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Walker, RT

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Rapid mantle-driven uplift along the Angolan margin in the late Quaternary

R. T. Walker¹, M. Telfer², R. L. Kahle³, M. W. Dee⁴, B. Kahle³, J.-L. Schwenninger⁴ R. A. Sloan³, A. B. Watts¹

1) Department of Earth Sciences, Oxford University, South Parks Road, Oxford, OX1 3AN

2) School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth, Devon, PL4 8AA

3) Department of Geological Sciences, University of Cape Town, Rondebosch 7701, South Africa

4) Research Laboratories for Archaeology and the History of Art, Oxford University, South Parks Road, Oxford,

It is recognized that mantle flow can cause the Earth's surface to uplift and subside, but the rates and durations of these motions are, in general, poorly resolved due to the difficulties in making measurements of relatively small vertical movements (hundreds of metres) over sufficiently large distances (~1000 km). Here we examine the effect of mantle upwelling through a study of Quaternary uplift along the coast of Angola. Using both optically-stimulated luminescence on sediment grains, and radiocarbon dating of fossil shells, we date a 25 m coastal terrace at ~45 ka, when sea level was ~75 m lower than today, indicating a rapid uplift rate of 1.8-2.6 mm/yr that is an order of magnitude higher than previously obtained rates averaged over longer time periods. Automated extraction and correlation of coastal terrace remnants from digital topography uncovers a symmetrical uplift with diameter of >1000 km. The wavelength and relatively short timescale of the uplift suggest it is associated with a mantle process, possibly convective upwelling, and that the topography may be modulated by rapid short-lived pulses of mantle-

derived uplift. Our study shows that stable continental regions far from the effects of glacial rebound may experience rapid vertical displacements of several millimetres per year.

It is a long held view that sea-level changes along mature continental margins, far from tectonic activity and glacial loading, represent global (eustatic) variations (e.g.¹). However, there is a growing realization that vertical motions at the Earth's surface may occur in the absence of lithospheric (plate tectonic) processes, and are instead driven by forces introduced by convection in the sub-lithospheric mantle (e.g.²). Many studies have focused on Africa, which has a long-wavelength topography composed of broad swells and basins, occurring both within the continental interior and at its margins (e.g. Fig. 1a-b)³. However, there is a range of interpretations of the origin of these topographic swells, from 'dynamic' causes of mantle upwelling, through flank uplift to adjoining subsiding basins, to the isostatic response to near surface density contrasts (e.g.²⁻⁹). The remaining challenge for understanding the origin of these events is the quantification of their rates, durations, and extents.

We focus on the coastline of Angola (Fig. 1c). Cenozoic uplift is recorded in the large-scale topography and drainage patterns, in offshore sedimentation and denudation, and in the emergence of Quaternary marine and coastal sediments^{7; 8; 10; 11}. Much of central Angola is occupied by the Bié plateau, a dome-shaped range of ~1000 km diameter, rising to an elevation of >2500 m (Fig. 1c). Inverse modelling of river profiles on the plateau flanks yield two uplift 'pulses', with rates of up to 0.5 mm/yr, and with durations of ~1 Ma⁸. Pulses of tilting and denudation in the mid-Oligocene (30-35 Ma) and post-Pliocene are also observed in seismic reflection profiles across the Angolan continental shelf⁷.

Pleistocene coastal uplift is demonstrated by Gilbert-type delta systems adjacent to the Kwanza and Benguela rivers (Fig. 1c). Coastal terraces representing late Quaternary uplift are observed adjacent to the Bié dome and the offshore regions that preserve evidence of Cenozoic denudation^{7; 8; 10; 11}. The marine terraces extend smoothly for long distances¹⁰ suggesting that active faulting, salt movements, and sediment loading are not the ultimate cause, and that deep, i.e. mantle, processes may instead be responsible. Existing age data for the terraces have been used to suggest relatively rapid uplift, accelerating from ~0.3 mm/yr at ~100 ka to 1.7 mm/yr over the last ~30 ka^{10,11}. This is an order of magnitude higher than longer-term uplift rates from this region^{7,8}, or from most^{12,13}, though not all^{14,15}, studies of long wavelength topography elsewhere. The existing estimates of late Pleistocene uplift in Angola are based primarily on unreliable dating methods, demanding skepticism and careful documentation. Here, we examine the late Pleistocene rates and extent of uplift inferred from coastal terraces through a program of age dating and regional correlation.

Pleistocene terraces of the Angolan coast

The Angolan coastal terraces were first recognized and described by¹⁶. Near Benguela they are observed up to ~250 m, including several prominent intermediate levels^{10; 11} (Fig. 1d and Supplementary Figure 1). The 120 m terrace contains Acheulian lithics and has a single U-series age of 200 ka¹⁰. A relatively indistinct ~50 m terrace has been interpreted as the penultimate interglacial¹⁰. The 25 m level has U-series dates ranging from 71 ka to 112 +/- 6 ka¹⁰. A terrace at ~10 m elevation has U-series ages of ~36 ka and radiocarbon ages of ~25 ka¹⁰. However, uplift rates derived from the ages are unlikely to be correct as U-series dating of mollusc shells is known to be unreliable (e.g.¹⁷).

75 The uplifted coastal terraces end northwards by the Congo estuary, do not extend south of central
76 Namibia¹⁸ (Fig. 1c), and peak near Benguela^{10, 11}. The existing studies of the terrace sequences are
77 unable to directly correlate the terrace fragments, which are separated by large longitudinal
78 distances, justifying the approach of mapping and correlation from remote-sensing.

79
80 Our field study focused on the 25 m terrace, which is well exposed close to Benguela, and which
81 has a relatively simple geomorphic expression. We sampled the terrace at three localities (A-C; Fig.
82 1d). The terrace is composed of an abrasion surface in soft early Tertiary mudstones that is
83 overlain by lagoonal, beach and near-shore sediments. We interpret the abrasion surface and
84 sedimentary cover to result from a single sea level excursion with several thousand years duration.
85 The sediments do not contain corals that would generate reliable U-series ages, but are rich in
86 quartz sand grains that can be dated with optically-stimulated luminescence (OSL). Several recent
87 studies have shown the utility of OSL dating of coastal sediments (e.g.^{19;20;21}). We collected eight
88 OSL samples from the 25 m terrace, using appropriate protocols to minimize any possible partial
89 bleaching effects. We also collected bivalve shells from the terrace deposits for radiocarbon
90 dating. The sampling methods and analytical procedures are described in Methods. Additional
91 information relating to the field sites and dating results are given as supplementary information
92 (Supplementary Figs. 2-3; Supplementary Tables 1-2).

93
94 **25 m terrace site descriptions and age constraints**

95 The first of our sampling sites (Site A on Fig. 1d, corresponding to location AN-54 in¹⁰) is located in
96 a river cutting ~5 km southwest of Benguela. A wide erosional platform cut into early Tertiary
97 mudstone is overlain by ~2 m thickness of Quaternary sediments (Supplementary Figs. 2-3). The
98 lower part of the sequence is composed of dark and finely-laminated sand/silt. The microfaunal
99 assemblage at Site A contains species indicative of brackish to marine environments¹⁰. Two U-

100 series ages of 112 +/- 6 ka and 103 +/- 5 ka are reported from bivalve shells¹⁰. We collected four
101 OSL samples. We also collected a number of shells from the deposit, of which two (*Arca sp.* and
102 *Ostreida sp.*) were selected for radiocarbon dating. We took another two OSL samples from Site B,
103 located just north of Benguela at 12°33'03.2"S 13°26'22.7"E (Supplementary Figs. 2-3). The
104 presence of heavily-ribbed bivalves at Site B indicates high-energy near-shore environments. A
105 single OSL sample (BNG10-12) was collected from Site C, situated behind the Benguela football
106 stadium, at 12°32'39.4"S 13°27'50.6"E (Supplementary Figs. 2-3). The fauna at Site C was
107 predominantly *Arca sp.*. Gypsiferous horizons indicate a similar lagoonal environment to that
108 interpreted for Site A¹⁰.

109

110 The eight OSL ages from the 25 m terrace range in age from 57.8 +/- 11.2 ka to 36.8 +/- 3.4 ka (Fig.
111 2, also see Methods, Supplementary Table 1, Supplementary Figure 3). Our results confirm that
112 the terrace is much younger than previously thought, and showing that uplift rates based on the
113 U-series ages are not reliable. For the radiocarbon dating (see Methods and Supplementary Table
114 2), oceanic upwelling adjacent to our field site will lead to reservoir effects being incorporated in
115 the shell carbonate, and no marine reservoir correction data exist for Angola. Such reservoir
116 offsets are only of the order of hundreds of years, however, in order to calibrate the two ¹⁴C ages
117 as accurately as possible we utilised the reservoir estimate of ~500 years from the NW coast of
118 South Africa²². The conventional radiocarbon ages obtained, 44,650 ± 500 BP (OxA-26335) and
119 40,340 ± 310 BP (OxA-26336), showed good agreement with the OSL measurements. We
120 therefore combined all OSL and ¹⁴C dates together into a Phase in the program OxCal²³ (see
121 Supplementary Data 1) to indicate that they form a coherent group but are not exact markers of
122 the same point in time (making the assumption that the ancient shoreline survived for a finite
123 period of time). OxCal then generated probabilities for the start, mid, and end dates of the
124 existence of the shoreline (see Fig. 2). The median midpoint date (~45.1 ka) was used as the input

125 in our models of uplift rate. To investigate the effects of differing depositional environment
126 between the three sites we re-ran the model excluding the two ages from site B (near-shore,
127 rather than lagoonal) and found negligible differences in the overall age.

128

129 We combined the ~45 ka age with different eustatic sea level curves^{24;25;26;27;28} to constrain
130 confidence intervals on uplift rates. A full discussion of the various sea-level data is given in
131 Methods, and a visual comparison of the various curves is presented in Supplementary Figure 4.
132 An example uplift rate calculation is given in Fig. 3a, using the curve of²⁴, the others are included
133 as Supplementary Fig. 5-7. We used a terrace elevation of 23 m in the calculation, corresponding
134 to the observed and predicted maxima in the histogram on the right hand side of panel b of Fig.
135 3. The maximum likelihood estimates for the uplift rates using the four sea level curves range
136 from 2.0-2.4 mm/yr, with 90% confidence intervals defining a range of 1.8-2.6 mm/yr.

137

138 **Automated correlation of terrace remnants**

139 Independent verification of an uplift rate of ~2.2 mm/yr comes from the comparison of
140 automatically identified terraces in the SRTMGL1 digital elevation model (DEM) with expected
141 terrace levels from past eustatic sea-level curves (see Methods). We identify terraces in the
142 region plotted in Fig. 1d as areas where the gradient is close to zero. Noise introduced by small,
143 low-relief regions such as hill tops and river beds, and small-scale topography on the terrace
144 surfaces, has the effect of breaking up even large terraces, meaning that terraces are often only
145 poorly recovered and might not be found at all. To improve spatial coherence we thus filter the
146 topographic gradients before calculating their magnitudes, as described in Methods. The
147 automated extraction at Benguela agrees well with terrace heights obtained from manual
148 identification of terraces (white dots on Fig. 3b, see Supplementary Figure 1), and has the
149 advantage that it can resolve multiple terraces that are closely spaced in height. However, it does

150 not recover the level at ~260 m due to its surface being heavily dissected and noticeably tilted (Fig.
151 1d, profile 1, also see Fig. 4).

152 The best-fitting uplift rates (honouring the measured age of the ~25 m terrace) for the four
153 separate sea-level curves²⁴⁻²⁸ are in close agreement (Fig. 3, and supplementary Figs. 5-8). In
154 addition, these uplift rates can be used to make predictions of other terrace elevations that should
155 be observed in the area (pale orange histograms in Fig. 3). When these are compared with the flat
156 areas extracted from the SRTM DEM, there is a generally good agreement. In particular, the three
157 most detailed sea-level curves^{24,25,27} agree that the ~155 m terrace appears to have formed at
158 ~80ka. Such agreement gives us additional confidence in our results, and allows us to extend the
159 approach outside the region where we have direct constraint on terrace age.

160 We extended the automated terrace identification along the length of the Angolan coastline. The
161 results are shown in Fig. 4a, with significant flood plains, alluvial terraces and water bodies
162 removed manually, and close-up views of parts of the terrace map in Fig. 4a are given as
163 Supplementary Figures 9-12. Fig. 4b shows the concentration of flat areas along a north-south
164 profile, and Fig. 4c shows the same profile with noise introduced by seaward dipping fluvial
165 systems removed (see Methods). The automated method allows lateral continuity of terraces to
166 be traced over long distances, particularly near Luanda in the north and Namibe in the south. The
167 terrace formed by what we model as the 81 ka high stand (at ~150 m elevation at Benguela) is
168 particularly prominent and can be identified along virtually the entire coastline (dotted line in Fig.
169 4c). Doming is evident, with terraces near Luanda climbing steadily towards the south, and
170 terraces near Namibe climbing steadily towards the north. We can construct an uplift model (Fig.
171 4d) and an uplift rate model (Fig. 4e) for the length of the coastline by honouring the terrace
172 continuity, the uplift rate given by the 25 m terrace dates at Benguela, and local maxima in the
173 correlation between observed and expected terrace elevations for different uplift rates along the
174 coastline. These models (Fig. 4d-e) suggest a domal uplift with an amplitude of ~300 m and a

175 diameter of >1,000 km centred near Benguela. This doming is coincident with the projection of
176 the Bié plateau on the coastline.

177

178 **Rate and origin of the Angolan uplift**

179 The field, remote-sensing, and modelling results combine to show that the Angolan coastline has
180 undergone rapid Pleistocene uplift relative to sea-level. A ~1.8-2.6 mm/yr uplift rate is significantly
181 faster than the 0.12 mm/yr obtained through the analysis of long river profiles²⁹, which are
182 sensitive to uplift rates on much longer time periods. The uplift is too broad to be caused by salt
183 movements or active tectonics, especially as we see no evidence for uplift variations on the scales
184 associated with fault segmentation (~15—20 km), and little seismicity. The southeastern Atlantic
185 margin is 120-140 Ma old, and any rim flank uplifts due to lateral heat flow and flexure during
186 rifting have long since subsided. The large lateral extent of the domal uplift (>1000 km) argues
187 against a flexural control on uplift caused by sediment offshore loading following rifting, such as
188 that proposed that the Guripe Arch in NE Brazil³⁰. The study region is also sited far from the
189 effects of glacial loading and unloading.

190

191 We propose that the broad wavelength of uplift, the apparent association with the Bié dome, as
192 well as the absence of viable alternatives provide compelling evidence that the uplift is caused by
193 mantle upwelling. Tomographic images are variable in their support for a velocity anomaly
194 beneath Angola (e.g.^{31,32,33}) and yet the Bié Dome is one of the few places to retain a free-air
195 gravity anomaly, consistent with the presence of mantle-supported dynamic topography, when an
196 isostatic correction is applied to the African gravity field⁹. This means that the gravity high over the
197 dome cannot be explained by isostatic compensation. A 25 mGal gravity residual is centred on the
198 dome, which suggests that there are at least 500 m of dynamic topography³⁴ (Fig. 1b) assuming a
199 long-wavelength admittance of 50 mGal/km³⁵.

200

201 The Pleistocene uplift event cannot have been sustained for long, as the identifiable coastal
202 terrace sequence peaks at an elevation of ~250 m near Benguela (Fig. 1d). The 1-2 km height of
203 the Cenomanian (93-100 Ma) surface onshore suggests a maximum total uplift in this region (e.g.
204 ⁸). At ~2 mm/yr this amount would accumulate in ~1 Ma, though both the inversion of river
205 profiles and the deltaic deposition in the Kwanza basin suggest that uplift began at ~25 Ma. As a
206 possible resolution to this apparent paradox, we suggest that the onset of regional uplift may have
207 been associated with the initial impact of a mantle plume, but that the topographic expression of
208 this plume may be modulated on shorter timescales, perhaps in processes similar to those invoked
209 to explain the V-shaped ridges associated with the Iceland plume or inferred transient periods of
210 uplift in the North Sea (e.g. ^{36,37}).

211

212 Our interpretation is that the late Pleistocene coastal uplift of Angola results from a pulse of
213 mantle-derived uplift, providing an opportunity to study this phenomenon in an area with
214 relatively few other complicating factors. We note that the >2 mm/yr uplift rate reported here is
215 theoretically detectable by long-term GPS measurements, though this analysis has not yet been
216 done to our knowledge. We are also unaware of any historical or archaeological sources that
217 might give insight into recent uplift, though we recognize that the ~1 m of uplift expected since
218 the Portuguese arrival would be visible in the event that any coastal historical buildings are extant,
219 and that the hundreds of metres of uplift on this length-scale will have had an important impact
220 on the palaeogeography of SW Africa over a time interval relevant to the study of prehistoric
221 human populations.

222

223 Constraining the processes responsible for swells and basins within the continents has been
224 difficult due to the lack of precise temporal and spatial limits on the uplift of topography. In Africa,

225 for example, differing explanations are postulated for the origin of the elevated regions, ranging
226 from whether uplift results from a large region of upwelling across southern Africa (e.g. ^{2; 3; 5}); as
227 small, isolated, swells (e.g. ^{7; 8}); or whether the topography is not in fact supported by thermal
228 upwelling at the present and instead results from processes such as the addition of underplated
229 material in earlier geological periods (e.g. ⁶) or rim flank uplifts to passive margin and interior rifts
230 (e.g. ^{39,40}). Our results show that Pleistocene uplift of Angola occurs with a >1000 km diameter and
231 correlates with regions of high topography, hence supporting a model of small isolated swells, at
232 least for the Angolan uplift.

233

234 The 25 mGal residual gravity anomaly centred on the Bie Plateau suggests the presence of at least
235 500m of dynamic uplift. This represents the lower limit for the dynamic component and it is
236 unclear whether there may be additional isostatic component, perhaps through the conversion of
237 relatively short-lived pulses of 'dynamic' uplift into permanent isostatic uplift through the addition
238 of crustal material during those pulses. Mantle processes have had a large effect on the recent
239 (~1 Ma) history of the Angolan coastline and a better understanding of the crustal structure of the
240 Bie Plateau is urgently needed to fully understand the processes that control the topography of
241 such 'stable' margins over a variety of time scales.

242

243

244

245 **Methods**, including statements of data availability, code availability, and references, are available
246 in the online version of this paper.

247

248

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334

335 **Author contributions**

336 R.T.W. and A.B.W conceived and designed the experiments; M.T. and R.T.W. performed the
337 fieldwork and undertook all sample collection; J-L.S. and M.T. performed the OSL sample analyses,
338 and M.D. performed the radiocarbon calibrations and age modelling; R.L.K. constructed the
339 method for automatic terrace extraction; B.K., R.L.K. and R.A.S. performed the regional terrace
340 correlations; M.D., R.L.K., R.A.S., M.T., and R.T.W. co-wrote the paper.

341

342 **Additional information**

343 Supplementary information is available in the online version of the paper. Reprints and
344 permissions information is available online at www.nature.com/reprints. Correspondence and
345 requests for materials should be directed to RTW (richard.walker@earth.ox.ac.uk)

346

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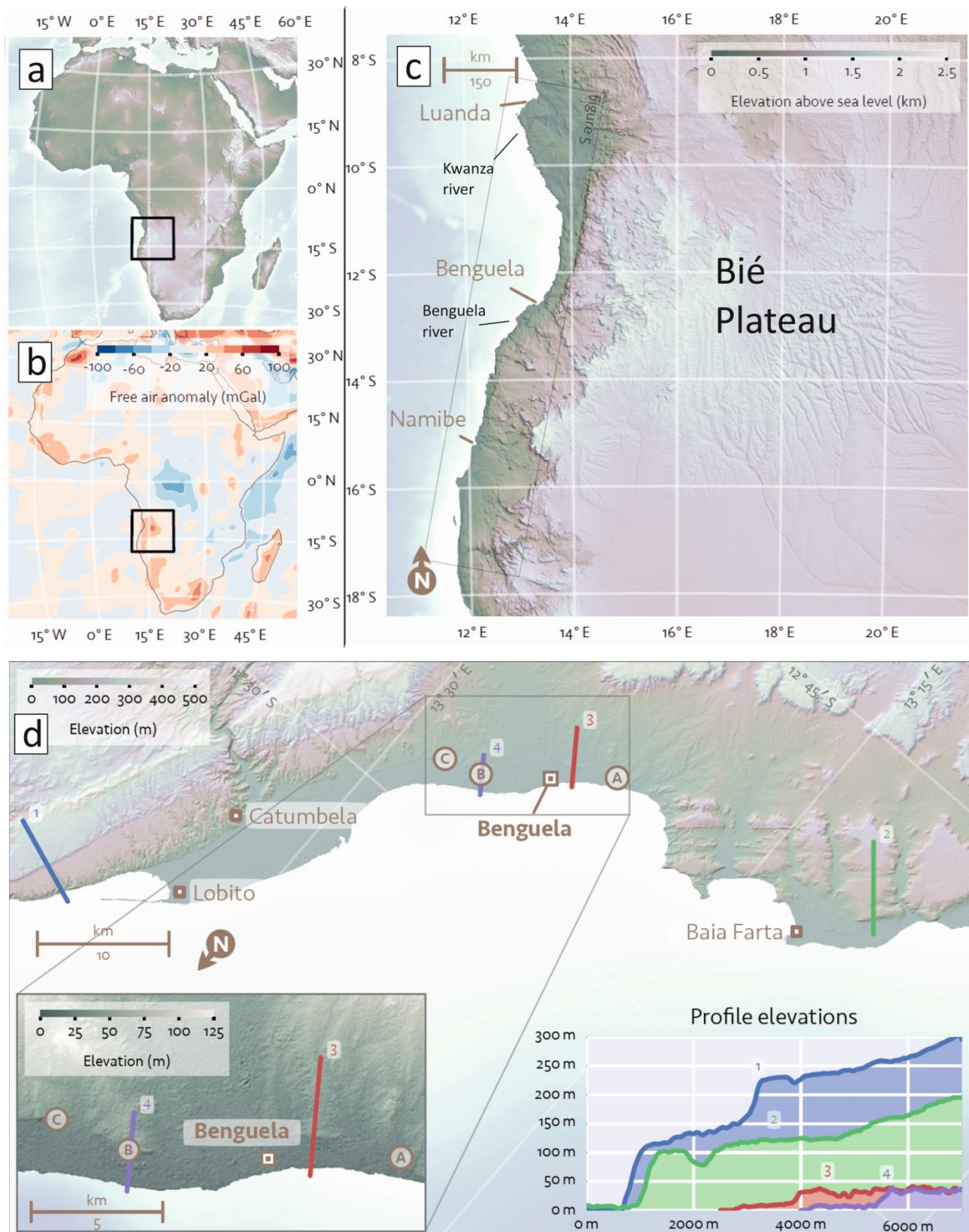
355

356 **Competing financial interests**

357 There are no competing financial interests

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 361 **Figure 1:** Regional setting of the study sites. (a,b) Topographic and Free air anomaly maps of
 362 Africa, adapted from²⁷. (c) Topography of the Angolan coastline and Bié Plateau. (d) Topography
 363 of the Benguela region, with a close-up of Benguela itself as an inset. The three sample sites (A-C)

are labelled and four topographic profile lines are marked. Prominent terrace treads are visible at elevations of ~120 m, ~150 m and ~230 m adjacent to Lobito (profile 2) and Baia Farta (profile 1). Our samples are taken from the 25 m terrace (profiles 3 and 4).

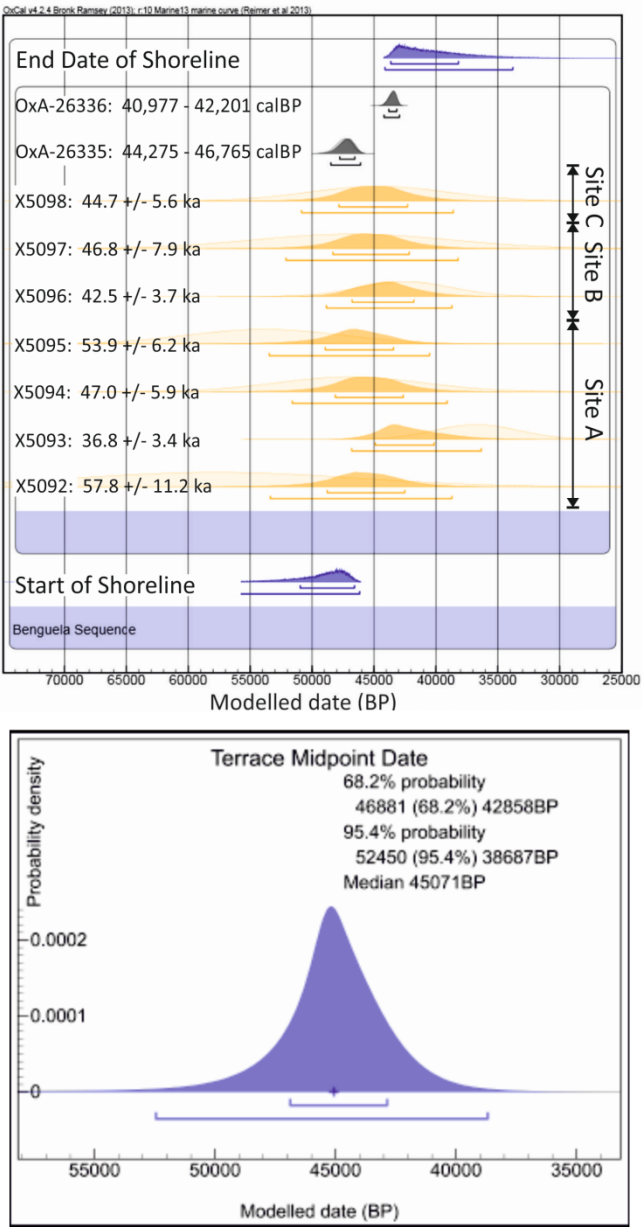
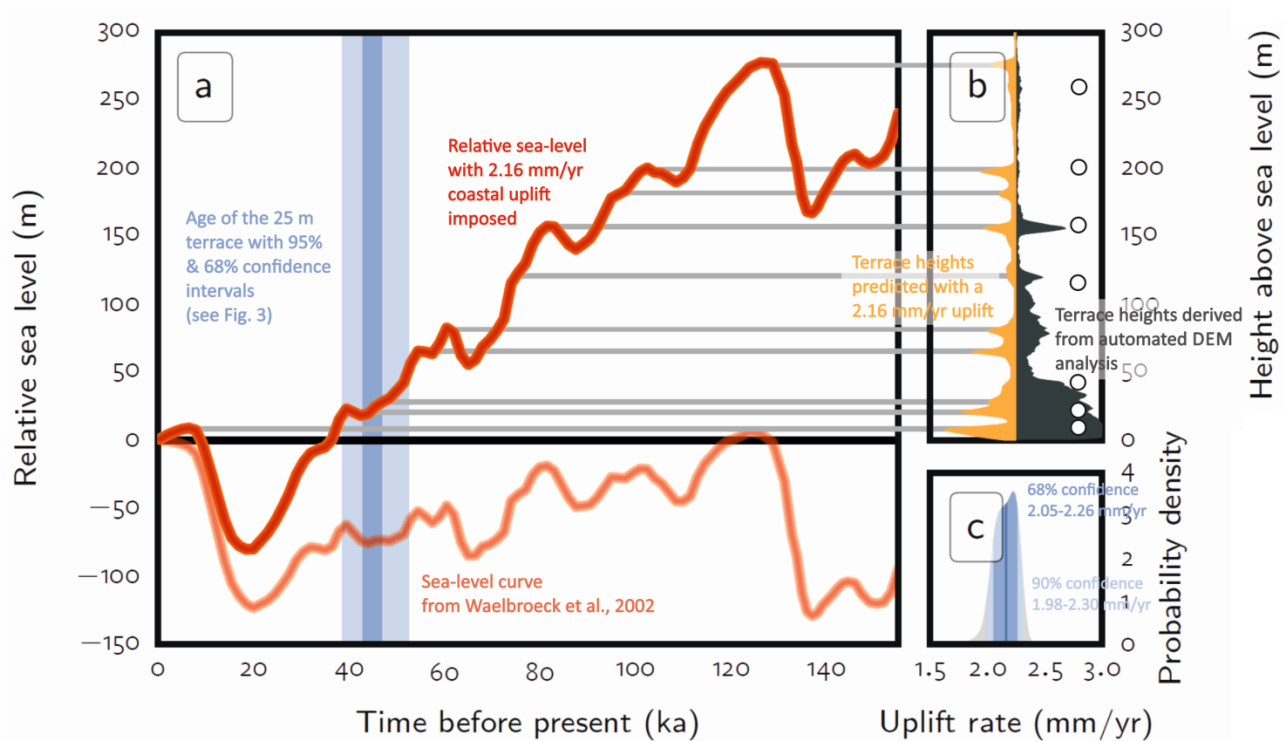


Figure 2: OxCal age model incorporating the eight OSL samples and two radiocarbon ages. Sample lab codes and ages are given in text at the left-hand side of the figure. Uncertainties are 95% for calibrated radiocarbon and 1σ for OSL. Individual sample age ranges are shown on the ‘Oxcal’ model plot as light colours, with the model output for each shown as the darker regions, as well as the modelled start and end date of the shoreline. The model ‘mid- date’ is shown in detail in the

374 lower panel. See methods for details of the dating methods.

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376

377 **Figure 3:** Uplift rates at Benguela. (a) The eustatic sea-level curve²⁰ is shown in pink, and the curve
378 'corrected' for an uplift of 2.16 mm/yr in red. The 25 m terrace age range (68% and 95%) is
379 indicated. (b) A comparison of the distribution of automatically identified terraces near Benguela
380 with those expected from the sea-level curve for a 2.16 mm/yr uplift. Terrace heights measured
381 manually from the DEM are represented by white dots. (c) The terrace age probability density
382 function is combined with the sea-level curve to give the uplift rate. This gives a maximum
383 likelihood uplift rate of 2.16 mm/yr.

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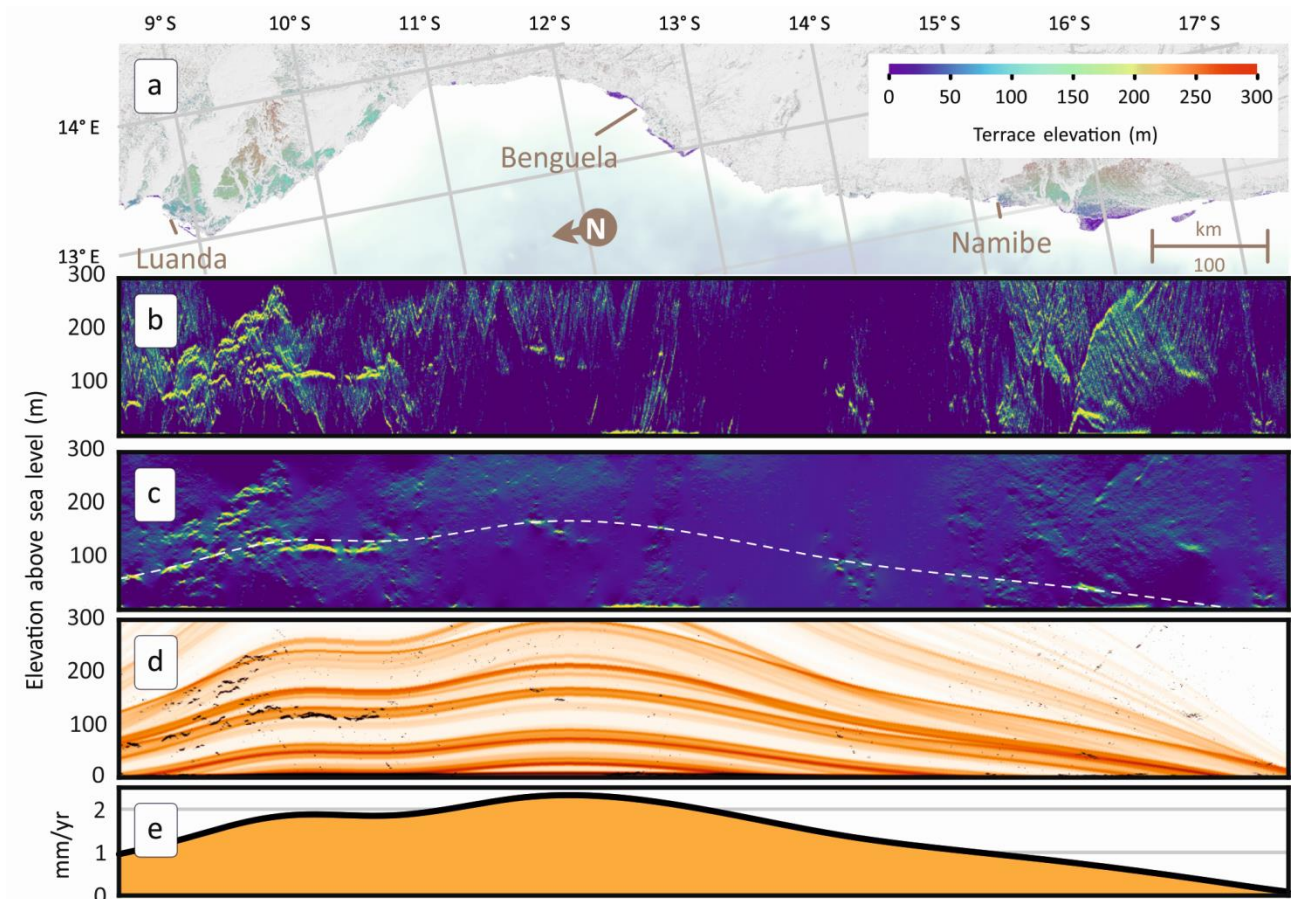


Figure 4: Regional terrace correlations. (a) Map of automatically identified terraces. (b) Normalised histograms of flat areas along the length of the map, with yellow tones indicating predominance of flat areas. (c) As before, with filtering to remove steep diagonal noise introduced by fluvial systems. The dotted line is a reconstruction of the prominent 150 m terrace at Benguela. (d) Synthetic terrace model (orange, given the uplift rates calculated from 'c') overlain on observed flat areas (black). (e) Inferred uplift rates along the coast given the interpretation of the 150 m terrace as the ~80 ka highstand.

Methods

OSL samples were collected and analysed followed standard protocols. All samples were collected in light-proof 50 x 125 mm black plastic tubes from cleaned exposures of the sections, and the ends capped. Once the sample had been extracted from the exposure, a 2" NaI probe attached to

400 an Ortec MicronomadTM portable gamma spectrometer was inserted into the hole to measure the
401 in-situ gamma radiation field. Samples were transported wrapped in additional light-proof bags to
402 the Oxford University Luminescence Dating Laboratory. Additional dosimetry data was provided
403 by ICP-MS (Inductively-Coupled Plasma Mass Spectrometry) and -AES (Atomic Emission
404 Spectrometry) at Royal Holloway, University of London on sediment from the light-contaminated
405 ends of the tubes discarded during sample preparation; the gamma contribution was derived from
406 the field spectrometry, and the beta contribution was calculated from isotope concentrations
407 derived from the mass spectrometry data.

408

409 Preparation followed conventional protocols, and began with discarding the light-contaminated
410 ends of the tubes. Sand was pre-treated with 35% HCl and 30% H₂O₂ until the cessation of any
411 reaction to remove, respectively, carbonates and organics. The sediment was subsequently sieved
412 to isolate the dominant sand-sized fraction (either 125-180 µm or 180-255 µm depending on the
413 sample), and heavy minerals were isolated with sodium polytungstate at 2.72 gcm⁻³. 35% HF was
414 used for 40 minutes to etch the alpha-irradiated rind of the quartz and to remove feldspars.
415 Where subsequent testing revealed continued presence of feldspars in the samples, an additional
416 room temperature treatment with fluorosilicic acid (H₂SiF₆) was used to ensure complete isolation
417 of the quartz fraction. A second treatment with HCl removed precipitates and a final sieving
418 removed any detrital fragments of grains left by the etching process.

419 All samples were analysed on Risø TL-DA-12 or -15 automated luminescence readers after
420 mounting small (3-4 mm diameter) aliquots onto aluminium discs with silicone spray. All samples
421 were analysed with a modified Single Aliquot Regeneration (SAR) protocol^{41,42}, incorporating a
422 post-IR blue feldspar purity check⁴³. Preheats of 260°C for the regeneration dose and 220°C for
423 the test dose were applied on the basis of plateau tests. Dose recovery tests on a subsample of
424 the aliquots were able to successfully recover a 120 Gy dose within ± 5%.

Between twelve and twenty-four aliquots were used for each sample, and seven regeneration points (excluding a zero-dose point, and recycling checks at both high and low doses) were typically used to characterise growth. Luminescence response of the samples was typically fairly low (400-1000 counts per 0.1s in the initial channels, with background typically around 50). Quantification of the luminescence signal was derived from the first 1 s of OSL measurement, using the subsequent 1.5 s integral of the decay curve as early background subtraction⁴⁴. This minimizes any risk of partial bleaching resulting in age overestimation, and the consistency between ¹⁴C and OSL ages, and between OSL ages from different depositional settings (i.e. lagoonal and nearshore), also suggests that these samples are adequately bleached.

Additional quality checks included recuperation, recycling and saturation; samples which failed any of these test were excluded from further analysis. . The mean recycling ratio data for accepted aliquots was 0.98 ± 0.07 , and the mean for all data 0.97 ± 0.13 ; both are consistent with unity. Aliquots which failed due to saturation, using $2D_0$ from a single saturating exponential fit as a criterion after⁴⁵, were used to derive minimum age estimates. Samples were best fitted with either single or double⁴⁶ saturating exponential fits, which were applied using Risø's Analyst v4.14 software, using 100 Monte Carlo repeats for error estimation. Since the use of the sum of two saturating exponentials has sometimes been reported as yielding underestimates of the true age of the order of $\sim 10\%$ ^{47,48}, the recommendations of⁴⁹ are followed here, and independent chronological control has been sought from ¹⁴C dating.

Single equivalent dose estimates (D_e) were derived using the Central Age Model⁵⁰, with over-dispersion values from 12-41%, and a mean of 24.4%. These values are likely to be due to the relatively low signal intensity and consequent high signal/noise ratio. Moisture content was assumed at $5 \pm 2.5\%$ giving a two-sigma confidence interval for time-averaged moisture content of 0-10%.

449

450 The two shell samples were radiocarbon dated at the Oxford Radiocarbon Accelerator Unit
451 (ORAU), using routine pre-treatment and measurement protocols^{51,52}, and with care taken to
452 ensure analysis of only endogenous aragonite. All of the carbonate samples prepared by ORAU
453 are treated in parallel with the IAEA marble standard from the Cretaceous period. The particular
454 aliquot treated at the same time as these shell samples has now been prepared 102 times by
455 ORAU and consistently produced results that are beyond the background limit of the ¹⁴C dating
456 method.

457

458 The radiocarbon sample preparation steps are as follows. The shells were first shot-blasted with
459 an air abrasive to remove the outer surface and expose the nacreous aragonite. The presence of
460 calcite (which may result from recrystallization and not be endogenous to the original organism)
461 was then tested for using Feigl's solution⁵³. In both cases, the samples passed this test. The
462 possibility that the dated fractions of the ostreida (OxA-26335) and arca (OxA-26336) shells
463 included recrystallised aragonite is considered highly unlikely. However, in order to be as robust as
464 possible, in addition to the Feigl's test for calcite described above, both shells were also visually
465 inspected under a binocular microscope. The ostreida shell was very well preserved and showed
466 no signs of either dissolution or recrystallisation; the arca shell showed limited signs of dissolution
467 on the outer surfaces, and care was taken to avoid these areas when sampling for dating.

468 The shells were crushed to powder in a mortar and pestle and aliquots (~50 mg) digested
469 overnight using concentrated H₃PO₄ in a closed rig under vacuum. The CO₂ gas liberated was
470 trapped cryogenically, sealed into a glass ampoule and subsequently combined with a
471 stoichiometric excess of H₂ and reduced to graphite (pure carbon) over an Fe catalyst. During this
472 process, a small proportion of the CO₂ was diverted into a isotope-ratio mass spectrometer for
473 δ¹³C measurement (relative to PDB). The graphite obtained from each sample was pressed into an

474 aluminium target and its ^{14}C activity obtained using Oxford's 2MV tandem accelerator mass
 475 spectrometer. The combined set of chronometric data was then incorporated within the same
 476 Phase of a Bayesian model in OxCal to refine the ages.

477

478 Expected terrace elevations were modelled by assuming that terraces were cut at a particular
 479 elevation whenever past sea-level was “close to” that elevation. In addition, we assume that
 480 terraces are eroded with time, with different erosion rates depending on whether or not the
 481 terrace is submerged. The likelihood $\phi(z, t)$ that at time t a terrace exists at elevation z can
 482 therefore be posed as the solution to the differential equation:

$$\frac{d\phi}{dt} = f(z - \tilde{\sigma}(t)) - \frac{\phi}{\tau}, \quad 1$$

483 where f is a smoothing function that spreads the terrace cutting at any time t over a finite
 484 interval, $\tilde{\sigma}(t)$ is the relative sea-level curve adjusted for uplift history and τ is a decay parameter
 485 which differs depending on whether z is above or below sea-level at time t . The first term
 486 represents terrace cutting while the second term represents terrace erosion. f must be positive
 487 when z is near $\tilde{\sigma}(t)$ and zero elsewhere. We choose f to be a Gaussian with FWHM of 8m. The
 488 finite width represents uncertainty in the sea-level curve, as well as effects of short period
 489 variations such as tides. The model does not take into account the effects of eustatic-induced
 490 water loading and unloading on the terrace profiles. We choose τ to be given by $\tau = w_0\tau_{\text{land}} +$
 491 $w_1\tau_{\text{sea}}$, where τ_{land} and τ_{sea} represent the subaerial and submarine erosion rates respectively, and
 492 $w_0 + w_1 = 1$. For consistency with f , we choose $w_0 = \int_{-\infty}^{z - \tilde{\sigma}(t)} f(z') dz'$ (i.e. the error function).
 493 Our results are fairly insensitive to reasonable choices of erosion rates. We choose $\tau_{\text{land}} = 100$ kyr
 494 and τ_{sea} to be small enough that submerged terraces are eroded almost immediately. Finally, the
 495 relative sea-level curve $\sigma(t)$ can be adjusted for a given uplift rate history $u(t)$ by integrating the

496 uplift rate backwards through time, namely $\tilde{\sigma}(t) = \sigma(t) + \int_t^0 \dot{u}(t') dt'$. This adjustment is simply
 497 the addition of a straight line through the origin for a constant uplift rate. The terrace model can
 498 now be calculated by integrating equation 1 from the distant past until the present for elevation
 499 ranges of interest.

500 Automatic identification of terraces in the SRTMGL1 DEM is complicated by small low-relief
 501 regions such as hill tops and river beds, and by small-scale topography on the terrace surfaces that
 502 has the effect of breaking up even large terraces, meaning that terraces are often only poorly
 503 recovered and might not be found at all. We therefore smooth the components of the gradient
 504 vector before taking its magnitude, which is effective at augmenting the continuity of terraces.

505 We define the smoothed gradient of the topography as $\|\mathcal{S}(\nabla z)\| = \sqrt{[\mathcal{S}(\frac{\partial z}{\partial x})]^2 + [\mathcal{S}(\frac{\partial z}{\partial y})]^2}$ where
 506 \mathcal{S} is the smoothing operator and $\frac{\partial z}{\partial x}$ and $\frac{\partial z}{\partial y}$ are the N-S and E-W partial derivatives of the
 507 topography, respectively. Gaussian filters tend to shrink terraces because the slopes at the edges
 508 are blended with the slopes of adjacent areas, while median filters cause flat regions to grow by
 509 about half the window width. To mitigate these problems, we used a more sophisticated filter on
 510 the horizontal derivatives: if ξ_0 represents the data to be smoothed, in our case the partial
 511 derivatives $\frac{\partial z}{\partial x}$ or $\frac{\partial z}{\partial y}$, then the filter is defined such that the result ξ minimises the expression
 512 $\iint (\xi - \xi_0)^2 dA + s \iint \|\nabla \xi\| dA$. The coefficient s is the smoothing weight; higher values of w
 513 result in more smoothing. The advantage of this filter is that it preserves sharp edges, yet
 514 gradually removes detail with higher values of s . After calculating the smoothed gradient, we use
 515 a simple Gaussian weighting function to map the distribution of terraces, where the weighting w is
 516 given by $w = \exp(-(a \|\mathcal{S}(\nabla z)\|)^2)$. The parameter a governs how flat an area must be to be
 517 given any weighting. We used $a = 200$, meaning that only slopes of less than 0.5° are assigned

any significant weight. Finally, we inspected the results visually and cut out regions that are clearly not marine cut terraces, such as flood plains, alluvial terraces and reservoirs.

Each column of the image in panel (b) in Figure 5 of the main text is a normalised weighted histogram of the topography for a small interval along the length of the map in panel (a) from left to right. The weighting is calculated using the method above, and the histograms are normalised by subtracting a Gaussian-smoothed version of the histogram with a Gaussian window of width $\sigma = 10$ m. The histogram columns are plotted as an image coloured such that high occurrences are yellow and low occurrences are blue. Panel (c) is the same as panel (b), but the image has been filtered in the wave-number domain to cut out steep coherent signals (by removing all signals with a wave vector close to horizontal). This is analogous to f - k filtering in seismic reflection processing.

The choice of eustatic sea-level curve impacts the calculated uplift rate. In order to explore variation between different curves, we used four different eustatic sea level curves in our analyses²⁴⁻²⁷, with d18O records in the latter converted to past sea level using equations from²⁸. Before converting the d18O data from²⁷ to relative sea level, we used a moving Gaussian average (FWHM 4 ka) to remove data scatter. The four sea-level curves are shown superimposed for visual comparison in Supplementary Figure 4. The uplift rates at Benguela, based on our dating of the 25 m terrace, calculated from all four curves are very consistent, bounded by respective 90% confidence intervals of 2.0-2.3 mm/yr, 2.1-2.5 mm/yr, 2.2-2.6 mm/yr and 1.8-2.1 mm/yr (see Fig. 3 in the main text, and supplementary Figures 5-7). The expected uplifted terraces given different uplift rates calculated for the respective sea level curves are plotted in supplementary Figure 8.

Data availability

543 We used the publicly available NASA Version 3 SRTM Global 1 arc second topographic dataset. In
544 this dataset, voids are filled using the ASTER GDEM2 for regions outside the USA. The global
545 dataset is available for processing and download from the OpenTopography Facility
546 (www.opentopography.org). KOMPSAT2 satellite imagery was provided under academic licence
547 through the European Space Agency and is not for distribution. The authors declare that all other
548 data supporting the findings of this study are available within the article and its supplementary information
549 files.

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552 **Code availability**

553 Enquiries about the computer code used for terrace modelling should be sent to Richard Kahle
554 (richard.kahle@uct.ac.za).

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557 **References only in Methods**

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