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1 **Landscape evolution of Dartmoor, SW England: a review of evidence-** 2 **based controversies and their wider implications for geoscience**

3

4 Yann Ginnell

5

6 **Abstract**

7 Dartmoor's landscape has been studied for ~200 years but is still imperfectly understood. Here we
8 explore Dartmoor as a geoscientific incubator, focusing on why such a small portion of the Earth's
9 surface has generated such a galaxy of diverse landscape evolution scenarios. A carousel of
10 controversies over rock weathering, drainage evolution, the chronology and intensity of base-level
11 changes and palaeoclimates is examined in detail. Their bearing on how we interpret the land
12 surface are discussed, with suggestions for future investigation. By also analysing the ontological
13 and epistemological underpinnings of the research, the review resonates with the wider history of
14 geoscience.

15

16 **Keywords:** landscape; landform; epeirogeny; regolith; palaeoclimate; base level

17

18

19 **1. Introduction: understanding Dartmoor's landscape**

20

21 As a conspicuous upland among lowlands (Fig. 1), Dartmoor culminates at High Willhays (621 m
22 a.s.l.) and forms an island-like topographic mass on the horizon from any vantage point in SW
23 England (Figs. 2–5). Its largest steep drops are at river gorges (typically 150–200 m), and the
24 relative relief of the outfacing escarpments is of a similar magnitude. While emphatically not a
25 mountain according to the conventional criteria of elevation, prominence, and isolation (Kirmse and
26 de Ferranti, 2017), the moorland of Higher Dartmoor certainly feels out of place amidst the milder
27 climate and green 'normality' of southern England (Ginnell and Jarman, 2020).

28 In the history of British Earth science, Dartmoor ranks high among a number of small flagship
29 regions where successive generations of naturalists and academics, ranging from civil engineers
30 (e.g., Richard Hansford Worth, a prolific author on Dartmoor, consultant engineer by profession
31 and son of a publishing amateur geologist: Bennett and Mather, 2018) to geographers and
32 Quaternary geologists, have sharpened their skills and concepts in trying to understand the upland
33 granite landscape and its value as a template for analysing other similar regions. Princetown was
34 accessible by horse-drawn tram from Plymouth as early as 1823, then Devon generally became

35 more easily accessible by broad-gauge steam railway from London via Exeter in 1844, and
36 subsequently via Plymouth in 1876 (with branch lines to Moretonhampstead in 1866 and
37 Princetown in 1883). According to a survey taken of all 65 geography and geoscience departments
38 in the UK, 30% visited Dartmoor and South Devon in 1998 (Moore and Gerrard, 2002), thus
39 making the area still one of the most popular fieldwork destinations among British higher education
40 institutions in recent time.

41 Geoscientific enquiry into Dartmoor, however, has played out in parallel worlds, partly governed by
42 affiliations to separate learned societies and thus by independent (and often competing: e.g.,
43 Bennett and Mather, 2018) scientific cultures. Foremost among these scholarly institutions was the
44 Geological Society of London, where its one-time president (1847–1849) Henry de la Beche, also
45 founder and first Director in 1835 of the Geological Survey, authored pioneering reports on
46 Dartmoor's geology during the 1830s. However, as illustrated in the reference list provided by this
47 review, many other learned societies have a sustained track record of publishing on Dartmoor. By
48 decreasing order of antiquity, these include the Royal Geological Society of Cornwall (founded in
49 1814); the Institution of Civil Engineers (1818); the British Geological Survey (1835); the Exeter
50 School of Science (1855, university of Exeter since 1955); the Geologists' Association (1858); the
51 Devonshire Association for the Advancement of Science, Literature and Art (1862); the
52 Geographical Association (1893); the Devon Archaeological Society (1928); the Institute of British
53 Geographers (1933); the Prehistoric Society (1935); the Field Studies Council (1947); the British
54 Society for Geomorphology (1958); the Ussher Society (1962); and the Quaternary Research
55 Association (1964). Dartmoor also attracted independent foreign scholars such as French
56 geomorphologist André Guilcher who, in 1949, set out on an exploratory mission to investigate
57 contrasts and similarities between SW England and Brittany; and, much later, Brigitte Coque-
58 Delhuille and Claude Klein, to whom we return later.

59 Whereas the Cornish stocks have entered textbooks as exemplars for understanding granite genesis
60 and its hydrothermal polymetallic mineralisations (Willis-Richards and Jackson, 1989; Chappell
61 and Hine, 2006), with international repercussions for economic geology (ore-forming processes:
62 e.g., Dines, 1956; Hosking, 1962; Jackson et al., 1989) and geothermal energy (Beamish and
63 Busby, 2016), the Dartmoor granite has aroused greater curiosity among geomorphologists.
64 Dartmoor is the largest outcrop of one of the largest granite bodies in the United Kingdom
65 (estimated volume of the Cornubian Batholith: 40,000 km³ according to Williamson et al., 2010; but
66 68,000 km³ according to Willis-Richards and Jackson, 1989), and despite being widely obscured by
67 peaty soil > 40 cm deep (with local maxima of 4 and perhaps up to 13 m: Gartis et al., 2019), the
68 size of the Dartmoor granite outcrop (~600 km²) equals the sum of all the other outcrops of granite
69 in SW England (Fig. 1). This explains why issues of landforms and landscape evolution are more

70 relevant to Dartmoor than in the case of the smaller Cornish stocks, which apart from Bodmin Moor
71 have been extensively transformed into man-made landscapes. Guilcher (1949), for example,
72 described the St Austell outcrop as an “étrange paysage d’allure volcanique”, implying here that its
73 most outstanding features were the 100 or so conical slag hills, each gullied with an intensity
74 proportional to its age, thus resulting in a landscape totally alien to natural granite scenery.

75 Dartmoor has been a fountainhead of scientific insights into long-term landscape evolution.
76 Because Dartmoor, for example, displays the largest concentration of easily accessible tors in
77 Europe and is one of the best-researched granite landscapes in the context of its cold climate
78 inheritance (Migoñ, 2006), it has been given a high profile in books on British geology and scenery
79 (e.g., Goudie and Gardner, 1985; Gunnell and Jarman, 2020), in geoheritage inventories (e.g., Floyd
80 et al., 1993; Campbell et al., 1998; Klemen, 2015), and displays multiple index entries in
81 geomorphology textbooks (e.g., Twidale, 1971; Small, 1978; Sparks, 1986; Gerrard, 1988a). The
82 Celtic word ‘tor’, meaning ‘rocky outcrop’ or ‘hill’, is closely associated with Dartmoor and has
83 also entered the international scientific vocabulary. A further deserving distinction is that “the
84 picture provided by Dartmoor is essentially repeated in other European granite uplands” (Migoñ,
85 2006), thus instituting Dartmoor as a model valid for the wider world.

86 It has also been said, however, that “the majority of geomorphological studies about Dartmoor have
87 been essentially speculative, particularly when discussing weathering processes and the evolution of
88 the Dartmoor landscape” (Williams et al., 1986). As this review will show, this wry statement rather
89 accurately sums up the mood of disillusionment that has prevailed since the end of the 1970s given
90 the many open-ended questions that still linger nearly 200 years after the early musings of de la
91 Beche. On the upside, because it has been intensely studied over a long period of time, one strong
92 appeal of Dartmoor is its potential for tracking the history of science, a dimension emphasised
93 throughout the review. On the downside, despite having been intensely studied, Dartmoor also
94 illustrates the persistent uncertainty that belies any geomorphological interpretation of regional
95 landscapes. As this review will thus also show, for almost every deceptively simple feature of the
96 Dartmoor landscape there has been a theory and its opposite (see also Bennett and Mather, 2018).

97 Scope for further investigation will be provided in closing Section 6.4.

98 The main reason why the granite landscape of Dartmoor is open to many interpretations lies in the
99 huge stratigraphic gap between the emplacement of the Cornubian Batholith in early Permian time
100 (294–274 Ma: Darbyshire and Shepherd, 1985; Chen et al., 1993; Chesley et al., 1993; Neace et al.,
101 2016) and its Quaternary cover deposits. Given this “great lost interval in the geological story”,
102 Wooldridge (1950) wrote of the “leapfrog antic” that geomorphologists had to perform in order to
103 link up in some coherent way “the topographical expression of ancient structures to the story of
104 glaciation” — an aptly phrased description of how Earth scientists strive to ‘join the dots’ in

105 landscape interpretation based on incomplete information. Yet Wooldridge (1952) also held the
106 view that

107 “Devon and Cornwall continue and supplement the physiographic record of our
108 lowlands, but they introduce also the very different problems of our uplands.
109 Unglaciaded, they have borne the full brunt of Tertiary uplift and erosion. Here, if
110 anywhere, we may hope to find the essential clues to the history of the British land
111 surface, but the record is hard to read...”.

112 In attempting to understand the evolution of thinking on Dartmoor amid these many expressions of
113 puzzlement, the concept of ‘consilience’ seems appropriate. It was coined (along with
114 ‘catastrophism’ and ‘uniformitarianism’) by William Whewell, president of the Geological Society
115 of London from 1837 to 1839, i.e., just as the first scientific investigations of Dartmoor were
116 commencing. Consilience conveys the principle that evidence from independent, unrelated sources
117 across disciplines can converge on strong conclusions (Whewell, 1840). In this spirit of consilience,
118 we will assemble here the various strands of factual evidence contributed by Earth scientists to the
119 understanding of Dartmoor over the last ~200 years in an attempt to provide a unified, evidence-
120 based, and up-to-date narrative on the evolution of the Dartmoor land surface.

121

122 **2. Explaining Dartmoor’s altitude, prominence, and isolation**

123

124 ***2.1. Lithology: a partial explanation***

125

126 Having explored SW England from experience acquired in Brittany, Guilcher (1949) was surprised
127 by the ubiquitous topographic prominence of granite on the English side of the Channel. In the
128 Armorican Massif, granite barely ever holds the high ground (e.g., Garreau, 1982), and higher
129 altitude is quite systematically the preserve of sandstone, with Exmoor accordingly feeling more
130 normal to expectation from Guilcher’s perspective. In terms of isolation, elevation and prominence,
131 the Dartmoor upland is indeed not unique within SW England given that the highest point on
132 Exmoor is 519 m; i.e., just 100 m less than High Willhays, and 100 m more than the top of Bodmin
133 Moor (Dartmoor’s runner-up among the granite outcrops of SW England). Exmoor is a Variscan
134 anticline in the Devonian ‘Hangman Grits’, suggesting that geological structure and resistant
135 lithology have at least partly conspired to uphold Exmoor at high elevations. Exmoor, Dartmoor,
136 and most of the Welsh uplands were classified by Clayton and Shamon (1998) as comprising
137 “Resistant and above-average-strength rocks”, only exceeded by “Very resistant lithologies” in the
138 Lake District and the Scottish Highlands. As with most cratonic upland environments around the

139 world (e.g., Godard et al., 2001), Clayton and Shamoan concluded that variations in the resistance
140 of rocks to erosion accounted for a large proportion of the relative relief of Britain.
141 The high topography of SW England nevertheless occurs on Dartmoor and Exmoor rather than in
142 Cornwall. The maximum altitude of the other Cornish granite outcrops declines westward to much
143 lower values (Bodmin Moor: 417 m; Hensbarrow Beacon: 312 m; Trendrine Hill, near Land's End:
144 245 m) even though local prominence in each case is maintained. In more detail, only Higher
145 Dartmoor forms a distinctive topographic island; the granite outcrop of Lower Dartmoor (~400 m)
146 being lower than Exmoor (Fig. 1). Whether factors other than lithology might explain the
147 topographic prominence of Dartmoor and Exmoor thus bears consideration, particularly given that
148 Higher Dartmoor is not a tectonically upthrown block bounded by faults on all sides. Clayton and
149 Shamoan (1999) filtered out the effect of relative rock resistance in a smoothed map of the mean
150 elevation of Great Britain and found indeed that Dartmoor displayed a positive anomaly of 100 m
151 of unexplained excess mean altitude (Exmoor ~50 m, by comparison). This is two to three times
152 less than the residual anomalies of positive elevation obtained for Wales, the North Pennines and
153 Scotland using the same method, but still remains unique within the English lowlands.

154

155 ***2.2. Epeirogeny: elusive but compelling***

156

157 The commonly held assumption for SW England is that Dartmoor and Exmoor are the most
158 prominent residual stumps of the Variscan orogen, having maintained their topographic prominence
159 continuously for 200 million years as part of a post-Variscan Cornubian Island (Fig. 2). Like
160 Brittany, Wales and Ireland, the Cornubian Island is a region with no post-Carboniferous cover
161 surrounded by a belt of on- and offshore areas bearing only a thin post-Carboniferous cover (Hart,
162 1999). This suggests an entire post-Paleozoic history spent above sea level, and thus indeed a “great
163 lost interval” of geological history wide open to interpretation. Not before mid-Cretaceous time did
164 shallow marine glauconitic bioclastic sand (Greensand) advance from the east as far as the Bovey
165 Basin (Gale, 2012a), but without consensus over whether Dartmoor was flooded either then or
166 subsequently during the maximum sea levels of the late Campanian (e.g., Smith, 1961; Lidmar-
167 Bergström, 1986). As during the early Cretaceous (Gale, 2012b), Paleogene shores once again
168 skirted around the modern coasts of Devon and Cornwall (Gale et al., 2012), never flooding the
169 Cornubian landscape.

170 Whether the relative buoyancy of the Cornubian Island since the Variscan Orogeny has been purely
171 a matter of passive crustal response to rock decay and erosional unloading is debatable.
172 Unfortunately, the study of intraplate uplands such as Dartmoor and other British uplands studied
173 by Clayton and Shamoan (1998, 1999), where the apparent amplitude of crustal deformation (< 1

174 km) is two to three orders of magnitude smaller than its wavelength, has stumbled on establishing
175 the physical mechanisms responsible for the observed land surface deformation (Şengör, 2003;
176 Bessin et al., 2015). Efforts to quantify and explain epeirogeny have been persistently hampered by
177 the insensitivity of geochronological methods to low-amplitude and low-velocity vertical crustal
178 movements. Some hypotheses indirectly relevant to Dartmoor have been addressed by recent
179 literature on the geophysics and geodynamics of the North Atlantic and the British Isles (e.g., Anell
180 et al., 2009). The main candidates, deemed responsible during the Cenozoic for either transient or
181 permanent vertical motion of Devon, are:

182

- 183 • Crustal thickening caused by magmatic underplating at the southern tip of the British Cenozoic
184 Igneous Province (BCIP) (Brodie and White, 1994);
- 185 • dynamic uplift, which may reflect Iceland-plume-related asthenospheric processes acting on
186 Britain from below (Bott and Bott, 2004; Arrowsmith et al., 2005; White et al., 2013);
- 187 • buckling of the crust, either in response to far-field oceanic ridge push in the Atlantic (Hillis et
188 al., 2008; Holford et al., 2009) or because of tectonic inversion of the Mesozoic basins of
189 southern England during Neogene time in response to regional stresses generated by the Alpine
190 Orogeny and transmitted laterally northwards (Blundell, 2002; Gale et al., 2012);
- 191 • buckling of the lithosphere in response to Alpine collision (Cloetingh and Ziegler, 2015).

192

193 *2.2.1. Magmatic underplating*

194 Asthenospheric magmatism is understood to have impinged on the lithosphere beneath Britain at
195 least as far south as the Bristol Channel, with geochemical signatures in basic dykes on Lundy
196 Island (Fig. 1) compatible with a North Atlantic Igneous Province (NAIP) source despite being
197 located ~500 km south of the nearest BCIP igneous intrusion (Mourne Mountains, in Ulster) (Kent
198 and Fitton, 2000). Barely 70 km from Dartmoor and 35 km from Exmoor, Lundy Island is the apex
199 of an intraplate granite intrusion which was emplaced between 60 and 57 Ma, and thus bears no
200 relation to the Cornubian Batholith of Permian age despite speculation over this possibility for the
201 last 100 years (Charles et al., 2018). Precise evidence of crustal thickening by a BCIP-related
202 magmatic underplate is clearly tenuous, but the Lundy magmatism suggests this hypothesis cannot
203 currently be ruled out.

204 After isostatically balancing crust and lithosphere, Davis et al. (2012) obtained a map of residual
205 topography for the British Isles. The signal in excess of +300 m for SW England was the only place
206 south of western Scotland (bar Anglesey) displaying such a strong anomaly. Among three different
207 classes of Moho interface geometry identified beneath Britain, Davis et al. (2012) also found that
208 the regions of high lower-crustal P-wave velocity detected beneath Scotland, the northern Irish Sea,

209 and SW England were associated with gradational, rather than sharp or layered, Moho interfaces.
210 These features also coincided with loci of Paleocene BCIP magmatism, and while the fast seismic
211 layer was thickest beneath Scotland, it also displayed a smaller but distinctive patch ~6 km thick
212 beneath Devon and central Cornwall. Such a magmatic underplate at depth can generate ~0.6 km of
213 permanent uplift at the surface (Brodie and White, 1994), which is a magnitude compatible with the
214 elevations of Dartmoor and Exmoor.

215

216 2.2.2. *Dynamic uplift*

217 Based on teleseismic P-wave travel-time patterns from 148 seismic stations across the British Isles,
218 Arrowsmith et al. (2005) detected three major low-velocity anomalies, distinguishable at depths of
219 100 km beneath western Scotland, the Irish Sea and western England, with a slightly weaker outlier
220 in SW England and the Bristol Channel. The anomalies, which as mentioned above coincide with
221 topographic anomalies and Paleogene magmatism, also coincide with positive gravity anomalies.
222 Given their magnitudes and matching spatial incidence, they were interpreted as an indication of
223 upwelling in the upper asthenospheric mantle rather than as compositional anomalies in the
224 lithospheric mantle or the crust.

225

226 2.2.3. *Crustal buckling and tectonic inversion*

227 Alternatives to underplating or dynamic uplift have focused on the effects of Atlantic ridge-push
228 forces (Hillis et al., 2008), and on far-field Alpine contributions to crustal uplift in and around
229 southern England. Throws of up to 700 m on reverse faults have been reported, for example, in the
230 Western Approaches Basin (Fig. 2; Le Roy et al., 2011); and tectonic inversion of the Weald and
231 compressional deformation of the Hampshire and Wessex Basin stratigraphies are well documented
232 (e.g., Chadwick, 1993; Blundell, 2002; van Vliet-Lanoë et al., 2002). The Purbeck–White
233 Disturbance (PWD), for example, is a well-studied example of extensional fault inversion in Dorset
234 (Underhill and Patterson, 1998). The strike-slip NW–SE Watchet–Cothelstone Fault (WCF, Fig. 2;
235 Dart et al., 1995) links the PWD to the Bristol Channel through Somerset and is likely a Variscan
236 wrench fault that became reactivated as part of the European Cenozoic Rift System (ECRiS) under
237 the regional Pyrenean and Alpine stress regimes, perhaps with mid-Atlantic ridge push countering
238 the forces from continental Europe in backstop fashion.

239 Nearly 70 km west of the WCF and exactly parallel to it, the Lustleigh–Sticklepath Fault (LSF;
240 Figs. 2, 4) strikes through the Dartmoor granite and extends to Lundy Island (while also quite
241 obviously guiding the strike of the lower Torridge River valley in north Devon; Fig. 1). The LSF
242 and WCF both share similar Paleogene deformation histories (Holloway and Chadwick, 1986).
243 Around Lundy, evidence of Cenozoic inversion of Mesozoic extensional faults has been

244 documented (Dart et al., 1995). Relays along the segmented LSF zone have acted as releasing bends
245 to produce three pull-apart basins: the Bovey, Petrockstowe and Stanley Bank (Lundy) basins,
246 which performed as very focused tectonic depocentres and are filled with Eocene to Oligocene
247 fluvial and lacustrine gravel, sand and clay with thin lignite beds.

248

249 *2.2.4. Lithospheric buckling*

250 Basin inversion and transtensional wrench-faulting of the ECRiS along reactivated older structures
251 in response to Alpine collision appear to have been additionally superimposed on a continental-
252 scale corrugated pattern of surface deformation initiated around 35 Ma. This is argued to have
253 produced a succession of 225–275-km-wavelength, low-amplitude cylindrical undulations striking
254 ENE–WSW and involving the entire lithosphere (Bonnet et al., 2000; Bourgeois et al., 2007).
255 Bessin et al. (2017) proposed that most of Brittany was located in one of these lithospheric furrows,
256 which would explain that from 30 Ma to 3.6 Ma Brittany underwent 60–70 m of subsidence,
257 allowing various marine transgressions to occur there. Under this scenario, the Cornubian Island
258 (Hart, 1999) may have coincided with the nearest of these lithospheric upwarps to the north of
259 Brittany (Fig. 2).

260

261 *2.2.5. Cenozoic uplift in SW England: persistent uncertainties*

262 Whatever the exact causes of epeirogeny among those listed above, crustal deformation is
263 considered to have generated 1–2.5 km of surface denudation in southern Britain during the
264 Cenozoic (Clayton and Shamooin, 1999; Hillis et al., 2008, Holford et al., 2009). These inferences
265 are based largely on apatite fission-track thermochronology. While the reconstructions recognise by
266 default the long-term persistence of the Cornubian Island throughout the Cretaceous and Cenozoic,
267 SW England actually remains undocumented by low-temperature methods and thus forms a gap in
268 the regional dataset. Spatial interpolation of the fission-track data from the surrounding on- and
269 offshore sedimentary basins postulates 1–1.5 km of rock exhumation over Devon (Hillis et al.,
270 2008), but this is based on exhumation depths for the peripheral regions, which themselves fall
271 short of a consensus. Disagreement arises from (i) controversies concerning the geophysical and
272 balanced cross-section methods for estimating the original thicknesses of lost material (e.g., over
273 the Wessex–Weald basins; see White et al., 2013 for a critique); and more generally (ii) from
274 divergent approaches to inferring Cenozoic crustal denudation depths from vitrinite reflectance and
275 low-temperature thermochronology. Rock-cooling estimates obtained from apatite fission-track
276 analysis typically depend on estimates of the geothermal gradient at the time of uplift, on the
277 possibility of fluid circulation in the crust, on the parameterization of fission-track annealing
278 behaviour (Gunnell, 2000; Dempster and Persano, 2006), and on spatial variations in crustal heat

279 production and rock thermal conductivity (for an extended understanding of this enduring debate
280 for Britain, see e.g., Bott, 2013; White et al., 2013; Łuszczak et al., 2017, 2018). Accurately
281 estimating depths of denudation over shorter (<10 km) to longer (~100 km) wavelengths (Hillis et
282 al., 2008) obviously also bears on potential estimates of the isostatic response to crustal unloading
283 at similar wavelengths, and thus of net uplift in southern Britain (e.g., Clayton and Shamon, 1999;
284 Holford et al., 2009).

285

286 **3. The granite outcrop and its mesoscale landform-producing potential**

287

288 Whether the potential drivers of epeirogeny examined above are mutually exclusive or acted
289 cumulatively is an open question, but they each constitute plausible inputs of potential energy into
290 the land surface for promoting the differential erosion which has occurred between the granite
291 (Dartmoor) or sandstone (Exmoor) and the other rocks and outcrops of the SW peninsula.

292

293 ***3.1. Pluton architecture and petrography***

294

295 Given that the upland is surrounded by fairly steep (10–20%), outward-facing inclines roughly
296 coinciding with the outer envelope of the pluton, the topographic mass of Dartmoor is clearly also a
297 second-order consequence of differential erosion between the granite and its metamorphic country
298 rock. The Cornubian Batholith comprises an amalgamation of shallow sheeted laccoliths which
299 were dyke-fed from a common melt region in the lower crust or upper lithospheric mantle during
300 the early post-orogenic extensional stages of the Variscan fold–thrust belt (Pownall et al., 2012;
301 Simons et al., 2016). The Dartmoor intrusion exploited the Devonian–Carboniferous interface in the
302 country rock and is shaped like a lopolith with a steep feeder along the southern border and outward
303 extrusion to the north (Taylor, 2007).

304 The presence of metamorphic roof pendants (contact-altered sedimentary rock), e.g., on Standon
305 Down and near Sharp Tor (Fig. 4), indicates that post-Variscan continental denudation, after having
306 removed some kilometres of overlying country rock (Ward et al., 1992; Chesley et al., 1993;
307 Taylor, 2007), has merely scratched the surface of the pluton itself. Intense tin mineralisations,
308 which would represent the ‘roots’ of mineral lodes eroded away and now leaving the cassiterite (tin
309 oxide) residate near the surface, also testify to the shallow depths of erosion below the pluton roof.
310 The deepest excavations for Sn ores on Dartmoor lie no more than ~70 m below the surface, and are
311 therefore one order of magnitude shallower than in Cornwall.

312 The rock mass is not uniform and displays three petrographic facies. The Roof Complex is an outer
313 envelope of porphyritic monzogranite that formed at the interface with the country rock and

314 involved partial assimilation at the magma margins (Ward et al., 1992). It has been dubbed ‘giant
315 granite’ because it contains up to 30% megacrysts of perthitic potassium feldspar set in a coarse-
316 grained matrix of quartz, 7–11% biotite, plagioclase, and some tourmaline (Cobbing and Clarke,
317 2006). The deeper-seated biotite granite (Ward et al., 1992), or ‘blue granite’, is finer-grained,
318 contains albite, up to 40% quartz, and a much lower density of K-feldspar megacrysts. It has been
319 the main target of the quarrying industry (e.g., Brunnsden, 1968), contributing to such monuments in
320 London as Nelson’s column in Trafalgar Square or the New London Bridge (1825–1831; Booker,
321 1970). The third facies is a leucocratic variant of the ‘giant granite’. It was generated by magmatic
322 brecciation (Ward et al., 1992; Cobbing and Clarke, 2006), and occurs for example as a sheet at the
323 base of Hound Tor (Fig. 3) and Corndon Tor. It is also quarried and is not known to form tors.
324

325 ***3.2. Jointing, pseudo-bedding, and magmatic layering***

326

327 Even in the absence of tensile tectonic stresses, the removal of country-rock overburden causes
328 plutonic rock masses to adjust to new pressure levels, with the rock expanding in all directions
329 normal to the former axis of loading. As a result, granite outcrops on Dartmoor exhibit at least two
330 mutually suborthogonal vertical joint sets. Waters (1957) held the variability of joint density on
331 Dartmoor as a major passive control on the genesis of mesoscale topographic patterns. Given the
332 rectangular pattern made by summit tors, cols, gorges and basins illustrated in Figure 6, Waters
333 inferred that the alignment of tors with valley gorges succeeded by alignments of cols with valley
334 basins coincided with alternating bands of sparser and denser parallel fractures.

335 Another important feature is internal layering within the Roof Complex granite. This pseudo-
336 bedding plays some role in tor disintegration and was described by de la Beche (1839, p. 163) as
337 “stratiform cleavage”. Pseudo-bedding (puff pastry appearance in Figure 7a) is widespread among
338 granite tors generally (Migoń, 2006). The pseudo-beds curve away from their horizontal attitude at
339 the tor itself and tend to dip parallel to the adjacent topographic slopes (Fig. 7b). Rather than an
340 expression of stress release parallel to the topographic surface as a consequence of denudation (so-
341 called offloading joint theory, wherein slope-parallel joints are thought to be expressions of
342 diminished lithostatic pressure caused by valley incision: McMahon, 1893; Waters, 1954), pseudo-
343 bedding is rather a primary structural feature resulting from magmatic cooling processes
344 (Brammall, 1926; Worth, 1930; Coque-Delhuille, 1987). Evidence that the pseudo-bedding formed
345 prior to the end of igneous activity comes from (i) late magmatic minor intrusions at Bellever Tor,
346 vertical aplite veins at Honeybag Tor, and other cross-cutting relations at Beardown Tor and on the
347 south side of Heltor; and (ii) the relationship between pseudo-bed geometry and magmatic
348 lineations in the rock fabric. At Blackingstone Rock, for example (Fig. 7c, d), Coque-Delhuille

349 (1987) mapped flow structures in individual pseudo-beds by measuring the pitch and strike of the
350 abundant feldspar phenocrysts. She concluded that their orientation patterns documented the
351 attitude of the roof contact and evidenced a sequential injection of planar sheets of magma.

352 A number of hillslopes are controlled by structural dips in the granite. Asymmetric tor-bearing
353 ridges are homoclinal structures in the granite (Coque-Delhuille, 1987); examples include: Hay Tor
354 Rocks (Fig. 7e, f, g); nearby Rippon Tor, where the Roof Complex caprock dips *ca.* 11° to the
355 south; and Belstone Tor (north Dartmoor). The pluton roof likely presented substantial topography
356 because of irregular contact with the country rock. Worth (1930), for example, ascribed the
357 wavelength of structural inflexions in the pseudo-bedding planes to moulding of the igneous mass
358 to the undersides of folds in the encasing metamorphic series. At least some tors would thus be
359 situated at the apices of granite bumps with diameters of 0.1–1 km, where the structural planes in
360 the granite dip radially away from the tor towards negative structural inflexions in the pluton's
361 upper surface (e.g., Brat Tor, Fig. 7b). This could imply that structural highs on the embossed
362 surface of the pluton are future placeholders for clusters of summit tors, and that rock weathering
363 patterns will naturally tend to follow the structural basin structures.

364 Systematic verification of these structural features has not been conducted on Dartmoor, but similar
365 lines of evidence have been provided by Volborth (1962) and Cunningham (1971), who studied the
366 location and structure of granite outcrops in Nevada and Idaho, respectively. Both studies
367 emphasised the original interaction between magma and country rock and its role in subsequently
368 guiding the action of surface and subsurface weathering processes, with inselberg domes coinciding
369 with cupolas where exposure depths were structurally still close to the pluton roof.

370

371 **3.3. Bedrock decay and its products**

372

373 Rock weathering contributes fundamentally to landscape evolution, and in igneous rocks this
374 involves transformation *in situ* of primary to secondary minerals: typically clay minerals. The
375 characteristic products of rotten granite in SW England classify as (i) grus, or growan (which, like
376 'tor', is another vernacular name from SW England gifted to international geomorphology;
377 Brunsden, 1964); and (ii) china clay, i.e., kaolin (relatively pure kaolinite). Where it is mined in
378 high quantities, china clay is indisputably of hydrothermal origin. Grus results instead from *in-situ*
379 granular disintegration of the bedrock under subaerial conditions, and is areally the most
380 widespread variant. This arenaceous material is relatively vulnerable to entrainment by hillwash,
381 piping, spring sapping, gulying, and freeze–thaw-related processes. Ball clays, which occur *ex situ*
382 as sedimentary deposits in tectonic basins along the LSF (Bovey and Petrockstowe), are a mixture

383 of kaolinite (20–95%), micaceous minerals (5–45%), and quartz (1–70%), and result from the
384 erosion of heterogeneous weathering products (Vincent, 1983).

385 Dartmoor grus profiles also contain (i) kaolinite, a clay mineral considered diagnostic of humid
386 tropical conditions; and (ii) gibbsite, a secondary mineral normally absent from hydrothermal
387 environments and usually indicative of intense silicate weathering typical of the tropics. As a result,
388 much debate has focused on establishing whether the kaolinite at any given location was of
389 hydrothermal rather than of meteoric origin, and whether it could confidently be used as a
390 diagnostic mineral for inferring palaeoclimatic conditions in SW England.

391 China clay works started at Lee Moor (Fig. 3) in 1830, and other analogous deep weathering
392 profiles occur on Dartmoor (Fookes et al., 1971) and among the Cornish stocks. Detailed
393 understanding of economic-grade kaolin formation in granite around the world owes much to the
394 early study of its occurrences in SW England (e.g., Bromley, 1989; Floyd et al., 1993; Bristow and
395 Exley, 1994; Tierney and Glass, 2016), highlighting for example that the presence of friable rock
396 beneath sound bedrock is diagnostic of hydrothermal weathering (e.g., Cunningham, 1971). This
397 aspect is illustrated by the construction of Burrator reservoir on the upper Plym River (Sandeman,
398 1901), which necessitated the addition of a 30-m-deep concrete cut-off wall into the deeply rotten
399 granite of that area. Borehole records for the Cowsic and Harter valleys also report alternating
400 layers of sound and unsound granite, with the unsound granite occurring up to ~40 m below the
401 surface (Palmer and Neilson, 1962). This “unsound granite” tended to increase in the direction of
402 valley bottoms, whereas ridges largely consisted of sound rock. Palmer and Neilson added:

403 “we find it impossible to explain such depth of weathering by the action of percolating
404 ground water, since the water-table is now and presumably always has been high under
405 the valley floors. Especially in Tertiary times one would expect that the wetter climate
406 and undoubtedly higher base-levels of erosion would have kept the water-table high and
407 greatly limited the depth of decomposition under valleys. If the decay is the result of
408 pneumatolytic processes, which penetrated the rock with a ‘cedar-tree’ laccolith
409 structure, then the considerable thickness involved, the alternation of rotten and firm
410 rock, and the valley floor position may all be readily explained”.

411 Alongside those emblematic occurrences of abundant kaolinite, depths of grus on Dartmoor are
412 variable but do not exceed 10 m; they are thus similar to other crystalline uplands of Europe
413 (Gerrard, 1988a; Godard et al., 2001; Migoñ, 1997). Given the abundance of poorly weathered
414 feldspar, low proportion of clay minerals, and minimal alteration of quartz-grain surfaces
415 (Doornkamp, 1974), the weathering intensity of grus is characteristically restrained compared to
416 saprolite in humid tropical regions. Mineralogical criteria, however, have their limitations as
417 palaeoclimatic indicators. For example, the presence of gibbsite in small quantities does not rule out

418 its neoformation under humid temperate conditions in well-drained hillslope environments (Green
419 and Eden, 1971; Dejoux, 2007). Conversely, crystallographic criteria for distinguishing hydrothermal
420 kaolinite (high mineralogical purity: Eden and Green, 1971; high kaolinite crystallinity: Vincent,
421 1983) from its meteoric variety do not conclusively rule out the impact of hothouse conditions on
422 rock decay during the Mesozoic, the Paleocene–Eocene Thermal Maximum (PETM), or even more
423 recently. Some geomorphologists (Linton, 1955; Fookes et al., 1971; Dearman and Fookes, 1972)
424 thus envisaged that a number of weathered granite profiles, though now largely stripped of their
425 upper (and potentially more characteristic) weathering horizons, were a legacy of earlier tropical
426 conditions. A kaolinite-rich weathering profile buried beneath Paleogene sediments in the
427 Petrockstowe Basin likewise supports that view (Bristow, 1968). Stripping of these tropical
428 weathering fronts would have occurred during the Pleistocene, only preserving a patchwork of
429 residual pockets.

430 Absence of evidence is not evidence of absence, but this putative stripping event, if correct, is not
431 well documented. Emphasising a more parsimonious approach, Hall and Sugden (2007) thus argued
432 instead that extant weathering depths on Dartmoor were too modest for a tropical model to be
433 realistic: grus found in patches across Dartmoor would have formed primarily during the middle
434 and late Pleistocene. This is plausible given the high annual rainfall today (e.g., 2100 mm/yr at
435 Princetown, with maxima of 2500 mm/yr in the highest part of the moor, as opposed to 1300 mm on
436 the leeward eastern edge and 800–1000 mm on the surrounding lowland). Thin grus was likely
437 regenerated and removed during each interglacial–glacial cycle. Inferring catchment-wide, spatially
438 averaged denudation rates in the Dart, Walkham, East Okement and West Okement river
439 catchments from ^{10}Be inventories in quartz from channel sediments, Hägg (2009) concluded that, in
440 the majority ($n = 13$), these denudation rates ranged between 20 and 40 $\text{mm}\cdot\text{ka}^{-1}$. They were evenly
441 distributed across the landscape and only slightly lower than the regolith denudation rate (38–62
442 $\text{mm}\cdot\text{ka}^{-1}$). Hägg's results thus tentatively support the alternative view that Quaternary climatic
443 conditions were able to maintain a balance in favour of shallow regolith production, never quite
444 superseded in the Dartmoor environment by erosional stripping.

445 Ultimately, the competing lines of argument do not strictly rule each other out, and evidence for this
446 is perhaps best documented *ex situ* from ball-clay occurrences off Dartmoor. Ball clays quarried
447 from the Bovey Basin contain a highly variable admixture of ordered (i.e., china clay) and
448 disordered kaolinite (the latter, diagnostic of meteoric neoformation, displays a higher degree of Al
449 substitution for Fe at certain lattice sites). The kaolinite thus originates potentially from two
450 sources. Meanwhile, the Petrockstowe Basin (Fig. 1b) contains only disordered kaolinite. Given
451 that the Petrockstowe ball clays are derived locally and exclusively from the Culm Measures (no
452 plausible input from granite; Fig. 1b), Vincent (1983) concluded that in the Bovey Basin the

453 hydrothermal (china) clay component must have been supplied by the Dartmoor granite, whereas
454 the disordered kaolinite component was supplied by meteoric weathering of the granite as well as of
455 its country rock. A tropical climate during the Cenozoic, regionally impacting the Cornubian Island
456 and all of its lithological outcrops, thus cannot be ruled out. What proportion of this inherited
457 regolith is preserved in the landscape remains the largest unknown.

458

459 **3.4. Dartmoor's tors and their disputed origin**

460

461 Being the only large, potentially un-glaciated granite outcrop of the British Isles (but see Section
462 5.2), and displaying kaolinite and inselberg-like features such as Hay Tor Rocks (Fig. 7e, f, g),
463 Dartmoor became an English test bed for linking British landforms with palaeoclimates (Gerrard,
464 1994a). Indeed, as the only bedrock features on the moor apart from the river gorges, Dartmoor's
465 granite tors appear to have resisted the onslaught of weathering. Because of their eye-catching
466 prominence in the landscape they also hold pride of place in the literature.

467

468 **3.4.1. Petrographic controls on Dartmoor's tors**

469 Dartmoor tors are primarily sculpted out of the K-rich Roof Complex, which has been spared from
470 intense quarrying. The 'giant granite' forms an incomplete envelope around the core of 'blue
471 granite' (Hawkes, 1982), nominally suggesting that areas of northern Higher Dartmoor where tors
472 are scarce, e.g., around High Willhays and Cut Hill, are natural windows of 'blue granite' in the
473 'giant granite' (Fig. 4). The spatial coincidence between the absence of tors and outcrops of granite
474 containing less than 10% of K-feldspar megacrysts, however, is not systematic (Fig. 4), so that tors
475 in certain areas may indeed (i) not exist because of geological reasons, but may also (ii) have
476 previously existed but been destroyed by decay or denudation; or (iii) have never developed widely
477 because they are located at drainage-divide areas, whether on northern (e.g., around Cranmere Pool)
478 or southern Higher Dartmoor (Figs. 4, 7). Rather than promoting bedrock exhumation, delayed river
479 incision would have preserved the weathering mantle and ensured instead the development of
480 Dartmoor's peat thickness maxima (well in excess of 2 m in those areas; Simmons, 1963).

481 Petrographic criteria unrelated to mineralogy may also explain the tor-no-tor dichotomy on
482 Dartmoor. Based on (i) thin section analysis (and incorporating the conclusions of Brammall and
483 Harwood, 1932, and Edmonds, 1968); on (ii) mercury porosity measurements on specimens in the
484 laboratory; and on (iii) outcrop-scale joint spacing counts (a proxy for estimating outcrop
485 perviousness to rainwater), Coque-Delhuille (1987) elaborated a bedrock weatherability scale for all
486 of the granite outcrops in SW England. In addition to the low perviousness of the bedrock ascribed
487 to wider primary joint spacing at tors than between tors, she concluded that the 'giant granite' owed

488 its resistance less to its mineralogical composition (counter-intuitively, for example, it contains less
489 quartz and more biotite and Ca-plagioclase than the ‘blue granite’) or to its texture (it exhibits
490 greater grain-size heterogeneity) than to its physical properties featuring low porosity and low
491 permeability.

492

493 *3.4.2. Tors as two-stage, warm-climate landforms*

494 Although de la Beche (1839) surmised that the granite boulders of SW England acquired their
495 shapes after exposure, he later integrated the notion that boulders also formed during subsurface
496 weathering (see Twidale, 2002). Linton (1955) defined a tor as “a residual mass of bedrock
497 produced below ground level by profound rock rotting effected by groundwater and guided by joint
498 systems, followed by a phase of mechanical stripping of the incoherent products of chemical
499 action” (Fig. 8a, b). Linton’s work addressed tors across Britain, but his keystone evidence relied on
500 the discovery of a buried tor in a quarry in central Dartmoor, corroborated by Handley’s (1952)
501 report that tors in Tanzania had a subsurface origin in warm and wet climates. Once exposed, the
502 tors retain their shape but continue to evolve subaerially (Fig. 8b).

503 Linton’s academic authority and persuasive style brought the subject of tors to the attention of
504 international geomorphology from a British vantage point, its type area being Dartmoor. Linton
505 speculated that deep chemical weathering by acidic groundwater under a tropical climate was
506 responsible for the formation of tors. The elegant logic of his two-stage theory was soon followed
507 by a flourish of extrapolations to much larger bedrock landforms in the Tropics, all emphasising the
508 importance of joint control (e.g., Ollier, 1959; Mabutt, 1961; Nossin, 1964; Thomas, 1965).

509 Debate soon broadened to whether mechanical erosion lowers the land surface at the same rate as
510 chemical etching lowers the irregular weathering front (theory of “double planation”: Büdel, 1957,
511 but ostensibly unknown to British geomorphologists at the time of its publication in German); or
512 whether a phase of deep chemical weathering precedes a phase of regolith stripping, as advocated
513 by Linton (1955). Discrete episodes of deep weathering followed by stripping can be envisaged in
514 settings subjected to abrupt base-level changes and/or climatic or land cover changes (Fig. 9).
515 Multiple stages of weathering and stripping have since been advocated as more realistic, suggesting
516 that at least larger bedrock landforms develop incrementally rather than just in two stages (Thomas,
517 1974; Gunnell et al., 2007).

518

519 *3.4.3. Tors as one-stage, cold-climate landforms*

520 Linton’s two-stage theory, tenuously imagined from an exposure in a Dartmoor quarry, was soon
521 challenged on its home ground by a one-stage model incompatible with climatic conditions in the
522 tropics. Following precursor ideas in Peltier (1950), Palmer and Neilson (1962) focused on the

523 widespread existence of angular tors in Britain to argue that they were the result of frost attack
524 assisted by debris evacuation via the permafrost's active layer on the surrounding hillslopes (Fig.
525 8c). By advocating that the Dartmoor tors had formed subaerially rather than in the subsurface,
526 Palmer and Neilson implicitly dictated that any Dartmoor kaolinite was chiefly hypogene (and thus
527 early Permian), ruling out any preservation of Cenozoic supergene kaolinite (the latter being a
528 strong requisite for the incubation stage 1 of Linton's two-stage tors). At about the same time,
529 Demek (1964) and Czudek (1964) elaborated a theory of lateral planation in which flat surfaces on
530 upland interfluves covered by angular debris produced an angular stump of residual bedrock which
531 they also called a tor (see also Martini, 1969). In this scenario, any regionally extensive population
532 of flat-lying topographic benches (known as cryoplanation terraces, which mimic pediment
533 development on a small scale; Bryan, 1946) was held to be a direct consequence of local frost
534 action.

535 Cryoplanation terraces and their associated one-stage tors are not, however, widespread on
536 Dartmoor. They are confined to highly fissile, non-granitic outcrops of the metamorphic aureole (Te
537 Punga, 1956; Gerrard, 1988a; Foster, 2003) and were studied by Waters (1962). An example is Cox
538 Tor (Gerrard, 1983), a metadolerite outcrop surrounded by hornfels and separated from the two
539 granitic Staple tors by a col in the Devonian slates of the metamorphic aureole. The rock-cut
540 terraces on the south and north of the metadolerite residual are between 10 and 70 m wide and up to
541 800 m long, with tread gradients ranging between 3 and 8°. The upstanding rock residuals are 2–12
542 m high. Other such altiplanation surfaces have been reported around the metamorphic rim of
543 Dartmoor at East Hill, Sourton Tors, Lake Down, Southerly Down, Smeadon Down, Peak Hill,
544 Brent Hill, and Black Hill (Brunsden and Gerrard, 1970), and on Exmoor (Guilcher, 1950). Czudek
545 and Demek (1971) also make it clear from their overview of the Bohemian Massif that differences
546 between one- and two-stage tors hinged on differences in behaviour between granitic and
547 metamorphic rock materials: tor–terrace systems in the Czech uplands, but equally in the Pennines
548 (McArthur, 1981) and Shropshire (Clark, 1994), all involve fissile rocks such as quartzite, schist,
549 shale and gneiss. It thus becomes clear that one-stage tors in non-granitic rocks can coexist with
550 two-stage tors in granite.

551 In summary, tors are strongly lithology-dependent. Tors in metamorphic rocks are mostly shaped by
552 periglacial processes, whereas granitic tors (i) are confined to the coarse-grained Roof Complex,
553 and (ii) incubate below the surface. Tors of both modes coexist on Dartmoor (Campbell et al.,
554 1998).

555

556 **4. Dartmoor's long-term denudation chronology**

557

558 Given that Dartmoor is an elevated, petrographically and structurally heterogeneous (Section 2.2)
559 mass of granite (Section 2) which has been exposed to various forms of late-magmatic as well as
560 supergene rock decay under different climates (Section 3), the imprint of Earth surface processes on
561 the geological fabric of SW England has given rise to a litany of landscape evolution scenarios.
562 The peneplain and the etchsurface have been two particularly relevant scenarios. Whereas W.M.
563 Davis (1899) famously defined his vision of a peneplain as a mosaic of “broad swells of gentle
564 convexity between wide valley floors” and viewed landscapes as ordered assemblages of partial
565 peneplains of increasing antiquity with elevation, the etchsurface model (e.g., Thomas, 1994) views
566 the landscape instead as a random assemblage of topographic highs and lows each determined by
567 their local histories and local bedrock attributes. As such, peneplains and etchplains are essentially
568 antagonistic views of landscape evolution, partly constructed around divergent appreciations of (i)
569 the rate and intensity of base-level change, and (ii) the response and susceptibility of the granite
570 mass to relief-enhancing (rather than to relief-erasing) geomorphological environments. Dartmoor
571 scholars have embraced both of these theoretical end members as well as composite variants.

572

573 *4.1. Dartmoor as a staircase of partial peneplains*

574

575 The presence of low-gradient interfluves across Dartmoor tempted early authors to join the dots
576 between statistically accordant altitudinal levels and to reconstruct the treads of hypothetical
577 erosion surfaces. Jukes-Browne (1904) and Barrow (1908) thus identified a 1000 ft (300 m) and a
578 800–750 ft (240 m) surface (the latter conspicuous on Bodmin Moor), both assumed of marine
579 origin. Davis (1909), however, interpreted the land surfaces of SW England instead as being of
580 subaerial origin, and research remained subsequently locked in the continental vs. marine debate,
581 with further issues about how many surfaces (i.e., ‘stages’ of base-level stability) could be mapped
582 in the landscape (Green, 1941, 1949; Balchin, 1952, 1964; Wooldridge, 1954; Waters, 1960a;
583 Brown, 1961; Orme, 1964). Authors affiliated to the British School of Platforms, which was
584 strongly inspired by a Frenchman (Baulig, 1935) and his work on the uplands of the Massif Central,
585 produced maps of erosional benches on and around Dartmoor. This approach was later described by
586 Jones (1980) as “the British obsession with the role of marine erosion” among followers of
587 Wooldridge and Kidson.

588 Brunsden (1963) advocated 17 distinct levels, the topmost 6 being of continental origin and the 11
589 lower ones all of marine origin. This rose to 23 levels in Brunsden et al. (1964) when including
590 Orme’s (1960, 1964) many strandlines in South Hams and Kidson’s (1962) Quaternary alluvial
591 straths, fill terraces and marine benches of the rivers Exe and Dart (Fig. 10, 11, 12a). Simplified, the
592 surfaces could be aggregated into 4 distinct bundles: (i) the uppermost surface of Dartmoor, or

593 'Summit Peneplain', of subaerial origin ("anything closer than this form to a subaerial peneplain as
594 described by W.M. Davis would be difficult to imagine": Brunnsden, 1963), and sloping southward
595 between 600 m in North Dartmoor and 460 m in South Dartmoor; (ii) a second, extensive partial
596 peneplain *ca.* 400–320 m, separated from the former by a "youthful fringe" of scarps and residual
597 hills deemed "typical of the junction between two peneplains" (Brunnsden, 1963, 1968; Brunnsden
598 and Gerrard, 1970); (iii) a group of four gravel terraces or valleyside benches notched in the partial
599 peneplain and all lying above 230 m; and (iv) a flight of marine terraces, all situated below the
600 highest (allegedly) marine shoreline known as the 690 ft bench (210 m) (Figs. 10, 11).

601 In tune with the Wooldridge and Linton (1955) orthodoxy, the 210 m bench was deemed of
602 Pliocene (Calabrian) age (Kidson, 1962). This Pliocene '210 m strandline', also widely reported in
603 the chalk scarplands of southern England (e.g., North Downs, Chilterns), was considered to have
604 been formed during a marine highstand, not considering that it may have formed at much lower
605 elevations and later been uplifted by crustal movements, or that it was something entirely different.
606 A critique of the Calabrian transgression hypothesis, which is no longer tenable, has been provided
607 by Jones (1980, pp. 112–125).

608

609 ***4.2. Pediments with inselbergs I: Dartmoor as a pediplain***

610

611 In a paper on "the canons of epigene landscape evolution", King (1953) had rejected the Davisian
612 concept of the peneplain prevalent in Britain. He used the "small and difficult example of
613 Dartmoor, Southern England" to underpin his views, and decreed that Dartmoor had

614 "the characteristic curve of pediments when the oldest ridge crests are viewed in profile,
615 and the famous tors are identical with the castle-kopje residuals of the Rhodesian veld.
616 There, apparent to the trained eye, was an ancient landscape which had reached the
617 penultimate stage in the pediplanation cycle. The dissection of the ancient summit
618 peneplain is far advanced, and indeed a second partial cycle was already developed
619 presumably before the end of the Tertiary. This younger landscape, still older than the
620 main dissection of the region, stands 300–500 feet below the original surface around
621 Postbridge, and itself shows small local pediments".

622 Accordingly, the Dartmoor surfaces were thus not the product of cycles of erosion involving stream
623 erosion and downwearing of the divides: they were instead a miniature version of the vast
624 pediplains that King himself had described in semi-arid Africa (Fig. 9a). It followed that Dartmoor
625 must be a relict tropical landscape situated on the 50th parallel. The controversy did not, however,
626 last beyond the short epistolary exchange between Linton and King (1958) because it turned out
627 King was mistaken on two counts: firstly, the granite landforms, whether inselbergs or tors, were

628 not characteristic of any particular climatic environment and were primarily controlled by bedrock
629 attributes (e.g., hardness, joint spacing). They were, in that sense, perceived until further notice as
630 landforms in the formation of which climate played a subsidiary role. Secondly, the land surface of
631 Dartmoor does not display any of the slope features typical of a pediplain, with concave slope
632 profiles connecting to escarpments that show evidence of recession as the pediments expand at the
633 expense of residual uplands. Instead, slope profiles on Dartmoor are characteristically convex and
634 convexo-concave, i.e., with a distinctly broad upper convexity as in most Variscan uplands (Godard
635 et al., 2001). Dartmoor has definitively been ruled out as a pediplain and the dogmatic controversy
636 of 1958 essentially retains historical value.

637
638 ***4.3. Pediments with inselbergs II: Dartmoor as a dome-flank benchland***

639
640 Klein (1924–2005) conducted systematic mapping of the basement uplands of Europe, and
641 produced a 1:100,000 scale geomorphological map of Dartmoor (Klein, 1990; Fig. 13). Klein
642 interpreted Higher Dartmoor as a three-tiered, Cenozoic dome-flank benchland, or Piedmontreppen
643 *sensu* Penck (1925), each pediment (i.e., surfaces S1, S2, S3) displaying its contingent of
644 unconsumed bedrock residuals (i.e., tors). His theory chimes with the views of King in descriptive
645 terms, with skyline tors occurring on interfluvial summits, and subskyline tors ornamenting the
646 dome-flank erosional benches, but not in terms of King's process of pediment development by
647 scarp retreat.

648 Klein's model of updoming in response to low-magnitude epeirogeny was equally advocated for
649 Bodmin Moor, and for the Vendée and other minor basement uplifts around the fringes of
650 Armorican Massif; and likewise for the Ardennes, the Limousin and Montagne Noire (Massif
651 Central), and parts of the Sudetes, as if uplands of any kind of topographic wavelength were eligible
652 to this doctrine. Klein was fundamentally inspired by the views of the German geologist Hans Stille
653 on the Mittelgebirge of central Europe, and on that basis anxious to test on a wide range of
654 European uplands a parsimonious hypothesis that avoided two excesses he had noted among his
655 contemporaries:

- 656 (i) the excesses of ultra-Davisian geomorphology, which had overenthusiastically multiplied
657 erosion surfaces in many uplands of the world including Dartmoor (although Klein apparently
658 knew nothing of the work summarised in Brunsden et al., 1964);
659 (ii) a tendency to over-emphasise faulting and neotectonics in Variscan uplands where, apart
660 from the obvious extensional fault systems of the ECRiS, Cenozoic updoming of crystalline
661 basements in stable platform regions should, according to Stillian theory, involve minimal fault
662 offsets (see Şengör, 2003, on Stille and the historical debates over epeirogeny). Crustal

663 deformation, according to Klein, was continuous, so that the periodic intervals of base-level
664 stability postulated by Davisian geomorphologists, which in theory allowed partial peneplains to
665 develop sequentially, were fictitious.

666 Klein's work broke the mould of the French as well as (unwittingly) the British orthodoxy, but his
667 constructs were untimely and have had limited traction on modern thinking. In advance of the
668 current literature on asthenosphere-driven dynamic uplift or on far-field crustal stress regimes (see
669 Section 2.2), Klein was not able to draw on some of those plausible geodynamic drivers to underpin
670 his geomorphological intuitions.

671 672 **4.4. Backlash against peneplains: Dartmoor rebranded as an etchplain**

673
674 Jones (1980) has named "stagnation phase" the critical transition period between 1962 and 1970
675 when British geomorphologists were still ploughing the Davisian furrow initiated in the 1920s by
676 Wooldridge, but with diminishing zeal and waning conviction. The cyclic nature of the Dartmoor
677 landscape was irrevocably abandoned by the early 1970s, with Brunsden himself recognising much
678 later that his own thesis on Dartmoor (at King's College, London University, under Sydney
679 Wooldridge) was "an artefact of the mapping methods and definitions used at that time" (Brunsden,
680 2007).

681 The Dartmoor landscape was thenceforth to be interpreted by John Gerrard, a younger postgraduate
682 student working at King's College under Denys Brunsden, as topography governed solely by the
683 "chance exposure" (Gerrard, 1974) of certain granitic outcrops through the interplay between joint
684 density and the drainage network. From an orderly staircase of partial peneplains, river straths and
685 marine benches (Section 4.1), Dartmoor was now viewed as a self-organised landscape, resulting
686 from randomly distributed positive and negative feedbacks between bedrock structure, weathering,
687 and surface processes. Where joint spacing was narrow, weathering progressed faster and deeper;
688 during the regolith stripping phase, rock masses with more widely spaced joints, which weathering
689 processes take longer to consume, would emerge as residual islands (Fig. 9).

690 These processes were the nuts and bolts of an etchplain, or etchsurface (Fig. 9d). The etchplain
691 model had first been briefly considered for Dartmoor by Waters (1957), but this minority view
692 could not override the Davisian views of Wooldridge and Linton (1939, 1955) prevalent for
693 southern England at the time. Gerrard could thus presumably only safely resurrect and elaborate on
694 it after the passing of Wooldridge (*d.* 1963) and Linton (*d.* 1971), and he thereafter used
695 quantitative methods and statistics in most of his Dartmoor studies to elaborate on this new
696 perspective. The etchplain model has gained currency to describe similar upland terrain in other
697 parts of Variscan Europe (e.g., Migoń, 2006) and is suited to the idea that the Dartmoor landscape is

698 an unevenly stripped weathering front in which tors become exposed randomly at different
699 elevations as a consequence of drainage incision and rock resistance in response to base-level
700 changes. The etchplain could now be analysed as a mosaic of mesoscale landforms arranged in a
701 basic leitmotiv: tors and semi-enclosed etch basins.

702

703 *4.4.1. Tors and topography*

704 An important component of the etchplain model is the relationship between tors and topography.
705 The total population of Dartmoor tors exceeds 150 on 1:50,000 scale maps but is considerably more
706 at finer resolution. In SW England tors occur predominantly on Dartmoor and Bodmin Moor, with
707 only rare occurrences on the Cornish cupolas farther west (e.g., Carn Galver on the Land's End
708 granite). This situation has been explained by three factors (Coque-Delhuille, 1987): (i) fracture
709 density is lower and petrographic texture more varied on Dartmoor than among the other Cornish
710 granite outcrops; (ii) fluvial incision has been deeper on Dartmoor owing to greater magnitudes of
711 uplift, thus providing greater opportunities for export of weathered debris (as on Dartmoor, tors on
712 Bodmin Moor are more abundant on the periphery than in the less incised interior); and (iii) greater
713 mean elevations have ensured a more powerful contribution from Pleistocene gelifluction to the
714 evacuation of grus around the bedrock cores.

715 Under the etchplain paradigm, the individual tor is the basic building block of the Dartmoor
716 landscape. After the earlier distinctions between 'ridge tors' and 'valley-side tors' (Linton, 1955;
717 Waters, 1957), tor positionality was expanded to 'summit tors', 'valleyside tors', and 'spur tors'
718 (Gerrard, 1974, 1978; Ehlen, 1991, 1992, 1994). Summit tors (around which elevation contours are
719 arranged concentrically) are often massive, but sometimes also separated into two clusters by an
720 intervening, rock-free 'avenue': e.g., at Hound Tor (Fig. 3) Hay Tor (Fig. 7e), or Great Staple Tor
721 (Fig. 3). The avenue invariably bisects the axial part of the tor, where it can be hypothesised that
722 tensional stresses in the bedrock are highest and will facilitate penetration of weathering. Quite how
723 large rock debris get evacuated from a hilltop to form an avenue up to 70 m wide such as at Hay
724 Tor (Fig. 7e), however, is not entirely clear. Spur tors occur at lower elevations relative to the
725 nearest summit tors, standing as bedrock sentinels overlooking a valley. They are often
726 asymmetrical, exhibiting greater relief on the valley slope face and a more gentle backslope.
727 Valleyside tors are usually the tallest and most tower-like (e.g., Vixen Tor, 37 m tall).

728

729 *4.4.2. Drainage catchments and etch basins*

730 Green (1949) worked on the drainage network of Dartmoor and attributed its rectangular pattern to
731 drainage superimposition, i.e., to an imaginary scenario postulating that a cover of Cretaceous and
732 Eocene strata had once entirely covered the Dartmoor granite. Because the onlapping cover rocks

733 had transgressed from the east, their strike was N–S and their dip towards the east. East-flowing
734 rivers were thus interpreted as consequent streams, and subsequent streams north- and south-
735 flowing. The Dartmoor drainage would thus be a legacy of this ancient, hypothetical situation, with
736 southward tilting of SW England in the Neogene explaining why the south-flowing subsequent
737 streams are now dominant and form deeper gorges. Drainage superimposition theory was also
738 convenient for justifying the straight course of many rivers across, rather than along, the E–W strike
739 of the belted outcrops in the metamorphic terrain of Devon (Fig. 1).

740 Counter to Green's views, Waters (1957) advocated instead that the drainage (of an age impossible
741 to determine) was quite directly and very narrowly controlled by joint density in the granite.
742 Measuring joint spacing (Gerrard, 1974; Coque-Delhuille, 1987; Ehlen, 1991, 1992, 1994; Gerrard
743 and Ehlen, 1999) and characterising patterns in the drainage net (Waters, 1957; Gardiner, 1971;
744 Gerrard, 1974, 1989a, 1993) thus became a major focus of investigation thereafter. Gerrard (1974)
745 confirmed the local accordance between valley strike and joint direction in the Dartmoor granite.
746 Despite greater scatter among the higher-order streams, the similarity in orientation of joints and
747 stream courses was remarkably close, with (i) constant direction over the entire lengths of first-
748 order streams (stream order being a relative indication of stream power); and (ii) sharp, 90° changes
749 in direction from N–S to E–W, with a few minority intermediate orientations (such as NW–SE).
750 Using the blue-line network of 1:25,000 scale topographic maps, Gerrard (1989a, 1993) also
751 inventoried 27 third-order catchments wholly or partly draining the Dartmoor granite. The
752 population of stream catchments fell into four groups of increasing size (mean class sizes of 6 to 33
753 km²), all of uniform drainage density (1.1 to 1.2 km/km²), with mean watershed relief values
754 ranging from 284 to 420 m and all directly proportional to watershed size.

755 Gerrard and Ehlen (1999) later took the etchplain paradigm to its logical extreme by conveying
756 through a fractal analysis of joint and drainage patterns the notion of a uniform structural control on
757 landforms, i.e., from rock pavements to outcrops, and from lineations to the stream network. Scale
758 invariance of this kind was held as evidence that topography on Dartmoor is controlled primarily by
759 the fracture net at all scales (Gerrard, 1989a, 1993). Gerrard's (1993) maps of relatively uniform
760 drainage density (inversely proportional to length of slope profile affected by stream action) and
761 stream frequency (a spatial index of the efficiency of debris evacuation by streams) also indicate a
762 high degree of randomness in the distribution of these variables across the granite and suggest
763 isotropic behaviour of the geomorphic system on Dartmoor at third-order catchment scale.

764 The pattern of depressions and hollows on Dartmoor, however, is not exclusively controlled by the
765 nested hierarchy of fluvial catchments. Instead of dropping steeply to a fluvial valley, many tor-
766 bearing interfluves descend gradually to non-fluvial low cols and boggy hollows (Fig. 6b).
767 Likewise, the valley system itself features successions of rocky river gorges and widened valley

768 reaches (Fig. 6b). The semi-enclosed basins in each of these two topographic subsystems display a
769 range in sizes. Guilcher (1949), for example, had puzzled over the enigmatic upper West Dart basin,
770 which cuts a large embayment into the granite dome *ca.* 200 m below the Summit Surface east of
771 Princetown (Fig. 14). The West Dart corresponds to Brunsdon's (1963) Middle Surface and its
772 population of valley benches (Figs. 10, 11), and also stood out as an outsized drainage basin in
773 Gerrard's (1993) watershed ranking scheme, i.e., not fitting into the 4 groups of third-order
774 catchments. L. Dudley Stamp had speculated (reported in Guilcher, 1949) that the West Dart was a
775 large pocket of softer china clay which had been scraped clean: thus perhaps a branch of the 'cedar-
776 tree' structure later imagined by Palmer and Neilson (1962) for the hydrothermal stockwork.
777 Guilcher, however, doubted this on grounds that the two main topographic depressions in the NE
778 quarter of the St Austell granite were not kaolinised, thus inferring that negative topography in the
779 Cornish granite stock most intensely mined for kaolin was not controlled by pockets of china clay.
780 Another semi-enclosed embayment of note is the West Webburn catchment (Fig. 14). It is not a
781 tectonic basin, nor is it extensively floored by alluvial fill. Coque-Delhuille (1987) concluded that
782 the West Webburn basin had been etched out by differential weathering. Hamel Down, to the east
783 (Fig. 3), consists of 'giant granite' reinforced by resistant veins and dykes of schorl-rock (also
784 abundant among the slope debris of Hamel Down Tor); meanwhile, the basin walls to the west
785 correspond to outcrops of 'reddened granite', where vertical pneumatolytic fluid circulation in the
786 'blue granite' has generated iron-rich, low-porosity granite dykes and veins. In contrast, the floor of
787 the basin, for example at Clapper Bridge, reveals hydrothermally weathered granite with
788 geothermal signatures characteristic of the base of the tin mineralization zone (i.e., feldspars
789 have entirely disappeared, leaving a residue of quartz and primary tourmaline with mica
790 systematically replaced by hematite). Thus at places where, instead of forming open joints, the
791 fracture net has been plugged by post-magmatic recrystallisations, Coque-Delhuille (1987) was able
792 to argue that fracture-rich areas behaved counter-intuitively as panels of resistant rock.

793 A third class of etch basin, smaller in size, is exemplified by the Burrator depression (occupied by
794 the reservoir) and Fox Tor Mire (elevation: 350 m; Fig. 15a) on South Dartmoor (Coque-Delhuille,
795 1987); and by the Fenworthy (reservoir) depression and Taw Marsh in North Dartmoor. The latter
796 is a flat-floored, 1 x 2 km enclosed basin lodged between Steeperton gorge and the Taw River gorge
797 (Belstone Cleave) as the Taw exits Dartmoor northward (Fig. 15b). Given its asymmetric east-to-
798 west topographic profile (where Cosdon Beacon, 550 m, stands 90 m higher than Belstone Tor, 466
799 m), Taw Marsh is clearly not the floor of a valley cut in an even-summitted plateau. Furthermore, its
800 west wall is noticeably steeper than the east (Fig. 15b) because Belstone Tor ridge is a homoclinal
801 scarp in the NW-dipping Roof Complex (Coque-Delhuille, 1987). Taw Marsh is thus an exposure
802 of the underlying 'blue granite', more vulnerable to weathering.

803 Etch basins are widespread in granitic uplands around the world (e.g., Godard et al., 2001) and
804 usually display sizes typical of those mapped on Dartmoor. They are often preserved upstream of a
805 river knickzone, which shields them from the drawdown exerted by stream incision, and have
806 attracted research on Dartmoor for their carbon sequestration potential in the peat they contain
807 (Lunt et al., 2019). Waters (1957) originally argued that the very nature of grus as the chief
808 component of stream bedload should dictate that rivers on low-gradient upland plateaus were
809 incapable of incising unweathered bedrock. Basin deepening was thus conditional on prior
810 weathering of the bedrock. The basin topography (guided by fractures or petrographic contrasts)
811 deepens incrementally by positive feedback under the dual action (i) of divergent weathering (i.e.,
812 the weathering front deepens faster at loci of negative topography, where water-table flowlines
813 converge, than on bedrock interfluves); and (ii) of leaching, piping, and outwash of grus debris by
814 first-order streams during flash floods.

815 There is always a danger of circular reasoning in the interpretation of granite landforms (Gerrard,
816 1988a), which has repercussions on the robustness of the granitic etchplain as a testable theory in
817 the absence of independent chronostratigraphic markers. Much of the evidence to test the
818 hypothesis of joint-spacing controls on weathering depth (Fig. 6) is concealed beneath the moorland
819 vegetation. Likewise, it can be assumed that granite is eroded preferentially at locations where it is
820 weaker, but this is purely inferred from the fact that we assume there is missing rock mass where
821 the negative topography exists (e.g., an etch basin, a tor avenue, etc.). In truth, however, the
822 evidence has often disappeared, except when, as in the West Webburn and Taw Marsh settings,
823 petrographic and structural evidence directly support the hypothesis of differential weathering.

824

825 ***4.4.5. Dartmoor as a composite landscape***

826

827 As in the case of the Bovey and Petrockstowe ball clays (Section 3.3), pivotal constraints on the
828 evolution of Dartmoor lie beyond the boundaries of granite outcrop itself. Coque-Delhuille (1987)
829 worked on a regional study of SW England which included Dartmoor as a centrepiece. This
830 produced quite a novel perspective on long-term landscape development in SW England.

831

832 ***4.5.1. The granite topography of Higher Dartmoor***

833 According to Coque-Delhuille (1987), Higher Dartmoor (the land corresponding to the Summit
834 Peneplain of Brunsdon, 1963, and the Upper Surface of Waters, 1960a) evolved by post-Variscan
835 surface degradation (Fig. 12b) and was not interrupted by marine flooding in the late Cretaceous.
836 The conformable stratigraphy in Devon between the Permian and the Trias (Warrington, 2017,
837 documents only a brief, 4 Myr hiatus) suggests continuous post-orogenic denudation, progressively

838 smoothing the upland topography to a time when the late Triassic marine transgression (*ca.* 205 Ma)
839 was able to advance over a low-elevation, low-relief land surface defined (as elsewhere in
840 continental Europe) as the late Triassic peneplain. This granite-cored island (see Fig. 2) maintained
841 itself slightly above sea level and evolved into a mosaic of differentially-weathered topographic
842 units controlled by petrographic heterogeneities and hydrothermal stockwork features of the pluton
843 (see Section 4.4.2). As such, although unwittingly, Coque-Delhuille's scenario for Dartmoor
844 endorses the etchplain model.

845 The antiquity and epigene nature of this Dartmoor Paleoplain is documented by the occurrence of
846 Dartmoor granite pebbles in the clastic Permian rocks of Devon. Counter to the belief that the bulk
847 of Permo-Triassic clastic sequences in English sedimentary rocks originated from the Armorican
848 Massif, Groves (1931) recognised instead that, "by the end of the Triassic period",

849 "the removal of the sedimentary cover [over Dartmoor] must have reached a very
850 advanced stage. The rocks which contributed mainly to the detritus were [...] all
851 consanguineous with the granite, possibly granitic veins and apophyses, together with the
852 rocks of the pneumatolytic and contact-zones. The amount of the material increases,
853 particularly in the Bunter Pebble Bed, in the area to the east and north-east of the Dartmoor
854 district".

855 A survey by Dangerfield and Hawkes (1969) later confirmed that the Dartmoor granite had indeed
856 already been unroofed and exposed by the end of Permian time. This inference is consistent with
857 the notion that when unroofing is rapid, the portion of the batholith that cools fastest loses chances
858 of mineralisation promoted by late-stage magmatism; and is verified by Dartmoor presenting
859 limited lode mineralisations compared to the other (much more intensely mined, as a result) Cornish
860 stocks (Beer and Scrivener, 1982; Willis-Richards and Jackson, 1989).

861 The predominance of carbonate rocks and scarcity of terrigenous sediment in the offshore record of
862 Paleogene sedimentation in the English Channel and Western Approaches basins (Green, 1985)
863 confirms that eroding hinterlands such as Higher Dartmoor were low-elevation and low-relief
864 islands of low erosion, probably tropical islands residing close to marine base level until at least late
865 Oligocene time (Bristow et al., 2002). This is corroborated by comprehensive work in neighbouring
866 Brittany, where the occurrence of very uniform sedimentary facies of Bartonian to Priabonian age
867 (41–34 Ma) preserved on shore and in surrounding basins points to a very flat and low-lying
868 regional topography (Bessin et al., 2017).

869

870 *4.5.2. The peripheral topography of Lower Dartmoor and the rest of SW England*

871 Coque-Delhuille (1987) defined another, this time regionally extensive land surface peripheral to
872 Higher Dartmoor, within an elevation bracket of 300–220 m but declining westward to ~150 m in

873 Cornwall. This Cornubian Paleoplain cuts across much of the low-grade metamorphic country rock
874 (Fig. 1b) of Devon and Cornwall (Fig. 12b). Its elevation coincides with the Lower Surface of
875 Waters (in Brunsten et al., 1964). It was fashioned by a wide range of climatic, fluvial and marine
876 agencies over a long period of geological time. Reconstructions by Edwards and Freshney (1982),
877 Walsh (1987, 1999), Ulyott et al. (1998), Jones (1999), and Migoñ and Goudie (2001, 2012; Fig.
878 12c) concur with this scenario, which envisions southern England as a polygenetic land surface with
879 a long record of climatic overprints generating a mosaic of erosional and depositional surfaces
880 (some hardened by duricrusts of various kinds; see Small, 1980; Summerfield and Goudie, 1980;
881 Isaac, 1981; Bristow, 1993) within a relatively narrow band of altitude.

882 The extensively flat areas of granite across Lower Dartmoor at ~300 m a.s.l. (Figs. 4, 5, 7e, 12) are
883 the only part of the Dartmoor granite outcrop cut by the Cornubian Paleoplain. These interfluves are
884 barely higher than the top of the sedimentary Haldon Hills to the east (275 m, Figs. 4, 5, 12, where a
885 76-m-thick layer of Upper Greensand Formation is still preserved). Unlike Higher Dartmoor, Lower
886 Dartmoor is thus not an epigene surface: it was covered by a feather-edge of the late-Cretaceous
887 marine transgression and exhumed later during the Cenozoic. Delayed exhumation of the Lower
888 Dartmoor granite surface would explain two features of its morphology: (i) its well preserved planar
889 summit topography, in contrast with the more rolling features of Higher Dartmoor (Fig. 5); and (ii)
890 the origin of the 210 m (690 ft) topographic bench, which Brunsten had mapped around the fringes
891 of Lower Dartmoor, e.g., along the LSF zone and the NW edge of the Bovey Basin (Figs. 10, 11).
892 Instead of an improbably elevated Calabrian strandline, the 210 m bench was reinterpreted by
893 Coque-Delhuille as an exhumed late-Cretaceous shore platform. Marine beach sands containing
894 glauconite and flints trapped in the Bovey Basin (Edwards, 1976) and in a small (previously
895 quarried) Oligocene graben at Christow (Fig. 4) suggest that the chalk and Greensand were stripped
896 off Lower Dartmoor during the Paleogene. Silicified caprock, which has variously developed at the
897 expense of the Greensand outcrops (e.g., Haldon Hills silcretes), and likewise patches of sandstone
898 and microconglomerate covering parts of Lower Dartmoor, further testify to this scenario. The
899 lower unit of the Paleocene Haldon Formation (Hamblin, 1972, 1973a, 1973b, 2014) is a flint
900 gravel (Tower Wood Gravel) comprising unabraded clasts in a ball-clay-dominated matrix
901 (Hamblin 1973c). It is interpreted as a weathering residue derived from a former cover of
902 Cretaceous chalk perhaps originally > 100 m thick in that area. Heavy minerals indicate that the
903 sediment was at least partly derived from the Dartmoor granite. Former presence of chalk is
904 confirmed across other parts of Devon and Somerset by Clay-with-flints, which is the weathered
905 residuum of impure chalk relatively enriched in intraformational flints (Isaac, 1983a, b; Gallois,
906 2009).

907

908 4.6. Cenozoic palaeogeography of Dartmoor

909

910 By Turonian and Campanian time (94–72 Ma), sea level had reached its all-time post-
911 Carboniferous highstand, with invertebrate fossils from that interval preserved in the stratigraphy of
912 the Haldon Hills (Hart, 1999, 2012), but no direct evidence of Dartmoor, Exmoor, or even Cornwall
913 being submerged at any time. The land surface across southern England (Jones, 1981, 1999),
914 Brittany and Normandy (Klein, 1970, 1975; Bessin et al., 2015) continued to evolve as a deeply
915 weathered etch surface during the Paleogene under a regime of low-magnitude vertical deformation
916 of the crust. Sand (channel fills) and carbonaceous clay sequences in the uppermost 300 m fill of
917 the Bovey and Petrockstowe grabens (Fig. 1b) suggest anastomosing or meandering floodplain
918 complexes in SW England during Oligocene time (Tappin et al., 1994), redistributing the products
919 of weathering and low-intensity denudation. The floodplain sequences formed at the periphery of a
920 low-relief, insular Higher Dartmoor upland, each representing a short period of sedimentation
921 preceded and followed by a lengthy period of clay-generating pedogenesis amidst dense *Sequoia*
922 forests (Edwards and Freshney, 1982).

923 The 25–30-m-thick Aller Gravel (see Fig. 13) south of Newton Abbott likewise provides evidence
924 of these Paleogene fluvial systems. It correlates with the Haldon upper unit (Hamblin, 1974), and its
925 debris contents confirm derivation from the Dartmoor granite and its aureole rocks (Daley, 1999).
926 The Buller’s Hill unit (upper Haldon sequence) is itself a clast-supported flint gravel in a sandy clay
927 matrix. Its pebble assemblage includes a range of lithologies from far afield including quartz and
928 quartzite, as well as thermally altered Carboniferous shale and chert. The heavy-mineral suite is rich
929 in tourmaline, hinting again to the Dartmoor granite. The clay matrix comprises of ordered and
930 disordered kaolinite, but with more illite than in the lower units. Hamblin (1973a) concluded that the
931 gravels accumulated under periodic, high-energy and unconfined alluvial flows alternating with dry
932 seasonal conditions of lower energy flow. These were perhaps driven by alternations of pluvial and
933 dry climatic periods, the latter compatible with arid, evaporite-generating conditions in the Paris
934 Basin during the Oligocene (Daley, 1972).

935 The Haldon Formation overall is considered an upstream equivalent of more distal continental
936 deposits such as the Poole Formation in Dorset (Gibbard and Lewin, 2003). Waters (in Brunson et
937 al., 1964) had suggested that ball clays in Dorset “attested to the conveyance eastwards of kaolinitic
938 waste from Dartmoor” during the Eocene. Overall, and despite tectonic activity along the LSF
939 generating coarser lateral debris fans along the fault zone, regional evidence of relatively fine
940 particulate river loads during the Oligocene supports the theory of sustained rock weathering and
941 subdued relief in a humid Paleogene climate. Fault slip rates even along the LSF were moderate,
942 and the nature of the Bovey Basin sediment fill suggests that tectonic subsidence (which faded

943 beyond detection after ~28–25 Ma) was most often matched by the rate of sedimentation. This
944 epeirogenic regime persisted until at least the middle Pliocene, after which much of the valley
945 incision on Dartmoor and elsewhere in southern England began, marking a shift to coarser
946 bedloads, higher sediment yields, and greater hillslope instability.

947

948 **5. Landscape evolution in the Quaternary**

949

950 *5.1. Dartmoor as a periglacial landscape*

951

952 Even before the controversy about the periglacial origin of tors (Palmer and Neilson, 1962), the
953 Dartmoor upland was held as “probably the purest relict periglacial landscape in Britain” by Waters
954 (1960b) (see also: Te Punga, 1957; Worsley, 2005). While noting the scarcity of relict permafrost
955 features in SW England, Williams (1965) concurred that Dartmoor was a notable exception. More
956 recent geomorphological mapping of the summit zone of Bodmin Moor has shown that even at
957 lower altitudes of 300–400 m the granite terrain of SW England displayed features of a fairly
958 mature, unadulterated periglacial landscape (Evans et al., 2017).

959 Evidence that frost weathering may trim tors is provided by Hay Tor Rocks, which display angular
960 slope debris supplied by the exposed underlayer of frost-susceptible ‘blue granite’. Tor height was
961 thus increased by basal lowering of the topography as a result of periglacial processes. A rock
962 shelter has developed in the ‘blue granite’ (Fig. 7f), whereas the poorly jointed ‘giant granite’ forms
963 the overhanging tor mass and remains mostly unscathed by Pleistocene frost cracking. On a scale
964 from 1 to 7, Waters (1964) proposed a hierarchy of relative resistance to frost weathering among
965 different rock types on Dartmoor; he noted that metasediments were the most susceptible, ‘giant
966 granite’ the least, with fine-grained granite, diabase, elvan, tourmalinised medium-grained granite,
967 and schorl holding intermediate positions in increasing order of relative resistance.

968 Evidence that periglacial processes were widespread on Dartmoor is provided by a rich catalogue of
969 relict permafrost-related landforms and deposits. “Head” was a term first employed by de la Beche
970 (1839) to describe on Dartmoor the economically worthless layer of debris forming the overburden
971 (and hence the top, or head) capping exposures in granite quarries and at gravel pits (e.g.,
972 Blackabrook, Shilstone, Lakemoor). The word is still used in Britain generically to describe a relict
973 active layer of late Pleistocene permafrost terrain (coombe rock describes similar materials in
974 chalk), and more specifically an unconsolidated accumulation of locally supplied angular debris
975 exhibiting a progressive downslope transition from a clast- to a matrix-supported texture, and from
976 coarser to finer fragments (Bryan, 1946). Whereas Green and Eden (1973) distinguished successive
977 generations on Dartmoor based on a stratification between texturally contrasting formations

978 involving a 'Main head' and a coarser 'Upper head'; Mottershead (1976) reached the opposite
979 conclusion based on a wider sample across SW England, finding that there was usually a coarser-
980 textured 'Main head' covered by a finer-textured 'Upper head'. In both cases, the assumption was
981 that the upper layer was Devensian and the lower perhaps of Anglian age. Coque-Delhuille (1987)
982 proposed instead a four-fold descriptive classification of head deposits in SW England, highlighting
983 the presence or absence of internal bedding with nuances between lowland environments near the
984 coast and more continental upland settings. Her chronological criteria hinged on the position of
985 Ipswichan (i.e., Eemian) beach deposits and presence of loess (indicative of Last Glacial Maximum
986 conditions) relative to the head occurrences in the stratigraphy. Coque-Delhuille concluded that all
987 head deposits in SW England were of Devensian age. Pre-Devensian occurrences of periglacial
988 head were only reported from the Scilly Isles, where glacial till overlying head on White Island
989 could testify to its relative age.

990 In addition to its cryoplanation terraces on metamorphic outcrops, western Dartmoor is known for
991 its marked valley-side asymmetry, with east-facing slopes displaying greater mean and maximum
992 angles than west-facing slopes, which also exhibit thicker head (Gerrard, 1982, 1988b). Plentiful
993 evidence otherwise occurs of granitic slope deposits with characteristic periglacial signatures (e.g.,
994 Scourse, 1987). The inventory includes boulder fields on gentle gradients near interfluvial summits
995 (Sheepstor, Black Tor, Sharpitor, Leeden Tor; Fig. 3); block streams or boulder runs (Bennett et al.,
996 1996; Harrison et al., 1996), with an estimated maximum distance of debris travel on east-Dartmoor
997 slopes ranging between 915 and 305 m (Williams, 1968); scree deposits (locally termed 'clitter', a
998 Cornish word for loose boulders), with for example an estimated 400,000 m³ of such debris below
999 Belstone Tor, and steep scree slopes in the Dart gorge; bedded grus (Green and Eden, 1973; Coque-
1000 Delhuille, 1987); solifluction deposits (e.g., in Leather Tor gravel pit); stone-edged embankments
1001 resulting from permafrost creep (e.g., SE of Leather Tor); stone stripes (e.g., at Sharpitor, Leeden
1002 Tor, Great Staple Tor; Figs. 3, 16); and earth hummocks (on the tread of altiplanation terraces at
1003 White Tor, at 400 m a.s.l. at the western edge of Dartmoor above the river Tavy; and 3 km to the
1004 south of White Tor above Merrivale: Bennett et al., 1996; see Fig. 3). Catt and Staines (1982) also
1005 reported loess up to 30 cm thick on Dartmoor.

1006 Many of these features are documented today as part of SW England's Quaternary geoheritage
1007 (Campbell et al., 1998), and all collectively testify to the pervasive impact of periglacial conditions
1008 on Dartmoor (Gerrard, 1983, 1989b, 1994b; Bennett et al., 1996; Foster, 2003). Palaeoclimatic
1009 modelling of permafrost thickness in the United Kingdom estimates the maximum depth of sub-
1010 zero temperatures to have attained 80 m below the Dartmoor land surface (Busby et al. 2016),
1011 confirming that the widespread periglacial clitter, patterned ground (Croot and Griffiths, 2001) and
1012 cryoturbation features (observed in Bovey Basin deposits to depths of at least 10 m) were produced

1013 by an active layer of some considerable energy. Some caution should nonetheless be urged
1014 concerning certain landforms, and thus their Pleistocene geoh heritage status. For example, extensive
1015 fields of vegetated earth hummocks (e.g., at Cox Tor) turn out to be affecting 3000 year-old
1016 archaeological sites and are thus unrelated to Pleistocene permafrost. Killingbeck and Ballantyne
1017 (2012) concluded that hummock formation by frost action could thus occur on silty soils in humid
1018 cool temperate climates with limited seasonal frost penetration, i.e., in a Holocene climate such as
1019 Dartmoor's (note that mean January temperature on Dartmoor today is ~3 °C). The chronology of
1020 Holocene soil erosion and other minor landforms, particularly in relation to Bronze and Iron Age
1021 land-cover change, has been well summarised by Gerrard (1993) and is not detailed here.

1022 Waters (1964) speculated that cryogenic transfer of debris on Dartmoor hillslopes had resulted in an
1023 inversion of normal weathering profiles, i.e., during a given glacial stage successive layers of grus
1024 would be removed from the upper part of the slope and deposited in reverse order lower down.
1025 During the next glacial stage, sound blocks detached from upper-slope granite outcrops would be
1026 transferred downslope, covering and armouring the slope deposits (a stratigraphic feature of interest
1027 to engineering geomorphologists and later also described on Hingston Down, Fig. 1, by Dearman et
1028 al., 1976). However, the validity of this scenario was challenged by Green and Eden (1973) and
1029 Gerrard (1982), who concluded that it was perhaps valid very locally but not typical of the wider
1030 hillslope evolution. Instead, they found that the transported layer received inputs from many
1031 segments of the slope. The heterogeneity of situations was found to vary substantially depending on
1032 initial slope form, on the local nature and availability of debris, and on the intensity of periglacial
1033 and gravitational slope processes as a function of local relief, slope gradient, and to some extent
1034 slope aspect.

1035

1036 **5.2. Was Dartmoor glaciated?**

1037

1038 Strong evidence now exists of extensive glaciation (i) of the Bristol Channel during the Pleistocene
1039 (eastward ice flow direction of a spreading ice lobe, parallel to the North Devon and South Wales
1040 coasts; Gibbard et al., 2017); (ii) of ice retreat from Lundy Island *ca.* 40,000 years ago (MIS 3),
1041 after a maximum ice advance south of Lundy probably during MIS 4 (Rolfe et al., 2012); and (iii)
1042 of glaciation as far as the northern edge of the Isles of Scilly during MIS 2 (Smedley et al., 2017).
1043 With the Irish Sea Ice Stream even reaching the continental shelf edge (i.e., ~49°N, the latitude of
1044 Paris) at around that time (Praeg et al., 2015), these conclusions confirm that the north coast and
1045 western tip of SW England were closely hugged by excursions of wet-based ice at least during the
1046 Devensian, and presumably on previous occasions (Anglian Stage). Erratic boulders on the coasts
1047 of north Cornwall and north Devon, and likewise the well-known Giant's Rock on the beach at

1048 Porthleven, are thus now less of a mystery than they might have been at the time when boulder clay
1049 was first reported by Maw (1864) near Barnstaple. Likewise the Punchbowl, a north-facing cirque
1050 on Exmoor, is entirely plausible in such an environment (Harrison et al., 1998, 2001, 2015).

1051 Indications of glaciation on the south side of the SW peninsula were mooted, for example, by Inglis
1052 (1877), who attributed the floor of Plymouth Sound to glacial action. Kellaway et al. (1975) pointed
1053 out that the bedrock profile of the Tamar valley above Saltash was almost flat for 3.2 km, whereas
1054 beyond that point it dropped to the Plymouth Sound to depths of –52 to –55 m. Worth (1898) had
1055 previously remarked that such a profile did not differ from Welsh valleys known to have been
1056 glaciated, and described the shape of the rock channels of other rivers in Devon (steep valley sides
1057 and flat bottoms) as suggestive of a glacial origin. For Kellaway et al. (1975), ice at some time thus
1058 flowed off Dartmoor, with bedrock deeps occurring where the erosive power of the ice would have
1059 been greatest. Clark (1970) and Durrance (1971) also noted a reverse gradient on the buried rock
1060 floor of the Teign, which they considered consistent with glacial action. Many of the morphological
1061 features detected by Kellaway et al. (1975) on the English Channel floor with the tools of the time
1062 have now been interpreted instead as channeled scabland features resulting from a megaflood
1063 caused by breaching of the Dover Strait (Gupta et al., 2017). A synthesis for the Erme River valley
1064 has also ruled out a glacial origin for the Devon and Cornwall rias, confirming them as drowned
1065 fluvial valleys partly filled by Holocene sediment (Creak, 1991).

1066 Climate models for the British Isles have nonetheless placed an autochthonous ice cap on Dartmoor.
1067 While uncertain as to whether it should be warm- (Hubbard et al., 2009) or cold-based (Clark et al.,
1068 2010), this has rekindled the prospect of detecting glacial deposits or landforms in the midst of what
1069 other scholars had considered to be the “purest relict periglacial landscape in Britain” (see Section
1070 5.1). Evans et al. (2012), for example, found a collection of local clues that could support the
1071 hypothesis of a cold-based ice cap of unspecified age on Dartmoor. Among these: a patch of
1072 hummocky drift on the southern slopes of Sittaford Tor and on other valley floors (interpreted as
1073 ablation moraine); a possible small terminal moraine just north of a sharp bend in the East Dart
1074 valley, also south of Sittaford Tor; a possible esker fragment below Quinton’s Man ridge; an
1075 incipient cirque at the Slipper Stones amphitheatre, suggesting an equilibrium line altitude around
1076 460 m; and weakly U-shaped valley sections in the upper Tay and West Okement valleys. Gunnell
1077 et al. (2013) also recognised a basis for glacial mimicry, and particularly the trough-like cross-
1078 profile of some valleys in north Dartmoor. They did not, however, rule out some structural and/or
1079 petrographic control over the slope profiles (such as the Belstone ‘giant granite’ homocline west of
1080 Taw Marsh; see Section 3.2 and Figure 15). The limited size of the putative icefield could be
1081 explained by the anomalously high surface heat flow everywhere on outcrops of the Cornubian
1082 Batholith (Beamish and Busby, 2016), which to some extent would have counteracted the tendency

1083 for atmospheric conditions to promote permafrost in SW England except on the higher ground of
1084 Dartmoor (Hutchinson and Thomas-Betts, 1990) and on the crown of Bodmin Moor (Evans et al.,
1085 2017).

1086 Linton (1955) had postulated that tors, like skittles in a bowling alley, were too fragile to survive
1087 the movement of basal ice and proposed that the spatial distribution of tors be used as an indication
1088 of ground untouched by the Pleistocene ice sheets. Evans et al. (2012) accordingly also argued in
1089 favour of a cold-based icefield on Dartmoor on the basis of tor morphology: whereas ‘Type 1’ tors
1090 (high-relief, castellated) had remained undisturbed by ice, the low-relief, ‘Type 2’ tors and plinths
1091 of North Dartmoor had been toppled by moving ice. In the South Pennines, Cunningham (1965)
1092 used weathering pits on tor summits as an indication of whether a tor was intact or had been
1093 decapitated by glaciers, with Hall and Phillips (2006) elaborating on this idea and producing a
1094 classification of Cairngorms tors in Scotland. A regionally more extensive survey of tor
1095 morphology, such as conducted by Ehlen (1992, 1994) and Gunnell et al. (2013) on Dartmoor,
1096 might suggest, however, that neither of these criteria are sufficient for discriminating between
1097 glaciated and unglaciated parts of the landscape. Furthermore, tors have been known to survive
1098 submergence beneath continental ice sheets, e.g., in Scotland (Linton, 1959, p. 43; see also Sugden,
1099 1968, p. 85) and in Lapland (Kaitanen, 1969), thereby casting doubt on tors as reliable dipsticks for
1100 mapping ice-sheet boundaries.

1101 Clearly, as emphasised by Evans et al. (2013) in the context of challenges levelled at their ideas by
1102 Straw (2013a, b), the clues in favour of plateau icefield glaciation on Dartmoor are fragmentary, not
1103 least because landforms originating from 80-m-thick permafrost (Busby et al., 2016) and landforms
1104 generated by relatively thin and stagnant glacier ice remain potentially difficult to tell apart.
1105 Unhelpfully, Gunnell et al. (2013) indicated that the ice cap, if present, was too short-lived for the
1106 ^{10}Be isotopic system to establish a nuclide production vs. radioactive decay regime capable of
1107 unequivocally evidencing a period of bedrock shielding by ice. The putative Dartmoor icefield was
1108 thus transparent to detection by ^{10}Be nuclide concentrations.

1109

1110 ***5.3. Fluvial action: its drivers and impacts***

1111

1112 *5.3.1. River bedloads and their origin*

1113 The possible existence of a small, perhaps short-lived and predominantly stagnant ice cap on NW
1114 Dartmoor during the Pleistocene cannot detract from the fact that all of Dartmoor’s rivers exit the
1115 upland through deep-cut, V-shaped gorges (Green, 1949; Guilcher, 1949; Brunsten, 1963; Figs. 14,
1116 15, 17a). Although there is no occurrence around Dartmoor of granite blocks beyond the pluton
1117 margin suggestive of glacial erratics, there are nonetheless extensive accumulations of large

1118 boulders of granite in some riverbeds. Expansion bars at the exit of steep gorges are commonplace,
1119 and at Ivybridge, for example, the Erme River valley has a noted bouldery deposit below the gorge
1120 exit. Gilbertson and Sims (1974) referred to it as an alluvial fan formed initially as an earthflow
1121 down the Erme gorge by periglacial melt-out, but partially reworked by fluvial processes given the
1122 imbricate character of the boulders. The perspective changes somewhat when outsize boulder bars
1123 occur some distance below the gorge, such as the Bovey up to 2 km downstream of the pluton
1124 margin. At Lustleigh Cleave, slopes of jumbled angular blocks up to several metres in length far
1125 exceed usual periglacial clitter in size. These occur at rather low level (150–250 m a.s.l.), possibly
1126 suggesting permafrost meltwater channeling along the Bovey gorge and adjacent cleaves (in
1127 modern environments of the British Isles, thaw-related floods often produce the most extreme
1128 flows; Foulds et al., 2014). The bed of the Teign in its long, off-granite gorge between Sandy Park
1129 and Clifford Bridge is likewise cluttered with granite boulders (Somervail, 1901). Rather than
1130 having travelled distances of up to 8 km, they could in this case have been sourced locally from the
1131 granite escarpment of Lower Dartmoor. The Dart (largest on-Dartmoor catchment) exhibits deposits
1132 of granite boulders 1–2 m in size also up to 8 km beyond the pluton margin, and the debris maintain
1133 near-metric dimensions for another 16 km to Staverton. A remarkable boulder bed (including
1134 blocks from the metamorphic aureole) is also buried in the first terrace slightly upstream of
1135 Staverton railway station, with excavated specimens displayed at Hood Manor Farm (transport
1136 distance: 12 km).

1137 It remains unclear as to what kind of peak flood event on Dartmoor rivers, which all have modest
1138 catchment areas (Gerrard, 1993), could mobilise metre-scale bedload clasts. Flash floods have
1139 nonetheless been recorded in the literature, and boulder berms are widely documented along
1140 Dartmoor rivers (Foulds et al., 2014). For example, as a result of a rainstorm impacting the West
1141 Okement on August 17, 1917, the Red-a-ven Brook carried large boulders and gravel blocking its
1142 own channel and generating an avulsion; also a small channel, 1 m deep and 1.5 m wide, was
1143 scoured to a depth of 5 m as a result of this single event (Worth, 1918). Channel steepness
1144 associated with peak rainfall thus clearly generates conditions for high bed shear stress and hillslope
1145 response. Foulds et al. (2014) used lichenometry to constrain the ages of boulder-berm flood
1146 deposits on the upper Tavy, Okement, Taw and North Teign since ~1800 CE. In an area where
1147 probable maximum precipitation is ~450 mm, they concluded that Dartmoor had the potential to
1148 generate very large and damaging Holocene floods.

1149 Under the hypothesis of a middle-Pleistocene icefield, perhaps associated with a short-lived
1150 permafrost meltwater lake in the upper Dart basin, an outbreak palaeoflood could explain some of
1151 the more exceptional transport distances observed. An alternative might be glacifluvial discharge
1152 augmentation during peak snowmelt, permafrost melt, or cold-based ice-cap melt. Rivers thus

1153 empowered would not just transport boulders already on the valley floor but could also trim debris-
1154 cluttered hillslope bases, meanwhile propagating slope-foot instabilities further up local valleysides.

1155

1156 *5.3.2. Influence of eustatic base-level changes*

1157 Each Dartmoor river joining the English Channel exits the upland through a short, narrow valley.
1158 The north-flowing rivers, i.e., the Taw and Okement / Torridge which both join the Bristol Channel,
1159 have cut shorter and shallower gorges as they exit Dartmoor through the metamorphic aureole. All
1160 of these steep valleys are poorly accessible and their study has been neglected in comparison with
1161 the wide-open scenery of Dartmoor's upland landscapes. Quite how rivers with small catchments
1162 can cut ~200-m-deep gorges in a tectonically inactive environment has never been explained
1163 conclusively, but tentative scenarios have been sketched.

1164 The rias of the south coast, and thus perhaps the Dartmoor gorges, may have begun to form in late
1165 Miocene time (Donovan and Stride, 1975), but the Pleistocene legacy is more clear-cut. During
1166 glacial periods, the floor of the English Channel was exposed as dry land to subaerial periglacial
1167 processes (e.g., Gibbard et al., 2017), with active-layer meltwater supplying enlarged English river
1168 catchments. At the longitude of South Devon, for example, the trunk streams of the English
1169 Channel flowed in river valleys at -80 m OD (Mellet et al., 2013). Substantial bedrock incision
1170 resulted along tributaries. Another important component of the puzzle is that the English Channel's
1171 Central Valley is twice as deep as the Bristol Channel, possibly a consequence of the inferred
1172 megaflood(s) through the Dover Strait (Gupta et al., 2017). Such asymmetry in base-level depth on
1173 either side of the SW peninsula certainly would explain why the majority of rivers leaving the
1174 Dartmoor upland, whatever their initial direction as they fall radially off the moor, join the English
1175 rather than the Bristol Channel (Figs. 1, 4). The drawdown was accentuated by a hanging tributary
1176 effect along the South Devon coast, where the land offshore plunges steeply to the sea floor
1177 compared to more progressive land-to-sea gradients farther east in the Channel (Westaway, 2010;
1178 Mellet et al., 2013). If the offshore slope during low sea levels is less than the interglacial onshore
1179 fluvial slope, the net effect would be to cause the onshore part of the river to aggrade in order to
1180 achieve transport of the upland-derived sediment load to the more distant coast. This should arise
1181 even without an increase in sediment delivery from the upland. The opposite occurs if the offshore
1182 slope is greater than the onshore slope: the river will in that case incise into the landscape, and
1183 promote bedrock knickpoint retreat into the headwaters of Devon, particularly at times of
1184 augmented catchment discharge during massive meltdown of the permafrost. These channel-
1185 steepening processes can be estimated from the depths of river bedrock channels beneath their
1186 estuaries (Durrance, 1980). The larger rivers such as the Exe and Teign are cut to depths of -52 m,
1187 and the Dart (Green, 1949) and Erme (MacFarlane, 1955) to -45 m, suggesting that they must have

1188 graded to successive sea levels in the English Channel at least as low as those bathymetric contours.
1189 Postglacial drowning of the south coast river valleys occurred extremely rapidly, for example,
1190 between 9000 and 7000 ¹⁴C cal. yr BP, with sea-level rising from -18 to -8 m during that brief
1191 interval at rates of 5 mm/yr (e.g., Gehrels et al., 2011).

1192

1193 5.3.3. *Influence of stream piracy*

1194 It is likely that the Dartmoor gorges were cut iteratively by successive waves of knickpoints
1195 migrating up-channel in response to the profile-steepening mechanisms described above. Wheeler
1196 (1979) analysed the long profiles of 115 British rivers and calculated a stream concavity index
1197 based on the maximum deviation above and below a constant gradient of percentage-drop to
1198 percentage-distance. With reference to the relationship obtained between trunk-stream relief and
1199 stream-profile concavity (watersheds with greater available relief have higher indices of concavity),
1200 Wheeler observed a number of atypical profiles positioned away from the line of regression through
1201 the data set. These anomalous stream profiles were either overconcave or underconcave, i.e., in
1202 either case in excess of the graded profile empirically defined for the data set. Overconcavity (rivers
1203 descending steeply and reaching low gradients at low elevations sooner than most) was encountered
1204 in areas where the river's lower reaches had been raised by glacial or post-glacial aggradation (e.g.,
1205 Somerset Levels, some estuaries). There were no such cases in SW England. Underconcave rivers,
1206 by contrast, showed anomalously convex-up profile sections, i.e., knickzones; among these: the
1207 Dart and Teign (Fig. 18).

1208 Underconcavity is ascribable to abnormal patterns of discharge change downstream, or to control
1209 by geological factors. Limestone karst excepted, discharge abstraction will typically occur in
1210 situations of drainage diversion or beheading. Around Dartmoor, processes of river piracy are
1211 facilitated by the outcrop pattern, where changes in channel steepness are potentially controlled by
1212 abrupt lithological contrasts over short distances between or within the parallel belts of
1213 metasedimentary country rock (Figs. 1, 12). Steeper rivers have an advantage over their neighbours
1214 and river beheading may arise as a consequence of knickpoint retreat.

1215 The Dartmoor gorges differ in character from one another. The moorland Plym, for example,
1216 displays a regular long profile for about 10 km (Waters, 1957) before losing a height of almost 150
1217 m down a 2-km-long knickzone above Shaugh Bridge. The Tavy, after its initially open 4 km
1218 stretch from Cranmere Pool, has also cut gorges for most of its course to the Tamar ria through
1219 granite, aureole, and slaty sedimentary outcrops alike. Its 430 m descent in 22 km (i.e., 2%),
1220 however, is relatively regular. Likewise, the Erme presents a constant channel gradient almost all
1221 the way to the sea (Fig. 18); this may reflect a low rate of increase in discharge, which is fairly
1222 typical of short rivers with few tributaries. The Lydford wind-gap (Brunsden and Gerrard, 1970;

1223 Goudie and Gardner, 1985) is a geoheritage attraction and the legacy of a River Tamar tributary
1224 (the Lyd) diverting a former tributary of the River Tavy (the Burn). The elbow of capture is situated
1225 just south of Lydford town (Figs. 4, 17b). Note that these competing watersheds of different sizes
1226 (the Tamar being the largest) nonetheless share the same marine base level. A minor elbow of
1227 capture in the headwaters of the Walkham River, tributary of the Tavy, has likely beheaded the
1228 Blackbrook stream, a tributary of the West Dart. This shows that the Tavy has been vulnerable to
1229 the Tamar, but the Dart has been vulnerable to the Tavy.

1230 Other rivers flowing across the Variscan fabric of Torbay and South Hams are locally defeated by
1231 the structure. The Avon, for example, makes a right-angle at Loddiswell and flows west instead of
1232 joining the Kingsbridge estuary (ria) to the south (Fig. 4). The Kingsbridge estuary, which
1233 compares in length and width to those of the Dart and Teign, thus appears disproportionately large
1234 for the small streams feeding into it, none of which rise on Dartmoor. The drainage pattern of the
1235 South Hams more generally, including smaller rivers such as the Harbourne (Fig. 4), suggests a
1236 complex response to lithology and geological structure, with streams of modest erosive power
1237 either maintaining antecedent courses across the outcrop pattern or bending to it as a function of
1238 relative channel steepness and of opportunities for local drainage capture in response to eustatic and
1239 other potential controls.

1240 Wheeler (1979) noted that the Teign and Dart steepened their gradients as they left the granite
1241 outcrop, suggesting that receding knickpoints have failed to make deep inroads into the granite
1242 core. Matters, however, are more complicated than the notion of a fall line separating the open
1243 landscape of etch basins and boggy cols on Higher Dartmoor from the steep peripheral topography
1244 (Fig. 18). The middle Dart, for example, appears to be a composite river with a history of drainage
1245 captures and diversions such as losing the upper Walkham and gaining the Ashburn. Green (1949)
1246 speculated that there was an old abandoned course of the Dart from Ashburton to the sea at
1247 Teignmouth, following a sinuous trajectory via Bickington along the (modern) A38 expressway
1248 (Fig. 4; and Brunnsden and Gerrard, 1970, Fig. 4 therein). The Dart makes an anomalous cut through
1249 the granite below the East- and West-Dart junction at Dartmeet, where it flows through a 5 km
1250 gorge but then takes a sinuous course around Holne Park for another 5 km when crossing the
1251 metamorphic aureole (Green, 1949; Brunnsden, 1963). The Dart also seems unperturbed by the strike
1252 of the metamorphic outcrops orthogonal to its course in the South Hams: the Dart ria, in particular,
1253 cuts a gorge through a 160-m-high ridge north of Dartmouth when, at Galmpton, it could have
1254 borrowed instead a broad corridor *ca.* 60 m a.s.l. leading east straight to Tor Bay north of Brixham
1255 (Fig. 4; Green, 1949). The Teign, by contrast, makes one of the shallowest exits across the granite
1256 to Chagford, but instead of heading through the gap across Whiddon Down at Castle Drogo to

1257 become an Exe tributary, it cuts instead the longest of the Dartmoor gorges, extending for 9 km
1258 along the granite/country rock boundary (Fig. 4).

1259

1260 *5.3.4. Influence of epeirogenic uplift*

1261 Indications of net Quaternary crustal uplift in the region are provided by the 130 m OD surface
1262 ('430 ft flat'; see Figs. 4, 10, 11). This conspicuous topographic bench was originally interpreted by
1263 Reid (1896) as a wave-cut platform observable above the drowned valleys of the south coast (e.g.,
1264 from Bolt Head to Start Point, Fig. 4) westward to Land's End. The marine St Agnes Beacon
1265 deposits at ~130 m OD in northwest Cornwall (Fig. 19; e.g. Coque-Delhuille, 1987; Walsh et al.,
1266 1987) are also key to understanding the regional significance of this raised '430 ft' shoreline, but
1267 establishing their age has long been a stumbling block. Proposed ages for the St Agnes deposits,
1268 which are "wrapped around the Beacon in the form of a crescent" (de la Beche, 1839), include the
1269 Oligocene (Atkinson et al., 1975; Jowsey et al., 1992), the Miocene (Walsh, 1999), the middle
1270 Pliocene (Coque-Delhuille, 1987), and the early Pleistocene (or late Pliocene if based on the
1271 accepted Pliocene–Pleistocene chronostratigraphic boundary still prevalent at the time of the
1272 following publications: Milner, 1922; Mitchell and Catt, 1973; Jenkins et al., 1986).

1273 The 130 m OD platform has no analogues at comparable elevations in either Brittany or Normandy
1274 (Guilcher, 1949; Coque-Delhuille, 1987), confirming that SW England has undergone greater
1275 neotectonic uplift than its Variscan counterparts further south. In Brittany, strandlines occur locally
1276 at 100 m (as at Plougastel-Daoulas, near Brest) but mostly below 80 m OD, while in Normandy
1277 they do not exceed 65 m OD (for post-Piacenzian uplift in Brittany, see also Van Vliet-Lanoë et al.,
1278 1997, 2000, 2002, and Bessin et al., 2017). The age and position of (i) the enigmatic St Erth Beds in
1279 Cornwall (Fig. 19), which contain marine microfossil assemblages diagnostic of warm seas; and (ii)
1280 a variety of reported marine erosional benches around Cornwall (Everard, 1977), have been
1281 comprehensively discussed by Hart et al. (2011). These authors hypothesised that the St Erth Beds
1282 could have been deposited at the time of the Mid-Miocene Climatic Optimum (MMCO, 17–14 Ma),
1283 which coincided with the Miocene eustatic maximum (Miller et al., 2011).

1284 Given that the mid-Pliocene Warm Period (mPWP, 3.3–2.9 Ma) is another sea-level highstand now
1285 also documented at a number of passive margins on several continents (Rovere et al., 2014), a
1286 Pliocene age for the St Agnes Beds as well as the 130 m OD platform in South Hams is an
1287 alternative option worth considering. Estimated mPWP highstand levels range between +14 and
1288 +30 m above present-day sea level (Rovere et al., 2014) and were controlled by polar ice-sheet
1289 volumes under global temperature conditions 2.7 to 4 °C higher than today's (e.g., Haywood et al.,
1290 2016). These scenarios would imply that between ~100 m and 115 m of surface uplift has occurred
1291 on the South Devon coast since 2.9 Ma, presumably involving Dartmoor. Accordingly, fluvial

1292 incision into the Pliocene wave-cut platform would have been occurring at rates of 35–40 m/Ma,
1293 i.e., ~0.03–0.04 mm/yr.

1294 Younger wave-cut platforms in limestone, slate or schist nonetheless occur in SW England as
1295 benches beneath the 130 m OD surface, such as locally along the Start–Bolt coastline (Figs. 4, 20).
1296 For example, the intermediate bench (or ramp) at Prawle Point (contained between the 105 m and
1297 40 m elevation contours; see Platform 2 in Fig. 20a, b) raises the problem of its age relative to the
1298 extensive 130 m OD level occurring above it. The possibility remains that this bench (median
1299 elevation: 70–75 m) is germane to Everard’s (1977) 92, 82 or 70–75 m OD levels previously
1300 mapped in Cornwall (‘Reskajeage Surface’ of Walsh et al., 1987) — thus making it, rather than the
1301 130 m OD platform, correlatable with the mPWP. Under that scenario, the 130 m OD surface of the
1302 Start–Bolt area would be Langhian, produced during the MMCO at the same time as marine
1303 deposits such as the Coralline Crag, St Erth Beds, and ‘Faluns’ documented in a number of marine
1304 gulfs and straits in England and western France (Hart et al., 2011; Dugué et al., 2012). Total post-
1305 Langhian uplift of South Devon would thus be substantially less than 35–40 m/Ma, setting mean
1306 rates closer to 10 m/Ma but nonetheless confirming an acceleration after the middle Pliocene.
1307 Neither Orme (1960, 1962) nor Mottersherad (1997), whose focus was on the more recent coastal
1308 geomorphology, were concerned by the ramp labelled Platform 2 in Fig. 20. Although the slope
1309 angle (6–7°) of Platform 2 is somewhat steep for a natural A-type shore platform, the antiquity of
1310 the landform leaves room for postformational slope accentuation by tilting in response to
1311 epeirogenic uplift. Landform width (~500 m) is realistic for a shore platform given the duration of
1312 the mPWP and the vulnerability of fissile micaschist to wave action; overall, however, further
1313 investigation is required to clarify the position, origin and age of this topographic ramp, and to
1314 identify possible analogues elsewhere in the region.

1315 The staircase of younger marine benches in South Hams (Fig. 20b) suggests continuing net uplift
1316 during the Quaternary. Mottershead (1997), contrary to Orme’s (1960) initial reconstructions, has
1317 shown in detail that the relative elevations of platforms 3 and 4 convey a deceptive impression of
1318 their relative ages (see caption, Fig. 20), but regional uplift during the Pleistocene is beyond doubt.
1319 For example, an electron spin resonance (ESR) age of quartz grains in oyster beds resting on the +7
1320 m OD platform at Hope’s Nose in Torbay has provided an age of 202 ± 32 ka (van Vliet-Lanoë et al.,
1321 2000), similar to the U–Th ages of $210 \pm 34/26$ and $226 \pm 76/53$ ka obtained for a cave speleothem
1322 from +7.2 m OD at nearby Berry Head (i.e., MIS 7, so-called Aveley Interglacial) (Proctor and
1323 Smart, 1991; see Proctor, 2018 for a wider review of Devon’s 500 ka cave record).

1324 Indirect approximations of the chronology of valley incision on Dartmoor can be further
1325 constrained from fluvial incision in the Exe valley, of which the Teign may have been a tributary
1326 during Pleistocene lowstands (Durrance, 1974). With eight terrace treads north of Exeter (Brown et

1327 al., 2009; Brown et al., 2010) and the uppermost five showing distinct altitudinal separation, the
1328 chronosequence totals 60 m of valley incision. Luminescence ages for the lower four indicate they
1329 formed during the Devensian, with terrace 4 in the early Devensian (MIS 4), terrace 3 in the middle
1330 Devensian (MIS 3), and terrace gravels 2 and 1 in the late Devensian (MIS 2). All of these are
1331 periods compatible with Dartmoor's Devensian tor growth 'event' (Gunnell et al., 2013; see below).
1332 Brown et al. (2010) thus propose that the topography of central Devon was incised by ~60 m in
1333 about 1 Ma, i.e., ~0.06 mm/yr since ~MIS 22. A similar inference has been advocated from the
1334 raised beach levels of the south Devon coast (Westaway, 2010). Other alluvial studies from the
1335 British and French sides of the English Channel likewise conclude that coastal rivers began to incise
1336 their valleys *ca.* 1 Ma at rates of 55–60 m/Ma (Antoine et al., 2003), thus ramping up the
1337 acceleration of epeirogenic uplift since the mPWP.

1338

1339 **5.4. A Quaternary age for Dartmoor's tors**

1340

1341 Uncertainty prevailed until recently about the age and longevity of tors. Lidmar-Bergström (1986)
1342 speculated that maybe the tors had been exhumed from beneath a Cretaceous layer of cover rocks,
1343 and were thus sub-Paleogene. Gunnell et al. (2013) measured concentrations of terrestrial ¹⁰Be
1344 accumulated in the topmost granite platform surfaces of 32 tors widely distributed across Dartmoor
1345 (Figs. 4, 21). They found that all the tor exposure ages were Devensian (i.e., less than 100 ka),
1346 ruling out that such young landforms had deep roots in the Cenozoic (e.g., as part of a tropical
1347 etchplain) and thus had persisted subaerially to the present day. Contrary to previous doctrines
1348 concerning granite landforms, upscaling tors to inselbergs was thus potentially misleading because
1349 tors are neither necessarily incipient inselbergs (young inselbergs with a big future), nor necessarily
1350 stunted inselbergs (old tors with a growth problem). Dating landforms based on their shape or size
1351 is thus a perilous exercise which requires (i) some assumptions involving space-for-time
1352 substitution (the ergodic hypothesis; e.g., Burt and Goudie, 1994), and (ii) a theoretical
1353 representation of what a fully-formed granite tor should initially look like in order to track its
1354 possible patterns of growth or decay. Given the hazards of circular logic when analysing granite
1355 landforms (Gerrard, 1988a), any assumptions concerning sequences of morphological changes over
1356 time may turn out to be misguided. Accordingly, Gunnell et al. (2013) found no evidence, for
1357 example, of tor exposure-age patterns being organised in altitudinal age belts consistent with the
1358 successive generations of Cenozoic erosion surfaces variously imagined by Brunsten et al. (1964)
1359 (Fig. 11) or Klein (1990) (Figs. 13, 21). Searching for links between the altitude of land surfaces
1360 and the age of tors in the Dartmoor context is thus a spurious exercise.

1361 The conclusions of Gunnell et al. (2013) concur with hypotheses formulated by Gilbert (1877), who
1362 suggested that dynamic links between bedrock weathering and regolith thickness might provide a
1363 mechanism for producing spatially variable tors exposures in areas of uniform geology. This is
1364 possible as long as climatic and local base-level changes on multi-decadal to multi-millennial time
1365 scales can cause mantled surfaces to lower at rates exceeding the bare bedrock weathering rate. A
1366 landscape model applied to the Mojave Desert has shown that when regolith thickness falls below a
1367 threshold value, the regolith will approach a stable attractor at zero thickness (Strudley et al., 2006).
1368 If this instability is triggered in a spatially heterogeneous pattern generated, for example, by
1369 ephemeral stream networks, a tor field will tend to develop. Incipient tors will then grow as a
1370 consequence of accelerated denudation on the mantled surfaces, but not on the bare rock surfaces.
1371 Subsequent shifts in climate or local base level that restore sediment surface lowering rates to less
1372 than the bare bedrock weathering rate will lead to progressive tor decay, ultimately leading to tor
1373 disappearance. On Dartmoor, periglacial slope processes during the Quaternary may have plausibly
1374 substituted for the runoff processes operating on the sparsely vegetated desert pediments.

1375 Indeed, tors evolve in response to processes occurring on surrounding slopes, from ice-age active-
1376 layer processes to interglacial and Holocene fluvial incision. Upstanding tors supply boulders to the
1377 surrounding slope system and downslope movement of the debris undermines the base of the tor
1378 stacks. The rock pillars of a tor may respond by leaning outward, horizontal joints (0–15° dips when
1379 *in situ*) will dip more steeply towards the slope, promoting rock slabs to topple off. The boulder
1380 trains may progress downslope aided by solifluction, sometimes forming stone stripes and thereby
1381 signaling the contribution of a permafrost active layer. Today, relict sorted stone stripes occur on
1382 the gentle western slopes of the Staple tors (Fig. 16) (Gerrard, 1988b). Their preservation indicates
1383 that the slope at that location, which is a topographic col (*sensu* Waters, 1957) sheltered from the
1384 deeper fluvial incision that has occurred on the eastern side of Great Staple Tor, has not undergone
1385 significant steepening since the late Pleistocene. On other slopes, which connect directly to deep
1386 valleys such as at Widecombe (Chinkwell Tor, Honeybag Tor) and near Belstone (Belstone Tor),
1387 fluvial incision is more obviously responsible for tor destabilisation by steepening of the slope base.
1388 Where this occurs, boulders with blunted edges (many perhaps corestones) replace the more angular
1389 slope debris of periglacial origin.

1390 Hay Tor (Fig. 7e, f, g), the tallest and most massive Dartmoor tor, is effectively a small
1391 inselberg, with a 35–45 m eastern rock face providing high-grade vertical rock-climbing routes.
1392 Hay Tor is atypical of most other tors on Dartmoor, however, and its relief perhaps indicates an
1393 upper limit on tor growth potential in this landscape.

1394

1395 **6. Discussion: in search of consilience**

1396

1397 **6.1. *The pitfalls of equifinality in landscape evolution***

1398

1399 In geomorphology it is likely that similar end-states (landforms) are achievable by a same set of
1400 processes acting upon dissimilar initial conditions and via different paths (Haines-Young and Petch,
1401 1983). As lively correspondence between Gerrard (1984) and Haines-Young and Petch (1984)
1402 testifies, and as this review has abundantly emphasised, Dartmoor has been a debating arena over
1403 the origins of patterned ground, tors, erosion surfaces, secondary minerals, palaeoclimates, and
1404 glacial landforms.

1405 Equifinality in geomorphology will often result from (i) imprecision in the classification or
1406 contextual understanding of landforms and deposits (with its equivalent of the ‘ill-posed problem’
1407 in numerical modelling of landforms: Ebel and Loague, 2006); (ii) misunderstanding (e.g., cases of
1408 mistaken identity when authors shaped by different scientific cultures independently study objects
1409 that they believe are similar but are not: e.g., Jarman, et al., 2013); (iii) the adversarial nature of
1410 science, where scholars may be reluctant to recognise that their divergent scenarios or theories
1411 could be compatible or cumulative pending some appropriate resequencing or rescaling of the
1412 argument; and/or (iv) a technical inability to implement investigative protocols capable of
1413 decisively discriminating between competing hypotheses. We have seen, for example, that (i)
1414 Cenozoic epeirogeny in SW England has many plausible causes, all based on some form of indirect
1415 inference; (ii) granite weathering follows hypogene as well as supergene pathways; (iii) the mode of
1416 tor evolution is lithology-dependent rather than just climate-dependent; (iv) an absence of tors could
1417 imply that they never existed, but perhaps also that they were destroyed; (v) earth hummocks can
1418 bear no relation to Pleistocene permafrost; etc. The following sections examine the extent to which
1419 some of the competing hypotheses and contradictory observations about the evolution of the
1420 Dartmoor landscape may actually be more compatible than they seem.

1421

1422 **6.2. *Twin engines of rock weathering: the hydrothermal and meteoric systems reunited***

1423

1424 The Critical Zone, i.e., the thin layer of the Earth’s surface where rocks, soil, atmospheric gases,
1425 and meteoric water interact and which forms the primary habitat for terrestrial life, has been
1426 compared by geochemists to a feed-through reactor (Anderson et al., 2007): in a region of net
1427 denudation or of topographic steady state (i.e., where uplift is balanced by erosion), solid materials
1428 enter the reactor through its lower boundary (e.g., as a result of epeirogeny), while debris of
1429 decayed rock are skimmed off the top by erosion and dissolved products leak out and enter the

1430 fluvial system. The Critical Zone concept, however, overlooks the hydrothermal system, which
1431 reaches deeper into the crust and yet also interacts with the surface.

1432 In the Dartmoor context, progress in ore mineralogy and granite hydrogeology has nonetheless
1433 contributed to considerably narrow the cognitive dissonance that has divides the two cultures of
1434 geomorphology and mining geology (Section 3.3). Hydrothermal alteration of rock is achieved by a
1435 combination of heat and solutions rich in water and other volatiles, and is the source of many ore
1436 bodies (Dines, 1956; Dearman and Baynes, 1978; Coque-Delhuille, 1987; Jackson et al., 1989). The
1437 pervasive hydrothermal alteration of the Dartmoor granite is manifest in the sericitization,
1438 chloritization and tourmalinization of biotite crystals (Ward et al., 1992). Heat flow and fluid
1439 temperature are also key to explaining the distribution of more focused late-magmatic processes:
1440 hematite mineralisation at the eastern margin of the Dartmoor granite, for example, represents the
1441 coolest level of activity of a hydrothermal system, and occurs accordingly at relatively shallow
1442 levels beneath the pluton's upper boundary. In contrast, the type of mineralisation seen at Birch Tor
1443 (Vitifer tin mine), in central Dartmoor (Fig. 3), represents a deeper level of hydrothermal activity. It
1444 has been exposed by erosion and removal of the higher parts of the system. This model could
1445 account for the presence of placer tin deposits over wide areas of western Dartmoor in which
1446 cassiterite-bearing veins have not been recorded. Tourmaline and (now eroded) cassiterite are
1447 precipitated from highly saline fluids at 250–400 °C.

1448 Even though the heat from the original intrusion has now dissipated, no longer altering the granite
1449 through the late magmatic processes known to occur at temperatures of 250–600 °C (so-called
1450 hypothermal hydrothermal activity), the long post-magmatic period is argued by Bristow (2006) to
1451 have sustained slow convective circulation of infiltrated meteoric water since Mesozoic time to the
1452 present. Convection was powered by heat produced by the radioactive decay of radiogenic elements
1453 abundant in the Cornubian granite, which by global standards contains anomalously high
1454 concentrations of U, K and Th and thus classifies as “high heat-producing” (Willis-Richards and
1455 Jackson, 1989; Bristow et al., 2002). Such convection can occur under heat gradients sustained by
1456 rock temperatures ranging between 200 °C and 30 °C (epithermal hydrothermal activity), and it
1457 seems that alteration was most effective wherever fracture-promoted downwelling of heated
1458 meteoric water occurred (Fig. 22). Hydrogeochemical evidence from the Carnmenellis granite (Fig.
1459 1) supports this model, with indications that water in tin mines was a mix between a meteoric
1460 component consistent with post-1957 signatures and a highly saline groundwater component that
1461 had been isolated from contact with the atmosphere for at least 1 Ma (Burgess, 1982; Edmunds et
1462 al., 1984, 1985). The detected mixing occurred at depths of up to 1.2 km.

1463 The southwestern edge of Dartmoor, where the china clay mines are still in production (Fig. 3), is
1464 interpreted as the downward limb of a hydrothermal convection cell, as may also be some of the

1465 narrower inverted funnels, troughs and inclined slabs of kaolinised granite described elsewhere on
1466 Dartmoor (Dearman and Baynes, 1978), where occurrences of china clay attain depths of 200 m as
1467 part of the ‘cedar-tree’ model. Other similar areas of maximum epithermal downflow are inferred to
1468 be centred on western St Austell, Land’s End and central Bodmin, all centres of china clay
1469 production. This model is supported by 3-D heat-flow modelling of SW England, where Sams and
1470 Thomas-Betts (1988a, b) found steep lateral variations of the modern temperature field over
1471 relatively short distances (8 measurement sites on Dartmoor), with a good spatial correlation across
1472 the entire Cornubian Batholith between the highest modelled vertical temperature gradients (~40
1473 °C/km) and the mineralised lodes mapped by Dines (1956). Many of these occur at the margins of
1474 the Cornubian granite outcrops (e.g., Lee Moor quarries, Fig. 3).

1475 With values of up to 8 $\mu\text{W}/\text{m}^3$, borehole-corrected heat production estimates indicate that the
1476 Dartmoor and Land’s End granites are endowed with the greatest potential in terms of radionuclide
1477 concentration (Beamish and Busby, 2016), and thus with the largest potential for sustaining the
1478 fluid circulation (and kaolinite-producing) ‘engine’ just described. Even though this coupled
1479 hydrothermal/meteoric weathering process may have been interrupted on occasions, kaolinization
1480 was intense at the surface during at least the Mesozoic and the PETM (Isaac, 1983a, b; Bristow,
1481 2006). Although it remains relevant to distinguish between well-ordered china clay and disordered
1482 meteoric kaolinite (forms between 30 and 50 °C), kaolinization is thus overall a shallow crustal
1483 process and the two varieties are interrelated. This could explain why, for example, K–Ar ages of
1484 274 Ma have been obtained for sericite extracted from kaolinised feldspar (Bray and Spooner,
1485 1983), while the oxygen and hydrogen isotope data of many ball-clay samples from SW England
1486 have yielded supergene signatures (Sheppard, 1977).

1487 Based on vein mineral distribution patterns in the St Austell and Carnmenellis granite stocks (Sams
1488 and Thomas-Betts, 1988a, b; Jackson et al., 1989; Willis-Richards and Jackson, 1989; Bristow et
1489 al., 2002; Bristow, 2006; Beamish and Bisby, 2016), and tentatively using them as analogues for
1490 Dartmoor, prevailing evidence is thus that kaolinisation on Dartmoor involved both hydrothermal
1491 and meteoric processes interacting in a dynamic system which is perhaps still active today.

1492
1493 **6.3. Dartmoor recast as a dynamic etchplain**

1494
1495 The etchplain view of Dartmoor has endured since the 1970s until now. For example, through
1496 correlation among 48 Dartmoor tors based on 22 variables (3 topographic, 5 structural, 4
1497 petrographic, 7 compositional, and 3 textural), Ehlen (1994) produced a classification of tors. Her
1498 results yielded few discriminating bedrock properties of significance to bring out consistent
1499 geographic patterns likely to illuminate the denudation history of Dartmoor or the behaviour of tors

1500 in some predictable way. The inevitable conclusion was clearly that the landscape evolution was
1501 implacably random, true to the “chance exposure” paradigm formulated by Gerrard (1974).
1502 Gunnell et al. (2013) found that other factors with no apparent influence on tor exposure age were
1503 tor height, joint spacing, petrography, topographic location (e.g., summit vs. spur tors), local
1504 topographic relief, and slope gradient. Altitude likewise appeared uncorrelated with tor exposure
1505 age (e.g., Fig. 21). Half the sites are tightly grouped around the median exposure age of 44 ka,
1506 which could suggest an ‘event’ or period of activity of sufficient impact to dominate the results.
1507 Nonetheless, the tor age distribution pattern mostly appears spatially random at all scales, thus
1508 favouring (in line with the conclusions of Hägg, 2009) a randomness in exposure patterns.
1509 Such randomness is compatible with the etchplain concept, and particularly with the dynamic
1510 etchplain hypothesis considered by Brunsden (2007) (Fig. 23). At the core of the dynamic etchplain
1511 scenario lies the appreciation of what drives base-level change over the long term (the dynamic
1512 component). In a recent study of western Scotland, which like SW England displays topographic
1513 anomalies that have proved challenging to explain, Fame et al. (2018) concluded that low-elevation
1514 passive margins “may experience variable burial, uplift, and erosion patterns and histories without
1515 exhibiting a single, dominant driver for behaviour before, during, and after rifting”. This open-
1516 ended view is a far cry from the rigid world views of the School of Platforms, or L.C. King or W.
1517 Penck, and resonates with the dynamic etchplain paradigm.

1518 The drivers of etchplain dynamics are speculative. In addition to the epeirogenic processes
1519 reviewed in this paper, Westaway (2010) has for example argued that changes in loads on the land
1520 surface (through erosion and sedimentation) could trigger an extremely rapid response in the ductile
1521 lower crust that scales with Quaternary climatic cycles. The lower crust would thus have the
1522 capacity to flow and bulge in ways held responsible for low magnitudes of short-wavelength
1523 topographic uplift and, by internal feedback, for producing sequences of fluvial incision and alluvial
1524 aggradation. This theory, however, is not universally endorsed (e.g., Łuszczak et al., 2018).

1525 Eustatic drivers of base-level change were emphasised instead by Brunsden (2007). In theory, the
1526 initial elevation of ancient sea-level markers (the 690 ft platform, the 430 ft platform, etc.) can be
1527 inferred from a global sea-level (GSL) curve and be used to quantify low-amplitude vertical
1528 movements. However, any such results will strongly depend on GSL curve calibration. Regions
1529 where the inferred amplitude of epeirogenic deformation is less than 200 m, such as most of
1530 England, are particularly sensitive to the choice of GSL curve because of the large discrepancies
1531 that exist between the GSL curve of Haq et al. (1987), discussed by Brunsden (2007), and more
1532 recent revised curves (Müller et al., 2008). There is, for example, up to 200 m of vertical difference
1533 between the Haq et al. (1987) and Miller et al. (2011) curves for the Upper Cretaceous (see Moucha
1534 et al., 2008), with obvious implications for the long-term insularity of Higher Dartmoor and the

1535 extent of late Cretaceous marine onlap over the granite.

1536

1537 **6.4. Scope for further constraints on the evolution of Dartmoor**

1538

1539 This review has pinpointed a number of unresolved, but also unexplored, topics which could
1540 collectively tighten existing constraints on Dartmoor's landscape evolution. A list of future
1541 investigations is provided here, which mainly emphasises the need for understanding the
1542 geochronology of Dartmoor's rocks, deposits and landforms.

- 1543 • No thermochronological data currently exists for Dartmoor despite the granite's averred apatite
1544 content (Ward et al., 1992). Insights gained from apatite fission-track and (U–Th)/He dating
1545 could document the history of pluton unroofing, although hydrothermal fluid circulation
1546 (Section 6.2) might complicate interpretations.
- 1547 • The Cornubian Island has been a persistent, long-term feature of the British Isles (Fig. 2), but
1548 the chronology and positions of its shifting shorelines still lack systematic precision.
1549 Quantifying eustatic variations, including the Langhian and mPWP sea-level highs (Section
1550 5.3.4), could gain from the methodology used for neighbouring Brittany (Bessin et al., 2015,
1551 2017) based on recent recalibrations of the global sea-level curves (Miller et al., 2011). Digital
1552 and field mapping of possible vestiges of mid-Miocene and/or mid-Pliocene strandlines (e.g.,
1553 based on Figures 19 and 20) could then serve as a basis for testing whether some of the drainage
1554 anomalies and epigenetic gorges around Dartmoor (Section 5.3.3) could be the result of local
1555 stream avulsions promoted by one of these highstands, followed by subsequent incision of the
1556 underlying geological structure and abandonment of some (now dry) valleys. A co-occurrence
1557 of (i) avulsion-related cases of drainage superimposition and (ii) knickpoint-related cases of
1558 drainage diversion is obviously possible, with staggered events occurring between the late
1559 Miocene and the Quaternary.
- 1560 • River channel knickpoints on and off the granite would require systematic mapping, followed
1561 by terrestrial cosmogenic dating of bedrock straths and quantitative analysis based on surface
1562 process models (e.g., Jaiswara et al., 2019) to estimate the key periods of river gorge cutting.
1563 Extension of channel profiles out into the English Channel in order to assess valley incision
1564 potential during glacial sea-level lowstands would be a bonus.
- 1565 • Off-granite occurrences of granite boulder deposits in river valleys (Section 5.3.1) would
1566 require a more systematic study in order to understand their provenance and mode of transport
1567 (e.g., Williams, 1983).
- 1568 • OSL thermochronometry is a new approach for evaluating post-glacial bedrock surface erosion
1569 (Lehmann et al., 2019). Given that OSL and ¹⁰Be data integrate over different timescales,
1570 inverting bedrock OSL signals and ¹⁰Be concentrations into quantitative estimates of post-

1571 glacial exposure duration could help to detect how tor erosion rates have varied through space
1572 and time since the last glacier melt-out event on Dartmoor.

- 1573 • Schmidt hammer exposure dating has gained from recent advances in other regions (Tomkins et
1574 al., 2018). The mechanical response of 13 ^{10}Be -dated tor summits was tested by Gunnell
1575 (unpubl.) with an N-type Schmidt hammer. A minimum of ten compressive strength
1576 measurements was made at each site. Results from this preliminary attempt (Fig. 24) reveal a
1577 positive correlation between ^{10}Be minimum exposure ages and rock-strength values, i.e.,
1578 strength increases with the antiquity of tor-summit exposure. Although this simple relationship
1579 (which also features outliers) would need to be unpacked as it may contain many layers of
1580 cumulative (and perhaps counter-intuitive) causation, this nonetheless suggests that mechanical
1581 rock properties could be used as proxies for tor exposure age over at least the span of the
1582 Devensian period. A wider sample and more systematic survey obeying recently advocated
1583 sampling and calibration protocols (e.g., Tomkins et al., 2018) could uncover interesting trends.
- 1584 • Seeking ages constraints on the formation of kaolinite can take advantage of the fact that $\delta^{18}\text{O}$
1585 values of meteoric waters globally have become progressively higher since the Permian, and
1586 that there is a strong correlation between the isotopic composition of meteoric waters and
1587 factors such as altitude, latitude and longitude. This approach has yielded dividends in Australia,
1588 where very long-distance continental drift since the Cretaceous has allowed $\delta^{18}\text{O}$ enrichment to
1589 be calibrated against independent geological age constraints, thus generating a regional proxy
1590 curve that can be used for dating secondary minerals in weathering profiles of unknown age
1591 (Chivas et al., 2019). Given, however, that Britain has remained relatively stationary in latitude
1592 and longitude since the early Jurassic, $\delta^{18}\text{O}$ age tuning may not be a powerful tool in the context
1593 of the Cornubian batholith. Electron paramagnetic resonance (EPR) spectroscopy, however, is
1594 another new method which has been implemented for dating kaolinite in tropical settings (e.g.,
1595 Mathian et al., 2019). Perhaps Dartmoor could gain from it in the future.

1596

1597 **7. Conclusion**

1598

1599 As cognitive psychologists commonly emphasise (e.g., Kahnemann, 2011), our perceptual
1600 experiences are really about our brain making up scenarios and seeing patterns. The way we see the
1601 world is most often the way we expect the world to be, and ‘truth’ fits into tribal narratives that
1602 define us. The search for scientific truth, which in principle should strive to erase cognitive bias and
1603 countervail confirmation bias (tendency to seek out information which confirms what we already
1604 believe is true), is fundamentally a process of human consensus building: truth is about evidence
1605 standing up to consensus. The consensus attained may hold up over time, in which case some

1606 essential dimension of physical reality may have been uncovered; otherwise it may crumble or bend
1607 under the weight of new evidence.

1608 Geomorphology and geology are disciplines which thrive on storytelling (Phillips, 2012), each
1609 narrative competing for breadth of consensus as a measure of its truthfulness. The history of
1610 research in the evolution of the Dartmoor landscape epitomises these processes at play. In the
1611 lexicon of philosopher Karl Popper (1972) it portrays how, between the World 1 (world of physical
1612 objects) and World 3 (world of ideas) approaches to reality, the much-avoided World 2 (world of
1613 consciousness and mental states) weighs in on scientific judgement. Petch and Haines-Young
1614 (2019), who as we saw in Section 6.1 have also in the past expressed ontological and
1615 epistemological views on the evolution of Dartmoor (Haines-Young and Petch, 1983, 1984),
1616 recently highlighted the psychological bias of scholars making judgements based on emotion or
1617 feeling — something cognitive psychologists have termed the ‘affect heuristic’ (e.g., Slovic et al.,
1618 2002). This is in no way a dismissive admission that affect-tainted judgements are shallow or
1619 unscientific. What it rather implies is that “there is a strong element of fashion in problem
1620 selection” (Sherman, 1996). Research on Dartmoor in the last 200 years clearly encapsulates the
1621 collision of Popper’s worlds 1, 2 and 3.

1622 This review has portrayed how components of entrenched theories or scenarios could eventually be
1623 assembled in more coherent ways. Despite being periodically touted as embodying purity, e.g.:
1624 Dartmoor as the ideal peneplain, or the perfect piedmont benchland, or a compelling example of
1625 superimposed drainage, or the purest of periglacial landscapes, or the unique vestige of an English
1626 tropical landscape, Dartmoor is fundamentally a palimpsest landscape; i.e., Dartmoor is an area
1627 where the imprints of successive regimes or events in this relatively low-energy intraplate setting
1628 have not been erased, and yet often remain faint because of the many successive overprints.

1629 The strongest lesson arising from the Dartmoor case history is the progressive acceptance by
1630 geomorphologists that landscapes do not develop, i.e., do not transform according to some pre-
1631 ordained succession of stages (e.g., Section 4.1). Rather, landscapes evolve. To understand their
1632 evolutionary trajectories, landscape histories need to be threaded through a succession of well
1633 constrained base-level changes and climate-driven events, but this remains the hardest challenge
1634 because the events require age constraints. The dynamic etchplain concept advocated by Brunson
1635 (2007) is an apt encapsulation of the evolving landscape paradigm: an open system driven by
1636 external and internal variables that combine to produce successions of landform mosaics as time
1637 passes. The typical external variables are epeirogeny (whether its causes are near-field or far-field,
1638 crustal or subcrustal, lithospheric or asthenospheric), sea-level variation (of contrasting magnitudes
1639 in the English and Bristol channels during the Pleistocene, to which must be added the impact of the
1640 mid-Pliocene Warm Period), Paleogene inversion tectonics, and regolith-impacting climate

1641 changes. Internal variables include the piecemeal effects of drainage piracy, joint density,
1642 petrographic variation, pluton roof geometry, stockwork heterogeneity, and feedbacks between all
1643 of these on valley incision and slope response. In being open-ended, etchplain theory is entirely
1644 suited, indeed conveniently tailored, to Gerrard's (1988a) maxim that "there is no single starting
1645 point and no inevitable end product in the sequence of landform development in granite".
1646 Using the vocabulary of etchplain characterisation developed by Thomas (1965, 1994), it is thus
1647 likely that under tropical and near-base-level conditions during the Mesozoic and Paleogene,
1648 Dartmoor was a 'mantled etchplain' or 'partly stripped etchplain' (Fig. 9e), i.e., the land surface
1649 was a mosaic of etch basins and their local wash divides. The presence or absence of tors being a
1650 matter of relative balance between the rates of weathering-front deepening and regolith stripping,
1651 differential erosion need not generate bedrock exposure if stripping remains outpaced by soil
1652 production. Such was perhaps the case during warmer and mostly humid pre-Quaternary times
1653 (Bristow et al., 2002; Bristow, 2006; Fig. 22). This continual modulation of the
1654 weathering/stripping ratio suggests that tors emerge somewhat randomly and autogenically
1655 (Strudley et al., 2006) as a result of local stripping intensities controlled by base-level changes and
1656 climate-driven sediment transport conditions (Gerrard, 1974). Subtle mesoscale structural and
1657 petrographic controls on susceptibility to rock weathering nonetheless apply because the granite and
1658 its hydrothermal stockwork system are not structurally or petrographically uniform (see Section
1659 3.2).

1660 Dartmoor's long-term Mesozoic and Cenozoic residence in a low-energy environment explains why
1661 the tors in the Roof Complex still belong to the outer shell of the pluton. During the middle to late
1662 Pleistocene, when valley incision in NW Europe accelerated substantially (Antoine et al., 2003;
1663 Brown et al., 2010), the landscape was likely transformed into a 'stripped' or 'complex' etchsurface
1664 (Fig. 9e) under the joint effects of periodically changing climatic conditions and valley incision.
1665 The possibility of dating bedrock landforms on Dartmoor (Gunnell et al., 2013) and alluvial terraces
1666 in the region (Brown et al., 2010) has contributed to clarify Linton's (1955) 'problem of tors'.
1667 Although visually prominent on moorland skylines, Dartmoor tors are insignificant in height and
1668 volume compared to the granite outcrop's extent. The general impression gained from exposure
1669 dating is that tors are prone to emerge quickly but equally to disappear — perhaps during every
1670 Pleistocene climatic downturn through partial or total destruction by frost action and slope
1671 undercutting by incising rivers. Rather than stable pins on a changing land surface (with the
1672 possible exception of the Hay Tor inselberg, and maybe a few others) successive tor populations
1673 may thus have flickered in and out of existence across the Dartmoor landscape as transient features.
1674 According to Hall and Sugden (2007, p. 308), "no evidence currently exists in the British Isles that
1675 allows tors to be regarded as inherited Neogene landforms". Tor development has thus probably

1676 been little more than a late Pleistocene footnote in the landscape evolution, the significance of the
1677 tors having been hitherto overplayed mostly because of their scenic importance and recreational
1678 value. None of this takes away the appeal of Dartmoor as a geoscientific incubator, where in the last
1679 200 years so much creative tension has spawned so many new ideas out of such a small portion of
1680 the Earth's surface.

1681
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1685
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2409

2410 **Figure legends**

2411

2412 Fig. 1. Topography and geology of SW England. **a**: yellow outline: granite, with name of outcrop in
2413 capitals (KH: Kit Hill; HD: Hingston Down). Black outlines: units of deformed low- to medium-
2414 grade metamorphic country rock (sub-greenschist facies) into which the post-tectonic granite
2415 batholith was emplaced. Map source: 1 arcsecond ALOS World 3D elevation model. **b**: the
2416 Cornubian granite and its pre-Variscan country rock (lithostratigraphic domains: British Geological
2417 Survey, <http://mapapps.bgs.ac.uk/geologyofbritain/home.html>). Note the roughly E–W strike of the
2418 outcrop pattern of Devonian and Carboniferous rocks, also reflected in the finer fabric of the
2419 topography and drainage net. The palaeogeographic domains, named “basins” because they each
2420 represent the fill sequences of individual rift-generated basins, corresponds to the passive-margin
2421 mosaic of sedimentary sequences that subsequently became compressed into a north-vergent fold-
2422 and-thrust belt during the Variscan orogeny. The Lizard Ophiolites are a legacy of the pre-
2423 collisional subduction and were eventually thrust over the metasedimentary succession to the north.

2424

2425 Fig. 2. Dartmoor (D) at the apex of a long-standing Cornubian Island: some first-order regional
2426 palaeogeographic feature of SW England (after Hart, 1999, 2012, modified). White areas: outcrops
2427 geologically younger than indicated by other ornaments.

2428

2429 Fig. 3. Oblique view of the rolling moorland of Higher Dartmoor, emphasising its separateness
2430 from the greener mosaic of “normal Devon”, except for the West Dart etch basin near Princetown
2431 (see text for details). Note predominantly agricultural land use on Lower Dartmoor, also in granite.
2432 Place names, tors and landmarks are mentioned in text. Dashed contour: approximate boundary of
2433 cold-based icefield discussed by Evans et al. (2012); see also Figs. 14, 15. CNES/Airbus imagery,
2434 oblique view in the Google Earth navigator; elevation exaggeration x3 in order to highlight
2435 interfluvial convexity and the sharpness of fluvial incision.

2436

2437 Fig. 4. The Dartmoor upland showing various geological features and radiometric results discussed
2438 in the text. LSF: Lustleigh–Sticklepath Fault. Map source: 1 arcsecond ALOS World 3D elevation
2439 model.

2440

2441 Fig. 5. Topographic profiles through the Dartmoor upland and its peripheral outcrops. Note the
2442 topographic smoothness of Lower Dartmoor compared to the more rolling features of Higher
2443 Dartmoor, the faint impact on relief of the Lustleigh–Sticklepath Fault zone between Higher and
2444 Lower Dartmoor, and the topographic continuity with the Haldon Hills (a Cretaceous-capped butte).
2445 Map source: 1 arcsecond ALOS World 3D elevation model.

2446

2447 Fig. 6. Relationship between jointing, weathering and mesoscale granite landforms on Dartmoor.
2448 After Small (1978), modified, to illustrate the views of Waters (1957). Intended scale: several
2449 kilometres across. See text for details, and Figure 15 for situated examples.

2450

2451 Fig. 7. Some geomorphological aspects of Dartmoor and its tors. **a**: aspect of pseudo-bedding on
2452 North Dartmoor, also showing the largely featureless appearance of the scenery in the background
2453 and emphasising the status of tors as mere pimples in the landscape. **b**: Brat Tor (452 m, NW
2454 Dartmoor), showing pseudo-bedding in the Roof Complex and progressively accentuated dip to the
2455 left (north) of the entire exposure. A few toppled boulders help to distinguish between the outcrop-
2456 scale dip direction and curvature, and local-scale boulder destabilisation. **c**, **d**: Blackingstone Rock
2457 (355 m), a massive valleyside tor on Lower Dartmoor. Note the sparse jointing and woolsacks
2458 generated by the pseudo-bedding. Frame **e**: CNES/Airbus imagery, oblique view in Google Earth,
2459 elevation exaggeration x3 to accentuate valleyside / plateau-edge location and tor asymmetry. **e**, **f**,
2460 **g**: aspects of Hay Tor Rocks (457 m), the only inselberg-like hilltop landform of Dartmoor. Note
2461 structural layering in the granite between the south-dipping ‘giant granite’ caprock and underlying
2462 ‘blue granite’. Widely spaced joints in (g) contribute to the massive appearance of the tor.

2463

2464 Fig. 8. The origin of tors: the Linton (1955) (panels a and b) and Palmer and Neilson (1962) (panel
2465 c) alternatives. Panel b: latent tor in grus quarry floor at Dunnabridge West quarry.

2466

2467 Fig. 9. Etch surfaces and their schematic variants in the literature. Note the conceptual importance
2468 of stages and sequences but the absence of quantified elevation, distance or time scales.
2469 Pediplanation: slope retreat across bedrock (**a**, compatible with King, 1953) or weathered rock (**b**).
2470 Etchplanation: differential downwearing of a deep regolith (**c**, **d**). In (b) and (c), fracture density
2471 predesigns the spatial pattern of bornhardt exposure and approximately reflects the views of Linton

2472 (1955), but in (c) bornhardt erosion accelerates because new curved rock sheets are generated as
2473 offloading proceeds through time. In (c), tall domes initially grow but subsequently decay over
2474 time, suggesting that tors could theoretically be stumps of once much larger inselbergs. The
2475 collapse of bornhardts into castle kopjes was imagined by Thomas (1965) by virtue of the
2476 possibility that, as the unsupported height of a bedrock mass increases, internal lateral stresses will
2477 increase because of gravitational loading. Attainment of this critical height beyond which the rock
2478 mass cannot stand unsupported (King and Linton, 1958) leads to extensional joints opening and to a
2479 hastening of bornhardt dislocation. In (d) the bornhardts grow as the surrounding plain is stripped
2480 away. In (b) and (c), deep chemical weathering preceded deep regolith stripping, whereas in (d),
2481 surface erosion and chemical etching lower the land surface and the basal surface of weathering,
2482 respectively, at similar rates and incrementally. In (e), note that lithological contrast, although
2483 potentially obvious, is never portrayed as a cause of differential down- or backwearing. Panels (a)
2484 to (e) adapted from Jessen (1936), Ollier (1959), Thomas (1974), Büdel (1957) and Thomas (1994),
2485 respectively. WR: weathered rock.

2486

2487 Fig. 10. The Dartmoor erosion surfaces according to Brunnsden (1963), adapted.

2488

2489 Fig. 11. The Dartmoor erosion surfaces according to Brunnsden et al. (1964), adapted.

2490

2491 Fig. 12. A gallery of alternative landscape evolution models reconstructed for Dartmoor and SW
2492 England over the last 60 years (modified after Brunnsden, 2007).

2493 **a:** traditional eustatic-cyclical British denudation chronology model (e.g., Brunnsden, 1963). 1: Post-
2494 Variscan surface; 2: Dartmoor considered submerged during Cretaceous sea-level highstand, with
2495 sub-Cretaceous surface possibly exposed on flank of Dartmoor; 3: early Cenozoic surface on
2496 Dartmoor; note distinction between Oligocene (3a) and sub-Eocene (3b) surfaces; 4: Miocene to
2497 Pliocene peneplain, marine abrasion surfaces, and Pleistocene river terraces; 5: Oligocene and
2498 Miocene graben-fill deposits (Bovey Basin).

2499 **b:** post-Variscan surface degradation model (partly after Coque-Delhuille, 1991). 1: continuous
2500 degradation of Dartmoor Paleoplain. 2: etch basins in post-Variscan surface; 3: Cornubian
2501 Paleoplain and its deposits west of Dartmoor, below the Haldon Hills, and in the Bovey Basin; 4:
2502 sub-Cretaceous surface; 5: mosaic of early Cenozoic surfaces capped by laterite and sarsen stones
2503 (i.e., silcrete); 6: exhumed sub-Eocene surface.

2504 **c:** inheritance model (Migoñ and Goudie, 2001). 1: Cenozoic weathering residuals; 2: deep
2505 kaolinitic weathering; 3: Oligocene and Miocene sediment residuals; 4: Eocene and Oligocene

2506 deposits in Cenozoic basins; 5: early Cenozoic gravels and other residual surface deposits; 6: sub-
2507 Eocene surfaces exhumed.

2508

2509 Fig. 13. Spatial distribution of the stacked erosion surfaces (benchland topography) according to the
2510 1:100,000 scale geomorphological map of Dartmoor by Klein (1990). One main difference with
2511 Brunsden (1968; see Figures 10 and 11) is that each pediment surface (S1, S2) is conceived of as
2512 sloping outward because of postulated Cenozoic updoming of Dartmoor following the model
2513 advocated by Penck (1925) for the southern Black Forest in Germany. Key – 1: Paleogene surface
2514 S1 (a legacy of post-Variscan surface degradation); 2: residual relief associated with S1; 3: Mid-
2515 Cenozoic surface S2; 4: residual relief associated with S2; 5: topographic bench (level S3); 6: cyclic
2516 scarp separating S1 from S2; 7: boundary scarp (generated by differential erosion between the
2517 granite and its metamorphic country rock); 8: other scarp; 9: Sticklepath Fault (S); 10: Lustleigh
2518 Fault (L); 11: pediment gap; 12: Bovey Tracey Basin; 12a: Aller Gravel (A); 12b: middle Bovey
2519 Formation; 12c: Southacre Clay and Lignite; 12d: Blatchford Sands; 13: outline of the granite
2520 outcrop; 14: towns and villages (listed at top right of map). See also Figures 4 and 21 for connecting
2521 information.

2522

2523 Fig. 14. The three types of topographic basin on and around Dartmoor: tectonic, weathering-related,
2524 and fluvial. Oblique 2.5-D view of Dartmoor's relief from the SW. **a**: the Bovey graben, which is
2525 largely erosional (overfilled basin bounded by fault-line scarps and partly hollowed out by post-
2526 tectonic fluvial erosion); **b**: the West Dart and West Webburn etch basins, two drainage basins
2527 strongly influenced by components of petrographic and structural control (see also Figure 15); **c**:
2528 the south coast rias. Source: 1 arcsecond ALOS World 3D elevation model. Colour coding – blue:
2529 higher plateau elevations; red: valleys and lower elevations.

2530

2531 Fig. 15. A gallery of small etch basins in first- and second-order catchments of Higher Dartmoor:
2532 Fox Tor Mire and Burrator Basin (South Dartmoor), and Taw Marsh and Fenworthy Basin (North
2533 Dartmoor). Rivers exit these etch basins via a knickzone, waterfall, gorge, or rapids. Some of these
2534 knickzones have been dammed (Fenworthy and Burrator reservoirs).

2535

2536 Fig. 16. Periglacial stone stripes on west-facing slopes at Great Staple Tor (455 m) and Middle
2537 Staple Tor (431 m). CNES/Airbus imagery, oblique view in Google Earth, no vertical exaggeration.
2538 Maps: 1 arcsecond ALOS World 3D elevation model. Colour coding – blue: higher plateau
2539 elevations; red: valleys and lower elevations.

2540

2541 Fig. 17. The Dartmoor river gorges. **a**: an early sketch by Guilcher (1949); **b**: the Lydford Gorge
2542 wind gap, suggestive of drainage rearrangement on and around Dartmoor in late Cenozoic and
2543 Quaternary time (see text for details). Map: 1 arcsecond ALOS World 3D elevation model. Colour
2544 coding – blue: higher plateau elevations; red: valleys and lower elevations.

2545
2546 Fig. 18. Longitudinal river profiles of Dartmoor. Note position of knickpoints, topographic benches,
2547 and overall departure among all the rivers from a theoretical graded profile. In addition to
2548 geologically recent drainage piracy (Fig. 17), these features suggest a strong influence on channel
2549 profiles of lithology, structure, and perhaps recent tectonic deformation. Channel profiles derived
2550 from 1 arcsecond ALOS World 3D elevation model. See text for details.

2551
2552 Fig. 19. Impression of SW England at the time of either the mid-Miocene eustatic high or the short-
2553 lived mid Pliocene Warm Period (mPWP). The images are factually spurious in terms of
2554 topographic rendition, but the key feature is the black elevation contour as a heuristic tool for
2555 searching the field for geomorphological and/or sedimentary clues of a Langhian or a Pliocene
2556 strandline in SW England. The main scenario depicted here is cast under the hypothesis of a +30 m
2557 (Langhian or mPWP) sea-level rise followed by (i) the subsequent 30 m sea-level fall and (ii) an
2558 additional 100 m of net uplift and valley incision. Accordingly, legacies of this eustatic event
2559 should be investigated at locations close to the +130 m OD contour. Yellow circles point to
2560 drainage anomalies (elbows of capture, etc.) mentioned in the text and also circled in Figure 4.
2561 Insets show two scenarios of the drowned landscape: +130 m, and +75 m (following an option
2562 proposed by Everard, 1977; Walsh et al., 1987; and Hart et al., 2011).

2563
2564 Fig. 20. Topographic benches of the Start–Bolt coastline in schist. **a**: the flat 125–130 m OD surface
2565 (1), and the 500-m-wide erosional ramp notched below it (2). Numbering is identical in panel b. **b**:
2566 view to the NE from Prawle Point. 1: edge of the 130 m OD shore platform ('430 ft flat'), the most
2567 elevated erosion surface of marine origin in the area (see text for details, and Fig. 19); 2: sloping
2568 erosional bench (raised platform?) with abandoned cliff line between 1 and 2, of uncertain age (see
2569 text); 3: narrow depositional bench of Devensian periglacial debris (head), connecting to platform 2
2570 via chutes that break up the craggy (and abandoned) cliff face which stands between 2 and 3
2571 (foreground included); 4: rocky shore platform extending mostly above the High Water Mark.
2572 Platforms 1 and 2 provide clear evidence of surface uplift since late Neogene time. The lower
2573 platform 4 (erosional) is difficult to interpret (Mottershead, 1997), as unit 3 has spilled slope debris
2574 onto platform 4. Platform 4 is thus probably from an earlier Pleistocene interglacial (Ipswichian
2575 highstand?), and has been exhumed as a result of late Devensian / early Holocene trimming, thus

2576 forming the earth cliff between 4 and 3. Note that Orme (1960) had interpreted the staircase 1 to 4
2577 as a straightforward chronosequence of terraces, whereas Mottershead (1997) offers a more
2578 discerning reinterpretation in which eustatic and epeirogenic processes are subtly intertwined.

2579

2580 Fig. 21. Age–elevation plot of tor-summit ^{10}Be exposure ages (data points situated in Figs. 4 and
2581 13) after Gunnell et al. (2013). Note weak correlation of age with altitude and large scatter within
2582 the two altitude bands of S1 and S2, regardless of whether the landscape models in Figures 10, 11
2583 or 13 are considered. This suggests that the tors are poor indicators of Cenozoic surface evolution,
2584 or that the surfaces are inferred from spurious criteria, or both (i.e., that the landscape is a result of
2585 random processes relevant to the etchplain concept). Previously unpublished.

2586

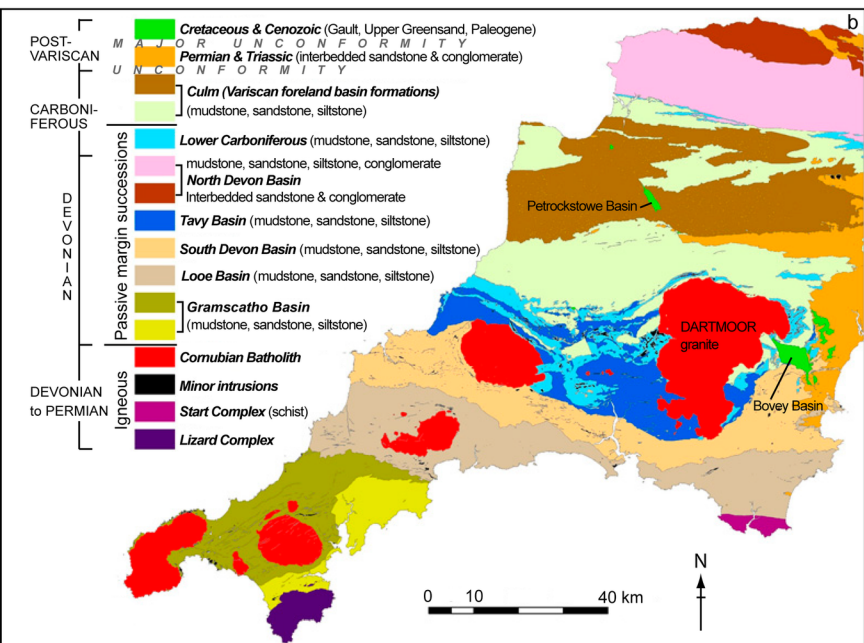
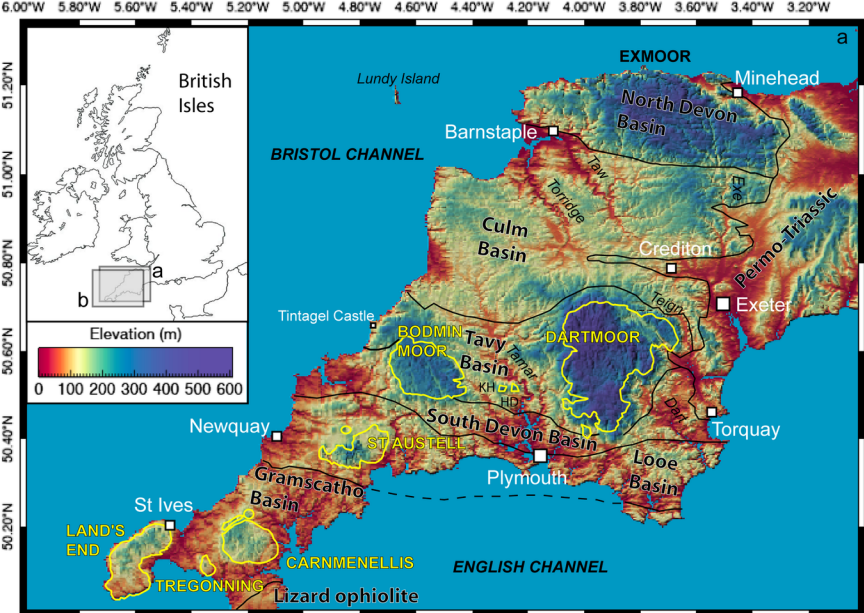
2587 Fig. 22. Cartoon sketches through the St Austell granite stock. This well-studied setting in Cornwall
2588 serves as an analogue for understanding how china clay, metalliferous deposits, and hot fluid
2589 convection could explain the dual — supergene and hypogene — origin of kaolinite on Dartmoor,
2590 and thus some of its first-order landscape evolution features from Permian time to the present day
2591 (after Bristow et al., 2002, and Bristow, 2006, modified).

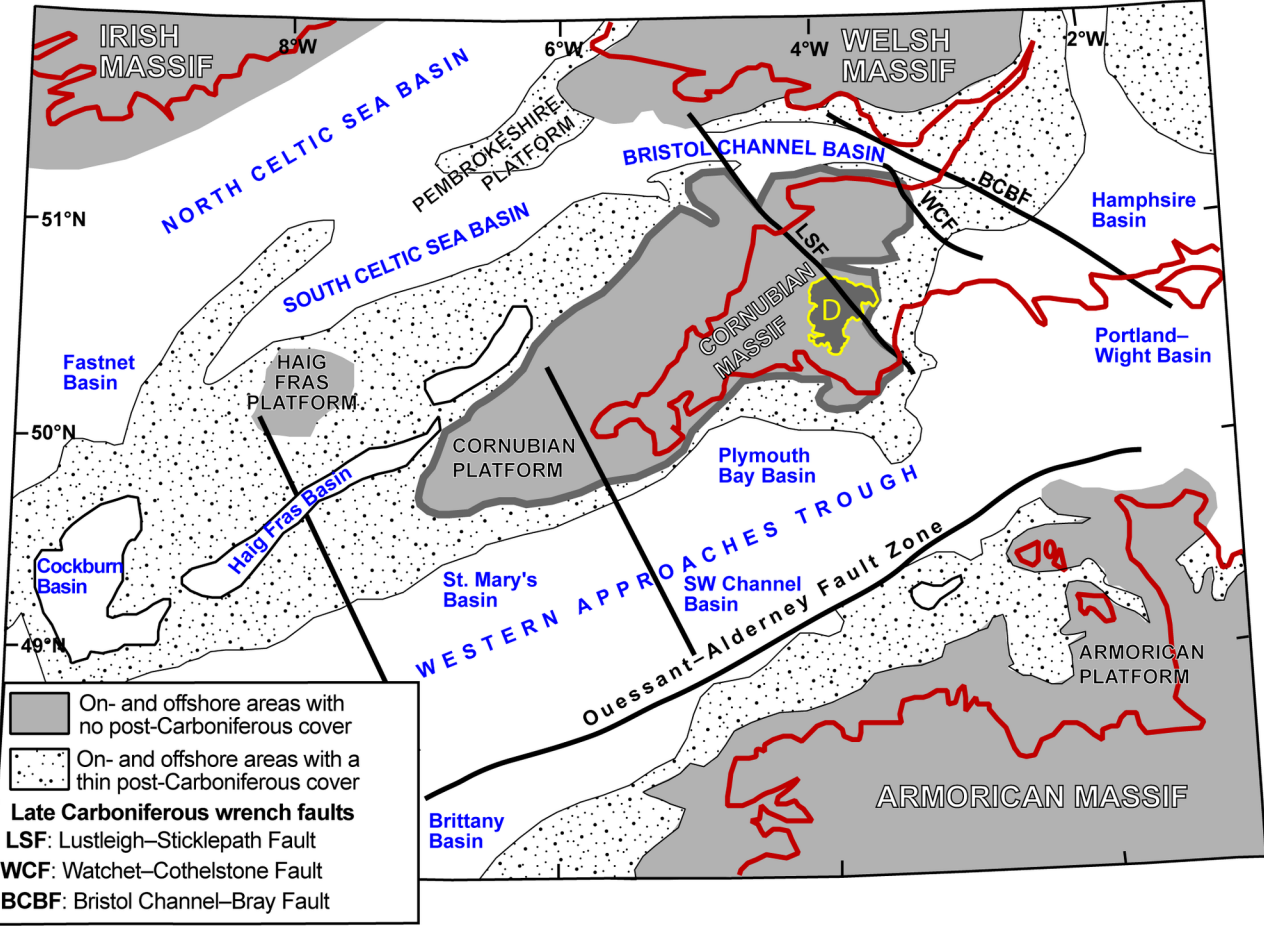
2592

2593 Fig. 23. The dynamic etchplain model (Brunsden, 2007). 1: base-level control assumed to have
2594 varied by ~300 m since Jurassic time; 2: Pleistocene raised beaches and terraces; 3: possible marine
2595 transgressions (Pliocene and Pleistocene); 4: Oligocene and Miocene residual deposits; 5: deep
2596 hydrothermal alteration; 6: early Cenozoic warped surface; 7: thin grus on interfluvial summits; 8:
2597 deep weathering below valleys; 9: Cenozoic basin fill. The dynamic etchplanation of Dartmoor
2598 involves incision controlled by uplift and regolith stripping modulated by climatic change and slope
2599 gradient.

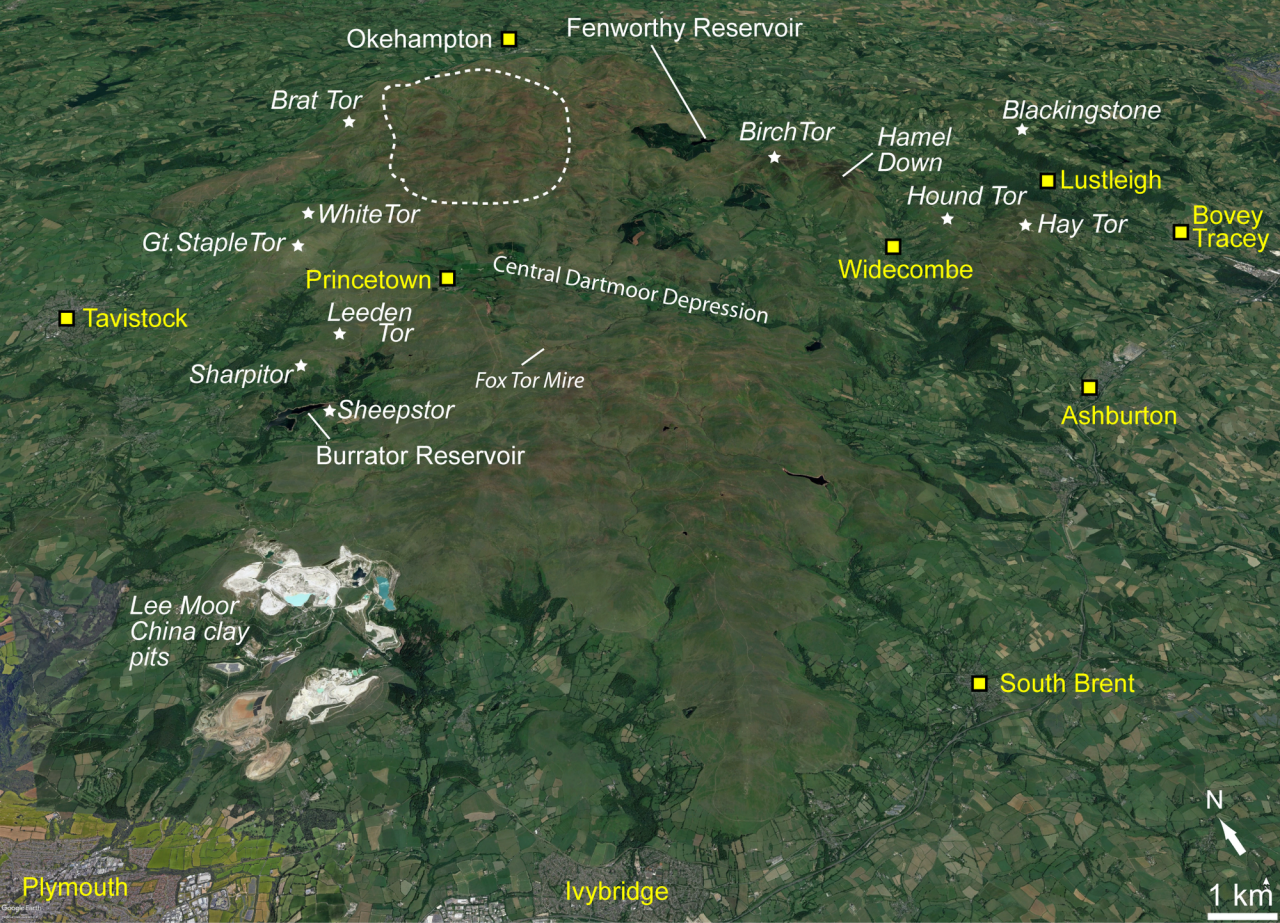
2600

2601 Fig. 24. Preliminary correlation between bedrock compressive strength and ^{10}Be minimum exposure
2602 age on a selection of Dartmoor tor summits. Red line: least-squares linear regression model. Age
2603 values (also shown in Figures 4 and 21) after Gunnell et al. (2013).





On- and offshore areas with no post-Carboniferous cover
 On- and offshore areas with a thin post-Carboniferous cover
Late Carboniferous wrench faults
 LSF: Lustleigh–Sticklepath Fault
 WCF: Watchet–Cothelstone Fault
 BCBF: Bristol Channel–Bray Fault



Okehampton ■

Fenworthy Reservoir

Brat Tor ★

Birch Tor ★

Blackingstone ★

White Tor ★

Hamel Down

Hound Tor ★

Lustleigh ■

Gt. Staple Tor ★

Princetown ■

Central Dartmoor Depression

Widcombe ■

Hay Tor ★

Bovey Tracey ■

Tavistock ■

Leeden Tor ★

Fox Tor Mire

Sharpitor ★

Ashburton ■

Sheepstor ★

Burrator Reservoir

Lee Moor
China clay pits

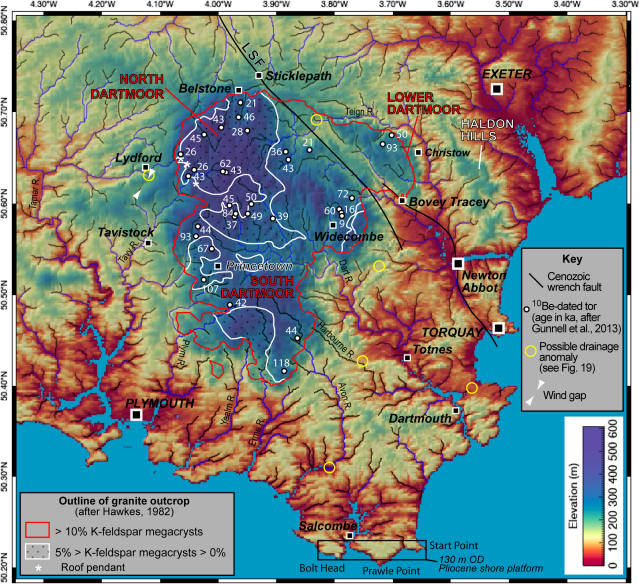
South Brent ■

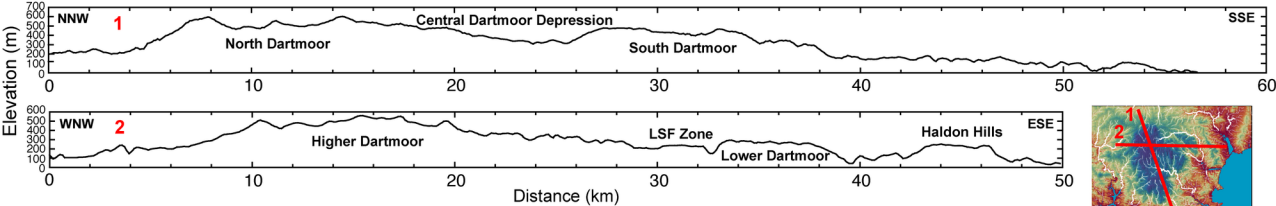
Plymouth

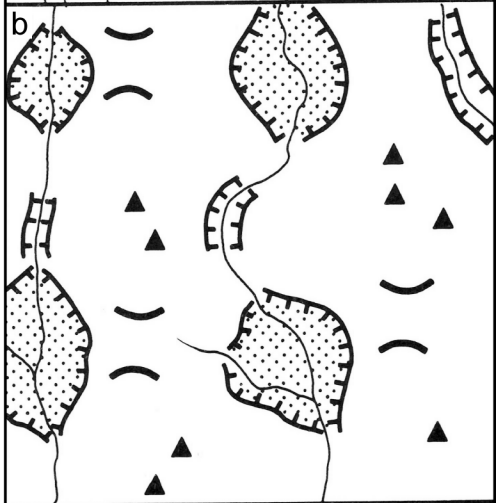
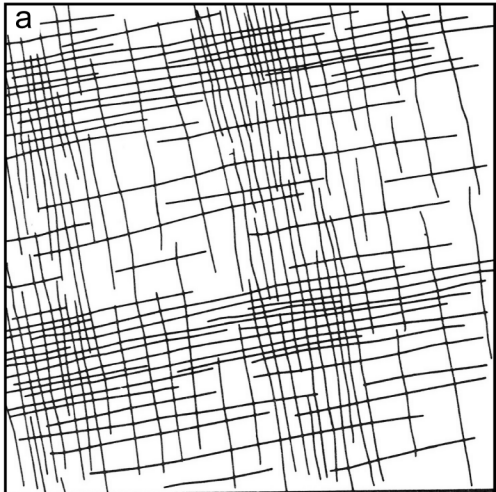
Ivybridge

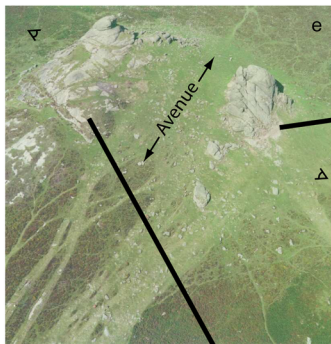


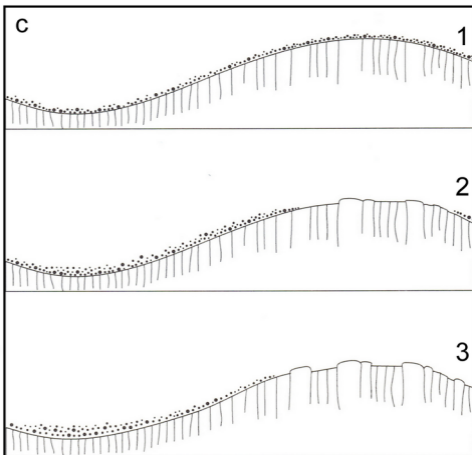
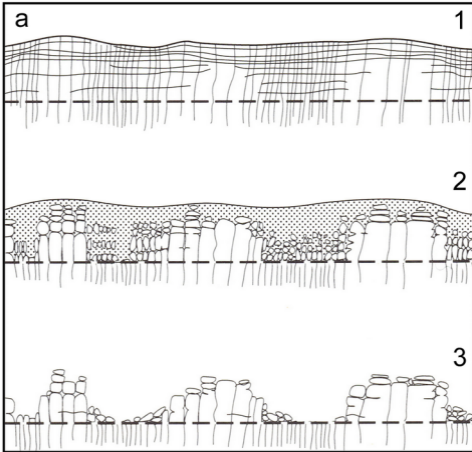
1 km

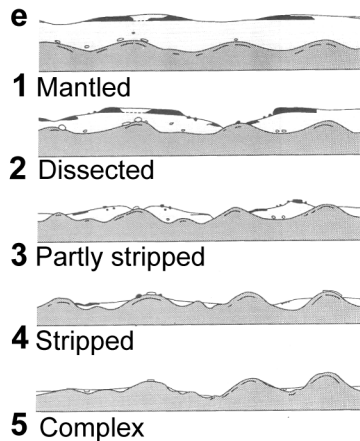
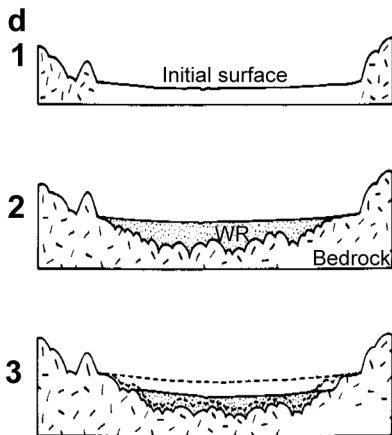
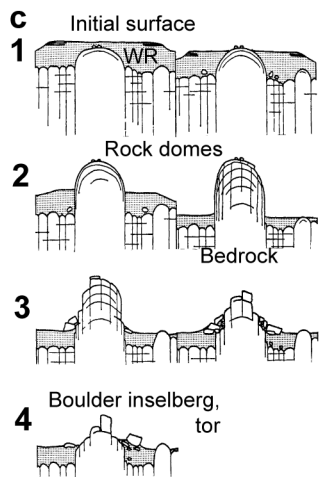
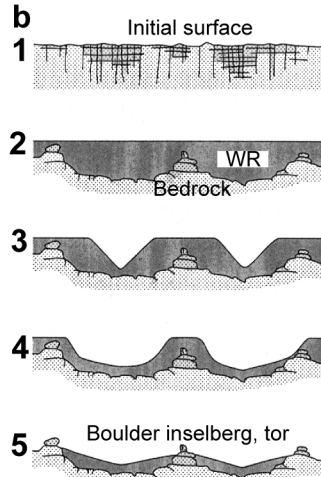
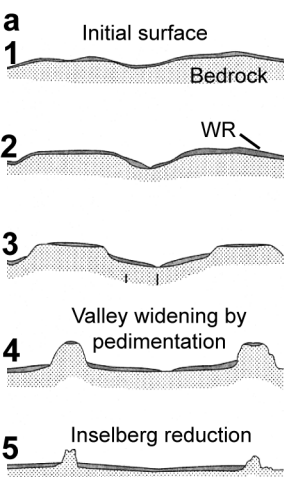









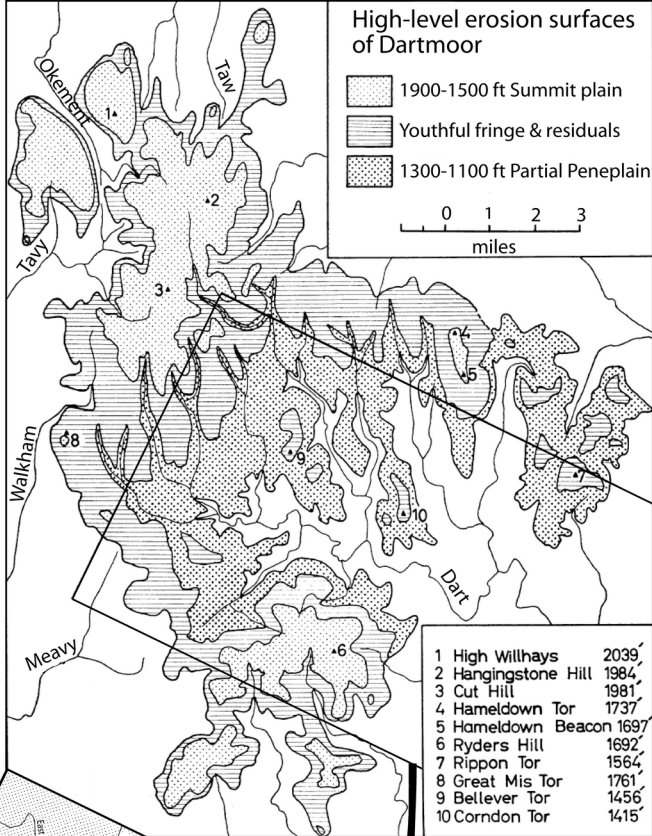
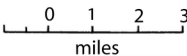




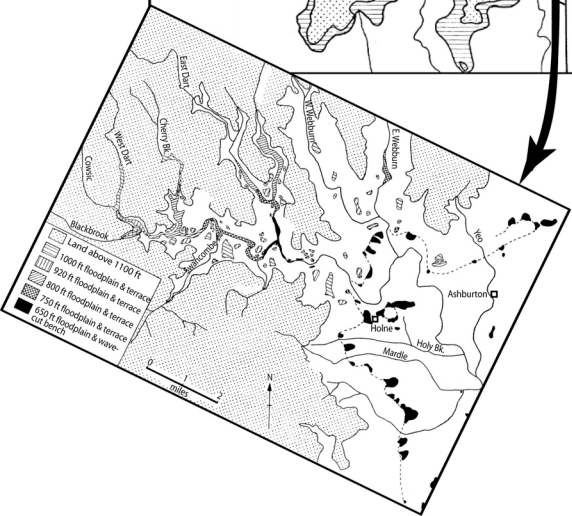


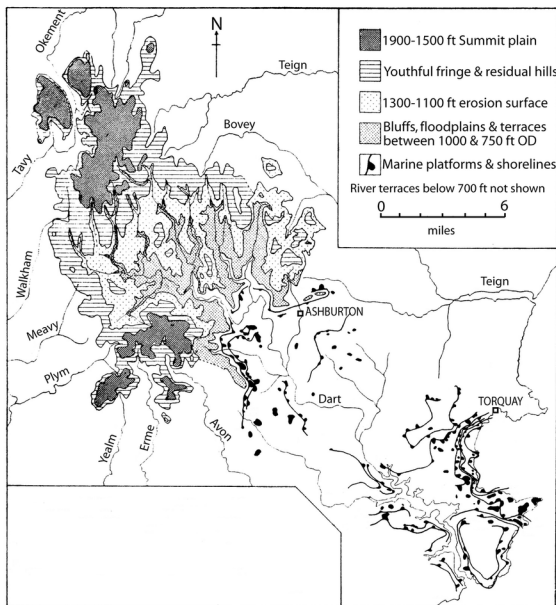
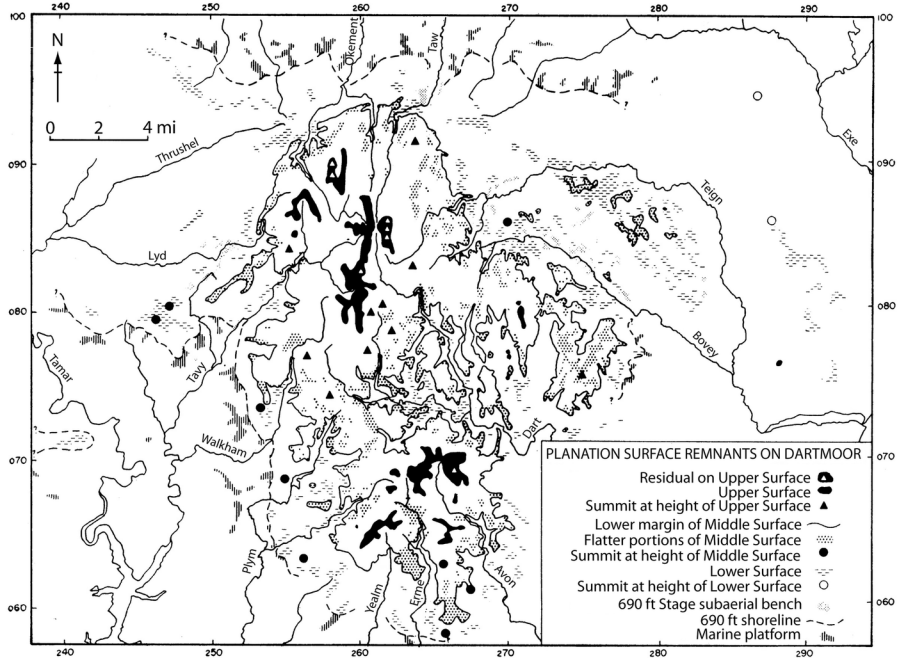
High-level erosion surfaces of Dartmoor

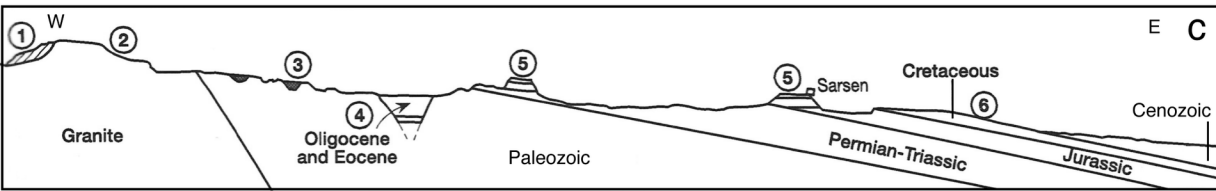
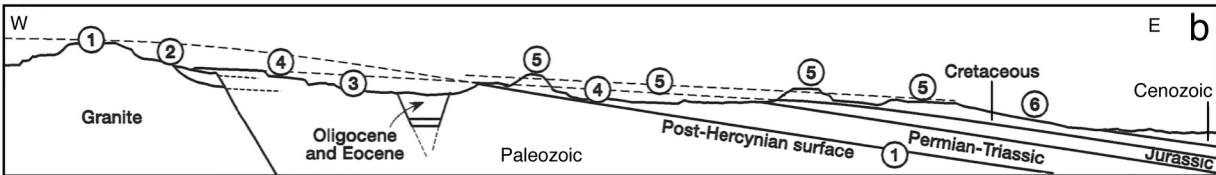
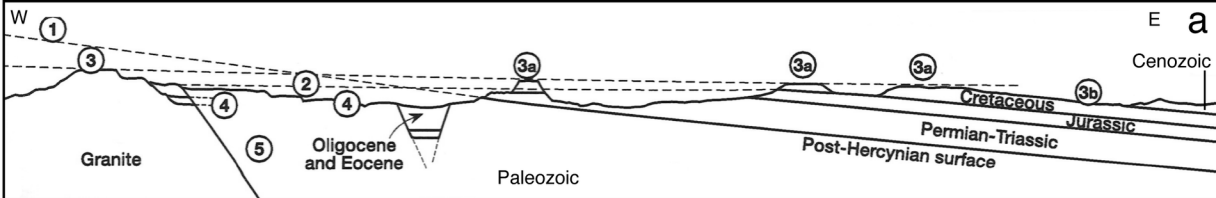
-  1900-1500 ft Summit plain
-  Youthful fringe & residuals
-  1300-1100 ft Partial Peneplain



1	High Willhays	2039'
2	Hangingstone Hill	1984'
3	Cut Hill	1981'
4	Hameldown Tor	1737'
5	Hameldown Beacon	1697'
6	Ryders Hill	1692'
7	Rippon Tor	1564'
8	Great Mis Tor	1761'
9	Bellever Tor	1456'
10	Corndon Tor	1415'



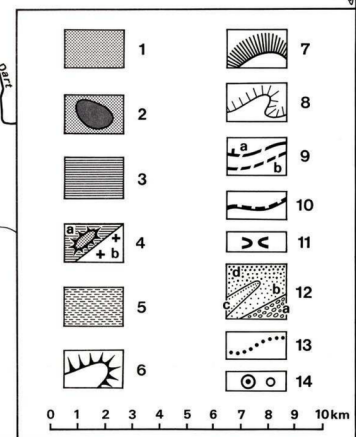
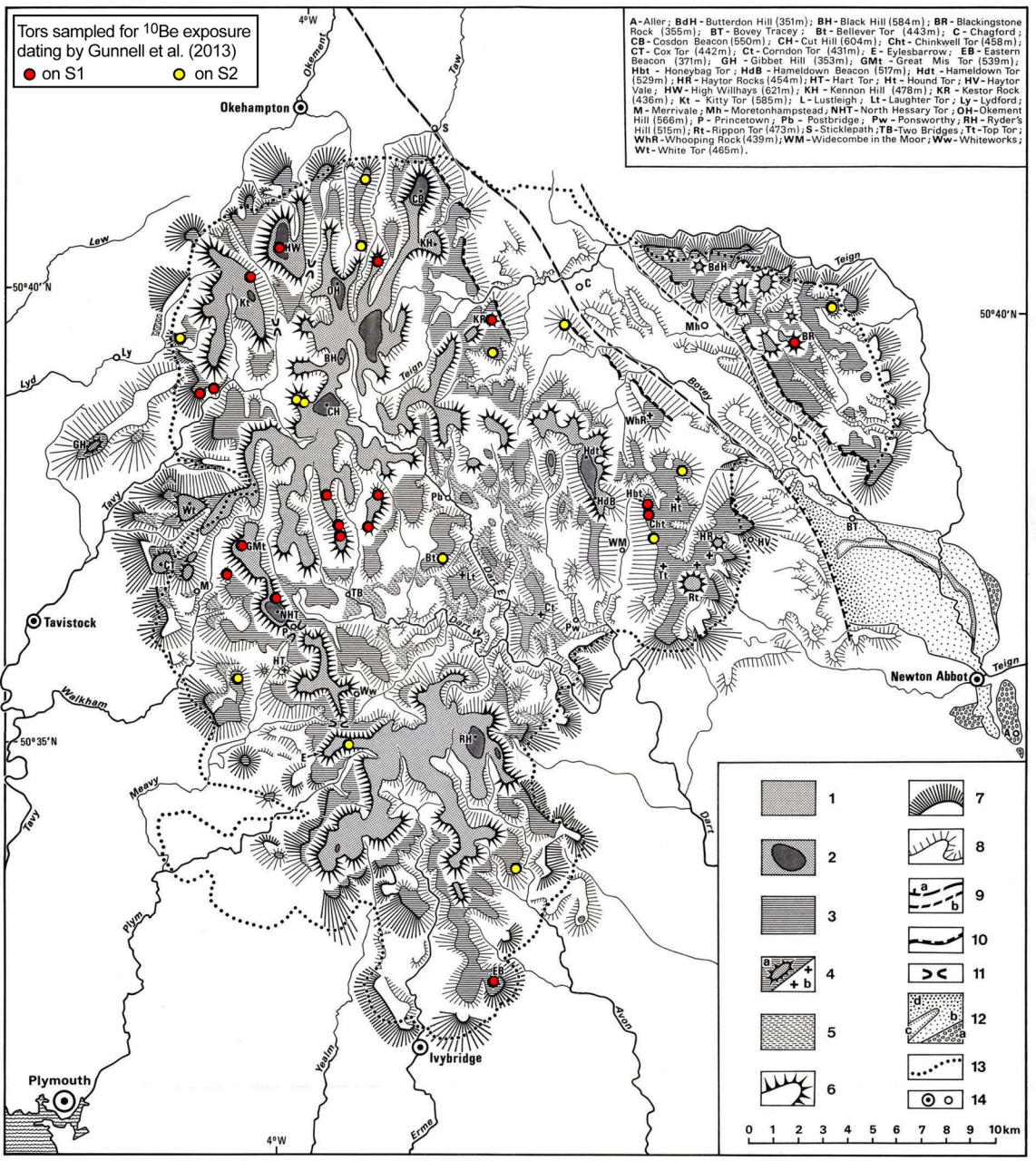


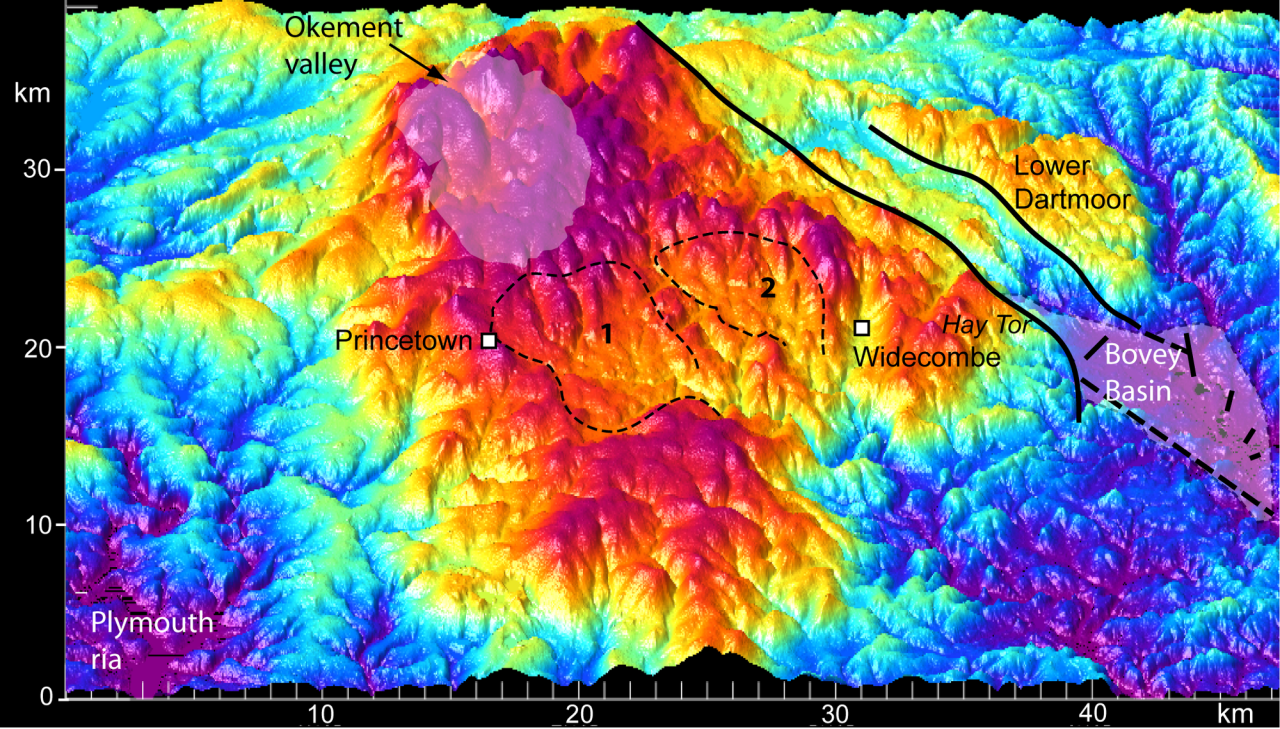


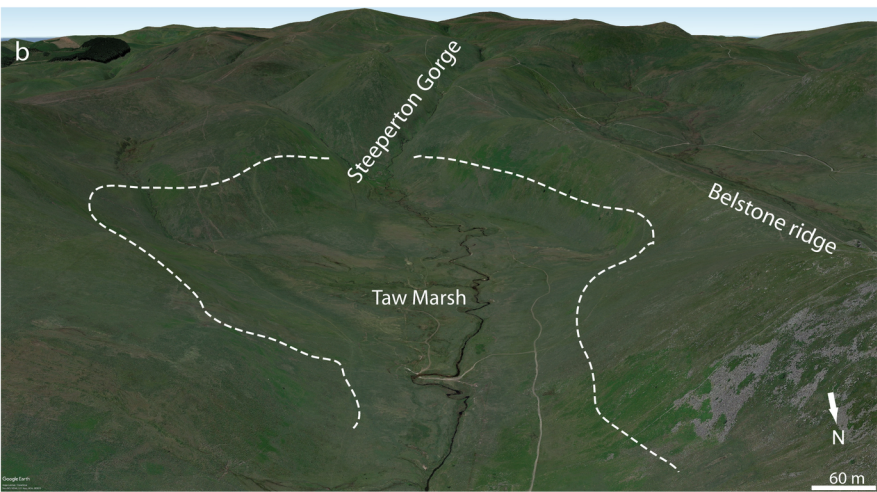
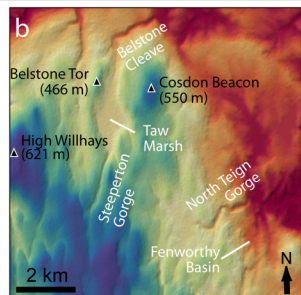
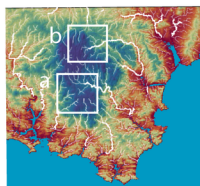
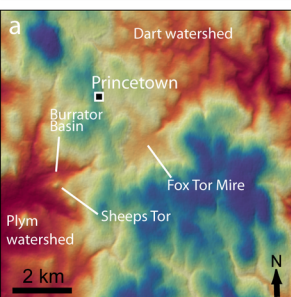
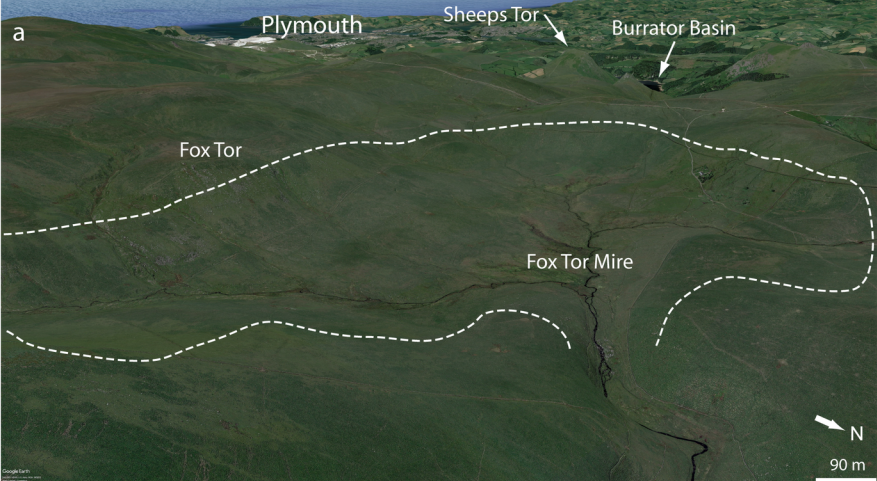
Tors sampled for ^{10}Be exposure dating by Gunnell et al. (2013)

● on S1 ● on S2

A - Aller; BdH - Butterdon Hill (351m); BH - Black Hill (584m); BR - Blackstone Rock (355m); BT - Bovey Tracey; Bt - Believer Tor (443m); C - Chagford; CB - Coston Beacon (550m); CH - Cur Hill (604m); Cht - Chinkwell Tor (438m); CT - Cox Tor (442m); Ct - Corndon Tor (431m); E - Eylesbarrow; EB - Eastern Beacon (371m); GH - Gibbet Hill (363m); GMt - Great Mis Tor (539m); Hbt - Honeybag Tor; HbB - Hameldown Beacon (371m); Hdt - Hameldown Tor (529m); HR - Haytor Rocks (454m); HT - Hart Tor; Ht - Hound Tor; HV - Haytor Vale; HW - High Willhays (621m); KH - Kennon Hill (478m); KR - Kestor Rock (436m); Kt - Kirky Tor (525m); L - Lustleigh; Lt - Loughter Tor; Ly - Lydford; M - Merrivale; MH - Moretonhamstead; NHT - North Hessay Tor; OH - Okement Hill (566m); P - Princetown; Pb - Postbridge; Pw - Ponsworthy; RH - Ryder's Hill (515m); Rt - Ripon Tor (473m); S - Sixknapth; TB - Two Bridges; Tt - Top Tor; WHR - Whoooping Rock (439m); WM - Widecombe in the Moor; Ww - Whiteworks; Wt - White Tor (465m).







Great Staple Tor

Avenue

Middle Staple Tor



