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Published in:
Quaternary International

DOI:
10.1016/j.quaint.2016.12.037

Publication date:
2018

Citation for published version (APA):
Laermanns, H., Kelterbaum, D., May, S. M., Elashvili, M., Opitz, S., Hülle, D., Rölkens, J., Verheul, J., Riedesel, S., & Brückner, H. (2018). Mid-to Late Holocene landscape changes in the Rioni Delta area (Kolkheti lowlands, W Georgia). *Quaternary International*, *465*(Part A), 85-98. https://doi.org/10.1016/j.quaint.2016.12.037

Mid- to Late Holocene landscape changes in the Rioni Delta area (Kolkheti lowlands, W Georgia)

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Abstract

The Kolkheti lowlands (Colchis, Colchian plain) form the central part of the extensive coastal lowlands along the Black Sea coast of Georgia. Situated between the Greater and the Lesser Caucasus, favourable climatic conditions resulted in a constant human occupation of the region during the Holocene. However, due to continued deltaic sedimentation and alluviation of the river Rioni, the configuration and the environmental conditions of the coast and its hinterland have changed considerably; this was related to sea-level fluctuations of the Black Sea and variation of the sediment supply. This study presents new data on the Holocene coastal evolution of Western Georgia. Based on the geochemical and sedimentological analysis of sediment cores and trenches from the northern part of the Kolkheti lowlands, between the Black Sea and the rivers Rioni and Khobistsqali, and a robust chronology (^{14}C and IRSL dating), our goals are (i) to document the chronostratigraphy along two coring transects; (ii) to decipher geographical and environmental changes along Georgia's Black Sea coast; and (iii) to trace the sea-level evolution of the study area. Based on the succession of eight facies, representing different depositional environments, our results suggest that significant environmental changes took place throughout the last eight millennia. At least since 5000 cal BC, the sedimentary record indicates the widespread existence of shallow lagoons. Floodplain-related fine-grained alluvium accumulated on top of the lagoonal stratum. The progradation of the delta plain between 3500 and 1500 cal BC was accompanied by the evolution of extensive swamps with peat formation. The data indicate a gradual and moderate sea-level rise since ~6000 BC. Ultimately, this and follow-up studies may provide a valuable background for the understanding of the palaeogeographical context of ancient settlements in the area.

1 Introduction

With an area of ca. 412,000 km² and a maximum depth of 2,212 m the Black Sea is the largest anoxic water basin in the world (Degens and Ross, 1972). It is connected to the Mediterranean via narrow and shallow straits (Bosporus, Dardanelles). Over the last millennia, the Black Sea has been subject to substantial environmental changes. In effect, from a giant freshwater lake during the Last Glacial Maximum (Panin and Popescu, 2007) it evolved to its present state of salinity and sea level. While some authors have evoked for remarkable oscillations of the postglacial sea-level rise (e.g. Ryan et al., 1997, 2003; Chepalyga, 2007; Yanko-Hombach et al., 2007; Balabanov, 2007), a number of follow-up studies reasonably challenged this interpretation by presenting new data on the Holocene sea-level evolution (cf. Brückner et al., 2010; Fouache et al., 2012; Kelterbaum et al., 2012). Recent studies have particularly focused on the northern and western parts of the Pontic region (e.g. Panin, 2007; Carozza et al., 2011; Cordova et al., 2011). In contrast, the eastern Pontic region has been neglected so far, although extensive lowlands exist, for instance along the Black Sea coast of Georgia. Here, protected between the Greater and the Lesser Caucasus, human occupation is evidenced in the so-called Colchian plain (Colchis) at least since the Late Chalcolithic and Early Bronze Age (Lordkipanidze, 1991; Papuashvili, 2002). In addition, as part of ancient Colchis, the famous Greek colony of Phasis is assumed to be located in the area of the present Rioni delta (Gamkrelidze, 1992, 2012; Lordkipanidze, 2000; Korenjak, 2003), although remnants of the city have hitherto not been discovered, and its exact position unknown (Lordkipanidze, 1991; Gamkrelidze, 2012). The lack of studies focussing on the coastal evolution, sea-level and environmental changes, particularly against the background of the continuous occupational history in Western Georgia (Gamkrelidze, 2012), demands an intensification of research activities in this area.

This paper contributes to fill knowledge gaps by adding new information on Holocene environmental changes in the Kolkheti lowlands, which constitute the central part of the Colchian plain. Based on eleven sediment cores, two sediment trenches, detailed sedimentological and geochemical analyses, as well as radiocarbon and infrared stimulated luminescence (IRSL) dating, our study presents the first systematic geoscientific investigation of the said coastal lowlands. More specifically, we aim at (i) documenting the chronostratigraphy between the Rioni and Khobistsqali rivers along two coring transects; (ii) deciphering palaeogeographical and palaeoenvironmental changes along the Georgian Black Sea coast and its hinterland; and (iii) reconstructing the sea-level evolution for the study area, and comparing it to other regional studies. Finally, this study represents a valuable background for the interpretation of (future) local to regional archaeological studies, e.g. on the identification of appropriate locations for the 'lost city' of Phasis.

2 Regional setting

2.1 Geological and geomorphological framework

The triangle-shaped Colchian plain (Fig. 1) is framed by the Black Sea in the west, the Greater Caucasus in the north and the Lesser Caucasus in the south. Both mountain ranges formed during the Alpine orogeny as a consequence of continent-continent-collision starting in the middle Pliocene (e.g. Adamia et al., 2011). They consist of Mesozoic to Neogene igneous and sedimentary rocks and, especially in the Lesser Caucasus, of Miocene to Quaternary volcanic rocks. In the east, where both mountain ranges meet, the Surami range (or Likhi range) separates the Colchian plain from the Kura basin, which drains into the Caspian Sea. The geologic basement of the Colchian plain mainly consists of Cretaceous and Palaeogene sediments and volcanoclastics (Bazhenov and Burtman, 2002). These strata are overlain by Quaternary strata, which were deposited by fluvial and marine processes (Adamia et al., 2011). The Colchian plain is influenced by tectonic subsidence. Gamkrelidze (1998) estimates subsidence rates of 2-4 mm/a for the central Colchian plain and 5-6 mm/a for the area around Poti near the outlet of the Rioni.

While foothills of both mountain ranges reach the Black Sea coast south of Kobuleti and north of Ochamchire, respectively, the floodplain of the Rioni dominates the Kolkheti lowlands. With a catchment area of 13,400 km^2 it is the largest river of Western Georgia. Most of its tributaries originate in the Greater Caucasus and dissect extensive foothills before entering the coastal lowlands. Here, expanded wetlands with peat bogs, ponds, open reed areas and low forests dominate; agricultural activities are impeded by the high water-table position. However, drainage measures and ridge and furrow systems enable agriculture between and along the two rivers (Nikolaishvili et al., 2015).

At the coast, the Rioni has formed a wave-dominated delta (Fig. 1), where longshore drift rapidly redistributes the mostly sandy sediments along the graded shoreline. The flat and wide beaches are backed by beach-foredune ridges, which are occasionally covered by pine forests. The main estuary of the Rioni, formerly debouching into the sea directly in Poti, was relocated to its present position during the Soviet era.

2.2 Palaeoenvironmental changes and sea-level fluctuations

Even though a number of studies on the Holocene landscape evolution exist from the second half of the 20^{th} century (e.g. Janelidze, 1980), most data from the Soviet era is difficult to access. During the last 25 years only a few publications provide valuable information on Holocene environmental development, with main focus on the vegetation history of Georgia's Black Sea coast since the mid-Holocene (e.g. Connor et al., 2007; de Klerk et al., 2009; Shatilova et al., 2010). Palynological records document a coastal plain vegetation and generally outline warm and humid conditions; however, while Connor et al. (2007) describe a gradual evolution from chestnut-dominated open woods in the Mid-Holocene followed by shrubby marshy landscapes and, caused by groundwater fluctuations due to coastal subsidence and sea-level changes, recent beach-hornbeam conditions, de Klerk et al. (2009) highlight a relatively constant vegetation history with only minor effects of anthropogenic land use change. Other studies investigated the degree of anthropogenic landscape changes, e.g. deforestation (Nikolaishvili et al., 2011), human-induced landslides (Nikolaeva et al., 2014; Vezolli et al., 2014), and soil contamination (Narimanidze and Brückner, 1999; Svanidze et al., 2008). Several geoarchaeological projects have been carried out concerning the environs of archaeological sites – e.g. the anthropologically famous Dmanisi (Messager et al., 2009; 2011); Bronze age settlements on the Bedeni Plateau (Kvavadze et al., 2015) – as well as the analysis of fluvial archives (von Suchodoletz et al., 2015).

The Holocene reconnection of the Black Sea with the Mediterranean Sea occurred around ~7400–6400 cal BC (Ryan, 2007; Giosan et al., 2009; Lericolais et al., 2009; in a previous publication a date of ~5500 cal BC had been suggested by Ryan et al., 1997). Several studies were dedicated to the subsequent sea-level rise, for which both a steadily rising (Hiscott et al., 2002; Giosan et al., 2009) and an oscillating (Balabanov, 2007; Chepalyga, 2007; Yanko-Hombach et al., 2007) curve were proposed. Based on his evaluation of ~400 radiocarbon ages from Black Sea coasts, Balabanov (2007) suggested several major regression-transgression cycles for the Holocene period. This interpretation was strongly opposed. Brückner et al. (2010) presented evidence for a gradual sea-level rise; they attributed the assumed regression-transgression wiggles of the Balabanov curve to local neotectonics and a misinterpretation of the data set (see also Kelterbaum et al., 2012). Especially the concept of the so-called Phanagorian Regression, which was postulated for the time span ~800 BC to ~500 BC, i.e. for the time when the Greek settlers had founded many coastal colonies in the Black Sea region, was rejected (Fouache et al., 2012).

For the Kuban delta plain (Taman Peninsula, Russia), Brückner et al. (2010) proposed a gradual sea-level rise from 7 to 6 m below present sea level at 5000 BC to ~2 m below sea level at 2000 BC, and a subsequent decelerated rise until today. For the Danube delta region, Giosan et al. (2006) assume a stable (± 1.5 m) sea level over the last 5000 years, based on morphodynamic and palaeogeographic data. As in other study areas, the local sea-level evolution is assumed to have influenced both sedimentation patterns and settling activities in Western Georgia as well.

2.3 Human occupation and archaeological background

In the Colchian plain, findings of Lower Palaeolithic (~12000 BC) tools indicate a long occupation history of the Kolkheti lowlands (Fähnrich, 2010). Although the transition from hunter-gatherer communities to a pastoral and agricultural sedentism is supposed to have taken place in the Neolithic (8^{th} to 5^{th} millennium BC) only few of these sites are known to date. Increasing numbers of settlements are know from the Late Chalcolithic and Early Bronze Age, the latter beginning in the first half of the 3^{rd} millennium BC (Lordkipanidze, 1991; Fähnrich 2010). Henceforth, settlement mounds occur in the northern part of the Kolkheti lowlands, which represent typical dwelling places of the Bronze Age society in Western Georgia (Jibladze, 2007; Fähnrich, 2010; Gamkrelidze, 2012). In the first half of the 2^{nd} millennium BC, the Colchian culture was formed, which was accompanied by an advance of technical innovations. It merged into the Kingdom of Colchis with a cultural heyday in the 8^{th} century BC (Lordkipanidze, 1991). At the same time, ancient Greek merchants reached the Black Sea area and founded several colonies along the Colchian coast. Early cultural exchange (supposedly originating from Mycenaean time) is likely reflected in the saga of the Argonauts, in which the Colchis is praised for its metal (particularly gold; 'Golden Fleece') works and its prosperous society (Lordkipandize, 1991).

The city of Phasis represents the most important ancient Greek colonial foundation in the Colchian territory. It was described by various ancient authors such as Strabo, Pliny the Elder, Pseudo-Scymnos, Pseudo-Scylax and Hippocrates. It was probably situated in the Rioni delta close to Lake Paliastomi (Fig. 1) (Gamkrelidze, 1992, 2012; Lordkipanidze, 2000; Korenjak, 2003). However, while the location of ancient Phasis has been related to ruins of a Roman fort (Montpéreux 1842) which existed until the construction of the former airport of Poti, remnants of the city hitherto have not been discovered, and its exact position remains unclear.

3 Methods

3.1 Field work

Our research is based on eleven sediment cores and two trenches, organized in two transects (transect A: general direction W – E; Figs. 1–3, 5; transect B: general direction N – S; Figs. 1, 3–6). Corings were done with the Cobra TT (Atlas Copco) percussion coring device. The sediment cores reached a maximum depth of 12 m below surface (b.s.), while core diameters were 6 and 5 cm, respectively. The trenches reached 2 m b.s. Field documentation included the description of sediment texture, colour, and the $CaCO_3$ test (with HCl, 10%). Samples were taken from the different sedimentary units, and at regular spacing intervals of 30-50 cm.

Three master cores which are representative of the study area were analysed in detail: Core KUL 3 (Fig. 2) represents the sand-dominated stratigraphy close to the recent shoreline and is situated in the direct vicinity of trench KUL 2 in the slope of the easternmost beach-foredune ridge facing the swampy hinterland. Cores KUL 7 and PAPO 2 represent the typical depositional sequence of the coastal hinterland. KUL 7 (Fig. 3) is situated in the eastern central part of the swamp, ca. 100 m north of the Tsiva river, an artificial drainage channel which crosses the swampy lowlands from southeast to northwest. Core PAPO 2 (Fig. 4) is located close to the Rioni, some 7 km south of KUL 7. From the three master cores, plant fragments and charcoal remains were taken for radiocarbon dating. The two trenches, KUL 1 and KUL 2 (Fig. 5), were dug on top of the most landward lying beach-foredune ridges just north of the Rioni river mouth.

The elevation of cores and trenches was measured by using a Topcon Hiper V DGPS with a spatial resolution of 2 cm. Soviet topographic maps (1:25,000 scale, approx. 1960s; 1:50,000 scale, approx. 1970s) served for supplementary information on surface changes over the last decades.

3.2 Geochemical and sedimentological analyses

They were conducted at the Geo-Laboratory of the Institute of Geography, University of Cologne. All samples were dried at 40 °C for 48 h, sieved to <2 mm, and gently pestled by hand for aggregate disintegration. Granulometric analyses were conducted for the fine-grained fraction (<2 mm) of all samples using a Laser Diffraction Particle Size Analyzer (LS 13320 Beckmann Coulter$_{TM}$). Samples were pre-treated with hydrogen peroxide (H_2O_2 15 %) to remove the organic matter, and sodium pyrophosphate ($Na_4O_7P_2$, 46 g/l) was added as a dispersant to avoid coagulation. Each sample was measured three times using the optical Fraunhofer model. Grain-size parameters based on Folk and Ward (1957) were calculated using GRADISTAT software version 8 (Blott and Pye, 2001).

Loss on ignition (LOI) was determined by oven-drying of 5 g sample material at 105 °C for 12 h and ignition in a muffle furnace (Carbolite ELF) at 550 °C for 5 h. Although possible uncertainties may result from the combustion of clay minerals and/or carbonates, LOI was used for estimating organic carbon contents in the sediments (Barsch et al., 2000; Heiri et al., 2001).

Furthermore, the samples of core KUL 7 were analysed for their C/N ratio using the method described by Meyers and Teranes (2001). Total organic carbon (TOC), total carbon (TC), and nitrogen (N) were determined on duplicate powdered samples using a Vario EL Cube (Elementar Analysensysteme GmbH, Hanau, Germany). Before measurement the material was homogenized and weighed out into tin boats. In a second aliquot of each sample $CaCO_3$ was dissolved with 10 % HCl, before TOC was determined.

In addition, selected samples were analysed for their mineral composition by X-ray diffraction (XRD; cores KUL 3 and 7; Fig. 7C) and for their element contents by X-ray fluorescence (XRF; cores PAPO 2, KUL 3 and 7). The material was homogenized using an automatic ball grinder (Retsch MM 400), pressed into 2 mm thick pellets, and measured with a portable XRF analyser (NITON XL3t). Each sample was measured three times in mineral mode for 160 sec to cover all possible filter options with an adequate time span. In case of the elements K, Ca, Fe, Mn errors were below 1 %, in case of S below 4 %. For XRD analysis, the homogenised powder was placed on a PVC slide and measured in a Powder X-Ray Diffractometer (Siemens D 5000) with a fixed focal distance of 0.5 mm. All samples were measured at 5-75° 2Θ in 0.05° steps and 10 sec per degree (Cu-K-alpha radiation source, operated at 40 keV and 40 mA). The data were analysed using the DiffracPlus EVA software package (Bruker AXS, Berlin, Germany).

To distinguish the different facies two forms of visualisation were chosen. For the principal component analysis (PCA; Fig. 7A) the PAST software (version 3.1.1) was applied (Hammer et al., 2001). The values were standardized and standard deviation was calculated. Altogether eight components (contents of K, Ca, Fe, Mn, LOI mud and sand, and sorting) were used. The spatial distribution bases on the principle components 1 and 2. The ternary plot (see Brumsack, 1989; Dellwig et al., 2000; Fig. 7B) was evaluated with the Grapher 9 software and predicates on the standardized values of mean grain size, sorting and Ca/K ratio.

Finally, six samples of core KUL 12 were analysed for their microfaunal content. Samples were sieved into fractions of >100 µm and 63-100 µm after adding sodium pyrophosphate ($Na_4O_7P_2$, 46 g/l) to avoid coagulation. Species determination was carried out under a light stereo microscope.

3.3 Dating techniques

Thirteen samples (plant remains and charcoal) taken from cores KUL 3, KUL 7 and PAPO 2, were radiocarbon-dated in the CologneAMS Laboratory, University of Cologne (Tab. 1). All ages were calibrated with the Calib 7.1 software (calibration data set: intcal13.14c, following the approach of Reimer et al., 2013). The age-depth-model was calculated with the OxCal version 4.2.4 (Bronk Ramsay and Lee, 2013), restricted to the deposition models for chronological records of Bronk Ramsay (2008).

In order to gain chronological information on the generation and last activation of the beach-foredune ridges north of the Rioni river mouth, infrared stimulated luminescence (IRSL) dating was carried out on four samples from trenches KUL 1 and 2. The luminescence samples were taken by pushing opaque steel tubes of 5 cm diameter into the cleaned vertical sections. The tubes were closed with plastic lids to avoid light contamination. For further information on sample preparation see Appendix 1.

4 Results

4.1 The beach-foredune ridges and the adjacent hinterland (KUL 1 – KUL 3)

KUL 1 and 2 were trenched down to a depth of ca. 2 m below surface (b.s.). They comprise of homogeneous coarse to medium sand layers, with a few roots. Only the upper ~30 cm reveal a slightly finer grain size and an increased content of organic matter. Sediment core KUL 3 (Fig. 2) is composed of well-sorted medium sand (mean grain size between 522 and 455 µm) with organic matter of <4 % (6.70-2.82 m b.s.) at its base. Subsequently, the mean grain size gradually decreases, and the organic content varies between 2.82 and 2.46 m b.s. The overlying peaty unit (2.46-1.95 m b.s.) shows grain size values of 254-237 µm and high LOI (15-67 %). Above, relatively homogeneous sand occurs. The uppermost part (0.38–0 m) is characterised by decreasing mean grain size and increased LOI.

4.2 The Kolkheti wetlands – master cores KUL 7 and PAPO 2

4.2.1 Sediment core KUL 7

The lowermost stratigraphical unit (12-11.68 m b.s.) is composed of grey homogeneous silt which is characterized by high Ca contents, also reflected in the Ca/Fe and Ca/Ka ratios (Fig. 3). The mineral composition of this layer differs from the subsequent layers; calcite was detected only in sample KUL7/44. The overlying stratum (11.68-11.55 m b.s.) consists of an intensely weathered dark-brown peat with high LOI values (up to 37 %) and TOC/N ratios, and low Ca/K and Ca/Fe ratios (Fig. 3). At 11.55 m b.s. the peat gradually changes into dark grey clayey silt (mean grain size <10 µm) with few shell fragments and elevated contents of organic matter, particularly between 11.31 and 11.28 m b.s. At 11.00 m b.s., LOI reaches a constant level below 5 %, while Ca remains high and TOC/N decreases. The clayey silt dominates until 7.71 m b.s., although it is intercalated by a dark brown peat at 9.56–9.40 m b.s. (LOI up to 23 %). Subsequently, the sand content increases considerably, and fine sand-dominated layers alternate with silt-dominated layers until 5.27 m b.s. While LOI and TOC/N remain relatively low, Ca/Fe and Ca/K show constantly decreasing values above 6.43 m b.s. In general, elevated Si and Ti values characterise the strata between 9.40 and 5.47, compared to the sediments below.

Above, the sedimentary succession is characterised by two distinct peats (5.27 and 2.49 m b.s.), intercalated by a light grey silt layer (3.89–3.59 m b.s.). The peat units are indicated by increased S and TOC/N; they are mainly composed of a clay- and silt-dominated matrix (mean grain size <9 µm) with high LOI values (10-34 %) and only few macroscopic plant remains. Subsequently, the peat layer gradually changes to clayey silt which prevails until 0.45 m b.s. Above the ground water table, the sediments have a reddish brown colour, contain root fragments and show signs of redox characteristics. The uppermost layer is the plough horizon.

4.2.2 Sediment core PAPO 2

From 10 to 9.78 m b.s. sandy silt with low LOI occurs. It is covered by silty sand with large plant remains, high LOI, Ca/K and Ca/Fe, and low Si and Ti values (Figs. 1, 4). Then follows a peat (LOI 41-79 %, 8.59-8.03 m b.s.) with very low Ca/K and Ca/Fe ratios. It gradually changes to grey homogeneous (8.03-~6.00 m b.s.) and laminated (~6.00-3.36 m b.s.) clayey silt, which is characterized by low LOI, but high values of Si, Ti, Ca/K and Ca/Fe. Sandy intercalations are found, e.g. between 6.39 and 6.03 m b.s. Then peat layers with macroscopic plant remains occur between 3.36 and 2.76 m b.s., and from 2.22 to 1.41 m b.s.; they are characterised by increased organic contents and reduced Ca/K and Ca/Fe ratios. The peats are separated by grey clayey silt (2.76-2.22 m b.s.). Red-brown silt with low LOI occurs in the uppermost ~2 m of the core.

4.3 Additional stratigraphic information along the coring transects A and B

Compared to master cores KUL 7 and PAPO 2, a number of similarities can be found in the sedimentary succession of all other cores along the two coring transects (Figs. 5, 6). All cores are predominantly composed of fine-grained (silt-dominated) and often laminated sedimentary units with macroscopic plant remains. However, depending on the location of each core along the coring transects, differences exist regarding the presence of basal sand layers as well as the position of sand and peat intercalations.

In the southern section of coring transects A and B, the lower parts (below 5.5 m b.s.l.) of cores SHAV 2 and PAPO 3 (Fig. 5) comprise fine sand-dominated and poorly sorted layers with varying silt contents (mean grain size ~30-200 µm), which is similar to the section between 9.78 m and 8.59 m b.s. in master core PAPO 2. In case of SHAV 2, this unit reaches a thickness of almost 3 m. In contrast, units of (silty) sand are better sorted and more homogeneous, which is expressed by reduced fluctuations of the mean grain size in cores KUL 7, 9, 10 and 11. Finally, medium sand with parts of coarse sand (~250-520 µm) are found in core KUL 3, in sediment profiles of trenches KUL 1 and 2, and in the uppermost 2.5 m of core KUL 12. Here, sand units are well-sorted (in general $\sigma < 2$), homogeneous and void of macroscopic plant remains.

The distribution and thickness of peats reveal a certain pattern as well. Except for KUL 6, all cores contain at least one distinct peat layer. The peats generally occur in the upper parts of the cores, predominantly in a sequence of 2-3 layers, which are separated by thin clay- and silt-dominated strata. In the lower core sections, peats were found in only 7 cores.

Six samples of core KUL 12 were analysed for their microfaunal content, with only two of them revealing scattered findings: At 11.74 m b.s. a few indeterminable remains of foraminifera occur; at 9.49 m b.s. a sample contains two indeterminable foraminifera specimens.

4.4 Radiocarbon and IRSL dating results

Tab. 1 gives the details of the radiocarbon dating results, including specifications of the dated material, sample numbers and depths. The ^{14}C ages (2 σ) are noted in the figures of the profiles at the position of the sampled depths (see Figs. 2, 3 and 4).

The fading-corrected IRSL dating of samples from trench KUL 1 resulted in ages of 1010 ± 134 a (KUL 1/2) and 1017 ± 129 a (KUL 1/4). The IRSL ages from trench KUL 2 are only insignificantly younger (KUL 2/1: 1047 ± 134 a; KUL 2/2: 1049 ± 134 a) (Tab. 2).

5. Discussion

5.1 Facies determination

Based on the samples taken from the master cores, eight facies were distinguished, which were adopted for the further cores of coring transects A and B. The facies represent depositional environments that differ in terms of grain size, sorting, organic content and elemental composition (Figs. 7A, B, C).

Facies A: shallow marine (?)

Facies A was only found in the basal section of KUL 7 (Fig. 3). From 12 m b.s. to the peat layer at 11.68 m b.s., the sediment shows low S values and the presence of (magnesium-) calcite (Fig. 7C), which is manifested in high Ca contents. Samples from this section contain few undetermined shell fragments and few foraminifera. This facies differs from facies D (alluvial, semi-terrestrial deposits) and facies C (lagoonal mud) in terms of lower Si, Ti and S contents. The slightly increased TOC/N ratio is a possible indicator for both shallow marine and terrestrial conditions (Meyers and Teranes, 2001). The PCA and the standardized ternary plot (Figs. 7A, B) both reveal no distinct differentiation of this sample to facies C and D. Therefore, a lagoonal or semi-terrestrial origin, e.g. related to a standing water body on the evolving delta floodplain, comparable to facies C1 or C2, cannot be excluded. In this case a continuous sea-level rise and drowning of the study area would have provoked the growth of a transgressive peat (KUL 7, 11.68-11.55 m b.s.).

Facies B: sublittoral to littoral

Relatively well-sorted medium to coarse sand between 6.70 and 2.82 m b.s. at KUL 3 points to hydrodynamic conditions with rather high sediment transport capacities, typical of wave-dominated sublittoral to littoral conditions (Dingler, 2005; Aavaard and Hughes, 2013). Sediments from facies B are coarser and better sorted than sediments from facies F (fluvial deposits). Based on Folk and Ward (1957), beach sands are characterized by good sorting and tend to unimodal distributions, even if they are located close to river mouths (Tucker, 1996; Hesp, 2002). In the ternary plot this facies is congruent to facies G due to the coarse grain size, but it is distinguishable from the other remaining facies (Fig. 7B). A slightly better differentiation is revealed by the PCA (Fig. 7A), although two samples from facies G plot similar to the samples of facies B as well.

Facies C: lagoonal

Sediments from facies C have a grey colour and tend to be indicated by low contents of organic matter. The lagoonal sediments differ from the semi-terrestrial and shallow marine deposits in terms of higher Ca/Fe and Ca/K ratios and low Si and Ti contents (Figs. 3, 4, 7B). Furthermore, the low TOC/N ratios point to a predominance of algae and low terrestrial input of vascular plant material (Meyers and Teranes, 2001) which supports the differentiation between those two facies.

Nevertheless, several samples from the lagoonal strata reveal a coarser grain size. Although strong storms are known from the Black Sea, neither the absence of microfauna, nor geochemical or sedimentological features typically related to storm deposition (e.g. lamination, fining upward sequences) were found. Therefore a deposition by wave events is unlikely (Morton et al., 2007). However, geochemical parameters are consistent with still water conditions as well. Therefore, facies C can be divided into two subunits: Facies C-1, which consists of the predominating fine-grained mud of the central lagoonal areas, and Facies C-2, which is formed by the coarser deposits of the lagoon areas close to the river mouths. This explains the similar composition between some lagoonal and alluvial samples in the PCA (Fig. 7A). The standardized ternary plot reveals a well-defined distinction of all other facies, except for two fluvial samples which may be explained by the fluvial origin of both facies C-2 and facies F (Fig. 7B).

Facies D: alluvial (overbank deposits)

As typical for alluvial sediments, facies D is characterised by silty to clayey deposits. The high TOC/N ratio is an effect of the increased content of vascular or even cellulosic plant material of terrestrial origin (Meyers and Teranes, 2001). Extensive inundation of low-lying delta areas and oxbow lakes during flood events typically induce the accumulation of fine sediments from slack waters as overbank deposits (overbank fines), when the stream overtops its banks (Blair and McPherson, 1994). In any case, major floods of the lower sections of the rivers Rioni and Khobistsqali can also provoke crevasse-splays by breaching of levees, most commonly leading to sand deposition on the floodplain (e.g., North and Davidson, 2012). However, crevasse-splay deposition typically goes along with basal erosional unconformities, and no such erosional surface was found in the presented cores. Core sections with varying fine sand contents and Ca/Fe and Ca/K values thus reflect the fluctuating hydrodynamic conditions on the delta plain which are predominantly characterised by the deposition of overbank fines (Boggs, 2006). These coarser layers have similar granulometric characteristics compared to facies C-2, but can be distinguished by differences in the geochemistry. Due to high LOI, many samples resemble those of facies E (Figs. 7A, B).

Facies E: semi-terrestrial (peat)

Facies E is represented by peat with numerous macroscopic plant remains and considerably elevated LOI and K values. Preservation of plants points to anoxic conditions (Turney et al. 2005). High TOC/N ratios are typical of peat bogs (Joosten et al., 2003; Haberl et al., 2006) and indicate a dominance of cellulosic plants (Meyers and Teranes, 2001). The most remarkable difference is revealed in elevated LOI and S values. The connection with the surrounding strata is reflected in the scattered distribution in the PCA and ternary plot (Fig. 7A, B), e.g. adjacent to facies B, C-1 and C-2.

Facies F: fluvial

A fluvial origin is assumed for some sections of cores PAPO 2, PAPO 3 and SHAV 2 and refers primarily to sediment input by distributary channels of the two rivers in the delta. These sediments show coarser grain size, moderate to poor sorting (Sun et al., 2002), and are void of macro- and microfauna. Elevated Fe and K values point to increased input of terrestrial material (Arz et al., 1998; Meyers and Teranes, 2001; Kujau et al., 2010). The varying grain size and sporadically occurring fining-upward sequences (e.g. PAPO 2) can for instance be explained by river avulsion and temporary lateral channel migration, deposition during larger floods in areas close to distributary channels, and/or – in contrast to facies D – crevasse splay deposition (Boggs, 2006). There are certain similarities with facies C-2 (Fig. 7B), but facies F reveals coarser mean grain size and elevated LOI, Si and Ti values. A better separation is revealed in Fig. 7A, where the plots of facies F and C-2 are disjoint.

Facies G: aeolian

Facies G is restricted to sediment profiles of trenches KUL 1 and 2, and the upper part of KUL 3. The elevation of these sediments with respect to sea level (2.50-3.00 m a.s.l.), the high degree of sorting and the dominance of medium sand (mean grain size 310–410 µm) suggest an aeolian origin. The location on the landward slope of the shore-parallel foredune ridges confirms this assumption (Hesp, 2002). The high degree of similarity to littoral sediments (facies B; Figs. 7A, B) can be explained by the shared source area and the short transport distance. This is reflected by slightly increased fine sand and reduced coarse sand contents (Fig. 2).

Facies H: anthropogenic

This facies reveals the same characteristics as facies B (sublittoral to littoral environments). The sediment was intentionally deposited at the site of KUL 12 in order to build a causeway.

5.2 Chronostratigraphic interpretation of sediment cores

5.2.1 Trenches KUL 1 and 2, core KUL 3

In KUL 3 the coastal evolution north of the present Rioni mouth is documented for the last 3500 years (Fig. 2). Due to the circulation pattern of the offshore currents (Korotaev et al., 2003), the Rioni is the main sediment source for the littoral deposits along the graded shoreline. Relatively well-sorted medium to coarse sands between 6.70 and 2.82 m b.s. point to relatively high transport capacities. Sublittoral to littoral conditions (facies B) at site KUL 3 established before ~1500 cal BC and ceased some time before ~350-50 cal BC, when decreasing mean grain size (3.25 m and 2.82 m b.s.; facies B and C) and a subsequent peat layer (2.82-1.95 m b.s.; facies E) indicate a back-barrier milieu with beach aggradation and/or delta progradation. These conditions continued at least until ~500 cal AD. Elevated S values and well-preserved plant remains suggest an anoxic milieu in the back-barrier swamp.

After ~500 AD, well-sorted medium sand was accumulated at site KUL 3, which is similar to the sediment in the upper 2 m of the adjacent foredune ridges (KUL 1 and 2, facies G) and therefore of aeolian origin. Based on the IRSL ages taken from the trenches, sand deposition on top of the foredunes was still active or was reactivated around AD ~830 – 1150 AD (1049 ± 134 a and 1010 ± 134 a, Tab. 2), before the eastern part of the ridges was finally stabilized. This is roughly in accordance with the uppermost radiocarbon age of KUL 3: ~500 cal AD is a *terminus post quem* for the deposition of the well-sorted medium sand.

However, several uncertainties may be related to the IRSL ages. Due to the low temperature of the preheat plateau not all narrow electron traps may have been emptied, which could lead to age overestimation (Auclair et al., 2003). Furthermore, the feldspar aliquots show a significant scatter of equivalent doses. Since the samples were taken from the upper section of the foredune ridges and likely experienced aeolian transport, sediments are assumed to be rather well-bleached. Therefore, post-depositional mixing may be a reason for the large scatter. The reforestation of the area with pine trees during the 20th century (De Klerk et al., 2009) and resulting root penetration could be a possible explanation. Thus, the IRSL ages should be treated as maximum ages for the last period of foredune activity.

5.2.2 Master cores KUL 7 and PAPO 2

The development of the central part of the swampy hinterland between the rivers Khobistsqali and the Rioni is documented by master cores KUL 7 (Fig. 3) and PAPO 2 (Fig. 4). For the lowermost section of core KUL 7 (12-11.68 m b.s.), two different scenarios may be considered: assuming a shallow marine environment of the basal unit, the following peat documents the establishment of semi-terrestrial conditions, e.g. in the form of a floodplain swamp (facies D), pointing to a westward shift of the coastal environments. Assuming that the basal unit of KUL 7 represents lagoonal to semi-terrestrial conditions, a western position of the coastline must be assumed, and back-barrier conditions existed at KUL 7 already before ~6000 cal BC.

However, as documented by the peat layer, back-barrier conditions dominate the entire study area, except for site KUL 3, at least since 5979-5740 cal BC (Tab. 1). Subsequently, peat growth could not keep pace with the, at that time, still considerably rising sea level (Giosan et al., 2006; Brückner et al., 2010). The establishment of open lagoonal conditions (facies C) is inferred from the following ~4 m thick unit of clayey silt, although the mineralogical composition (i.e. absence of calcite) of these sediments and the absence of micro- and macrofossils point to conditions inappropriate for the development of faunal assemblages. Depositional conditions remained stable for the following centuries, and, despite the development of a thin intercalated peat, were most likely characterised by a lagoonal back-barrier situation. While no microfauna was found to determine salinity conditions, the geochemical parameters are the most reliable indicators for this facies determination. High depositional rates are inferred from the ^{14}C age of plant fragments taken from the uppermost part of the silt layer: with an age between 5529 and 5346 cal BC (Tab. 1) it is only slightly younger than the sample taken from the peat below.

In the following units we assume an increasing significance of alluvial processes, e.g. overbank deposition during major floods of the lower sections of the rivers Rioni and Khobistsqali. The increased alluvial deposition marks the transition to subsequently evolving semi-terrestrial conditions (facies D), which were likely related to the gradual evolution of the Rioni-Khobistsqali floodplain, i.e. the Kolkheti lowlands, established around 3600 cal BC. Subsequently, the stratigraphy is dominated by thick peat units (facies E). Peat formation at KUL 7 dominated at least until ~900 cal AD; sporadic sand input on the floodplain is inferred from the sand fraction in the peat layers.

Additionally, different rates of peat accretion may be inferred from the radiocarbon ages. While 1.50 m of peat accumulated between 3695-3521 cal BC and 3348-3025 cal BC (5.27-3.89 m b.s.) (Tab. 1), reduced rates of peat formation must be assumed for the section between 3.59 and 2.49 m b.s., where 1.10 m of peat formed during a period of 4000 years (3348-3025 cal BC to 655-861 cal AD). If it is not a dating error, this might be explained by different rates of groundwater level changes. However, the development of paralic peats is dependent on the local sea-level evolution (Fouache et al., 2012), and a sea-level rise of only 1.1 m in ~4000 years is problematic. Thus, possible uncertainties have to be considered, e.g. dating of different material, a possible hiatus within the sequence and floating peat (Haberl et al., 2006; Vött et al., 2007). Finally, the peat is covered by fine-grained alluvial deposits and 0.45 m of anthropogenic infill.

The stratigraphy recorded in core PAPO 2 reflects a similar evolution. The stratigraphy starts with lagoonal deposits (facies C). The following sandy stratum of fluvial origin (facies F) was deposited between 5297-5044 cal BC and 3517-3118 cal BC. When the riverine input declined, peat (facies D) formed, indicating semi-terrestrial conditions and the establishment of a lagoonal environment, still affected by episodic flooding. The end of input of coarser-grained sediments may reflect an avulsion of the Rioni. After 1618-1441 cal BC, peat growth indicates the end of the lagoonal conditions (3.36-2.76 m b.s.). Related to the extending delta floodplain of the Rioni, alluvial sediments (facies E) had been deposited at the site at least since 82-322 cal AD.

5.3 The evolution of the Kolkheti lowlands

The evolution of the Kolkheti lowlands can be deduced from coring transects A and B (Figs. 5, 6). The facies of the three master cores were adopted to the cores along the coring transects. In addition, the cores were classified into four groups based on their site-specific sedimentary succession.

Group 1 consists of core KUL 3 and trenches KUL 1 and 2. It is dominated by sublittoral to littoral (KUL 3) and aeolian sands (upper part of KUL 3, KUL 1 and 2). Similar deposits are absent in the other parts of the coring transects.

Cores SHAV 2, PAPO 2 and PAPO 3 comprise group 2, which is restricted to the southern part of the research area. In these cores, the lowermost sections (below ~6 m b.s.l.) show lagoonal environments (facies C), which were episodically affected by sediment input from the Rioni river (facies F). Especially in the case of SHAV 2, a 3 m thick layer of fluvial sand occurs, which can be related to similar sand intercalations at PAPO 2 and PAPO 3. Due to ^{14}C-dated plant material in PAPO 2 (Tab. 1, sample PAPO2/31), the distinct sand layers was accumulated after ~5300 cal BC. It is assumed that by then the course of the Rioni was located at a similar position as today. When lagoonal conditions (facies C) were established in the area after ~3000 BC, major sand intercalations are absent. Instead, intercalated peats indicate recurrent siltation and shoreline shift of a shallow lagoon. In the southern part of transect B, the transformation from lagoonal (facies C) to semi-terrestrial and later terrestrial depositional environments (facies D and E) occurred after ~1500 BC.

Further north, cores KUL 6, 9 and 12 (Fig. 1) comprise group 3. The cores represent the central part of the Kulevi swamps between the rivers Rioni and Khobistsqali. They almost entirely consist of clayey silt, which is interpreted to represent lagoonal (facies C) and, subsequently, alluvial strata (facies E). Alluvial and fluvial deposition was reduced wherefore intercalations of coarser material are missing. It seems that these core sites had been located in the centre of the former lagoon. Only a thin sand layer suggests flood-related deposition at KUL 9. The sand layer in the upper 2.5 m of KUL 12 is artificial infill (facies G; Figs. 5, 7) since the coring site is located in close proximity to the road.

Group 4 comprises cores KUL 5, 7, 10 and 11 and exhibits parallels with group 2. KUL 7 is the deepest core and reaches ~10.50 m b.s.l. It is the only core where shallow marine conditions (facies A) are inferred at the base. However, the subsequent strata are dominated by fine-grained sediments of the lagoonal facies (facies C-1), with sand intercalations indicating episodic alluvial sediment input (facies C-2) particularly at sites KUL 7 and 10 which are located close the river mouth. While peat layers are almost absent in the lower core sections, thick peat units are present in the upper part of the cores from this group. We have not yet resolved whether alluvial deposition is related to the Rioni or the Khobistsqali.

In summary, the presented findings allow to sketch a general scenario for the evolution of the Kolkheti lowlands over the last eight millennia.

Around 6000 cal BC, a shallow marine environment may be inferred from the base of two cores (KUL 7 and 12); these sediments show slightly different characteristics compared to all other strata. However, samples from this unit cannot be unambiguously separated from the lagoonal and semi-terrestrial samples based on the sedimentological and geochemical characteristics (Fig. 7). It thus remains open whether the Holocene transgression is reflected in the form of shallow marine deposits, or in the form of landward migrating back-barrier conditions.

Around 5900 cal BC, the coastline was located west of coring transect B, most likely between KUL 12 und 3. In all cores, a thick sequence of fine-grained sediments points to standing water bodies and quiescent depositional conditions, evidencing the existence of a coastal barrier. As suggested by peat intercalations and input from the rivers, recurrent siltation and re-establishing open water bodies characterised this back-barrier environment.

Since ~3500 cal BC (at KUL 7), the delta plain is assumed to have reached the area of the coring transects. The final transition from lagoonal to semi-terrestrial environments is represented by the development of peat. In other parts of the lowlands, this change took place significantly later, e.g. ~1500 cal BC at site PAPO 2. Further west, at KUL 3, the siltation was connected to the subsequent westward shift in the shoreline. North of the present Rioni mouth it took place sometime before ~350 cal BC.

This scenario is in agreement with the results presented by Connor et al. (2007) and de Klerk et al. (2009), who suggested an interaction of sea-level rise and fluvial infill causing fluctuating groundwater conditions in peat bogs at the site of Ispani. Furthermore, the establishment of a floodplain with peat bogs is indirectly corroborated by historical sources from Antiquity: although uncertainties remain regarding the locations and landscape descriptions given by Hippocrates (c. 460 – c. 370 BC) and Strabo (64/63 BC – c. AD 24), both describe the surroundings of Phasis and the Rioni as marshy forests and swamps (cf. Gamkrelidze, 2012).

5.4 Implications for the local relative sea-level evolution

Although the reconstruction of a relative sea-level curve for the research area remains challenging due to the lack of unambiguous sea-level index points, the relationship of each dated sample to the respective past sea level allows for an approximation of the relative sea-level position for each data point (Fig. 8). Based on the facies succession inferred for the cores, the peat in the lower part of core KUL 7 (sample KUL 7/44) is assumed to represent a paralic peat layer. Since paralic peats are directly related to the back-barrier groundwater table, and, thus, to the local relative sea level (Pirazzoli, 1991; Vött, 2007), we defined a vertical error range of ~±0.5 m (Pirazzoli, 1996; Behre, 2003) for this and for similar (KUL 3/9, KUL 3/10; back-barrier position) samples. The local relative sea level thus was ca. -9 m around 6000 BC.

The three ages of KUL7/37, PAPO2/31 and PAPO2/28 derive from plant remains taken from lagoonal mud (facies C). Since the material was deposited below the former local sea level, these samples represent minimum values for the sea level position at ~5450 BC (-8 m), ~5200 BC (-7.4 m) and ~3300 BC (-6.3 m). Rather shallow lagoonal conditions and a deposition close to the lagoonal water table is most likely, since subsequently peat evolved (KUL7/37, PAPO2/31).

In contrast, samples taken from an alluvial facies (facies D), i.e. related to the deposition of overbank fines, derive from elevations above the former local sea level. At present, the dry flood plain with episodic overbank deposition shows maximum elevations of ~3 m a.s.l. Therefore, samples KUL 7/20, KUL 7/13, PAPO2/11, PAPO 2/9 and KUL 7/7 indicate maximum values for the respective sea level position. However, while KUL 7/20, KUL 7/13, PAPO2/11 give valuable information about the maximum sea-level position for the time span between ~3500 and ~1500 BC, the latter two samples (PAPO 2/9, KUL 7/7) may be neglected since samples KUL3/10 and KUL 3/9 (paralic peat in back-barrier position) represent more reliable sea-level index points for this time period, with a rather narrow error range. For KUL3/14, representing sublittoral to littoral facies (facies B), an error range of several meters must be assigned as well. Finally, the peat sample PAPO2/6 derives from a core section dominated by alluvial sediments, indicating an oxbow peat, which only gives a maximum estimate for the position of the local sea level.

Altogether, our data points (Fig. 8) indicate an estimated relative sea level at ~-9 m ~6000 cal BC, and a subsequent sea-level rise until 2000-1500 cal BC, when a sea level of ~3-2 m below present level was reached. Afterwards sea-level rise decelerated until it reached today's level.

Compared with the local sea-level curves for the Taman Peninsula in SW Russia (sites Semebratnee [Brückner et al., 2010], Golobitskaya [Kelterbaum et al., 2011], and Dschiginka [Fouache et al., 2012]) (Fig. 8), our curve shows a rather similar trend, in particular when compared to the RSL curves of the former two sites which point to a relatively slow sea-level rise throughout the last ~4000 years as well as to other RSLs of the Eastern Mediterranean (Vött et al., 2007; Brückner et al., 2010). However, the data presented here point to an even slower local relative sea-level rise in the Rioni delta. The differences can be explained by the different tectonic settings of the central Georgian coast and the Taman Peninsula. Sites on Taman Peninsula are related to subsidence (i.e, related to tectonic subsidence and/or compaction) according to Fouache et al. (2012). This may also be the case for the study area as a back-arc marginal extensional basin between the Caucasus ridges (Yılmaz et al., 2013), though at a more moderate pace. Based on the findings presented here, the high subsidence rates suggested by Gamkrelidze (1998) for the study area of 2-6 mm/a may be questioned.

Finally, as already suggested by the studies of Giosan et al. (2006), Brückner et al. (2010), and Kelterbaum et al. (2011, 2012), no remarkable wiggles of the curve, representing regression-transgression cycles, can be inferred, which further challenges the theory of the presumed Phanagorian Regression (e.g. Balabanov, 2007).

6. Conclusion

Based on a total of eleven vibracores and two sediment trenches, this study presents, for the first time, detailed information on the chronostratigraphy of the Kolkheti lowlands (Colchis) in Georgia. Using a combination of sedimentological and geochemical parameters, we identified different facies, the succession of which reflects the palaeoenvironmental evolution of these coastal lowlands. Radiocarbon and IRSL ages show that the sedimentary record presented here covers the last ~8000 years.

During this period, the area of research was subject to considerable landscape changes. While a shallow marine origin for the very basal part of cores KUL 7 and KUL 12 remains ambiguous, the rapid establishment of lagoonal conditions, sometime before ~5000 cal BC, can be demonstrated based on sedimentological indicators. The lagoon was separated from the Black Sea by a barrier. Its sedimentation was influenced by the discharge of the rivers Rioni and Khobistsqali. Subsequently, alluviation transformed the lagoon into a delta plain with wetland-dominated sections, characterised by peat bogs, and sections with fine-grained alluvium. Depending on the location within the delta area, this transformation took place between 3500 and 1500 cal BC. Today, a substantial part of the area is still occupied by wetlands with peat bogs and forests, while other parts remain open waters or have been transformed into farmland.

As for the sea-level evolution, no evidence for significant oscillations of the local relative sea level was found, in particular no regression-transgression cycles as suggested by Balabanov (2007). Instead, our results point to a progressively and moderately rising sea level, with decelerated speed since 3000-2000 BC. This evolution resembles sea-level curves inferred for the Taman Peninsula (Brückner et al., 2010; Kelterbaum et al., 2011; Fouache et al., 2012). Differences between the curves may potentially reflect different tectonic settings.

Against the background of the early establishment of a permanently changing delta plain, it remains difficult to draw conclusions about the possible location for the, as yet, undiscovered location of the ancient city of Phasis. Due to the persistence of extended peat bogs and open water bodies, a location close to the Rioni, for example on a palaeo-levee of the river, seems likely. However, ancient reports locate Phasis south of the Rioni (Gamkrelidze, 1992, 2012; Lordkipanidze, 2000; Korenjak, 2003). Further research, including geophysical surveying techniques to detect subsurface palaeochannels of the Rioni, is needed to find the lost city of Phasis.

~~.~~Based on this study, future research will reveal more detail on the sea-level evolution of Georgia's coast, thereby making an important contribution to the ongoing debate on the sea-level evolution of the Black Sea throughout the Holocene. Plus, the peat bogs to the north of the Rioni and the Lake Paliastomi are promising archives for palynological research and will add new information on Georgia's Holocene vegetation history

Acknowledgements

H. L. gratefully acknowledges the funding of his PhD project by the Heinrich Böll Foundation, Berlin. The Graduate School of Geosciences (GSGS) of the University of Cologne financially supported H. L. to attend the IGCP 610 conference in Baku, Azerbaijan, in 2015. Radiocarbon dating was carried out by Janet Rethemeyer, Alfred Dewald and Stefan Heinze and their teams at the CologneAMS Centre at the University of Cologne. Several colleagues from Georgia rendered administrative and logistic help during field work. Accommodation was provided by the Marine Research Centre of the Ilia State University in Grigoleti. Nick Marriner (CNRS Besançon) is thanked for language editing of an earlier version of this manuscript.

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Figure captions

Fig. 1: Overview of the research area with location of coring sites and trenches. They are arranged in transects A (blue line) and B (yellow line). Prominent features are the areas of agricultural use on the levees of the rivers Rioni and Khobistsqali. They are in great contrast to the open grasslands, peat bogs and swamp forests. Figure based on Esri basemap and www.naturalearthdata.com.

Fig. 2: Facies interpretation, granulometry, geochemistry and ^{14}C age estimates of the sediment core KUL 3. It represents the stratigraphy of the landward part of the coastal barrier complex, consisting of a (sub-) littoral base, semi-terrestrial back-barrier facies, and aeolian cover sands (deposits of the foredune ridges).

Fig. 3: Facies interpretation, granulometry, geochemistry and age-depth model of the sediment core KUL 7 (caption see Fig. 2). It represents the stratigraphy of the central coastal lowlands, and comprises the entire range of facies: possibly shallow marine deposits at the base (see discussion in chapter 5.1), followed by an interdigitating of lagoonal, semi-terrestrial and alluvial strata.

Fig. 4: Facies interpretation, granulometry, geochemistry and age-depth model of the sediment core PAPO 2 (caption see Fig. 2). The stratigraphy, which is typical for the three southernmost cores, shows river sediments covered by lagoonal deposits. According to the age-depth model, the siltation of the lagoon took place ~2000 years later than at the site of KUL 7.

Fig. 5: Transect A crossing the research area from W to E (position in Fig. 1). While KUL 1, 2 and 3 belong to core group 1 representing the evolution of the coastal barrier complex, KUL 12 belongs to core group 3, which represents the evolution in the centre of the swamps. Cores KUL 7 and KUL 11 are part of core group 4 (see text for further explanations).

Fig. 6: Transect B crosses the research area in S-N direction (position in Fig. 1; legend in Fig. 5). The southernmost cores (SHAV 2, PAPO 3, PAPO 2) belong to core group 1; they are characterized by strong fluvial influence in the lower parts. KUL 9 and KUL 6 represent the evolution in the central part of the swamps, dominated by fine-grained lagoonal mud without intercalation of sand or peat. KUL 7, 10 and 5 belong to group 4 which contains several peat layers, but no major fluvial of alluvial input.

Fig. 7A: Principal component analysis (PCA) of the samples taken from the master cores KUL 3, 7 and PAPO 2. Eight PCs were estimated. The spatial distribution is based on components 1 and 2.with a variance of 36.9 and 19.8% (further variances: PC 3: 14.3%, PC 4: 10.5, PC 5: 8.4%, PC 6: 6%, PC 7: 0%). For the colour code of the samples see Fig. 5.

7B: Ternary plot of mean grain size, sorting and Ca/K ratio, plotted for all samples of the three master cores. For the colour code of the samples see Fig. 5.

7C: Mineralogical compositions of the samples KUL7/36 and KUL 7/45. Qu = quartz, Mu = muscovite, Al = albite, Ca = magnesium-calcite. The obvious difference is that KUL 7/45 contains magnesium-calcite.

Fig. 8: Compilation of ^{14}C-dated samples from the Kolkheti lowlands and their relative position to the local sea level. Horizontal bar shows ^{14}C dating result (2 sigma). The arrows pointing up/down indicate that sea level was higher/lower than the dated sample. In case of paralic peat (facies E; KUL 7/44, KUL 3/10, KUL 3/9), the sea-level range was narrowed to ±0.5 m (see text for further explanations). The data set is compared to sea-level curves from the Taman Peninsula in SW Russia, with the sites of SEM = Semebratnee (Brückner et al., 2010), GOL = Golobitskaya (Kelterbaum et al., 2011), and DZHI = Dschiginka (Fouache et al., 2012). The differences are due to different tectonic settings. For the study area, a continued and rather moderate rise in sea level for the last eight millennia is assumed.

supplementary data

Appendix 1: Sample preparation for luminescence (IRSL) dating

The following sample preparation and luminescence measurements were carried out in the Cologne Luminescence Lab (CLL) under subdued red light. After HCl, H_2O_2 and $Na_4O_7P_2$ treatments to remove carbonates, organics and clay contents, gravity separation was carried out using heavy liquid solutions (sodium polytungstate; ρ_1 = 2.68 g/cm^3, ρ_2 = 2.62 g/cm^3, ρ_3 = 2.58 g/cm^3) in order to separate coarse-grained (100-200 µm) quartz and feldspar. All measurements were carried out on an automated Risø TL/OSL DA 20 reader equipped with a ^{90}Sr/^{90}Y beta source delivering 0.08 Gy/sec.

Quartz is commonly used to date Holocene deposits due to its ubiquity and a generally stable signal for dating young deposits. However, in this study, potassium-rich feldspars were preferred for dating because of inappropriate luminescence properties of the quartz (e.g. low signal intensities). Nonetheless, feldspar can exhibit anomalous fading, which is defined as a signal loss due to leakage of electrons at room temperature. This can cause an age underestimation (see Wintle, 1973; Lamothe and Auclair, 1999; Balescu et al., 2001; Huntley and Lamothe, 2001). To include the effect of anomalous fading in the age calculation, several sub-samples were tested and measured to observe a possible decrease in the IRSL response over time, following Auclair et al. (2003). Indeed, a signal loss was detected in all sub-samples. The g-values (1.9 and 1.3 %/decade) were calculated for the samples KUL 1/4 and KUL 2/2. Thus, the fading was corrected by using the procedure proposed by Huntley and Lamothe (2001), as the equivalent dose was derived using linear parts of the growth curve. The resulting ages are given both with uncorrected and fading corrected values. The fading correction for sample KUL 1/2 refers to the g-value of KUL 1/4, and the fading correction for sample KUL 2/1 was conducted using the g-value of KUL 2/2 (Tab. 2).

For the feldspar measurements an infrared stimulation (880 ± 80 nm) and an interference filter (410 nm) were used. All measurements were carried out following the single aliquot regenerative dose protocol (SAR) after Murray and Wintle (2000, 2003) and Wallinga et al. (2000). Due to the preheat plateau test, which indicated no plateau building at higher temperatures, a preheat temperature of 180 °C was chosen. Each aliquot was thus preheated at 180 °C (according to combined preheat-plateau-dose-recovery-tests) for 10 sec and then measured for 300 sec at 50 °C (IRSL 50 protocol after Wallinga, 2000).

To calculate the annual dose rate derived from the decay of lithogenic radionuclides in the sediments, the concentrations of uranium, thorium and potassium were determined by laboratory high-resolution γ-spectrometry using the software DRAC by Durcan et al. (2015). The conversion factors of Adamiec and Aitken (1998), and α- and ß- attenuation factors of Bell (1979) and Mejdahl (1979) were applied. Following the approach of Prescott and Hutton (1994) the cosmic dose rate was calculated. An internal radiation of 12.5 ± 0.5 % potassium (Huntley and Baril, 1997) and an α-efficiency factor of 0.07 ± 0.02 (Preusser et al., 2005) were assumed for feldspars.