

Quaternary Research (2018), 1–6Copyright © University of Washington. Published by Cambridge University Press, 2018. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.
doi:10.1017/qua.2017.111

No evidence from the eastern Mediterranean for a MIS 5e double peak sea-level highstand

Barbara Mauz^{a,b}, Zhixiong Shen^c, Nouredine Elmejdoub^d, Giorgio Spada^e^aSchool of Environmental Sciences, University of Liverpool, Liverpool L69 7ZT, UK^bSchool of Geographie und Geologie, University of Salzburg, 5020 Salzburg, Austria^cDepartment of Marine Science, Coastal Carolina University, Conway, South Carolina 29528, USA^dInstitut Supérieur des Sciences et Techniques, Université de Gabès, Zrig, 6072, Gabès, Tunisia^eDipartimento di Scienze di Base e Fondamenti, Urbino University, 61029 Urbino, Italy

(RECEIVED June 3, 2017; ACCEPTED December 5, 2017)

Abstract

To understand past and future sea-level variability, it is important to know if during an interglacial the eustatic sea level is constant or oscillates by several meters around an average value. Several field sites within and outside the tropics have been interpreted to suggest such oscillations during Marine Oxygen Isotope Stage (MIS) 5e (129–116 ka). Here, we present our analysis of one such non-tropical site, Hergla, where a facies succession indicates two foreshore deposits above each other, previously interpreted as MIS 5e sea-level highstand amplified by a second rise. Our study, based on field, microfacies, and optical age Bayesian statistics shows a sea-level rise forming the upper foreshore strata that coincided with the global sea-level rise of the MIS 5a interstadial. The site does therefore not provide evidence for the MIS 5e double peak. We conclude from our analysis that the facies-based proxy is insensitive to small-scale sea-level oscillation. Likewise, uncertainties associated with age estimates are too large to robustly infer a short-term sea-level change.

Keywords: Last Interglacial; Sea Level; Carbonate Sediments; Mediterranean

INTRODUCTION

Significant uncertainties exist when projecting modern sea-level rise into the future. These are partly caused by the challenge of reconstructing the past dynamics of large ice sheets on millennial time scales, which is required to have confidence in the projections. It is generally accepted that short-term climate excursions can occur (e.g., Bakker et al., 2014) during an otherwise stable climate period. Such climate variations could have led to ice-mass and sea-level oscillation during the last interglacial (LIG; 129–116 ka), but the magnitude of the oscillation remains elusive. The global LIG sea level could have remained stable, accentuated in a second, rapid rise at the end of a period of stability (Hearty et al., 2007; Blanchon et al., 2009; O’Leary et al., 2013), or oscillated repeatedly or twice (Chen et al., 1991; Stein et al., 1993; Israelson and Wohlfahrt, 1999; Blanchon and Eisenhauer, 2001). We note the small scale of the oscillation (<6 m) and ask to what extent the sea-

level proxy can resolve such oscillations where the proxy’s qualification should be a function of sea-level sensitivity and datum and age uncertainty. The question is challenging because the reconstruction of the LIG global sea level suffers from the dilemma that non-eustatic glacio-isostatic adjustment (GIA) contribution to sea-level change cannot be predicted for a specific location unless the ice history is known, but this is what the proxy is trying to reconstruct. To circumvent this problem, sites are investigated where the non-eustatic component is minimal. Hergla, situated on the North African coast, does satisfy this requirement (Mauz et al., 2015). It is an often-cited sea-level site (e.g., Hearty et al., 2007; Kopp et al., 2009) outside the tropics that seems to show a highstand amplified by a second rise after a brief drop. Focusing on the two-peak hypothesis, we show that the two-peak interpretation changes drastically when the study integrates stratigraphy, sediment architecture, and high-resolution chronology.

The two-peak hypothesis during MIS 5e

Some authors (e.g., O’Leary et al., 2013; Hansen et al., 2016) argue for a second rise occurring after the sea level has been

*Corresponding author at: School of Environmental Sciences, University of Liverpool, Liverpool L69 7ZT, UK; School of Geographie und Geologie, University of Salzburg, 5020 Salzburg, Austria. E-mail address mauz@liverpool.ac.uk (B. Mauz).

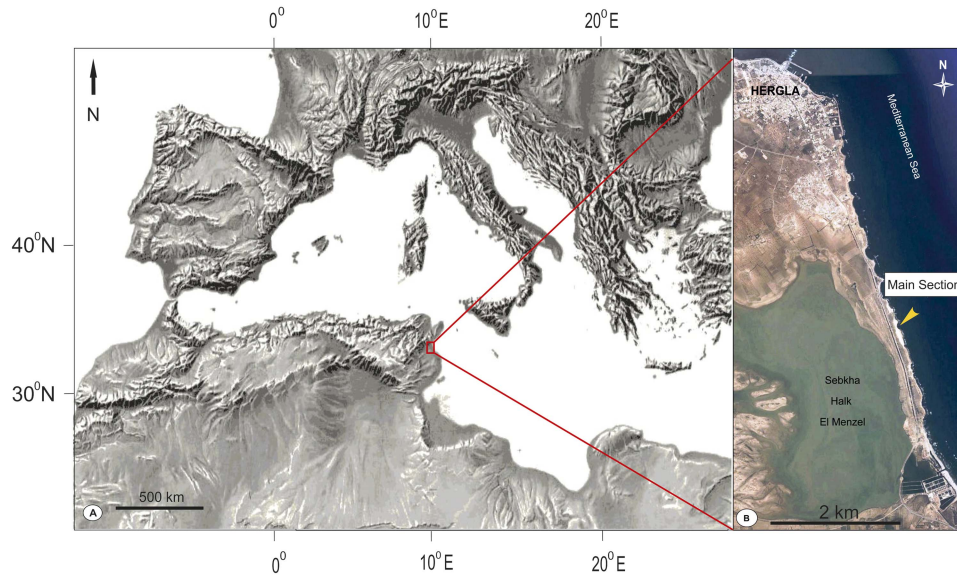


Figure 1. (color online) The location of the Hergla site.

60 stable for several millennia. Their evidence are erosional surfaces
 61 and/or notches in reefs crests behind the wave-cut platform at
 62 Bahamas (Neumann and Hearty, 1996), western Australia
 63 (O’Leary et al., 2013) and Yucatán (Blanchon et al., 2009). The
 64 geomorphic feature is supported by the regional extend of the
 65 erosional surface – a compelling stratigraphic evidence for two
 66 separate reef units in the northern part of the Caribbean (Frujtier
 67 et al., 2000). Others found field evidence for a sea-level
 68 jump (Bahamas; Chen et al., 1991; Barbados; Blanchon and
 69 Eisenhauer, 2001) or, on the contrary, weak stratigraphic evi-
 70 dence (Seychelles; Israelson and Wohlfahrt, 1999) contradicting
 71 earlier work on the same Seychelles reef (Montaggiore and
 72 Houg, 1988). Ideally, bimodal age distribution is found for two
 73 reef units. Apart from data published by Stein et al. (1993; Huon

Peninsula, reef complex VII), however, bimodal age distribution
 does not emerge from the age data published probably due to the
 diagenetic overprint limiting both accuracy and precision of age
 estimates. ^{230}Th age plots generated by Melinda-Elizalde (2013),
 however, clearly show the multi-peak pattern of the LIG sea
 level even after probabilistic Monte Carlo simulation of data that
 should have masked millennial-scale oscillations.

SITE DESCRIPTION

The Hergla site (Fig. 1) is a 2-km-long cliff situated on a
 microtidal coast (20–50 cm tidal range). The cliff constitutes
 a former coastal barrier anchored on Pliocene hills. The main
 section of the barrier (Fig. 2) shows sediment succession of

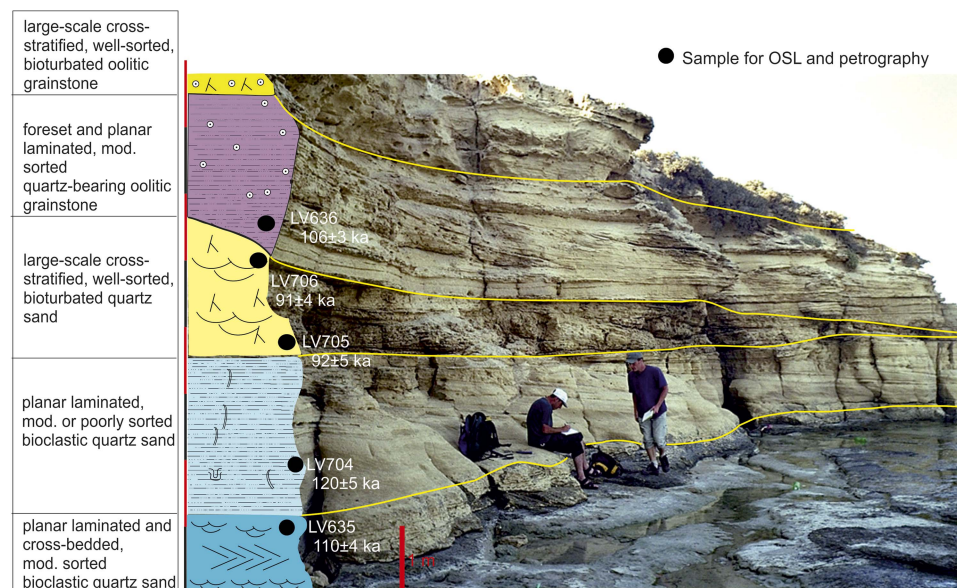


Figure 2. (color online) The main section at Hergla. Deposits are classified following the results from thin section analysis. Dots and numbers indicate sample position and OSL ages. Photo courtesy of E. Davaud.

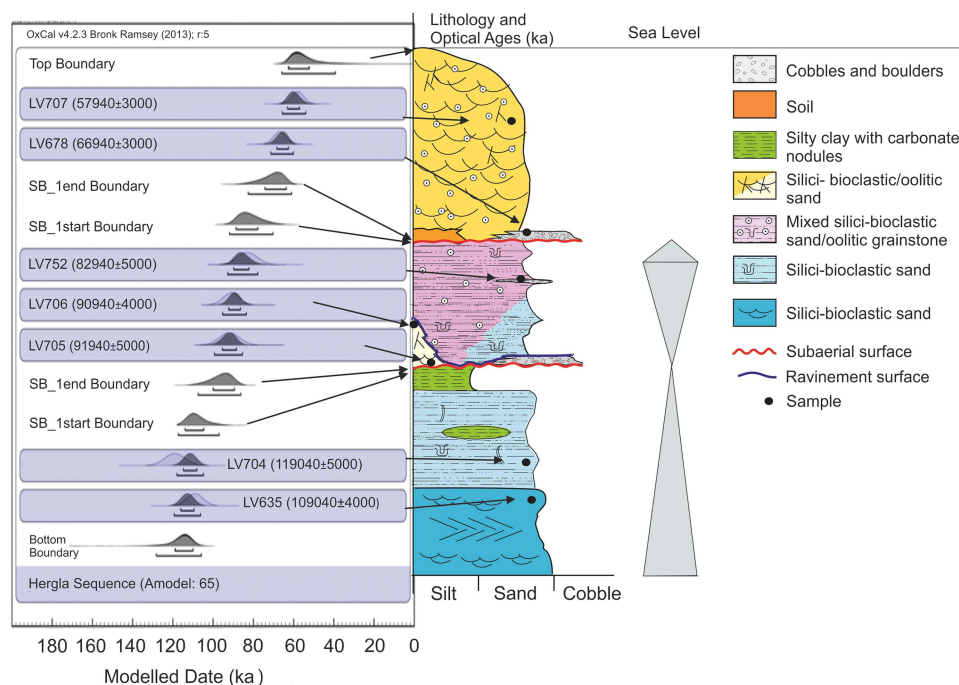


Figure 3. Generalized vertical succession of the Hergla cliff and Bayesian model of the optical ages using the OxCal program (Bronk Ramsey, 2013). Optical ages (*likelihoods*) are in light gray and the modeling results (*posteriors*) in dark gray. Blue bands highlight likelihoods based on an optical age, white band are likelihoods inferred from the respective upper and lower bounding ages. For details of age data and facies correlation, see Supplementary Material. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

86 mixed carbonate-siliciclastic planar laminated and cross-
 87 bedded moderately sorted sand, followed by laminated and
 88 foreset bedded oolitic grainstone. The stratigraphic succession,
 89 including stratigraphically significant surfaces, is summarized
 90 in Figure 3 (see also Supplementary Material). According to
 91 Hearty et al. (2007, p. 2099), the top of the lower aeolian
 92 deposit is a "weathering surface" and is associated with a sea

level "fall to near or below present level (0 m)." The surface
 would allow to postulate a brief drop followed by a second,
 higher than the previous, sea-level highstand during MIS 5e
 (Hearty et al., 2007). In our correlation panel (Supplementary
 Fig. S2), the aeolian deposit is in juxtaposition to the lagoonal
 deposit, suggesting the shoreline was situated seaward at an
 unknown distance to the dune. The dune's top is a buried
 subaerial surface that is spatially limited to the central and
 northern part of the cliff, where the exposure of the bay to the
 northeast allowed aeolian sand to accumulate.

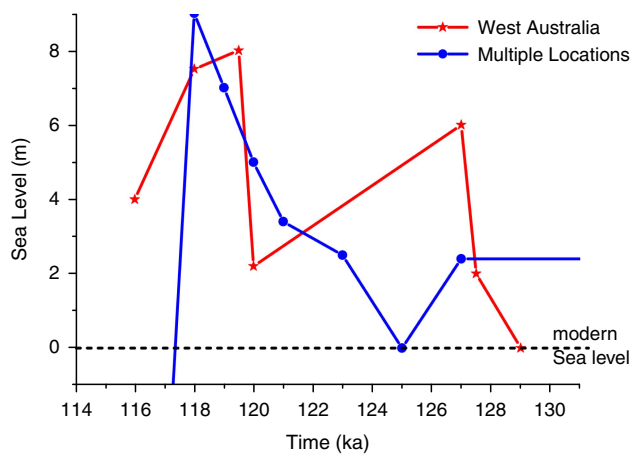


Figure 4. (color online) Last interglacial sea-level oscillations reported from two studies: O'Leary et al. (2013) for the Western Australia site (24°S, 114°E); Hearty et al. (2007) for multiple locations including Bermuda, Barbados, Bahamas, Hawaii, W-Australia, and the non-reef site in the Mediterranean. For the sake of clarity, no error bars are depicted. For all data, see Supplementary Fig. S1.

METHODS

We revisited the Hergla site aiming at approximating the ages of stratigraphic boundaries, constraining the stratigraphically informed depositional sequence of dated strata, and at improving the accuracy of age estimates. The ~2-km-long lateral cliff exposure was mapped and logged in detail. Samples were collected at key points in the succession (Fig. 3) for optical stimulated luminescence (OSL) dating and for further describing the sediments and their depositional environment through thin section microscopy. Sea-level index points (SLIPs) were established following Shennan (2015), where the midpoint of the foreshore deposits and the top of the lagoon are the reference water levels; an average tidal range of 0.3 ± 0.2 m and the square-root rule are used for error calculation. Stratigraphic boundaries were identified following standard concepts of sequence stratigraphy (e.g., Catuneanu et al., 2011), where a subaerial surface is the land behind the shoreline

120 and the ravinement surface is an erosional surface formed by
121 wave action while the sea level rises.

122 Because quartz OSL tends to underestimate ages beyond
123 ca. 80 ka (Shen and Mauz, 2011), extended dose-recovery test
124 were performed to semi-quantitatively assess potential age
125 underestimation caused by variable saturation doses of natural
126 sedimentary quartz. The ages of the OSL samples, indicated in
127 kilo years (ka) after sampling datum (AD2015), and key strati-
128 graphic boundaries were modeled with a Bayesian approach.
129 This statistical model takes OSL age data as a probability
130 distribution alongside stratigraphic information to produce age
131 estimates of the OSL samples and of key points in the strati-
132 graphy for which no age information is available (e.g., strati-
133 graphic boundaries). The Agreement Index is calculated for
134 each sample and for the whole model to evaluate confidence of
135 the modeling results, where a value >60% corresponds to
136 about >95% probability of a chi-squared distribution (Bronk
137 Ramsey and Lee, 2013). To solve an apparent age inversion
138 (see Fig. 2), multiple Bayesian runs were performed until the
139 >60% Agreement Index was obtained (for details see
140 Supplementary Material). Ages of MIS 5 substages were
141 adopted from Martinson et al. (1987).

142 RESULTS

143 The result of optical dating, Bayesian modeling, and facies
144 correlation is shown in Fig 3. The succession starts with a
145 package of siliciclastic deposits of shoreface, foreshore, and
146 lagoonal environment. The second sediment package is
147 composed of siliciclastic, partly oolitic foreshore, aeolian
148 oolitic dune deposits, two gravel layers, and soil. The base of
149 the lower package, dated to 110 ± 4 ka and 120 ± 5 ka is not
150 exposed; its top is the top of the lagoon bounded by a sub-
151 aerial surface, which lasted from 107 ± 10 ka to 97 ± 11 ka
152 (Fig. 3). An aeolian dune bed and a gravel layer bury this
153 surface and both are, alongside the lagoonal deposit, trun-
154 cated by the transgressive surface. The latter surface forms
155 the base of the second, 2- to 3-m-thick package dated to
156 86 ± 4 ka and 106 ± 3 ka that is bounded at the top by a sub-
157 aerial surface. This surface lasted from 81 ± 9 ka to
158 72 ± 11 ka before it was covered by gravel bed, soil, and
159 aeolian dune. The lower part of the cliff represents a shallow-
160 ing upward sequence subsequently overlain by an incomplete
161 transgressive sequence. The OSL data show negligible age
162 underestimation for ages above 80 ka. The multiple Bayesian
163 runs led to the rejection of the sample LV636 (106 ± 3 ka). See
164 Supplementary Material for details of data.

165 DISCUSSION

166 Evidence for two peaks during MIS 5e

167 Following the stratigraphy and corresponding geochrono-
168 logical intervals (Fig. 3), the succession shows two incom-
169 plete sequences, each topped by a subaerial surface. The
170 lower sequence's top is the top of the lagoonal deposit, which
171 is in some bays marked by beach pebbles and a foredune.

This surface lasted around 107–97 ka, covering the timing of
the two separate global sea-level drops of the MIS 5d and 5b
stadials. The upper sequence's top is the top of the upper
foreshore which is marked by soil, foredune, and beach
pebbles. The timing of this upper subaerial surface coincides
with the global sea-level fall after this highstand. The upper
foreshore deposit, embedded by the two surfaces, starts with a
transgressive surface forming above existing beach and dune
deposits (see Fig. 3 for illustration of surfaces). The timing of
this upper foreshore coincides with the global sea-level rise of
MIS 5a at around 85 ka. This clearly shows that Hergla does not
provide evidence for a second sea-level rise during MIS 5e.

The global highstand of MIS 5c (ca. 110 ka) is missing in
the succession; the sample that would represent this time
interval (LV636, 106 ± 3 ka) was rejected as a result of
Bayesian modeling (for details see Supplementary Material).
This implies that at Hergla the MIS 5c sea-level peak
remained below 0 m, allowing the lowstands of MIS 5d and
MIS 5b to coalesce in one subaerial surface, the regional
extent of which is documented in earlier studies (e.g.,
Paskoffe and Sanlaville, 1983). During the subsequent
transgression, the surface was reworked to a ravinement
surface, eroding terrestrial material such as carbonate crust,
soil, and colluvium.

Our interpretation differs from other authors (e.g., Hearty
et al., 2007). They believed the sediment succession is con-
tinuous and the subaerial surface between the two foreshore
deposits lasted around 8 ka. More importantly, given limited
time available, the two-peak hypothesis requires a rapid sea-
level drop of several meters at the end of MIS 5e (Fig. 4).
Such an extremely rapid fall seems physically impossible to
achieve through ice growth only.

The quality of facies-based sea-level proxies

Key features to identify shoreline migration in a geological
record are vertical facies succession and surface. This should
be supported by bi- or multi-modal distribution of ages,
which, in turn, are in-line with the stratigraphy. The vertical
uncertainty of the sea-level index point deduced from these
two criteria must be smaller than the ~3 m uncertainty range
of the LIG sea level (Kopp et al., 2009; Dutton et al., 2015) to
be a robust feature.

Facies successions allow localizing the position of the
shoreline and facies analysis of fining or coarsening upward
sequence allows inference of the sea-level trend. However,
most coastal landforms evolve into a well-preserved clastic
deposit under a positive sediment budget, which occurs when
sea level falls because more coastal plain sediment is avail-
able for littoral transport during regression than during
transgression (Lobo and Ridente, 2013; Mauz et al., 2013).
On some coasts, the stratigraphic dominance of the falling
stage is further enhanced by the solid-earth response to water
load in the far field, leading to coastal sea-level fall.

Surfaces are created by waves (ravinement) or by subaerial
processes (weathering, dissolution, erosion, or deposition of
terrestrial sediment). The example of Hergla shows that, as

172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226

the sea returns, the subaerial surface is transformed to a ravinement surface, a process that is likely to obliterate the signature of the pre-existing subaerial exposure.

Thus, the facies-based sea-level proxy is likely to be incomplete or too poorly preserved to show small-scale sea-level change. Moreover, the uncertainties associated with a sea-level datum often exceed 3 m and 8 ka, a resolution required to identify the two peaks at Hergla.

The sensitivity of the proxy to sea-level change

A certain amount of sea-level rise related to glacial meltwater should be detected everywhere on earth, albeit at different times and with different magnitudes due to the geographically variable effects of glacio-isostatic adjustment processes (e.g., Lambeck et al., 2012). The response rate of the proxy relative to the rate of sea-level change is key to recording the change. Clastic coasts vary its sensitivity due to local morphodynamics in addition to physical accommodation. Experiments on sea-level signal preservation suggest that internal and external controls on the stratigraphic record cannot be separated (Li et al., 2016) below a certain threshold. In addition, where the stratigraphic discontinuity is not a regional feature, numerical modeling (e.g., Prince and Burgess, 2013) is required to test the ability of the particular proxy to record small-scale sea-level change.

The analysis of Melinda-Elizalde (2013), however, shows that ^{230}Th data are able to robustly record a 2 m sea-level jump in reefs. This seems to show that, despite uncertainties associated with diagenesis, the ^{230}Th ages are more sensitive to the change than the clastic stratigraphic record.

CONCLUSION

Hergla is a remarkable site, not only because it shows a stack of two foreshore strata above each other, but also because it reveals how reworking during transgression can obliterate evidence of sea-level fall. Its chronostratigraphy does not confirm a MIS 5e double peak but confirms the two sea-level highstands during MIS 5e and MIS 5a. These findings from a mid-latitude site do not preclude the evidence for the MIS 5e sea-level jump elsewhere. Such sites, for instance in the Caribbean, deserve reconsideration, bearing in mind preservation potential of strata and diagenetic overprint of facies. Moreover, the geographically variable GIA effects and millennial-scale climate oscillations with contrasting timings in both hemispheres should be taken into account. Notwithstanding such an elucidated approach, inferring a small global sea-level signal from stratigraphic records that are spatially limited, remains a challenge.

ACKNOWLEDGMENTS

Mauz and Elmejdoub acknowledge the support of Leverhulme Trust International Network IN-2012-113 for “A New Network for Research into Past Shifts of the Mediterranean-Saharan Climate Boundary.”

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit <https://doi.org/10.1017/qua.2017.111>

REFERENCES

- Bakker, P., Masson-Delmotte, V., Martrat, B., Charbit, S., Renssen, H., Groeger, M., Krebs-Kanzow, U., Lohman, G., Lunt, D.J., Pfeiffer, M., Phipps, S.J., Prange, M., Ritz, S.P., Schulz, M., Stenni, B., Stone, E.J., Varma, V., 2014. Temperature trends during the Present and Last Interglacial periods - a multi-model-data comparison. *Quaternary Science Reviews* 99, 224–243.
- Blanchon, P., Eisenhauer, A., 2001. Multi-stage reef development on Barbados during the Last Interglaciacion. *Quaternary Science Reviews* 20, 1093–1112.
- Blanchon, P., Eisenhauer, A., Fietzke, J., Liebetrau, V., 2009. Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. *Nature* 458, 881–884.
- Bronk Ramsey, C., Lee, S., 2013. Recent and planned developments of the program OxCal. *Radiocarbon* 55, 720–773.
- Catuneanu, O., Galloway, W.E., Kendall, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E., 2011. Sequence Stratigraphy: Methodology and Nomenclature. *Newsletter on Stratigraphy* 44, 173–245.
- Chen, J.H., Curran, H.A., White, B., Wasserburg, G.J., 1991. Precise chronology of the last interglacial period: ^{234}U - ^{230}Th data from fossil coral reefs in the Bahamas. *Geological Society of America Bulletin* 103, 82–97.
- Dutton, A., Carlson, A.E., Long, A.J., Milne, G.A., Clark, P.U., DeConto, R., Horton, B.P., Rahmsdorf, S., Raymo, M.E., 2015. Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science* 349, aaa4019. <http://dx.doi.org/10.1126/science.aaa4019>.
- Frujtier, C., Elliott, T., Schlager, W., 2000. Mass-spectrometric ^{234}U - ^{230}Th ages from the Key Largo Formation, Florida Keys, United States: constraints on diagenetic age disturbance. *Geological Society of America Bulletin* 112, 267–277.
- Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., et al., 2016. Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous. *Atmospheric Chemistry and Physics* 16, 3761–3812.
- Hearty, P.J., Hollin, J.T., Neumann, A.C., O’Leary, M.J., McCulloch, M., 2007. Global sea-level fluctuations during the Last Interglaciacion (MIS 5e). *Quaternary Science Reviews* 26, 2090–2112.
- Israelson, C., Wohlfahrt, B., 1999. Timing of the Last-Interglacial High Sea Level on the Seychelles Islands, Indian Ocean. *Quaternary Research* 51, 306–316.
- Kopp, R.E., Simons, F.J., Mitrovica, J.X., Maloof, A.C., Oppenheimer, M., 2009. Probabilistic assessment of sea level during the last interglacial stage. *Nature* 462, 863–867.
- Li, Q., Yu, L., Straub, K.M., 2016. Storage thresholds for relative sea-level signals in the stratigraphic record. *Geology* 44, 179–182.
- Lambeck, K., Purcell, A., Dutton, A., 2012. The anatomy of interglacial sea levels: The relationship between sea levels and ice volumes during the Last Interglacial. *Earth and Planetary Science Letters* 315–316, 4–11.

- 337 Lobo, F.J., Ridente, D., 2013. Stratigraphic architecture and spatio-
 338 temporal variability of high-frequency (Milankovitch) deposi-
 339 tional cycles on modern continental margins: An overview.
 340 *Marine Geology* 352, 215–247.
- 341 Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C.,
 342 Shackleton, N.J., 1987. Age dating and orbital theory of the ice
 343 ages: Development of a high-resolution 0–300,000 year chrono-
 344 stratigraphy. *Quaternary Research* 27, 1–29.
- 345 Mauz, B., Hijma, M., Amorosi, A., Porat, N., Gallili, E.,
 346 Bloemendal, J., 2013. Aeolian beach ridges and their significance
 347 for climate and sea level: concept and insight from the Levant
 348 coast (East Mediterranean). *Earth Science Reviews* 121, 31–54.
- 349 Mauz, B., Ruggieri, G., Spada, G., 2015. Terminal Antarctic melting
 350 inferred from a far-field coastal site. *Quaternary Science Reviews*
 351 116, 1–11.
- 352 Melinda-Elizalde, M., 2013. A global compilation of coral sea-level
 353 benchmarks: Implications and new challenges. *Earth and*
 354 *Planetary Science Letters* 362, 310–318.
- 355 Montaggiori, L.F., Houg, C.T., 1988. The last interglacial high sea
 356 level in the Granitic Seychelles, Indian Ocean. *Palaeogeography,*
 357 *Palaeoclimatology, Palaeoecology* 64, 79–91.
- 358 Neumann, A.C., Hearty, P.J., 1996. Rapid sea-level changes at the
 359 close of the last interglacial (substage 5e) recorded in Bahamian
 360 island geology. *Geology* 24, 775–778.
- 385
- O’Leary, M.J., Hearty, P.J., Thompson, W.G., Raymo, M.E.,
 361 Mitrovica, J.X., Webster, J.M., 2013. Ice sheet collapse following
 362 a prolonged period of stable sea level during the last interglacial.
 363 *Nature Geoscience* 6, 796–800.
- 364 Paskoff, R., Sanlaville, P., 1983. Les côtes de la Tunisie. Variations
 365 du niveau marin depuis le Tyrrénien. Collection Maison de
 366 l’Orient, Lyon, France.
- 367 Prince, G.D., Burgess, P.M., 2013. Numerical modelling of falling-
 368 stage topset aggradation: Implications for distinguishing between
 369 forced and unforced regressions in the geological record. *Journal*
 370 *of Sedimentary Research* 83, 767–781.
- 371 Shen, Z., Mauz, B., 2011. Estimating the equivalent dose of late
 372 Pleistocene fine silt quartz from the Lower Mississippi Valley
 373 using a common OSL growth curve. *Radiation Measurements* 46,
 374 649–654.
- 375 Shennan, I., 2015. Handbook of sea-level research: framing research
 376 questions. In: Shennan, I., Long, A.J., Horton, B.P. (Eds.),
 377 *Handbook Of Sea-Level Research*. John Wiley & Sons, Ltd.,
 378 Chichester, UK, pp. 3–25.
- 379 Stein, M., Wasserburg, G.J., Aharon, P., Chen, J.H.,
 380 Zhu, Z.R., Bloom, A., Chappell, J., 1993. TIMS U-series
 381 dating and stable isotopes of the last interglacial event in
 382 Papua New Guinea. *Geochimica et Cosmochimica Acta* 5,
 383 2541–2554.
- 384