Detailed Response to the Reviewers & Associate Editor

Ms. Ref. No.: esurf-2016-62

Title: Distinct phases of eustatism and tectonics control the late Quaternary landscape evolution at the southern coastline of Crete

Dear Associate Editor,

On behalf of my co-authors, I am now in the pleasant position to return to you the revised version of our manuscript, together with the detailed answers to all the comments raised by the reviewers/commentators of this manuscript. As you may see below, we have taken very seriously all concerns expressed here and we have devoted some time in trying to address each comment (regardless whether we agreed or disagreed).

Overall, the whole review process has been interesting and beneficial and we firmly believe that our work improved for all the useful comments provided by the reviewers. Having said this, at the same time, we felt that there was an overall pressure to make our work what it clearly isn't: a detailed sedimentological study, mainly because of the detailed sedimentological studies provided by Pope et al. (2008 & 2016) and Nemec & Postma (1993) at a nearby alluvial fan system in western Crete.

At this point, we would like to make clear that although we have all worked with alluvial fans, our motivation and objectives are markedly different to those of Pope et al. (2008 & 2016) or Nemec & Postma (1993). Our primary interest in our work on Crete is to help constrain its late Quaternary tectonic development. With the submitted work we aim to use first-order geomorphic features and stratigraphic relationships to understand the late Quaternary vertical deformation of western Crete. This objective does not include a comprehensive description of the materials of the Domata fans and their developmental chronology, as has been undertaken for other fans of southern Crete by others (Nemec & Postma, 1993; Pope et al., 2008, 2016). Neither is the objective to compare Domata fan stratigraphy with that of other alluvial fan systems on Crete.

For addressing our objective, we recognised the importance of the Domata fan sequence and the important marine bench cut in upper-fan at Domata. This feature allows us to independently derive a late Quaternary uplift rate from this section of western Crete. The paper is important because of this independence from previously derived uplift rates on western Crete (e.g., Shaw et al., 2008; Strasser et al., 2011; Tiberti et al., 2014; Mouslopoulou et al., 2015). The latter is something that our work achieves – and something that, for example, the work of Pope et al. (2008 and 2016) or Nemec and Postma (1993) has not achieved (exactly because the scopes of our manuscripts are different).

Nevertheless, we have taken on the advice of most reviewers to present a detailed stratigraphic log of the two fan deposits in the revised version and we have added extensive discussion comparing the first-order conclusions of our study to that of Pope et al. (2016) and others studies as well. And we do welcome the prospect of additional work that would enhance insight into the processes of fan deposition and a refined chronology that may help better understand relationships between sediment transfer rates and climate in this area.

In summary, we do hope that this revised version, together with our detailed response to the numerous review comments, will convince you that our work warrants publication in the Journal of Earth Surface Dynamics.

In the following paragraphs, we carefully address the comments and suggestions of:

- *the Associate Editor (Dr.* Veerle Vanacker*),*
- *Each of the two reviewers of our manuscript (the Anonymous Reviewer ≠1 and M. M. Tiberti)*
- *Gallen and Wegmann's two short-comments, uploaded during the online interactive discussion (one posted on January 27th, 2017 and the second on January 30th, 2017).*

Our responses appear in 'red italics' while the comments of the Reviewers/Asocciate Editor appear in black.

At places where the reviewers refer to specific pages and line-numbers we answer point-by-point; in circumstances where the reviewers do not refer to specific line numbers, we present answers below each of their comments.

In the revised version we have put effort to rephrase the scope of this paper, to more clearly describe the main geomorphic features observed and their interrelations, to present the lithostratigraphic logs of the two studied alluvial fans and to compare our work with the work undertaken by Pope et al (2016) and others on western Crete by:

- *Including additional text (see tracked changes throughout our manuscript),*
- *Modifying our former Figure 5 (now Figure 5a) to include schematic sketch of the volumes of the upper and lower fan materials and the stratigraphic position of each of our IRSL samples within these volumes.*
- *Including a new figure (Figure 5b) that presents the lithostratigraphic logs of the two alluvial fans examined.*
- *Re-annotating/modifying the existing Figures 6b*
- *Introducing a new figure (Figure 6c) that shows the details of the relationship between the bioerosional AD 365 notch and the unconformity at the base of the fan sequence.*
- *Including discussion on the important work of Pope et al. (2016), that was missing from our originally submitted version as its publication post-dated our work.*
- *Expanding on comparing our work with other published studies on Crete.*
- *Updating our reference list.*

In addition, we have modified accordingly the revised version to accommodate all other specific secondary comments of the reviewers/commentators.

Response to the comments of Associate Editor, Dr Veerle Vanacker

We now have three detailed reviews back on the manuscript, that provide valid and very useful suggestions for the improvement of the final document. The revised version of the paper needs to address all comments raised by the reviewers, and I would like to suggest you to take the following four elements along in your revisions:

1. The conclusions should be robust and based on facts and data. In the paper, the authors conclude (p14, L 1-7) that "sea-level fluctuations in response to varying climatic conditions formed the landscape at Domata during MIS 3 (57-29 kyr BP). It is, however, because of the fast tectonic uplift that Crete experienced during the subsequent 20 thousand years that the entire alluvial sequence escaped destruction and/or modification due to marine inundation and is preserved sub-aerially today". As tectonism, sea level variation and paleo climate have regional impact, the observations at Domata cannot be isolated from other studies on nearby alluvial fans. A discussion of the findings from the Domata fan, in the light of previous work on alluvial fans in Crete is essential (see comments raised by reviewer#1, reviewer#2). If there exist different hypotheses about the Quaternary evolution of the region, try to give the different models of evolution and discuss alternative interpretations based on facts and data.

We agree that there should be some discussion comparing our results with other published results on nearby alluvial fan systems. The only such work in the vicinity of our study area is that of Pope et al. (2016) on the alluvial fan system of Sfakia [the latter study builds on previous work undertaken on the same fan-system by Pope et al. (2008) and Nemec & Postma (1993)]. Although the two studies have very different motivations and objectives (see introduction of our response), we agree that there is a reason for comparison. This is why now, in the revised version, we have added discussion at the end of Section 5 (Page 13, lines 17-30) to compare the results of these two studies and also provide possible explanations as to why aspects of 'theirs' and 'our' findings may differ. Please note that despite these differences, both studies have come up to the same conclusion: the recognition of the importance of base level (sea-level) changes to the process of incision (in addition to Section 5, we also state this in Page 3, lines 5-6). Besides, reference to these and other studies (on western and eastern Crete), especially those related to tectonic information and how they may compare to our findings, exist now throughout our revised manuscript:

- *Page 2, lines 24-31*
- *Page 3, lines 5-6*
- *Page 3, lines 24-31*
- *Page 4, lines 1-10*
- *Page 5, lines 14-19*
- *Page 6, lines 25-31*
- *Page 8, lines 7-9*
- *Page 9, lines 20-26 and 30-33*
- *Page 10, lines 1-5*
- *Page 12, lines 25-33*
- *Page 13, lines 1-4 and lines 10-11.*
- *Page 13, lines 18-30.*

2. The text misses some consistency in the interpretations as outlined by the reviewers. To give one example: p4, Line 5-10: the interpretation of the tilted paleoshoreline. The authors state that..." A number of studies have constrained the timing of this prominent paleoshoreline at 1.5-2 kyr BP, with some attributing it to the AD 365 historic earthquake". However, we see on p6, L24-30 : "bioerosion notch indicating an uplifted paleoshoreline at 6 m "..." seismically uplifted paleoshoreline dated at 365 AD"..." the AD 365 bioerosional notch ". Also in Figure 6, the authors only refer to the "365 AD paleo-shoreline" not mentioning alternative explanations (Pirazzoli et al., 1982; 1996; Stiros, 2001; Shaw et al., 2008).

There is no alternative explanation. Both of the above statements are correct. The prominent paleoshoreline that we discuss has been dated all around western Crete (more than 65 radiocarbon ages from 5 different studies) and all ages range between 1500-2000 yrs BP, with a strong clustering of ages around the AD 365. Well, this is not a surprise as the dawn of July 21st, 365 AD there was a massive (M~8.3) earthquake that hit eastern Mediterranean, triggering a mega tsunami that affected numerous cities in middle east and north Africa, as well as Cyprus, Turkey, south Italy/Sicely and, of course, Greece (as its epicentre was offshore western Crete).

Nevertheless, to ease the Associate Editor's concern we have 'corrected' the statement in Page 4 (line 5-10) in order to read as following: 'A number of studies attribute the timing of this prominent paleoshoreline to the AD 365 historic earthquake'. Thus now the age of this prominent paleoshoreline on Crete is stated, throughout the manuscript, as AD 365.

3. As the chronological framework of the sedimentary events is not well constrained (5 samples, with four samples giving a broad time interval of 30 to 60 kyr BP, Figure 9), one needs to be very careful with the interpretation of landscape evolution (section 4, and Figure 10). Supplementary information (either from soil chronosequences, or lithostratigraphy) would be very helpful. Two reviewers have recommended to include lithostratigraphic logs, or detailed stratigraphic and sedimentological evidence of the fan sequences, and I fully support these recommendations. See details in review#1 and 1-bis and review#2.

To address the reviewers and Associate Editors concern we have done our best to produce detailed lithostratigraphic logs of each of the two fans preserved in the alluvial system. These new logs are now presented in a brand new figure: Figure 5b. Reference to this figure has been added throughout Section 3.1. Their locality is shown now on Figure 5a.

*We firmly believe that the insertion of the new Figure 5a, the insertion of new Figure 5b, the serious revision of Figure 6b and the insertion of new Figure 6c, together with our revised text where we more explicitly describe the stratigraphic evidence present in the study area, **leave no space for misunderstanding regarding the stratigraphy encountered at Domata.** And it is this stratigraphy, that is established on a concrete base, that dictates the sequence of events presented ultimately in Figure 10. The IRSL dating is only supplementary and helps placing **this sequence of events**, for which we feel much confident, within a chronologic context (and that is MIS 3).*

4. Carefully revise and edit the figures 5 and 8. Figure 5 is a new figure showing the topography of the fan surfaces. Can you give the orientation of the profiles (or location on Fig 4), and the unit of the X-axis? Figure 8 shows two soil profiles. One would typically give the soil depth (depth till C horizon, starting at 0 cm at the surface). Also, what is meant with "parent rock"?

We have now carefully revise Figure 5 and 8 as indicated by the Associate Editor. Specifically, in the old Figure 5 (now Figure 5a) we have included the orientations of the profiles (their location is also indicated on Figure 4) and we have added units (m) on both x-axes. Regarding Figure 8, we have reversed the log, so that now zero being the ground-surface (as requested). We have also replaced the phrase 'parent rock' with 'fan-gravel'.

Reviewer≠1 (anonymous)

From our understanding, his/her main concern is the unsatisfactory results of the luminescence dating. We totally agree, as we clearly state in the manuscript, that the luminescence results have large uncertainties and are, therefore, unsatisfactory. However, our sequence of events presented in this manuscript is not based on the luminescence dating. It is based on, and demanded by, the stratigraphy and the stratigraphic relationships that we recorded at Domata.

Before we go addressing in some detail this and other secondary remarks made by the Reviewer, we would like to make a general statement about the objectives of our work and constrain its scope. This may help allay some concerns expressed by the Reviewer.

Our primary interest in our work on Crete is to help constrain its late Quaternary tectonic development. With this work we aim to use first-order geomorphic features and stratigraphic relationships to understand the late Quaternary vertical deformation of western Crete. In doing so, we recognised the importance of the Domata fan sequence and the important marine bench cut in upper-fan at Domata. This feature allows us to independently derive a late Quaternary uplift rate *from this section of western Crete. The paper is important because of this independence from previously derived uplift rates on western Crete (e.g., Shaw et al., 2008; Strasser et al., 2011; Tiberti et al., 2014; Mouslopoulou et al., 2015 – all references included in the submitted version).*

To achieve these objectives, we needed to understand the first order fan geomorphology and from it dissect out the sequence of events required in landscape evolution. ***We derived a basic sequence of events that is demanded by the stratigraphic relationships present at Domata and present these in the manuscript.*** *We have gone to some effort to place the Domata fan sequence within its stratigraphic and chronologic context so that we fully understand the uplift rate derived. The final piece of the puzzle required to derive our uplift rate was its integration with a high quality sea level curve for the last 125 kyr. We chose Siddall et al.'s (2003) sea level curve because of its precision, relative proximity to the Mediterranean, yet its isolation from the variable tectonic signatures and isostatic problems associated with glacial loading of that region, and for its similarity with the Lisiecki & Raymo (2005) stacked curve.*

The luminescence dating we undertook simply provides confirmation of the chronological framework for the events that we had previously deduced with reasonable confidence from other stratigraphic and geomorphic observations. We completely agree with the reviewer that our luminescence dating, with its large uncertainties, cannot provide adequate resolution to separate the individual events presented here. The landscape evolution proposed in Figure 10 is not based on the luminescence dating: it is based on the ***sequence of events*** *that is demanded by the stratigraphic relationships present at Domata. The luminescence dating comes only to provide the chronologic frame (MIS 3) within which this sequence of events took place.*

For detailed discussion on the major issues relating to the IRSL dating we kindly direct the Reviewer to Pages 3-4 of our response to the short comment of Gallen and Wegmann (dated 27 Jan 2017) during our online interactive discussion.

General Comments (Reviewer ≠*1*)

The Mouslopoulou et al. paper deals with a topic that has both environmental and tectonic implications, focusing on a well-expressed sea-side alluvial fan. Compared to the other fans that make up the coastal bajada of south Crete that develops ca 20 km further east, Domata fan is a relatively small one (area c. 0.2 km_2), along with a string of other isolated fans that border the steep southern Cretan coast. Nonetheless, its stepped morphology, with an escarpment running roughly parallel to the present-day coastline may be indicative of processes that significantly affect fan-shape evolution, as the 'marine trimming' suggested by the authors. Indeed, Mouslopoulou et al. have tried to link fan evolution to climatic changes, coupled with uplift rate scenarios for the past few kyr and come up with a scenario that ties the evolutionary stages of the fan to successive marine high- and lowstands.

To achieve such a target, one has to resort to high-res geochronology, something that is not always feasible. Her lies, in my opinion, the main drawback of Mouslopoulou et al.'s work, which is found in their sampling strategy and the resulting dating accuracy: while the latter may not be the authors' fault, the former is a weak point in this work. Sampling did not include the body of the 'lower fan': this might clarify –and probably strengthen the authors' distinction of the Domata fan in an 'upper' and a 'lower' one. (Of course, this might not help, either, as the results from the other samples contain significant errors).

Having said these, I acknowledge the fact that the number of dated samples (and possibly the range of dating methods applied) are dictated by research funding; nonetheless, one has to make do with what they have, I'm afraid. At any rate, the resulting OSL ages contain significant errors (as also acknowledged by the authors: P.8, l. 14); it is also unclear whether standard deviation and standard error refer to 1-σ or 2-σ *(they refer to 1σ, as it is stated in Figure 9).* Hence, temporal resolution is too poor to support such a detailed evolution scenario, whose resolution is as high as 1kyr, while most ages overlap significantly and the correlation of successive events to KDE_{max} is not satisfactorily constrained. *For this comment, please see our introductory statement above.*

The lithostratigraphy of the Domata fan is poorly described; lithostratigraphic logs are missing – and these could help place the obtained samples in a coherent geological context. *We have now added detailed lithostratigraphic logs (Fig. 5b) and have also modified the old Figure 5 (now Fig. 5a) to illustrate the relationship of the samples and the geomorphic units.* Moreover, it might clarify any probable lithological or other difference between the units described as "upper" and "lower" fan. *Yes, we have now added detailed lithostratigraphic logs (Fig. 5b).* This could also be aided if appropriate figures (esp. photographs) were included, to show the lithological composition of the fan(s) *Yes, we have now added logs and associated photograps (Fig. 5b)*. Panoramic photos are fine, but some close-ups would be very useful for the reader to understand the distinction made between Upper and Lower Fans *Yes, we have now added close ups, see Figure 5b and Figure 6c*. Figure 8 (b and c) focus on the soil cover and do not serve this purpose.
The above stated objectives do not include a comprehensive description of the materials of the Domata fans (lithostratigraphic logs) and their developmental chronology, as has been undertaken for other fans of southern Crete by others (e.g., Nemec & Postma, 1993; Gallen et al., 2014; Pope et al., 2008, 2016). Nevertheless, we have rephrased the text in the revised version of our manuscript to better describe these geomorphic features and their interrelations. Besides, to better illustrate the first-order stratigraphic relationships between the main geomorphic features, we have now modified Figure 5 by illustrating schematically the volumes beneath the measured profiles to indicate the likely extent of the volumes of upper fan and lower fan materials. We have also added the locations of each of the luminescence samples. We have also now included stratigraphic logs (new Figure 5b) of the two fans, and associated close-up photographs, to show the detailed stratigraphy (and the differences) on the fans examined. We have further followed the Reviewer's advice and we have modified Figure 6b to better reflect the relationships between lower and upper fan units. In addition, we have also included a close-up image (Fig. 6c) to better reflect the relationship between the unconformity at the base of the fan sequence and the AD365 bioerosional notch.

Between Domata and Sougia (c. 9 km to the west) there is a number of fans in practically the same a geomorphological and geological environment (the same could also be supported for the bajada the east, with Sfakia fan being its westernmost member). Processes suggested in this paper (i.e. "marine trimming") are not localized ones and affect extended tracts of land. So if such a process was responsible for the modification of the Domata fan, why it is not found elsewhere along this coast?
It is true that along the southwestern coastline of Crete (e.g., east and west of Domata), there is a number of alluvial fans in roughly the same geomorphological setting. Many of these fans are indeed clearly truncated by the sea (Figure A below, near Trypiti, west of Domata). Although the 'double trimmed' alluvial fan-system at Domata is unique in its kind (as each episode of the two alluvial fan-building episodes has been followed by episodes of alluvial incision and subsequent marine trimming), evidence for 'double marine trimmings' exists elsewhere on western Crete as well. In Figure B below, for example, we provide evidence for a similar geomorphic feature that occurs at Agia Roumeli (about 4 km east of Domata), where an alluvial fan-system is truncated by two distinct marine-trimming events. It is hard to argue that these cliffs (illustrated in Photo B) are not trimmed by marine processes as they are parallel to the coast and on steeply sloping fans. Besides, on the upper cliff, the one with the sea-caves (where the hiking-track from Domata to Agia Roumeli passes through), we have found beachrock with shell-hash.

Figure A: Marine-trimmed alluvial fan near Trypiti (west of Domata)

Figure B: Double marine trimming of alluvial fan-system at Agia Roumeli (east of Domata).

The authors did not take into account the work by Pope et al., (2016), on the nearby, wellstudied Sfakia fan. This may be due to the fact that the m/s postdated the publication date of this paper, but nonetheless, the authors should take it into consideration in their revised version.
That is correct. When our research was compiled the work of Pope et al. (2016) was not yet published; this is why we did not include it in the submitted version. In the revised version, not only have we included reference to Pope et al. but we have added the following extensive comment relating our main findings to those of Pope et al. (2016):

'This work was undertaken prior to the publication of the latest results of OSL and U series dating of the Sfakia fan sequence (Pope et al., 2016). Intriguing conclusions of their high resolution dating work include that at Sfakia, three sometimes overlapping phases of fan deposition since the last interglacial are separated by two phases of fan entrenchment, the first close to the MIS 5/4 (c. 70 kyr) boundary, the other close to the MIS 2/1 boundary (c. 14 kyr), triggered by major climatic changes. Fan deposition there has to a large degree persisted through stadial and interstadial periods during the last 125 kyr. Periods of entrenchment at Sfakia do not appear to correlate with the two entrenchment periods at Domata. The Sfakia fan is significantly different from the Domata fan in catchment size (c. 28 km^2 compared with c. 11 km^2), fan size (5.3 km^2 compared with 0.1 km^2), the presence of more than one feeder channel at Sfakia, and in the nature of deposits (primarily clast-supported gravels compared with primarily matrix-supported gravels). Whether these differences are responsible for differences in depositional and entrenchment histories and in preservation of marine cliffs at Sfakia, or differences in local climatic regimes or vegetation changes is uncertain. However, one compatible conclusion of their work with our own is recognition of the importance of base level (sea level) change to the process of entrenchment.'

Specific Comments of Reviewer *≠1*

Page 4, l. 20-21. Bedrock geology is grossly misrepresented, both in terms of lithology and age. Klados Gorge runs through platy crystalline limestones with phyllite intercalations and chertbearing dolomites, chert-nodule-bearing limestones and quartzitic sandstones and shales, not through the platform carbonates of the Tripolis Unit (which is a Mesozoic carbonate platform). Moreover, the aforementioned lithologies (i.e. Kingilos group) belong to the metamorphosed Plattenkalk Unit, also known as Mani Unit. (e.g. Creutzburg and Siedel, 1975; Fassulas et al., 1994; and Jolivet at al., 1996).
This suffices to explain the occurrence of quartz detritus in the Domata fan; the authors, however, did not seem to wonder why a purely carbonate-fed fan (as they describe it), contains so much quartz! *We apologise for this – it slipped out of our attention and the correct rock-type and some associated comments are now included in the revised version (bottom of Page 4 and start of Page 5). We completely agree with the Reviewer that the Plattenkalk unit outcrops in our study area. Specifically, the platy limestones and the platy limestones with cherts are the main units that occupy the largest part of the Klados gorge valley. The Gigilos layers appear in the northern part of the Klados watershed, which drains mainly towards the Omalos plateau and the northern part of the Samaria Gorge (Fassoulas et al., 2004). However, we doubt that the Gigilos beds (shales and quarzitic sandstones and chert bearing limestones) have been contributing in the mass of sediments within the Klados gorge since they are only outcropping in the northern parts of White Mountains (Lefka Ori) and they are north dipping. In contrast, the Klados gorge developed in the overlying platy limestones with cherts which eventually developed in platy marbles with limited chert intercalations (Unit 4d and 4e at Manutsoglu et al., 2003). Thus, Klados gorge has mainly developed in platy limestones with some cherts and platy marbles and the erosion of these units supplied the Domata area mainly with carbonate clasts and limited chert clasts (from the lower units) which explain the abundance of carbonates in the alluvial fans and fluvial terraces.*

1. *Manutsoglu, E., Soujon, A., and Jacobshagen, V., 2003. Tectonic structure and fabric development of the Plattenkalk unit around the Samaria gorge, Western Crete, Greece. Z. Dtsch. Geol. Ges. 154, 85-100.*
2. *Fassoulas, C., Rahl, J.M., Ague, J., and Henderson K., 2004. Patterns and conditions of deformation in the Plattenkalk nappe, Crete, Greece: a preliminary study. Bull. Geol. Soc. Greece, vol. XXXVI, 1626-1635.*

P.3, l.20. Please use appropriate term instead of "vertical deformation".
We don't understand what the reviewer means. We have replaced 'vertical deformation' to 'vertical movement', hoping that this is more appropriate.

P.21, Figure 2. How confident are the authors that the quasi-planar landforms west of the gorge are marine benches? Is there any piece of evidence supporting this suggestion?
These quasi-planar surfaces are very common in southwest Crete and are generally well-studied. As we state in the manuscript, 'while we cannot assign ages to these benches, their altitude and geomorphic similarity with known and dated (MIS5) late Pleistocene marine benches elsewhere in Crete (e.g., Strasser et al., 2011; Gallen et al., 2014; Strobl et al., 2014), provides some stratigraphic and chronologic context for the age of the alluvial fans at Domata (i.e., because of their lower elevation, the alluvial fan surfaces that are subject of this paper are expected to be younger than 125 kyr)'.

Moreover, marine materials (shell-hash beachrock) have been found by the authors on such a planar surface of similar (~100 m) elevation, 2.5 km west of Domata (towards Sougia). However, we did not date these materials as we expect their age to be outside the radiocarbon age-range.

P25, Figure 6b. The red dashed line that is suggested to represent a low terrace riser on the west side of the river seems rather ambiguous; it is hard to say from this photo.
We have now modified and re-annotated 6b to satisfy the Reviewer.

Technical Corrections
N/A

Reviewer≠2: Mara Monica Tiberti

We thank the reviewer M.M. Tiberti for her useful and positive comments. Below we respond in detail to each comment.

General comments of Reviewer *≠2*
This paper presents the results of measurements and datings on a fan deposition sequence at Domata, on the southern coast of Crete (Greece). Crete Island is a key region in the Mediterranean area, as it is one of the few pieces of emerged land in the forearc domain of the Hellenic subduction zone. Dating geomorphic markers such as alluvial fans and comparing the results with the eustatic curve can contribute to separate the eustatic and tectonic components of apparent coastal uplift, thus constraining vertical tectonic rates. The Authors reconstruct the deposition history of the two alluvial fans and constrain their temporal evolution using IRSL results only (because OSL did not work properly) and stratigraphic considerations. Their results imply that the formation of the two alluvial fan was controlled mainly by climatic and eustatic factors during the general marine regression of MIS 3. No tectonic contribution is necessary to explain their evolution during this period. The state of preservation of the alluvial fans, however, requires that they have been never submerged during

the sea-level rise after the last glacial maximum, thus implying that tectonic uplift rates constantly outpaced the eustatic rise during the last 20 ka.

This work presents new data that add an important piece of knowledge to a growing dataset of dated geomorphic markers along the coast of Crete by various authors. These data contribute to constrain the Quaternary geologic evolution of the coast of Crete, helping in separating climatic, eustatic and tectonic components in the Hellenic subduction zone. Hence, the paper address relevant scientific questions within the scope of ESurf, reaching substantial conclusions.

Despite the general good quality of the work, however, the paper lacks clarity and readability. I suggest the Authors to reorganize it in the classical section "Introduction", "Method", "Results" and "Discussion". The Method section should contain the description of how the survey and the datings were carried on, including technical details on OSL and IRSL determinations and soil analysis. The Results section is supposed to contain the Authors' findings, the measurements and age determinations for the alluvial fan deposits and the tentative reconstruction of their evolution. I recommend the Authors to not include other workers' results in this section. Comparison with other researchers' results should be placed in the Discussion section, along with the implications of their own results upon tectonic rates estimates. Considerations on the reliability and accuracy of the datings and their implication should also be included in the Discussion.
We thank the reviewer for this suggestion. However, we will not change the structure of the paper, as the current structure is pretty classical: introduction, geological setting, data-methods, interpretation and conclusions. What M. Tiberti suggests is not too dissimilar to what already exists. Also, we don't agree that the comparison with other people's results should be done in an independent section. We feel it is more natural if comparisons are made within each relevant section. We believe, that in the submitted/revised versions it is clear which results are our own and which are published.

In particular, the Author should add the discussion of their results in the general framework of existing data, including those that lead to different interpretations. This important point is at present almost completely disregarded.
We thank the reviewer. Although we do discuss/compare in our manuscript fan chronology/development with published chronologies of other fans along the southern coastline of Crete (e.g., Nemec & Postma, 1993; Gallen et al., 2014; Pope et al., 2008, 2016 – the latter included in the revised version) and despite the fact that we do compare the uplift rate value derived from Domata (this study), to other published uplift rates derived from study of marine terraces on western or eastern Crete (Shaw et al., 2008; Strasser et al., 2011; Tiberti et al., 2014; Gallen et al., 2015; Mouslopoulou et al., 2015 – all references included in the submitted version), to satisfy the reviewer, in the revised version, we have added another 8 references to Tiberti et al (2014), a publication that we value highly and is relevant to this study. We have also included, in the revised version, extensive discussion (including comparison) of Pope et al.'s (2016) findings at a nearby fan system with the findings of our work – the latter article was missing from our submitted version as our work predated the publication of Pope et al. (2016).

Please see below specific sections in the revised manuscript that discuss our work with respect to relevant published work:

- *Page 2, lines 24-31*
- *Page 3, lines 24-31*
- *Page 4, lines 1-10*
- *Page 5, lines 14-19*
- *Page 6, lines 25-31*
- *Page 8, lines 7-9*

- *Page 9, lines 20-26 and 30-33*
- *Page 10, lines 1-5*
- *Page 12, lines 25-33*
- *Page 13, lines 1-4 and lines 10-11.*
- *Page 13, lines 18-30.*

The fact that some (only some) of these comparisons are made with our own published work is something we cannot avoid. Perhaps the reviewer means that we didn't include their work (Tiberti et. al., 2014) in lines 1-15 of Page 12 (original version)*, and this oversight has been corrected. We should have referred to their work which, for the last 20 kyr, also shows rapid uplift in western Crete whereas for the period 20-40 kyr shows slow subsidence. This, however, won't lead to any different conclusions of the current manuscript.*

They should also discuss the intrinsic limitations of the methods used and the consequent implications.
We have expanded our discussion of the stratigraphic and geomorphic requirements for development of the Domata fan sequence and comment more specifically on errors in our IRSL dates and the way we use them (sections 3 and 4).

Specific comments from Reviewer ≠2
There is some confusion about OSL and IRSL datings throughout the text and in tables and pictures. In the text the Authors state that two kind of measurements were performed: quartz OSL and feldspar IRSL. Quartz OSL datings results were not used to constrain the evolution history of the alluvial fans, as they proved to be of poor quality. *[Please see our detailed response to Gallen and Wegmann on January 27th, 2017 about this issue].* They are cited in the text, but never appear in tables or pictures. *[We agree. We should use the term IRSL instead of OSL throughout the text].*

Figure 7 and table 1 apparently report only the results for feldspar IRSL. The Authors should be specific (i.e.: "quartz OSL" and/or "feldspar IRSL") when refer to these measurements, as the use of the general term "OSL" in titles and captions could be somehow confusing *[corrected]*. In addition, quartz OSL results should be shown in any case, at least as supplementary material. *[See above].*

In the text, the Authors repeatedly state the "uniqueness" of the Domata site, without discussing it. Are they sure that there is not any similar situation along the southern coast of Crete? What is the difference between the Domata site and the other alluvial fan sequences described in the literature? (e.g. Peterek, et al., 2003; Pope et al., 2008; 2016).
The geomorphology at Domata, and the Klados River Gorge itself, differ to other gorges in south Crete. For example: The Sfakia fan (Nemec & Postma, 1993; Gallen et al., 2014; Pope et al., 2008, 2016), is significantly different from the Domata fan in catchment area (c. 28 km^2 compared with c. 11 km^2), fan size (5.3 km^2 compared with 0.1 km^2), the presence of more than one feeder channel at Sfakia, and in the nature of deposits (primarily clast-supported gravels compared with primarily matrix-supported gravels). Please see our response to Gallen and Wegmann's short comment below (January 27, 2017) where we explain in detail this issue.

Technical and other line-by-line comments (Reviewer ≠2)

Abstract
Line 20: conventionally, the last glaciation corresponds to MIS2 not MIS3 *[last glaciation removed].*
Line 23: *most* instead of *mot* *[corrected].*

1 Introduction Line 30: please specify which sea-level curve are you using. From Figure 9 it turns out to be the one by Siddal et al. (2003). What do you mean with "international"? *We have now removed the term 'international'.* The curve by Siddall et al. is reconstructed using oxygen isotope records from Red Sea sediment cores. *Our reasons for using the Siddall et al. curve are explained in our response to the Gallen & Wegmann's short comment, submitted at the online interactive discussion on January 27th, 2017.*

2 Geological setting of Crete and vertical tectonics
Lines 11-16: see also Zachariasse et al., 2008. *Reference included now.*

Line 18-21: *Using dated paleoshorelines and numerical models, it is shown that the island of Crete experienced, during the last 20 thousand years, periods of severe uplift (at rates of up to 8 mm/yr) while in the preceding ~30 thousand years, the vertical deformation on Crete was minimal (Mouslopoulou et al., 2015b).* Please add also Tiberti et al. (2014; already cited in other parts of the text) to Mouslopoulou et al. (2015b), as they state "*Attaining the S4 to S5 vertical separation thus requires a net subsidence rate of 2.6–3.2 mm/y in the period from ~42 to 23 ky ago. A period of sustained uplift of ~7.7 mm/y should have then followed the S5 abandonment (~23 ky ago) as suggested by the formation of S2, with sea level at -120 m, and S3 and S1-low with sea level at about the same elevation as today*". *Yes, we have added extensive reference to this work now throughout the revised version →*
Page 3: lines 25-30
Page 12: lines 25-30
Page 12: lines 30-34
Page 13: lines 1-3
Page 13: lines 10-12
Page 21: lines 13-15

Line 24: please add also Tiberti et al. (2014; same reason explained above). *[Yes, see above].*

Line 28: Strasser et al., *2011* instead of *2010* *[Thanks].*

Lines 28-30: Not only historical accounts, however, about the tsunami: see, for instance, Polonia et al., 2013. *[Reference included now, thank you].*

3.2 OSL dating of alluvial fans
Line 21: *The results of OSL analysis are presented in Table 1 and Figure 7.* Please specify exactly which kind of analysis: both Table 1 and Figure 7 seem to show only IRSL results. *[Yes it corrected now, see above].*

3.2.2 OSL results
Page 8, Line 15: *IRSL* instead of *OSL* *[Yes, done].*

3.3 Soil development
Line 33: *IRSL* instead of *OSL* *[Yes, done].*

Page 9, Line 14: *IRSL* instead of *OSL* *[Yes, done].*

4 Landscape evolution at Domata

Line 18: *international sea-level curve*: please remove "international" *We have removed "international" and replaced it with "the Siddall et al. (2003) sea level curve". Our reasons for using the Siddall et al. curve are explained in our response to the Gallen & Wegmann's (see our response below to their comment of 27th January, 2017).*

Page 10, Line 31: *deposition of the upper and lower-fan deposits*: please remove "deposits" *[Yes, done].*

5 The importance of tectonic uplift at Domata

Lines 24-30: for the sake of completeness, you should mention the other average uplift rates estimates over the last 50 ky based on quantitative datings along the SW coast of Crete:

1.5 mm/y by Wegmann (2008)

2 mm/yr by Shaw et al. (2008)

1-1.5 mm/y by Strasser et al. (2011)

2.5-2.7 mm/y by Tiberti et al. (2014)

But…. we do say that our results (ca. 2.2 mm/yr) are in very good agreement with the published results above (and we provide the references). Now we have also provided a range of uplift rates for the proposed studies (Page 12, lines 25-30).

Page 12, Lines 5-6: *no significant uplift was accommodated on Crete as the region between ca. 20-45 kyr was experiencing a tectonically quiet period (Mouslopoulou et al., 2015b).* Please notice that for the same period (42 to 23 ky ago), Tiberti et al. (2014) postulated a net subsidence rate of 2.6-3.2 mm/y.

Yes, we have included a statement including reference to your findings - thanks.

Page 12, Lines 14-15: *Comparable uplift rates have been independently recorded at numerous localities on western and eastern Crete for the last 20,000 years by Shaw et al. (2008), Tiberti et al. (2014) and Mouslopoulou et al. (2015b).* Shaw et al. (2008) never mention an uplift rate of 7 mm/y or similar values over the last 20 ky. They estimate a ca. 2 mm/y uplift rate on the basis of a 20-24 m elevated shoreline dated 41-53 ka.

For Shaw et al.: we mean the rate over the last ~2 kyr - since the 365 AD event. But in order to avoid confusion we have removed this reference from this sentence.

6 Conclusions

Line 23: *IRSL* instead of *OSL* *[Yes].*

Figure 1

Please add a coordinates reference frame. Use bold for numbers indicating GPS values. Enlarge letters indicating the sites on the southern coast of Crete and use a darker color (e.g. blue instead of yellow) for the circles. In the caption: *WM* instead of *WG* = White Mountains. *[Yes, done].*

Figure 6

Caption, Line 5: *100 m* instead of *100's metres* – *[No, it is 100's as the Domata beach is more than 500m long]*

Figure 7

Caption, Line 11: *IRSL* instead of *OSL*. Please change this also in the picture. *[Yes, done].*

Figure9

Caption, Line 21: *IRSL* instead of *OSL.* Please change this also in the picture. *[Yes, done].*

Response to Gallen and Wegmann's short-comment (27 January 2017)

We take this opportunity to thank S. Gallen and K. Wegmann for their comments on our manuscript.

Before we respond in detail to their comments, we would like to make a general statement about the objectives of our work and constrain its scope. This may help allay many of the concerns they expressed.

Objectives:

Our primary interest in our work on Crete is to help constrain its late Quaternary tectonic development. With this work we aim to use first order geomorphic features and stratigraphic relationships to understand the late Quaternary vertical deformation of western Crete. In doing so, we recognised the importance of the Domata fan sequence and the important marine bench cut in upper fan at Domata. This feature allows us to independently derive a Late Quaternary uplift rate from this section of western Crete. The paper is important because of this independence from previously derived uplift rates on western Crete (e.g., Shaw et al., 2008; Strasser et al., 2011; Tiberti et al., 2014; Mouslopoulou et al., 2015 – all references included in the submitted version).

This objective does not include a comprehensive description of the materials of the Domata fans and their developmental chronology, as has been undertaken for other fans of southern Crete by others (e.g., Nemec & Postma, 1993; Gallen et al., 2014; Pope et al., 2008, 2016). Neither is the objective to compare Domata fan stratigraphy with that of other alluvial fan systems on Crete. We welcome the prospect of additional work that would enhance insight into the processes of fan deposition and a refined chronology that may help better understand relationships between sediment transfer rates and climate in this area.

Methods:

To achieve these objectives, we needed to understand the first order fan geomorphology and from it dissect out the sequence of events required in landscape evolution. We derived a basic sequence of events that was demanded by the stratigraphic relationships present at Domata and present these in the paper. We have gone to some effort to place the Domata fan sequence within its stratigraphic and chronologic context so that we fully understand the uplift rate derived. The final piece of the puzzle required to derive our uplift rate was its integration with a high quality sea level curve for the last 125 kyr. We chose Siddall et al.'s (2003) sea level curve because of its precision, relative proximity to the Mediterranean, yet its isolation from the variable tectonic signatures and isostatic problems associated with glacial loading of that region, and for its similarity with the Lisiecki & Raymo (2005) stacked curve.

The luminescence dating we undertook simply provides confirmation of the chronological framework for the events that we had deduced with reasonable confidence from other stratigraphic and geomorphic observations. We completely agree with Gallen & Wegmann that our IRSL dating, with its large uncertainties, cannot provide adequate resolution to separate the individual events presented here. Similarly, the soil descriptions provide a supporting understanding for our stratigraphic conclusions, independently confirming that the two fans are built over distinct time-periods.

In our revised version we explain more clearly these objectives and the evidence for our interpretation of the sequence of events in our 'landscape evolution' at Domata, so that there can be no misunderstanding.

Our detailed responses are presented below in red.

(1) Lack of a sedimentologic and stratigraphic descriptions of the Domata fan in the context of other alluvial fans on Crete in the current version of the manuscript. ***[In addition now, March 2017, we have added lithostratigraphic logs of the alluvial fan-system studied: new Figure 5b]***

The Klados River gorge itself is not unique, but one of five similar gorges *[Actually, the Klados R. gorge is significantly shorter and its catchment size is much less than the other gorges of the Lefka Ori (c. 11 km^2 compared with 28 km^2 for the Sfakia fan).The size of the Domata fan sequence is also very small (0.1 km^2 vs 5.3 km^2 for Sfakia). Therefore, they are not necessarily similar.]* that drain the Lefka Ori (White Mountains) and there is little difference in the coastal geomorphology at the mouths of each of these gorges [*We disagree with this statement either. Please compare the geomorphology at the mouths of Tripiti, Klados, Samaria and Eligia gorges. They are very different. And the entrenched Aradaina Gorge at Marmara, with its marine benches is very different to the alluvial fan systems that extend from Hora Sfakion to Skaloti. There are significant differences in the coastal geomorphology at the mouth of each of these gorges. In addition, V.M., J.B. and D.M. who have walked down all five of them through the years, can confirm that these gorges also differ internally – that was also reflected in the significantly different degree of effort/difficulty to cross them]*. However, having visited this fan sequence and studied numerous other fans on Crete, we can say that the Klados (Domata) fan sequence is sedimentologically and stratigraphically unique among fan deposits on Crete *[Please see the statement preceding this section. Our paper is not focussed on this issue. The authors of this short comment have made these observations and have the opportunity to write such a paper making this comparison.]* Most alluvial fans in Crete are coarse grained, clast supported, and weakly stratified. By contrast the Domata fan sequence is finer grained, having horizons that are variably clast and matrix supported, and better stratified than any other fan that we have seen on the island to date. It is these sedimentological details that will provide the most insight into the origins of the fan unit *[We believe that this is a value judgement. Our paper does not alter the opportunity for these reviewers to prove this point in their own paper].* The unique sedimentology and stratigraphy of this fan relative to other fans in Crete suggests that a different process is responsible for the deposition of this fan sequence *[Presumably to be included in their paper].* Given the short transport distance through the Klados River gorge (~ 5 km) *[transport distance is not necessarily a significant factor in the energy of a depositional environment, a high base level is]* and the relatively fine grained nature of the fan deposit, the Domata fan sequence is suggestive of a high-energy process *[Our interpretation differs – we believe the depositional environment is lower energy, influenced by high sea-level].* Stratigraphic and sedimentological descriptions of the fan sequence and discussion of how these observations compare with other studies of fans on Crete would substantially improve the manuscript *[As explained above, these descriptions and comparisons can still be made by these reviewers or by others; they are not the subject of this paper. See our objectives statement above. Further, it is inappropriate to suggest modification of our manuscript on the basis of their interpretation of their data, when we don't even have these data].* Based on the data presented current version of the manuscript it is difficult to evaluate whether or not the authors' argument that the fan sequence represents two fan *[We have now included a specific sentence stating unequivocally that the relict fan sequence at Domata represents two distinct phases of fan deposition within a single channel feeder fan. We have also added a sentence clarifying that both fans are sourced from the entrenched Klados River gorge, the feeder channel].* An alternative interpretation is that the Domata fan sequence represents a single depositional phase followed by unsteady incision, as is common in alluvial fill-cut terrace sequences (also known as complex-response fill terraces of Bull, 1990) *[The presence of a marine cliff at the shoreward side of the upper fan that also truncates an alluvial entrenchment of the upper fan surface indicates clearly that the depositional phase present during upper fan deposition is interrupted, and pre-dates deposition of the lower fan]*.

Importantly, our own observations indicate that the entire Domata fan sequence overlies a beach deposit that is the lateral continuation of the Holocene bioerosional notch (see figure below). If correct, such a stratigraphic relationship demands that the Domata fan sequence is Holocene, rather than Pleistocene, which is in direct challenge to the geochronology presented in this manuscript. [*We firmly believe that this interpretation is* *seriously flawed. The "bioerosional notch" in their figure (c), with its interpretation clearly points to the 6 m a.s.l. AD 365 earthquake bioerosional notch that we can follow westward all the way to Sougia and beyond to Palaiochora and Elafonisi and from there around the corner all the way to Falasarna. At the point indicated in their figure, the elevation of this notch coincides with the elevation of the contact between the lower fan deposits and bedrock. The bench indicated in the supplementary figure has been preferentially eroded because it relict from an earlier erosion surface (upon which the lower fan deposits sit here.) The same bioerosional notch is also present in bedrock immediately to the east of the indicated location, 1 m and more below the bedrock/lower fan deposits contact, the latter represented by an uneven morphology (see our Fig. 6b, newly annotated to illustrate this point and the onlapping relationship between the fan deposits and bedrock). The contention therefore, that beach deposits underlie the lower fan deposits on the basis of the reviewers' illustration, is stratigraphically unfounded. The lower fan deposits must pre-date the bioerosional notch. To interpret this bioerosional notch as pre-dating the lower fan deposits as an older Holocene feature requires the entire lower fan to post-date c. AD365. This bioerosional notch is cut in bedrock, has been eroded from fan gravels (note the rockfall deposits at the base of the cliff in the lower fan behind the main beach, illustrating that the loose gravels of the fan deposits erode very differently to the bedrock), but is further represented by the young, abandoned terraces at the Klados River mouth].*

Furthermore, we are curious as to why luminance dating was only attempted on a fan sequence that is almost entirely comprised of carbonate detritus? Why not also try to date the underlying beach deposit that contains more material suitable for luminance dating and is less likely to suffer from incomplete bleaching?

[The reason is clear: no "beach deposit" as interpreted by the commentators underlies the fan. Dating the "bioerosional notch" they refer to would provide an incorrect estimation for the age of the fans. The reviewers appear to be suggesting that entire >60 m thickness of these fans was deposited in <10kyr. Compare this thickness to those of other fans in Crete, such as those recorded at Sfakia region or even those recorded in central-eastern Crete by Gallen (2013). In addition, no beach deposit was identified on the marine bench cut in upper fan deposits, presumably because if deposited, it was subsequently eroded early in the deposition of the lower fan].

(2) The luminescence geochronology and the lack of tests for, or detailed discussion of the potential for and implications of incomplete bleaching.

The proper tests needed to confirm or reject whether or not incomplete bleaching has occurred were not reported. Without these key tests of samples from a depositional environment that is notorious for incomplete bleaching (Rhodes et al., 2010), it is difficult to interpret the luminescence data as being a trustworthy chronometer reflecting a true burial age. Every other study that has used luminescence dating to constrain the timing of alluvial fan deposition on Crete has successfully used quartz OSL (Pope et al., 2008; 2015; Gallen et al., 2014; Runnels et al., 2014). The fact that this method did not work for this study is of significance provided that the setting is geologically, tectonically and climatically similar to the locations of all of the aforementioned studies. The only thing that makes the Domata fan sequence unique in its sedimentology and stratigraphy, which suggests that a different process is responsible for its deposition (see comment above). Our suspicion is that the unique origin of the Domata fan sequence is why quartz OSL was unsuccessful. Furthermore, we question the reliability of the feldspar IRSL data without bleaching tests. It is acknowledged in the text that incomplete bleaching can explain the noisy IRSL data (P. 8, Lines 4-5), but the significance of this signal and the proper tests for incomplete bleaching are not present in the manuscript. Provided the unique problems with quartz OSL signals in this deposit, coupled with the known problems of incomplete bleaching in alluvial fans, and results that are difficult to explain, one is hard pressed to interpret this data at face value without prior proper vetting of the luminescence signals.

<u>We summarise the reviewer's concerns in three main groups:</u>
1) Quartz seemed not to have worked at Domata but has worked in other studies nearby on Crete (Pope et al., 2008, 2016; Gallen et al., 2014)

2) Feldspar dating at Domata yields imprecise IRSL ages with high uncertainties
3) Feldspar IRSL dating was not carried out following standard procedures (no testdose correction during SAR measurement, no fading test to correct for potential age underestimation).

<u>1:</u> Why was quartz OSL so dim? For readers of the above mentioned studies it's hard to believe that quartz didn't work at Domata, a few kilometres away from the Sfakia fan system with comparable geological settings. But it is an empirical fact, that the OSL signal intensities were very low and that linear modulation (LM) measurements showed that there was almost no "fast component" in the natural OSL signals. Thus, quartz dating is wrong. A possible explanation is that the dated quartz was not sensitized before sedimentation. Quartz needs repeated cycles of daylight bleaching and radioactive irradiation to emit any analysable OSL signal. Dim quartz not suited for OSL dating is often reported from geologically young environments (e. g. the Alps). But, of course, this does not explain why the behaviour of Domata quartz is different from quartz of other locations on Crete.

<u>2:</u> Why are our error in age so large? Our samples consisted almost entirely of carbonate detritus with only few quartz and feldspar grains of a suitable size (exception: UF-2) and the samples were collected mostly near the surface. This implies some problems leading to high age uncertainties: 1) In such inhomogenous and coarse grained samples one can expect radioactive inhomogeneities. 2) Near the surface, any kind of postdepositional mixing is possible (roots, bioturbation, penetration of bleached material into voids). 3) The dominance of carbonate causes an extremely low dose rate of roughly 0.5 Gy/ka for quartz and 1.0 Gy/ka for potassium feldspar. Hence, the contribution of the cosmic dose rate to the total dose rate is relatively high (ca. 40% for quartz, 20% for potassium feldspar). But the cosmic dose rate is only estimated from the sample position and cannot be measured. 4) Incomplete bleaching (insufficient daylight exposure) is always a risk in fluvial environments. The coarse grain sizes suggest runoff events of high energy, where incomplete bleaching is more likely. The studies of Pope et al. (2008, 2016) suffer less from the mentioned problems because they sampled homogenous sandy material from sand layers/sand lenses within the fan body.

<u>3:</u> Problems appeared with potassium feldspar IRSL dating? In addition to the problems discussed above (large errors), IRSL dating failed using standard SAR procedures. For instance, it was not possible to recover a known laboratory dose with standard SAR protocols. It was deduced that the testdose correction did not work, but rather caused a systematic underestimation of known laboratory doses. Thus, testdose correction was omitted, but all aliquots affected by sensitivity changes were rejected. Another constraint is the so-called anomalous fading, which affects almost all potassium feldspar samples. Anomalous fading is the unwanted signal loss during burial leading to age underestimation. Often, age underestimation up to 30% of the true age is observed. It is possible to determine fading rates to correct the resulting IRSL ages, but this is very time consuming and there is currently discussion questioning whether this technique is reliable. Nevertheless, such fading tests reveal whether anomalous fading plays an important role or not. Fading correction was not carried out here, because fading is the "antagonist" of incomplete bleaching. Fading causes age underestimation, incomplete bleaching causes age overestimation. It is probable, that our feldspar samples suffer both from fading and incomplete bleaching and it's hard or even impossible to distinguish the two effects.

*Bleaching tests were not conducted. This is to test, whether the IRSL signal is bleachable in an appropriate time. For this test, aliquots are bleached stepwise in a solar simulator and the remaining signals are measured. This could be easily done. Tests for incomplete bleaching (possible age overestimation) are important and we did it by analysing the OSL and IRSL data (e.g. analysis of age distributions or plotting the signal intensities vs. dose). And yes, **there is evidence for incomplete bleaching**. Unfortunately, the amount of unbleached signal inherited cannot be quantified clearly. For quartz OSL there are statistical models to select the best bleached grain population when measuring single grains or "small aliquots" containing only few grains. These models are less reliable for feldspar.*

(3) Incomplete review of pertinent literature.
Much of the literature on 1) Cretan alluvial fans and 2) alternative models for the tectonics of the Hellenic forearc are missing from the manuscript. *[We agree that there is some missing literature, mainly because this work was compiled before Pope et al. (2016) was published. We will include this work in the revised version. Also, we will include discussion on alternative tectonic interpretations, although whether or not there are uplift*

transients on Crete will not impact at all on the results of this study.] In addition to the excellent work of Pope et al. (2008), Pope et al. (2016), Runnels et al. (2014), and Gallen et al. (2014) employ luminescence geochronology to date alluvial fans on Crete. Pope et al. (2016) and Runnels et al. (2014) are absent from the current version of the manuscript *[For Pope et al., (2016) the reason is explained above. For Runnels et al. (2014): this publication was published in the journal of European prehistory, and it escaped our attention. We thank the reviewers for pointing this article out].* While Gallen et al. (2014) is cited, no acknowledgement is made for this studies contributions to understanding the Quaternary coastal stratigraphy of Crete *[We have amended the ms to include Gallen et al.'s studies, indicating that they have recognised elevated benches in central-eastern Crete dated as last Interglacial in age. This supports our interpretations on relative age of the Domata fan sequence. Our objective in this ms was to provide a post-Last Interglacial temporal context for the Domata fans].* In addition to successfully dating alluvial fans with quartz OSL, the Gallen et al. (2014) study dates marine terrace deposits with OSL that are buried by alluvial fans. The authors of the above cited studies, and especially Gallen et al. (2014) use detailed mapping, stratigraphy and sedimentology of the deposits, pedology, OSL geochronology and a global sea level curve to derive a model for the coastal stratigraphy in southern Crete that relates interactions between tectonics, climate and eustacy. Discussion of the findings and interpretations presented by Mouslopoulou et al. in the context of other, similar studies from Crete would greatly improve the manuscript *[See our objectives statement above].*

The review of the Quaternary tectonics of Crete is incomplete. In the background section and again in the discussion, alternative models for the Quaternary vertical tectonics of the island are not discussed *[See above].* Section 2 reads as though consensus has been reached regarding "Late Quaternary uplift transients". However, there is an ongoing scientific debate in the literature about whether or not these Late Quaternary uplift transients actually exist or if there are problems with the geochronology used to derive this model *[The geochronology used in our ms is consistent with the Gallen et al. (2014) OSL geochronology for the Last Interglacial. Furthermore, it contradicts the suggestion that the entire Domata fan sequence is Holocene in age].* While this may be the favored interpretation of the authors of this manuscript, other interpretations should be acknowledged and the ongoing controversy in the literature noted *[We will make this change in the revised version – but it is unrelated to our conclusions].*

To answer to some of the reviewer's concerns, we will add the following text in our revised manuscript:
This work was undertaken prior to the publication of the latest results of OSL and U series dating of the Sfakia fan sequence (Pope et al., 2016). Intriguing conclusions of their high resolution dating work include that at Sfakia, three sometimes overlapping phases of fan deposition since the last interglacial are separated by two phases of fan entrenchment, the first close to the MIS 5/4 (c. 70 kyr) boundary, the other close to the MIS 2/1 boundary (c. 14 kyr), triggered by major climatic change. Fan deposition there has to a large degree persisted through stadial and interstadial periods during the last 125 kyr. Periods of entrenchment at Sfakia do not appear to correlate with the two entrenchment periods at Domata. The Sfakia fan is significantly different from the Domata fan in catchment size (c. 28 km^2 compared with c. 11 km^2), fan size (5.3 km^2 compared with 0.1 km^2), the presence of more than one feeder channel at Sfakia, and in the nature of deposits (primarily clast-supported gravels compared with primarily matrix-supported gravels). Whether these differences are responsible for differences in depositional and entrenchment histories and in preservation of marine cliffs at Sfakia, or differences in local climatic regimes or vegetation changes is uncertain. However, one compatible conclusion of their work with our own is recognition of the importance of base level (sea level) change to the process of entrenchment.

Line-by-line comments:

Introduction:

P. 2, Line 14-16: There is little mention of sediment supply here. The interplay between sediment supply and discharge is an important factor controlling alluvial fan deposition and may have little to do with changes in

base level (e.g. rising sea-level). Furthermore, enhanced rainfall does not necessarily translate into alluvial fan deposition, as implied. Enhanced rainfall may favor increased discharge at the expense of reduced hillslope sediment supply because the hillslopes are vegetated more during times of increased annual precipitation and thus, the alluvial fan experiences an episode of incision. The interplay between climate and tectonics, deposition and incision is not straightforward. We would also like to point the authors to alternative models for channel aggradation that might be relevant to this study. In particular, the recent work of Scherler et al. (2016) documents that Late Pleistocene fill terraces in southern California (a region climatically similar to Crete), which were traditionally interpreted as the result of climate change, are more likely the result of changes in sediment supply due to a large landslide in the catchment. This research is also relevant because they use luminance dating of the alluvial fill and discuss at length the geochronologic problems associated with incomplete bleaching.
[We have modified these sentences on the revised version to accommodate some of the reviewer's concerns.]

P. 2, Line 20-24: These types of interpretations are difficult to discern from field data alone as the drivers of aggradation and incision reflect the interplay between sediment supply and discharge. What seems to be implied by this review is that deposition is driven solely by enhanced precipitation and incision by tectonic uplift. Yes, ultimately, the accommodation space needed for alluvial fan deposition is a result of tectonic processes, but at the time scale of the Late Pleistocene, the amount of tectonic uplift is insignificant in comparison to variations in climate-driven discharge and hillslope sediment supply from the mountainous catchment to the alluvial fan system. Furthermore, precipitation, temperature, and thus, vegetation co-vary in ways that make it difficult to predict how changes in precipitation relate to variations in catchment sediment supply and discharge. Depending on the climate and vegetative response, increased precipitation can lead to a reduction in sediment supply and incision, rather than aggradation.

The authors also appear unaware of a critical new body of research by Pope et al. (2016). *[See above explanation].* In this paper, Pope and colleagues 30 present 32 new OSL and U-series dates for what is undoubtedly the best dated alluvial fan sequence on the south coast of Crete, the Sfakia fan. Importantly, Pope et al. (2016) conclude that over the entirety of the late Quaternary, the Sfakia fan only experienced two episodes of entrenchment (incision), during the transition between Marine Isotope Stages (MIS) 5a/4 and MIS 2/1. They propose that the MIS 5a/4 period of fan incision was driven by sea level-induced base level fall; whereas the MIS 2/1 interval of incision (during a time of rapid eustatic sea level rise) was the result of reduced hillslope sediment supply to the fan resulting from landscape stabilization (re-vegetation) during the onset of the current interglacial (Holocene). If their data is correct – and they have lots of reliable geochronology to support their conclusions – the most 5 recent episode of fan incision, for example had little if anything to do with base level fall or tectonic uplift. Pope and colleagues conclude that, with the exception of the above mentioned intervals of fan entrenchment (incision), fan aggradation occurred across the entire last interglacial/glacial cycle in all climatic settings (i.e. interglacials, interstadials, and stadials). The Domata fan is at the same latitude and only 25 km west of the Sfakia fan studied by Pope and colleagues (2016). It would be surprising if two nearby fan sequences on the south coast of Crete had markedly different aggradation-incision histories if the driving processes were climate change and/or eustatic variations, as both of these factors should almost certainly be nearly identical for the two sites. If there are real differences in the timing of fan aggradation and incision episodes between Domata and Sfakia they likely are the result of internal stochastic variations in catchment hillslope sediment supply to the channels feeding the alluvial fans.
[We have modified these sentences on the revised version to accommodate the reviewer's concerns]

P. 2, Line 26-29: It is an inference, based solely upon a morphogenetic interpretation of the topography of the Domata fan that the sequence represents two episodes of fan building as no stratigraphic evidence is provided. An alternative interpretation is that the Domata fan sequence represents a single depositional phase followed by unsteady incision, as is common in alluvial fill-cut terrace sequences (also known as complex-response fill terraces of Bull, 1990). For the former interpretation to be convincing, stratigraphic data delineating two distinct fan depositional units needs to be provided and would substantially improve the manuscript.
[We believe that the stratigraphic evidence inherent in the presence of a marine cliff that truncates both the upper fan surface and underlying deposits, and the alluvial entrenchment wall of the Klados River suffice as convincing stratigraphic data.]

Geological setting of Crete and Vertical tectonics:
P. 3, Lines 18-24: We think that it is important to qualify these statements. The way that it is written herein is that there is scientific consensus on this topic, which is not the case. The debate is ongoing about uplift transients in the Hellenic forearc and it is important to acknowledge that this only presents one side of the argument. Many researchers favor a slow, mostly steady (at least at time scales greater than several earthquake events) Quaternary history of uplift for the island.
[We will modify this sentence on the revised version but actually, the only two studies that have derived a series of uplift rates through time on western Crete are Tiberti et al. (2014) and Mouslopoulou et al.(2015) show transient uplift. But in reality, whether there is transient uplift or steady-state uplift doesn't change our conclusions regarding Domata].

P. 3-4, Lines 32, 1-2: The Holocene notch is buried by the fan at Domata (see supporting data). Basic stratigraphic principles demand that if an extensive coastal geomorphic (geodetic) marker is locally buried by a sedimentary deposit, the deposit must by younger than the geomorphic marker, in this case the Holocene notch. This single field geomorphic observation places the geochronologic results and subsequent conclusions of this manuscript into doubt.
[In our view, the reviewers' interpretation is incorrect. The notch is cut in the surface of the bedrock, but eroded from the alluvial fan gravel surface due to its susceptibility to erosion. The notch is not preserved behind the beach in the gravel cliffs at Domata for this reason. However, its presence is represented by the low, relict alluvial terraces at the mouth of the Klados River. Between the reviewers' illustration and the Klados River mouth, the bioerosion notch (which we correlate with the c. 365AD paleoshoreline) underlies the base of the fan gravels and is preserved as a notch in bedrock. It is therefore not possible that this feature underlies the alluvial fan sequence].

Data – methods – Chronology:
P. 4, Lines 4-5: This is an interpretation that requires supporting data. *[The supporting data are presented in the following paragraphs, as we state in the following sentence of the manuscript].* The morphology of the fan might equally well be represented by a single filling episode followed by unsteady incision into the fan deposit *[see above].*

Coastal geomorphic features at Domata:

P. 4, lines 20-21: Where does the quartz and feldspar in the fan come from if the bedrock in the Klados River catchment is mostly carbonate? *[This is now incorporated in the text through better description of the bedrock units].*

P. 5, Lines 16-17: This is a key observation, but from figures 2-3 there is no evidence that the "lower fan" onlaps the "upper fan". The lower fan surface could simply be a fill-cut terrace into the maximum aggradational surface of the "upper fan". Please provide stratigraphic observations to support this interpretation. *[Upper fan deposits are cut by alluvial entrenchment and subsequent marine cliffing. Alluvial deposits of the lower fan lap against the cut alluvial entrenchment cliff and the lower fan surface is seamless between the alluvial cliff and the marine cliff. This stratigraphic relationship is clear and there is no other explanation needed, or indeed possible.]*

P. 5, Line 23-24: It is difficult to see these details in Figure 6a. Is it possible to add some close-up photos of what the deposit looks like in detail with examples of the features provided? It would help readers' understanding of the stratigraphy if they could "see" what the fan deposit looks like. All of the overview photographs are great, but readers will be left wondering what the deposits looks like up close.
Also, what lithology makes up the fan deposits? We assume that it is carbonate, but no details are provided. If the deposit is mostly carbonate, where is the quartz and feldspar used for OSL coming from? *[See above]*

P. 5, Lines 23-25: Details on the stratigraphy for the "lower-fan" are great! How does the "upper-fan" stratigraphy differ? In other words, how does one distinguish between the lower and upper fan units as illustrated in figure 6b? These details are essential to the interpretation of two distinct fan units. Perhaps a composite stratigraphic column of the fan sequence would help. *[We have added some more descriptions in the revised version and we have replaced old Figure 5 with a new Figure 5 (attached below) that illustrates clearer the stratigraphic features we discuss as well as the location of the luminescence samples with respect to* *these features. The two deposits are clearly distinguishable using surface geomorphology. Figure 6b is at the west end of the Domata fan exposures and far removed from the luminescence age sampling sites. The geomorphic and stratigraphic context of these sites are now illustrated schematically in the revised Fig. 5. Lithological characterisation of the two fans units is not a key part of our study].*

P. 5, Lines 25-31: This is a key observation, but the level of detail in Figure 6 is insufficient for the reader to be able to see this relationship. *[See comment above].*

P. 5, Lines 33-34 & Page 6, Lines 1-2: From the way that this section of the text is written, it is unclear if the paleoshoreline (marine bench) is cut into, or buried by the fan. Our interpretation of Figure 6 is that it appear as though the paleoshoreline is buried by the fan. Our field observations from this area suggest that this Holocene shoreline is buried by the fan (see supporting figure).
[We firmly disagree with this interpretation. This is a surficial bioerosional notch cut into the fan (now removed through erosion) and the bedrock (where applicable). This notch can be nicely followed westward along the bedrock all the way to Sougia and relates to the 365 AD earthquake that uplifted western Crete up to 10m (Pirazzoli et al., 1982, 1996; Shaw et al., 2008; Stiros, 2010; Mouslopoulou et al., 2015)].

P. 6, Line 10: Wegmann, (2008) and Gallen et al. (2014) also studied Pleistocene terraces on Crete and interpreted them in the context of stratigraphic relationships with interfingered alluvial fan deposits. Furthermore, Gallen et al. (2014) and Runnels et al. (2014) dated several alluvial fans in southern Crete with OSL, in addition to dating marine terraces with the same technique. *[We now include reference to Gallen et al. (2014) in this statement].*

P. 6, Line 10-13: Based on stratigraphic relationships, pedology and OSL geochronology, Gallen et al., 2014 suggest a stratigraphic model for the genesis of marine terraces and alluvial fans based on tectonic, climatic and eustatic considerations in which marine abrasion platforms are cut and marine terrace deposits emplaced during eustatic transgressive-to-highstand phases , whereas Pleistocene alluvial fans are deposited during cooler (and drier) periods associated with relative sea-level low stands when sediment supply presumably is elevated relative to discharge. In addition to the geochronologic constraints on alluvial fan age, the other observation that implies deposition during cool periods is that the surface gradient of coastal alluvial fans on the south coast of are steep and prograde to a base level far lower than modern day sea level. This observation suggests that the Pleistocene fans are deposited when relative sea level is lower than the present day. This stratigraphic model is relevant because, if preservation potential were not a problem, a fan at lower elevation might be older than a marine terrace found at a high elevation relative to modern sea level. *[We agree that MIS3 and MIS2 represent relative sea level low stands compared to the present day. We make no assumptions of sediment supply or river carrying capacity. We base our ms on clear stratigraphic and geomorphic data that require explanation by a certain sequence of events. We recognise that the Domata fan deposits are MIS3 in age, and the older fan is benched by marine trimming. Given the well-established sea level curve, our objective is to calculate an uplift rate from this observation. We propose no model, but are familiar with those of Gallen et al. (2014) and Pope et al. (2016). To propose a model or even support one existing model on the basis of our work at Domata would be presumptuous.]*

OSL dating of alluvial fans:

P. 6, Line 13: Perhaps consider changing the heading of this section and all subsections. OSL stands for optically stimulated luminescence and IRSL stands for infra-red stimulated luminescence. They are different techniques and should be treated as such in the section headings. Similarly, figure 7 shows IRSL results, rather than OSL results as is indicated by the caption and the labels on the x-axis of the figures. Perhaps use "Luminescence dating of alluvial fans"?
[We agree it may be better to differentiate OSL from IRSL and now use the general term "luminescence dating"].

P. 6, Line 14-21: The sampling strategy is well thought out; however, why are there no samples from the base of fan unit 2? *[As stated previously, the reason is simply because the deposits below the lower fan are not part of the fan.]* Also what did the sampled horizons look like? The only information on this is for UF-2. Our field observations of this deposit suggest that it is composed primarily of carbonate sediment. Were there individual fine sand-to-silt lenses that were sampled, or simply stratigraphic horizons that were soft enough to hammer a tube into? *[We have added some more descriptions in the revised version and we have replaced old Figure 5 with a new Figure that illustrates clearer the stratigraphic features we discuss as well as the location of the luminescence samples with respect to this features].*

OSL results:
P. 7, Line 19-20: Gallen et al. (2014) and Runnels et al. (2014) also dated alluvial fans in southern Crete with Quartz OSL. There is also a new paper by Pope et al. (2016) that has an abundance of OSL data on the Sfakia fan sequence (see comment above). *[See comments above and elsewhere].*
P. 7, Line 19-27: This might be better reserved for the discussion, but what makes Domata unique in that quartz OSL of the fans there does not work? Quartz OSL has worked fine for multiple other studies where geologic conditions are similar 20 (Pope et al., 2008, 2016; Gallen et al., 2014; Runnels et al., 2014). *[See general comments on luminescence dating in our first set of answers].*

P. 7, Line 29: What about the ages makes them reliable? *[Reliable in terms of the sampling and measurement methodology regardless of problems like incomplete bleaching].*

P. 8, Line 4-5: In alluvial fans, incomplete bleaching is a problem (e.g., Rhodes, 2010). It appears that the Domata fan samples suffer from incomplete bleaching. What tests, if any, were preformed to rule-out incomplete bleaching? For quartz OSL results that deviate from every other published study that has been performed on alluvial fans on Crete it is worth 25 investigating why the signals are so different. Provided the short transport distance of the Klados River gorge (~ 5 km) and the high-energy nature of the Domata fan sequence, incomplete bleaching is potentially a major concern.
Taken at face value, the IRSL ages reported in Table 1 imply that the lower (supposedly younger) fan unit was emplaced before the end of deposition of the Upper (older) Fan unit. This is difficult to reconcile with the stratigraphic arguments advanced in this manuscript. Furthermore, the observation that the fan buries a presumably Holocene age paleoshoreline is problematic (see supplemental figure). Some experiments to test for incomplete bleaching or at least a detailed explanation of why incomplete bleaching isn't an issue should be added. *[See general comments on luminescence dating in our first set of answers].*

Soil development:
P. 8, Line 28-29: Were these colors derived from a Munsell color chart? *[A Munsell chart was not used. The described colour is the obvious macroscopically difference in colour which is presented also clearly in figure 8b and 8c. However, the difference in colour was obvious and we consider it as in dry conditions (sampling performed in summer, after prolonged period without rainfall)].* If so, the hue, value and chroma values should be provided as they represent a semi-quantitative measure of color and several combinations of hue, value and chroma have the 5 same color name. It would be useful to point out where the weak B horizon is on the Upper fan soil in figure 8C and the soil texture evidence used to support this interpretation. *[The B horizon in the upper fan is already indicated with a dashed line in Figure 8c. It is not clear to us why the reviewer made this comment.]* Having worked on soil profiles on Crete, and based on the photo presented in Fig. 8C, it looks like this profile could be characterized as a thin A horizon over a C horizon. *[As it is stated in our study, a macroscopic approach in the field was used in order to describe the soils, thus the possible B horizon in the upper fan was identified by the technique of knife penetration in the excavated profile. The lower knife penetration (less friable), the change in the texture (accumulation of finer material clay+calcite) and the absence of organic material (aggregates due to organic accumulation are obviously less also in figure 8c) lead us to the conclusion of possible B horizon in the upper fan. However, ongoing work in the soil horizons in the special case of Domata (as it appears from the spectacular alluvial fan development) will reveal further evidence on what we describe as a "(weak) B horizon". In addition, the authors believe that whether the horizon is B or A/B (A/B: in the initiation stage of B horizon), doesn't impact on our basic argument that the upper fan soil is better developed compared to the lower fan soil].*

P. 8-9, Line 31-34, 1-4: Gallen (2013) provides detailed descriptions of alluvial fan soil profiles with OSL geochronology in Chapter 2. Gallen et al., 2014 and Runnels et al., 2014 describe the pedology of alluvial fans of Crete in conjunction with OSL geochronology. These studies should be discussed in the context of this study, as soils formed on alluvial fans of reportedly the same age are distinctly different. Furthermore, aside from color, observations supporting the notion that the soil profiles shown in figure 8B and C are consistent with the descriptions of stage 2C soils from Pope et al., 2008, particularly soil textures consistent with an increase in clay content (e.g. Bt horizon), are not provided. Based on observations presented in Gallen (2013) and Gallen et al. (2014), the soils on these fan surfaces are less mature than fans dated to ca. 40 ka that have evidence of pedogenic alteration to > 1.5 m below the present-day surface (see figure 4 of Gallen et al., 2014 and Appendix of Chapter 2 in Gallen, 2013).

[The reviewers imply that the soil in our study area is less mature compared to the thicker and better developed soils of the same (or older) ages presented by Gallen (2013) and Gallen et al. (2014). However, we believe that several parameters can dramatically change the soil cover thickness in areas of similar ages, especially when these regions span several 10's of kilometres. Rainfall on the south flanks of Lefkai Ori varies radically from the crest of the 2450 m of mountain range to the south coast (i.e. Domata). The elevation change in the 6.5 km north from the coast is 2100 m, (a gradient of 32%) while in Tsoutsoros area where the Gallen et al. 2014 studied the 'marine terrace soil profiles, has a relief of 0 to 480 m within 3.44 km (13% gradient). There is clearly a difference in orographic rainfall. Overcoming the local rainfall variability, another parameter which is decisive in the soil development is the texture and lithology of the parent rock. Gallen et al. 2014 investigated terraces developed in both Neogene formations and in Mesozoic limestones-sandstones-mudstones of Pindos nappe which are absent from our site. Thus, the results of the soil profiles which are presented by Pope et al. 2008 are the best available "benchmark" where we could interpolate our findings. As already mentioned, the soil depth and the physical characteristics presented by Pope et al. (2008) showed several similarities with those profiles presented in our work. Finally, chronosequence studies on soils are those which are explicitly giving answers in the above questions, however, constrains and limitations of a chronosequence study make them rare especially on the island of Crete where landscape is dictated by intense tectonic evolution. Lin (2011) nicely summarised soil development as an archive of the cumulative effects of tiny repeatedly cyclic changes where even a small difference in soil parameters can create a remarkable difference in pedogenesis].

P. 9, Line 11-13: This isn't supported by the geochronology (keep in mind the difference between OSL and IRSL). The data suggests that the alluvial fan units are synchronous. The Upper fan unit is bracketed between ~54 and 23 ka and the lower fan unit ceased deposition ~40-28 ka.

[The authors thoroughly understand the meaning of the data. The IRSL data (with inherent errors) presented in our article support the chronology demanded by the stratigraphy that we have established. The soil development independently supports our stratigraphic interpretation. We conclude that the stratigraphy, luminescence dating and soil analysis independently point to the same interpretation: that the upper fan is older than the lower fan and that they are last glacial (MIS4 to MIS2) in deposition].

P. 9, Line 13-15: Aside from the problem that the geochronology suggests that the Upper fan surface was abandoned ~5-15 ka *after* the lower fan surface *[this is wrong and we don't understand why the reviewers have included this comment; they appear to be taking the geochronology out of the stratigraphic context and we regard this as inappropriate, particularly given the error margins on IRSL ages]*, is the Liar et al. (2009) reference relevant in this context? Liar et al. (2009) work on Holocene soils. This study, according to the authors is about Pleistocene soils. The effects of a 5 ka difference in geomorphic surface age for surfaces that are presumably an order of magnitude older than that would need to be shown. One would expect that soils forming on different aged surfaces would become more similar over time. For example, a 5 ka time gap for the initiation of soil formation might be negligible after a 30-40 ka shared history of soil development.
[We acknowledge that the study of Liar et al. (2009) presents Holocene soils and that the soils at Domata are upper Pleistocene. So in the revised version we complete our argument by presenting the study from Huang et al (2016), where they found a clear difference in amorphous and crystalline Fe oxides concentration (hematite) in the soils from 135 ka and 125 ka. In our study, soil age differences of between 4 ka (minimum) and 14 ka (maximum) could easily have left a significant weathering imprint if this time span was characterized by more intense rainfall resulting in faster soil development than today (e.g. see our evolution model, Figure 10). We disagree with their argument that over greater time periods, soils always progressively assume a similar appearance. Soil development is related to climatic (and other) parameters. Our interpretation (Figure 9) is that the upper fan was deposited within the MIS3 and the soil development started after surface abandonment at 40-45 ka; the time that followed was climatically warm and wet in Greece (intense weathering; Tzedakis et al., 2004). The lower fan was deposited from 36 to 29 ka, the start of a dry and cold period. Thus, the soil beneath the lower fan surface developed under cold and dry conditions, while the upper fan soils developed under warm

and wet conditions. It is difficult to conceive that soil development has converged during MIS2 and MIS1, "erasing" the past pedogenic processes].

Landscape evolution at Domata:
P. 9, Line 29-30: Why would falling sea-level promote deposition? *[This has been corrected in the revised version].*

P. 10, Line 10-11: Why does relatively high sea-level now promote deposition? What are "deteriorating climate conditions", what evidence is there to support them and why do they promote fan deposition? *[Fan deposition is promoted by a high base level, in this case, sea level of the time. When climatic conditions deteriorated, resulting in a falling sea level, the balance between sediment supply, gradient, rainfall and catchment vegetation re-adjusts, but with on-going sea level fall, entrenchment is the likely outcome (e.g., see Pope et al. 2016)].*

P. 10, line 27-29: But isn't the fan burying this Holocene deposit (see supplemental figure)? *[We firmly believe that the reviewers' interpretation is wrong].*

P. 9-11, Line 17 – 32, 1 – 34, 1-3: Provided that the geochronology is correct, any number of interpretations could be argued to be equally valid within the uncertainty of the data. For a given date the authors utilize either the mean or the median as preferred to provide an older or younger age estimate, respectively. Furthermore, taken at face value the data indicate that the upper fan surface was active until 25 ka. *[We don't believe this is true. The dates are single samples, and they have errors that are presented and documented. Deposition could be anywhere within the error limits. Stratigraphy determines the sequence of events, but dated events provide some chronological information (within error)].* It isn't until lines 1-3 on page 11 that the reader is told that this sandy horizon is a fine-grained cap on the entire deposit. The position of the luminescence samples in a composite stratigraphy of the fan sequence is needed in order to understand the context of the data. *[We have replaced old Figure 5 with a new Figure that illustrates clearer the stratigraphic features we discuss as well as the location of the OSL samples with respect to this features].*

Another observation which should be addressed in the context of the stratigraphic model is how an unvegetated near-vertical cliff of unconsolidated gravel can remain between the Upper and Lower fan units for ~ 39 ka? Furthermore, why is the morphology of the cliffs on the Upper and Lower fan units so similar despite an inferred 35 kyr age difference (see figures 5 and 10 in manuscript)? *[We don't understand how the reviewers get a 35 kyr age difference. The time period between abandonment of the upper fan surface (c.45 kyr) and abandonment of the lower fan surface (36 kyr) is a 9 kyr age difference].* When fault scarps are formed in unconsolidated alluvial fan sediments in places like the Basin and 10 Range of the southwestern United States, they may initially be vertical geomorphic features, but through hillslope erosional processes, the morphology of the scarp changes through time (e.g. McCalpin, 1996). Diffusion of scarps through time has proven to be a useful relative dating tool in studies of both fault scarps (e.g. Nash, 1980) and paleo-shoreline scarps (e.g. Andrews and Bucknam, 1987). Perhaps this could be attempted in this study.

Why aren't similar fan deposits observed in the five gorges that drain southward off the Lefka Ori (White Mountains)? The Klados River gorge is the only one that preserves such spectacular fans. Despite the contention that Domata beach is geomorphically unique along the southwest coast of Crete, it is not. *[We don't agree with this statement. Catchment sizes vary, river lengths vary, gradients vary, vegetation varies, rainfall varies, and none of the others have the bedrock ridge that forms a gorge close to present day sea level (see Fig. 1 in our manuscript)].* All the major gorge outlets to the ocean along the Lefka Ori are morphologically similar, yet none host similar fan deposits. Each gorge should preserve similar features if, as it is implied the forcing that generated the fans is a coupled climate-tectonic-eustasy signal that should affect the island regionally. *[Again, we disagree. Each gorge is different as indicated above and in lots of other ways, too. Regional signals are always complicated by local factors].*

The importance of tectonic uplift at Domata:
P. 11 Line 17-18: Where is the marine terrace that cut this cliff? Based on the stratigraphic model, one world expect marine deposits between the two fans. *[While it would be useful if this was the case, it is not necessarily true. Cliff collapse, as well as the 365AD uplift, keep the sea at bay from the foot of the Holocene sea cliff. In an*

erosional setting, marine deposition is not necessarily likely, and in addition, early phase fluvial erosion associated with lower fan deposition may have removed such marine deposits, if they were ever deposited]. An uncertainty analysis on the elevation of the inner shoreline and some evidence that this cliff corresponds with a marine abrasion platform would be beneficial for readers. Furthermore, if it is assumed that the base of the fan lies on a marine abrasion platform (e.g. marine terrace), the difference in age between the marine platform and the overlying alluvial fan can be substantial (see Gallen et al., 2014 for examples from southern Crete). *[This appears to contradict the reviewers' suggestion that the fans were both deposited within the Holocene. Given the nature of the Siddall et al. (2003) MIS3 and MIS2 sea-level curve and other high resolution sea-level curves that have been published to date, where sea-level declines from 55 kyr to the last glacial maximum, the time period between platform cutting and renewed alluvial deposition cannot be long. Any tectonic uplift that occurred during this period would merely exacerbate a tendency for rapid entrenchment].*

P. 11 Line 11-32: There is reason to suspect that Pleistocene radiocarbon ages might suffer from alteration of primary material, shifting radiocarbon dead ages to ones that are younger. This is nicely discussed by Wegmann, 2008 and can be noted in δO_{18} and δC_{13} shifted to more negative (terrestrial) values, relative to marine standards, in Triberti et al., 2014. *[The ages presented in Mouslopoulou et al. (2015) are only of secondary importance in this manuscript. Nevertheless, the results of the current study, using completely different methods, provide an independent test on the results of the Mouslopoulou et al. (2015) study. In both cases uplift rates, averaged over the last ~40 kyr, are similar to one another and are also similar to those derived by dating other marine terraces in western Crete (Shaw et al., 2008; Strasser et al., 2011; Tiberti et al., 2014].*

P. 12 Lines 1 – 15: Again, this is only the opinion of a few and does not represent the view of many other researchers that study the tectonic geomorphology of Crete. It would be useful to include a more thorough discussion of all the relevant literature.

P. 12, Line 17-20: No evidence is provided for the climatic link. The geochronology is simply not precise enough to permit such interpretations. *[Sea-level fluctuations are controlled by (and reflect) climate fluctuations].*

Conclusions:

P. 12, Line 25-26: This is an inference based on uncertain geochronology. Perhaps it is better to say "One interpretation of the data" rather than "Data analysis shows". *[We have altered the text to read 'our interpretations suggest'. Also we have altered the title of Section 4 to 'Interpretation of landscape evolution at Domata].*

P. 12, Line 28-29: It's not entirely clear to us how this interpretation is supported by the data *[see above]*.

References cited in review that are not cited in the manuscript:

The references below that are indicated in red are ones we find relevant to our study and will be included in the revised version.

Andrews, D. J., and Bucknam, R. C., 1987, Fitting degradation of shoreline scarps by a nonlinear diffusion model: Journal of Geophysical Research: Solid Earth, v. 92, no. B12, p. 12857-12867.

Bull, W.B., 1990, Stream-terrace genesis: implications for soil development: Geomorphology, v. 3, p. 351-367.

Gallen, S.F., 2013. The Development of Topography in Ancient and Active Orogens: Case Studies of Landscape Evolution in the Southern Appalachians, USA and Crete, Greece. Ph.D. Dissertation, North Carolina State University, Raleigh, NC, 171 pp.

McCalpin, J., 1996, Paleoseismology: San Diego, Academic Press, p. 583.

Nash, D. B., 1980, Morphologic Dating of Degraded Normal Fault Scarps: The Journal of Geology, v. 88, no. 3, p. 353-360. 15

Pope, R.J.J., Candy, I., and Skourtsos, E., 2016, A chronology of alluvial fan response to Late Quaternary sea level and climate change, Crete: Quaternary Research, v. 86, p. 170-183.

Rhodes, E.J., 2011. Optically Stimulated Luminescence Dating of Sediments over the Past 200,000 Years, *Ann. Rev. Earth planet Sci.,* **39,** 461-488, doi:10.1146/annurev-earth-040610-133425.

Runnels, C., DiGregorio, C., Wegmann, K.W., Gallen, S.F., Strasser, T.F., and Panagopoulou, E., 2014, Lower Palaeolithic 20 artifacts from Plakias, Crete: Implications for Hominin Dispersals: Eurasian Prehistory, v. 11, p. 129-152.

Scherler, D., Lamb, M. P., Rhodes, E. J., and Avouac, J.-P., 2016, Climate-change versus landslide origin of fill terraces in a rapidly eroding bedrock landscape: San Gabriel River, California: Geological Society of America Bulletin.

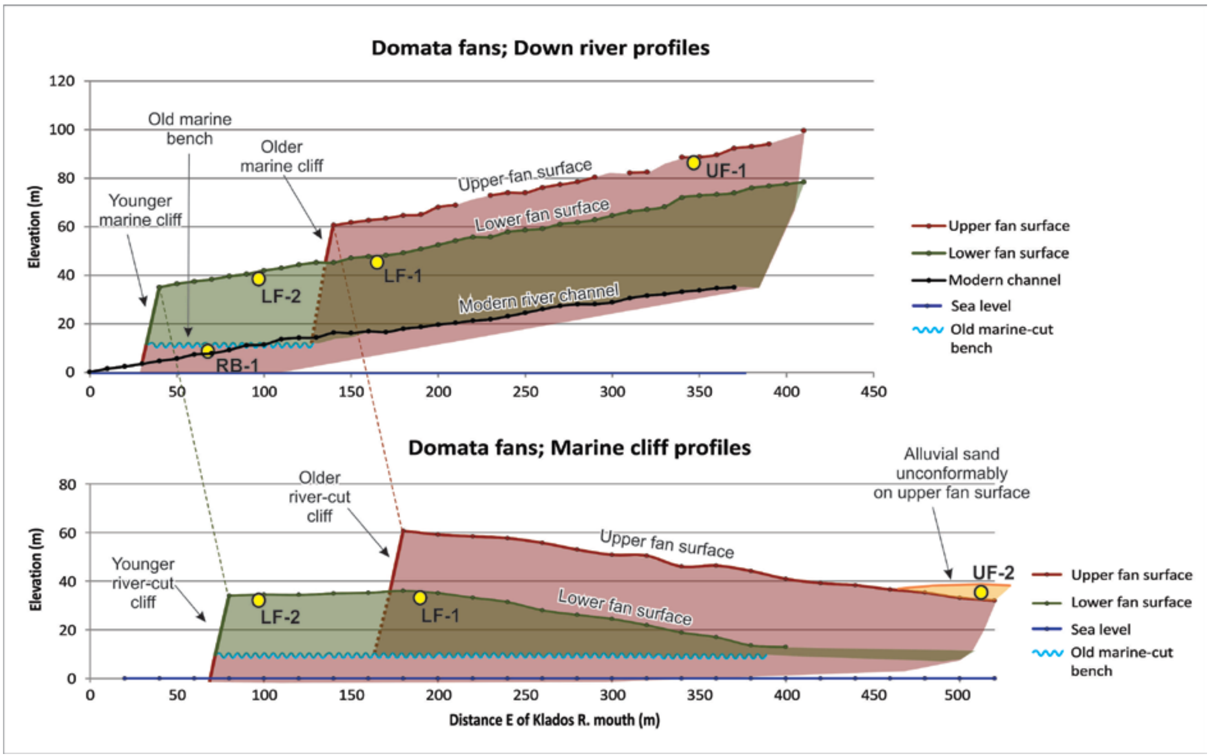
Wegmann, K.W., 2008. Tectonic geomorphology above Mediterranean subduction zones; northern Apennines of Italy and Crete, Greece, Ph.D. Dissertation, Lehigh University, Bethlehem, PA, 169 pp. 25.

We have also used the following additional references in response to the reviewers' comments:

Tzedakis, P.C., Frogley, M.R., Lawson, I.T., Preece, R.C., Cacho, I., de Abreu, L., 2004. Ecological thresholds and patterns of millennialscale climate variability: the response of vegetation in Greece during the last glacial period. Geology 32 (2), 109–112.

Wen-Shu Huang, Shih-Hao Jien, Heng Tsai, Zeng-Yi Hseu, Shiuh-Tsuen Huang, 2016 Soil evolution in a tropical climate: An example from a chronosequence on marine terraces in Taiwan. Catena, 139, 61–72.

Lin Henry 2011 Three Principles of Soil Change and Pedogenesis in Time and Space. Soil Sci. Soc. Am. J. 75:2049–2070.



New Figure 5: *Profiles of fan surfaces projected onto common planes parallel with the modern Klados River channel (above) and parallel with the modern coastline (below). Horizontal and vertical scales for each profile are similar, with a VE of c. 1.25. Note that the downstream slope of the upper and lower-fan surfaces are about the same, both a little steeper than the slope of the modern stream channel. Also note that the upper-fan surface slopes less to the east than the lower-fan surface, so that the upper-fan marine cliff is higher at the eastern end of the beach than at the west. The highest elevation of the lower-fan surface is close to the foot of the incision of the upper-fan, while the upper-fan surface is highest at its incision point. We schematically illustrate the volumes beneath the measured profiles to indicate the likely extent of the volumes of upper fan materials (pink) and lower fan materials (green) and have added the locations of each of the luminescence sample points (annotated yellow dots).”*

Updated Figure 6b: Looking west across the Klados River mouth (foreground), the uplifted shoreline attributed to the 365 AD earthquake (dashed red line, lower left) aligns well with a low terrace riser on the west side of the river (dashed thick white line, middle). Incision of the modern channel below the surface is attributable to post-earthquake adjustment to new base levels. Note the sea-cliffing of the last interglacial? marine bench (thick red dashed line at the top of the image) and the upper and lower fan deposits. The upper fan and western parts of the lower fan are overlain by accumulated rockfall debris and the solid thin white line approximates its surface. The lower fan surface is marked with fine dotted white line.

Response to the new short-comment by S. Gallen & K. Wegmann (30 January 2017)

Below, we respond again briefly to the additional comments of Gallen. For a more detailed answer, please refer to our first response, dated January 27th, 2017.

1. **Lack of sedimentologic and stratigraphic context**:

[In addition now, March 2017, we have added lithostratigraphic logs of the alluvial fan-system studied: see new Figure 5b]

This is not true. The stratigraphy, and the stratigraphic context of the major geomorphic features described in this work, is the major tool that we use to support our main observations. We copy and paste here text from our first response: '*Our primary interest in* *our work on Crete is to help constrain its late Quaternary tectonic development. With this work we aim to use first order geomorphic features and stratigraphic relationships to understand the late Quaternary vertical deformation of western Crete. In doing so, we recognised the importance of the Domata fan sequence and the important marine bench cut in upper fan at Domata. This feature allows us to independently derive a Late Quaternary uplift rate from this section of western Crete. The paper is important because of this independence from previously derived uplift rates on western Crete (e.g., Shaw et al., 2008; Strasser et al., 2011; Tiberti et al., 2014; Mouslopoulou et al., 2015 – all references included in the submitted version). To achieve these objectives, we needed to understand the first order fan geomorphology and from it dissect out the sequence of events required in landscape evolution. We derived a basic sequence of events that is demanded by the stratigraphic relationships present at Domata and present these in the paper. We have gone to some effort to place the Domata fan sequence within its stratigraphic and chronologic context so that we fully understand the uplift rate derived. The final piece of the puzzle required to derive our uplift rate was its integration with a high quality sea level curve for the last 125 kyr. We chose Siddall et al.'s (2003) sea level curve because of its precision, relative proximity to the Mediterranean, yet its isolation from the variable tectonic signatures and isostatic problems associated with glacial loading of that region, and for its similarity with the Lisiecki & Raymo (2005) stacked curve. The luminescence dating we undertook simply provides confirmation of the chronological framework for the events that we had deduced with reasonable confidence from other stratigraphic and geomorphic observations. We completely agree with Gallen & Wegmann that our IRSL dating, with its large uncertainties, cannot provide adequate resolution to separate the individual events presented here. Similarly, the soil descriptions provide a supporting understanding for our stratigraphic conclusions, independently confirming that the two fans are built over distinct time-periods. In our revised version we explain more clearly these objectives and the evidence for our interpretation of the sequence of events in our 'landscape evolution' at Domata, so that there can be no misunderstanding'.*

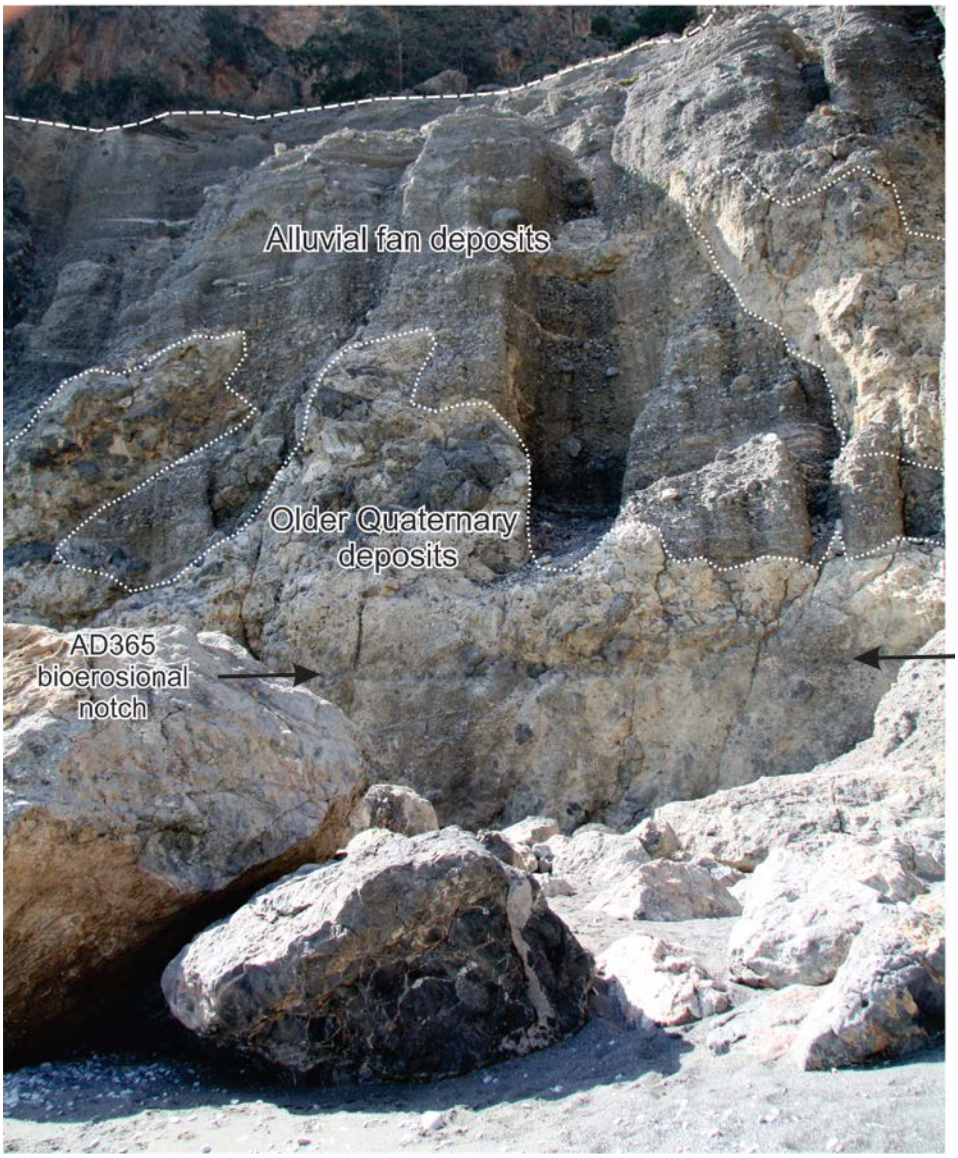
And we continue (regarding the sedimentological context): *'This objective does not include a comprehensive description of the materials of the Domata fans and their developmental chronology, as has been undertaken for other fans of southern Crete by others (e.g., Nemec & Postma, 1993; Gallen et al., 2014; Pope et al., 2008, 2016). Neither is the objective to compare Domata fan stratigraphy with that of other alluvial fan systems on Crete. We welcome the prospect of additional work that would enhance insight into the processes of fan deposition and a refined chronology that may help better understand relationships between sediment transfer rates and climate in this area.'*

2. **The beach underlying the fan sequence and the 365AD paleo-shoreline**: *We repeat that we do not agree with the correlations proposed by Gallen and Wegmann between the surface on the beach deposits, the "wave cut bench" and the AD365 bioerosional notch. The bedrock "wave-cut bench" underlying fan deposits at the west-end of Domata beach shown in their supplementary figure may locally be at the same elevation as the AD365 notch, but there is no genetic linkage between that bioerosional notch and the "wave-cut bench". At the west-end of the beach, east of the red area highlighted in Gallen & Wegmann's supplementary* *figure (c), fan deposits sit on a deeply dissected and weathered surface that lies above the AD365 bioerosional notch. This relationship is illustrated and confirmed <u>in the Figure that we provide below, in this response letter, and which we intend to include in the revised version of the manuscript as Figure 6c.</u> If the deposits at the <u>east-end</u> of the beach indeed represent beach deposits (we have limited data on these materials), they may represent shoreface deposits of the marine trimming event. This information is entirely consistent with our interpretation as it stands.*

3. **The age of the Domata fan sequence**: *Gallen and Wegmann's interpretations are based largely on their correlation of the beach deposits with the AD365 bioerosional notch and their inference that the fan deposits are therefore Holocene in age. Our response to this correlation is discussed above, and our interpretation is corroborated independently by the relative scales of the Sfakia fan and its catchment and those of the Klados catchment and the Domata fans. Despite the contrasting catchment sizes, the area covered by Holocene materials at the Sfakia fan is insignificant compared with the size of the Domata fan deposits. The Sfakia fan Holocene materials rise to a maximum elevation of c. 40 m, while those of the Domata fan rise to close to 100 m. Even under the most extreme local conditions, this incongruence points to an age older than Holocene for the Domata fan deposits. In addition, interpretation of the Domata materials as Holocene in age would contradict our geochronological data. In addition, and further reinforcing our interpretation, the resultant uplift rates conform with previously published rates (including Gallen's) derived independently in areas nearby and on central-eastern Crete. These three strands of independent data, each support our interpretation of a last glacial age for the Domata fan deposits. By far the most rational option is to accept the age constraints provided by the geochronological data, as we do in our paper.*

4. **Soil development:** *We never stated that we did not perform a proper description of the soils. This statement is from the two commentators who obviously consider macroscopic observations 'improper'. In our previous response, we put significant effort to address all the soil-related comments posed by the two commentators. And while we state openly, in both the submitted manuscript and our response to their comments, that our observations are mainly macroscopic, these macroscopic observations completely support our independent conclusion (based on geomorphic evidence) that the soil in the upper fan is better developed, and thus more mature, compared to the soil of the lower fan. How these macroscopic observations support this conclusion, is explained in our previous response to Gallen & Wegmann and we encourage whoever interested to look at pages 8-9-10 of the uploaded file (27 Jan 2017). It is also explained in the corresponding section (3.3) of the submitted and revised version.*

To summarise, we agree that there is additional work that could and should be done at Domata to help answer Gallen & Wegmann's questions and others as well. In this paper, we are reporting specifically on an investigation that provided interesting results that constrain the late Quaternary vertical deformation of western Crete. In our view, and in the view of the other reviewers, this manuscript achieves this objective.



Annotated image illustrating the relationship between the unconformity at the base of the fan sequence and the AD365 bioerosional notch. This picture is taken between the location illustrated by Gallen & Wegmann's (first comment) in his supplementary figure (c) and the mouth of the Klados River. Our interpretation of the stratigraphy is as follows: a dissected erosional surface on older Quaternary sediments pre-dates the fan deposits, while the AD365 bioerosional notch post-dates both the surface and the fan deposits that rest on it. In other words, the coincidence of the "wave-cut bench" and the AD365 bioerosional notch which Gallen & Wegmann illustrate in their supplementary figures cannot mean that the entire Domata fan deposits are Holocene in age. Here it is evident that the unconformity does not represent the same feature as the AD365 bioerosional notch. This Figure will be included in our revised manuscript as Figure 6c.

Distinct phases of eustatism and tectonics control the late Quaternary landscape evolution at the southern coastline of Crete

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Abstract. The extent to which climate, eustacy and tectonics interact to shape the late Quaternary landscape is poorly known. Alluvial fans often provide useful indexes that allow decoding the information recorded on complex coastal landscapes, such as those of Eastern Mediterranean. In this paper we analyse and date (using luminescence IRSL dating) a double alluvial-fan system on southwest Crete, an island straddling the forearc of the Hellenic subduction margin, in order to constrain the timing and magnitude of its vertical deformation and discuss the contributing factors to its landscape evolution. The studied alluvial system is exceptional because each of its two juxtaposed fans is recording individual phases of alluvial and marine incision, providing, thus, unprecedented resolution in the formation and evolution of its landscape. Specifically, our analysis shows that the fan sequence at Domata developed during Marine Isotope Stage (MIS) 3 due to five distinct stages of marine transgressions and regressions and associated river incision, as a response to sea-level fluctuations and tectonic uplift at averaged rates of ~2.2 mm/yr. Interestingly, comparison of our results with published tectonic uplift rates from western Crete, shows that uplift during 20-50 kyr BP was minimal (or even negative). Thus, most of the uplift recorded at Domata must have been accrued in the last 20 kyr. This implies that eustacy and tectonism impacted on the landscape at Domata over mainly distinct time-intervals (e.g. sequentially and not synchronously), forming and preserving the coastal landforms, respectively.

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1 Introduction

Sea-level fluctuations relative to modern sea-level are well constrained for the last 0.5 Ma (e.g., Imbrie et al., 1984; Martinson et al., 1987; Bassinot et al., 1994; Chappell et al., 1996; Dickinson, 2001; Siddall et al., 2003; Rabineau et al., 2005; Lambeck and Purcell, 2005; Lisiecki and Raymo, 2005; Antonioli et al., 2007). When these fluctuations are used in conjunction with dating techniques, they provide a powerful tool for interpreting coastal geomorphology and assessing vertical deformation from marine and marginal marine deposits through the middle and late Quaternary (e.g., Pirazzoli et al., 1996; Rabineau et al., 2005; Antonioli et al., 2007; Mouslopoulou et al., 2015a). While there is little debate about the role of tectonic uplift in generating the topographic relief required for the processes of erosion and deposition, uncertainty still exists as to the relative significance of tectonic, eustatic and climatic contributions to deposition and incision of fans of Quaternary age and their variation through time (e.g., Waters et al., 2010).

Alluvial fans are excellent proxies for Quaternary landscape evolution in a climate such as the Mediterranean and their study could potentially place some constraints on the factors that impacted the landscape during its formation and evolution (e.g., Pope et al., 2008, 2016; Zacharias et al., 2009). Overall, alluvial-fan deposition is influenced by rising or relatively high sea-level, by catchment size and sediment supply, by major changes in climatic conditions (such as high rainfall and/or short, intense storms), and by vegetation coverage in the catchment area. These factors regulate stream carrying capacity and sediment supply (e.g. Bull, 1979; Pope et al., 2016) and are responsible for whether deposition or river entrenchment processes predominate at any one time. Alluvial-fan surface abandonment and river entrenchment is favoured by eustatic sea-level fall or tectonic uplift (or a combination of both), reduction in sediment supply due to climatic amelioration, densification of catchment vegetation or reduced rainfall (e.g., Pope et al., 2008, 2016; Waters et al., 2010). Fan aggradation is encouraged by factors such as rising base level (sea-level for Domata), sediment supply, increased stream carrying capacity (rainfall/temporal rainfall distribution) and reduction in catchment vegetation cover.

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For example, in southwest Crete (eastern Mediterranean), Nemec and Postma (1993) and Pope et al. (2008, 2016) studied a fan system and showed that fan deposition was associated with all last glacial stadial and interstadial conditions, and that fan entrenchment was governed by the major climatic transitions between MIS5/4 and MIS2/1. Despite this progress in understanding, however, we are still unable to precisely appreciate the interplay between, and the relative importance of, climate and tectonics during late Quaternary in the Mediterranean. Here we capitalise on a well-preserved alluvial-fan system at Domata in southern Crete (Fig. 1), to study the late Quaternary (~50 kyr BP) interplay between sea-level fluctuations and tectonics. To our knowledge, the site at Domata is unique on the island of Crete as each episode of two alluvial fan-building episodes has been followed by episodes of alluvial incision and subsequent marine trimming (Figs. 2 and 3).

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Using luminescence dating together with the Siddall et al (2003) sea-level curve, we find that the alluvial-fan system at Domata was consecutively affected by: 1) Sea-level fluctuations, triggering building of the fans and subsequent river and marine incision between ~45 and 20 kyr BP, during a period of minimal tectonic activity and 2) Intense tectonic uplift between ~20 kyr and present, at rates that exceeded that of the rising sea-level, resulting in the preservation of the entire fan sequence. These findings are in accord with Pope et al. (2016) in showing that regional tectonics did not necessarily play a key role in fan incision in southern Crete.

2 Geological setting of Crete and vertical tectonics

The Mediterranean island of Crete is a mountainous and elongate landmass (~260 km long from west to east, 60 km wide from north to south) that lies within the uplifted forearc section of the Hellenic subduction margin, the most active seismically region in Europe (Fig. 1). The total relative convergence rate between the subducting African Plate and the overriding Eurasian plate is ~35-40 mm/yr (Reilinger et al., 2010). The subduction trench lies ~225 km to the south of Crete (e.g. Ryan et al., 1970; Le Pichon and Angelier, 1979) while the north-dipping subduction interface lies at a depth of ~40 to 65 km beneath Crete (Papazachos et al., 2006; Vernant et al., 2014), with the projection of the down-dip end of the locked zone aligning with the southern coastline of Crete, where the study area is located (Fig. 1) (Meier et al., 2007). The Hellenic Trough, a major bathymetric and tectonic feature within the forearc, lies south of Crete and includes three secondary features which, from west to east, are named as the Ptolemy, Pliny and Strabo troughs (Fig. 1).

Crete has been characterised by a complex history of vertical movements during Cenozoic (e.g., Peters et al., 1985). Onshore sediments record a period of subsidence and basin development through the Middle and Late Miocene (Serravalian to Messinian) with a change to rapid uplift in the Early Pliocene (Zanclean), followed by slower long-term uplift that continues to the present day (e.g., Le Pichon and Angelier, 1981; Angelier et al., 1982; Meulenkamp et al., 1994; Zachariasse et al., 2008; Roberts et al., 2013; Gallen et al., 2014).

Late Quaternary tectonic uplift on Crete is uniform but transient (Tiberti et al., 2014; Mouslopoulou et al., 2015b). Using dated paleoshorelines and numerical models, Tiberti et al. (2014) and Mouslopoulou et al. (2015b) show that the island of Crete experienced, during the last 20 thousand years, periods of severe fluctuations in its vertical deformation (at rates of up to 8 mm/yr) while in the preceding ~30 thousand years, vertical movement on Crete was either minimal or reversed (subsidence of 0-3 mm/yr). High uplift rates (~7-8 mm/yr) are also documented on western Crete since 2 kyr BP, in response to co-seismic uplift (that locally reached up to 10 m) (Pirazzoli et al., 1996; Shaw et al., 2008; Mouslopoulou et al., 2015a). Uplift rate transients on Crete are thought to result from non-uniform stress accumulation and release on upper-plate reverse faults in the overriding plate (Shaw et al., 2008; Stiros, 2010; Tiberti et al., 2014; Mouslopoulou et al., 2015b).

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Historical and archaeological records have been also used to link uplift in western Crete to earthquakes (Pirazzoli et al., 1982, 1996; Stiros, 2001; Papazachos and Papazachou, 2003; Papadimitriou and Karakostas, 2008; Shaw et al., 2008; Stefanakis, 2010; Strasser et al., 2011). In particular, historic accounts of a major earthquake in Crete in ~AD 365 are approximately coincident with historic documents recording tsunami inundation of parts of the Libyan and Egyptian coastlines, particularly Alexandria (Ammianus Marcellinus, translated by C.D. Yonge, 1862; Polonia et al., 2013). A gently tilted paleoshoreline (tidal notch) can be followed along the western shoreline of Crete for ~150 km from the area of maximum uplift near the southwest tip (Elafonisi) to as far east as Agios Georgios (Fig. 1). At Domata, our study site, this notch is at 6 m above sea-level. A number of studies attribute the timing of this prominent paleoshoreline to the AD 365 historic earthquake (e.g., Pirazzoli et al., 1982; 1996; Stiros, 2001; Shaw et al., 2008).

3 Data – Methods - Chronology

At Domata a unique sequence of two juxtaposed generations of an alluvial fan are documented, each truncated by different episodes of river and marine incision (see Figs. 2, 3 and 4). The discussion that follows gives a detailed account on the materials and the geometry of the alluvial fan system at Domata, establishes the stratigraphic relationships of its key geomorphic features and provides the chronological framework (sequence of events) within which the established stratigraphic relationships developed.

3.1 Coastal geomorphic features at Domata

The landmass of the White Mountains (Lefka Ori) dominates the landscape of western Crete (Figs. 1 and 2). At the southern coastline of Crete, and proximal to our study area, the White Mountains drop abruptly by >1800 m to sea-level over a distance of <10 km, forming a steep and rugged landscape, often incised by narrow south-draining gorges (Fig. 2). One such gorge is Klados which reaches the sea at the beach of Domata (Figs. 2 and 3). This steep subaerial landscape extends offshore along most of the southwest coast of Crete, as evidenced by the regional bathymetric slopes which are steeper offshore than onshore (Le Pichon and Angelier, 1979; Mascle et al., 1986). As bedrock crops out along much of the southwestern coastline of Crete, it is clear that bathymetric slopes are also cut in bedrock, implying that the Quaternary sediment sequence recorded at Domata has no significant thickness offshore.

The rivers within the gorges of western Crete are usually ephemeral and scour to bedrock, depositing gravels only locally, commonly where valleys widen at junctions with side valleys, across faults (e.g., Sfakia fans; Pope et al., 2008), or close to the coast. As the rivers approach the sea, gradients shallow and stream carrying capacity decreases resulting in deposition from bedload of fans grading to the shoreline. The headwaters of the Klados River, only 7 km from the coast, reach an elevation of ~1800 m in the White Mountains, and no significant areas of sediment accumulation exist between its upper reaches and the fans near the coast that are the subject of this paper. In the Klados Gorge area, bedrock comprises mainly

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crystalline platy limestones with some cherts and platy marbles (Creutzburg and Siedel, 1975; Manutsoglu et al., 2003; Fassoulas et al., 2004). The erosion of these units supplied the Domata area mainly with carbonate clasts and limited chert clasts which explains the abundance of carbonates in the alluvial fans and fluvial terraces.

In order to better interpret the geomorphology at Domata we topographically surveyed and modelled the entire study region (Figs. 3 and 4). The data acquisition was performed with a double precision Real Time Kinematic (RTK) GPS receiver and was corrected to provide coordinates under the Greek Geodetic Reference system (GGRS 87). The topographic dataset includes a total of 4,156 survey points, measured under an excellent geometric dilution of precision (GDOP) and accuracy of <1 cm. Some areas were not surveyed due to dense vegetation; however, values for these regions were interpolated using the 'nearest neighbour method'. A series of breaklines and sparse elevation models from the National Cadastre and Mapping Agency of Greece were incorporated in the model (Fig. 4a) to optimise representation.

Older geomorphic features are present at Domata in the form of two marine benches cut in bedrock at elevations of about 100 and 360 m on the western slopes above the Klados River (Fig. 2). While we cannot assign ages to these benches, their altitude and geomorphic similarity with known and dated (MIS5) late Pleistocene marine benches elsewhere in Crete (e.g., Strasser et al., 2011; Gallen et al., 2014; Strobl et al., 2014), provides some stratigraphic and chronologic context for the age of the alluvial fans at Domata (i.e., because of their lower elevation, the alluvial fan surfaces that are subject of this paper are expected to be younger than 125 kyr).

At Domata, two triangular, elevated fan surfaces (a lower and an upper surface) covering a combined surface area of ~0.1 km^2 near the mouth of Klados River, rise to an inland elevation of ~100 m (Figs. 2, 3 and 4). The fan surfaces are derived from a single feeder channel, the Klados River that drains a relatively small catchment (immediately west of the larger and better known Samaria Gorge) and lie at the seaward end of a narrow entrenched gorge. They are unique in south Crete as they are protected from alluvial erosion by a low bedrock ridge (see Fig. 2) which channels the river flow to the western side of its narrow valley. Where the Klados River leaves its bedrock gorge, ~500 m from the coast, its channel is incised into gravels ~40 m below an abandoned fan surface, the lower of the two surfaces (Figs. 2 and 3). Gravel deposits beneath the surface on lap bedrock on both sides of the valley without structural deformation (e.g., faulting). Downstream, ~40 m from the river mouth, the seaward extent of the lower-fan surface is at c. 35 m above sea-level (Fig. 4). Here, both the fan surface and its alluvial entrenchment cliff are trimmed parallel with, and close to, the present shoreline (Figs. 2 and 3). The linearity and parallelism of this cliff to the modern coastline clearly implies that this cliff has been trimmed by the sea. The elevation of the lower-fan surface decreases eastwards along the sea-trimmed cliff to <10 m above sea-level near the east end of Domata beach (Figs. 2 and 5a). Along this coastal cliff, the highest elevation of the lower-fan surface occurs ~90 m east of the Klados River (Figs. 2 and 5a).

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The upper-fan surface lies at ~100 m elevation at its upstream extent, ~60 m above the active river bed and ~20 m above the lower-fan surface (Figs. 4 and 5a). The upper-fan deposits are truncated by an old river incision (trending ~200º) that is older than the lower-fan surface, as the deposits of the lower-fan lap against the buried upper-fan deposits (Fig. 3). Downstream, the seaward extent of the upper-fan surface and its entrenchment cliff are truncated by another marine cliff (trending ~130º) that pre-dates deposition of the lower-fan, as the lower-fan surface also laps against this (Figs. 2 and 3). Where the marine trimming truncates the upper-fan surface and its river entrenchment cliff, the upper-fan surface has an elevation of c. 60 m, and this decreases eastwards to ~30 m at the east-end of the beach (Figs. 2, 4 and 5a). In the east, the upper-fan surface is overlain by silty sand near the eastern end of Domata Beach (Fig. 5a). This deposit is preserved seaward of the only stream gully that crosses the upper fan surface, draining the bedrock area behind that fan; this ephemeral stream is undoubtedly the source of this younger silty sand (UF-2 sample in Table 1).

Lower-fan materials exposed in the sea-cliff are dominantly poorly sorted, matrix-supported gravels, moderately stratified, with coarser beds commonly < 2 m thick and sometimes clast-supported, and finer beds < 1 m thick that display lateral lensing and channelling (see stratigraphic log in Fig. 5b). Along the coastal cliff bedding is convex up, sub-parallel with the lower-fan surface (Fig. 6a). Some individual beds can be traced laterally up to 200-300 m (see thin dashed lines in Fig. 6a). In the coastal cliff, lower-fan materials lap onto a gently undulating, sub-horizontal discontinuity on an underlying older alluvial gravel (e.g. remnants of the upper-fan) that is coarser and more commonly clast-supported (Fig. 5b), and has a higher fine-grained content (Figs. 2, 3, 5b and 6a). The contact surface between the two fan units is very clear and extends along the length of the beach (Figs. 5 and 6a) and also up the Klados River for ~100 m (Fig. 3). In places, the contact is locally obscured by fallen debris, but it is clearly subhorizontal, with low relief and undoubtedly separates the two fan units (Fig. 6a). At each end of the beach, the older gravel materials lap onto older sedimentary rocks (gravel and sand) (Fig. 6c).

Another subtle geomorphic feature of interest is a bioerosion notch indicating an uplifted paleoshoreline at ~6 m above present sea-level at the west end of Domata beach (Fig. 6b and c). This notch continues west and east from Domata and has been mapped around the coastline of western Crete and attributed to a seismically uplifted paleoshoreline dated at ~365 AD (e.g., Pirazzoli et al. 1982, 1996; Shaw et al. 2008). Figure 6c shows that the AD 365 bioerosional notch post-dates both the deeply dissected erosional surface (of older Quaternary deposits) and the fan deposits that rest on it. The presence of a small terrace on the west side of the Klados River (Fig. 6b) at approximately the same elevation (6m) represents an alluvial terrace stranded by that uplift. As with the lower-fan surface, this terrace has been trimmed by the sea. This late-stage uplift resulted in a readjustment of the Klados River bed and incision near the mouth of the stream (Fig. 6b).

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3.2 Luminescence dating of alluvial fans

To place chronologic constrains on the series of geomorphic features described here from Domata, we collected in steel tubes five samples for OSL dating from depths ranging from 0.24 to 1.1 m below the ground surface (Table 1). One sample was collected from close to the surface of the upper-fan (UF-1) to constrain the end of the upper-fan aggradation (surface abandonment) and the initiation of incision (Figs. 3 and 5a). A further sample (RB-1) was collected from the upper-fan deposits exposed in the lower reaches of the Domata stream cliff to constrain the age of deposition of the early upper-fan deposits (Figs. 3 and 5a). Two samples collected from close to the lower-fan surface (LF-1a/b and LF-2a/b) were to provide constraints on the timing of lower-fan abandonment and initiation of incision (Figs. 3 and 5a). A further sample (UF-2) was collected from deposits (silty sand) mantling both the lower and upper-fan surfaces, near the east-end of the Domata beach, to test its age relative to UF-1 and UF-2. The results of the luminescence analysis are presented in Table 1 and Figure 7.

3.2.1 Sample preparation and measurements

All samples were dated in the luminescence lab at Humboldt University of Berlin (Germany), where they were prepared under subdued red light according to standard procedures. After separating the wanted grain size fractions by wet sieving (38-63 µm and 90-200 µm), carbonates and organic material were removed using 10% hydrochloric acid and 10% hydrogen peroxide. Quartz and potassium feldspar were extracted from the coarser grain fraction by density separation using heteropolytungstate heavy liquid (LST) of 2.75, 2.62 and 2.58 g/cm^3.The subsequent etching of the separated quartz with hydrofluoric acid (40%, 60 min) eliminated any potential feldspar contamination and removed the alpha irradiated outer grain layer. From the finer fraction of 38-63µm quartz was isolated by a two-week treatment with 38% hexafluorosilicic acid. After renewed sieving small multiple grain aliquots (2mm) were prepared of etched quartz (90-200 and 38-63µm) and potassium feldspar (90-200µm).

Quartz OSL (optical stimulated luminescence) measurements were performed on a Risø TL/OSL-DA 15 reader (blue LED stimulation at 470 nm and detection through a Hoya U340 filter with transmission centered on 330 nm) and on a Lexsyg luminescence measurement system (green LED stimulation at 525 nm and detection through a Schott BG3 Delta-BP365/50 EX-Interference filter combination at 380 nm). Feldspar IRSL (infrared stimulated luminescence) measurements were conducted on a Lexsyg luminescence measurement system (IR-LD stimulation at 850 nm and detection through a Schott BG39 AHF-BrightLine HC 414/46-Interference filter combination at 410 nm). Quartz paleodoses were measured using a SAR (single aliquot regenerative) protocol according Murray and Wintle (2000, 2003) with preheat temperature set to 240°C (10s) and test dose cutheat to 160°C. Wallinga et al. (2000) introduced the SAR protocol to the IRSL dating of potassium feldspar. It was here modified following Blair et al. (2005) applying equal preheat procedures after every irradiation step (250°C, 60s). The appropriate preheat temperatures and durations were identified conducting dose recovery tests on samples RB-1 and LF-2a/b (SAR equivalent dose determinations of known lab doses with varying preheat temperatures). Quartz was

Moved up [1]: Further, older geomorphic features are also present at Domata: two marine terraces, elevated at about 100 and 360 m respectively, are cut on the south-facing mountain, west of the Klados River (Fig. 2). While we cannot assign ages to these benches, their altitude and geomorphic similarity with known and dated late Pleistocene marine benches elsewhere in Crete (e.g. Shaw et al., 2008; Strasser et al., 2011; Strobl et al., 2014; Mouslopoulou et al., 2015a), provides some stratigraphic and chronologic context for the age of the alluvial fans at Domata (i.e., the alluvial fans, which have lower altitude compared to these marine terraces, are expected to be younger than 125 kyr). ¶

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stimulated at 125°C for 40 s, feldspar at 50°C for 300 s. The built-in beta sources (Sr-90) emitted 0.068 Gy/s (Lexsyg) and 0.093 Gy/s (Risø) respectively. The sediment dose rates were estimated by measuring the contents of uranium, thorium and potassium on a high resolution gamma spectrometer. The cosmic-ray dose rates were estimated from geographic position, elevation and burial depth (Prescott and Hutton, 1994). The internal potassium content of the measured feldspar was assumed to be 12.5 ± 0.5 % according to Huntley and Baril (1997).

3.2.2 Luminescence results

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Quartz OSL dating results reported in Pope et al. (2008) and OSL and U series dating of Pope et al. (2016) proved the suitability of standard quartz SAR protocols for dating fan sediments along the nearby Sfakia piedmont in southern Crete (Fig. 1). In contrast, the investigated quartz from Domata showed poor luminescence properties: the OSL signals were dim, dose recovery tests yielded unsatisfactory results, the highly scattering paleodoses produced positively skewed broad distributions and the resulting quartz ages showed no relationship with stratigraphy (underestimation of true age). This led to the conclusion that quartz is not the appropriate material for dating the alluvial fans at Domata. The most likely explanation for the non-suitability of the quartz (weak, or even missing, fast OSL signal component) is the dominance in our samples of fresh insensitive quartz, which had undergone few sedimentation cycles (Preusser et al. 2006; Steffen et al., 2009). Thus, potassium-feldspar (IRSL) was used instead to date the landforms at Domata.

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The feldspar (IRSL) dating produced reliable age ranges (Fig. 7). Best results for dose recovery tests on laboratory-bleached feldspar samples from Domata were obtained without applying any sensitivity correction. Thus, a simplified SAR protocol without testdose measurement was used for the paleodose determination of the natural potassium-feldspar samples. No fading tests were made to correct for any potential age underestimation. Sensitivity changes were assessed by repeating the first irradiation step at the end of each SAR cycle assuming that the luminescence intensities should coincide (recycling ratio close to 1.0). Here, a recycling ratio between 0.85 and 1.15 was tolerated. The a-value for assessing the alpha particle contribution to the paleodose was set to 1.5 ± 0.5 (Balescu and Lamothe, 1994). Basic statistical values are presented in Table 1. Under perfect conditions the arithmetic mean and the median should coincide. But here the mean value is always larger compared to the median, typical for positively skewed age distributions. This can indicate insufficient exposure of the sediment to daylight during the last sedimentation cycle. But also post-depositional mixing, contamination with younger grains from the surface (low sampling depth, bioturbation) or microdosimetric inhomogeneities are possible reasons for skewed age distributions. Compared to the mean, the median is less sensitive to large outliers (RB-1, LF-1a/b) while the peak of the kernel density estimation (KDEmax) reflects the value with the highest probability within the distribution applying a fixed bandwidth (Galbraith and Roberts, 2012).

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Collectively, our potassium-feldspar measurements suggest that the ages of the landforms at Domata range between ~55 and 25 kyr BP (Table 1). Thus, the chronostratigraphy of the majority of the geomorphic landforms formed during MIS 3 (29-57

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kyr). When used in conjunction with the sequence of events dictated by the stratigraphy presented in Section 3.1 and the Siddall et al. (2003) sea-level curve, the chronology of the geomorphic events that formed the landscape at Domata can be established reasonably well, despite the significant errors in the luminescence measurements (Fig. 7). The landscape evolution, including its chronology, is discussed in Section 4.

3.3 Soil development

We have performed a macroscopic soil-profile characterization for the soil-horizons that develop on the two fan surfaces (Fig. 8a). The fan surfaces are gently dipping, with a maximum gradient of ~7 to 8º and incision restricted to few dry and shallow (<1m) creek courses. Thus, erosion on these surfaces is expected to be minimal. Nevertheless, to minimise the effect of soil erosion, we located our soil profiles away from creek incisions.

The soils at Domata are categorized as Leptosols (Soil Atlas of Europe, 2005; FAO, 2006) and comprise a shallow (<0.5 m) soil cover over coarse sediment of highly calcareous material (Fig. 8). Soils on both the upper (UF) and lower (LF) fans have common parent material (fan gravels), mainly consisting of limestone pebbles and cobbles, and the fans are covered by pine trees (Pinus brutia) (Fig. 8a). However, the soils of the upper (UF) and lower (LF) fan surfaces differ macroscopically and in their physical, biochemical and geochemical parameters. Soil thickness, averaged from 6 soil profiles, varies from 0.1 m (Fig. 8b) beneath the lower-fan surface to 0.4 m (Fig. 8c) beneath the upper-fan surface. The UF soil is yellowish-brown with A and (weak) B horizons and texture from subangular to granular while the LF soil is yellowish with granular texture and has no distinct horizons (apart from a very thin horizon A) (Fig. 8b and c).

Comparison of the macroscopic characteristics of the soils at Domata with the soils identified at the piedmonts at the nearby region of Sfakia (Fig. 1) by Pope et al. (2008), provides additional evidence that the alluvial fan system at Domata was formed during MIS 3 (as constrained by the IRSL dating). Specifically, at Domata we find soils the characteristics of which closely resemble the soils that developed at Sfakia during stage 2C (70-16 kyr BP), while there is total absence of older soils that developed during stage 2A (~144 kyr) (Pope et al., 2008). The former (stage 2C) is a brown to yellowish-brown soil with limited B horizon and subangular texture, characteristics that match the soils at Domata, whereas the latter contains highly crystalline iron oxides with a clear B horizon.

The macroscopic observations (UF soil thicker and redder) also imply that the upper-fan soil is more mature compared to that of the lower-fan. Preliminary geochemical analysis (Moraetis et al., 2015) confirms that the soil in UF is more mature (e.g., older), as it has lower *specific surface area* and higher content of well-shaped hematite (and less goethite) compared to that in the LF (Wang et al., 2013). This observation is also in agreement with soil analysis at the nearby region of Sfakia (Fig. 1), where Pope et al. (2008) showed that the soil redness and the content of crystalline iron oxide (hematite) increase

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with increasing alluvial fan age. The greater age of the UF soil compared to the LF soil is also independently demanded by our stratigraphic observations on crosscutting and incision of fans and the luminescence dating that shows that the upper-fan surface developed at least 5 kyr earlier than the lower fan surface (see discussion in Section 4; Table 1). According to Lair et al. (2009) and Huang et al. (2016), the ~5 kyr of difference in the residence time between the two soil horizons is sufficient to generate the recorded macroscopic and geochemical changes.

4 Interpretation of landscape evolution at Domata

According to our luminescence age-range and the relative location of the fan surfaces below the marine bench (see Fig. 2) of inferred MIS5 age, the majority of the geomorphic landforms at Domata we discuss formed during MIS 3 (29-57 kyr) (Table 1 and Figs. 2 and 7). The sequence of events that resulted in the development of the landscape at Domata, as dictated by the analysis of the geomorphic landforms and the superposition of the luminescence dating onto the well-established sea-level curve of Siddall et al. (2003)[1] (Fig. 9), is as following (from old to young) (Fig. 10): *a)* deposition of the upper-fan materials (Fig. 10a); *b)* river entrenchment leading to abandonment of the upper-fan surface (Fig. 10b); *c)* marine trimming of the upper-fan surface deposits, the fan deposits and its alluvial entrenchment cliff (Fig. 10c); *d)* deposition of the lower-fan materials against the upper-fan materials in its alluvial entrenchment cliff and the sea-cliff in the upper-fan (Fig. 10d); *e)* river entrenchment leading to abandonment of the lower-fan surface (Fig. 10e); *f)* marine trimming of the lower-fan deposits and the alluvial entrenchment cliff (Fig. 10f); *g)* seismic uplift resulting in a stranded paleoshoreline, the development of a river terrace riser and the oversteepening of the lower river channel (Fig. 10g). In the following discussion we provide evidence in support of each stage of the landscape evolution at Domata and establish its relative chronology.

The initiation of deposition of the upper-fan (Fig. 10a) is likely to have occurred post ~50 kyr BP and prior to 45 kyr (RB-1 sample; within MIS 3 of Lisiecki and Raymo 2005; Table 1); this coincides with a period of elevated sea-level (c. -70 to -80 m according to Siddall's sea-level curve; Fig. 9). We argue that upper-fan deposition is unlikely to have started as early as 53.4 kyr (mean of RB-1 sample; Table 1) because there is no geomorphic evidence (e.g., marine cliffs) representing the two subsequent high sea-level stands at c. 45 and 39 kyr. Thus, the deposition of the upper-fan postdates 53 kyr and is completed by ~45 kyr BP, when sea-level rose to reach at c. -72m (Siddall et al., 2003). The period that follows, between 45-41 kyr, reflects the start of a cooling climatic period (possibly with an increase in sediment supply) and falling sea-level to -87 m (Fig. 9). During this period, alluvial-fan entrenchment resulted in fan surface abandonment and development of the alluvial cliff in the upper fan deposits (Fig. 3) and the upper-fan was eventually abandoned (Fig. 10b). This was followed, at ~39 kyr BP, by marine transgression resulting in marine trimming of the upper-fan surface, the alluvial entrenchment cliff and

[1] The shape of the sea-level fluctuations varies slightly globally, so we designate in this work the empirical, high resolution, sea-level curve of Siddall et al. (2003) from the Red Sea that covers the last 128 kyr. Siddall et al. (2003) estimate the error in their sea-level curve at ~12 m, so all sea-level elevations discussed subsequently are subject to this uncertainty.

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development of a sub-horizontal marine-cut bench in early upper-fan deposits at about the sea-level of the time (c. -70 m) (see yellow dashed line on the river cliff in Fig. 3; Figs. 9 and 10c). This allowed up to 10,000 years for upper-fan deposition and incision before the fan is trimmed by the sea during the high sea-level peak at c. 39 kyr.

Lower-fan deposition commenced (Fig. 10d) soon after marine trimming of the upper-fan (Fig. 9). The relatively high sea-level at 37 kyr (c. -75 m; see Fig. 9) promoted fan deposition and the possibly deteriorating climatic conditions, involving episodically increased river flow/carrying capacity and diminishing vegetation density in the upper catchment, resulted in increased sediment supply. Lower-fan deposits lapped against alluvial entrenchment and marine cliffs cut previously in upper-fan deposits by alluvial incision along the Klados River and by the marine trimming sub-parallel to the modern shoreline (Fig. 10d). Lower-fan surface abandonment and river entrenchment through incision commenced at ~36 kyr (LF-2a/b sample; Table 1). We argue that the lower-fan surface was abandoned (Fig. 10e) sometime between ~36 kyr and 29 kyr due to river entrenchment resulting from rapidly falling sea-level (that continued until ~18 kyr) (Fig. 9).

Marine trimming of the lower-fan surface and deposits is unlikely to have occurred between deposition and the last glacial maximum (~18 kyr), as sea-level progressively declined during that period. Following 18 kyr, sea-level rose rapidly by ~100 m in less than 10 kyr (Fig. 9). The Holocene high sea-level stand is the most likely candidate period for the marine trimming of the lower-fan surface and deposits and this is expected to have commenced as sea-level approached roughly the present level c. 4-5 kyr ago (Fig. 10f). Between 18 kyr and 5 kyr BP, while sea-level was rising fast, tectonic uplift at Domata must have outpaced rising sea-level, protecting the entire sequence from marine inundation and destruction. Immediately prior to the co-seismic uplift that affected western Crete at AD 365 (Pirazzoli et al., 1982), the foot of the lower marine cliff would have been within the intertidal zone. Today, due to the 6 m of uplift associated with that earthquake, the prominent stranded paleoshoreline and the foot of the marine-trimmed cliff are at approximately similar levels and the sea cliff may be isolated from further trimming (Figs. 6b and 10g). We interpret a low terrace riser at about this elevation near the mouth of the Klados River (see lower white dashed line in Fig. 6b) to be relict from the river channel of that time and, in the lower c. 100 m of its course, the river has downcut in response to that first-millennium earthquake uplift.

In summary, deposition of the upper and lower-fan was controlled by a marine base level and, in both cases, fan incision resulted due to falling sea-level. The deposition of the upper-fan was largely completed by ~45 kyr BP, during a period of relative high sea-level (c. -70 m), and fan incision resulting in surface abandonment occurred between c. 45 and 40 kyr. Marine trimming of the upper-fan deposits occurred during a sea-level high (c. -72 m) at c. 39 kyr. Lower-fan deposition was initiated soon afterwards and fan surface abandonment occurred between 36 and 29 kyr. The age of the sandy unit that mantles both the upper- and the lower-fan surfaces is ~25 kyr (UF-2; Fig. 9 and Table 1), postdating both fans as expected by its stratigraphic relationship with respect to the fans (silty sand that mantles both the lower and upper-fan).

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5 The importance of tectonic uplift at Domata

The fan sequence at Domata provides a unique opportunity to link terrestrial deposition with sea-level fluctuations on southwestern Crete. Geomorphic analysis combined with dating shows that the development of the fan sequence can be accounted for by eustatic changes coupled with vertical tectonics. The latter can be rationalised if we consider that the landforms at Domata were formed 70 to 90 m (within the known error margins) below the current sea-level, implying that, unless tectonic uplift was significant, the entire sequence would have been inundated, and thus modified or destroyed, by the rising sea-level during the last 20 kyr (Siddall et al., 2003). A requirement of its preservation is that since its deposition, the tectonic uplift rate has outpaced rising sea-level. A question that arises from this reasoning concerns the rate of the tectonic uplift at Domata and how it relates to the rate of rising sea-level. Dating key terrestrial and marginal marine geomorphological features at Domata, thus, provides an average uplift rate for this part of Crete that can be compared to the rate of rising sea-level and also to other rates of tectonic uplift on western Crete (which have been independently derived).

Our data show that the marine trimming episode at c. 39 kyr left a coastal cliff and cut an erosional intertidal bench in the upper-fan deposits (see yellow dashed line in Figure 3). This marine bench provides a good datum upon which to estimate subsequent uplift. Indeed, a total uplift of 86 m (± the 12 m error margin of the sea-level curve) is required to elevate this marine bench to its current altitude of 14 m a.s.l. Thus, the minimum uplift rate required to accomplish this is c. 2.2 mm/yr. Indeed, the plot in Figure 11 shows that with an average rate of ~2.2 mm/yr since formation (black line), the fan sequence would have escaped the destructive interaction with the wave-zone and, therefore, modification due to erosion (e.g., the black line of uniform uplift rate does not intersect the sea-level curve during the last 39 kyr). Independent support for similar uplift rates comes from published radiocarbon ages on beachrock materials that mantle marine paleoshorelines in nearby localities: a calibrated radiocarbon age of 36,790 - 38,694 yrs BP from reworked rhodoliths in beachrock at an elevation of 10.5 m at Sougia, 9 km to the west of Domata, is within a few thousand years of the proposed timing of marine trimming of the upper-fan, and yields a required average uplift rate of 2.4 mm/yr (Mouslopoulou et al., 2015a). Similarly, beachrock on a marine bench at 17 m elevation at Palaiochora, 20 km west of Domata, yields a calibrated radiocarbon age of 36,682 - 38,732 yrs BP, producing an average uplift rate of 2.5 mm/yr (Mouslopoulou et al., 2015a). Comparable uplift rates (1.8-2.7 mm/yr) have been independently recorded for the last ~40,000 years at numerous localities on western Crete by Shaw et al. (2008), Strasser et al., (2011) and Tiberti et al. (2014). Thus, the preservation and sub-aerial exposure of the landscape at Domata is due to the sufficient tectonic uplift that southern Crete experienced during late Quaternary.

In order to quantify the relative contribution of tectonics and eustacy on the formation of the landscape at Domata, here we compare published information on incremental uplift rates calculated by Tiberti et al. (2014) and Mouslopoulou et al. (2015b) for western Crete over the last ~40 kyr with the uplift rate calculated for Domata over the last 39 kyr (c. 2.2 mm/yr; this study). Comparison shows that during the time period over which the key features at Domata formed (MIS 3), no

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significant uplift was accommodated on Crete as the region between ~20-45 kyr was experiencing a tectonically quiet period with no uplift (Mouslopoulou et al., 2015b) or even gentle subsidence (Tiberti et al., 2014). Thus, the shaping of the landscape at Domata during MIS 3 must have been largely achieved by sea-level fluctuations. This comparison also suggests that most of the ~80 m of uplift (subtracting 6m of late Holocene co-seismic uplift), have been accumulated sometime between 5 and 20 kyr BP, resulting in an average uplift rate of 5.3 mm/yr (Fig. 11; dashed red line). However, this uplift rate would have been insufficient to outpace the rising sea-level between 8 and 12 kyr BP (see dashed red line intersecting the sea-level curve in Fig. 11) and, thus, the fan sequence would have been inundated and modified or destroyed by the rising sea-level. This, in turn, implies that the uplift rate at Domata was higher than 5.3 mm/yr. We favour a scenario in which uplift was mostly accommodated by about 9 kyr BP, at an average of ~7 mm/yr (see solid red line in Fig. 11 that does not intersect the sea-level curve). Comparable uplift rates (7-8 mm/yr) have been independently recorded at numerous localities on western and eastern Crete for the last 20,000 years by Tiberti et al. (2014) and Mouslopoulou et al. (2015b).

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Thus, the development and evolution (~50-20 kyr BP) of the suite of geomorphic features at Domata can be largely explained by eustatic sea-level fluctuations and sedimentation variations controlled by climatic conditions, without the requirement for significant vertical movements. However, it is the subsequent tectonic uplift that preserved and exposed sub-aerially the coastal geomorphic features.

This work was undertaken prior to the publication of the latest results of OSL and U series dating of the Sfakia fan sequence (Pope et al., 2016). Intriguing conclusions of their high-resolution dating work include that at Sfakia, three sometimes overlapping phases of fan deposition since the last interglacial are separated by two phases of fan entrenchment, the first close to the MIS 5/4 (c. 70 kyr) boundary, the other close to the MIS 2/1 boundary (c. 14 kyr), triggered by major climatic changes. Fan deposition there has to a large degree persisted through stadial and interstadial periods during the last 125 kyr. Periods of entrenchment at Sfakia do not appear to correlate with the two entrenchment periods at Domata. The Sfakia fan is somewhat different from the Domata fan in catchment size (c. 28 km^2 compared with c. 11 km^2), fan size (5.3 km^2 compared with 0.1 km^2), the presence of more than one feeder channel at Sfakia, and in the nature of deposits (primarily clast-supported gravels at Sfakia compared with primarily matrix-supported gravels at Domata). Whether these differences are responsible for differences in depositional and entrenchment histories and in preservation of marine cliffs at Sfakia, or differences in local climatic regimes, or vegetation changes, is uncertain. However, one compatible conclusion of Pope et al.'s work with our own is recognition of the importance of base level (sea-level) changes to the process of incision.

6 Conclusions

Alluvial fans often provide a useful index with which to decode the information recorded on the landscape in complex tectonic settings, such as those of Eastern Mediterranean. Herein we use analysis of geomorphic landforms and luminescence

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dating on an alluvial-fan system with two separate periods of depositional activity in Crete, an island straddling the forearc of the Hellenic subduction margin, to constrain its vertical deformation and discuss the contributing factors responsible for its landscape evolution. Our interpretations suggest that sea-level fluctuations in response to varying climatic conditions formed the landscape at Domata during MIS 3 (~57-29 kyr BP). It is, however, because of the fast tectonic uplift that Crete experienced during the subsequent ~20 thousand years that the entire alluvial sequence escaped destruction and/or modification due to marine inundation and is preserved sub-aerially today. Thus, both eustacy and tectonism impacted on the formation and preservation of the landscape at Domata, but over temporally distinct time periods.

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Author's contributions

V.M, J.B. and D.M conceived the research idea, pursued all associated fieldwork and analysis of the results. A.F. performed the IRSL dating and P.P. pursued the RTK survey. O.O. provided guidance and contributed to the development of the ideas presented in this article. The manuscript was written collectively by all authors.

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Competing interests

The authors declare that they have no conflict of interest

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Figure captions

Figure 1: Map illustrating the location of Crete within the forearc of the Hellenic subduction margin. The locations of the Hellenic Trough and its splays (the Ptolemy, Pliny and Strabo troughs) are indicated. Numbered arrows show geodetically-derived convergence rates between the African and Eurasian plates and their azimuths at selected sites (after Reilinger et al., 2010). The study area at Domata is indicated by white filled circle while the regions of Sfakia (S), Elafonisi (E), Palaiochora (P) and Agios Georgios (AG) are marked with blue circles. WM=White Mountains. Hillshade is derived from GeoMapApps.

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Figure 2: Northward view of the beach at Domata illustrating the two generations of fan surfaces and their separate episodes of marine trimming. The location of the Klados gorge, the two elevated marine benches cut on bedrock and the AD 365 uplifted shoreline are indicated (for a close-up view of the bioerosional AD 365 notch see Figure 6c).

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Figure 3: The fan sequence at Domata looking obliquely towards southeast. The two fan surfaces and their respective stream-incised cliffs are illustrated. The yellow dashed line in the present stream cliff indicates the benched upper-fan erosional surface, which is overlain by the deposits of the lower-fan. This important marker was used to calculate a long-term (39 kyr) uplift rate at Domata (see text for details). White spots mark the location of IRSL samples.

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Figure 4: a) Digital elevation model of the study area at Domata as viewed obliquely from the southwest. The model is derived by using the nearest neighbour algorithm along with the GPS measurements marked and colour coded by 10 m elevation bands. Note the upper and lower-fan surfaces, each incised following surface abandonment, and each trimmed by marginal marine processes. b) Digital elevation model with National Greek Cadastre Agency orthophoto draped, along with the GPS measurements. Yellow polygon depicts the area illustrated in the DEM of panel (a). Red polygons indicate the localities of the profiles presented in Figure 5a.

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Figure 5: **a)** Profiles of fan surfaces projected onto common planes parallel with the modern Klados River channel (above) and parallel with the modern coastline (below). The likely extent of the volumes of upper-fan materials (pink) and lower-fan materials (light green) are schematically illustrated beneath each measured profile. The locations of each of the luminescence sample points are annotated by yellow dots. The locations of the stratigraphic columns presented in Figure 5b are also indicated. Horizontal and vertical scales for each profile are similar, with a VE of c. 1.25. Note that the downstream slope of the upper and lower-fan surfaces are about the same, both a little steeper than the slope of the modern stream channel. Also note that the upper-fan surface slopes less to the east than the lower-fan surface, so that the upper-fan marine cliff is higher at the eastern end of the beach than at the west. The highest elevation of the lower-fan surface is close to the foot of the incision of the upper-fan, while the upper-fan surface is highest at its incision point. **b)** Schematic stratigraphic columns for the upper (left) and lower (right) alluvial fan deposits. Note that vertical scale bars indicate elevation in metres above mean sea level

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for each column. The lower-fan column reflects a stratigraphic section close to the junction between the lower-fan coastal cliff and the river entrenchment. The upper-fan section is located close to the western end of the marine-cliff. Their stratigraphic location is indicated on Figure 5a. Note that the right-hand edge of the lower-fan section represents relative competence of materials.

Figure 6: a) The present marine cliff at Domata (above), annotated to highlight various sedimentary relationships (below). The cliff comprises mostly moderately bedded gravels of the lower-fan sequence. The lower contact of the lower-fan gravels (white dashed line) is irregular, but sub-horizontal and lower-fan bedding (white dotted lines) laps onto it. Some individual horizons within the lower-fan deposits can be traced laterally for 100's metres, but channelling, bed-lensing and pinch-outs are present. Note also that the exposed marine cliff beneath the upper-fan surface (behind the forested lower-fan surface). **b)** Looking west across the Klados River mouth (foreground), the uplifted shoreline attributed to the AD 365 earthquake (dashed red line, lower left) aligns well with a low terrace riser on the west side of the river (dashed thick white line, middle). Incision of the modern channel below the surface is attributable to post-earthquake adjustment to new base levels. Note the sea-cliffing of the last interglacial? marine bench (thick red dashed line at the top of the image) and the upper and lower fan deposits. The upper fan and western parts of the lower fan are overlain by accumulated rockfall debris and the solid thin white line approximates its surface. The lower fan surface is marked with fine dotted white line. **c)** Annotated image of the west-end of Domata beach illustrating the relationship between the unconformity at the base of the fan sequence and the AD 365 bioerosional notch. Specifically, the picture shows a dissected erosional surface on older Quaternary sediments that pre-dates the fan deposits, and the AD 365 bioerosional notch post-dating both the erosional surface and the fan deposits that rest on it.

Figure 7: Individual ISRL ages for all selected aliquots and resulting kernel density estimates. Mean = arithmetic mean, sd = standard deviation (relative and absolute; shaded area), se = standard error (relative and absolute). KDE $_{max}$ = empirical estimate of the probability density function of the observed age distribution. Shaded area: standard deviation.

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Figure 8: a) The two alluvial fans with their tree cover (*Pinus brutia).* Arrows indicate the soil-cover that develops on each of the fan surfaces. **b)** The soil development on the lower-fan (LF) surface is ~12 cm (as indicated by the white arrows). **c)** The soil development on the upper-fan (UF) surface is ~40 cm (see white arrows). The fan gravel in both cases is indicated.

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Deleted: from 16 to 56 cm, as indicated by the

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Figure 9: The ISRL chronology of the geomorphic features at Domata plotted against a simplified version of the global sea-level curve after Siddall et al. (2003). The shaded zone in the background represents Siddall et al.'s stated error range. Large filled circles represent means of ISRL dates, small filled circles medians and the bars are error bars (at 1σ). The geomorphic event sequence described in the text is shown above the figure and the favoured of three alternative high sea-level stands

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within MIS 3 to have trimmed the upper-fan surface prior to lower-fan deposition, is identified with a solid vertical blue line at 39 kyr BP.

Figure 10: The sequence of events that contributed to the development of the landscape at Domata is schematically illustrated: a) Upper-fan deposition due to sea-level high stand (base level); b) Abandonment of the upper-fan surface due to falling sea-level; c) Sea-level rise resulting in the trimming of the upper-fan deposits and cutting a marine bench; d) Lower-fan deposition starts during relatively high sea-level, and laps against both the river incision cliff and the coastal cliff in the upper-fan; e) As sea-level falls, the lower-fan surface is abandoned through entrenchment; f) A return to high sea-level results in coastal trimming of the lower-fan deposits; g) One or more earthquakes in the first millennium AD resulted in 6 m of uplift at Domata and corresponding adjustments to the lower Klados River geomorphology. The approximate chronology of each stage is annotated.

Figure 11: The plot discusses the required uplift rate to elevate the marine cliff/bench of the upper-fan from its elevation at genesis (39 kyr BP) to its present elevation (+14 m). The simplified sea-level curve (after Siddall et al., 2003) is illustrated by thick blue line. The black line represents a constant uplift rate of 2.2 mm/yr (established in this study). The red dashed line represents a minimum uplift rate for Domata of ~5.3 mm/yr tailored to empirical data (Tiberti et al., 2014; Mouslopoulou et al., 2015b). The red solid line represents the uplift rate required for the fan-system to escape marine inundation and destruction/modification (see text for details).

Table 1: Luminescence dosimetry measurements and IRSL ages (potassium feldspar).

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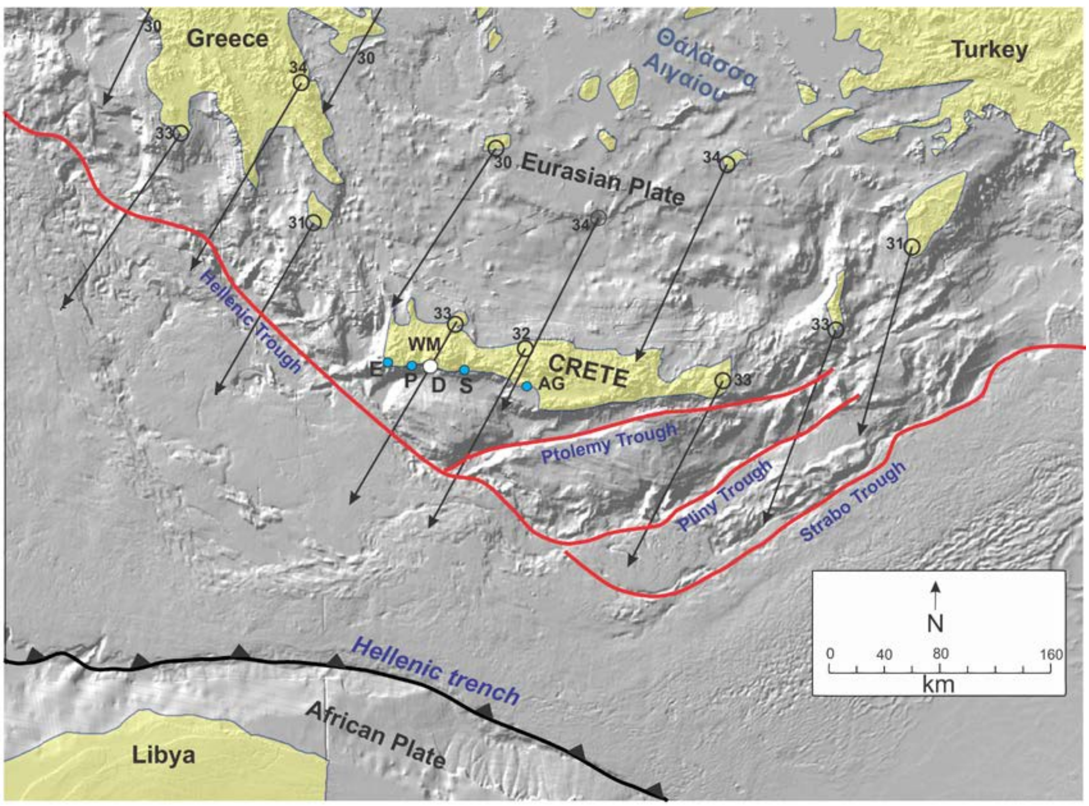

Greece
Θάλασσα
Αιγαίου
Turkey
Eurasian Plate
Hellenic Trough
WM
E
P
D
S
AG
CRETE
Ptolemy Trough
Pliny Trough
Strabo Trough
N
0
40
80
160
km
Hellenic trench
African Plate
Libya

Figure 1

5

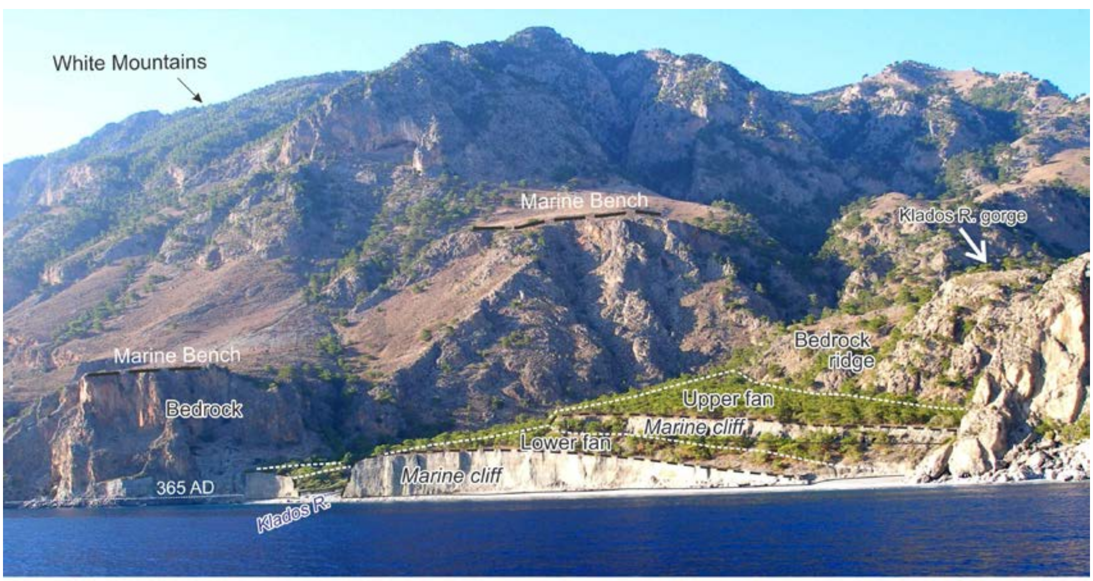

White Mountains
Marine Bench
Klados R. gorge
Marine Bench
Bedrock
Bedrock
ridge
Upper fan
Marine cliff
Lower fan
Marine cliff
365 AD
Klados R.

Figure 2


Bedrock
UF-1
Upper fan surface
UF-2
Marine trimming
Marine trimming
Post-upper fan river incision
LF-2
LF-1
Lower fan surface
Post-lower fan river incision
RB-1
Upper fan gravels
Klados R., active river channel

Figure 3

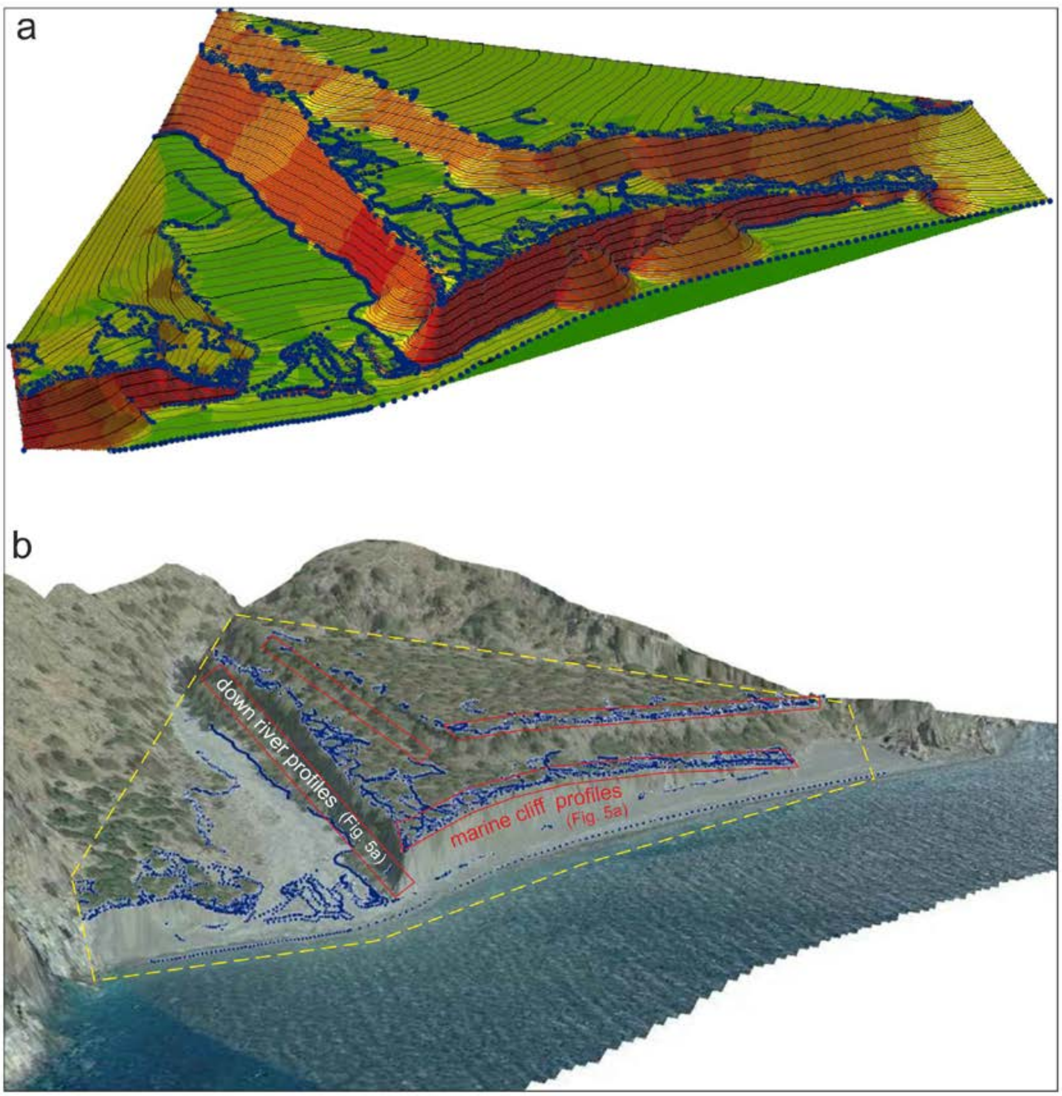
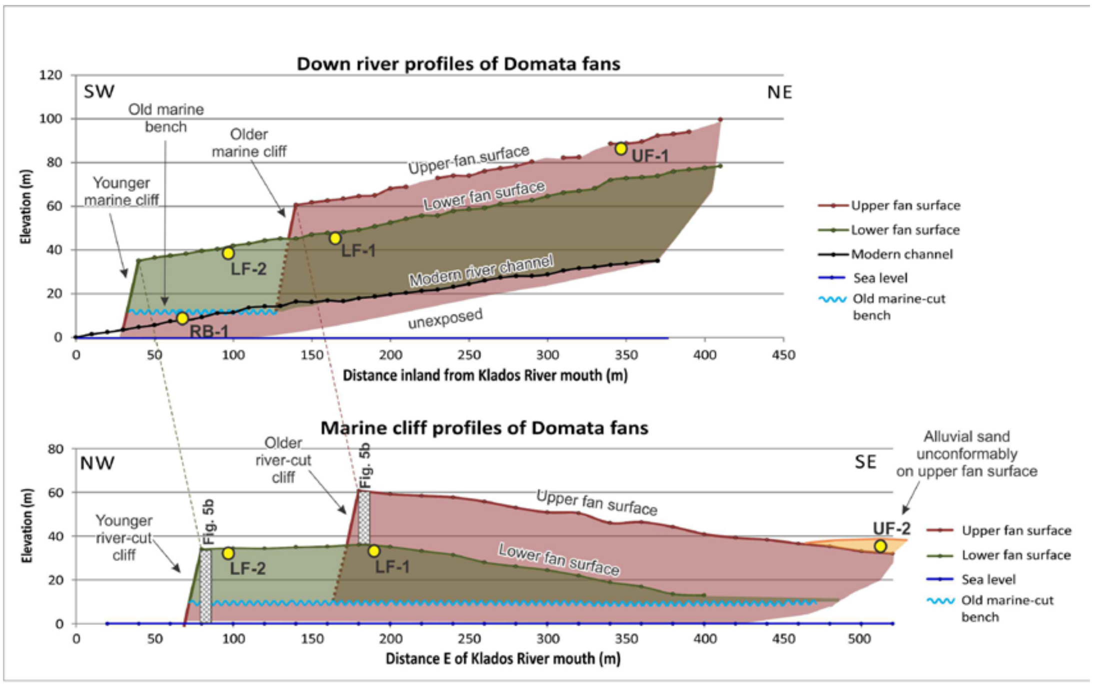


Figure 4



Down river profiles of Domata fans
SW
NE
Old marine bench
Older marine cliff
Younger marine cliff
Upper-fan surface
Lower fan surface
Modern river channel
unexposed
UF-1
LF-1
LF-2
RB-1
Elevation (m)
Distance inland from Klados River mouth (m)
Upper fan surface
Lower fan surface
Modern channel
Sea level
Old marine-cut bench
Marine cliff profiles of Domata fans
NW
SE
Older river-cut cliff
Younger river-cut cliff
Fig. 5b
Alluvial sand unconformably on upper fan surface
Upper fan surface
Lower fan surface
UF-2
LF-1
LF-2
Elevation (m)
Distance E of Klados River mouth (m)
Upper fan surface
Lower fan surface
Sea level
Old marine-cut bench

Figure 5a

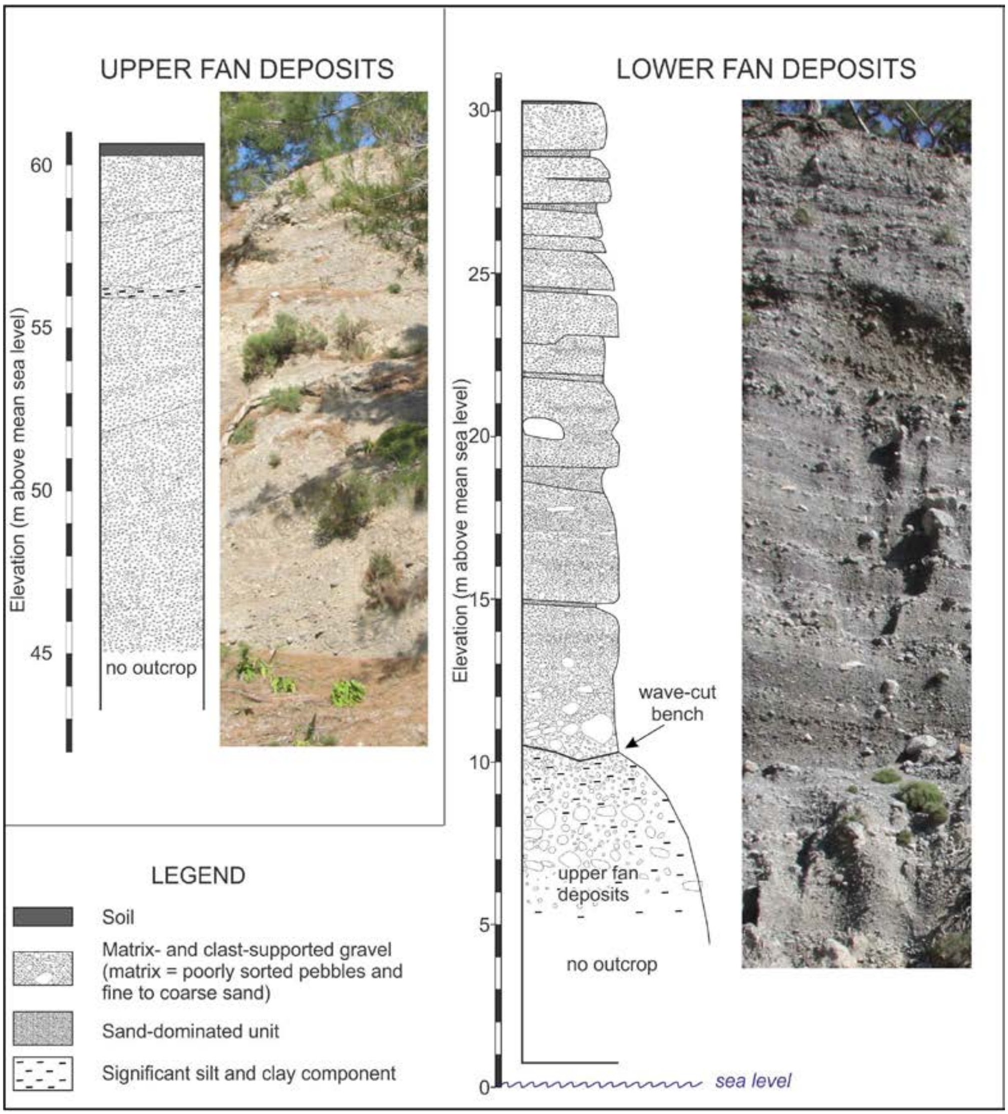

UPPER FAN DEPOSITS
LOWER FAN DEPOSITS
Elevation (m above mean sea level)
60
55
50
45
no outcrop
30
25
20
15
10
5
0
wave-cut
bench
upper fan
deposits
no outcrop
sea level
LEGEND
Soil
Matrix- and clast-supported gravel
(matrix = poorly sorted pebbles and
fine to coarse sand)
Sand-dominated unit
Significant silt and clay component

Figure 5b


a
Upper fan surface
Upper fan marine cliff
Lower fan surface
Lower fan marine cliff
Lower fan gravels
marine bench
Upper fan gravels

Figure 6a


b
elevated last interglacial? marine bench
upper and lower fan
deposits lapping
against basement rocks
rockfall debris post-dating
upper fan deposition
lower fan surface
abandoned alluvial
terrace, ?pre-c.365AD

Figure 6b

Figure 6c

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IRSL age distributions

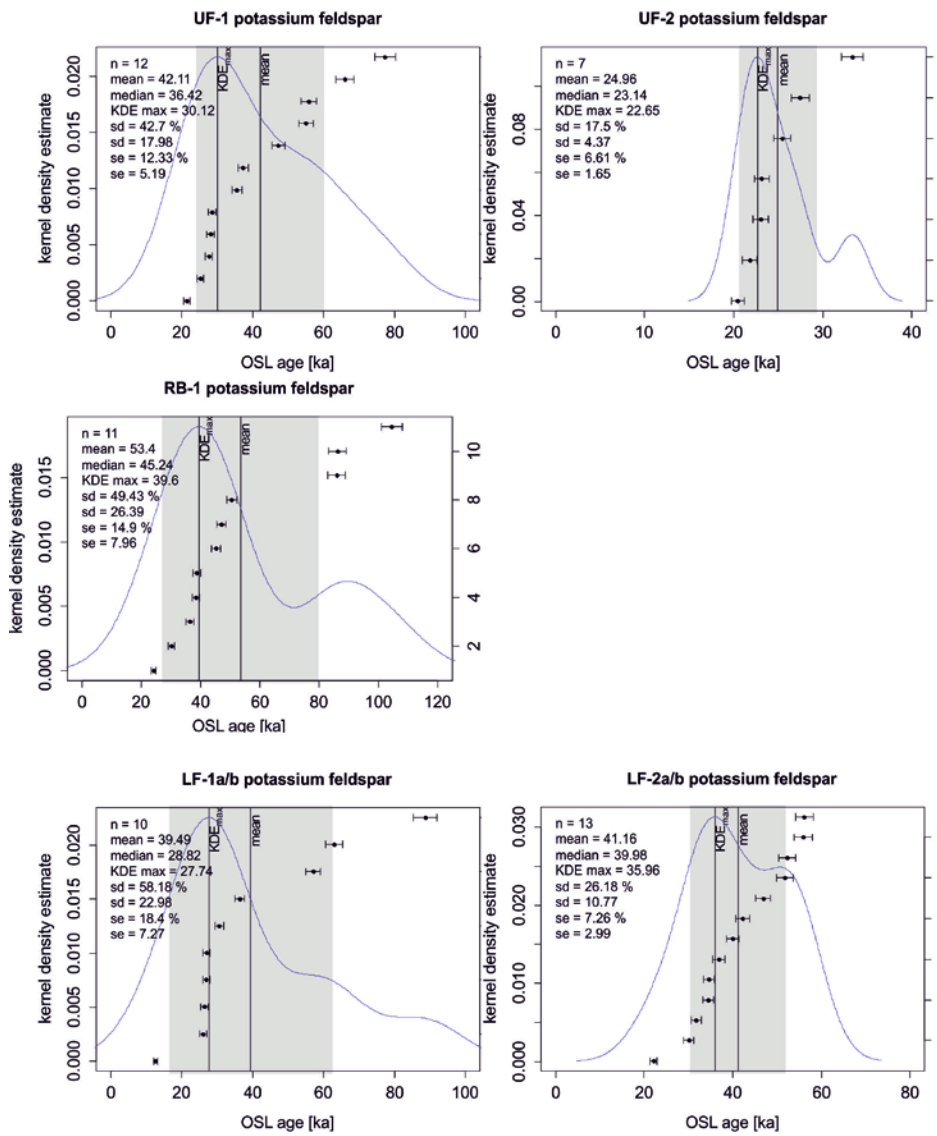


Figure 7

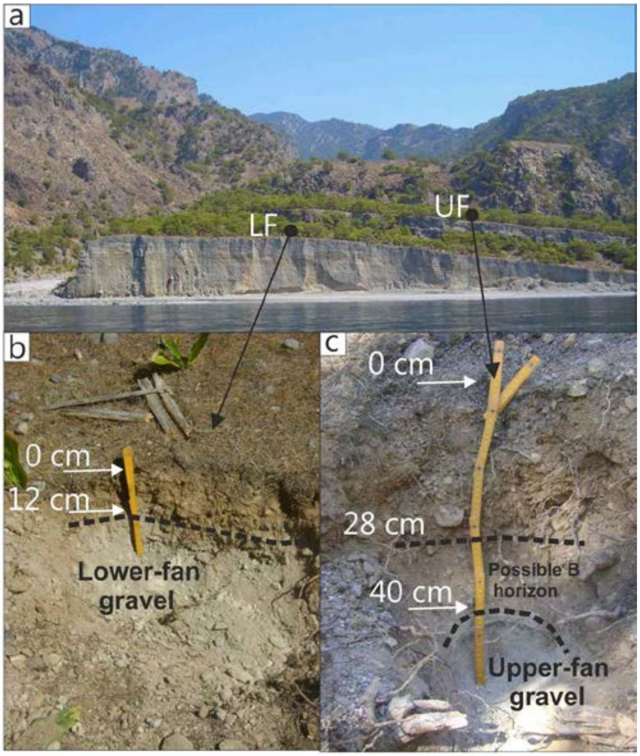
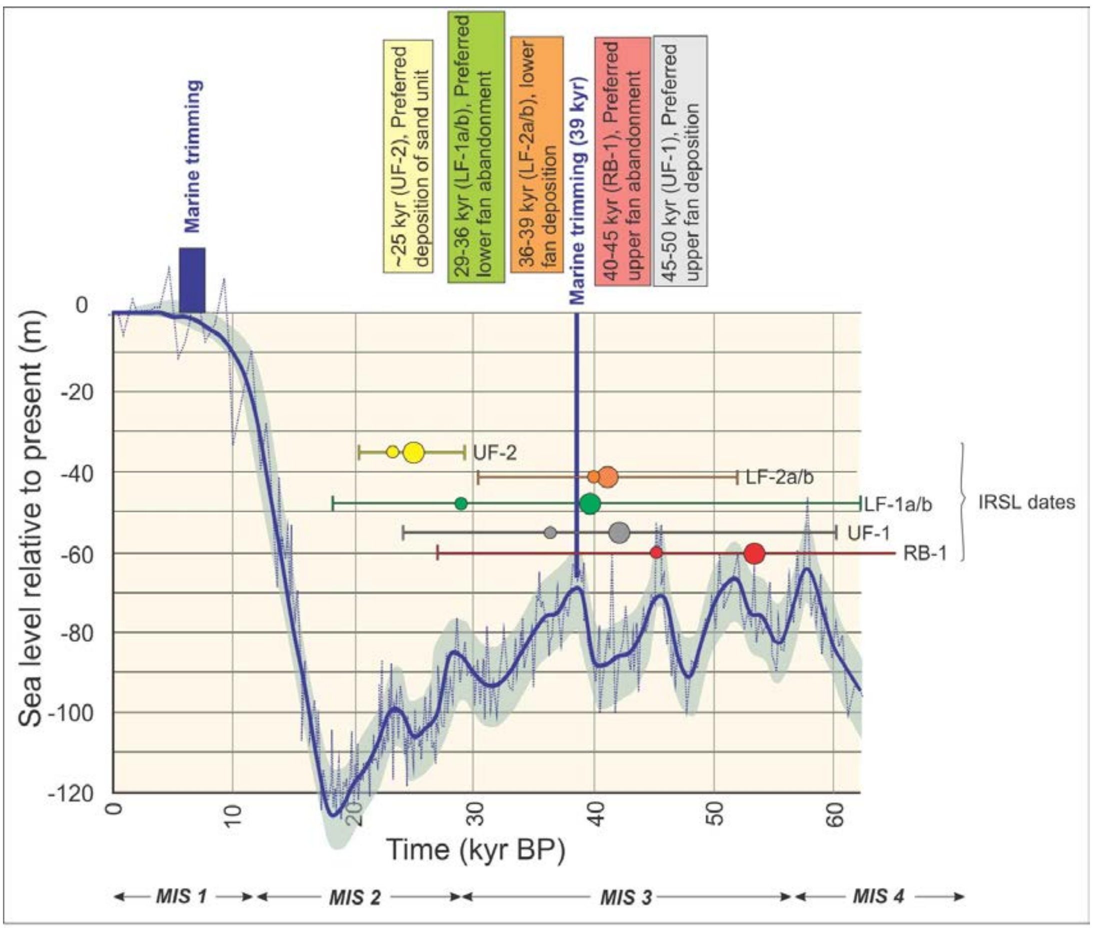

a
LF
UF
b
0 cm
12 cm
Lower-fan
gravel
c
0 cm
28 cm
Possible B
horizon
40 cm
Upper-fan
gravel

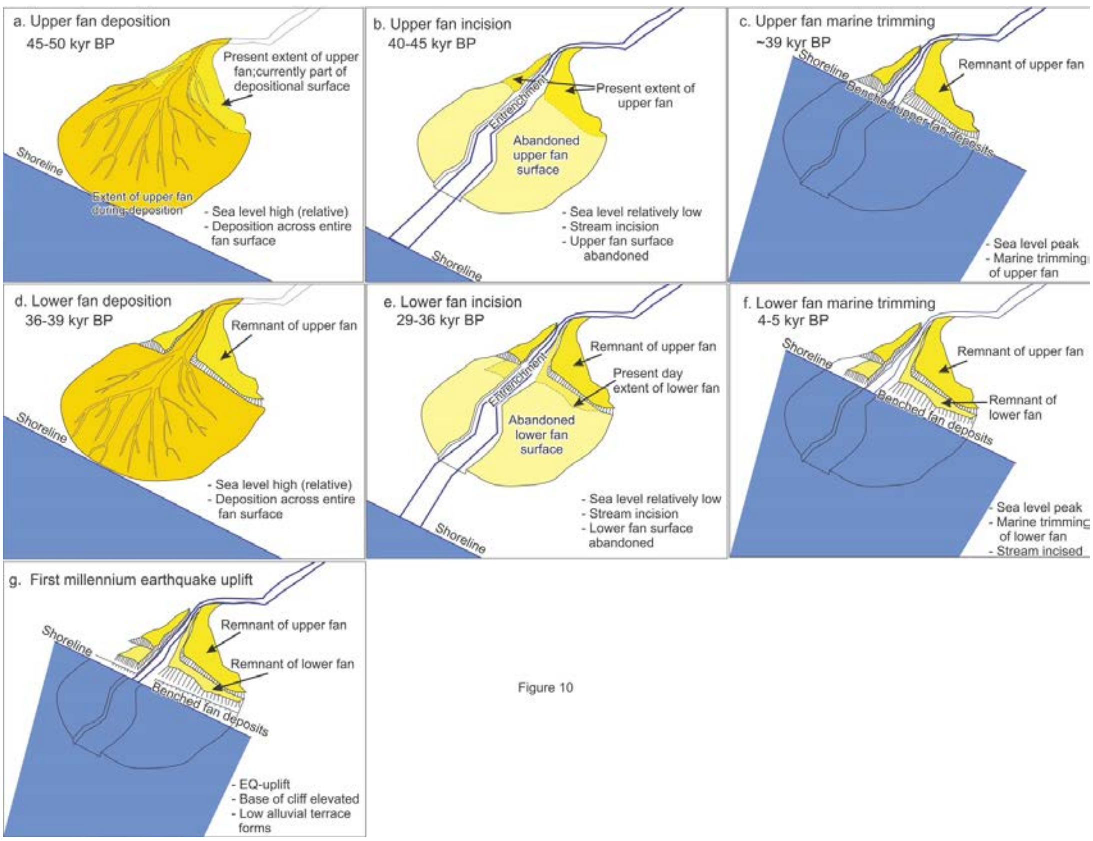
Figure 8

5



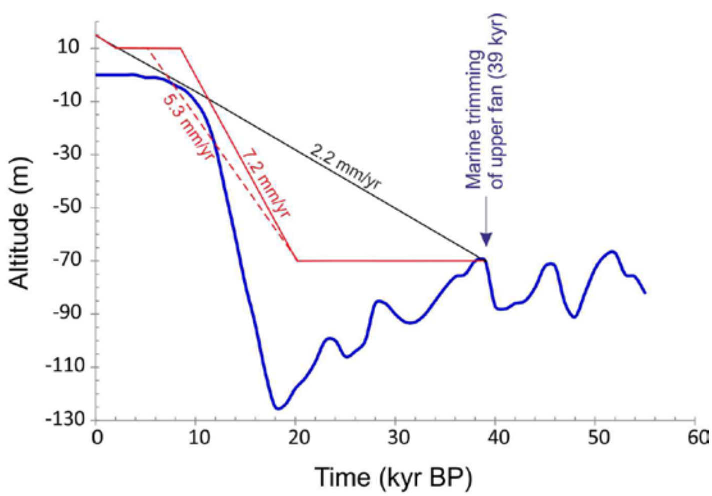
Marine trimming
~25 kyr (UF-2), Preferred deposition of sand unit
29-36 kyr (LF-1a/b), Preferred lower fan abandonment
36-39 kyr (LF-2a/b), lower fan deposition
Marine trimming (39 kyr)
40-45 kyr (RB-1), Preferred upper fan abandonment
45-50 kyr (UF-1), Preferred upper fan deposition
Sea level relative to present (m)
0
-20
-40
-60
-80
-100
-120
UF-2
LF-2a/b
LF-1a/b
UF-1
RB-1
IRSL dates
0
10
20
30
40
50
60
Time (kyr BP)
MIS 1
MIS 2
MIS 3
MIS 4

Figure 9



a. Upper fan deposition
45-50 kyr BP
Present extent of upper fan;currently part of depositional surface
Shoreline
Extent of upper fan during deposition
- Sea level high (relative)
- Deposition across entire fan surface
b. Upper fan incision
40-45 kyr BP
Entrenchment
Present extent of upper fan
Abandoned upper fan surface
- Sea level relatively low
- Stream incision
- Upper fan surface abandoned
Shoreline
c. Upper fan marine trimming
~39 kyr BP
Shoreline
Remnant of upper fan
Benched upper fan deposits
- Sea level peak
- Marine trimming of upper fan
d. Lower fan deposition
36-39 kyr BP
Remnant of upper fan
Shoreline
- Sea level high (relative)
- Deposition across entire fan surface
e. Lower fan incision
29-36 kyr BP
Entrenchment
Remnant of upper fan
Present day extent of lower fan
Abandoned lower fan surface
- Sea level relatively low
- Stream incision
- Lower fan surface abandoned
Shoreline
f. Lower fan marine trimming
4-5 kyr BP
Shoreline
Remnant of upper fan
Remnant of lower fan
Benched fan deposits
- Sea level peak
- Marine trimming of lower fan
- Stream incised
g. First millennium earthquake uplift
Shoreline
Remnant of upper fan
Remnant of lower fan
Benched fan deposits
- EQ-uplift
- Base of cliff elevated
- Low alluvial terrace forms

Figure 10



Altitude (m)
10
-10
-30
-50
-70
-90
-110
-130
0
10
20
30
40
50
60
Time (kyr BP)
5.3 mm/yr
7.2 mm/yr
2.2 mm/yr
Marine trimming
of upper fan (39 kyr)

Figure 11

Sample (depth)	Easting	Northing	Altitude (m)	Lab. no. (aliquot no.)	U	Th	K	Cosmic dose	Water cont.	Water cont.	Dose rate (D_0)	Equivalent dose (D_e) [Gy] **IRSL age [ka]**			Standard deviation	Standard error (g)
					[ppm]	[ppm]	[%]	[mGy/ka]	[%]	[%]	[Gy/ka]	Mean	Median	KDE max (f)	[%]	[%]
					(a)	(a)	(a)	(b)	(c)	(d)	(e)				**[ka]**	**[ka]**
UF-1 (0.3 m)	023° 54' 50.9"	35° 13' 47.8"	84	HUB-0423 (12)	0.46 ± 0.02	0.63 ± 0.06	0.11 ± 0.01	195 ± 20	1,1	3 ± 2	0.99 ± 0.07	41.7 Gy	36.0 Gy	29.8 Gy	42,7%	12,3%
												42.1 ka	**36.4 ka**	**30.1 ka**	**18.0 ka**	**5.2 ka**
UF-2 (1.1 m)	023° 54' 56.9"	35° 13' 35.9"	30	HUB-0424 (7)	1.06 ± 0.04	2.36 ± 0.13	0.53 ± 0.01	173 ± 17	5,1	5 ± 2	1.67 ± 0.11	41.7 Gy	38.6 Gy	37.8 Gy	17,5%	6,6%
												25.0 ka	**23.1 ka**	**22.7 ka**	**4.4 ka**	**1.7 ka**
RB-1 (28.0 m)	023° 54' 41.1"	35° 13' 44.5"	14	HUB-0425 (11)	0.84 ± 0.02	0.62 ± 0.05	0.15 ± 0.01	17 ± 2	1,6	3 ± 2	0.96 ± 0.06	51.3 Gy	43.4 Gy	38.0 Gy	49,4%	14,9%
												53.4 ka	**45.2 ka**	**39.6 ka**	**26.4 ka**	**8.0 ka**
LF-1a/b (0.28 m)	023° 54' 44.1"	35° 13' 45.1"	43	HUB-0426 (10)	0.67 ± 0.02	0.4 ± 0.05	0.09 ± 0.01	194 ± 19	0,3	3 ± 2	1.01 ± 0.07	39.9 Gy	29.1 Gy	28.0 Gy	58,2%	18,4%
												39.5 ka	**28.8 ka**	**27.7 ka**	**23.0 ka**	**7.3 ka**
LF-2a/b (0.24 m)	023° 54' 43.8"	35° 13' 41.9"	46	HUB-0427 (13)	0.73 ± 0.02	0.67 ± 0.04	0.1 ± 0.01	195 ± 20	1,3	3 ± 2	1.07 ± 0.07	44.0 Gy	42.8 Gy	38.5 Gy	26,2%	7,3%
												41.2 ka	**40.0 ka**	**36.0 ka**	**10.8 ka**	**3.0 ka**

(a) Uranium, thorium, and potassium contents were determined via high resolution gamma ray spectrometry (HPGe detector).
U-238: U-234 (53.2 keV), Th-234 (63.3 keV), Ra-226 (186.1 keV), Pb-214 (295.2 keV, 351.9 keV), Bi-214 (609.3 keV, 1120.3 keV, 1764.5 keV), Pb-210 (46.5 keV).
Th-232: Ac-228 (338.3 keV, 911.2 keV, 969.0 keV), Pb-212 (238.6 keV), Bi-212 (727.3 keV), Tl-208 (583.2 keV).
K-40: 1461.0 keV.
U-238 and Th-232: The arithmetic means of the activities of the above mentioned natural daughter products were used (± standard error).
The internal K content of the potassium feldspar was set to 12.5 ± 0.5 % (Huntley & Baril 1997).
(b) Cosmic dose rates were estimated regarding geographic position (35°N, 24°E), altitude and sampling depth.
(c) Water content of sediment samples in % of dry mass (oven dried for 24 h at 105 °C).
(d) Water content used for dose rate calculation.
(e) For coarse grain potassium feldspar an a-value of 0.15 ± 0.05 was assumed (Balescu & Lamothe 1994).
(f) KDE max: Maximum density of the kernel density estimation.
(g) Standard error of the mean: standard deviation devided by the square root of the number of measured aliquots.

Table 1