A chronology of alluvial fan response to Late Quaternary sea level and climate change, Crete

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Introduction

The Mediterranean basin lies at the climatic boundary between arid North Africa and temperate mid-latitude Europe (Harding et al., 2009; Tzedakis, 2009; Rohling et al., 2015) and is, consequently, highly sensitive to environmental change. This sensitivity is well-expressed in the palaeo-record (Allen et al., 1999; Moreno et al., 2004). Marine and speleothem records from the Mediterranean provide clear evidence for temperature and rainfall variations on both orbital and millennial/centennial timescales during the Late Quaternary (Cacho et al., 1999; 2000; Emeis et al., 2003; Bar-Matthews et al., 1999; 2003). Many researchers have subsequently suggested that these archives record climatic events that are the correlatives of the high-magnitude/high-frequency Dansgaard-Oeschager events that are preserved in the Greenland ice core record (Bar-Matthews et al., 1999; 2003; Sànchez Goñi, et al., 2002; Moreno et al., 2004). The long pollen records that are preserved in the sedimentary basins of this region show that ecosystems of the Mediterranean are also highly sensitive to environmental fluctuations and provide evidence for vegetation response on both orbital and sub-orbital timescales (Allen et al., 1999; Tzedakis, et al., 2003).

As prevailing climate and vegetation will dictate surface hydrology and sediment supply, there is good reason to suppose that surface processes, such as fluvial systems, should also be highly responsive to Late Quaternary environmental dynamics (Rose and Meng, 1999; Rose et al., 1999; Macklin et al., 2002; 2012). This suggestion has been supported by a number of pioneering studies that have applied a range of geochronological techniques (primarily luminescence-based approaches and U-series techniques) to fluvial sediments and landforms from a number of catchments across the Mediterranean basin (see Fuller et al., 1998; Rose and Meng, 1999; Rose et al., 1999; Rowan et al., 2000; Candy et al., 2004; 2005; Pope and Wilkinson, 2005; Pope et al., 2008; Adamson et al., 2014). These studies suggest a broad consistency in Mediterranean fluvial response with phases of large-scale alluviation correlating to cold-dry stadial environments, i.e. Marine Isotope Stages (MIS) 5d, 4 and 2, whilst warm-moist interstadial/interglacial environments, i.e. MIS 5e and 5a, appear to be characterised by either widespread catchment stability or by fluvial incision (Rose et al., 1999; Macklin et al., 2002). A number of authors have also proposed that sediment/landform-evidence for fluvial response to abrupt climatic events during MIS 3 can be observed in several Mediterranean catchments (Fuller et al., 1998; Macklin et al., 2012). Such studies are part of a consistent palaeoenvironmental narrative that highlights the sensitivity of Mediterranean environments, ecologies and geomorphic systems to climate forcing.

The early attempts to construct chronologies for Mediterranean fluvial archives have a number of limitations that restrict a full understanding of the relationship between climate forcing and geomorphic response. These limitations are primarily related to the dating techniques that have been applied and can be placed into two categories: 1) the magnitude of uncertainties associated with the ages and with the resulting age estimates for fluvial response, and 2) the number of age estimates that are used to constrain a fluvial sequence. For example, OSL ages of Mallorcan alluvial fan sequences by Rose and Meng (1999) and Rose et al. (1999) defines a phase of alluviation to MIS 5d (age estimate = 109.2 ka) but the uncertainties associated with that age are twice the duration of the substage with which the alluviation phase is correlated (uncertainties = ±16.7 ka). Furthermore, many of these chronologies are based on a relatively small number of age estimates. For example, U-series dating of river terraces of the Rio Aguas in southeast Spain has been used to produce a landform chronology for the past 300 ka but this is based on just 13 dates (Candy et al., 2004; 2005). Furthermore, the Sparta basin chronology of Pope and Wilkinson (2005) is constrained by just 14 OSL ages, spread across multiple fan systems and spanning the last 240 ka. Consequently, although the timing of fluvial response in some of these studies appears to relate to climate forcing it could be argued that such conclusions are based on a restricted number of age estimates and a more extensive dataset is required to robustly prove such a relationship.

It should be highlighted that these comments are not a criticism of these studies, but a reflection of the limitation of the techniques that existed at the time that such work was undertaken. A number of developments in both OSL and U-series dating over the past 20 years has meant that it is now possible to routinely analyse samples that were previously problematic for dating and to generate age estimates of much greater precision (Murray and Wintle, 2000; 2003; 2006; van Calsteren and Thomas, 2006; Geach et al., 2015). It is now possible to produce more extensive fluvial chronologies with lower uncertainties, allowing better links between geomorphic response and climate forcing.

In this study we present an OSL and U-series based chronology for the small (surface area = <6.5 km^2) Sphakia alluvial fan, in southwest Crete. This alluvial fan has been described elsewhere (Nemec and Postma, 1993; 1995; Pope et al., 2008; Ferrier and Pope, 2012). On the basis of detailed mapping and U-series dating, the formation of Sphakia fan has previously been placed within a Quaternary timeframe and comprises three main phases of alluviation (segments 1, 2 and 3) separated by downcutting and fan entrenchment (Nemec and Postma, 1993; 1995). The new chronology presented here is based on >30 age estimates. The dataset is used to: 1) test the agreement between the OSL and U-series age estimates in order to assess the validity of the derived chronology; 2) test whether the main phases of fan entrenchment are associated with significant changes in either sea level or climate; and 3) determine if there is a clear link between the timing of fan alluviation and cold/dry stadial climates. The paper discusses the factors that drive alluviation and incision within Sphakia fan over the late Quaternary and concludes by highlighting the importance of generating extensive chronological datasets to robustly understand the timing of Quaternary fluvial response.

Regional setting and site context

The Sphakia fan is one of a number of alluvial fans along the Sphakian piedmont in southwestern Crete (Pope et al., 2008; Figure 1). The Sphakian piedmont forms a prominent 24-km long and 1.5 to 2.5-km wide east to west trending coastal plain between Chora Sphakia and Skaloti (Figure 1). The piedmont represents the onshore segment of the southern Cretan margin and preserves a complex regional sedimentary history relating to the interplay of tectonics and climate over Late Neogene to Quaternary timescales (Skourtsos et al., 2007). Following the formation of the extensive Sphakian fault system, the piedmont underwent rapid subsidence culminating in the deposition of Miocene to lower Pleistocene littoral sands, marls, and clays (Skourtsos et al., 2007). Subsequent uplift and the gradual re-emergence of the piedmont at the end of the lower Pleistocene led to significant erosion of marine sediments and formation of a low relief sub-aerial platform that provided the accommodation space for coalescent alluvial fans (Skourtsos et al., 2007).

The southern margin of the east-west piedmont is clearly marked by a 10 to 30 m high coastal cliff that formed by a combination of marine erosion and continued tectonic activity during the Holocene (Postma and Nemec, 1990). The northern margin of the piedmont is delimited by the southeastern flanks of the Lefka Ori range (Pope et al., 2008). Structurally, the Lefka Ori is the southernmost portion of a late Eocene to early Oligocene thrust-pile, comprising intensely folded carbonates, meta-siliclastic sediments, mica-schists and quartzites of late Triassic to late Cretaceous age (Skourtsos et al., 2007). Continuous uplift since the late Pliocene has elevated the Lefka Ori to create four distinctive zones (Pope et al., 2008): 1). the high mountains (c.2400 to 1700 m amsl) comprising karstic landscapes thought to have been sculpted by glaciers associated with a localised Pleistocene ice cap; 2). the lower glacial/periglacial mountainous zone (c.1700 to 900 m amsl) that serves as the main sediment source area for the piedmont; 3). the foothills (900 to 200 m amsl); and 4). the badaja (<200 m amsl), which comprises nine coalescing fans dissected by a series of north-south trending gorges.

Intermittent alpine savanna comprising *Cupressus sempervirens* and *Juniperus oxycedrus* extends across the high mountain zone and defines the tree line at c.1500 m amsl (Rackham and Moody, 1996). Below the savanna, extensive woodland dominated by *Pinus brutia* and *Quercus coccifera* occupies a well-defined altitudinal zone (200 to 1300 m amsl) across the lower mountain and foothill zones, with phrygana and steppe covering the coastal plain (Nixon et al. 1988). The region is characterised by a highly seasonal precipitation regime with rainfall concentrated into the late autumn and winter period. Mean annual rainfall is estimated to range between c.180 mm on the coastal plain (Nemec and Postma, 1993) and 800 to 1100 mm in the mountain zone (Rackham and Moody, 1996). For the high mountain zone estimated annual rainfall varies between 1500 and 2000 mm, producing significant snow cover during between the winter and late spring period (Rackham and Moody, 1996).

The Sphakia fan (Figure 1) occupies the western end of the piedmont (Nemec and Postma, 1993; Pope et al., 2008; Ferrier and Pope, 2012). This fan is fed by a steep-sided and entrenched gorge, which drains zones 1 to 3 of the Lefka Ori. The three telescopic segments occur downstream of the entrenched fan headcut (Figure 2). These segments comprise three main phases of fan aggradation (Pope et al., 2008); segment 1 (oldest), segment 2 and segment 3 (the youngest). Field surveys confirm that segment 2 consists of three distinct surfaces namely 2A (oldest), 2B and 2C (youngest [Figure 3]). Each segment consists of aggradations of sediment that are primarily coarse-grained (cobble and pebble dominated with occasional boulders) with interbedded, laterally discontinuous units of fine to medium sands and silts (Nemec and Postma, 1993; Pope et al., 2008). Two types of coarse-grained deposit can be identified (Figure 4); 1) poorly-sorted units with a high proportion of fine (silt/clay) matrix (typically matrix supported) or 2) moderately-sorted units of sands and gravels (typically clast-supported fabric). These sediment types are suggested to reflect the operation of mass-flow/debris-flow (poorly-sorted, matrix-supported sediments) and current/fluvial flow (moderately-sorted, clast supported sediments) (Pope et al., 2008). Deposits of segment 2 and 3 are dominated by the moderately-sorted/clast supported sediments suggesting that, during these episodes of fan aggradation, fluvial sedimentation was the dominant process (Pope et al., 2008). Deposits of segment 1 contain both poorly-sorted/matrix-supported sediments and moderately-sorted/clast supported sediments, implying that both fluvial and debris flow processes played a significant role during this phase of fan aggradation (Pope et al., 2008). The segment 1 and 2 deposits have undergone localised cementation by secondary carbonate. These cements predominantly consist of large, equant spar crystals that are typical of phreatic cements (Candy et al., 2012).

Methodology

Optically Stimulated Luminescence (OSL) ages

Twenty four samples from Sphakia fan were collected in copper tubes (5 cm in diameter and 20 cm in length) from sections logged by Pope et al. (2008). Potentially light exposed material from the tube ends was removed and used to for measuring *in-situ* water content. The quartz fraction of the 180–250 μm size was obtained by sieving, 10% HCI and H_2O_2 treatments, heavy liquid density separation, and 20% HF etching (Murray et al., 1987). All quartz particles were screened for contamination by feldspars by examining the response to infrared stimulated luminescence (IRSL) with contaminated samples undergoing further HF treatments and infrared bleaching. Following these treatments, approximately 300 grains were mounted on 9.8 mm diameter stainless-steel discs prior to measurement. All luminescence measurements were carried out in accordance with the single-aliquot regenerative (SAR) protocol of Murray and Wintle (2000, 2003). The equivalent dose (De) for each quartz-rich extract was calculated from radionuclide concentrations and cosmic ray contributions based upon each sample’s burial depth (Prescott and Hutton, 1994). To assess the reliability of the measured SAR data all samples were subjected to dose recycling and dose recovery tests using a 10-s preheat range of 240-260°C. Age estimates were derived by dividing De by the total dose rate (D).

U-series dating

Eight carbonate samples were collected using a hammer and chisel. Wherever possible, carbonates were sampled in close proximity and in stratigraphic relationship to OSL samples so that ages derived by the two methods could be directly compared. In almost all cases phreatic spar cements were targeted as these, like speleothems, are well-suited for U-series dating (van Calsteren and Thomas, 2006), being; 1) densely-cemented and consequently resistant to post-formational U/Th loss or gain, and 2) relatively pure with minimal detrital contamination. Samples that contained ^{230}Th/^{232}Th ratios of <20 were considered to be detritally contaminated (Cr-015, Cr-019 and Cr-025). These samples were corrected using an assumed detrital ratio following the procedure of Clark-Balzan et al. (2012). The other samples contained ^{230}Th/^{232}Th ratios from 20 up to 418, although detrital corrections will change the ages of these sediments, the corrected ages are still within the uncertainty of the original age and so corrections were not carried out.

In the laboratory, thin sections of each sample were investigated by optical microscopy for evidence of recrystallisation, porosity, and multiple growth layers. Where multiple layers occurred, samples were extracted from particular crystal layers using a low-powered microscope. U-series sample preparation, separation geochemistry and mass spectrometry techniques follow the procedure of Seth et al. (2003). The U/Th isotopic ratios of the carbonate samples were analysed by an IsoProbe multicollector ICP-MS at Royal Holloway University of London (see Seth et al., 2003 for details and operating parameters), using static mode on Faraday collectors and the ion-counting Daly detector in the axial position. U and Th analyses were carried out for a mass range 228 to 238. Th and U were analysed separately, with mass ^{230}Th and ^{234}U on the Daly detector used to measure Th and U isotope ratios samples were run in conjunction with total procedural blanks and rock standards (Table Mountain Latite and the OU Young speleothem).

Results

The morphology and sedimentology of Sphakia fan has been discussed in Pope et al. (2008) and Ferrier and Pope (2012), consequently only the dating results are discussed here. The OSL and U-series analytical data are shown, along with the derived age estimates, in Tables 1 and 2. Dates are shown against the stratigraphic profiles in Figure 5. The dates are described in the following section by fan segment.

Chronology of fan segment 1

Fan sediments relating to segment 1 were analysed at sections A, B and C. The nine OSL ages, four from section A, four from section B, and one from section C, span a range between 144 ±15 ka and 72 ±3 ka and are in stratigraphic order (Figure 5 and Table 1). Two U-series ages from section A yield ages of 123.9 ±7.4 ka and 75.4 ±2.9 ka, whilst one age of 70.9 ±1.0 ka was generated from section B (Figure 5 and Table 2).

Chronology of fan segment 2

Sediments of segment 2A are poorly exposed. Section D represents the most extensive record of this phase of fan aggradation however, the absence of fine-grained units and the strong degree of cementation in this section made it unsuitable for OSL dating. Two U-series ages were derived from this section (Figure 5), one from a phreatic cement towards the base of the sequence (72.3 ±6.1 ka) and one from a carbonate clast rind at the land surface associated with a weakly developed pedogenic calcrete (59.0 ±2.3 ka). These, two samples have $^{230}Th/^{232}Th$ ratios of <7 and were, therefore, corrected following the procedure outlined above. The dates quoted here are the corrected ages.

Section E records a sediment profile through segment 2B sediments. In this section carbonate cementation was either absent or the cements were too porous to be appropriate for U-series dating. Three OSL ages were derived from this section. From the lower gravel units upwards these ages are: 55 ± 4, 49 ± 4 and 28 ± 2 ka (Figure 5).

Sections F and G record sediments of segment 2C. Section F is a coastal exposure within one of the thickest parts of the fan sequence and has yielded seven OSL ages which are all in stratigraphic agreement. From the base upwards these ages are: 102 ±10, 71 ±4, 46 ±5, 40 ±3, 20 ±2, 14.2 ±1.5 and 11.2 ±0.7 ka. Two U-series ages have been derived from phreatic cements below the oldest OSL age (102 ±10 ka) and yield ages of 300 ±21 ka and 172.8 ±4.3 ka, respectively. A third U-series age of >350 ka has been derived from a reworked flow stone from the lowest (currently) exposed gravel unit. The lowermost 2 to 3 metres of sediments are suggested to represent an older sedimentary unit which is separated from the overlying deposits by a hiatus or erosional unconformity. This is proposed because; 1) there is a significant time gap between the ages of the lowermost 2 to 3 metres and those of the overlying deposits, and 2) the degree of diagenesis and the pattern of sediment alteration in the lowermost 2 to 3 metres is different from that in the overlying sediments. The lowermost sediments are very heavily indurated and contain complex faults and fractures, infilled with phreatic carbonates up to 15 cm thick, that are entirely absent in the overlying sediments. The deposits exposed in section G have yielded five OSL ages, again in good stratigraphic agreement. From the base of the section upwards, these ages are: 18.2 ±1.2, 17.2 ±1.2, 16.1 ±1.1, 15.2 ±1.1 and 13.8 ±1.2 ka.

Chronology of fan segment 3

There were limited exposures through segment 3 sediments and, where sediments were available, they contain insufficient fine-grained sediment for OSL dating and no visible carbonate cements. This unit was not, consequently, dated. Nevertheless, a later prehistorical age (2500 to 1000 BC) for the fine-grained segment 3 sediments is provided by well-preserved Middle to Late Minoan sherds exposed within in the distal part of Patsianos fan (Sphakia survey, 2002; see also Figure 1 of Pope et al., 2008).

Interpretation of the Sphakia fan chronology and system response

Reliability of the OSL and U-series chronology

The reliability of the derived age estimates can be assessed in the following ways. Firstly, through the stratigraphic integrity observed within the OSL ages in each section. In each sequence the ages become progressively younger upward without age inversions. Secondly, the consistency of the derived ages with the relative ages of the individual fan sediments e.g. ages from segment 2 deposits are younger than those derived from segment 1 deposits. The youngest OSL age (72 ±3 ka) from the top of section A and the OSL age (71 ±4ka) from segment 2 sediments are coeval but there are no ages from segment 1 deposits that are demonstrably younger than those from segment 2 deposits. Furthermore, this implies that the incisional phase that occurred between segments 1 and 2 was relatively short.

The chronologies for the fan segments 2A, 2B and 2C, are more complicated. In general terms the ages from these units are in stratigraphic agreement. The U-series age from the pedogenic carbonate that caps the surface of the segment 2A deposits in section D is 59.0 ±2.3 ka, implying that accretion of this unit had ceased prior to this date. The oldest age within segment 2B deposits (section E) is 55 ±4 ka and is, therefore, stratigraphically consistent with the U-series age for the end of segment 2A accretion. There is, however, overlap between the OSL ages of segments 2B and those of segment 2C. The youngest age derived from segment 2B is 28 ±2 ka and the oldest ages in the segment 2C sediments are 46 ±5 ka and 40 ±3 ka (Figure 5; Table 1). This implies that sedimentation was still occurring on the segment 2B surface whilst segment 2C sediments were beginning to accumulate. This scenario is not impossible. In the mid- and lower-fan areas of the Sphakia system the difference between the height of the 2B and 2C surfaces is minimal i.e. typically less than 2m. Furthermore, the fan surface is fed by a series of tributary systems that drain directly onto the surface of the fan. It is possible that sedimentation was coeval in part on the surfaces of segment 2B and 2C.

The OSL and U-series age estimates are consistent and this suggests that the chronology is robust (See Clark-Balzan et al., 2012). However, OSL ages date the age of sediment deposition and burial. In contrast U-series ages date the age of carbonate cementation of the host sediments; consequently they post-date deposition. As a result, for the same sampling location, the OSL ages should always be older than the U-series ages.

This is the pattern observed throughout the Sphakia sequences wherever OSL and U-series ages are paired (e.g. in section A, approximately 10 metres above the section base, the OSL age is 84 ±8 ka and the U-series age of the carbonate that cements this sediment is 75.4 ± 2.9 ka. Such consistency also exists in section B; an OSL age of 81 ±4 ka at 9 metres above the base is associated with a cementation age of 70.9 ±1.0 ka. In section F a sand unit with an OSL age of 102 ±10 ka is underlain by a gravel unit whose carbonate cement dates to 172.8 ±4.3 ka. A lower gravel unit is cemented by carbonate that dates to 300 ±21 ka, while the lowest (currently exposed) gravels contain reworked flow stone that dates to >350 ka. As these different ages are consistent and the stratigraphic order of the ages is maintained throughout all the sequences the derived chronology can be used to discuss the timing of different phases of alluviation within the Sphakia system.

Relationship between the timing of geomorphic response within the Sphakia system to Late Quaternary environmental change

The timing of geomorphic response within the Sphakia alluvial fan is placed into environmental context in two ways. First, the age-range covered of each fan segment (i.e. segment 1, 2A, 2B and 2C) and the timing of fan entrenchment can be compared to local and regional records of environmental change (Figure 6). Second, OSL ages for alluviation can be separated from their stratigraphic context and plotted against the local and regional records of environmental change to establish whether patterns or clusters of ages occur and whether or not these relate to specific climatic intervals (Figure 7). There are no long records of palaeoenvironmental change from Crete that span the time interval represented by the

Sphakia chronology. A $U^{k'}_{37}$ (unsaturated ratio of long-chain ketones) derived sea surface temperature (SST) record has been constructed from marine core M40-4/71 that was collected southwest of the Sphakian piedmont (Emesis et al., 2003 and see Figure 1). Key regional records from the eastern Mediterranean are also used; the long-pollen record of Tenaghi Philippon (Tzedakis et al., 2001; 2004) and the $\delta^{18}O$ speleothem record from Soreq cave (Bar-Matthews et al., 1999; 2003). Both of these records should be strongly controlled by precipitation regime/aridity but may also contain a temperature component. These three palaeoenvironmental archives can be compared to the stacked benthic $\delta^{18}O$ record of Lisiecki and Raymo (2005).

The ages from segment 1 span the final part of MIS 6 and the whole of MIS 5 with the youngest age from this unit (72 ±3 ka) corresponding to the early part of MIS 4 (Figure 5). Fan entrenchment occurs after this but alluviation resumed by late MIS 4. This is consistent with the U-series ages for the carbonate cements that have formed within the sediments of section D which implies that, at this site, segment 2 alluviation had begun by ca 72ka. Incision and fan entrenchment must, therefore, have occurred during MIS 4. The OSL ages derived from segment 2 sediments span MIS 3, MIS 2 and early MIS 1. The top 3 metres of sections F and G date to the late MIS 2 and MIS 1 and correspond to the Lateglacial interval. The youngest OSL age within the segment 2 deposits is 11.2 ±0.7 ka, implying that the incision and entrenchment between segment 2 and 3, and the deposition of the segment 3 sediments themselves, must have occurred after this date i.e. during the Holocene (Figure 6).

The literature on investigating links between alluvial fan process and climate forcing, on both long and short term timescales, is extensive (see Bull, 1979; Ritter et al., 1995; McDonald et al., 2002; Bacon et al., 2010; Miller et al., 2010). In this study we place our results primarily in the context of the Mediterranean literature on fluvial response to Quaternary climate change as this is the region of most relevance to the present study. The response of the Sphakia fan, as outlined above, can be linked to environmental forcing through the concept of critical power (Bull, 1979, see also Mather et al., 2000). That is to say that under conditions where stream power, primarily a function of discharge and channel gradient, exceeds resistance power, primarily a function of sediment load and calibre, critical power, the power needed to transport all available sediment, is overcome and the fluvial system will begin to incise and the alluvial fan will become entrenched (Bull, 1979). Conversely, under conditions where the stream power is lower than the resistance power, the threshold of critical power is not exceeded and the fluvial system is incapable of transporting all of the sediment available from the catchment (Bull, 1979). Under these conditions the fan will undergo alluviation or aggradation. These ideas are closely linked to environmental change (Rose and Meng, 1999; Rose et al., 1999). For example climate, through its impact on vegetation density/type and patterns/rates of weathering, will control the nature and rate of sediment supply (Rose et al., 1999; Macklin et al., 2002; Candy et al., 2004; 2005). Furthermore, long term changes in precipitation regime, through the magnitude and frequency of rainfall events, will strongly control the discharge and stream power of the system (Harvey and Wells, 1987). Finally, sea level changes coupled with the steep near-shore gradients associated with the southern Cretan margin will control the magnitude of channel gradient across the fan system (Alves et al., 2007; Waters et al., 2010). Major falls in sea level will greatly increase channel gradient which will potentially increase stream power sufficiently to trigger fluvial incision and entrenchment (Waters et al., 2010). The ages associated with the two key phases of fan entrenchment in the Sphakia system, segment 1 to 2 and segment 2 to 3, suggest that incision occurred in association with two of the key climatic transitions of the last 125,000 years; 1) the major cooling and rapid lowering of sea level that occurred between MIS 5a and 4, and 2) the climatic amelioration that occurred during the transition into the current interglacial.

It is during the MIS5a/4 transition that the greatest decrease in global sea levels occurred (Waelbroeck et al., 2002; Siddall et al., 2003). This transition does not represent the glacial maximum or the lowest sea level during the last glacial (Waelbroeck et al., 2002). However, during the MIS 5a/4 transition sea levels fell by 70 to 100 metres over ca 10,000 yrs (Waelbroeck et al., 2002; Siddall et al., 2003). It is proposed here that this sea level fall associated with the steep offshore gradients of the southern Cretan margin caused an increase in the channel gradient across the Sphakia fan surface. The transition into MIS 4 was, therefore, characterised by fan entrenchment. It is noticeable that the other major fall in sea level during the last glacial (the MIS 3/2 transition) has no clear response in alluvial fan dynamics. In relative terms, the fall in sea level between MIS 3 and 2 was smaller than in MIS 5a/4 (Waelbroeck et al., 2002; Siddall et al., 2003) resulting in less of an effect on the fan. However, it is also important to note that the ages associated with segment 2 alluviation imply that entrenchment between segments 2A/2B and 2B/2C occurred during MIS 3 and 2. It is, therefore, possible that part of the geomorphic complexity associated with the segment 2 fan surface could reflect base level changes during this interval. The overlap between ages in some of these deposits indicates that attributing an absolute timescale to these geomorphic shifts is not currently possible.

The shift from fan aggradation during MIS 2 to incision during the Holocene, which is represented in the Sphakia fan by entrenchment after the accumulation of segment 2 deposits but prior to the deposition of segment 3 deposits, is a phenomena that is seen in many catchments across the Mediterranean (White et al., 1996; Rose et al., 1999; Rowan et al., 2000; Macklin et al., 2002; Candy et al., 2004; 2005; Pope and Wilkinson, 2005). This is widely suggested to be a response to climatic controlled changes in hydrology and sediment supply rather than gradient shifts associated with sea level change. During stadials, such as during MIS 2, palaeoclimatic and palaeoecological records indicate that, in the Mediterranean, climates were arid (Bar-Matthews et al., 1999; 2003), vegetation was dominated by *Artemisia* steppe (Pons and Reille, 1988; Allen et al., 1999; Tzedakis et al., 2003; Margari et al., 2009) and weathering rates were high (Rose et al., 1999). These conditions resulted in high rates of sediment supply to catchments producing river systems that did not have sufficient stream power to transport this load and consequently they underwent aggradation/alluviation. At the onset of the Holocene, the increase in moisture availability resulted in an increase in vegetation cover and a recolonization of the landscape by woodland (Pons and Reille, 1988; Allen et al., 1999; Tzedakis et al., 2003; Margari et al., 2009), this stabilisation of the landscape reduced sediment supply which, in combination with wetter climates, overcame the threshold of critical power causing incision (Candy et al., 2004). This model is also the most likely explanation for the episode of fan entrenchment between segments 3 and 2.

Despite climate being proposed as the cause of fan entrenchment between fan segments 2 and 3 the currently accepted model of fluvial response to Quaternary climate change in the Mediterranean, i.e. aggradation during stadials and incision/stability during interglacials and interstadials (Macklin et al., 2002), is not seen in the Sphakia chronology. That is to say that although many of the OSL ages do constrain alluviation phases to stadial climates, alluviation is not restricted to such intervals. The OSL chronology for Sphakian sedimentation phases shows no clear relationship to any particular climatic type or MIS with alluvial sediments dating to (see Figure 6): interglacials (ages from segment 1 deposits of 123.9 ±7.4 ka and 124 ±10 ka correspond to MIS 5e), interstadials (ages from the segment 1 deposits of 84 ±8 ka and 81 ±4 ka date to MIS 5a), stadials within MIS 5 (with OSL ages of 101 ±8 ka and 102 ±10 ka corresponding to MIS 5d), interstadials from the last glacial (ages from segment 2 deposits of 55 ±4 ka, 48 ±4 ka and 46 ±5 ka correspond to the main climatic peak of MIS 3) and stadials from the coldest parts of the last glacial (ages from segment 2 deposits if 20 ±2ka and 18.2 ±1.2 ka correspond to the climatic minima of MIS 2). Clearly between each of the dated levels in these sequences there are sediments that have no age associated age estimates, consequently, the OSL chronology presented here is not a definitive record of the timing of alluviation within the Sphakian sequence. However, the dates presented do not show a clear relationship between alluviation and any specific climatic types. This is in contrast with other such studies from the Mediterranean that show a clustering of alluviation phases around glacial/stadial climates (Rose and Meng, 1999; Rose et al., 1999; Rowan et al., 2000; Macklin et al., 2002; 2012; Candy et al., 2004 and 2005; Pope and Wilkinson, 2005). The dataset presented here, therefore, suggests that alluviation in the Sphakia system was a persistent process that operated across the entire last interglacial/glacial cycle (Figure 7).

Discussion

The chronology generated from sediments sequences of the Sphakia fan is different from previous summaries of Quaternary fluvial activity in the Mediterranean. In this fan there is no clear relationship between the age of alluviation and orbital scale climate change of the Late Quaternary. The established chronology implies that, with the exception of the two fan phases of entrenchment, rates of sediment supply to the Sphakia fan during most of the last interglacial/glacial cycle were sufficient to cause the fan to aggrade rather than incise. The climate and vegetation of the Mediterranean, during stadials, produced landscapes that were highly susceptible to erosion and, consequently, the sediment yield was high. Alluviation within the Sphakia fan during interglacials and interstadials is more surprising as the extensive and higher density vegetation cover of such intervals is supposed to produce more stable landscape that would generate lower sediment yield (e.g. Pope and Wilkinson, 2005).

To place the Sphakia chronology into context it is useful to compare this record with that of Rose and Meng (1999) and Rose et al. (1999) from alluvial fans on Mallorca. In the Mallorcan sequences climatic ameliorations (MIS 5e, 5c and 5a) are characterised by fan surface stability and pedogenesis and fan alluviation is restricted to stadial climates (MIS 5d, 5b, 4 and 2). The Mallorcan fan sequences, therefore, show a clear response to Quaternary climate change and one which is consistent with our understanding of the control played by climate (partly through vegetation) on hydrology and sediment supply. In the Mallorcan sequences sediment supply to fan systems appears to be greatly reduced, or even switched off during interglacials and interstadials, whereas in the Sphakia fan, even during interglacials, the supply of sediment was capable of causing alluviation and preventing fan surface stabilisation or entrenchment. It is here suggested that the most probable cause for the difference in fan response between these two study regions is catchment topography.

The Mallorcan fan systems drain relatively low hills (maximum altitude ca 560 metres amsl (Rose et al., 1999)), whereas the Sphakia fan drains high mountainous region reaching up to 2452 metres amsl (Pope et al., 2008). The relatively low altitude of the Mallorcan hills means that for most of the Late Quaternary they were rarely characterised by cold mountain climate. When this moderate climate is combined with the rainfall of ca 500 mm/a, they are always likely to be well-vegetated and, therefore, limited in sediment supply. Only during the extremes of climatic deteriorations i.e. the stadial episodes of the last interglacial/glacial cycle, are temperatures and rainfall likely to decrease enough to cause vegetation to decline to expose areas of bare-ground and allow sediment supply to increase. It is, therefore, postulated that, in such a subdued topography, drastic climatic deteriorations are required to trigger fan alluviation (see Rose et al., 1999).

The Sphakia fan operates in a different topographic setting, draining high mountains with present-day tree line around 900 metres below the highest peaks (Rackham and Moody, 1996). This produces large areas of exposed bedrock which, combined with the high rainfall (up to 1100 mm/a), means that the fan source areas have the potential to both generate and transport sediment even during the interglacial conditions of the present day. Consequently, major climatic deteriorations are not required to stimulate fan alluviation and this system has the potential to undergo alluviation during both interglacials, interstadials and stadials.

The ages of alluvial fan sedimentation presented above are different from that proposed by Macklin et al. (2002; 2012) which argued for a consistent pan-Mediterranean response of fluvial systems to Quaternary climate change. Although it could be argued that this difference is a function of the specific conditions in the catchment of the Sphakia fan it is important to highlight that several of the studies presented in the Macklin et al. (2002) compilation are also high altitude catchments. They are, therefore, also sensitive to the same factors that would have affected alluvial fan aggradation in southern Crete. Consequently, it is not simply the case that the topographic setting of the Sphakia fan makes it insensitive to climate forcing in comparison to other fluvial systems that have previously been studied. Fundamentally, it is important to recognise that the twenty four OSL dates and eight U-series ages make the Sphakia system the most dated small alluvial system in the Mediterranean constraining the timing of fluvial response more strongly than any previously published record. Furthermore, the uncertainties associated with each age (average uncertainty of ca 9%), are lower than the uncertainties associated with the ages presented in Macklin et al. (2002), which are typically ≥10% of the derived age. This reflects the development of chronological techniques over the last 15 years. The dataset presented here, therefore, advances the discussion of fan response to climate change because not only are there sufficient ages to allow the timing of fan alluviation to be discussed, but also the age estimates are of high enough precision to allow them to be robustly correlated with specific marine isotopic stages and substages. Whether the idea of a consistent pattern of Quaternary fluvial response across the Mediterranean is valid or whether catchment specific factors play a key role in the timing of alluviation can only be truly understood with detailed studies in the style of that presented here. If the role of long-term forcing on Quaternary geomorphic response in the Mediterranean is to be understood in detail this can only be achieved by the production of sediment/landform chronologies that are based on large numbers of high-precision age estimates.

Conclusions

A coupled OSL and U-series chronology has been constructed for the Sphakia alluvial fan in southern Crete. This chronology is based on 32 age estimates showing that the evolution of this fan spanned the time interval from late MIS 6 through to the Holocene. The entrenchment that occurs between the different stages of fan aggradation corresponds to MIS 4 (the incision that occurs between fan segments 1 and 2) and the early Holocene (the incision that occurs between fan segments 2 and 3). The incision that generates this entrenchment is suggested to be a function of sea level fall, which drives the incision between fan segments 1 and 2, and the climatic amelioration at the onset of the Holocene, which appears to drive the incision between fan segments 2 and 3. In contrast the timing of fan alluviation shows no correlation to any specific climatic state with dated fan sediments corresponding to interglacial, interstadial and stadial episodes. This is in strong contrast to the majority of Quaternary fluvial studies in the Mediterranean which correlate alluviation phases to stadial events. It is likely that the topographic setting of the Sphakia fan, a steep catchment which drains a high mountain region much of which is currently above the treeline, means that sediment supply during most climatic stages of the Late Quaternary is sufficient to promote persistent alluviation across the Late Quaternary. Despite these catchment specific conditions it is also suggested that the large number of ages presented here, and their relatively high-precision, allows the timing of fan alluviation to be understood in more detail in the Sphakia system than in any other currently dated Mediterranean geomorphic sequence.

Only through the application of large numbers of high-precision age estimates can the timing of alluviation in Quaternary fluvial sequences be robustly constrained and such an approach is necessary to test whether the previously proposed synchroneity in the response of Mediterranean river systems to Quaternary environmental change is truly valid.

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List of Figures

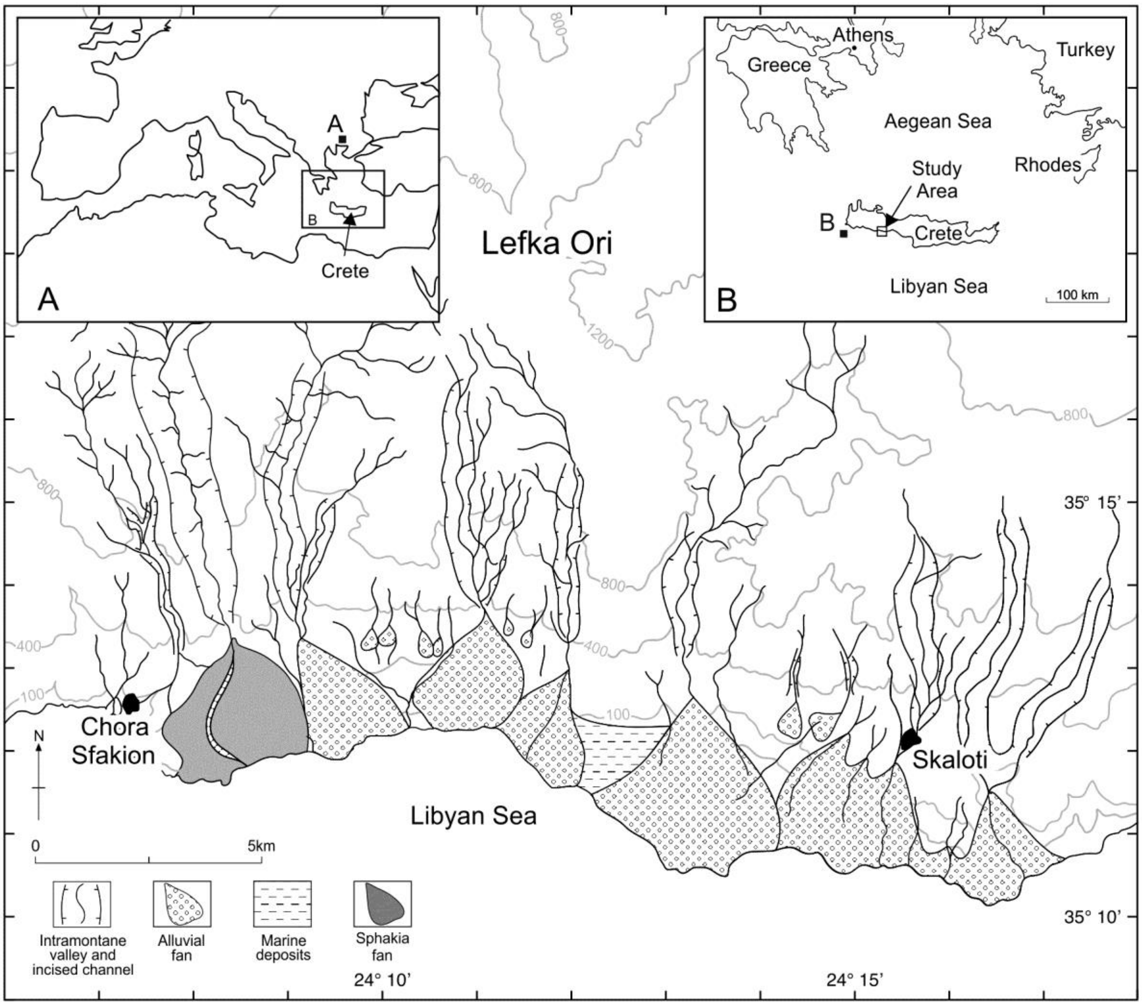
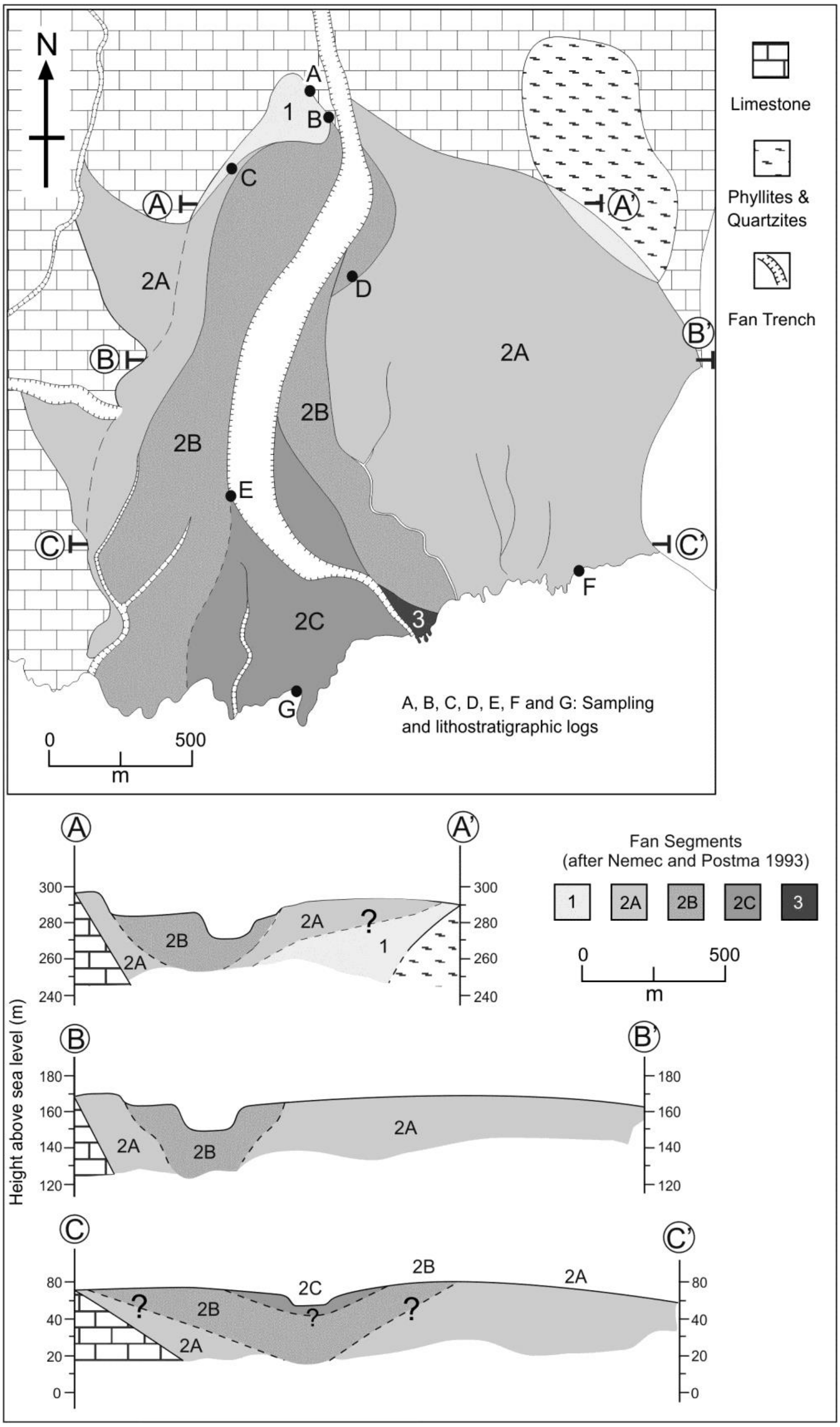


Figure 1 - The coastal piedmont and distribution of the Sphakia fan systems, southwest Crete. Note that Sphakia fan is indicated by the grey shading. Inset (A) shows the location of Tenaghi Philipon indicated by the letter A. Inset (B) shows the location of core site M40/71 indicated by the letter B in respect of the study area.

Figure 2 -



Simplified surface morphology and depositional stages within Sphakia fan (modifield after Pope et al., 2008). See text for a full discussion of the main depositional stages. Note that the letters A to G refer to the OSL/U-series sampling locations and chronostratigraphies shown in Figure 5

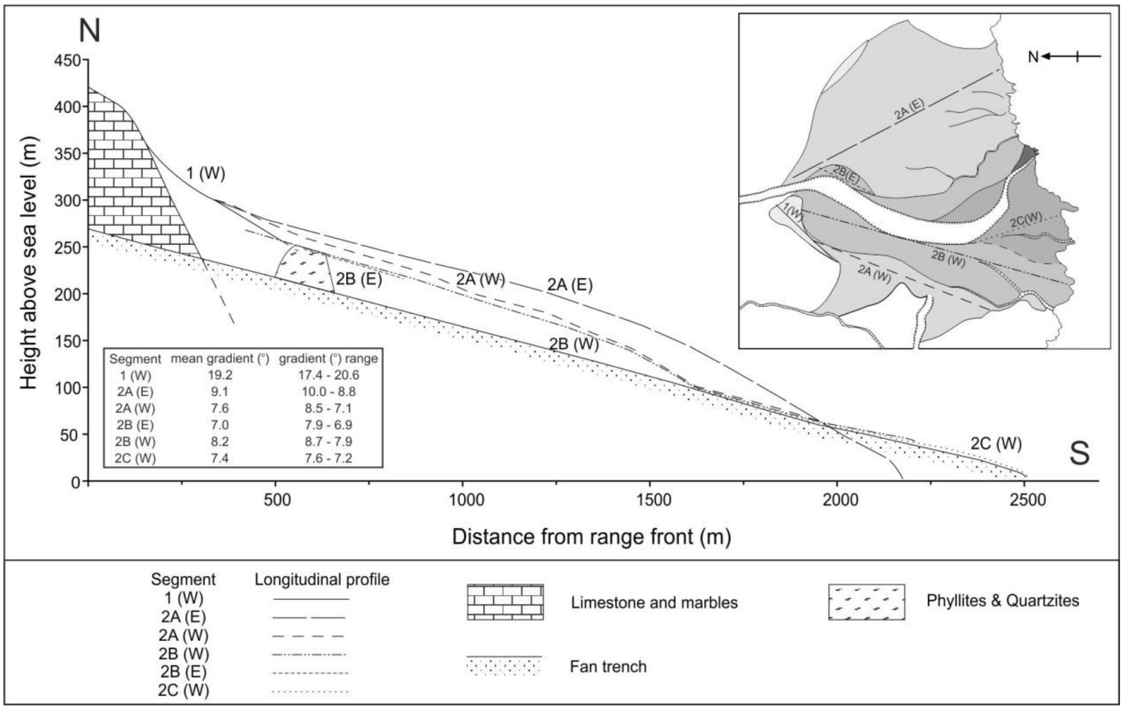


Figure 3 Long profile of Sphakia fan. The inset indicates the locations of survey transects across individual fan segments.

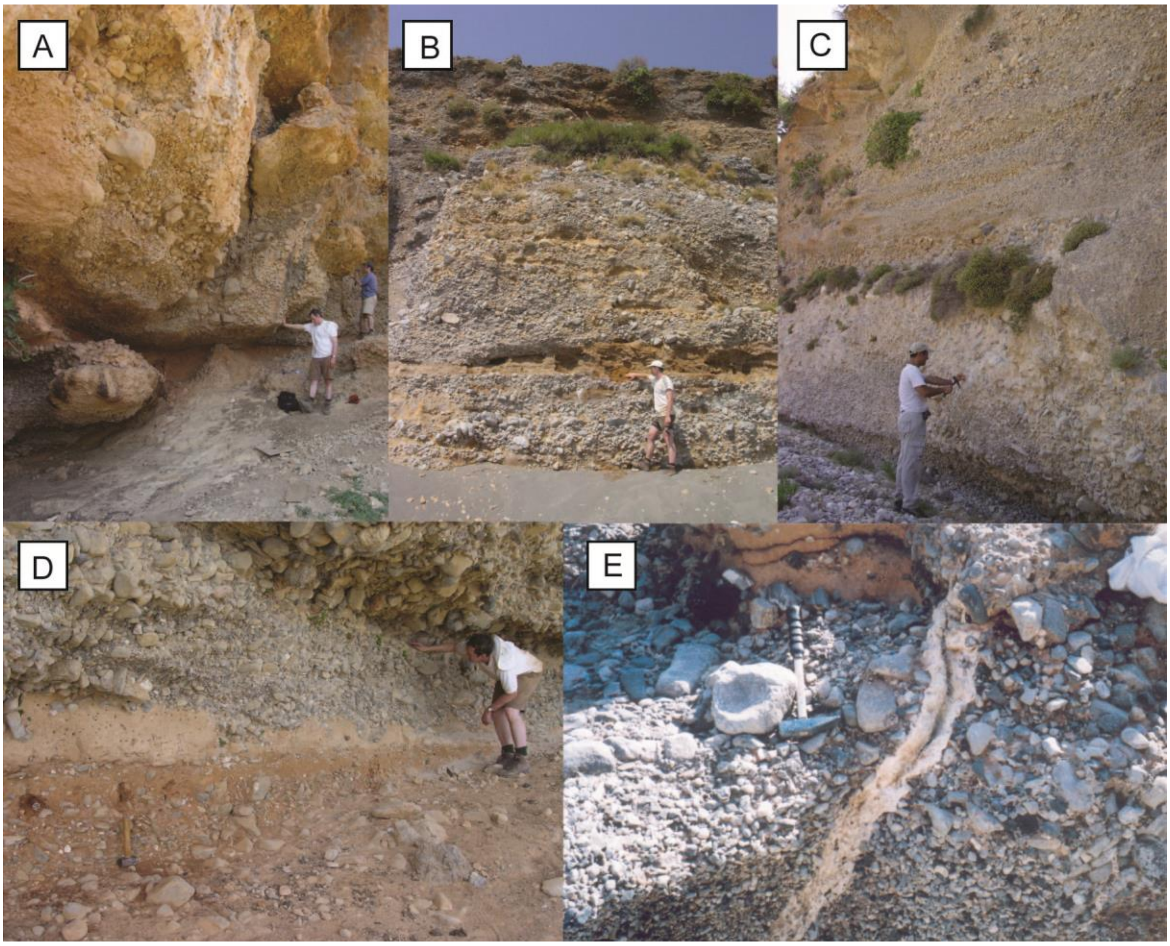


Figure 4 – Photographs showing the sedimentary characteristics of the deposits studied and dated in this study. A) Segment 1 gravels showing poorly sorted characteristics typical of mass flow/debris flow deposition. OSL dating of these sediments is based on the analysis of the fine-grained red units that interbed with the coarser units (base of section) and the analysis of the inter-clast matrix. B) Segment 2B gravels that express moderate sorting and crude horizontal stratification. The gravels lenses are interbedded by the buff, fine-grained sediments that were the focus of OSL dating. C) Segment 2B gravels showing well-developed horizontal stratification and a stronger degree of sorting. D) Segment 2C gravels showing reddened fine-grained material interbedded with imbricated, stratified gravels. E) A well-developed calcitic groundwater that has formed within the fan gravels. The calcite has formed as a result of precipitation along a fault within the sediments. Cements also develop as inter-clast, pore infill cements.

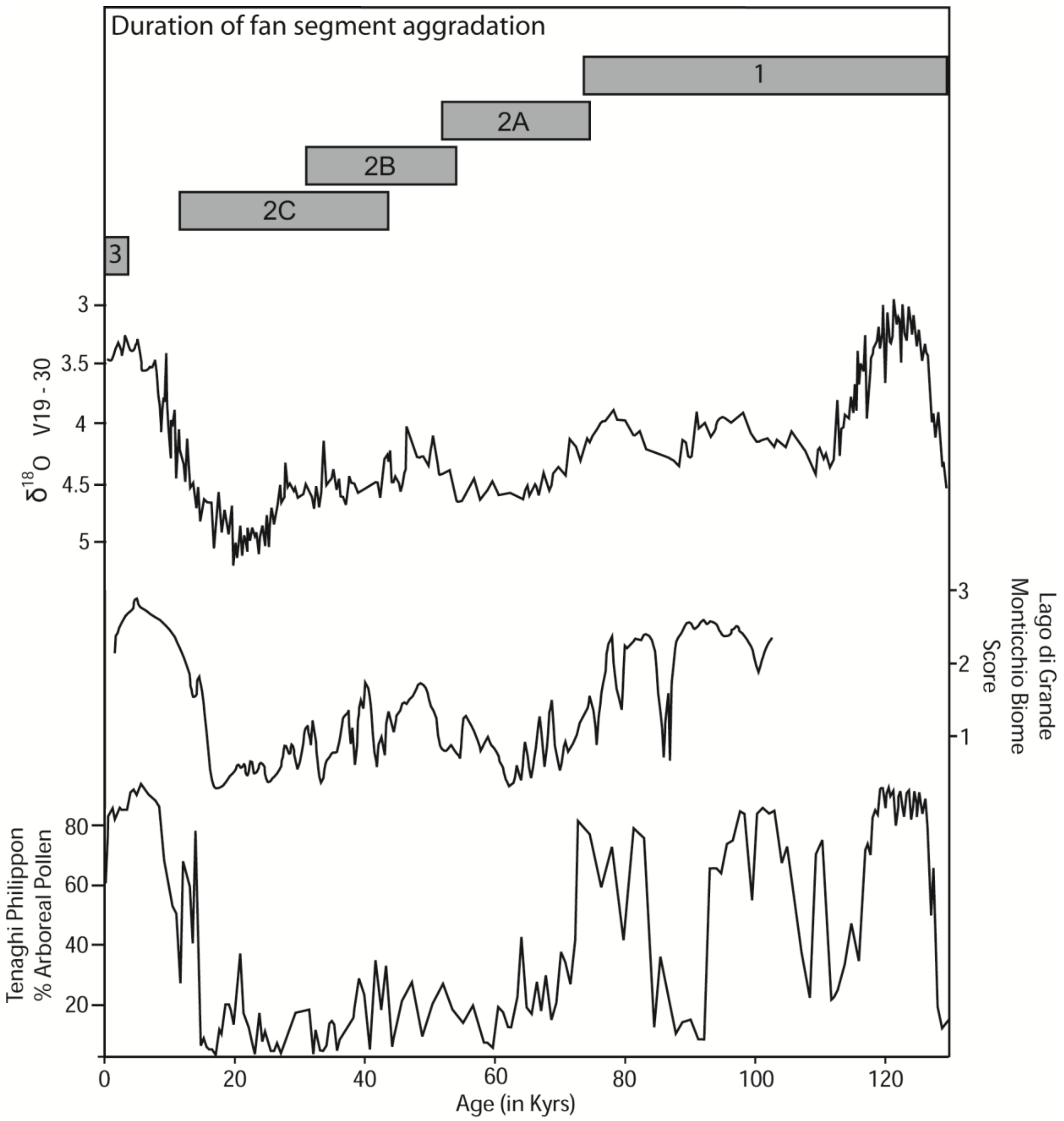


Figure 5 – OSL and U-series age estimates plotted against the stratigraphic logs of each sampling site. See Figure 2 for the location of each site and Tables 1 and 2 for the data on which age estimate is based.

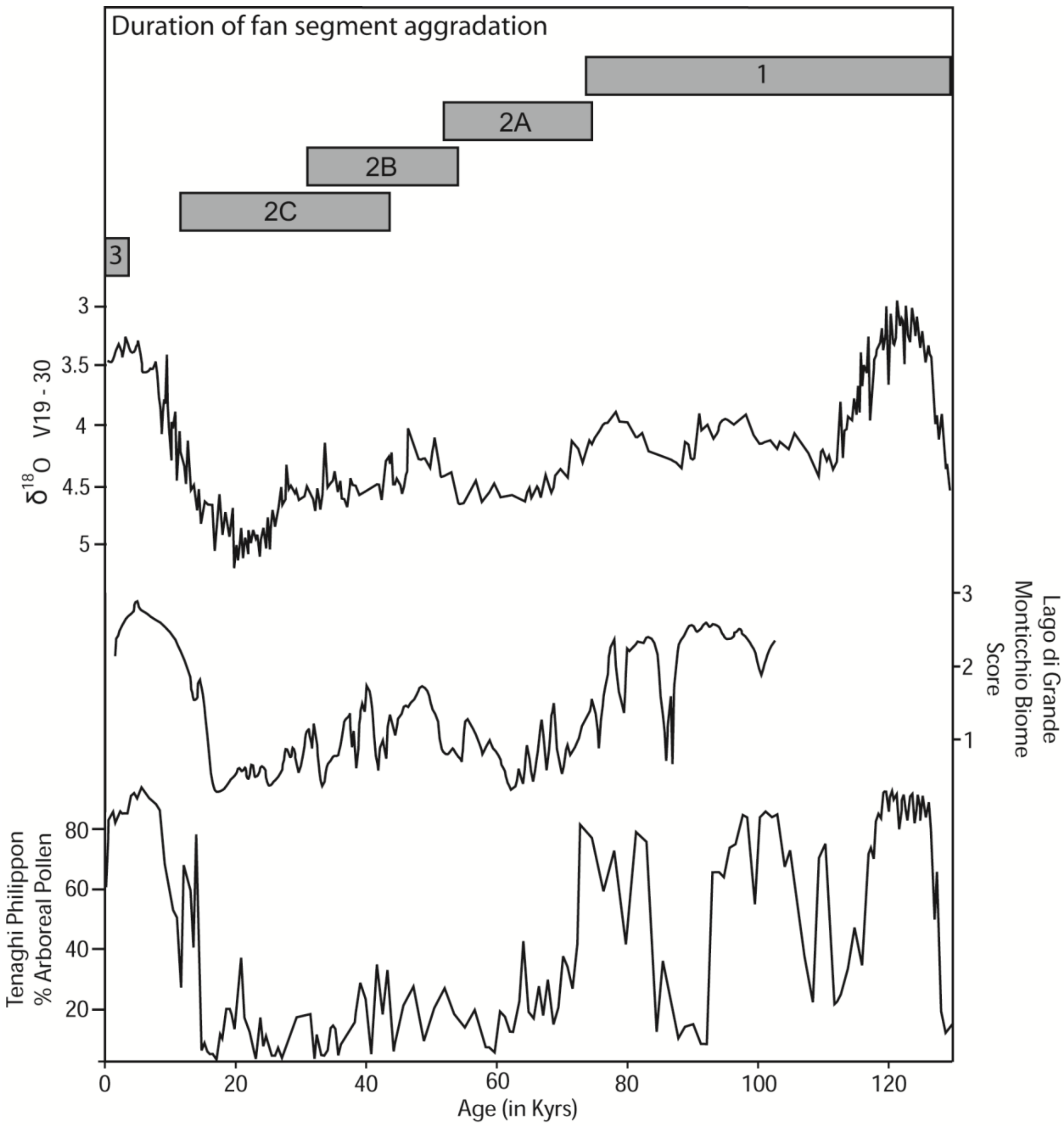


Figure 6 – Age of fan depositional segments plotted against: (A) V19-30 benthic $\delta^{18}O$ isotope record (Shackleton et al., 1983); (B) Grande Lago di Monticchio Biome score (based on pollen assemblage zones [Allen et al., 1999]); and (C) Tenaghi Philippon record of % arboreal pollen (excluding pine (Tzedakis et al., 2006)).

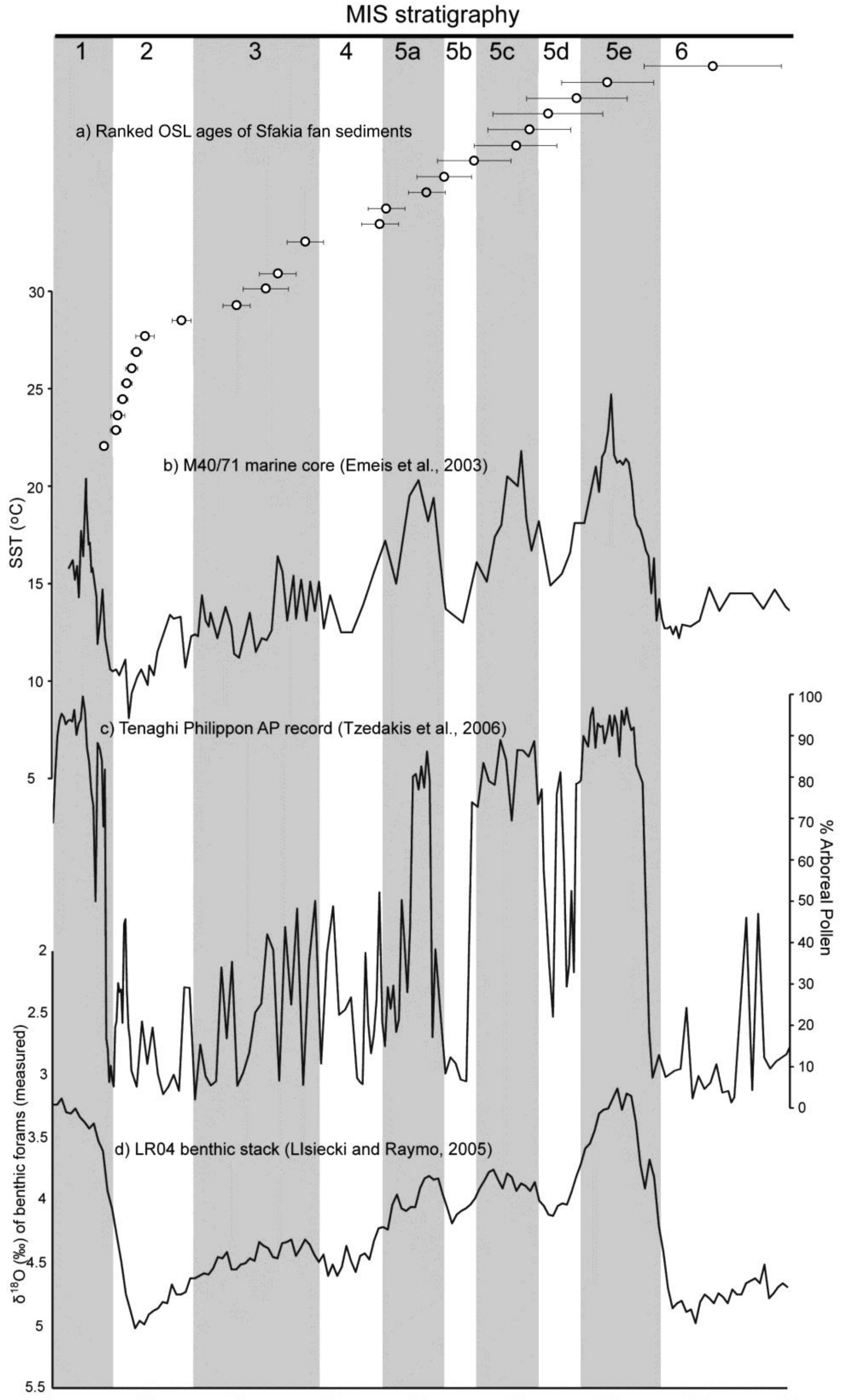


Figure 7 – Age ranked OSL dates plotted against: (A) marine isotope stages; (B) sea surface temperature data from southwest of Crete (Emeis et al., 2003); (C) the arboreal pollen record from Tenaghi Philippon (Tzedakis et al., 2006); and (D) the LRO4 benthic stack (Lisiecki and Raymo, 2005).

Table 1. OSL determinations for the 180–250 µm quartz fraction from the Sphakia fan

Risø code	Site	Depositional segment	Depth from surface (m)	D_e (Gy/ka)	Aliquot No	D_e, (Gy)	Water content %*	Age (ka)
082401	Sfakia	1	15.2	0.62 ± 0.05	23	73 ± 4	24	118 ± 8
062402	Sfakia	1	11.7	1.49 ± 0.08	22	137 ± 6	15	92 ± 6
102404	Sfakia	1	7.5	1.49 ± 0.04	23	126 ± 5	12	84 ± 8
102405	Sfakia	1	1.3	1.14 ± 0.03	24	82 ± 2	28	72 ± 3
082402	Sfakia	1	14.8	0.61 ± 0.04	32	73 ± 3	12	120 ± 10
082405	Sfakia	1	13.2	0.74 ± 0.05	18	81 ± 3	17	110 ± 9
072404	Sfakia	1	11.9	0.84 ± 0.05	16	85 ± 6	31	101 ± 8
102403	Sfakia	1	6.4.	1.49 ± 0.04	22	121 ± 5	11	81 ± 4
042412	Sfakia	1	5.8	1.68 ± 0.14	26	242 ± 14	26	144 ± 15
072408	Sfakia	2B	3.8	2.59 ± 0.12	17	142 ± 8	9	55 ± 4
042407	Sfakia	2B	21.3	2.90 ± 0.14	24	144 ± 8.0	5	49 ± 4
062401	Sfakia	2B	1.0	2.31 ± 0.11	27	64 ± 7	27	28 ± 2
082411	Sfakia	2C	16.2	0.84 ± 0.05	18	85 ± 6	31	102 ± 10
082403	Sfakia	2C	14.5	1.1± 0.061	22	78 ± 2	8	71 ± 4
042410	Sfakia	2C	8.9	1.61 ± 0.06	30	74 ± 7	22	46 ± 5
072403	Sfakia	2C	19.8	1.22 ± 0.05	25	50 ± 3	40	40 ± 3
072409	Sfakia	2C	7.6	2.77 ± 0.15	27	55 ± 4	7	20 ± 2
062408	Sfakia	2C	3.3	2.89 ± 0.15	25	41 ± 4	9	14.2 ± 1.5
062410	Sfakia	2C	0.9	0.74 ± 0.09	13	8.3 ± 1.3	18	11.2 ± 0.7
072410	Sfakia	2C	3.5	1.27 ± 0.07	17	23.2 ± 1.6	2	18.2 ± 1.2
072411	Sfakia	2C	2.9	2.46 ± 0.12	22	42.0 ± 2.0	2	17.2 ± 1.2
072412	Sfakia	2C	2.3	0.79 ± 0.05	20	12.9 ± 0.8	2	16.1 ± 1.1
072409	Sfakia	2C	1.9	2.33 ± 0.12	18	35.4 ± 1.6	2	15.2 ± 1.1
062409	Sfakia	2C	0.9	0.71 ± 0.09	13	9.7 ± 1.8	18	13.8 ± 1.2

The moisture content of the samples varied overtime in response to surface and groundwater fluctuations resulting from changes in humidity and base level. To ensure that realistic water content figures were calculated an average of the present-day and saturated water content values were derived for each sample since this represents the closest approximation of water content throughout the burial history (A. Murray, pers.comm.). Note that age estimates for 082401, 102404, and 082403 differ slightly to those presented in Ferrier and Pope (2012) due to a recalculation of the original sampling depths.

Table 2. U-series age estimates and geochemistry. All ages calculated using ISOPLOT (Ludwig, 2003)

Royal Holloway code	Sample description	^{230}Th /^{232}U	Depositional segment	^{230}Th /^{238}U	^{234}U/^{238}U	Age ka
Cr-0615	Sparry cement***[1]**	5.18 ± 0.14	1	0.74±0.02	1.08±0.0100	123.9±7.4
Cr-0648	Sparry cement	35.56 ± 0.24	1	0.56±0.01	1.10±0.0049	75.4±2.9
Cr-0617	Sparry cement	34.42 ± 0.25	1	0.55±0.01	1.13±0.0049	70.9±1.0
Cr-0621	Sparry cement***[2]**	6.83 ± 0.16	2C	0.74±0.02	1.09±0.0060	72.3± 6.1
Cr-0619	Soil carbonate***[3]**	1.81 ± 0.03	2C	0.46±0.01	1.08±0.0100	59.0±2.3
Cr-0616	Reworked Flow stone	418.75 ± 2.43	2C	1.04±0.01	1.02±0.0039	>350
Cr-0639	Sparry cement	19.01 ± 0.14	2C	1.01±0.01	1.06±0.0100	300±21.0
Cr-0650	Sparry cement	298.32 ± 2.34	2C	0.89±0.01	1.10±0.0043	172.8±4.3

1,2, 3 - Detrital correction applied due to contamination, ages shown are corrected following Clark-Balzan et al. (2013)