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Sensitivity of the Eastern Mediterranean geomorphic system towards environmental change during the Late Holocene: a chronological perspective

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Abstract

Alluvial and colluvial sediment deposition form a vital record of environmental change during the Holocene. Firm chronological control on these archives is necessary to enable us to relate sediment dynamics to human activity and climate variability. In the Eastern Mediterranean, such relationships are hard to establish due to the lack of spatially well distributed sediment archives with good chronological control. This scarcity is problematic with respect to regional-scale reconstructions of the temporal variation of sediment dynamics. Here, we present a radiocarbon database (n = 178) of geomorphologic activity collected from multiple distinct sediment archives within the territory of Sagalassos in south-western Turkey. The data were grouped according to their sedimentary facies for analysis using cumulative

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probability distributions (CPD) and sedimentation rate (SR) modelling. Two small-scale colluvial valleys, where chronological information was abundant, were investigated in more detail.

Results show that sedimentation chronology differs between individual, nearby cores, since it strongly depends on the local geomorphic situation. A generalizing approach combining multiple cores' results yields more widely valid conclusions. High sedimentation rates coincided with the initial major anthropogenic disturbance of the landscape and decreased afterwards, probably due to hillslope soil depletion. CPD and SR analysis indicates that generally colluvial sedimentation rates did not change much from 2000 BC onwards. River floodplain sedimentation, in contrast, increased markedly during the first millennium BC and during recent times and a significant time lag in enhanced sediment deposition between the upper and lower reaches of the river valleys was observed.

Keywords: radiocarbon dating, sedimentation rates, geomorphic activity, Sagalassos, Turkey, cumulative probability distributions

1. Introduction

Ancient soil erosion has received considerable attention within the scientific community (e.g. Montgomery, 2007). Past civilizations have modified the landscape through agriculture, logging and grazing, while climate variations also have had a significant impact. As is the case nowadays, humans have consistently attempted to contain sediment dynamics by building e.g. terraces and check dams (e.g. Van Andel et al., 1990). In the Eastern Mediterranean, many studies have studied sediment archives in order to assess landscape changes from both a qualitative and quantitative standpoint. Moreover, these studies have investigated the geomorphic system from small scale colluvial deposits (e.g. Fuchs et al., 2004) up to large river catchments and coastal deltas (e.g. Brückner et al., 2006). Results have been compared to other palaeo-environmental information, both on a small scale (e.g. Lespez, 2003) and on a regional scale (Dusar et al., 2011). However, every palaeo-environmental study relies heavily on temporal information to establish relationships between e.g. land use changes and changes in sediment archives.

Therefore, firm chronological control on past environmental change is critical for palaeo-environmental research, also in the Eastern Mediterranean region. Archaeological investigations mostly rely on cultural indicators such as ceramics for dating, while for the reconstruction of the past landscape sediment archives are a valuable data source. From

65 sediment archives in the Eastern Mediterranean, chronologies of past environmental change
have been reconstructed, but these are mostly limited to specific locations (e.g. Gölhisar Gölü,
Turkey: Eastwood *et al.*, 1999; Drama basin, Greece: Lespez, 2003; Phlious basin, Greece:
Fuchs, 2007; Kinet Höyük, Turkey: Beach and Luzzadder-Beach, 2008; regional overview:
Dusar *et al.*, 2011). These studies illustrate the large spatial variability in the chronology of
70 geomorphic processes in the region, probably due to the influence of local factors. An
integration of these small-scale investigations into a region-wide analysis of the temporal
variation of geomorphic process intensity has only recently been presented (Dusar *et al.*,
2011). However, to properly relate geomorphic process intensity to other palaeo-
environmental variables such as vegetation, climate and human activity, chronological
75 information concerning the entire geomorphic system must be integrated.

Several studies have integrated chronological data concerning the geomorphic system at a
regional scale in Western and Central Europe (e.g. Lewin *et al.*, 2005; Macklin *et al.*, 2006;
Hoffmann *et al.*, 2008; Macklin *et al.*, 2010; Turner *et al.*, 2010; Notebaert *et al.*, 2011a), in
80 the Western Mediterranean (Thorndycraft and Benito, 2006a), India (Kale, 2007), North
Africa (Zielhofer and Faust, 2008), and in south-western USA (Harden *et al.*, 2010).
Previously developed techniques to establish site specific chronologies and analysis tools for
large chronological databases were applied. The spatial integration of temporal information
for colluvial deposits in Germany allowed for the reconstruction of the so-called sediment
85 pathway, which was described as a cascade model with several temporary, intermediate
sediment sinks (Lang and Hönscheidt, 1999). Moreover, reliable chronologies were
reconstructed for small river basins by combining both radiocarbon and luminescence dating
(e.g. Lang and Nolte, 1999). In order to attain to a regional scale analysis, dating information
from several individual locations can be integrated by summing the age probabilities of
90 obtained chronometric data (Lang, 2003; Lang *et al.*, 2003; Thorndycraft and Benito, 2006b).
Recently, this method was further refined by grouping the obtained data according to their
geomorphic situation (Macklin *et al.*, 2010; Turner *et al.*, 2010), and by attempts to take the
influence of the shape of the radiocarbon calibration curve and preservation potential into
account (Hoffmann *et al.*, 2008; 2009; Notebaert *et al.*, 2011a). Cumulative probability
95 distribution and age-depth analysis, as well as floodplain sediment storage quantification for
different parts of the large-scale Rhine river catchment enabled to establish the importance of
past human impact, primarily through land use change, on the geomorphic system at this scale
(Hoffmann *et al.*, 2009). Thorndycraft and Benito (2006b) established a fluvial chronology of

Spain and the links with driving forces by applying the same techniques. However, the validity of some analysis techniques applied over the last few years is a matter of ongoing discussion (Chiverrell *et al.*, 2011a; Macklin *et al.*, 2011; Chiverrell *et al.*, 2011b).

In the Eastern Mediterranean only few landscape scale chronologies have been established. Some studies have dated the formation of alluvial and colluvial fans (e.g. Van Andel *et al.*, 1990), embayment siltation (e.g. Lespez, 2003) or floodplain sedimentation in small river basins (e.g. Casana, 2008). However, most research lacks integration over several spatial scales or morphologic processes, and chronologies differ strongly over the region (Bintliff, 2002; Dugar *et al.*, 2011). Most scholars rely on limited data to establish a chronology of geomorphic activity, which hampers the interpretation and link with the driving factors of landscape change. The limited availability of organic material, a major issue in Western Europe (Lang and Nolte, 1999), is even more problematic in the Mediterranean, since the region's climate is even more unfavourable to preserve ancient organic matter. A firm chronology of past geomorphic processes in the region can be obtained, however, by integrating chronological information from various archives along the sediment redistribution pathway.

The aim of this study is to investigate the temporal variation in geomorphic system response to environmental change during the late Holocene in the territory of Sagalassos, a Hellenistic-Roman city in the Taurus mountain range in south-western Turkey (Waelkens *et al.*, 1999). Over the last two decennia, several case studies have investigated the local history of several aspects of the geomorphic system in the region (Kaniewski *et al.*, 2007a; Six *et al.*, 2008). Here, a database of all available radiocarbon data ($n = 178$) was analyzed to study the chronology of geomorphic activity on a regional scale and to assess the importance of various geomorphic processes. First, an investigation and comparison of two small endorheic basins can clarify the importance of local factors and small-scale spatial variability in sediment dynamics. Second, a regional analysis of the spatial variability of sedimentation rates can inform us about the timing of the principal periods of geomorphic activity across multiple spatial scales. Using a scale dependent approach and by distinguishing between colluvial and alluvial deposits, time lags in the response of the geomorphic system to changes in driving forces can be detected. These driving forces, primarily land cover and climate change, have been studied extensively in the study area (Kaniewski *et al.*, 2007a; 2007b; 2008; Bakker *et*

al., submitted a and b; Duser *et al.*, 2011). This allows us to thoroughly compare the geomorphic system chronologies with the palaeo-environmental record.

2. Study area

This paper concerns the 1000 km² territory of antique site of Sagalassos in southwest Turkey (Fig. 1). The topography of the territory ranges from Burdur Lake (850 m a.s.l.) to the summits of the Beşparmak mountains (2000 m a.s.l.) in the west and from the Aksu valley (650 m a.s.l.) to the summit of the Akdağ Mountain (2250 m a.s.l.) in the east. The main river systems are the Büğdüz River in the west and the Ağlasun River in the east. The geological setting of the territory of Sagalassos is complex, since it is situated at the north-western apex of the Isparta angle and at the north-eastern extremity of the Fethiye-Burdur fault zone (Verhaert *et al.*, 2006). The autochthonous Bey Dağları massif has been overthrust from the east by the Antalya nappes during the Late Cretaceous and Paleocene (65-56.5 Ma), and from the northwest by the Lycian nappes during Late Miocene times (11.6-5.3 Ma) (Glover and Robinson, 1998). Dominating lithologies are limestone (27 %), marls (24 %) and ophiolitic mélangé (12 %), as well as extensive quaternary deposits on the valley floors.

Palaeo-environmental research within the Sagalassos project has focussed on several distinct research goals; therefore, sediment archives have been studied in various geomorphic situations. Initially, the hillslopes neighbouring the archaeological excavation site of Sagalassos were studied (Six *et al.*, 2008), as well as the nearby Ağlasun Çayı valley (Fig. 1; Six *et al.*, 2008). Later, the Gravgaz intramontane basin (Fig. 1) became a major focus, since the marsh in its valley bottom allowed for the combination of geomorphologic research with palynological investigation and the reconstruction of past land use (Six *et al.*, 2008; Vermoere *et al.*, 2000, 2002). Recently, the Büğdüz river system in the west of the Sagalassos territory was studied (Fig. 1), in order to study the Holocene changes of the Eastern Mediterranean geomorphic system on a larger scale, and to quantify sediment fluxes. The relatively flat-bottom, low gradient and wide valley upstream reaches of the Büğdüz river system differ markedly from the lower reaches, which are characterized by an incised river channel and significant height differences within the floodplain. In fact, the upstream reaches largely resemble the smaller scale zero-order colluvial valleys lacking a natural drainage system in the area, such as at Gravgaz.

In the Sagalassos territory, human occupation in the form of villages can be traced back to the Chalcolithic period (ca. 6000 BC). However, sites recovered from these early periods are low

in number and the archaeological periods are of long duration. With the start of the first millennium BC the situation changes (Fig. 2). While the first two centuries remain elusive in the territory of Sagalassos, with the advent of the Archaic period (750 - 550 BC) several newly founded settlements appear that often continue into the subsequent Classical (550 - 330 BC) and Hellenistic (330 - 25 BC) periods. During these periods settlements were primarily located on easily defensible hilltops with agricultural and grazing lands close by. During the subsequent Roman period (25 BC - 300 AD) and Late Roman-Early Byzantine times (300 - 700 AD) the settlement number increased, the total settled area expanded and settlements were located primarily on fertile, flat areas (Vanhaverbeke and Waelkens, 2003). Throughout these two periods, agricultural activities were concentrated in the flat, fertile valley bottoms and relatively low-lying hilly areas, while the surrounding hill slopes were used for grazing. It is assumed that pressure on the landscape was at its maximum during the Roman period (25 BC - 700 AD) in the area (Vanhaverbeke and Waelkens, 2003). During the post-Roman periods the number of sites decreased. Periods marked by sedentary agriculture were alternated by periods for which archaeological evidence of occupation is lacking, and during which nomadic pastoralism was probably the main mode of subsistence.

3. Methods

In order to investigate the geomorphic system chronology for the territory of Sagalassos, a database was assembled containing the radiocarbon data (n=178) obtained from all palaeo-environmental case studies conducted over the last 20 years. 110 of the data were obtained by the authors from the Büğdüz river catchment west of Sagalassos (Fig. 1); 33 were retrieved from the Gravgaz basin (Six *et al.*, 2008; Fig. 1); a further 35 data originate from the eastern part of the territory, primarily from the Ağlasun river catchment (Six *et al.*, 2008; Fig. 1).

Samples for radiocarbon dating were obtained through hand augering, percussion drilling or using a Dachnowski coring device. Selected samples were sieved and organic material was handpicked from the fraction larger than 125 µm. Only terrestrial plant remains, seeds and wood were selected for dating, in order to avoid the hard water effect (e.g. Moore *et al.*, 1998) and the reservoir effect for non-terrestrial plant remains (e.g. Törnqvist *et al.*, 1992). All radiocarbon data, also those obtained from previously published research, were calibrated using OXCAL 4.1 (Bronk Ramsey, 2001, 2009) and the IntCal09 calibration curve (Reimer *et al.*, 2009). To avoid confusion, all calibrated ages are reported in years (a) BC/AD.

200 Additionally, information concerning stratigraphy and geomorphic information was added for
each sample contained in the database. Stratigraphical information mainly distinguished
between fluvial channel and overbank deposits. Geomorphic information concerned the
discrimination between process domains: colluvial versus alluvial deposition. Subsequently,
the database was grouped by geomorphic situation and stratigraphical position of the samples.
205 Peat layer samples were separated from detrital sediment samples, since the former may
indicate landscape stability or a decoupling between the hillslopes and the sediment archive
(e.g. Notebaert *et al.*, 2009). Detrital sediments were further grouped based on their
geomorphic situation: colluvial deposition samples were distinguished from upper and lower
reach alluvial samples. The alluvial samples were further subdivided into relatively fine
210 overbank deposits samples and coarse channel bed deposits samples.

Recent investigations of chronological databases from western Europe frequently make use of
cumulative probability distributions (CPDs), e.g. in Britain (Macklin and Lewin, 2003; Lewin
et al., 2005; Macklin *et al.*, 2010), Poland (Starkel *et al.*, 2006), Spain (Thorndycraft and
215 Benito, 2006a, b), Germany (Hoffmann *et al.*, 2008), the Rhine catchment (Hoffmann *et al.*,
2009) and the Belgian Dijle catchment (Notebaert *et al.*, 2011a). The methodological
framework was further improved by grouping ages corresponding to active sedimentation
phases and normalization of the probability curve to limit the shape effects of the calibration
curve, preservation potential and sampling bias (Hoffmann *et al.*, 2008, 2009; Notebaert *et*
220 *al.*, 2011a).

However, Chiverrell *et al.* (2011a) strongly doubt the validity of much of the aforementioned
cumulative probability distribution analyses. Firstly, Chiverrell *et al.* (2011a) state that the
assumption that each radiocarbon measurement is a true age estimate for a point in time is not
225 valid. Secondly, they argue that much of the CPD structure is related to the shape of the
radiocarbon calibration curve. Thirdly, Chiverrell *et al.* (2011a) claim that temporal
relationships between the dated material and the supposedly dated event are not always
straightforward, e.g. due to pre- or postdating, giving rise to the integration of variable time
lags in the analysis. Finally, they state that chronometric data that were not tested for their
230 robustness, such as from stratigraphies with temporal inversions, should not be included in a
CPD analysis (Chiverrell *et al.*, 2011a). These arguments are all valid if the CPD approach is
applied to investigate a database of geomorphologic events of relatively short duration, such
as floods. For the Sagalassos regional database, we do not aim to establish a very detailed

chronology, but rather a general picture of geomorphic activity with a centennial-scale
235 resolution (cfr. Macklin *et al.*, 2010). The identification of single events which occurred over
the entire landscape is impossible, since the spatial and temporal resolution of the investigated
sediment archives is limited. Therefore, the cumulative probability values in the CPD were
averaged over 100 year bins, which agrees with a more generalized interpretation of the
CPDs. This approach allows to identify the principal periods of geomorphic activity within
240 the study area. This generalization effectively counters the first and third arguments brought
forward by Chiverrell *et al.* (2011a). The second argument, concerning the influence of the
shape of the radiocarbon calibration curve on the CPD structure, was already countered by
Hoffmann *et al.* (2008) and Notebaert *et al.* (2011a). These authors divide the CPD of all
radiocarbon data by a CPD of 100 equally spaced radiocarbon ages, in order to eliminate the
245 calibration curve structure. In this paper, the original CPD was divided by a CPD of 1000
equally spaced radiocarbon ages with the average standard deviation of the entire database,
namely 45 years. The fourth and final argument by Chiverrell *et al.* (2011a), concerning the
robustness of the radiocarbon data, is partially answered by the generalizing approach
discussed above. Stratigraphical inversions indeed yield unreliable chronologies for single
250 sediment archives (Chiverrell *et al.*, 2011a), but each dated stratigraphical layer still
represents a period of geomorphic activity, and should therefore be included in the
generalized CPD approach. However, in case multiple radiocarbon samples from the same
layer were dated and yielded statistically not significant inversions, these data were
aggregated to give a more generally valid age datum for that stratigraphical layer. After
255 cleaning up the dataset following this approach, only in 5 out of the 39 available dated cores
significant inversions remained.

In this study CPDs were constructed for subgroups (colluvial samples, upper and lower valley
alluvial samples) of the Sagalassos radiocarbon database, in order to detect the most
260 significant periods of geomorphic activity. For peat growth, a process limited to one study site
in the region (i.e. the Gravgaz basin; n=16) and therefore not deemed regionally significant,
no CPD was constructed. Additionally, the data obtained from coarse alluvial channel bed
deposits originated from only two study sites (n=11). Since this undoubtedly important
process is poorly dated, these data were not included in the CPD analysis. The CPD of
265 colluvial (n=57), upper (n=23) and lower valley (n=30) alluvial data were corrected for the
influence of the calibration curve by dividing it by the CPD of 1000 equally spaced ages (cfr.
Hoffmann *et al.*, 2008) with a standard deviation of 45 a, corresponding to the average

standard deviation of the entire database. An alternative correction for preservation potential by dividing by the CPD of all available ages (Hoffmann *et al.*, 2008) was not applied, because of the variable preservation potential for the different depositional environments. These differences in preservation potential would lead to an overestimation of the importance of processes with a high preservation potential for a certain period, and vice versa. Finally, the cumulative probabilities were averaged over 100 year bins in order to avoid the interpretation of single peaks as ‘events’ and to deal with the fact that radiocarbon data are no true age estimates for a point in time (Chiverrell *et al.*, 2011a).

Besides the CPD analysis, the temporal changes in geomorphic response to environmental change can be studied through analysis of sedimentation rates (e.g. Hoffmann *et al.*, 2009; Notebaert *et al.*, 2011a). Sedimentation rates (SR_a) are calculated in most studies (e.g. Kaniewski *et al.*, 2007a) for each radiocarbon dated sample i using the following equation:

$$SR_{a,i} = (D_i - D_{i-1}) / (T_i - T_{i-1}) \quad (1)$$

with D_i and T_i the depth and age of the sample, and D_{i-1} and T_{i-1} the depth and age of the stratigraphically younger sample.

Although this approach was applied to all radiocarbon data most of these results are hard to interpret since the majority of cores in the Büğdüz and Ağlasun river catchments contained only few datable samples, a very common problem (e.g. Hoffmann *et al.*, 2008). For the 10 km² Gravgaz basin (Fig. 1), however, 10 cores with detailed stratigraphical description and dated by 33 radiocarbon samples were available (Six *et al.*, 2008; Fig. 4). This basin is drained through a small karstic outlet, hence the sediment export from it is assumed to be insignificant. Additionally, for the Bereket basin (Fig. 5) four well-dated ($n=22$) cores were available (Kaniewski *et al.*, 2007a and this study; Fig. 6). The relatively large amount of data within these small-scale catchments allowed for a detailed scrutiny of the local variability of valley sedimentation. In the Gravgaz basin it was even possible to estimate the total sediment volume stored in the closed basin (Fig. 7), enabling us to calculate average hillslope erosion rates (E_{avg}):

$$E_{avg} = \frac{S_m}{A_{tot} - A_{dep}} \times \frac{1}{BD_{avg}} \quad (2)$$

Where S_m is the total mass of sediment stored within the depositional zone in the Gravgaz valley; A_{tot} is the total catchment area; A_{dep} is the depositional zone area; BD_{avg} is the average bulk density of the hillslope topsoil (1.35 t/m³, analogous to Hoffmann *et al.*, 2008). In order

300 to assess the uncertainty on the calculated valley bottom storage, a Monte Carlo approach was used. This approach was taken because the age datum provided by radiocarbon dating is uncertain within a certain time interval. Therefore, 2000 Monte Carlo iterations were calculated, in which the age datum for each radiocarbon dated sample was randomly chosen within its confidence interval, proportional with its calibrated age likelihood. These ages were
305 then used to calculate sedimentation rates using equation (1). The result of this uncertainty analysis is shown in Fig. 7.

Sedimentation rates vary significantly depending on the core's geomorphic setting and the age of the deepest stratigraphical layer reached. Additionally, radiocarbon dating density and
310 hence temporal resolution strongly differs between cores, blurring the comparison between the SR_a of individual cores and between distinct study areas. To overcome these problems, Hoffmann *et al.* (2009) and Notebaert *et al.* (2011a) suggest the use of mean sedimentation rates (SR_m), calculated as follows:

$$SR_{m,i} = (D_i)/(T_i) \quad (3)$$

315 with D_i and T_i as defined above. The principal advantage of this approach is that it allows for the comparison between cores with different sampling densities. However, this approach assumes that aggradation was continuous since the sample age datum, which might be problematic if an erosion hiatus is present (Sadler effect: Sadler, 1981). The interpretation of SR_m graphs may be less straightforward than the interpretation of SR_a diagrams, but the use of
320 SR_m allows for the application of a simple modelling approach, which can provide additional insight into the chronological database (Hoffmann *et al.*, 2009; Notebaert *et al.*, 2011a).

The modelling approach takes advantage of the straightforward SR_m calculation. Model input consists of SR_a per period of 100 years over the last 10000 years, from which the SR_m at each
325 point in time is calculated. A Monte Carlo modelling approach was applied to explore the sedimentation rate trend in alluvial overbank deposits over the last 4000 years. Following the visual inspection of the SR_m graph, a period of enhanced sedimentation rates during the first millennium BC was modelled, as well as an increase to modern rates during the last several centuries. The start of the first millennium BC enhanced sedimentation was varied from 1000
330 BC to 0 AD, and its duration was varied from 100 to 1000 years. The onset of the recent increase was varied between 1300 AD and 1900 AD. Moreover, sedimentation rates during the peak periods were varied from 2 to 15 mm a⁻¹. Overall, the over 160 000 model runs were evaluated using the Model Efficiency (ME; Nash and Sutcliffe, 1970):

$$ME = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - O_{mean})^2} \quad (4)$$

With O_i the individual radiocarbon dated SR_m (observations), P_i the model-predicted SR_m for each individual observation and O_{mean} the average of all observed SR_m .

It must be noted that the high alluvial SR_m during recent centuries on the right hand side of Fig. 8 were omitted from the modelling approach. These samples are located directly behind a dam, and represent direct anthropogenic alterations to the geomorphic system rather than the impact of changing land use and climate on the hillslope-floodplain geomorphic processes.

4. Results

Cumulative probability distribution analysis

These CPD plots are based on relatively limited data; therefore only general trends are described. The cumulative probability distributions (Fig. 9) provide information on the principal periods of geomorphic activity as preserved within sediment archives from different geomorphologic situations. The CPD of colluvial ages (Fig. 9A; $n=57$) shows major activity phases around 900-400 BC and the 7th century AD and minor activity around 4000 BC and generally since 2000 BC. Upper river valley ages (Fig. 9B; $n=23$), on the other hand, show major activity generally since 2000 BC and a marked gap from 0-300 AD. Minor activity is observed around 6600 BC and 3600 BC. The CPD of lower river valley ages (Fig. 9C; $n=30$) shows major activity around 1000 BC and from 1400 AD until present.

Temporal analysis of sediment accumulation at Gravgaz and Bereket

A detailed sedimentation chronology was established for the 10 km² Gravgaz catchment (Fig. 7). Generally, valley sedimentation was limited prior to 850 BC (below 300 t a⁻¹; Fig. 7), corresponding to an average hillslope erosion rate (E_{avg}) of 0.03 mm a⁻¹. From 850 BC onwards, valley sedimentation increased dramatically, peaking between 525 BC and 300 BC (± 2700 t a⁻¹; $E_{avg} = 0.28$ mm a⁻¹). After this peak valley sedimentation stabilized at 1300-1500 t a⁻¹ ($E_{avg} = 0.14$ -0.16 mm a⁻¹). Two minor peaks (± 1900 t a⁻¹; $E_{avg} = 0.20$ mm a⁻¹) are observed between 0-300 AD and 940-1130 AD (Fig. 7). The amplitude of the latter peak is highly uncertain, as it relies on closely related radiocarbon data within one single core.

Similar to Gravgaz, the Bereket basin represents a closed depression, since the valley outlet was at least partially blocked by a fan originating from a colluvial zero-order valley until the 20th century (Kaniewski *et al.*, 2007a; Fig. 8). Sedimentation rates for this valley were

obtained from four cores (Fig. 6), and spatial variability is similarly significant as in the Gravgaz valley. This variability appears to be due to the differing geomorphic situation between the cores (Fig. 5), as core SA10GV-B13 is located in a zero-order colluvial valley, while core SA09JB-Drill02 is situated on a small colluvial fan at the outlet of a steeper zero-order catchment; cores BKT1 and BKT 2 (Kaniewski et al., 2007a) are situated in the centre of the former Bereket marsh (Fig. 4). Moreover, the averaging effect for relatively poorly dated time periods is significant, as illustrated for both the Bereket and Gravgaz basins (Fig. 10).

Mean sedimentation rate analysis

Regional-scale mean colluvial and alluvial sedimentation rates (SR_m) show strongly differing trends (Fig. 8). Colluvial sedimentation was rather constant in the last 4000 years, indicating relatively continuous sediment fluxes at small spatial scales. Alluvial sedimentation rates, conversely, peak during the first millennium BC and during recent centuries. This signal results from fluvial processes directly linked to hillslope erosion, such as overbank deposition, but floodplain reworking and channel migration may also be significant.

The results of the Monte Carlo modelling approach (Fig. 11 and 12) show that scenarios with an early increase in sedimentation rate of short duration during the first millennium BC fits best to the field data. Moreover, the increase in sedimentation rates towards the modern values also started rather early, during the late Middle Ages. However, the Monte Carlo simulations did not predict the amplitude of the enhanced sedimentation well (Fig. 12).

5. Discussion

To establish a chronology of geomorphic system response to past environmental change, most palaeo-environmental research in the Eastern Mediterranean relies on data which are spatially severely limited (e.g. Eastwood *et al.*, 1999; Kaniewski *et al.*, 2007a). Therefore, in order to establish a detailed chronology of geomorphic response to Holocene environmental change for the territory of Sagalassos, a large database comprising 178 data was assembled. Although this is the largest database on sediment dynamics in the late Holocene for the entire Eastern Mediterranean Region, the available data is still severely limited. For instance, in the 260 km² Büğdüz river system 31 valley cross-sections were investigated and 14 yielded reliable radiocarbon data, but only from six cross-sections three or more radiocarbon samples could be retrieved. The limited availability of datable organic remains in floodplain deposits of Eastern Mediterranean rivers results in such imperfect temporal information: some time periods are

400 represented rather poorly in the database compared to other periods. This is problematic as the length of the time period over which sedimentation rates are integrated strongly influences the resulting sedimentation rates (Fig. 10). The Sagalassos radiocarbon database was analyzed combining multiple approaches in order to establish a temporal framework of geomorphic activity and sediment fluxes during the Holocene. Consequently, general trends could be
405 detected for specific depositional environments, such as alluvial and colluvial deposits. The integration of data from multiple case studies into one database is not unproblematic, since each radiocarbon dated sample was taken bearing a specific research objective in mind. For example, the study by Kaniewski *et al.* (2007a) at Bereket focused primarily on the Classical-Hellenistic and Roman time periods (roughly from 500 BC to 700 AD) and the research
410 objective of core SA09JB-Drill02 is to study specifically the post-Roman environmental changes. Although the differing level of temporal detail for various periods hampers proper interpretation, it is evident that sedimentation rates between single coring locations differ strongly for sub-periods of the late Holocene.

415 In the Bereket valley, a significant time lag can be observed between sedimentation in the upper, zero-order colluvial valleys (core SA10GV-B13) and the lower main valley (cores BKT1 and BKT 2: Kaniewski *et al.*, 2007a; core SA09JB-Drill02). This time lag may be due to all core locations being situated in different geomorphic settings (Fig. 5): core SA10GV-B10 is located in a small upland colluvial valley; cores BKT1 and BKT 2 (Kaniewski *et al.*,
420 2007a) are located in the marsh upstream the valley-blocking colluvial fan; core SA09JB-Drill02 is located right on a smaller colluvial fan at the outlet of a small zero-order valley coming from the south. This example indicates the importance of a proper geomorphic mapping of a basin for a reliable reconstruction of its sedimentation history. Point based information may not be representative of the evolution of the larger geomorphic system. The
425 reconstruction of the latter requires an approach integrating data from multiple geomorphic situations. These results clearly show that a reconstruction of the sediment dynamics, as well as its interpretation in terms of climate or land use change, based on a single or even a limited number of corings has no scientific basis (Richards, 2002). Poorly dated cores result in less detailed SR_a curves and yield lower peak sedimentation rates. Combining all available data
430 for the Gravgaz basin allowed establishing a sediment accumulation chronology in the valley bottom. To quantify sediment storage, however, detailed information concerning core stratigraphy, organic matter content and sediment bulk density is necessary. All these factors influence the total mass of accumulated sediment (Fig. 7). Peat growth in the central marsh

area of the Gravgaz valley increased from about 650 BC onward, due to decreased hillslope-derived sediment input. When sediment bulk density and thus organic matter content are taken into account, the results provide a more reliable sedimentation history than a pure volumetric approach does, which in itself is already better than the analysis of site-specific sedimentation rates.

Also at other locations in the territory of Sagalassos multiple dated cores were available. In the Ağlasun River and Çanaklı valleys (Six, 2004), however, a detailed sedimentation history analysis for the last few millennia was not possible. Firstly, radiocarbon data from both catchments are significantly older than in the western part of the territory of Sagalassos, resulting in a low temporal resolution of the sediment archives during recent periods.

Secondly, sediment archive stratigraphies are hard to interpret due to the presence of step-like travertine dams in the Ağlasun River floodplain (Degryse *et al.*, 2008). In the 110 km² Çanaklı basin only two cores were available. These cores are situated near the north-western edge of the basin, making their catchment-wide significance doubtful.

The analysis of mean sedimentation rates (SR_m) provides information about the timing and intensity of past geomorphic activity. This approach, however, is sensitive to averaging effects, since the longer the integration time period, the higher the likelihood over variations in sedimentation rates or the occurrence of erosion (Sadler, 1981; Fig. 10). The so-called Sadler effect may hamper the interpretation of SR_m , especially in systems with discontinuous sedimentation and the possible occurrence of erosion phases, like the Sagalassos territory. However, from sedimentological analysis it was concluded that erosion phases during the Holocene were insignificant in colluvial valleys such as at Gravgaz (Six *et al.*, 2008) and Bereket (Kaniewski *et al.*, 2007a). The same applies most likely to the upper river valleys in the territory of Sagalassos, since these represent similar geomorphic situations.

However, in the lower Büğdüz river valley, at least one significant erosion hiatus, dated to around 0 AD, was found in one floodplain cross-section. This hiatus influences the obtained SR_m for samples older than the erosion phase, and the SR_a calculations for periods which include the erosion phase. Nevertheless, it is evident that this hiatus does not obliterate the significant peak in observed SR_m during the first millennium BC (Fig. 11). Additionally, the number of samples affected by this erosion hiatus adds up to only 15% of the alluvial data used in the analysis. It must be noted that interpretation of the SR_m analysis is only valid over a centennial time scale (Fig. 12).

The combination of the SR_m analysis and the Monte Carlo model simulations provides further insight into the Holocene sediment dynamics. Enhanced sedimentation started early in the first millennium BC (most probably around 700 to 800 BC, and the peak period was of relatively short duration (200-300 years). Moreover, the rise towards contemporary sedimentation rates started already during the 14th century. The amplitude of the sedimentation rate peaks, however, is less obvious from the modelling results. The best sedimentation rate scenarios for the Sagalassos region differ strongly from the pattern of sedimentation rates modelled for western European regions (e.g. Hoffmann *et al.*, 2009; Notebaert *et al.*, 2011a). Geomorphic activity in the Eastern Mediterranean seems to have started well before the large settlement expansion of the Hellenistic and Roman periods indicated by archaeological evidence. However, the peaks in sedimentation do correspond to an increase in archaeologically visible activity in the region. In the territory of Sagalassos, the peak that started around 800 or 700 BC corresponds to the start of the Archaic period when, after a period devoid of artefacts, several settlements appear. These settlements are still limited in number but often located at hilltops. Forest clearing on slopes, e.g. for building material, fuel, or to attain agricultural fields, will have impacted sedimentation much more than similar activities in the valley bottoms. To a smaller degree this also applies to the peak in the 14th century BC, when Late Bronze Age (1450 - 1180 BC) hilltop sites were first founded after the as of yet elusive Middle Bronze Age (2000 – 1450 BC) (Vanhaverbeke and Waelkens, 2003). Later, sediment dynamics declined, probably due to interplay between changing strategies for settlement location and land use, the declining pressure on the landscape after the Roman period, and the depletion of the soil reservoirs in the region. Similar soil depletion-driven land use changes were also observed in Lesvos, Greece during the 20th century (Bakker *et al.*, 2005). The recent increase in sedimentation rates, on the other hand, may be related to more intensive agricultural activity on the lower hillslopes and floodplains. Additionally, recent landscape modification by engineering works such as terrace construction, dam building and the construction of irrigation systems also has an indirect impact on sediment dynamics. In Western Europe, and more specifically in the loess belt, geomorphic activity increased rather continuously during the late Holocene, in line with the continuous increase in anthropogenic pressure on the landscape through land use changes, mainly deforestation (Hoffmann *et al.*, 2008; Notebaert *et al.*, 2011a; Notebaert *et al.*, 2011b). Moreover, soil depletion in the loess belt is not an issue, since soils are homogeneous and deep.

To discuss the role of the driving factors in the timing of geomorphic activity, first the changes in these driving factors must be assessed. Climate and vegetation changes in the Eastern Mediterranean during the Holocene are discussed in detail by Dusa *et al.* (2011). Apart from the natural variations, mainly expressed by periods of relative wetness or dryness similar to the Medieval warm period or Little Ice Age in Western Europe (Bakker *et al.*, accepted), human impact on the geomorphic system was obviously important during the late Holocene in the Eastern Mediterranean. In the Sagalassos territory, palaeo-environmental investigations have resulted in very well established chronologies of natural and human-induced environmental change (Vermoere *et al.*, 1999; 2000; 2001; 2002; Kaniewski *et al.*, 2007a; 2007b; 2008). Comparing the land use and climate history with the chronological analysis of geomorphic activity in the territory of Sagalassos, it is observed that the initial landscape-wide disturbance by man, mainly through deforestation, during the early first millennium BC (Fig. 2) coincided with a major sedimentation pulse in the small-scale basins of Gravgaz and Bereket. A similar response to the initial human disturbance is reported by various studies in the Eastern Mediterranean (e.g. Bintliff, 2002; Fuchs, 2007; Lespez, 2003), but these studies do not indicate the declining intensity of geomorphic activity during subsequent periods of even more enhanced landscape pressure. For Gravgaz and Bereket detailed palynological data are available, which allows for the proposition of another hypothesis of the principal driving forces of hillslope soil erosion. The relation with the regional settlement history is not obvious, however, probably due to the relative lack of data concerning the period before 350 BC.

The timing of alluvial sedimentation obtained from the CPD and SR_m analysis shows a time lag between upper and lower valley floodplains in the territory of Sagalassos. In small scale colluvial valleys such as the Gravgaz basin, enhanced sedimentation coincided with the initial landscape disturbance, and time lags between individual cores were not significant. In Bereket, the temporal variation in sedimentation rates between the three coring locations may at least partly due to their differing geomorphic situation, as well as variable landscape disturbance in the sub-catchments, as opposed to actual time lags within the same geomorphic system. The upper Büğdüz River valley floodplains largely show a similar sedimentation history during the late Holocene. The onset of floodplain overbank sedimentation in the lower reaches, however, shows a time lag of several centuries (Fig. 9) compared to the upper and colluvial valleys. This time lag is partly explained by the changing land use pattern from the

Hellenistic towards the Roman period and the increased agricultural activity on the easily accessible hillslopes directly bordering the Büğdüz River trunk valley. Both factors enhanced connectivity of the geomorphic system, on the one hand between upper and lower valley floodplains, on the other hand from the lower hillslopes towards the trunk valley.

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Results from this study show that spatial variability in past sedimentation rates cannot be neglected in the Eastern Mediterranean. Therefore, chronologies of late Holocene geomorphic activity obtained in this region must be critically reviewed, since most studies rely on limited coring data, or investigate a single type of sediment archive (Dusar et al., 2011). In Western Europe, Australia and the USA sediment budgets integrating the different components of the entire sediment pathway throughout the geomorphic system have been established indicating the temporal variability between sub-periods of the late Holocene (e.g. Fryirs and Brierley, 2001; Trimble, 1999; Notebaert *et al.*, 2009). This implies that research cannot concentrate on one location or one type of sediment archive to establish a chronology of past geomorphic activity, since the signal recorded in e.g. colluvial or lacustrine sediment archives is strongly dependent on the configuration of the geomorphic system at that time. Therefore, past geomorphic system can only be studied by integrating data from multiple locations and various types of sediment archives. Moreover, the application of quantifying approaches and geomorphic modelling is recognized (Dusar et al., 2011), and will be applied on the study area. Still, this study provides an indication of the potential of this integrative approach in the Eastern Mediterranean region. Results from small endorheic colluvial basins can be combined and compared to the chronology of geomorphic activity in a much larger river basin. However, this study does not rely on single archives to come to regional scale conclusions, but rather combines a large array of data from previous and present-day research. This is probably the largest distinction between this study and much geo-chronological research in the Eastern Mediterranean, as discussed by Dusar et al. (2011).

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6. Conclusions

In this study, a database of 178 AMS radiocarbon ages was assembled from the 1000 km² Sagalassos territory in south-western Turkey. This database was analyzed using cumulative probability distributions, sedimentation rates and a Monte Carlo modelling approach (Fig. 13).

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Results indicate that variability between individual cores is significant due to differences in local geomorphic situation. Therefore, single sediment archives cannot be used for landscape reconstruction purposes, since the temporal variation in connectivity between landscape elements is significant. Additionally, the settlement history and land use history in the territory of Sagalassos show that historical human landscape disturbance is diachronic. This partly explains time lags between various parts of the geomorphic system. As a result, variations in sediment fluxes and sedimentary archives in different parts of the geomorphic landscape do not show a linear relationship with driving force variations. Harvey (2001, 2002) demonstrates how variations in connectivity between different parts of the sediment pathway influence the relative importance of the different sedimentary sinks. While colluvial deposits in zero-order valleys are more likely to be directly influenced by changes in erosion rates due to their spatial connection, downstream floodplains may show a less direct link due to buffering by intermediate sinks. Therefore, the link between driving forces and geomorphic response is much harder to establish for larger river systems (Trimble, 1999). This paper provides evidence that this issue also applies to the Eastern Mediterranean: sedimentation rate studies from lakes, colluvial deposits, river mouths and generally single locations within the geomorphic landscape do not record overall changes in geomorphic activity within their catchment area. Therefore, multiple locations within the landscape must be dated and investigated in order to establish a chronology at various scales and for different processes (Verstraeten *et al.*, 2009). The application of cumulative probability distribution analysis on a regional database containing chronological information about geomorphic activity can indicate the principal periods of geomorphic activity. Sedimentation rate analysis aided by a modelling approach allows for the assessment of the timing and duration of the most important activity phases.

Results from the CPD and SR_m analysis show the contrast in timing and sedimentation rates of colluvial deposits versus alluvial deposits. Colluviation occurred continuously over the last four millennia, although a distinct major activity phase was observed around 500 BC. Since then, colluvial sedimentation rates apparently have remained constant. On the other hand, upper valley alluviation peaked in the first half of the 1st millennium BC, with significantly less activity afterwards. The same applies to lower valley alluviation, although sediment deposition was more important during the 2nd millennium AD. The results from the CPD and MSR analysis mutually agree, however (Fig. 13).

Chronologies established for the small-scale colluvial basins of Gravgaz and Bereket have shown that a first disturbance phase caused a marked hillslope erosion peak and hence enhanced valley sedimentation rates. Still, they do not agree on the timing of the initial, widespread landscape disturbance. After the initial phase valley sedimentation rates decreased, to only rise again during the last several centuries. Comparing with palynological information, the timing of this initial pulse appears to coincide with important human-induced land-use changes. Its amplitude, along with subsequent declining sedimentation rates, was determined by the landscape sensitivity towards erosion. Hillslope soils in the Eastern Mediterranean are relatively shallow, and they get progressively deprived of erodible material with ongoing erosion, causing sedimentation rates to decline. At a larger scale, alluvial sedimentation shows principally the same trend, although slightly delayed. This time lag appears to increase further down the Büğdüz river system, since the systems' buffering capacity probably slowed the propagation of the upstream signal for a certain time period.

In order to further test the possible causes for the observations drawn from this studies' database analysis, further dating refinement is needed, as well as the application of a geomorphic landscape evolution model (cfr. Notebaert *et al.*, 2011b; Peeters *et al.*, 2006). This model should take land use and climate change into account, along with the specific landscape characteristics of the Eastern Mediterranean, such as soil depth and topsoil stone content, both significantly affecting soil erosion in the region. Combined with reliable chronological research, it can form the basis of a holistic investigation approach towards the history of Mediterranean landscapes.

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Fig. 1. Location of the territory of Sagalassos in south-western Turkey. All radiocarbon dated sediment archives are indicated (black dots), as well as the outline of the territory of Sagalassos (dotted line) and the extent of the Bügdüz River catchment (continuous black line). The location of the ancient city of Sagalassos is also indicated (red star).

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Fig. 2. Number of settlements in the territory of Sagalassos (± 1000 km²) per time period (full line; adapted from Vanhaverbeke and Waelkens, 2003) and arboreal pollen concentration at Gravgaz (broken line; Vermoere et al., 2002).

Fig. 3. Profile with three of the cores in the Gravgaz valley floor indicated. Sedimentology and radiocarbon dating was carried out by Six et al. (2008). This profile was redrawn based on Six (2004, pp. 136).

895 Fig. 4. Sedimentation rates (mm a^{-1}) for 3 cores in the Gravgaz valley. The cores are ranked by distance to the karstic basin outlet (far: black; close: grey).

Fig. 5. Geomorphic map of the Bereket area with indication of sediment cores.

Fig. 6. Sedimentation rates (mm a^{-1}) for three cores in the Bereket valley. The cores are sorted by upstream area size (small: full line; medium: broken line; large: dotted line). The core labelled 'Kaniewski' is a synthetic record based cores BKT1 and BKT2 (Fig. 5) that were integrated based on correspondence in the pollen records (Kaniewski et al, 2007a).

915 Fig. 7. Average valley sedimentation mass (t a^{-1}) in the Gravgaz valley. This graph is the result of 2000 Monte Carlo simulations to account for the uncertainty on the calibrated radiocarbon ages.

Fig. 8. Mean sedimentation rates (MSR, mm a^{-1}) for all dated samples, sorted per depositional environment.

Fig. 9. Cumulative probability distributions (CPDs) for radiocarbon data in the territory of Sagalassos. Probabilities were divided by the probabilities of equally spaced ages. Furthermore, the relative probability was averaged per 100 year time period. (A) Colluvial ages (n = 57) (B) Alluvial upper valley ages (n = 23) (C) Alluvial lower valley ages (n = 30).

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Fig. 10. Sedimentation rate (mm a^{-1}) versus integrated time period (a) for all radiocarbon dated samples retrieved from the Gravgaz basin (squares) and from the Bereket basin (triangles).

Fig. 11. Mean sedimentation rates (SR_m) of chronometric data from alluvial overbank deposits in the Sagalassos territory (black dots) and two of the top 20 model results from the mean sedimentation rate (SR_m) modelling approach on alluvial overbank ages. The black lines represent the optimal scenario (ME = 0.566), while the broken lines represent an alternative scenario with a slightly longer, but less intense sedimentation peak during the early 1st millennium BC (ME = 0.563). These scenarios were selected to depict the variability between the best model runs based on ME. The black dots represent the data used to test the model. All points correspond to clear alluvial overbank deposits not disturbed by man.

Fig. 12. Histograms of the 1% best mean sedimentation models based on model efficiency (ME) for alluvial overbank sedimentation in the territory of Sagalassos. Bars are centred at the period assumed for the start of increased sedimentation; bar fill is chosen according to the assumed duration of the enhanced sedimentation period. (A) Start and duration of the increased sedimentation period during the 1st millennium BC. (B) Start of the most recent phase of increased sedimentation.

Fig. 13. Synthesis of the chronological information analyzed in this study, compared to the settlement density in the territory of Sagalassos. The line thickness is related to the number of settlements, sedimentation rate and cumulative probability value, respectively. (a) Number of settlements in the ± 1000 km² territory of Sagalassos (Fig. 2). (b) Valley sedimentation in the Gravgaz valley bottom (Fig. 7). (c) Sedimentation rates in the three cores analyzed in the Bereket basin (Fig. 6). (d) Cumulative Probability Distribution values (Fig. 9): (d-c) colluvial deposits; (d-uv) upper river valley deposits; (d-lv) lower river valley deposits. (e) Results from the Monte Carlo modelling approach on mean sedimentation rates.