporation of old carbon from ground water during shell formation in these minute molluscs (i.e. carbon-reservoir effects, Pigati *et al*., 2004) can be regarded as little in the Ma'rib region, since substrates of soils are aeolian sediments with low carbonate content. They do not occur in direct contact to Jabal Balaq, a ridge of Jurassic limestone.

Soil physical and chemical data

The layering can be easily noticed in the vertical grain size distribution of single profiles (Table 1). Sandy cover sediments can clearly be distinguished from more silty-clayey sediments wherein the palaeosol is formed. Grain size quotient Q (sum 630–63 µm sand fraction/sum silt fraction) clearly marks the boundaries between soil layers. Organic carbon contents of the buried soils reach 0.6 %, plant available phosphate contents 200 mg/kg in some soils.

Table 1. Grain size distribution and soil chemistry of a buried soil (Mat03, ND not determined).

Horizon	Depth (cm)	2000-630 µm	630-200 µm	200-125 µm	125-63 µm (%)	63-20 µm	20-6.3 µm	6.3-2 µm	<2 µm	Q	C_{org} (%)	PO_4 (mg/kg)	TiO_2/Zr
C	0-10	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2Cw	10-25	5.4	5.4	10.4	44.0	19.4	5.6	3.5	6.3	2.1	ND	126	23
3Cw	25-43	4.0	4.6	10.1	40.5	20.3	7.3	3.7	9.5	1.8	0.21	125	24
4Ahb1	43-60	3.3	6.1	7.2	32.4	20.0	10.2	5.3	13.4	1.3	0.58	135	28
4Ahb2	60-85	4.9	3.2	6.8	34.8	22.6	9.1	4.9	13.7	1.2	0.42	102	29
4Ck1	80-100	0.4	2.0	6.5	40.6	29.3	7.4	4.8	9.0	1.2	0.40	64	25
4Ck2	100-125	0.9	1.7	4.1	33.3	36.2	9.3	5.1	9.3	0.8	ND	ND	25
5Ckm	125+	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Geochemistry
Minor and major elements have been taken into consideration to detect soil layering. TiO_2/Zr quotients show significant changes of contents of rather immobile heavy minerals from fluvial loams (3Cw) to those of mixed aeolian and aquatic sediments and volcanic ashes (4Ahb).

Conclusions
Pedostratigraphic position and properties of the marker horizon imply *in situ*-soil formation at all sites. It may serve therefore as a tool to refine the over-regional interpretation of the proxy climate data (marine and speleothem) on a regional or even local scale.
The Early Holocene palaeosol in Ma'rib region was formed until around 7500 yr BP representing an Early Holocene moister period. Between 5800 and 7500 yrs BP the soil was covered by sandy-gravelly sediments. Desert varnish developed on stones on top of cover-sediments formed a desert pavement over time. The cover sediments show no signs of pedogenesis corroborating arid and dry climate conditions after its formation. Pedogenic processes would have destroyed sedimentary layering. Events with intense precipitation may have caused the development of cover sediments most probably formed as a result from sheet wash.
Based on the fact of an abrupt discontinuity between the cover sediment and the buried palaeosol as well as lacking signs of pedogenesis we infer an arid climate after the formation of the cover sediment, i.e. after around 5800 yr BP. Therefore we assume a southward retreat of the ITCZ and the associated zone of rainfall to the Yemen highlands at 15°N at that time. Only single outriders of the ITCZ to the north may have caused rainfall in the southwestern desert margin of the Ar'Rub al-Khali.
On the other hand, fluctuating climate conditions, evident at the southwestern margin of the Ar-Rub' al-Khali, contribute better understanding to the timing of pedogenic response to Holocene moisture changes at the desert margin in Southern Arabia.

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