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## Medieval demise of a Himalayan giant summit induced by mega-landslide

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1 **Title: Medieval demise of a Himalayan giant summit induced by mega-landslide.**

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34 **Abstract**

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37 Despite numerous studies on Himalayan erosion, it is not known how the very high Himalayan  
38 peaks erode. While valley floors are efficiently eroded by glaciers, the intensity of periglacial  
39 processes, which erode the headwalls extending from glacial cirques to crest-lines, appears to  
40 decrease sharply with altitude<sup>1,2</sup>. This contrast suggests that erosion is muted and much less than  
41 regional rock uplift rates for the highest Himalayan peaks raising questions about their long-term  
42 evolution<sup>3,4</sup>. Here we report geological evidence for a giant rockslide that occurred around 1190  
43 AD in the Annapurna massif (central Nepal), involving a total rock volume of ~23 km<sup>3</sup>. This event  
44 collapsed a paleosummit culminating likely above 8000 m in altitude. Our data suggest that a mode  
45 of high-altitude erosion could be mega-rockslides, leading to the sudden reduction of ridge crest  
46 elevation by several hundred meters and ultimately preventing the disproportionate growth of the  
47 Himalayan peaks. This erosion mode, associated with steep slopes and high relief arises from a  
48 greater mechanical strength of the peak substratum, probably due to the presence of permafrost at  
49 high altitude. Giant rockslides also have implications for landscape evolution and natural hazards:  
50 the massive supply of finely-crushed sediments can fill valleys >150 km farther downstream and  
51 overwhelm the sediment load in Himalayan rivers for a century or more.

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54 **Main text**

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56 On the human time scales, mountain peaks appear eternal. Yet, on geological time scales,  
57 mountain peaks are ephemeral: their shape and altitude are constantly evolving in response to the  
58 competition between tectonic uplift and erosion. However, very few direct observations exist of  
59 how Earth's highest mountain peaks evolve. Whereas their growth can be considered progressive  
60 over time, we don't know if their erosion is also progressive or episodic, or whether summit  
61 erosion proceeds at the same rates as valley-floor lowering<sup>5</sup>?

62 It has been postulated that a glacial buzzsaw mechanism places an upper limit on mountain  
63 elevation and relief irrespective of the tectonic uplift rate<sup>3,6</sup>, confining mountain heights to within  
64 about 1.5 km of the local Equilibrium Line Altitude<sup>7</sup> (ELA). In this concept, efficient periglacial  
65 weathering, frost cracking, and rock falls along steep hillslopes produce rapid retreat of glacier  
66 cirque headwalls, limiting peak elevation at rates commensurate with rapid valley-floor  
67 downcutting by glaciers<sup>8</sup>. In various settings, however, this concept has been challenged<sup>9-12</sup>. In the  
68 Himalayas, one of the most active mountain range on Earth, the >8000-m peaks culminate ~3000  
69 m above the ELA and seem to contradict the notion of a comprehensively operating glacial  
70 buzzsaw<sup>1,12</sup>. At these extreme elevations, local measurements of cirque headwall retreat show rates  
71 mostly lower than regional erosion rates<sup>13-16</sup>. Frozen-based ice cover, as well as a sharp decrease in  
72 frost-cracking efficiency for increasing altitudes, due to the absence of common freeze-thaw  
73 cycles<sup>1,2</sup>, are suspected to strongly limit the erosion of the glaciated peaks protruding far above the  
74 ELA<sup>1</sup>. If high-elevation summit erosion is unable to match rapid valley-floor downcutting rates,  
75 this mismatch could lead in theory to disproportionate growth of the Himalayan peaks.

76 In steep and active mountains, it is conjectured, however, that mechanical strength of the  
77 mountain rock mass sets an upper limit to peak elevation and the height of oversteepened slopes<sup>4</sup>,

78 such that slope adjustment might occur through landslides at a rate paced by river downcutting.  
79 This equilibrium has been corroborated in non-glaciated and vegetated landscapes, where  
80 landslides can be tracked from satellite-image inventory<sup>17-19</sup>. The 2021 rock-and-ice avalanche of  
81 the Ronti peak (India)<sup>20</sup> illustrated that landslides can also contribute dramatically to the erosion of  
82 high-elevation glaciated Himalayan peaks. Nevertheless, the lack of systematic landslide  
83 inventories precludes any reliable assessment of the relative contribution of this erosive process in  
84 long-term evolution of high-elevation mountainous areas. Instead, the few coseismic landslide  
85 inventories show an apparent sharp decrease in landslide occurrence at high elevations<sup>21</sup>. This  
86 observation indicates either an erosion mechanism distinct from landsliding, or a size-frequency  
87 distribution of landslides<sup>17</sup> that would be clearly skewed in favour of very large landslides,  
88 remaining infrequent enough not to be seen by remote sensing techniques.

89 In the present study, we document evidence of a recent giant rockslide in the Annapurna  
90 region (central Himalayas, Nepal; Fig.1), which illuminates the topographic evolution of high  
91 Himalayan peaks, their abrupt erosion by large rockslides, and the disproportionate consequences  
92 of such collapses along downstream drainage systems.

### 93 **Uncovering a giant rockslide deposit**

94 The southern flank of the Annapurna massif, currently culminating at 8091 m a.s.l., presents  
95 a 6 km drop in elevation from the high summits to the Lesser Himalayas hills. The area  
96 encompasses steep slopes, active microseismicity<sup>22</sup>, and strong ground shaking by major  
97 earthquakes<sup>23,24</sup> ( $M_w \geq 8$ ). Heavy monsoon precipitation prevails over its southern slopes. This  
98 tectonic and climatic setting induces some of the highest regional erosion rates in the Himalayan  
99 range, with values of 3-5 mm/yr<sup>25-27</sup>.

100 The Annapurna massif, dominated by calcareous metasediments of the Tethyan  
101 Sedimentary Series<sup>28,29</sup> (TSS) (Extended Data Fig. 1), is punctuated by several large glacial cirques,  
102 separated by >7500-m glaciated peaks (Fig. 1). Between Annapurna III and IV, the Sabche cirque  
103 is a deep and wide depression bordered by extremely steep cliffs (Fig. 1). The cirque bottom is  
104 filled with light-colored sedimentary deposits, which have been eroded into large and tapering  
105 penitents several hundred meters high (Fig. 1d). Inaccessibility has so far prevented precise field  
106 description of these deposits, which have been interpreted from afar as subglacial tills or  
107 glaciolacustrine sediments<sup>30</sup>. Up close, these massive deposits are well consolidated, especially in  
108 the southern, most basal part, comprising finely-crushed matrix-supported breccia with centimetric  
109 to decimetric angular clasts from various TSS carbonate lithologies (Extended Data Fig. 2 and  
110 Supp. Info. SI-1). The coarse elements are more abundant in the upper part of the deposit and reach  
111 sizes of several meters. The breccia color is quite uniform (white to grayish) except locally with  
112 yellowish units reminiscent of the yellow limestones of the Annapurnas<sup>28</sup> (Fig. 1c). The breccia  
113 sediment infill appears as relatively continuous without any apparent unconformity but displays  
114 incomplete mixing, internal shear zones and rare jigsaw facies (Extended Data Fig. 2). These  
115 sedimentary features<sup>31</sup>, the intense rock fragmentation, the exceptional thickness (>400 m \_ Fig.  
116 1d), and the exclusive presence of these breccia among all cirques of the Annapurna massif,  
117 unequivocally indicate that these breccia sediments were generated by a single rockslide granular  
118 avalanche.

119 The elevation of the breccia remnants along the southern side of the cirque and of a few  
120 preserved top surfaces in its northern part (Fig. 1) suggests that the cirque was completely filled by  
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122 rockslide debris (Supp. Info. SI-4), with thickness locally  $>1$  km. In addition, a debris avalanche  
123 overflowed the cirque and spilled into the upper Seti valley where scattered outcrops of massive  
124 breccia deposits can be observed for  $\sim 10$  km downstream along the valley walls or as isolated  $>200$ -  
125 m-high massive spur remnants (Extended Data Fig. 3 and Supp. Info. SI-2). These remnants are  
126 dominated by angular TSS limestone clasts in a finely-fragmented and pulverized carbonate-rich  
127 matrix. Little mixing appears at the metric scale (as observed for Sturzströme in motion<sup>32</sup>), dyke  
128 injections are deformed by brittle deformation, and the basal shearing contact with the gneissic-  
129 bedrock valley flanks is overlain by a mixing zone incorporating fragmented vegetal debris.

### 131 **Volume and Age of the rockslide deposit**

132 Subtraction of the restored basal topography of the Sabche cirque from the initial breccia  
133 deposit surface provides an estimated volume of the rock avalanche deposits of  $23.5^{+4}_{-3}$  km<sup>3</sup>. An  
134 additional volume of  $\sim 3.5$  km<sup>3</sup> is similarly inferred along the upper Seti valley (see Method,  
135 Extended Data Fig. 4 and Supp. Info SI-4). Accounting for an average breccia porosity of  $15 \pm 5\%$   
136 (Supp. Info SI-5), this reconstructed deposit would correspond to a total volume of collapsed rock  
137 of  $23^{+3.5}_{-3}$  km<sup>3</sup>, constituting the largest rockslide described in the Himalayas to date<sup>33,34</sup>.

138 Four 2- to 5-m high blocks of Silurian marly limestone were sampled on a large blocky and  
139 chaotic remnant of the original deposit surface (Extended Data Fig. 5) for <sup>36</sup>Cl surface-exposure  
140 dating (Supp. Info table SI-11-2). They display consistent <sup>36</sup>Cl concentrations with an average  
141 surface-exposure age of  $1196 \pm 75(2\sigma)$  yr AD (fig. 2a).

142 In parallel, infra-red stimulated luminescence (IRSL) dating on feldspar were conducted on  
143 three breccia samples from an internal shear zone, assuming that increased temperature and/or  
144 shear heating<sup>35</sup> during the rock avalanche did partially reset the IRSL signal (Extended Data Fig. 6,  
145 and Supp. Info. SI-12). The observed partial reset is moderate for two samples with average  
146 apparent IRSL ages of several kyr, but is highly pronounced for one sample taken in the most-  
147 deformed levels. For the latter, the IRSL age distribution is highly-scattered with an apparent  
148 modal age of  $\sim 1200$  yr BP and an estimated minimum age of  $\sim 900$  yr BP (Fig. 2a), consistent with  
149 surface-exposure dating of the top relict surface.

150 Finally, eight <sup>14</sup>C analyses on plant fragments of stripped vegetation in the contact zone  
151 between rock-avalanche material and bedrock in the upper Seti valley (site K on Fig. 1), provided  
152 reproducible calibrated ages (Fig. 2a, Supp. Info. Table SI-10-1). The most probable age of  $1190$   
153  $\pm 26(2\sigma)$  AD is strikingly consistent with the <sup>36</sup>Cl surface-exposure ages of the rockslide deposit  
154 surface, thereby confirming the monogenic nature of the rock avalanche between the Sabche cirque  
155 and the upper Seti valley.

### 157 **Reconstruction of the collapsed paleo-peak**

158 In order to understand the origin of the collapsed rock mass, we identified the failure  
159 surface in the NE cirque part below the Annapurna IV (Figs. 1 and 3). There, the morphology of  
160 the rock cliffs stands out (see Methods and Extended Data Fig. 4d) with fresh planar or prismatic  
161 structural surfaces, devoid of any major glacier or runoff-related erosion. The proposed giant  
162 rockslide, collapsing along this uneroded failure surface, would have beheaded the paleo-summit of  
163 Annapurna IV.

164 To reconstruct the initial geometry of the paleo-Annapurna IV from the restored rock  
165 volume of  $23^{+3.5}_{-3}$  km<sup>3</sup>, we hypothesized that the stability of the paleo-summit hillslopes follows

166 mechanical characteristics that prevail for the whole Annapurna massif, for similar altitudes and  
167 lithologies. Stability of 82-100% of the high elevation slopes requires an apparent rock mass  
168 cohesion of 1-2 MPa, assuming a friction angle of 35 degrees (Methods and Extended Data Fig. 7  
169 & 8). For these geomechanical properties, we generated thousands of random possible topographies  
170 for the Annapurna IV paleo-summit, and considered as acceptable only those fitting both the  
171 collapsed rock volume and the regional hillslope stability (Methods and Extended Data Fig. 9).  
172 Through this Bayesian approach, we estimated that the paleo-Annapurna IV may have peaked at an  
173 average elevation of ~8100 m (~600 m above the modern summit and comparable to the  
174 Annapurna I), and exceeded 8000 m with a probability of 0.65-0.76 (Fig. 3d). The eroded volume  
175 corresponds to an average 1 km of bedrock lowering, and involves lithologies ranging from  
176 Silurian to Cambrian (Fig. 3c) in good agreement with the diversity of colour and carbonate content  
177 of the breccia material (Fig. 4)

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### **Sediment export and downstream consequences**

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The collapse released a huge amount of potential gravitational energy of  $\sim 1.2 \times 10^{18}$  J (Fig. 3). Significant energy release was consumed in rock-material fragmentation, which, aided by the schistose nature of the marly-calcareous bedrock, likely explains the extreme degree of disintegration observed in the breccia material. After the paleo-summit collapse ~830 years ago, the erosion of the fine-grained breccia by rainwash, landsliding, pro-glacial streams, or glaciers, and their export by the upper Seti river, were extremely efficient and rapid: of the initial 23.5 km<sup>3</sup> of rockslide debris, only ~10% can still be observed today in the Sabche cirque (Extended Data Fig. 4c). Assuming long-term denudation rate of ~3mm/yr in the High Himalaya<sup>26</sup>, the return time of a giant rockslide of similar volume would be >100 kyr at the scale of the entire Sabche cirque headwalls. The response time of the glacio-fluvial system to evacuate the Sabche breccia material appears therefore very short in comparison.

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Farther downstream of the Seti river, the Pokhara Basin (Fig. 1) is known to have been filled very rapidly 500-1000 years ago<sup>30,36</sup> by ~5 km<sup>3</sup> of mostly conglomeratic sediment with calcareous clasts, whose only possible origin is the Sabche cirque. Sedimentary fill is characterized by the stratigraphic continuity of a succession of planar beds with varied facies (Supp Info. SI-9) that reflect rapid aggradation by fluvial, hyperconcentrated, or turbulent, sediment-laden flows<sup>30,36</sup>.

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Extensive <sup>14</sup>C dating of organic fragments found in the fine-grained units of the Pokhara sediments<sup>36-38</sup>, collected at different burial depths, and complemented by eight new dates (Supp. Info. table SI-10-1), provide robust constraints on the timing of aggradation (Fig. 2b). They indicate onset of aggradation around 1200 AD at an average rate of 1m/yr until ~1300 AD. Taken together, the similarity in carbonate content (Fig. 4) and the age of the basal units in close agreement with the giant rockslide age, but stratigraphically postdating the breccia (Extended Data Fig. 3a) strongly suggest a co-genetic link between these two sedimentary units. The Pokhara conglomerates are thus best explained by the active erosion of the Sabche rock-avalanches breccia and by the rapid sediment transfer by Seti river down to Pokhara valley.

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Fine conglomerates with calcareous pebbles irregularly crop out far downstream of Pokhara, along the Seti, the Trisuli and even the Narayani river (Fig. 4) in the foreland (site N on Fig. 1). There, a fine, carbonate-rich conglomerate unit, dated at 1150-1220AD (<sup>14</sup>C dating, Fig. 2a), shows how the Narayani was temporarily overwhelmed by sediments from the paleo-Annapurna IV collapse. Such sediment pulse may even have reached the mid-Ganga plain, as

210 suggested by a >3-m thick unit at the top of a core drilled into an elevated Narayani megafan lobe  
211 (site G on Fig. 1). This unit is anomalously rich in TSS carbonate (30-60%) as compared to the  
212 average proportion of ~10% in Late-Pleistocene to modern Narayani sediments (Fig. 4, and  
213 Extended Data Fig. 10).

214 The amalgamated sediment volume in the Pokhara basin, middle Seti valley, and Narayani  
215 megafan lobe may have reached 15 km<sup>3</sup> (Supp. Info. SI-9-C), thereby representing ≤50% of the  
216 initial Sabche breccia volume (assuming 30% fluvial sediment porosity). The other half was  
217 presumably partly dissolved and partly exported farther downstream as suspended load, and may  
218 have ended up in the Bengal fan, the largest sediment sink for most Himalayan sediment<sup>39</sup>.

219 Sediment aggradation in Pokhara valley suggests that the most intense phase of breccia  
220 removal in the Sabche cirque and associated sediment supply downstream lasted for a century (Fig.  
221 2b) and impacted the whole downstream sediment routing system. During that period, the rate of  
222 sediment yield (0.1-0.2 km<sup>3</sup>/yr exported from a 60-km<sup>2</sup> area) was comparable to the highest  
223 measured values of post-volcanic eruption sediment transport<sup>40</sup> and led to an overwhelming content  
224 of TSS material in river sediments >300 km downstream. Compared to the Narayani basin (30,000  
225 km<sup>2</sup>), which exports annually ~0.05km<sup>3</sup>/yr of sediment<sup>41,42</sup>, post-collapse erosion of the Sabche  
226 breccias (only 0.2% of the Narayani total basin area) would have increased this annual flux by a  
227 factor of 3 over 100-150 years (see also carbonate-based budget in Supp. Info. SI-9-D).

228 The collapse has paradoxically positive and negative downstream consequences. In the long  
229 term, the creation of a large flat surface in the Pokhara valley has undoubtedly been beneficial,  
230 allowing the development of extensive agricultural areas, and, above all, the recent development of  
231 the country's second largest city with all of its infrastructures. On the contrary, in the short term, if  
232 the paleo-Annapurna IV collapse occurred today, the Pokhara metropolitan area would be  
233 decimated, with appalling human and economic costs. Not only would the upstream parts of the  
234 valley be swept away by the granular avalanche, but numerous sediment-laden flows would rapidly  
235 bury the valley under tens of meters of sediment, leaving a vast gravel plain in the Seti valley. Even  
236 the Indian side of the Ganga plain, i.e. a densely populated region, might be impacted by increased  
237 probability of river-channel avulsions and rapid sedimentation along the Narayani megafan.  
238 Although such events are rare, understanding the causes of the paleo-Annapurna IV collapse and its  
239 downstream consequences appears thus fundamental to comprehend the major threat that potential  
240 giant rockslides can pose to the local populations and infrastructures in these high-mountain  
241 regions.

### 243 **Possible causes for the Sabche rockslide**

244 Several factors make the High Himalaya region clearly prone to large-scale slope failure.  
245 Glacial valley deepening due to sub-glacial carving, combined with intense frost cracking close to  
246 the ELA<sup>2</sup>, represents one of the major pre-conditioning factors that produce steep, unstable  
247 headwalls surrounding glacier cirques. Schistosity orientation and structural planes also likely  
248 guide slope failure of the paleo-Annapurna IV (Extended Data Fig. 4d).

249 By contrast, causes triggering the Sabche rockslide remain speculative. It has been  
250 suggested previously<sup>36</sup> that the filling of the Pokhara Basin arose from various pulses of debris  
251 flows following numerous landslides activated by 3 large earthquakes, at 1100 ±50AD<sup>23</sup>, 1255AD  
252 and 1344 AD<sup>24</sup>. According to <sup>14</sup>C dating of breccia at Karuwa (site K on Fig. 1), the Sabche  
253 rockslide occurred after 1150AD and before 1255AD at >99% confidence. Seismic triggering due

254 to one of these 3 large earthquakes seems therefore excluded. Nevertheless, as the current catalog  
255 of paleo-earthquakes is likely incomplete for medieval times, we cannot exclude the impact of an  
256 undocumented earthquake in the region.

257 Independently, climate might also be involved as a preparatory or/and triggering factor for  
258 the Sabche collapse. The Medieval Climate Anomaly<sup>43</sup>, from 900 to 1200AD, was possibly  
259 characterized by  $>+1^{\circ}\text{C}$  warmer temperatures in the High Himalaya. This could have thawed part  
260 of the failure surface (see estimate in Supp. Info. SI-8) and favoured high-elevation rockslide(s)<sup>20</sup>.  
261 Although the cohesion loss from thawing appears to have been likely insufficient to trigger the  
262 paleo-Annapurna IV collapse (unless the rock mass was already close to a critical state), such  
263 climatic factor on high-elevation bedrock destabilization calls for closer attention on the effects of  
264 current global warming when assessing future gravitational hazards related to the high Himalayan  
265 peaks.

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### 267 **The fate of the High Himalayan peaks**

268 The identification of a cataclysmic rockslide around 1190 AD, which beheaded what may  
269 have been the Himalaya's 15th 8,000-m peak, provides key insights into the likely evolution of the  
270 highest Himalayan peaks. First, this is not an isolated case. Several giant rockslides have been  
271 documented<sup>33,34,44</sup> in central Nepal with deposits reaching up to  $10\text{-}15\text{ km}^3$ . All are located in the  
272 high Himalayas and originated from summits/ridges between 4500 and 6000m elevation. Although  
273 the current catalogue is incomplete and precludes definition of a precise erosion budget, massive  
274 summit collapses resulting in a sudden reduction of their height by several hundred meters could be  
275 the primary denudation mode of high, glaciated Himalayan peaks.

276 Notably, high summits commonly display steeper slopes, with median values rising from  
277  $35^{\circ}$  below the ELA to  $50^{\circ}$  above it<sup>2,45</sup>. Steep slopes surrounding the glacial cirques of the  
278 Annapurnas are maintained by higher bulk material strength. The regional cohesion values ( $C\approx 1\text{-}2\text{MPa}$ )  
279 calculated for the glaciated relief cannot be considered as absolute values, because the  
280 transient effects of pore pressure or seismic acceleration have not been taken into account<sup>46</sup>.  
281 Nevertheless, they appear, for similar internal friction angles,  $\sim 4$  times higher than the cohesion  
282 values ( $C\approx 0.2\text{-}0.7\text{MPa}$ ) for the fluvially-dominated High Himalayan landforms (below 4000 m,  
283 south of the glaciated Annapurna ridges Supp. Info. SI-6), and an order of magnitude higher than  
284 in other non-glaciated high mountains<sup>47</sup> ( $C\leq 0.1\text{MPa}$  but using a distinct approach to derive  
285 cohesion values). In the Himalayas, this higher rock strength is not related to a lithological effect<sup>12</sup>,  
286 given that the steeper slopes at high altitudes in central Himalaya have values independent of the  
287 rock type<sup>2</sup>. Instead, we surmise that the higher rock mass strength is favoured by permanently  
288 frozen conditions at high elevations. Such climatic conditions hold rocks in place by ice-rock  
289 interlocking<sup>48,49</sup>, while preventing regolith formation, penetrative chemical weathering, and  
290 limiting groundwater recharge and high pore pressures at depth. If permafrost strengthens the first  
291 tens or hundreds of meters below the ground surface (Supp. Info. SI-8), and/or if weakened  
292 bedrock is absent near the surface, then the initiation of small and medium-sized landslides  
293 becomes more difficult. This could explain their very rare occurrence at high altitudes, and the  
294 need to erode the high summits through rare, but large deep-seated rockslides.



295 The above considerations on the evolution of glaciated high peaks allow us to revisit the  
296 concept of glacial buzzsaw. While topographic data suggest that the mean elevation of mountain  
297 ranges may be directly limited by active glacial and periglacial erosion processes<sup>3,7</sup>, the glacial  
298 buzzsaw mechanism is not sufficiently effective, where rock uplift is sustained, to prevent the  
299 emergence of high peaks >3000 m above the snowline<sup>12</sup>, as observed in the Annapurnas massif.  
300 On the contrary, once a mountain peak passes over the zone where rock mass is permanently frozen  
301 and the intensity of frost cracking drops drastically, the frozen conditions provide enhanced  
302 protection against surface erosion. This may even initiate a positive feedback. The increased  
303 mechanical strength of the frozen, unweathered rock mass promotes headwall stability, and an  
304 increase in both their length and steepness<sup>46</sup>. In turn, the increased steepness of the headwalls that  
305 prevents the accumulation of ice and glacial erosion<sup>11</sup>, combined with headwall lengthening<sup>12</sup>,  
306 allows the growth of high peaks and their further protrusion into the realm of permanently frozen  
307 and muted periglacial erosion conditions (Fig. 5). This positive feedback has a limit, however, set  
308 by the cohesion of the deep unweathered rock mass, and our observations suggest that deep-seated  
309 rockslides are ultimately the controlling mechanism that limits the persistent growth of the high  
310 Himalayan glaciated summits (Fig. 5).

311 Such a conceptual scenario (Fig. 5) might operate both on a regional (central Himalaya) and  
312 global scale. Many large-scale tectonic zones undergoing local sustained uplift rate present high  
313 peaks that protrude well above the snow line (i.e. by 2500 to 4000 m), either in the Himalayan  
314 syntaxes (Nanga Parbat and Namche Barwa), the Karakoram, the Pamir, the Western Kunlun  
315 Cordillera, the Gongga Shan, the central TianShan (Jengish Chokusu and Khan Tengri massifs), or,  
316 far from the India-Asia collision, e.g. in the Denali or St Elias massifs in Alaska. Future work  
317 should assess the erosive contribution of giant rockslides on the long-term topographic evolution of  
318 these regions, and also quantify a likely relationship between the rock uplift rate and the amplitude  
319 of relief above the snowline<sup>50</sup>.

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463 **Figure Legends :**

464

465 **Figure 1: Location maps of the Sabche breccia deposits.** (a) Map of Nepal and Narayani basin (in  
466 red) with the >8000m summits (triangles) (G=drill cores GR1-2 (purple symbols) in Dudahi in India;  
467 S=Sabche; P=Pokhara; k=Kathmandu). (b) Topographic map of central Nepal focusing on the Seti  
468 river with the rock-avalanche breccia deposit (in yellow) in the Sabche cirque (headwaters of the Seti  
469 river) and along the upper Seti valley due to the rockslide of the Annapurna IV SW-flank. Subsequent  
470 erosion of this brecciated material led to the downstream sediment aggradation with massive  
471 conglomeratic terraces (in pink) in Pokhara basin and as far as south of the Main Boundary Thrust  
472 (MBT), near Narayangad (N). (S=Sabche; K=Karuwa; P=Pokhara; MCT=Main Central Thrust;  
473 STD=South Tibetan Detachment). (c) Zoomed map of the glaciated Sabche cirque showing contrasting  
474 breccia facies of and sample locations. (d) Aerial view of the Sabche cirque; its breccia filling  
475 (outlined by dashed line and 'br') exposed by large whitish penitents, hundreds of meters high, left by  
476 the erosion of the rock avalanche deposits.

477

478 **Figure 2: Chronological constraints on deposits related to the Sabche rockslide.** (a) Dating of the  
479 rock-avalanche deposit and Pokhara conglomeratic formation along the Seti river from the Sabche  
480 cirque down to Narayangad (site locations according to letters on fig. 1). From top to bottom: the  
481 probability density function (pdf) of  $^{36}\text{Cl}$  exposure ages on blocks located on a upper surface relic of  
482 the rockslide deposit; zoom-in on the young tail of the feldspar IRSL age pdf showing partial signal  
483 reset (see complete pdf and individual aliquot ages on Extended Data Fig. 6) of a shearing band toward  
484 the base of the rockslide deposit in Sabche cirque; calibrated  $^{14}\text{C}$  age pdf (black or gray solid lines) of  
485 wood debris sampled in the rock avalanche deposit in Karuwa (site K on Fig.1b) at the bedrock contact  
486 of the Seti valley; calibrated  $^{14}\text{C}$  age pdf of organic fragments taken in the most basal conglomeratic  
487 units in Pokhara basin<sup>36,38</sup>; calibrated  $^{14}\text{C}$  age pdf of a charcoal sampled in fine conglomerates north of  
488 Narayangad. The red curve represents the composite pdf, combining all available dating at each site.  
489 The numbers in parentheses indicate the number of dated samples.

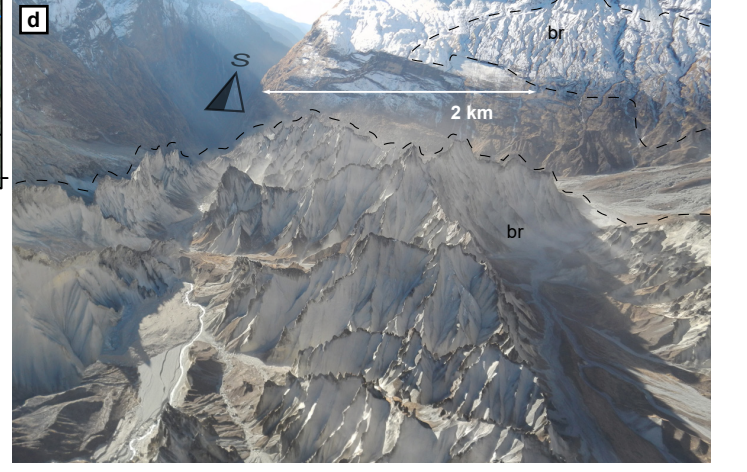
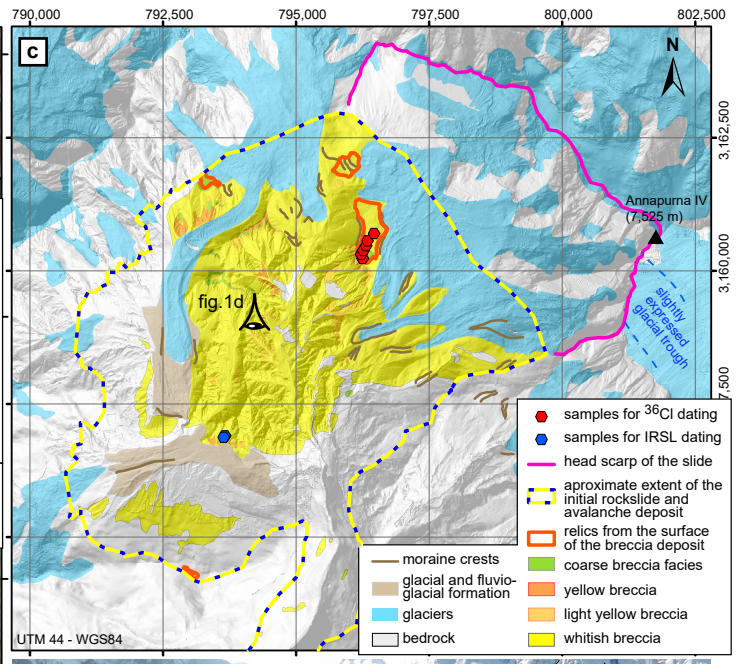
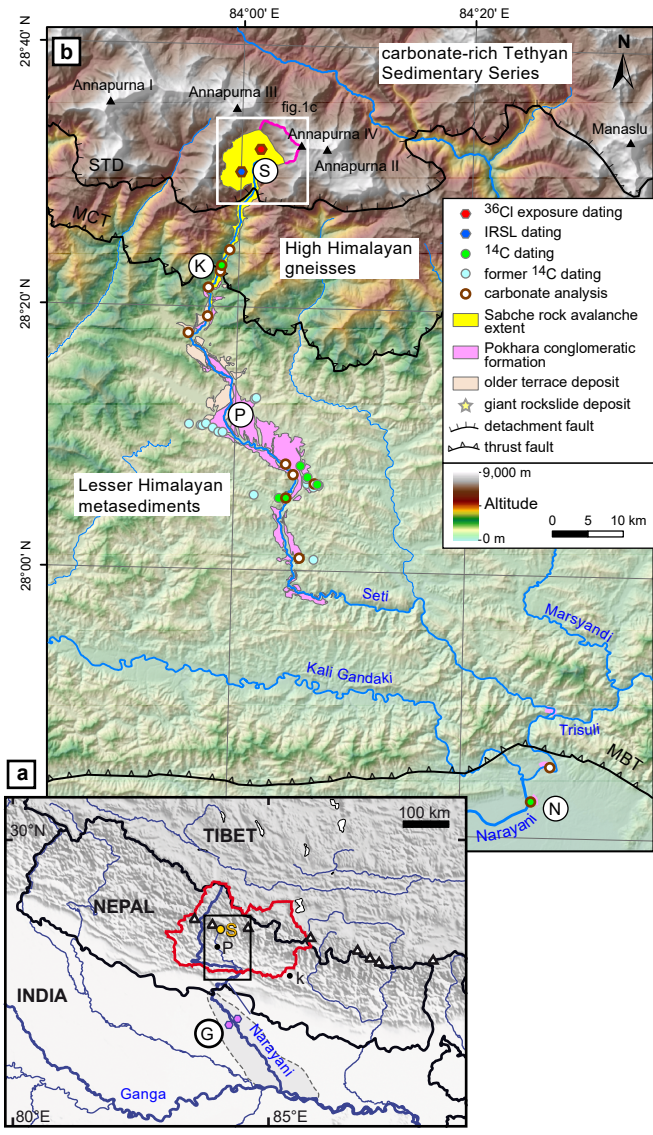
490 (b)  $^{14}\text{C}$  ages of numerous organic-debris samples from the central part of Pokhara basin (published and  
491 new dating), represented according to their stratigraphic relative elevation. Points and error bars  
492 correspond to the median value and the 95% confidence interval of the calibrated ages pdf,  
493 respectively. Analyses restricted to leaves, wood fragments, and tree trunks, in order to minimize the  
494 effect of suspected reworking in particular for charcoals. A notably rapid sedimentation rate of ~1m/yr

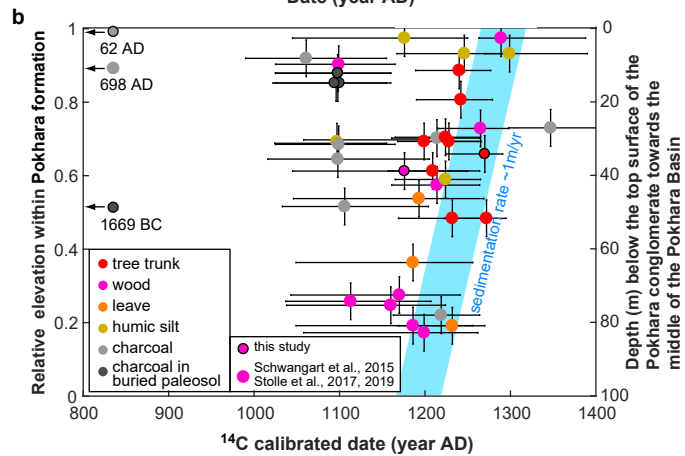
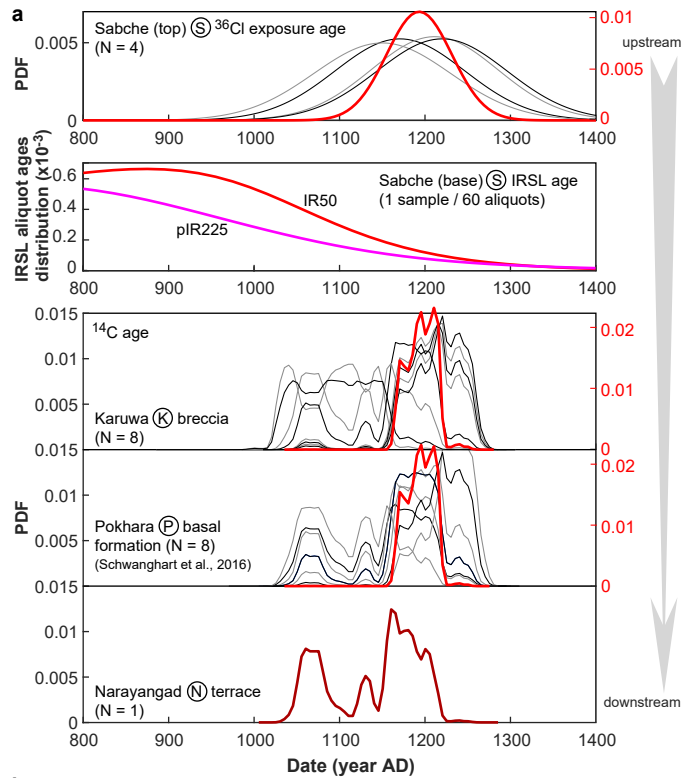
495 is documented. Note that "charcoal in buried paleosols" refers to charcoal collected from former soils  
496 on the flanks of the Seti Valley that were buried by and predate the Pokhara conglomerate.  
497

498 **Figure 3: Reconstruction of the Annapurna IV paleo-summit before its collapse.** (a) Thickness of  
499 the rock-avalanche deposit estimated from breccia relics in Sabche cirque and along upper Seti valley.  
500 The orange arrow (oriented at N245) corresponds to the optimal direction of collapse (see Extended  
501 Data Fig. 9e). Circled black letters correspond to sites described in Fig. 1b. (b) Average shape of the  
502 reconstructed paleo-topographies that satisfy rock volume and hillslope stability constraints (grayed  
503 paleo-summit on top the present topography in slight transparency). (c) Cross section (location in a)  
504 through the middle of the Sabche cirque, with averaged paleo-topography before collapse and  
505 approximate geometry of the post-collapse breccia deposit; *rsb* and *bdb* indicate the projection on the  
506 section plane of the centres of mass of the rock slide and breccia deposit volumes respectively, and  
507 whose elevation difference is used to calculate the released potential gravitational energy. (d)  
508 Probability densities (presented as histogram and resulting from 2000 random paleo-topographies) of  
509 the summit point elevation of the paleo-Annapurna IV satisfying increasing levels of requirement:  
510 firstly, the collapsed volume  $V_{RS}$  is in the range between 20 and 26.5 km<sup>3</sup> (grey); secondly, the  
511 summit slopes were stable regarding small to medium-size landslides (pink); thirdly, the safety factor  
512 (SF) along the failure surface was rather minimal (red) (see Method and Extended Data Fig. 9). The  
513 probability that the summit point could have exceeded 8000 m (thick line) is 65% and 76% if the  
514 paleo-topographies satisfy the first two and three conditions respectively.  
515

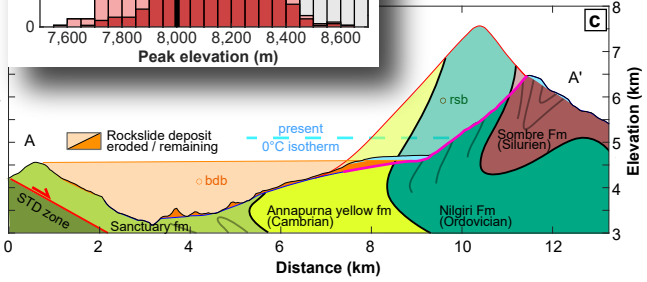
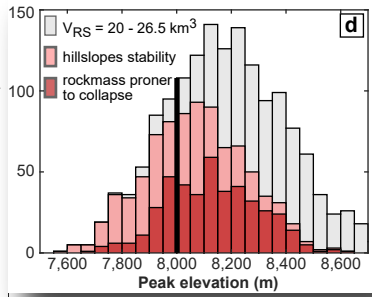
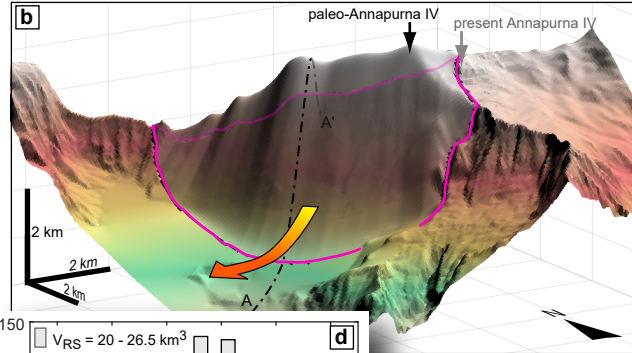
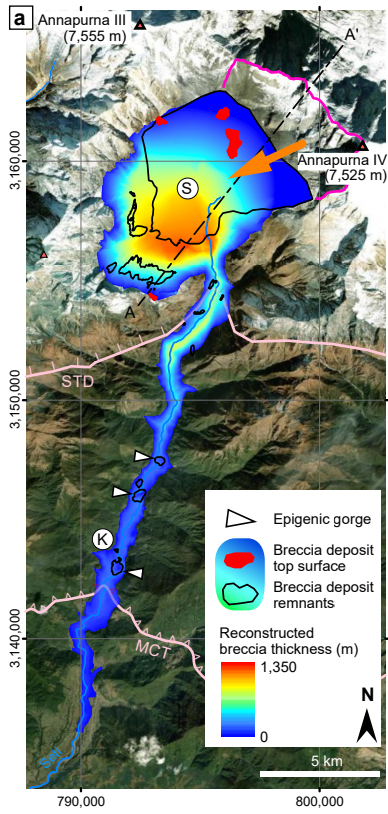
516 **Figure 4: Far downstream signature of the reworked rockslide deposits evidenced by sediment**  
517 **carbonate content.** Comparison of the carbonate content in brecciated rock avalanche material, in  
518 TSS units at the source of the rockslide, in Pokhara conglomeratic formation, and in modern sediment  
519 along the Seti river (see also Supp. Info table SI-13). Unlike rockslide-derived sediments, which show  
520 a very high and relatively constant proportion of carbonate, modern sediments display downstream  
521 increasing dilution of the carbonate fraction, in particular after the confluence of the Seti with the Madi  
522 or Trisuli rivers. (Rivers: Ma = Mardi; M = Madi; Tr = Trisuli; Ka = Kali Gandaki; numbers in  
523 parenthesis = ratio of drainage areas with the Seti as denominator). Circled black letters and red  
524 acronyms correspond to the sites and faults mentioned in Fig. 1a and 1b.  
525

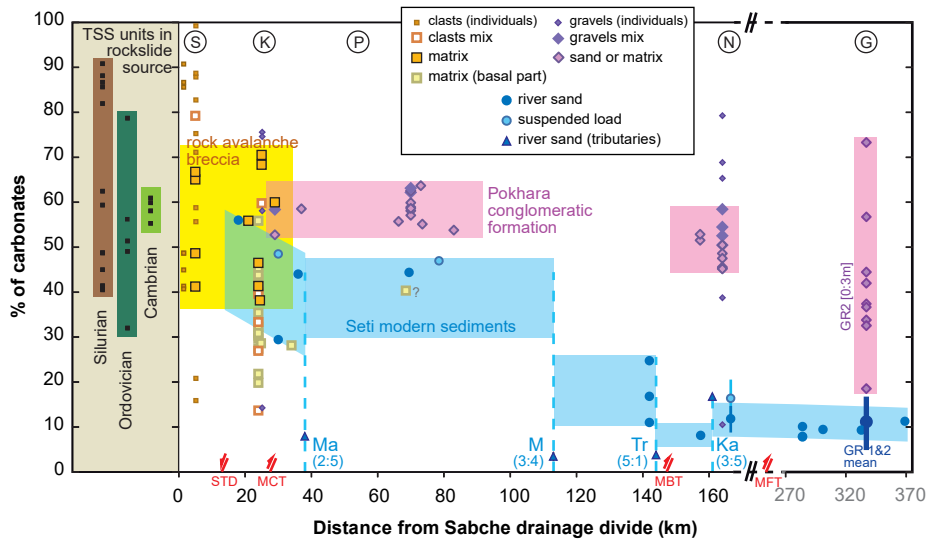
526 **Figure 5: Evolutionary sketch of the high peak emergence well above the ELA (Equilibrium Line**  
527 **Altitude)** in a glaciated landscape undergoing sustained rock uplift. Starting from a fluvially-  
528 dominated landscape (A) raised above the ELA (white dotted line), glacier development and subglacial  
529 erosion leads to lengthening and steepening of headwalls (B and C). Whereas sub-glacial erosion  
530 keeps much of the relief below the ELA (i.e. buzzsaw effect<sup>3</sup>) and frost cracking erosion above the  
531 upper glaciated rim steepens the headwalls, further rock uplift drives the summit into the zone where  
532 the rock mass becomes permanently frozen and undergo minimal surface erosion (C and D). The  
533 continued growth of the peak elevation ends in a major gravitational instability (D and E), i.e. a giant  
534 rockslide that beheads the summit and results in a thick rock-avalanche deposit (yellow shading in E)  
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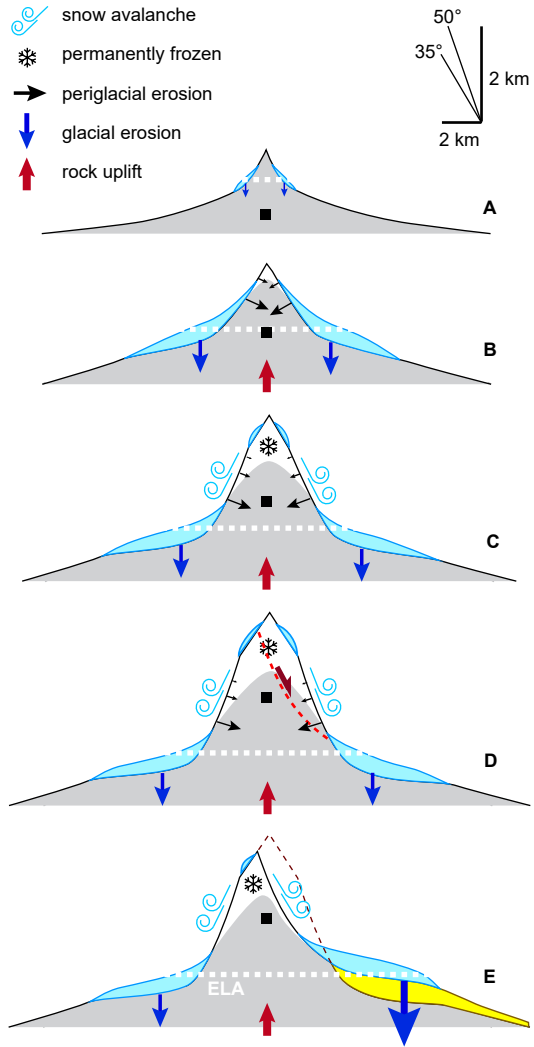












537 **Methods**

538

539

540 **<sup>14</sup>C dating**

541

542 16 organic fragments were collected from 3 distinct areas for <sup>14</sup>C dating: 7 wood-fragments  
543 samples taken in the breccia deposit at Karuwa (K site on fig.1), 8 samples of charcoal and wood  
544 fragments in the southern part of the Pokhara basin (P site), and one micro-charcoal sample found  
545 in Pokhara type sediments outcropping at the range outlet (site N in Fig. 1b).

546 Organic fragment preparation includes standard cleaning and ABA treatment, and  
547 combustion at 850°C as described in ref.51. The CO<sub>2</sub> was converted to graphite and analysed on  
548 the LMC14 AMS facility<sup>52</sup> “ARTEMIS”, except for one sample prepared and analysed at the  
549 National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility at the Woods Hole  
550 Oceanographic Institution.

551 Radiocarbon ages are calculated<sup>53</sup> by correcting the fractionation with the δ<sup>13</sup>C calculated  
552 from the <sup>13</sup>C/<sup>12</sup>C ratio measured on ARTEMIS. We used the IntCal13 curve<sup>54</sup> for calibrating our  
553 <sup>14</sup>C ages to calendar years using Oxcal online calculator  
554 (<https://c14.arch.ox.ac.uk/oxcal/OxCal.html>) (Supp. Info. table SI-10-1).

555

556 **<sup>36</sup>Cl exposure age dating**

557

558 We sampled plurimetric blocks of Siluro-Devonian black shale and calcschists, deposited  
559 on top of the main northern remnant of the original Sabche breccia surface. Samples were prepared  
560 at the CEREGE (Aix-en-Provence, France), following standard procedures<sup>55,56</sup>. <sup>36</sup>Cl and Cl  
561 concentrations were obtained on each sample by isotope dilution accelerator mass spectrometry at  
562 ASTER-CEREGE. Major and trace elements were measured at the French National facility for  
563 geochemical analysis (SARM-CRPG) (Supp. Info. table SI-11-3).

564 <sup>36</sup>Cl production rate was calculated according to concentration in target elements (Supp.  
565 Info. table SI-11-2) and Lal/Stone time-dependent scaling using Chronus Online calculator  
566 ([http://hess.ess.washington.edu/math/index\\_dev.html](http://hess.ess.washington.edu/math/index_dev.html)). Several blocks made of finely schistosed  
567 rocks show evidence of frost cracking and physical weathering, but the shape of the original  
568 surface is generally still identifiable and indicates a maximum surface erosion of ~10cm (Supp.  
569 Info. table SI-11-1). An additional correction for snow shielding was considered from snow cover  
570 measurements on the Himalayan southern flanks 25km to the east<sup>57</sup>. Snow and erosion corrections  
571 represent ~25 and 40 yr respectively.

572

573 **Infra-red stimulated luminescence (IRSL) dating on sheared breccia deposits**

574

575 TSS carbonate units may contain small amounts of quartz and feldspar grains. The luminescence  
576 signal can be reset (called triboluminescence) by heating, mechanical crushing or shearing<sup>35</sup>  
577 processes in intense sheared bands such as frictionnites. In the southern part of the rockslide  
578 deposit, we collected three samples from two sites approximately ~50 m apart within an internal  
579 basal shear zone (CA-13-273, -274, and CA-13-283); Extended Data Fig. 6). Collected samples  
580 measured 15x12x7cm and 7x7x5cm respectively. Sample preparation followed the procedure

581 described in ref.58 to isolate K-feldspar fraction. Bulk samples were sent to Actlabs or SARM-  
582 CRPG for major and trace element analysis, used to estimate (see Supp. Info. SI-12 for full details)  
583 the total dose rate with the online Dose Rate and Age Calculator<sup>59</sup>.

584 Luminescence measurements have been performed at the University of Lausanne (Switzerland)  
585 using a post-IR IRSL protocol<sup>60</sup> at 50°C (IR50) and 225°C (pIR225), as described in the Supp.  
586 Info. SI-12. Dose-equivalent distributions were statistically analysed<sup>61</sup> using the Central Age  
587 Model (CAM), and also the Minimum Age Model (MAM) for sample CA-13-283 which best  
588 represent luminescence reset during shearing (Extended Data Fig. 6). Final ages were calculated  
589 with individual fading corrections<sup>62</sup>.

590

### 591 **Volume of the rockslide deposit**

592

593 To calculate the total volume of the initial rock-avalanche deposit in the Sabche cirque and  
594 the upper Seti (fig. 3), we consider the difference between the initial surface of the breccia deposit  
595 and the original topographies of the cirque bottom and upper Seti valley before the collapse  
596 (Extended Data Fig. 4).

597 The original cirque surface is based on the recognition from air views and satellite images  
598 of the outcropping substrate areas beneath the deposits (Fig. 1 and Extended Data Fig. 4a). These  
599 outcrops spread outwards from near the cirque centre (and after removing the ice cover in the NE  
600 part of the cirque) and permit a rough interpolation of a smoothed initial surface. It is difficult to  
601 assess the second order relief (mostly small ridges separating glacier streams, considering by  
602 equivalence the cirque of the Annapurna Sanctuary located just west of that of Sabche).  
603 Introducing an a priori moderate relief carved by glaciers suggests an uncertainty on the volume  
604 reconstruction of the order of  $+3/-2 \text{ km}^3$ . Based also on observations made in the Annapurna  
605 Sanctuary cirque, the volume of moraines and ice that could have been entrained by the rock  
606 avalanche was estimated to be  $<0.1$  and  $0.5 \text{ km}^3$ , respectively.

607 The initial top surface of the rockslide deposit has been estimated based on a few remnants  
608 in the northern and north-western parts of the cirque (Extended Data Figs. 4b, 5a) and on top of the  
609 ridge along its southern part (Extended Data Fig. 2f). These surfaces are all located at an altitude of  
610  $\sim 4600\text{m}$ , but are not sufficient to constrain the geometry of the deposit surface in its central part,  
611 where the breccia penitents left by erosion provide only a minimum elevation (Fig. SI-4-1c).  
612 Nevertheless, literature evidence from the geometry of large collapses characterized by frontal  
613 confinement, as the Sabche one, suggest that this central part was likely at an elevation above 4600  
614 m (Supp. Info. SI-4). The present course of the glacier descending from the Annapurna III, which  
615 has been diverted westward, requires also the presence of an initially convex surface of the rock-  
616 avalanche deposit (Fig. 1). Despite uncertainties related to secondary hummocky features, a central  
617 convexity or a downward transition between the cirque and the Upper Seti valley, the mean rock-  
618 avalanche surface can presumably be approximated by a nearly horizontal deposit at an elevation of  
619  $\sim 4600 \text{ m}$  (Extended Data Fig.4b). We estimate that these uncertainties affect the reconstruction of  
620 the breccia volume by an error of  $2-3 \text{ km}^3$  (Supp. Info. Fig. SI-4).

621 Along the upper Seti, a similar approach was used to estimate the breccia volume,  
622 assuming, for the rock-avalanche deposits' original surface, a progressive thickness decrease along  
623 the upper Seti valley down to the last breccia occurrence (Supp. Info. Fig. SI-1-1) and relying on  
624 the minimum thickness indicated by the relic breccia spurs.

625 The combination (mean squared error) of the different sources of error on the basal and  
626 summit surfaces of the breccia deposit results in a final uncertainty in the volume reconstruction of  
627  $+4/-3 \text{ km}^3$ .

628 Finally, to derive the volume of solid rock that collapsed from the Annapurna IV summit,  
629 the breccia deposit volume was corrected for breccia porosity, measured from various rockslide  
630 breccia sampled in the Annapurna region (Supp. Info. SI-5). An average value of  $15\pm 5\%$  was  
631 found, consistent with previous estimates on rock-avalanche material<sup>63</sup>.

### 633 **Original failure surface of the Sabche rockslide**

634  
635 The entire NE and NNE area of the Sabche cirque displays numerous structural surfaces  
636 related to stratification or schistosity, and oriented at  $N110^\circ$  (Extended Data Fig. 1). The eastern  
637 part of the ridge joining the Annapurnas-III and -IV (Fig. 3) shows large structural slabs with dips  
638 of  $\sim 45^\circ$  to the south, i.e., quite well-oriented to represent slip planes. Below the Annapurna IV, the  
639 cliffs are characterized by geometric breaks (prisms, dihedrals) that connect these structural  
640 surfaces to irregular surfaces oriented at  $\sim N0^\circ$ . In contrast with slopes that dominate the western or  
641 eastern sides of cirque, these cliffs do not display any obvious trace of glacial or avalanche erosion,  
642 i.e. any trace of channelizing forms. This absence suggests that their surfaces were created by  
643 recent fracturing, and most probably correspond to the rockslide failure surface.

644 To corroborate these observations in a more objective way and to draw the a priori  
645 extension of the failure surface, a morphological criterion is defined by looking at the transverse  
646 curvature (Extended Data Fig. 4d) of the high-resolution topography (2-m Pleiades tri-stereo-  
647 derived DTM, see realization details in Supp. Info. SI-3), excluding ice and snow-pack areas. The  
648 structural surface appears with minimal curvature, whereas the slopes affected by erosion display  
649 converging thalwegs underlined by negative curvature. Using these indicators, we identified a zone  
650 of “fresh” planar or prismatic surfaces just south and west of the Annapurna IV summit, distinct  
651 from the areas beyond where erosion has begun to carve out channelized or converging relief. This  
652 first area (the upper and lateral limits of which are represented by the pink line in Fig.1c and  
653 Extended Data Figs 1-4) is considered as delimiting the original failure surface of the rockslide.

654 Even if we cannot exclude the possibility that small/secondary rock slides or rock falls  
655 would have partly rejuvenated this surface, analogous to the May 5<sup>th</sup> 2012 rockslide event<sup>64</sup> at the  
656 SE end of the Annapurna IV, the absence of deposits on top of the northern remnant of the original  
657 surface (Extended Data Fig. 5) suggests that no major reshaping event has affected the initial  
658 failure surface.

### 660 **Paleo-Summit Reconstruction**

661 To reconstruct the paleo-summit, three constrains must be verified: first, the restored rock  
662 volume must equal the collapsed one, i.e.  $23^{+3.5}/_{-3} \text{ km}^3$ ; second, the paleo-topography has to be on  
663 the verge of collapse; and third, the slopes and cliffs below the paleo-summit must be mechanically  
664 stable, otherwise they would have failed before the giant mass through smaller rockslides. The  
665 failure surface follows large portions of structural surfaces associated with the local schistosity  
666 developed in marly limestone and possibly presenting lower cohesion and friction angles. Defining  
667 a Safety Factor (SF) associated with this failure plane is difficult in absence of specific

668 measurements on these planes, and because of uncertainties on the exact geometry of the most  
 669 basal part of the failure surface (below modern glaciers and debris). Other than mass conservation,  
 670 the restoration therefore relies only on cliff average stability.

### 671 **Mechanical characteristics of the Annapurna range substratum**

672  
 673 To check the stability of headwalls below the paleo-summit, we explored the average  
 674 mechanical rock properties that ensure the stability of the regional relief in the entire high  
 675 Annapurna range. Estimating the average material properties of a region can be done by  
 676 considering the best-fitting strength parameters that reproduce the frequency-area distribution of  
 677 landslides<sup>47</sup>. Here, in the absence of such a landslide distribution in the Annapurna region, we  
 678 instead estimate the stability of the Annapurna summits by exploring the maximum value for the  
 679 cohesion that allows the stability of all regional slopes. At this scale, testing slope stability through  
 680 complex numerical approaches is computationally too demanding, and simplified limit *equilibrium*  
 681 analysis, despite its limitations, is usually preferred<sup>65,66</sup>.

682 In order to calculate the spatial distribution of the Safety Factor (SF) in the Annapurna  
 683 region, we have developed a Matlab© code largely adapted from previous approaches<sup>66</sup>. The slope  
 684 stability analysis is based on the limit equilibrium concept for a 3D model with rotational  
 685 movement on a potential ellipsoidal slip surface.

686 At each topographic grid point, our model evaluates the slope stability conditions for a large  
 687 number of randomly selected ellipsoidal slip surfaces (Extended data Fig. 7). These are defined by  
 688 the geographic coordinates of the centre, the length of their three half-axes  $a$ ,  $b$  and  $c$ , by their  
 689 orientation  $\alpha$  in the direction of the steepest topographic slope  $\beta_0$  and inclination  $\beta$  that follows the  
 690 steepest slope plus or minus  $15^\circ$ , and by an offset of the ellipsoid centre above the terrain  $z_c$ . For  
 691 each failure surface, the SF is computed using the 3-D sliding surface Hovland's model<sup>67</sup>:

$$692 \quad SF = \frac{\sum_{slip\ surface} C \cdot A(x,y) + \rho g D(x,y) \cos(\beta_c) \tan(\varphi_c)}{\sum_{slip\ surface} \rho g D(x,y) \sin(\beta_m)} \quad (1)$$

$$693 \quad \text{with } \beta_m = \tan^{-1}(\tan(\beta_c) \cdot \cos(\alpha_c - \alpha)), \text{ and } A(x,y) = \frac{1}{\cos(\beta_c)}$$

694  
 695 where the summation sign corresponds to the pixel summation of the resisting and driving forces  
 696 (projected on each surface element) applied on each vertical rock column of thickness  $D$ , and  $A$  is  
 697 the 3-D area of the slip surface for the considered pixel,  $\rho$  the rock density,  $C$  the apparent cohesion  
 698 of the substrate,  $\varphi$  its internal friction angle,  $\beta_c$  and  $\alpha_c$  the local slope and aspect of the surface of  
 699 rupture at the base of the considered column. The driving force and sliding act in the direction of  $\alpha$ .  
 700  $\beta_m$  is the apparent dip of the slip surface at the considered column in the direction of sliding. No  
 701 inter-column forces or external forces, such as seismic loading, are considered in the model.

702 In contrast with a previous model<sup>66</sup>, and because soil is absent above 4500m, we don't  
 703 consider potential slip at the soil-substratum interface, but assume a homogeneous substratum.  
 704 Because we are not interested in exact friction and cohesion values, but only by apparent regional  
 705 values that could be applied to the slopes of the Annapurna IV, we do not consider either seepage  
 706 forces, or pore pressure effects.

707  
 708 Practically (Extended Data Fig. 7), we employ a brute force procedure by exploring at  
 709 regular steps different parameters. First, we iterate on the pixels of the topography. For each pixel,

710 we iterate between the extreme geometric limits of the ground trace, calculating the average aspect  
711 and steepest slope over the given scale. For each explored ground window, we iterate on the  
712 parameters ( $a$ ,  $b$ ,  $c$  and  $\beta$ ) of the ellipsoids that fit the ground trace and calculate the SF (failure  
713 surfaces displaying an overhanging portion are rejected). For each pixel, the parameters giving the  
714 minimum SF value are retained and the associated potential rockslide is located at the coordinates  
715 of its center of mass. Finally, in the result grid, if a pixel contains several centres of mass of  
716 potential rockslides, we keep only the one with the lowest SF.

717 Before applying our model to the glaciated Annapurna area or to the fluvially-dominated  
718 region farther south (Supp. Info. SI-6), we tested it on a benchmark case and ensured that the  
719 searching procedure was finding: (1) similar solution (SF value) as previous studies<sup>65,66</sup>; and (2)  
720 optimal ellipsoidal failure geometries not too far from the semi-analytic circular<sup>68</sup> or log-spiral<sup>69</sup>  
721 solutions. Regarding this later point, our optimal surfaces are a bit more concave than the semi-  
722 analytic solutions, but the SF values match to within <10%.

723 To explore the mechanic stability of the Annapurna range, we consider the steep areas  
724 within similar elevation range and lithology as the Annapurna IV collapse, i.e., for elevations  
725 higher than ~4000 m and for TSS units, excluding the flat cirque bottom (Extended Data Fig. 8).  
726 For the SF calculation, a fixed value of the internal friction angle at  $\varphi=35^\circ$  (ref. <sup>70</sup>) is considered.  
727 Only cohesion values were varied. For each cohesion value, we plot the distribution of SF values.  
728 If most prominent cliffs are near the verge of failure as expected in mountains with both high uplift  
729 and high erosion<sup>16</sup>, then the distribution mode has to be slightly above the critical value of 1, i.e. for  
730 an apparent cohesion  $\geq 1$ MPa for the high relief of the Annapurna range.

731 Locally, the geometry of gravity instabilities is most often related to the orientation of  
732 fracture families and/or to schistosity: at the scale of our approach, such a consideration of local  
733 factors is not possible, and the explored cohesion value should be viewed as an average estimate. In  
734 addition, as neither the effects of pore pressure, seepage forces, nor seismic acceleration are taken  
735 into account, this value can be seen as a minimum<sup>46</sup> for the glaciated relief of the Annapurnas.  
736 More importantly, because the internal friction angle has not been explored, the cohesion values  
737 tested in our procedure must be viewed as an apparent value. However, the precise value is of little  
738 importance insofar as we are looking for a relative criterion to test realistic topographies of the  
739 paleo-Annapurna IV in a second step (Supp. Info. SI-7), or to compare apparent cohesion values  
740 between glaciated and unglaciated areas (Supp. Info. SI-6).

## 741 **Paleo-topographic reconstruction**

742  
743  
744 To explore a family of possible geometries for the Annapurna IV paleo-summit, we  
745 generated 2000 topographies from fixed ground support points along the northern ridge and from  
746 random paths for the crest and the southern basal footprints (see also computing chart in Supp.  
747 Info. SI-7). Whereas the elevation of the southern basal footprints is interpolated from the initial  
748 cirque surface (Extended Data Fig. 4a), the crestline elevation is randomly varied within a fixed  
749 range (the northern slopes between the present head scarp and the crest are allowed to vary between  
750 35 and 50°, whereas the horizontal path is oriented in continuity with the present ridgelines at their  
751 eastern and western terminations). Intermediate points with randomly varying elevations are also  
752 generated before performing surface interpolation and volume calculation.



753 To consider a paleo-topography as acceptable, besides producing a rockslide volume  
754 between 20 and 26.5km<sup>3</sup>, its hillslopes must be stable according to the SF criterion defined for the  
755 Annapurna region. For each randomly generated paleo-topography, we thus apply the same  
756 procedure described in the previous section (Extended Data Fig. 7), and derive the distribution of  
757 minimal SF values. For the high relief of the Annapurnas and assuming  $\varphi = 35^\circ$ , all SF values were  
758 found to be  $\geq 1$  for a cohesion value  $C=2\text{MPa}$ . Based on this absolute cut-off, any paleo-  
759 topography presenting SF values lower than unity for  $C=2\text{MPa}$  were rejected. From the final set of  
760 acceptable geometries, we calculate a mean topography, a distribution of volumes, of crest profiles  
761 and of paleo-summit elevations (Fig. 3d and Extended Data Fig.9).

762 It should be noted that for the modelled paleo-topographies the optimal ellipsoidal failures  
763 predict a steeper and shallower rupture surface than that actually observed and preserved in the  
764 present topography beneath Annapurna IV. Applying Hovland formula<sup>67</sup> (eq. (1)) on the actual  
765 failure surface, and exploring various sliding directions in order to reach a minimal stability, leads  
766 to  $SF_{fs}$  values of  $1.42 \pm 0.1$  for  $C=2\text{MPa}$  (vertical red line in Extended Data Fig. 9g), well above the  
767 collapsing threshold of 1. Although this high value results in part from the surface roughness  
768 compared to that of a smooth ellipsoid, it also reflects the likelihood that the rupture was strongly  
769 guided by existing schistosity planes, especially in the western part of the collapse. It is  
770 hypothesized that these schistosity planes exhibit friction angles and cohesion significantly lower  
771 than  $35^\circ$  and  $1-2\text{MPa}$ , respectively. Nevertheless, if we attempt to reduce the set of possible paleo-  
772 topographies, we could potentially add a third criterion that the  $SF_{fs}$  along the failure surface has to  
773 be minimal or not too high: we might, therefore, preferentially select a subset of paleo-topographies  
774 with  $SF_{fs} \leq 1.42$  (for  $C=2\text{MPa}$ ), which would be more prone to collapse (dark red histogram in Fig.  
775 3d).

776  
777

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## Extended Data Figure Legends

**Extended Data Fig. 1: Geologic map and cross section of the Sabche cirque area.** (Upper) Interpretative geologic map of the Sabche cirque area based on published maps<sup>28,71</sup> West and North of the cirque. The TSS units that outcrop along those cliffs correspond to the base of the TSS series, namely carbonate-rich sediments, Cambrian to Silurian in age, and presenting an upward decreasing degree of metamorphism<sup>28</sup>. The different lithologic limits were extrapolated across the cirque based according to our observations made on photos taken from ultralight aeroplane and helicopter, and from satellite images. Structures and bedding attitudes were also estimated from photos or from the tri-stereo DEM. (Lower) Interpretative structural cross section AA' (see location on main map) built according to published sections further West<sup>28,71</sup> and to the bedding attitude we estimated from a large set of airplane photos or from the DEM. The northern part of the section, which has been affected by the rockslide, is relatively well constrained since bedding are pretty well identifiable on photos. The southern part is much less constrained because the Sanctuary units display less identifiable beddings and because the structure is much more heckled with numerous small-scale folding. STD = South Tibetan Detachment, DD = Deodali detachment.

**Extended Data Fig. 2: Different facies of the breccia deposit in Sabche cirque** (photos a to f = taken from an ultra-light aeroplane \_ See pictures location on fig. 1 in Supp. Info.): (a) compact, homogeneous, pulverized and indurated fine grained breccia exposed over ~200 m high cliffs; (b) and (c) package of coarse and blocky material topped by more finely pulverized fine grained breccia material; (c) and (d) Internal contacts between grey and yellowish breccia facies (issued from the Annapurna Yellow Limestone formation<sup>28</sup>) presenting inverted order and suggesting limited mixing during the rockslide collapse; (d) Contact close to the southern base of the cirque deposit in its southern part: this contact, slightly sloping towards the N or NW, presents as a thin band of shearing and micro-crushing where IRSL samples were taken (CA-273, -274 and -283). (e) Rare preserved phantom of limestone dismantled strata, or jigsaw facies. (f) In the southern part of the cirque, veneers of breccia deposit are preserved on the N-dipping flank of the cirque up to 4350m altitude (z2), and at the top of the eastern ridge of Macchapuchare (fig. 1) at ~4570m altitude (z1 = satellite image taken on 30/12/2011); (g) Saw-cut samples of compact and indurated facies exposed in the basal part of the deposit (CA-273, site of panel d): the breccia is made of finely crushed material with a few angular clasts.

**Extended Data Fig. 3: Outcrops near Karuwa (site K on fig. 1) exposing the stratigraphy of the granular avalanche breccia deposit.**

(a) 40-m-high cliff overhanging the Seti river, exposing breccia of the granular avalanche material and cut by a small inset terrace capped by a filling of (b) finely-layered limestone rich gravels of Pokhara conglomerates. (c) Breccia facies with juxtaposition of parts made of limestone/marble of different colors with pockets of whitish elements and matrix within a set of darker elements and matrix. The size of elements, the proportion of clast vs. matrix, as well as the carbonate content remain however similar between the different colored areas. They are interpreted as figure of incomplete mixing at meter-scale of the avalanche material issued from the basal Ordovician units

886 that display alternation of light and dark layers in the Sabche cirque along the steep SW face of the  
887 Annapurna IV (c'). (d) Internal part of the breccia displaying dyke injection of a fluid rich phase  
888 that coloured the breccia, and the post-injection (e) multiple brittle to ductile faulting and shearing  
889 of this dyke and of its shoulders. (f) Schematic section of the contact between the avalanche  
890 brecciated deposit and the gneissic bedrock of the Seti valley flanks. This contact displays a  
891 transition in terms of lithology and clast size: breccia with large (up to >1m) and sub-angular to  
892 rounded boulders of local biotitic gneisses are progressively replaced by smaller angular elements  
893 (<30cm) within a matrix-dominant material made of ~100% of TSS lithologies. The gneiss rich  
894 unit, which corresponds to local material dragged and entrained at the base of the avalanche,  
895 contained quantity of millimetric to sub-metric pieces of vegetal debris (root, branch and trunk (g))  
896 ripped from the sides of the valley, and whose density decreases also rapidly away from the former  
897 valley wall. (h) Bedrock/breccia contact in the upper part of the talweg displaying a contact zone,  
898 0 to 40-cm thick, made of a mixture between limestone breccia, local gneissic clasts, and paleosol  
899 pockets, including numerous wood debris, and the presence of a (i) shearing zone of a few  
900 centimetres thickness. Green numerical codes correspond to the names of the samples (CA-xx-xx)  
901 dated by <sup>14</sup>C.  
902

903 **Extended Data Fig. 4: Elements for reconstructing the volume of collapsed rockslide material**  
904 **in the Sabche cirque and the initial rockslide failure surface.** Maps of the base (a) and top (b) of  
905 the rock avalanche brecciated deposits, including the interpolation constraints, and (c) present-day  
906 residual thickness of the breccia deposits. (d) Sabche rockslide scar identification from the  
907 transverse curvature (m<sup>-1</sup>) computed from the high resolution (2-m pixel) topography. The recent  
908 scar surface (3 and 4) is characterized by step like dihedrals that delineate planar faces with low  
909 curvature along the stratification/foliation planes and irregular faces following a set of fractures at  
910 90°. In contrast, outside the scar (1 and 2), the topography displays the first marks of erosion and  
911 gullies organisation toward a converging network.  
912

913  
914 **Extended Data Fig. 5: The main dated relic of the rockslide deposit surface in the upper**  
915 **Sabche cirque**

916 (a) Satellite image (Google Earth) of a large flat area in the northern part of the Sabche cirque. This  
917 flat area corresponds to the top of the rockslide deposit (4600m), which was amply resurfaced by  
918 glaciers except along its southern part where the original surface is covered with numerous multi-  
919 metric blocks. (b) Picture taken from an ultra-light aeroplane of the area, south of which the multi-  
920 meter blocks CA-13-260 to 265 were sampled. (A: original chaotic upper surface of the rockslide  
921 deposit; B: gently hilly surface of the hummocky moraine deposits; C: crested moraine left by the  
922 glacier issued from the South-Eastern face of the Annapurna III and which is now deeply  
923 entrenched into the breccia deposit; D: recent moraine left by the glacier issued from the West face  
924 of the Annapurna IV; E: present-day glacier issued from the West face of the Annapurna IV). (c)  
925 Five of the six blocks sampled for cosmogenic <sup>36</sup>Cl dating at the top of this relic surface. All the  
926 blocks of the surface consist of carbonate rocks: limestone, marly to sandstone limestone,  
927 sandstone marl. These lithologies are finely schistosed and their surface physically weathered.  
928

929 **Extended Data Fig. 6: Internal shear zone near the basal part of the rockslide deposit in the**  
930 **Sabche cirque and IRSL dating** (see location on Fig. 1C). (a) The shear zone varies in thickness  
931 from a few centimetres up to 30cm at the level of fish-like structures (to the left of the hammer). (b)  
932 The shear zone (sample CA-13-283) appears as colored bands of relatively compact breccia made  
933 of centimeter size angular clast within a finer yellowish matrix; (c & d) Thin sections observed  
934 under polarizing microscope, cut into the shear zone perpendicularly to the shearing plane and  
935 showing thin zones of homogeneous finely fragmented almost glassy material within microbreccia  
936 facies with locally remnant of larger clasts. (e) Schematic sedimentologic description of the breccia  
937 around shear zone at 2 sites, around 50m apart (Extended Data Fig. 2d). (f and g) Age distributions  
938 (fading-corrected) and kernel density estimate (KDE) plots for samples CA-13-283 and -273  
939 respectively. IR50 ages and KDE are represented by filled circles and thick line, respectively.  
940 pIR225 ages and KDE are represented by open circles and dashed line, respectively.

941  
942 **Extended Data Fig. 7: Definition and validation testing of the hillslope safety factor (SF)**  
943 **exploration procedure in the Annapurna Range region.** (a) Definition of the variables for the  
944 computation of the Safety Factor (SF) according to 3D-Hovland criterion<sup>67</sup>, and (b) computation  
945 chart of the searching procedure of the ellipsoid-type failure surfaces that minimize the SF all over  
946 the topography of a given region. (c) Validation test of the searching procedure in the case of a  
947 topographic step, 1-m high, dipping at 60° with  $\varphi = 15^\circ$  and  $C = 0.116$  Pa. The optimal ellipsoids  
948 surfaces at the four increments that present minimal SF are compared with close-formed  
949 solutions<sup>68,69</sup>. The SF values remain within 5% of the ones associated to these solutions whatever  
950 the nominal value (solid line) or the one calculated with 3D-Hovland criterion applied to their  
951 geometry (dashed line) is considered.

952  
953 **Extended Data Fig. 8: Results of the hillslope safety factor exploration in the Annapurna**  
954 **Range region.** (a) Map of the minimum SF along the hillslopes of the Annapurna high relief found  
955 using the systematic searching procedure (Extended Data fig. 7) within the area delineated by the  
956 dashed line. Calculation is made for an internal angle of friction of 35° and a cohesion,  $C$ , of 1.15  
957 MPa. The steepest faces surrounding the highest peaks (black triangles), like the SSE face of the  
958 Annapurna I (A-I), one of the most challenging climbing route in High Himalaya, present a Safety  
959 Factor lower than 1 and would be considered as unstable for this given cohesion value. Note that  
960 for a given pixel, the search procedure may have found several optimal failures, of different sizes,  
961 whose centers of mass related to the same pixel: in this case, the failure with the minimum SF was  
962 chosen. A-II =Annapurna II, A-III =Annapurna III, A-IV =Annapurna IV, and Ma =  
963 Machapuchare. (b) Histograms of the values of the SF for different values of cohesion,  $C$ , between  
964 0.5 and 2 MPa. For  $C=2$ MPa, almost all the hillslopes are apparently stable.

965  
966 **Extended Data Fig. 9: Paleo-summit reconstruction**

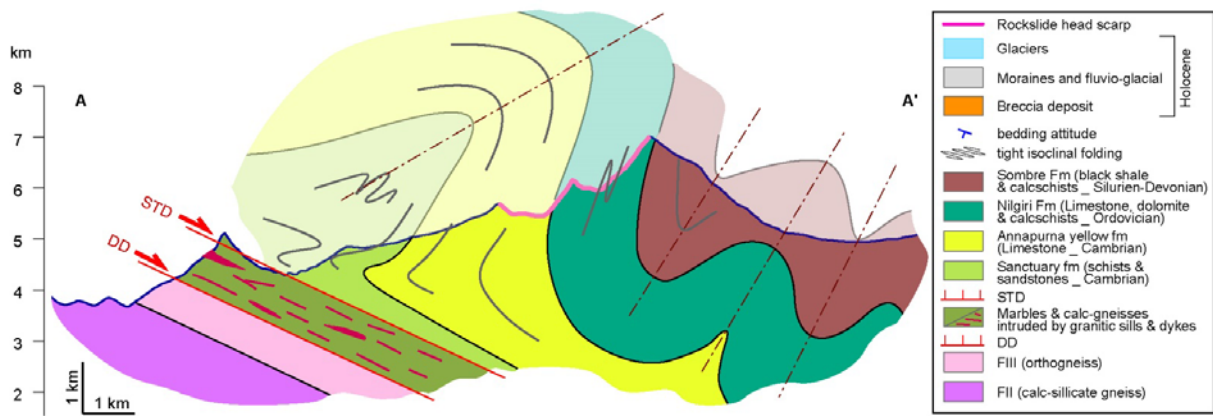
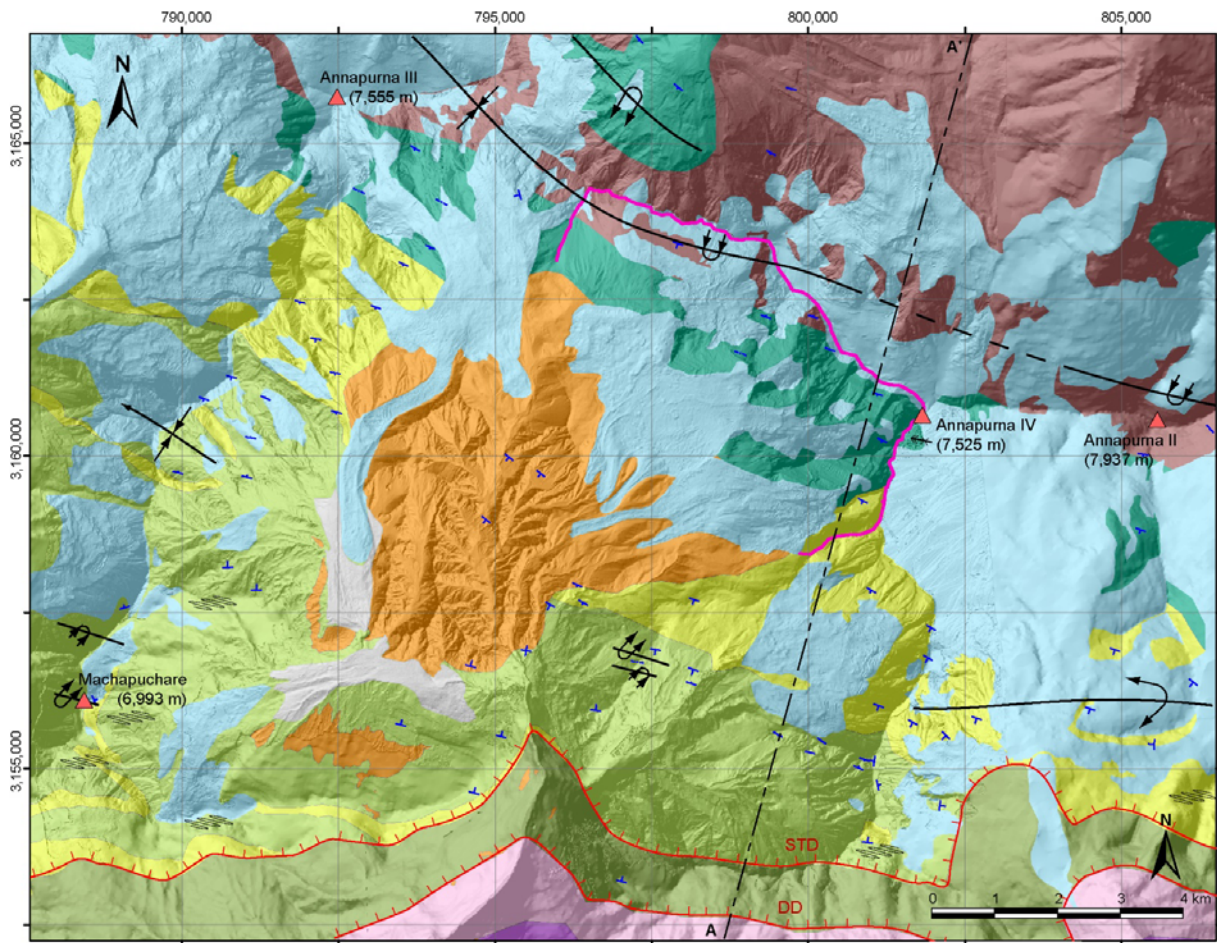
967 (a) Construction points used to build simplified topography of the paleosummit. This construction  
968 is essentially based on two main lines, whose geometry is explored in a random way: the paleocrest  
969 (in cyan) and the paleocliff SW base (in blue). These lines are built as the sum of harmonics  
970 function (up to the 8<sup>th</sup> term) of random amplitude and phase. The two extremities of the paleocrest  
971 have been chosen to prolong on average the direction of the present crests line further West and  
972 East. Similarly, the extremities of the base of the SW cliff and the isolated mobile point (in cyan)

973 were chosen to prolong the SW-facing cliffs of the Sabche cirque. Densifying points are then added  
974 before using Matlab© interpolation function *griddata*. (b) Map extent of the density (in log scale)  
975 of the random paths explored for the paleocrest and the paleobase, with one random example of  
976 path (black solid line). (c) Same as (b) but for the elevation profile of the paleocrest. In both  
977 graphs, purple lines indicate the 95% probability of the density of the a posteriori paths that respect  
978 both rockslide volume and hillslope stability constraints. (d) Map and histogram (inset graph) of  
979 the SF values obtained through the searching procedure (ED-fig. 7) applied, within dashed lines  
980 and for a cohesion value of  $C=2$  MPa, to one of the randomly generated paleotopography. (e)  
981 Average shape of the topographies that satisfy rockslide volume and regional stability criterion,  
982 including a rose diagram of the optimal sliding direction N245 (i.e. the direction that minimizes the  
983 SF on the failure surface). (f) Histogram of the volumes of the collapsed summit explored by the  
984 generator of random topographies. 75% of the values fall within the range of the volume estimated  
985 for the rockslide. The topographies that satisfy the regional stability criterion are superimposed in  
986 pink colour. (g) Histograms of the SF on the failure surface for cohesion values  $C=2$  MPa. The  
987 topographies that satisfy the rockslide volume are superimposed in darker colour, and the ones that  
988 satisfy both rock volume and regional stability criterion in pink colour.

#### 990 **Extended Data Fig. 10: Possible Sabche rockslide signature in the Gandak fan?**

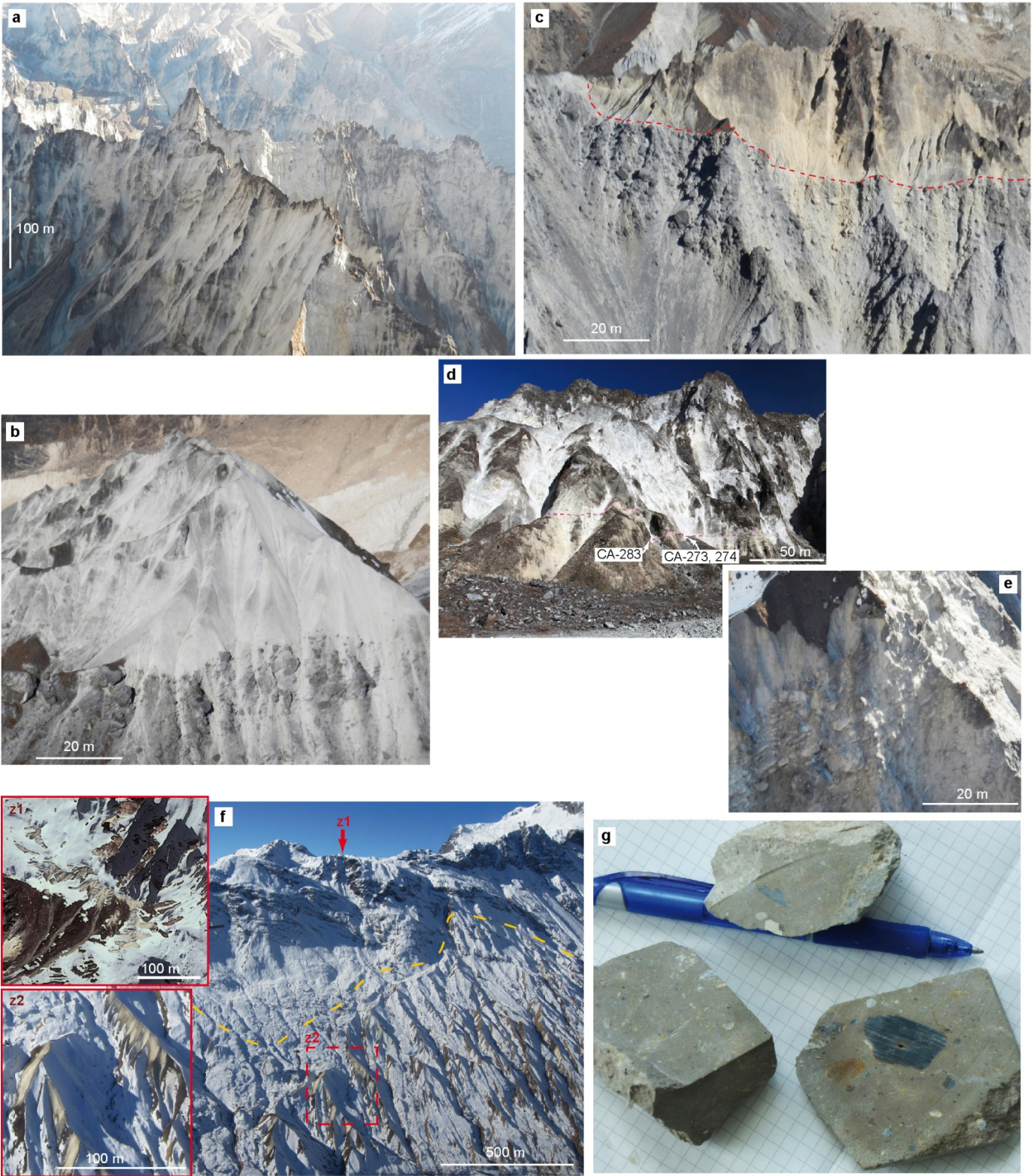
991 (a) Stratigraphic log and carbonate content of two 50-m long cores, GR1 and GR2, drilled in the  
992 Gandak fan<sup>72</sup>. The two boreholes GR1 and GR2 show relatively constant carbonate percentages  
993 close to the current river values (represented by the blue and gray lines respectively). Nevertheless,  
994 GR2 is characterized by a 25-30% anomaly between -10 and -3m, and by a very strong 35-70%  
995 carbonate anomaly between -3m and the surface. This anomaly was corroborated by additional  
996 measurements on samples taken in a 3-m-deep small pit dug in the close vicinity of the GR2 drill  
997 site. Such a recent anomaly in carbonate content might correspond to deposition of the fine fraction  
998 of the sediments issued from the Sabche cirque erosion, 300km further downstream. Whereas these  
999 carbonate rich units are not directly dated, <sup>14</sup>C ages in GR1 core indicate that they are probably  
1000 younger than ~1.5 kyr, which is compatible with a deposit related to the Annapurna IV collapse  
1001 and more or less synchronous of the Pokhara conglomerate deposits.

1002 (b) Residual topography obtained by subtracting a second order polynomial fit (dashed lines =  
1003 Trend function in ArcGis) to the topography (30m SRTM) of the Narayani fan. This residual  
1004 topography enables to highlight small topographic variations on the surface of the fan. It is seen  
1005 that GR1 was drilled in the recent flood plain of the Narayani (in yellow to reddish colors), while  
1006 GR2 was drilled in a N-S lobe 3 to 5 m higher than the rest of the fan (in bluish colors). This lobe,  
1007 which was then re-incised on its eastern border by the Narayani (see zoomed image) could have  
1008 been built during the episode of strong sediment input that followed the collapse in the Sabche  
1009 cirque.

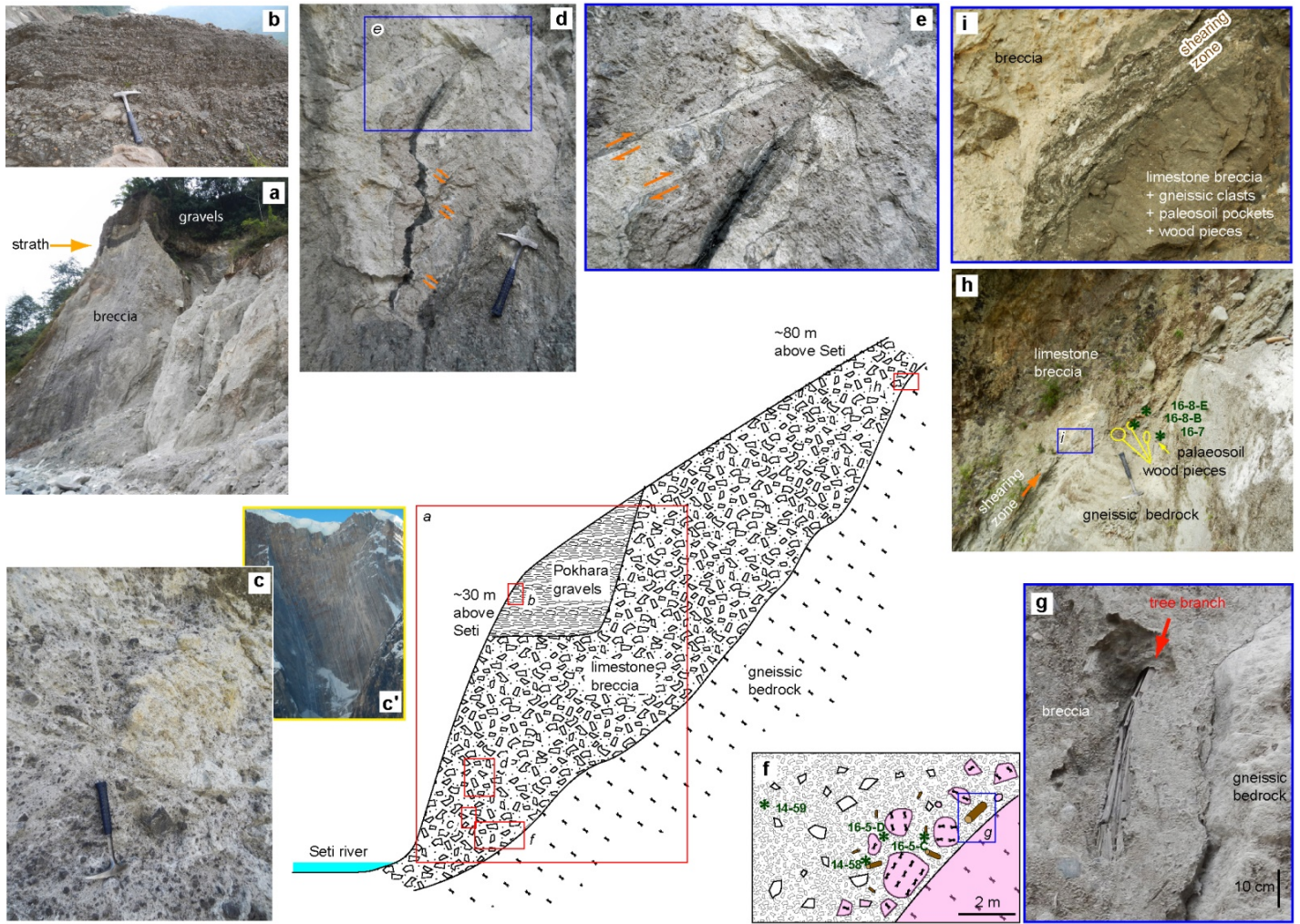


Extended data figure 1

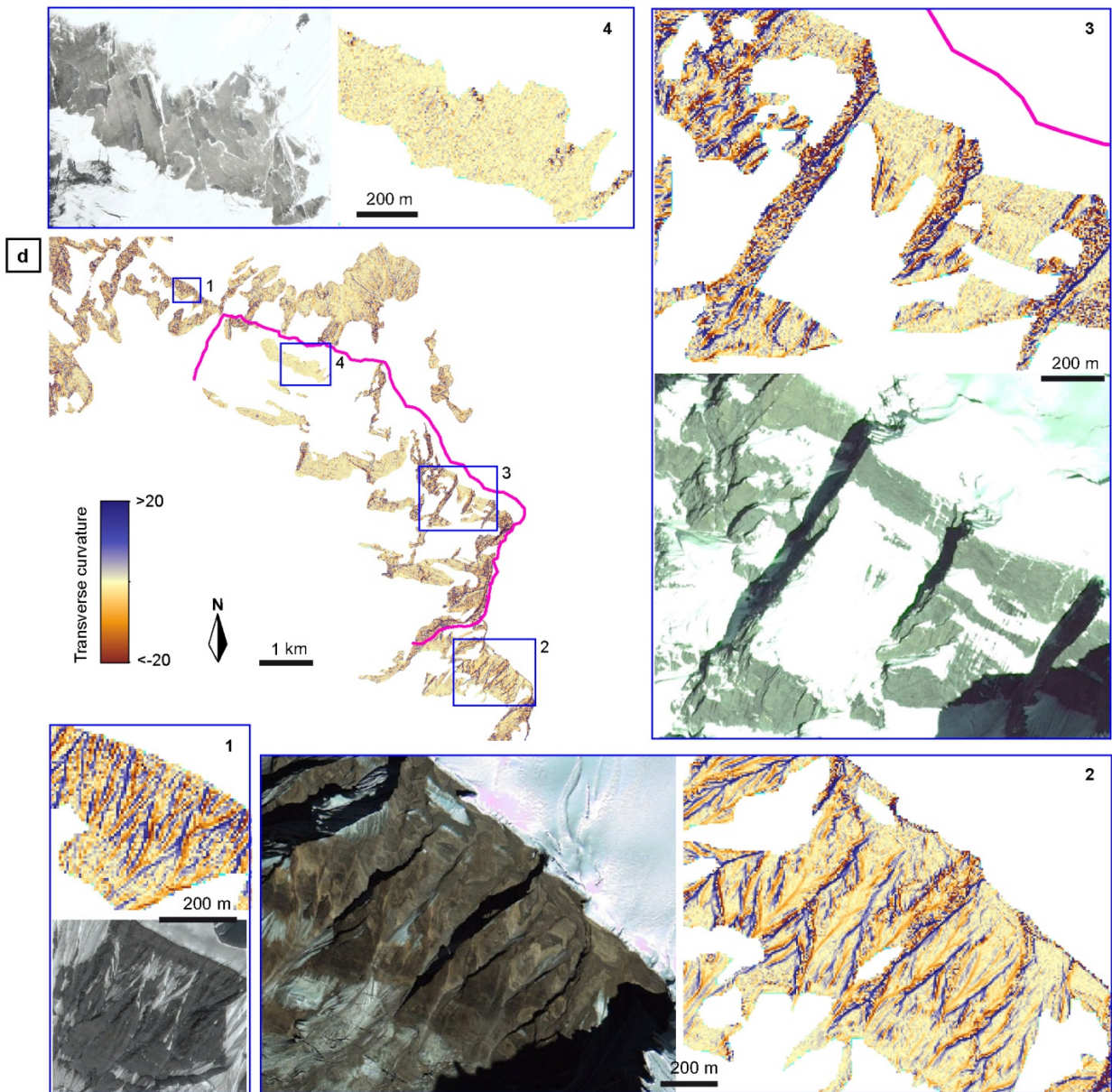
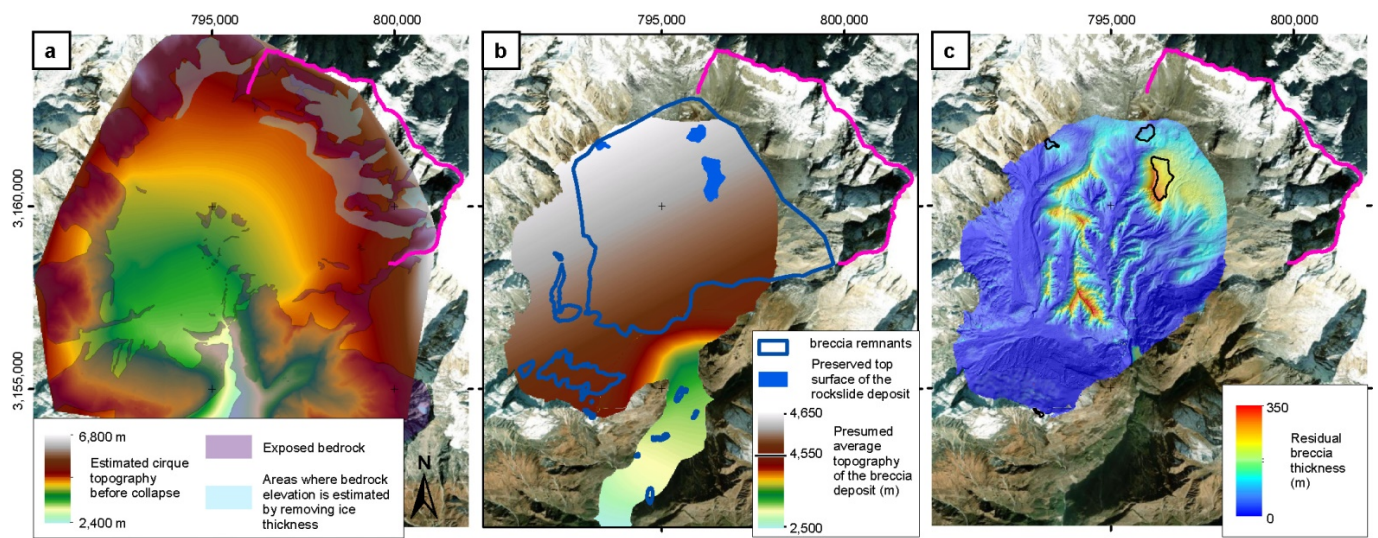




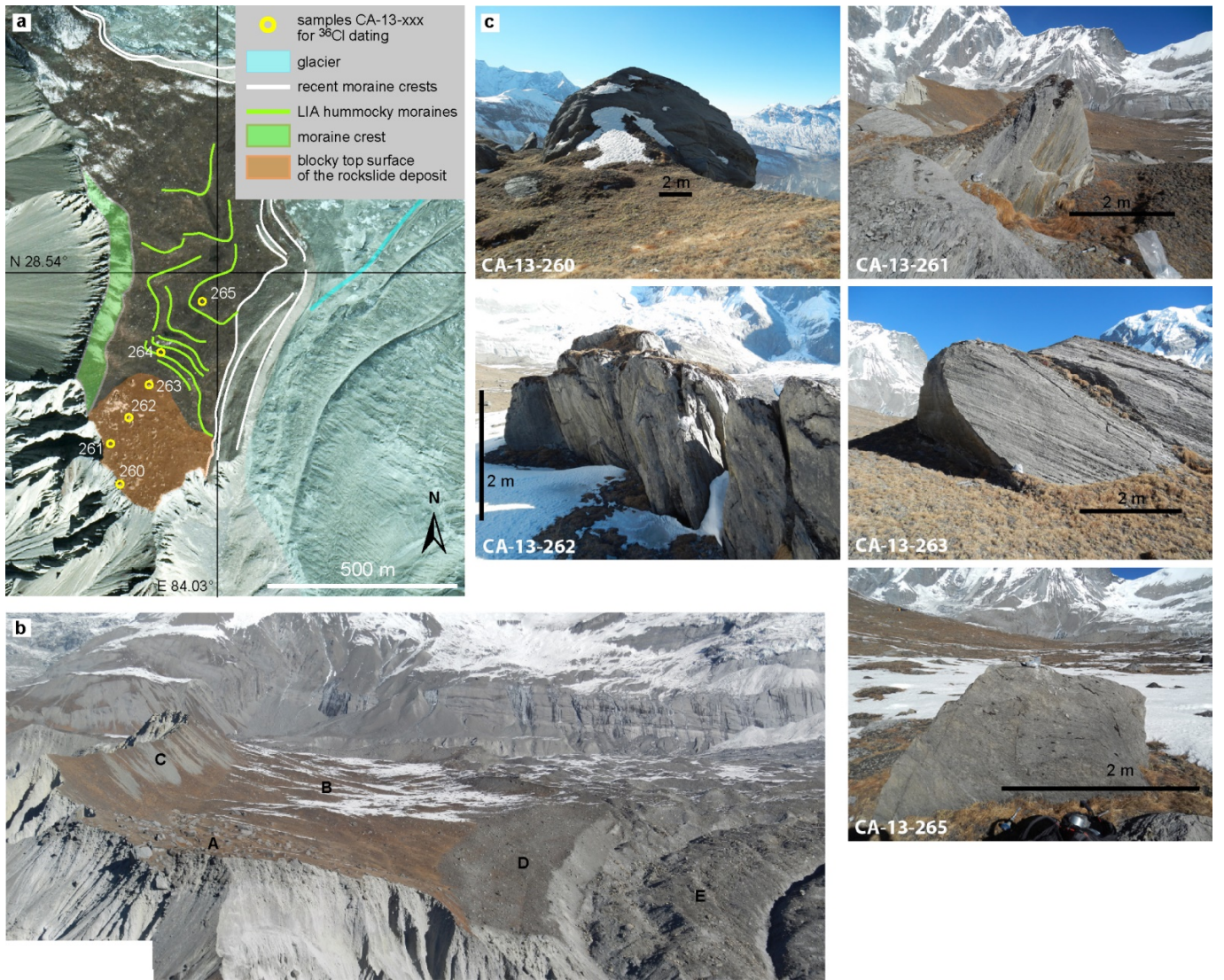
Extended data figure 2



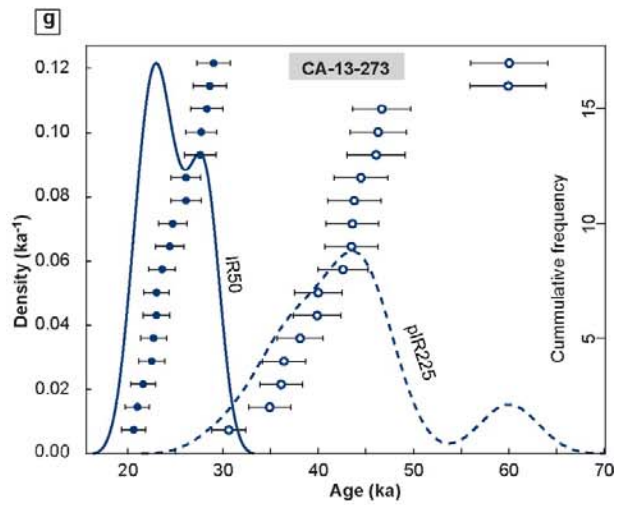
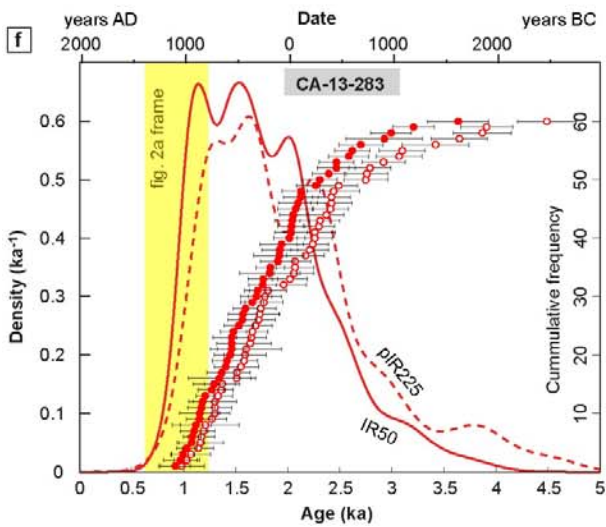
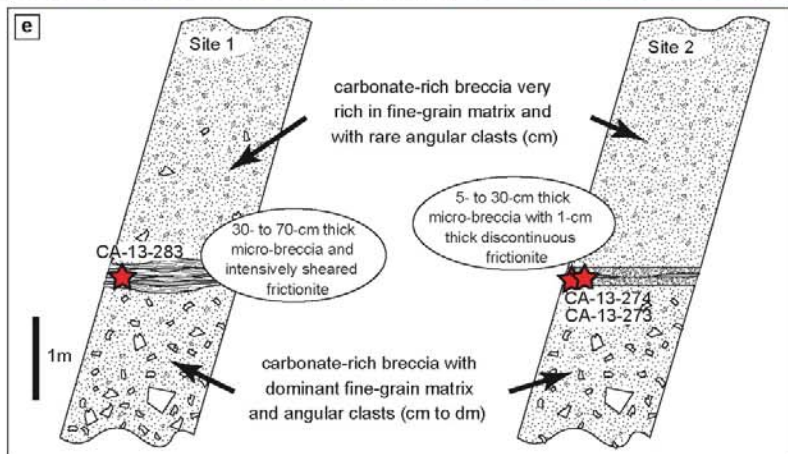
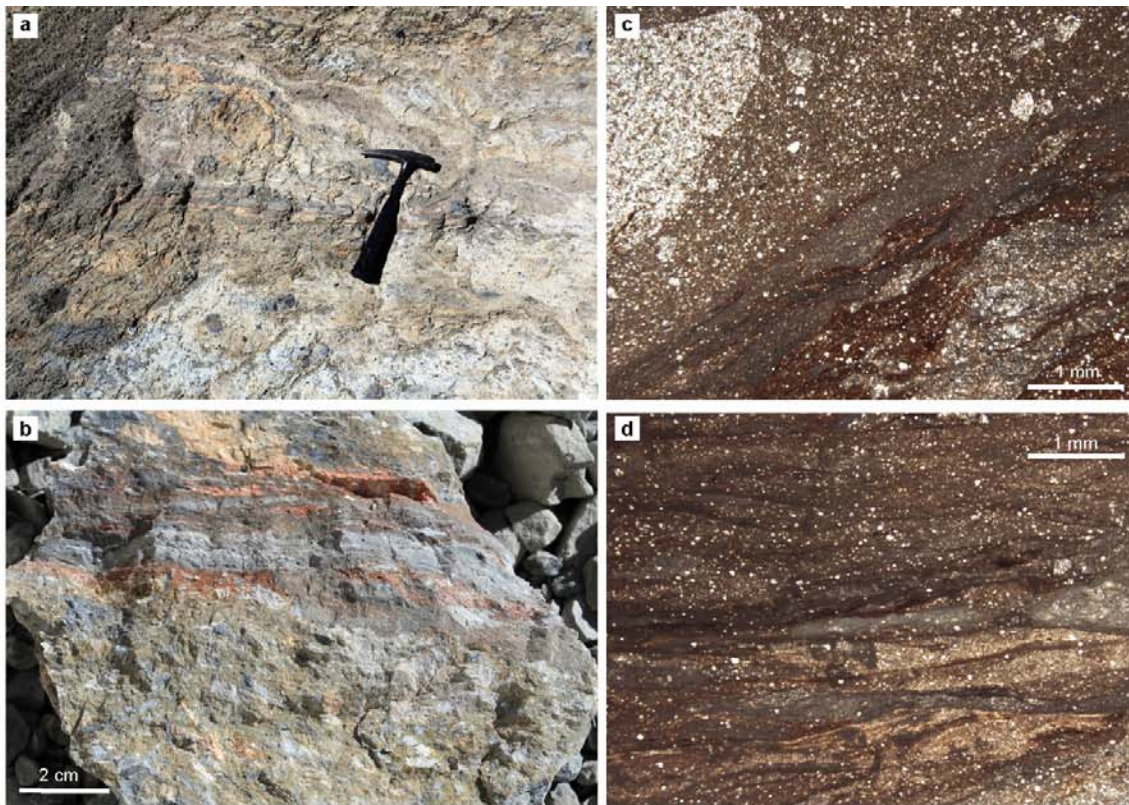
Extended data figure 3



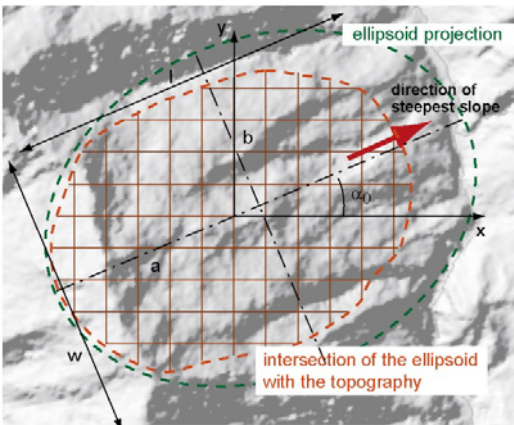
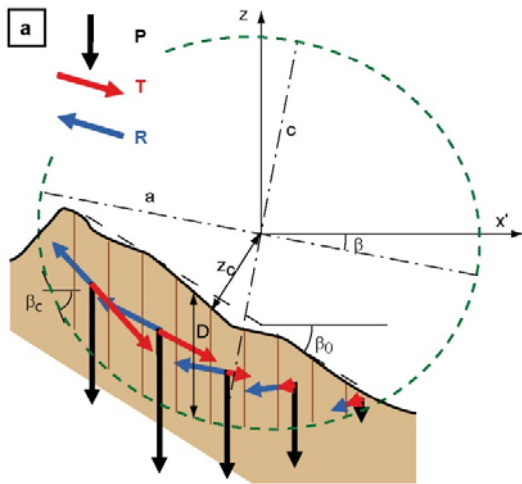
Extended data figure 4



Extended data figure 5



Extended data figure 6



**Parameters:**

- $\rho$  = bedrock density ( $\text{kg/m}^3$ )
- $dx$  = topography grid size
- $\varphi$  = internal friction angle (fixed at  $35^\circ$ )
- $C$  = cohesion ( $\text{N/m}^2$ ) (incrementally varied)

**Local topographic variables:**

- $\beta_0$  = downward slope angle
- $\alpha_0$  = orientation or aspect of the topographic slope

**Explored ellipsoid parameters:**

- $z_c$  = distance of the ellipsoid center to the topography
- $\beta$  = tilting angle of the ellipsoid
- $a, b, c$  = ellipsoid eccentricity parameters

**Local variables along the ellipsoid surface:**

- $D$  = local thickness of rock column
- $\beta_c$  = local slope of the surface of rupture
- $\alpha_c$  = local orientation of the surface of rupture
- $\beta_m = \text{atan}(\cos(\alpha_c - \alpha_0) \cdot \tan(\beta_c))$  = apparent dip of the failure surface in the slip direction (equated to  $\alpha_0$ )

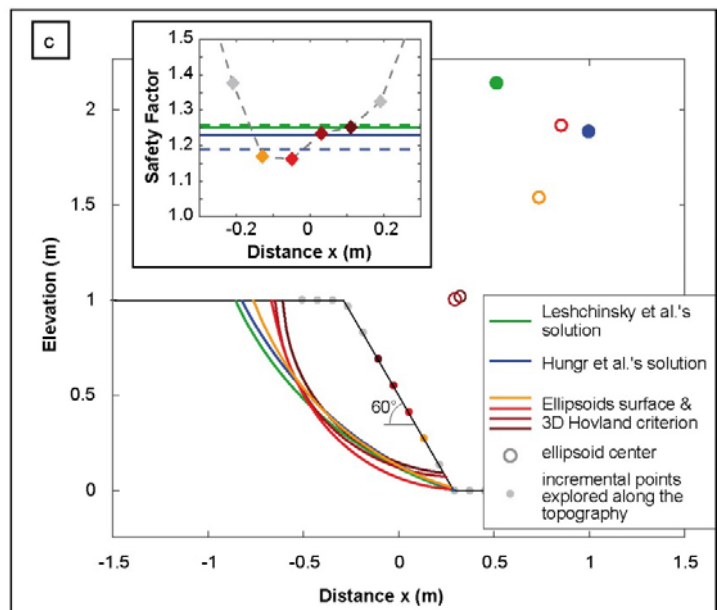
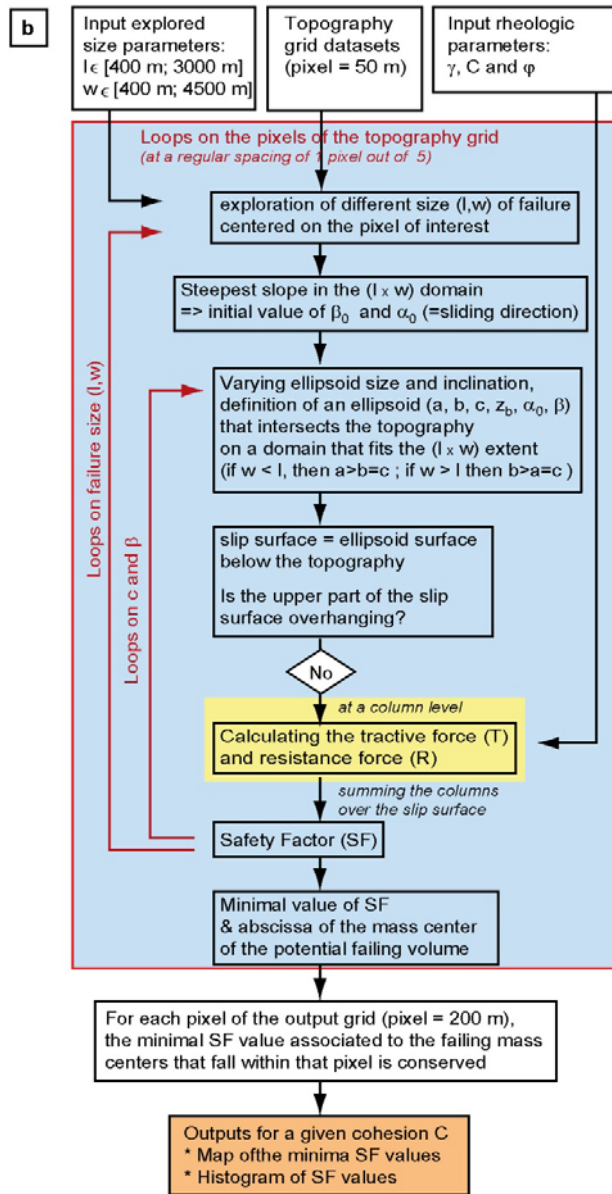
**Local Forces along the ellipsoid surface:**

Weight of a column of material:  $P = \rho g D dx^2$

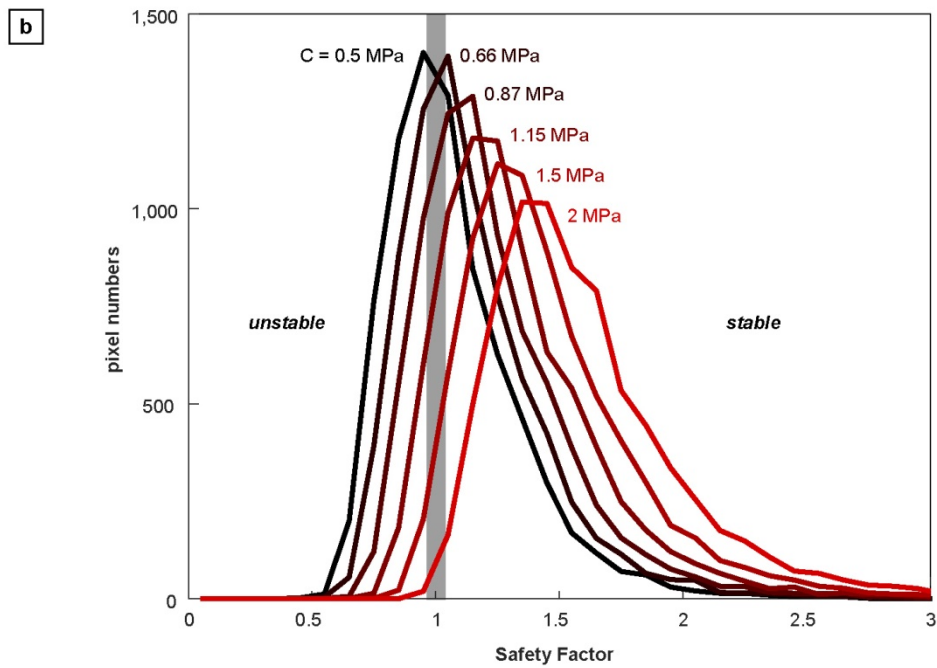
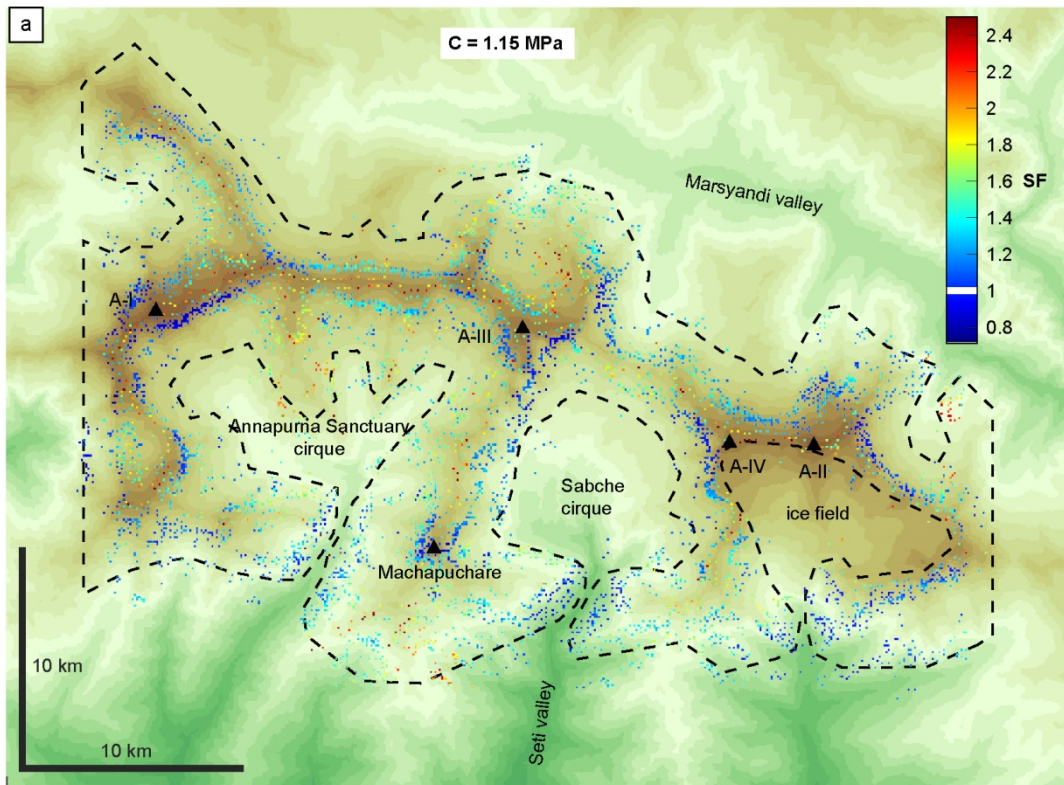
Tractive force:  $T = dx^2 \cdot \rho g D \cdot \sin(\beta_m)$

Resisting force:  $R = dx^2 \cdot (C / \cos(\beta_c) + \tan(\varphi) \cdot \rho g D \cdot \cos(\beta_c))$

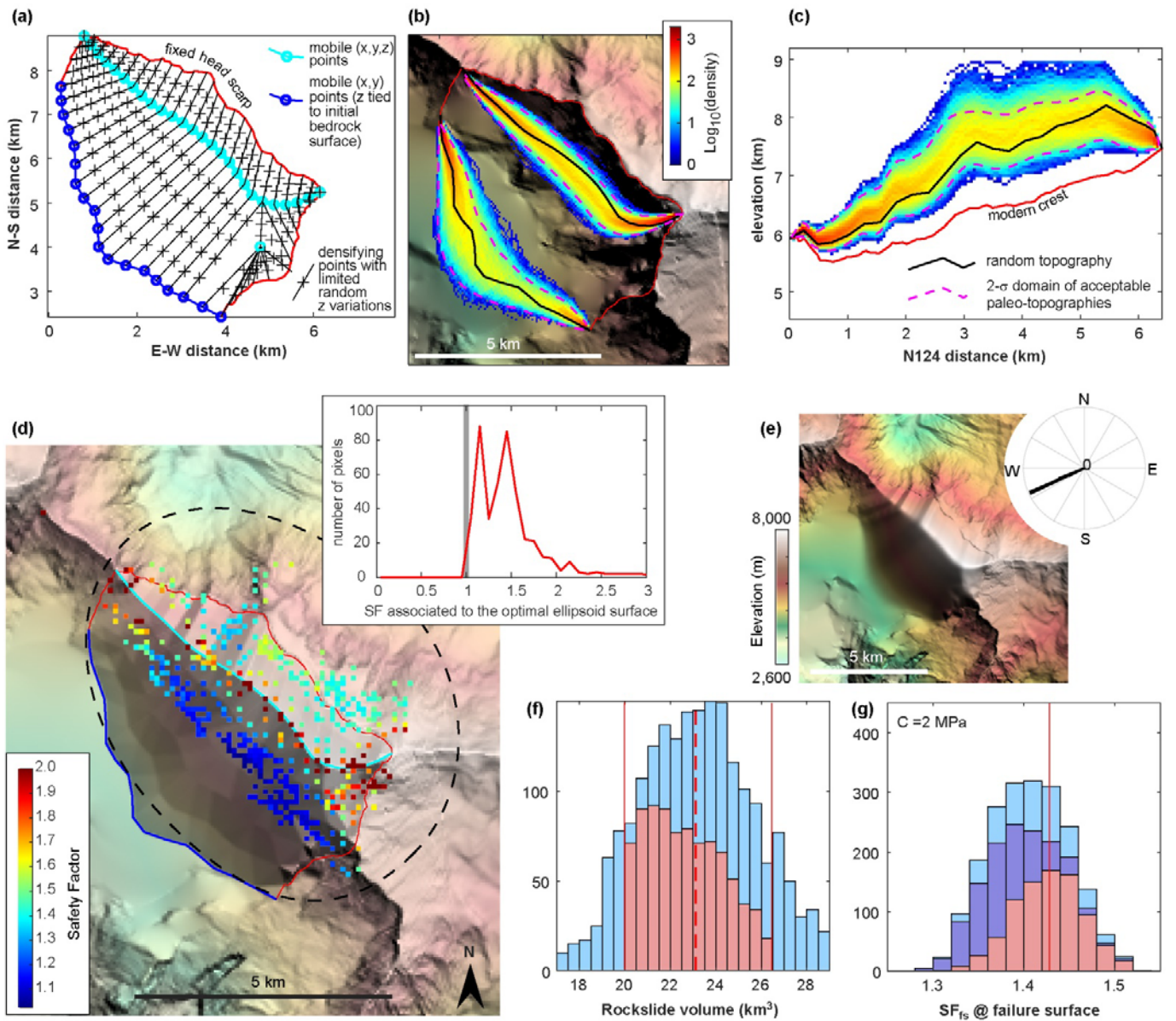
Safety Factor:  $SF = \frac{\sum R_{(x,y)}}{\sum T_{(x,y)}}$



Extended data figure 7

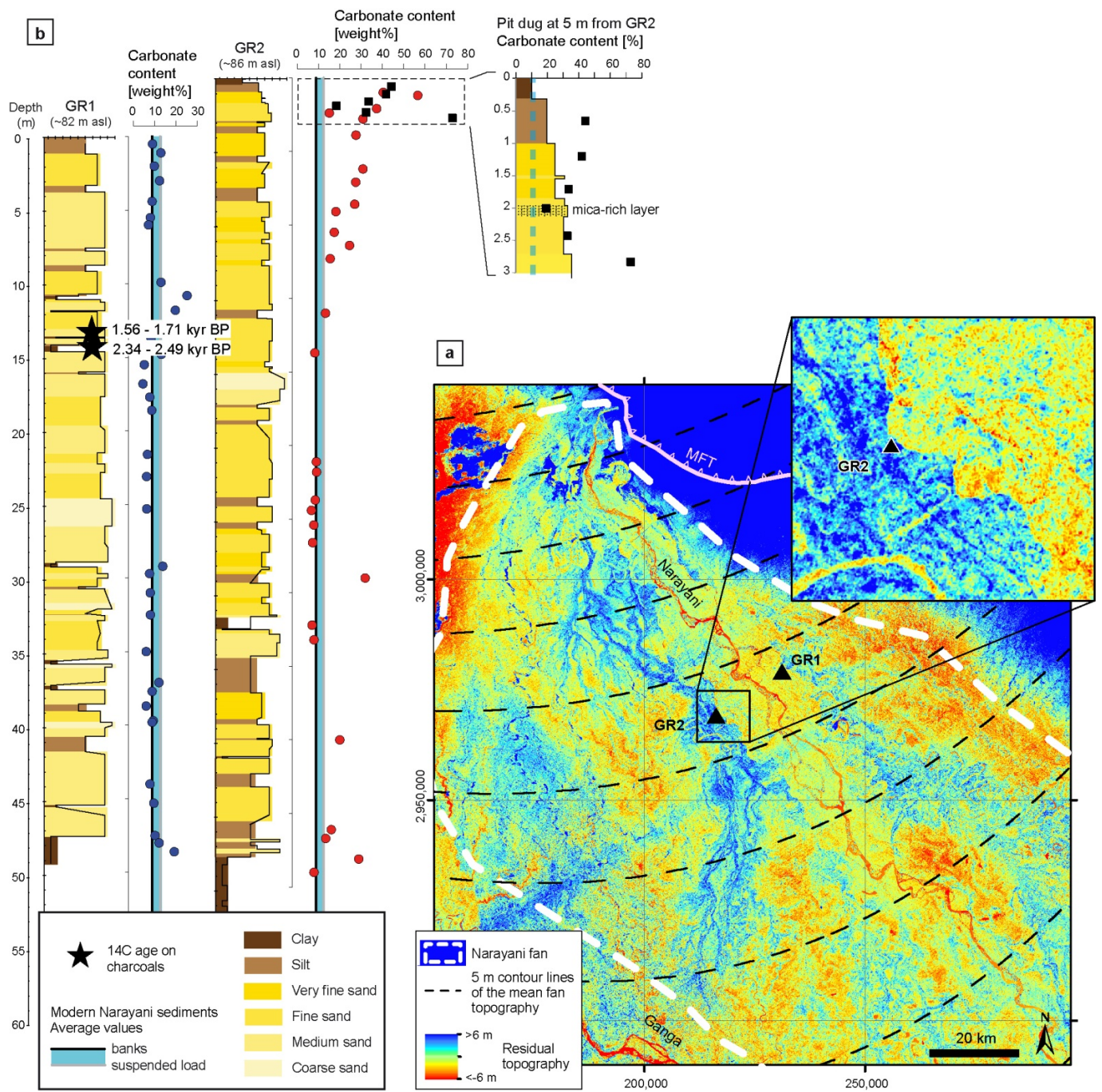


Extended data figure 8



Extended data figure 9





Extended data figure 10

1011 **Data availability:**  
1012 All data used in this study are from the published literature as referenced<sup>36-38</sup>, or presented in Sup.  
1013 Info. tables SI-10-1,2 , SI-11-1,2,3 , SI-12-1,2 and SI-13-1.  
1014

1015 **Code availability:**  
1016 To calculate minimal SF maps and reconstruct Annapurna IV paleo-topography, as shown in  
1017 Extended Data Figs. 8-9, we wrote two original codes in MATLAB, described in the Methods. The  
1018 two codes are available from the corresponding author upon reasonable request.  
1019  
1020

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1031 ASTER national facility (Cerege (CNRS, Univ Aix Marseille)) for the <sup>36</sup>Cl AMS results.  
1032  
1033

1034 **Author contributions:** J.L. designed the study, conducted the modelling and wrote the manuscript,  
1035 J.L. and A.G. collected observations and samples, C.G. realized the DTM, P.G.V. the IRSL  
1036 measurements, V.Gu. and L.B. the <sup>36</sup>Cl measurements, C.M., JP.D. and V.Ga. conducted the <sup>14</sup>C  
1037 measurements, and T.R., C.F-L., G.M. and J.L. handled the carbonate data and core drilling in the  
1038 Ganga plain. P.G.V., C.F.L. and V.Ga. actively participated in the manuscript polishing.  
1039

1040 **Competing interests:** The authors declare no competing interests.

1041 **Supplementary Information is available for this paper.**

1042 **Correspondence and requests for materials should be addressed to J. Lavé.**  
1043

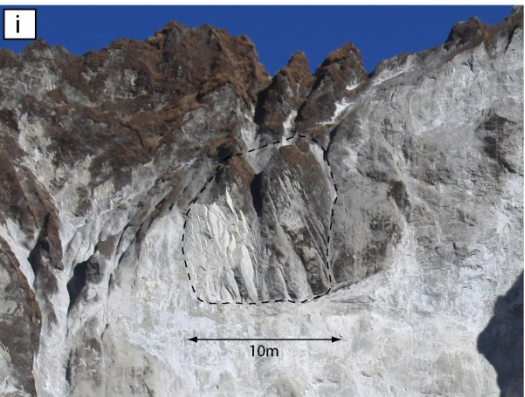
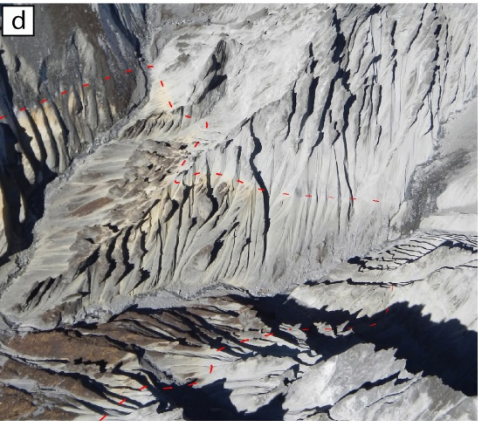
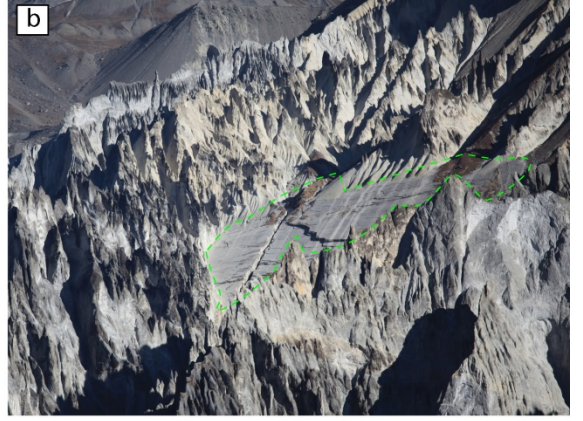
## Supplementary Information

### SI-1: The breccia deposits of the Sabche cirque.

#### Figure SI-1-1: Additional sedimentologic description of the breccia deposit in Sabche cirque.

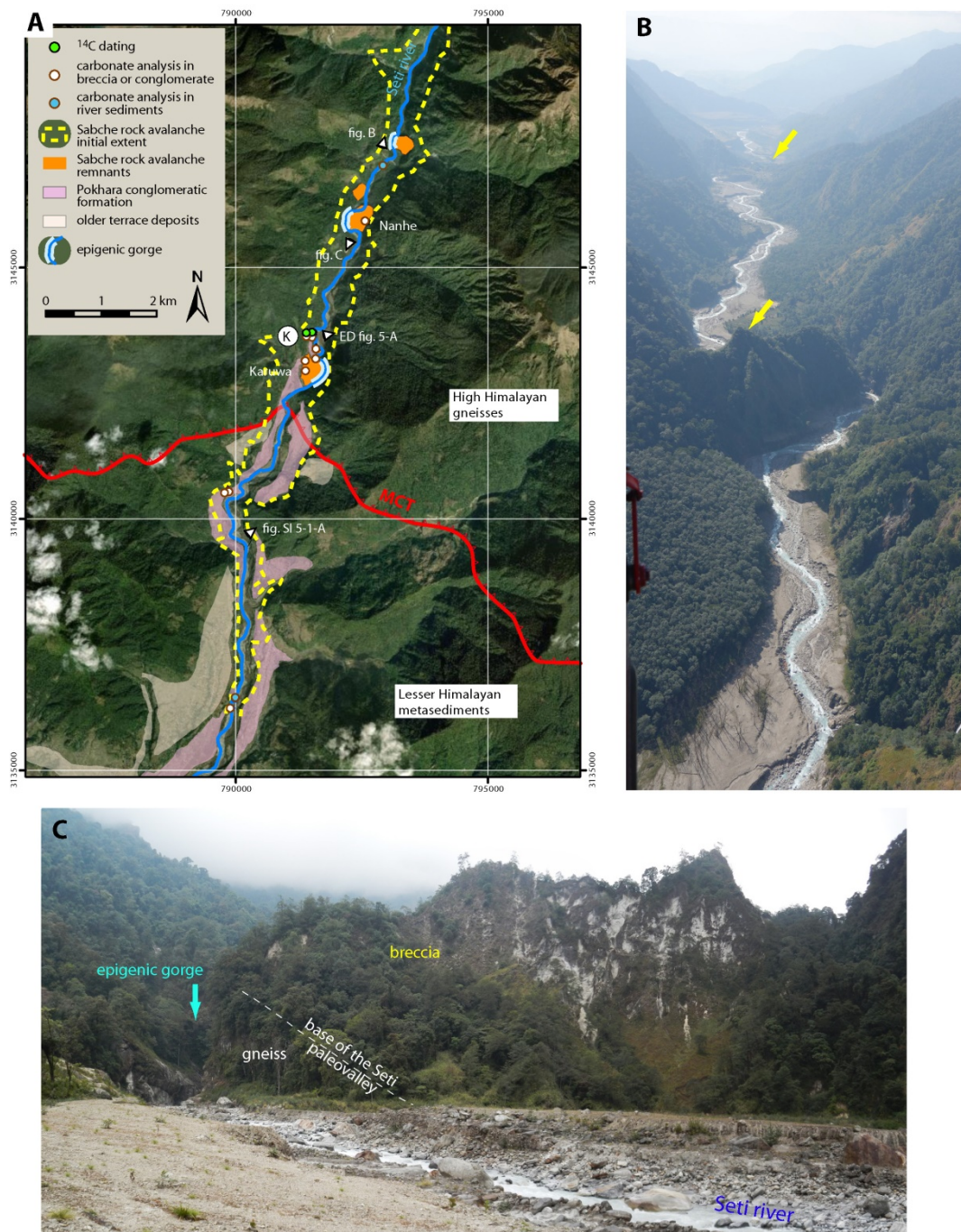
- (a) Aerial view of the Sabche cirque towards the north west with, in the background, the Annapurna III summit and the ridge between the Annapurna Sanctuary cirque and the Sabche cirque, made up of the Annapurna Yellow Limestone formation<sup>28</sup>. The breccia of the rock avalanche depositions is visible on a large area of highly dissected landforms.
- (b) Outcropping contact between the underlying bedrock and the breccia deposit (green dashed line).
- (c) Compact, homogeneous, pulverized and indurated fine grained breccia exposed over the cliff of a steep penitent.
- (d) Internal contact between yellowish and greyish breccia facies in the central part of the deposit, as observed from above and suggesting limited mixing during the rockslide collapse;
- (e) and (f) Coarse and blocky material close to the top, displaying reverse granular grading.
- (g) and (h) Contacts close to the southern base of the cirque deposit: the yellow arrow indicates a contact between yellowish and whitish breccia facies with a larger proportion of coarse elements embedded in the matrix of the yellowish facies; the red arrows highlight the shearing contact where thin band of shearing and micro-crushing were sampled for IRSL analysis (CA-13-283 is located in between the two arrows pointing toward the right).
- (i) Zoom in on a rare ten-metre block of layered marly limestone (outlined by the black dashed line), within the breccia, in the basal part of the deposit.
- (j) and (k) Characteristic matrix of the breccia deposit with millimetre (j) to centimetre (k) fragments

Photos (a) to (f) = taken from an ultra-light aeroplane or from helicopter.



## SI-2: Remnants of granular flow avalanche deposit in the upper Seti valley.

Along the upper Seti, few remnants of the Sabche rock avalanche deposit are preserved along the valley walls or as isolated >200-m-high massive spurs remnants (figure SI-2-1). The preservation of the spurs is closely linked to the pinning of the very dynamic Seti River by epigenetic gorges carved into the gneisses of the High Himalayan Crystalline units. These epigenetic gorges have been interpreted as resulting from local landslides deposits<sup>36</sup>. However, the fine and whitish brecciated material, rich in carbonates, as well as the absence of gneissic elements, except at the contact of the wall of the valley, indicate without any ambiguity an origin located in the cirque of Sabche.



**Figure SI-2-1:** A. Map of the main remnants of the Sabche rock avalanche deposit along the upper Seti. B. Aerial view (looking southward) of the upper Seti showing two major breccia spurs associated to epigenetic gorges at Nanhe (yellow arrow in the foreground) and Karuwa hill (yellow arrow in the background). C. Picture of the south face of the breccia spur at Nanhe.

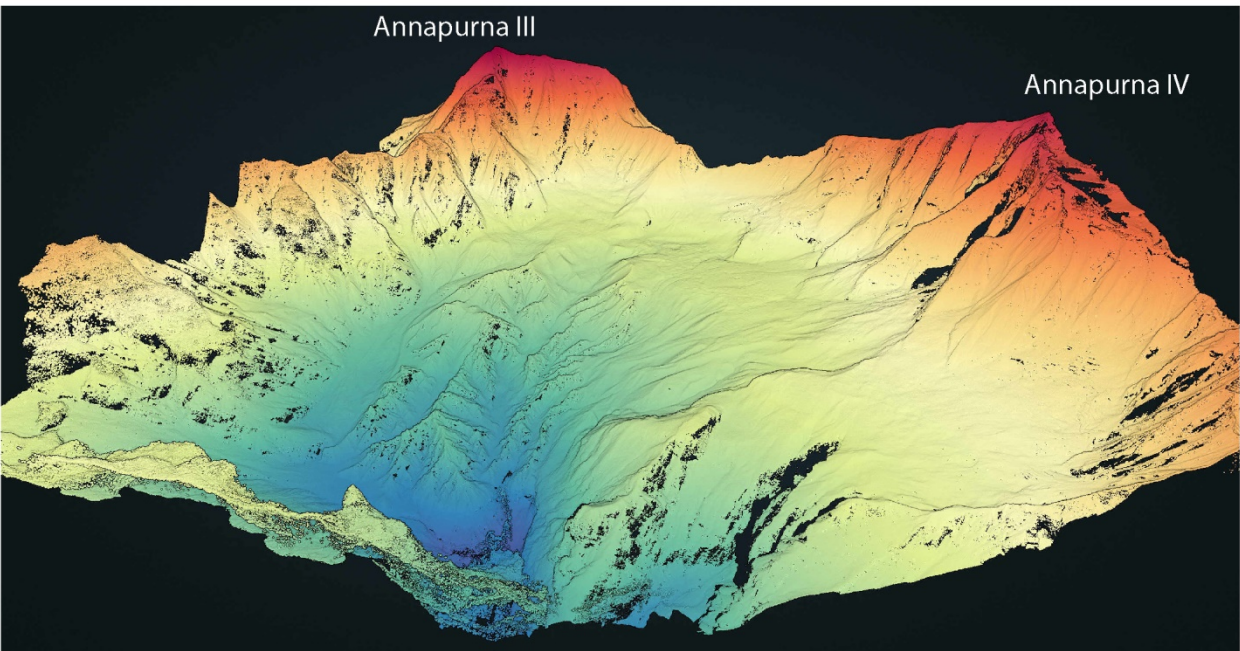
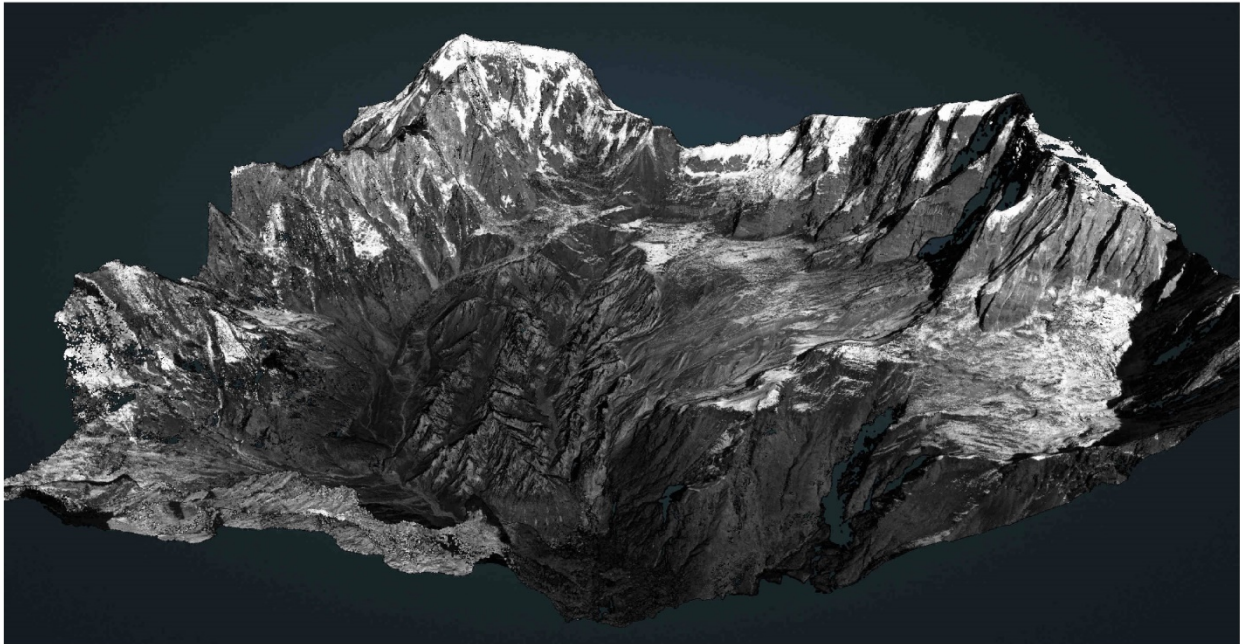
### **SI-3: Digital Terrain Model realization**

A high-resolution DTM (Digital Terrain Model) (fig. SI-3-1) has been computed from Pleiades tri-stereoscopic panchromatic images acquired on December 12, 2014 and November 19, 2015 at ~0.5 m spatial resolution.

The DTMs have been calculated through an automatic pipeline which performed the data co-registration and the DTM generation as described in (Guerin, 2017). The data co-registration is realized as a pre-processing step in order to ensure that the images (and hence the DTM) are finely registered between each other's. This operation consists in a bundle-block adjustment of all the data available that can be performed without any Ground Control Points (GCP).

Once the registration is performed, the DTMs are generated at each date according to the methodology described in (Guérin, 2017) and based on the so-called ground space image matching, performed with the open source software MICMAC, developed by the IGN (French Geographic Institute) (Pierrot-Deseilligny, 2006). This methodology enables the calculation of an elevation value for each point on a grid defined on the ground with a determined planimetric and an altimetric step. Thus, for each ground point of the grid, the images coordinates are obtained according to the refined acquisition models of the images that links the ground position of the point and its coordinates on the images. A correlation score is then computed between the pixels windows selected over each image and at each altitude of the grid. The final altitude value is chosen considering the correlation score and a regularization term. Figure SI-3-1 represents the final DTM generated from the Pleiades tri-stereoscopic images. For this study, both DTM have been generated at a 1 m planimetric and altimetric step and resampled to 50 m for the need of the study.

Cloudy areas partially affect the summits and crests surrounding the southern and western parts of the cirque. In those areas, the DTM was complemented from digitized 1/50,000 topographic maps (40 m contour elevation). However, the breccia deposit and the failure surface of the rockslide in the central and north-eastern part of the cirque respectively are well resolved, and well adapted for reconstructing the initial volume of the deposit, measuring bedding dip of structural cliffs or for the calculation of the transverse curvature.



**Figure SI-3-1:** 2 m *Tri-stereo DTM* (lower), before holes filling and cloud corrections, and panchromatic 0.5 m Pleiade image draped on top of the DTM (upper).

#### SI-4: The geometry of the initial surface

To reconstruct the initial upper surface of the landslide deposit, we can first rely on a few remnants in the northern part of the cirque (Fig. 1c, Extended Data Fig. 4b and 5a) and on the constraints given by the breccias outcropping on the crest that borders the southern flank of the cirque (Extended Data Fig. 2f). These surfaces are all located at an altitude of  $\sim 4,600$  m. However, they are not sufficient to constrain the geometry of the deposit surface in its central part, and the remnants of uneroded breccias forming the steep penitents in the centre of the cirque provide only a minimum elevation (fig. SI-4-1c).

To try to constrain this surface, it is possible to refer to the geometry generally observed for rockslides and rock avalanches. Depending on the fall height, basal friction, degree of internal fragmentation, or the morphology of the valley, a rock avalanche can travel a variable distance. If an avalanche is unimpeded, it is generally characterised by a thickness and surface elevation that decreases downstream. On the other hand, in the case of frontal confinement by a relief that hinders the avalanche flow, depending on its residual kinetic energy, the avalanche can go up the slope (runup), and the final deposit can be characterised by an inverse topographic gradient (e.g. Aaron and Scott McDougall, 2019). The most commonly used parameters characterizing the geometry of rock avalanche deposit and the avalanche mobility are the runout distance and the ratio of the fall height over the runout distance. These parameters have been extensively documented in the past, whether or not differentiating the type of flow confinement (e.g. Strom et al., 2019). In contrast, the shape of rock avalanche deposits has been much less parametrically described.

The case of the Sabche cirque is quite uncommon since the avalanche was confined both frontally and laterally, despite the fact it could overflow the  $\sim 4,600$ -m-high E-W crest in the southern part and also find a lateral exit through the Upper Seti gorges. In the absence of other well-documented examples of a collapse with such a configuration, we consider frontally confined collapses as the closest analogous and compare with a set of 8 giant collapses. Disregarding numerous secondary depressions and ridges that can exceed 100m in amplitude, the average geometry of these deposits shows 3 end members: a classically decreasing elevation gradient (schematic case A on fig. SI-4-1a, and natural cases 3, 4 and 8 on fig. SI-4-1-b), a uniform elevation surface (schematic case B on fig. SI-4-1a, and natural cases 1, 5 and 6 on fig. SI-4-1-b), and an inverted gradient with a strong runup (schematic case C on fig. SI-4-1a, and natural cases 3, 4 and 8 on fig. SI-4-1-b). Transversely, all deposits are characterised by a convex shape (Fig. SI-4-1-b) with a more or less flattened central part (respectively schematic cases E and D on fig. SI-4-1a).

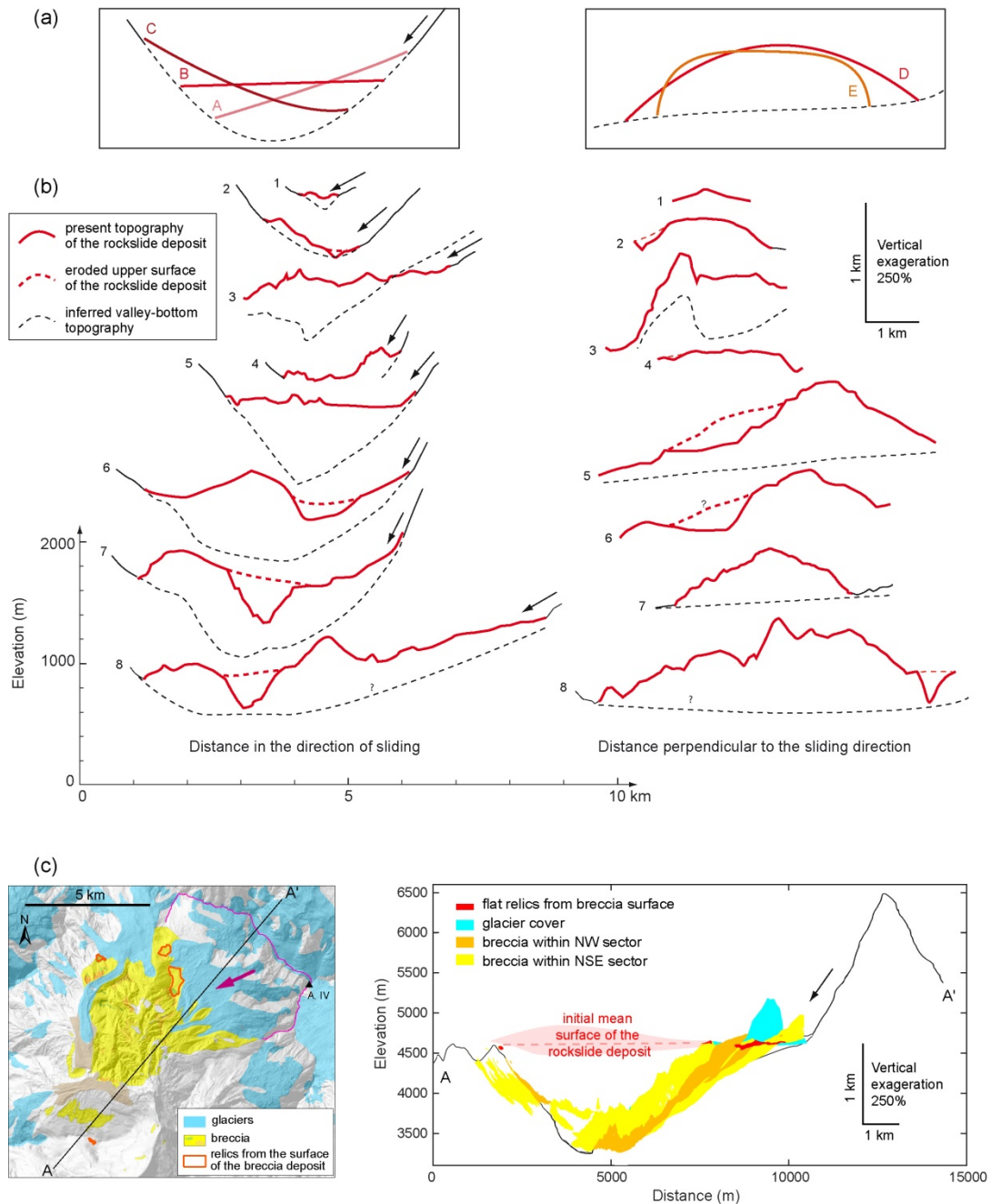
The comparison with frontally confined collapses suggests that the presence of a depression in the centre of the deposit is very unlikely. Longitudinally, irrespective of the type of surface deposit geometry (type A, B or C), the centre of the deposit would be expected to be either higher than the SW edge (type A) or higher than the NE edge (type C). In addition, the flat surface remnants in the northern part of the cirque (red spots on Fig. SI-4-1c) display a fairly horizontal surface without any slope in either direction. Transversely, even if the 8 collapses presented in Table SI-4-1 and Fig. SI-4-1b are not subject to lateral confinement, a maximum elevation in the centre of the cirque with a more or less convex shape is expected. The centre of the deposit was therefore likely  $\geq 4,600$  m. The present position of the main glacier of the cirque, originating from Annapurna III, to the NNW, also supports this conclusion: it is strongly deflected along the western wall of the cirque, whereas it should have flowed towards the centre of the cirque if the deposit had been affected by a central depression.

On the basis of the above considerations, and even if one can imagine a possible convex shape in the centre of the deposit and a chaotic surface (secondary depressions and ridges), the simplest hypothesis is to consider that on average the initial surface of the Sabche rock avalanche can be approximated by a sub-horizontal surface at an altitude of  $\sim 4,600$  m. The local geometry at the transition between the cirque and the Upper Seti valley remains however partly unresolved: there the initial surface of the Sabche deposit plunges toward an avalanche valley deposit, the minimum altitude of which can only be estimated from the few remnants plastered on the walls of the Upper Seti gorge (Extended Data fig. 4b and Fig. SI-2-1). Because this zone only concerns a few square kilometres, we estimate that the associated uncertainties remain limited to  $\leq 1$  km<sup>3</sup>. Taking into account this uncertainty as well as the possible variations in altitude of 100 to 200 m linked to an irregular surface (secondary depressions and ridges) or a central convexity, we assume that the uncertainties on the volume of breccia in the cirque related to the over- and under-estimation of the deposit upper surface reaches +2 and -3 km<sup>3</sup> respectively.



Name	Country	n° on fig. SI-4-1b	Latitude (°N)	Longitude (°E)	Estimated volume of the deposit (km <sup>3</sup> )	reference
Baige	China	1	31.08	98.70	0.025	Zhang et al. (2019)
Dukur Pokhari	Nepal	2	28.59	84.19	1	ref. 34
Daguangbao	China	3	31.63	104.12	1.3	Chen et al. (2014)
Ringmo	Nepal	4	29.18	82.94	1.5	Weidinger and Ibetsberger (2000)
Aricota	Peru	5	-17.37	-70.33	2	Delgado et al. (2019)
Kalopani	Nepal	6	28.65	83.59	3	Fort (2000), ref. 34
Kofels	Austria	7	47.11	10.94	4	Zangerl et al. (2021)
Flims	Swiss	8	48.83	9.30	12	Polet and Schneider (2004)

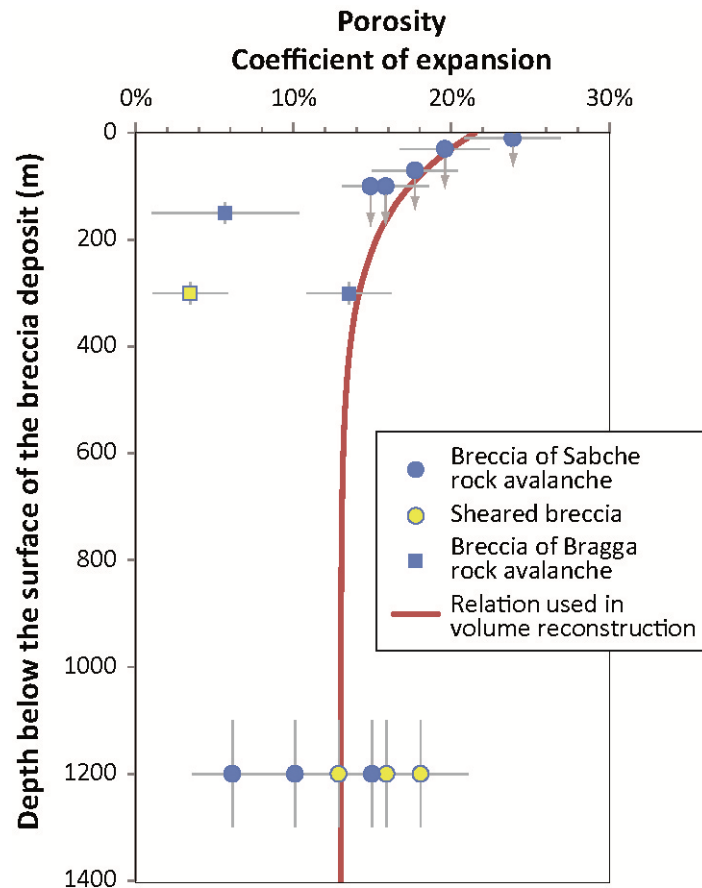
**Table SI-4-1:** Catalogue of the frontally confined rockslides and rock avalanches used in fig. SI-4-1b.



**Figure SI-4-1:** (a) Schematic models of the geometry of rock avalanche deposits. (b) Geometries of various frontally confined rockslides or rock avalanche deposits (see Table SI-4-1). (c) Longitudinal cross section on which all outcrop areas of the Sabche rock avalanche breccias have been projected (orange and yellow areas correspond to areas SE and NW of line AA' shown on the left map), and the hypothesized geometry of the initial surface connecting the northern and southern relics at ~4,600 m.

## SI-5: Coefficient of expansion of the breccia material

In order to derive the volume of solid rock that collapsed from the Annapurna IV ridge, the volume of breccia deposit was corrected from breccia porosity. Porosity measurements made on various samples of breccia taken at different places in Annapurna region were realized by measuring density through weighing of samples plunged into water and Archimede's principle and assuming a rock density of  $\rho = 2.68 \pm 0.06 \text{ g/cm}^3$ , for the Late Cambrian to Silurian TSS rocks. The porosity or expansion rate of the breccia material slightly depends on the burial depth (Fig. SI-5-1). Average value of  $15 \pm 5\%$  was found consistent with previous estimates of 15% made on rock avalanche material<sup>66</sup>.



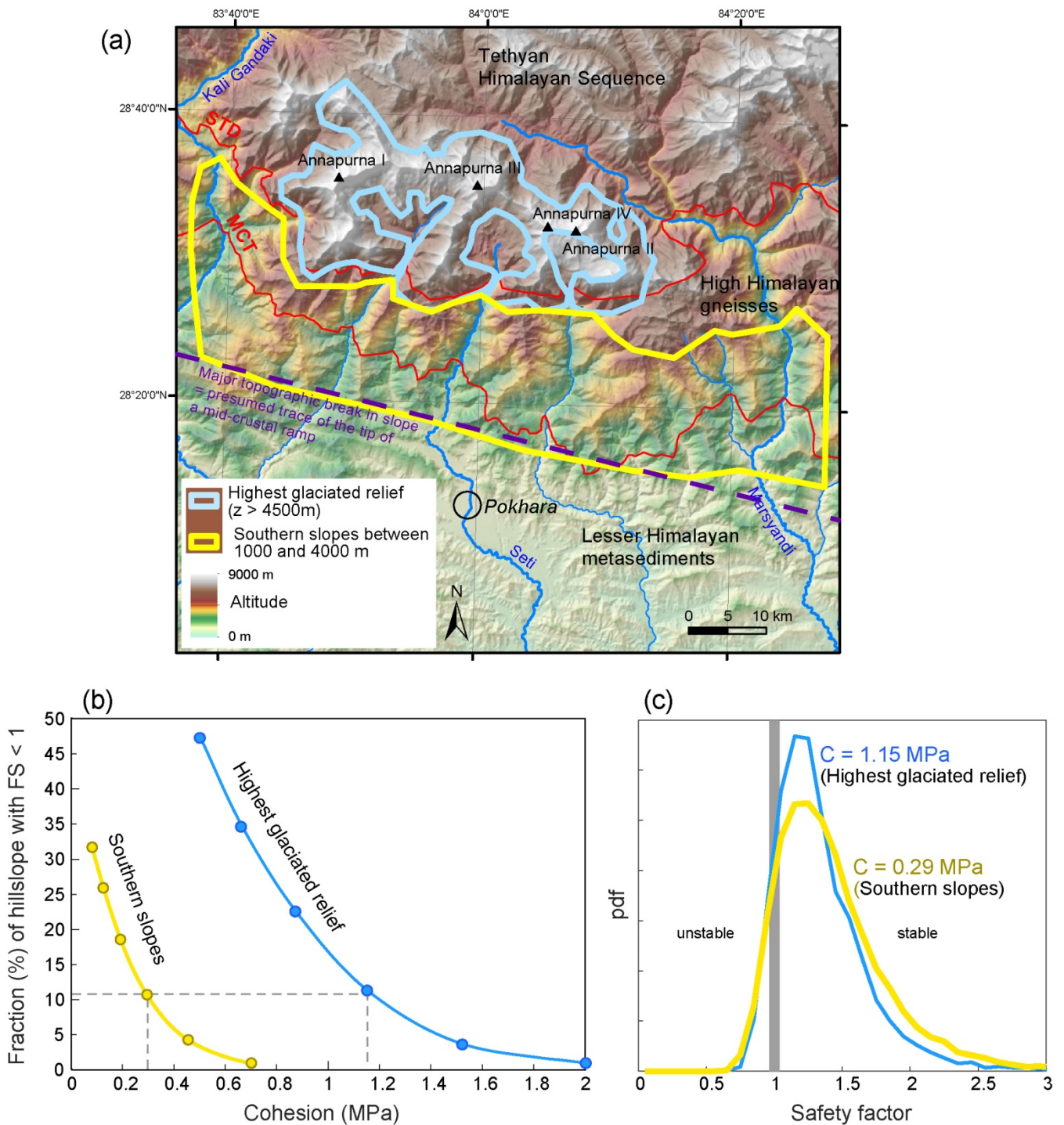
**Figure SI-5-1:** Average curve of the coefficient of expansion of the breccia material vs burial depth, as derived from density measurements made on rock and granular avalanche deposits in Sabche cirque, Upper Seti valley and upper Marsyandi in Bragga area on the northern part of the Annapurna massif.

## SI-6: Cohesion of the unglaciated areas along the southern flank of the High Himalaya

To demonstrate the higher apparent cohesion of the rock mass building the high-altitude peaks of the Annapurna range (Extended Data Fig. 8a), we could compare with values of the literature<sup>47</sup>, derived in unglaciated areas. However, these previous studies in fluvially-dominated regions, which indicate cohesion values generally <0.1 MPa, use a distinct approach and were conducted in a different setting (Longmen Shan characterized by lower tectonic activity than the Himalaya).

In order to provide cohesion values of rock mass in unglaciated, fluvially-dominated Himalayan areas, we applied our method (see Methods and Extended Data Fig. 7) to the landforms south of the Annapurna massif. We defined an area (polygon in yellow color on Fig. SI-6-1a) bounded to the north by elevation < 4,000 m and to the south by a line that follows the major topographic break in slope and river gradient steepening (purple dashed line on Fig. SI-6-1a). Because this southern boundary is assumed to correspond to the top of the Main Himalayan Thrust mid-crustal ramp<sup>25</sup>, this ensures that both glaciated and non-glaciated landforms are analysed in areas affected by similar high uplift rates (~3-4 mm/yr)<sup>25,26</sup>, and that the comparison between both landforms is relevant. Although the influence of the tectonic variable can be ruled out, the influence of the lithology might remain, however, possible: the glaciated zone concerns carbonate sedimentary series, whereas the non-glaciated zone is mainly dominated by gneisses. Nevertheless, the change in slopes with altitude observed in the Everest region<sup>2</sup> have been identified as independent of lithology and suggests that here too lithology might not be a major controlling variable.

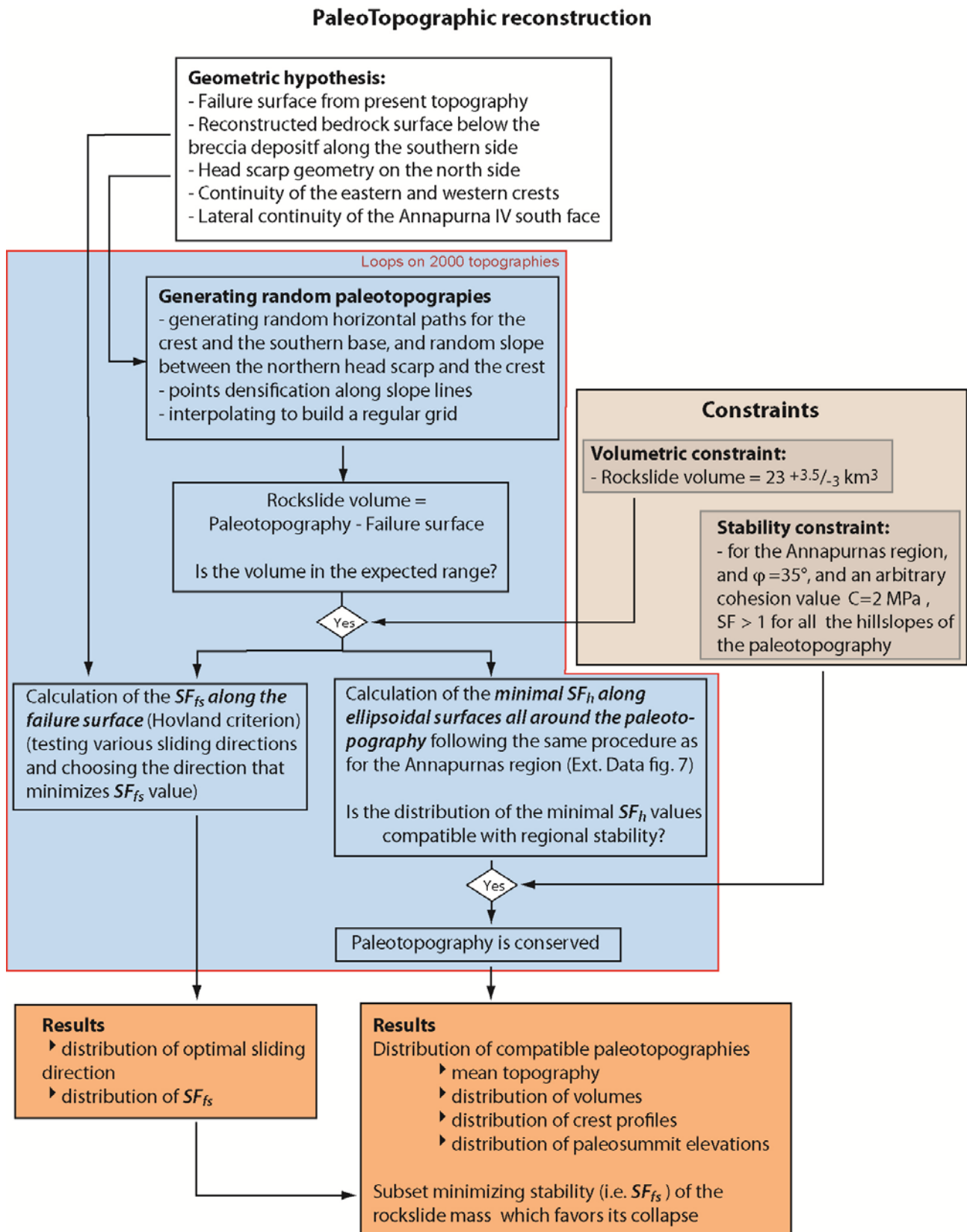
Our analysis shows that the rock mass building the fluvially-dominated landforms has a much lower strength than the glaciated high-altitude ridgelines, with a proportion of unstable slopes much higher whatever the cohesion value explored (Fig. SI-6-1b). As a matter of example, to account for ~90% of stable slopes in fluvially-dominated landforms, the cohesion must be reduced by a factor of 4 (from 1.2 to 0.3 MPa) (Fig. SI-6-1c).



**Figure SI-6-1:** (a) Map of the High Himalaya in the Annapurna region displaying the two distinct areas of fluviably-dominated southern landforms (delineated by a yellow polygon) and highest glaciated landforms (delineated by a blue polygon), in which the systematic searching procedure (Extended Data fig. 7) has been realized using variable cohesion values but a fixed internal angle of friction of  $35^\circ$ . (b) Comparison for these two areas of the fraction of unstable slopes as a function of the imposed cohesion value. (c) Histograms of the values of the SF for values of cohesion  $C = 0.29$  MPa and  $C = 1.15$  MPa that lead to a similar proportion of unstable slopes ( $SF < 1$ ) for the fluviably-dominated southern landforms and the highest glaciated landforms respectively.

## SI-7: Paleotopographic reconstruction

To reconstruct the paleotopography of the collapsed summit, as also explained in the Method section, we have applied the following computing chart:

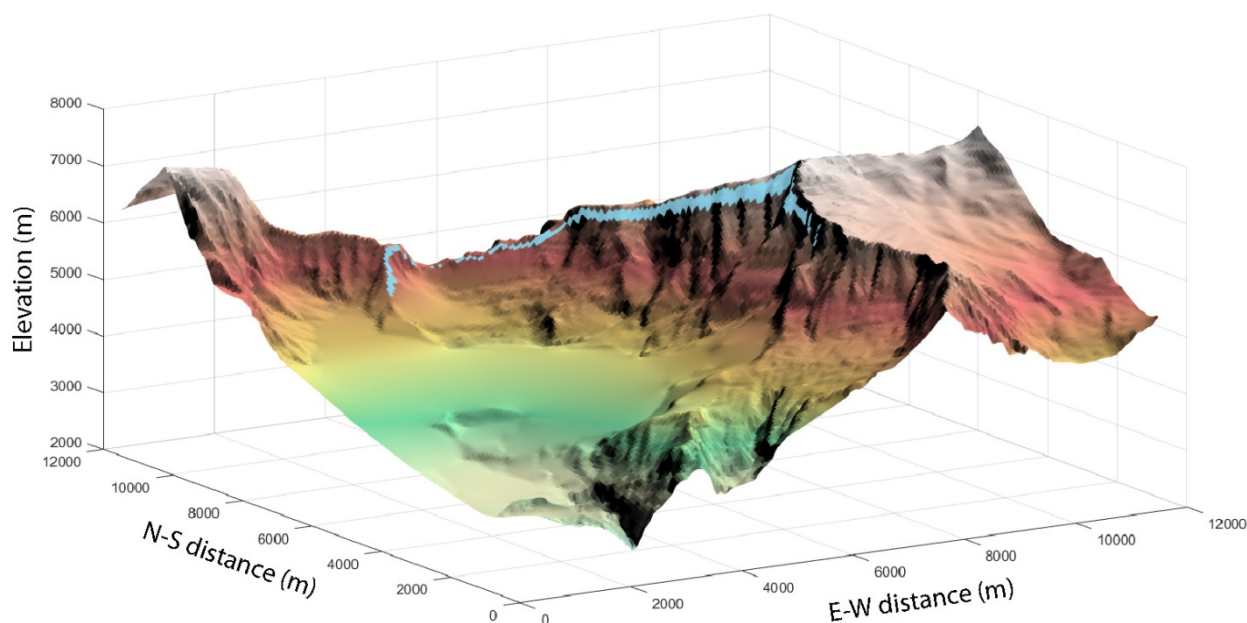


## SI-8: Effects of a rise of the 0°C isotherm within the Annapurna massif at the end of the Medieval Climate Anomaly

The Medieval Climate Anomaly from 900 to 1200AD is characterized in some parts of the Northern Hemisphere by warmer temperatures<sup>43</sup>. Temperature anomalies were presumably maximal north of the Indian sub-continent, at high elevations, and at the end of the 12<sup>th</sup> century (Zhou et al., 2011). In the High Himalaya region, this temperature increase might have exceeded +1°C, inducing a rise of the 0°C isotherm by ~200 m.

Assuming only heat diffusion and an average thermal diffusivity for marly limestone of  $1.4 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ , after 300 yr, this temperature anomaly would have propagated (with an e-fold decrease) ~150 m into the Annapurna massif and caused a fraction of the frozen section of the future failure surface to melt, mainly in its basal part (Fig. 3c).

To estimate this melted fraction, we consider a highly simplified and conservative 1D diffusion thermal model applied to the substrate of the paleo-Annapurna IV. We first estimate the thickness of permanently frozen rock below the surface, i.e. the high altitude permafrost. For that, it is assumed that the topography consists of ~45° slopes, that the 1D (vertical) thermal gradient in the massif substrate is of the order of 25 °C/km, that the atmospheric lapse rate is 6 °C/km and that the 0°C isotherm is located at 5000m. Projected onto the failure surface of the giant rockslide, the model predicts that permafrost affected a portion of about 3 km<sup>2</sup> along the future rupture plane (light blue area in Figure SI-8-1), or 10% of the total failure surface. Next, we diffuse (analytical solution based on the Gauss error function) the assumed medieval climate anomaly (1°C warming for 300 years) into the massif, and calculate the area that has thawed. The melted area would have been ~0.1 km<sup>2</sup>: this would have changed the frozen area of the failure surface by less than 3%, and it would have changed the cohesion of a portion that represents less than 0.3% of the total slip surface. This is a very simplified model which does not take into account the 3D effects of topography, nor the effects of snow or ice cover, but it suggests that the change in cohesion over the entire failure plane is proportionately very small. Unless the massif is close to a critical state or the temporary rise in temperature also affects fluid flow, or pore pressure via a change in the water table, it is likely that the thermal anomaly was not sufficient to trigger the slide.



**Figure SI-8-1:** 3D view of the presumed topography of the giant rockslide sliding surface with the frozen parts in light blue shading.

## SI-9: The Pokhara conglomeratic deposits

### A. Sedimentology of the Pokhara conglomeratic formation in the Pokhara basin

The Pokhara conglomeratic Formation is characterized by a succession of planar metric to multi-metric conglomerate beds ago<sup>30,36</sup>, with different facies (Fig. SI-9-1) and extend from upper Seti (Karuwa = site K of fig.1, down to the mountain front at Narayangad (site N)). All the units are essentially made of angular to sub-angular dark limestone pebbles: the origin of the gravels and pebbles is at >95% of TSS limestone and marly limestone, with a few rare granitic or gneissic pebbles, and whose only possible origin is in the Sabche cirque.



**Figure SI-9-1:** Pictures of some of the typical facies of the Pokhara conglomeratic Formation

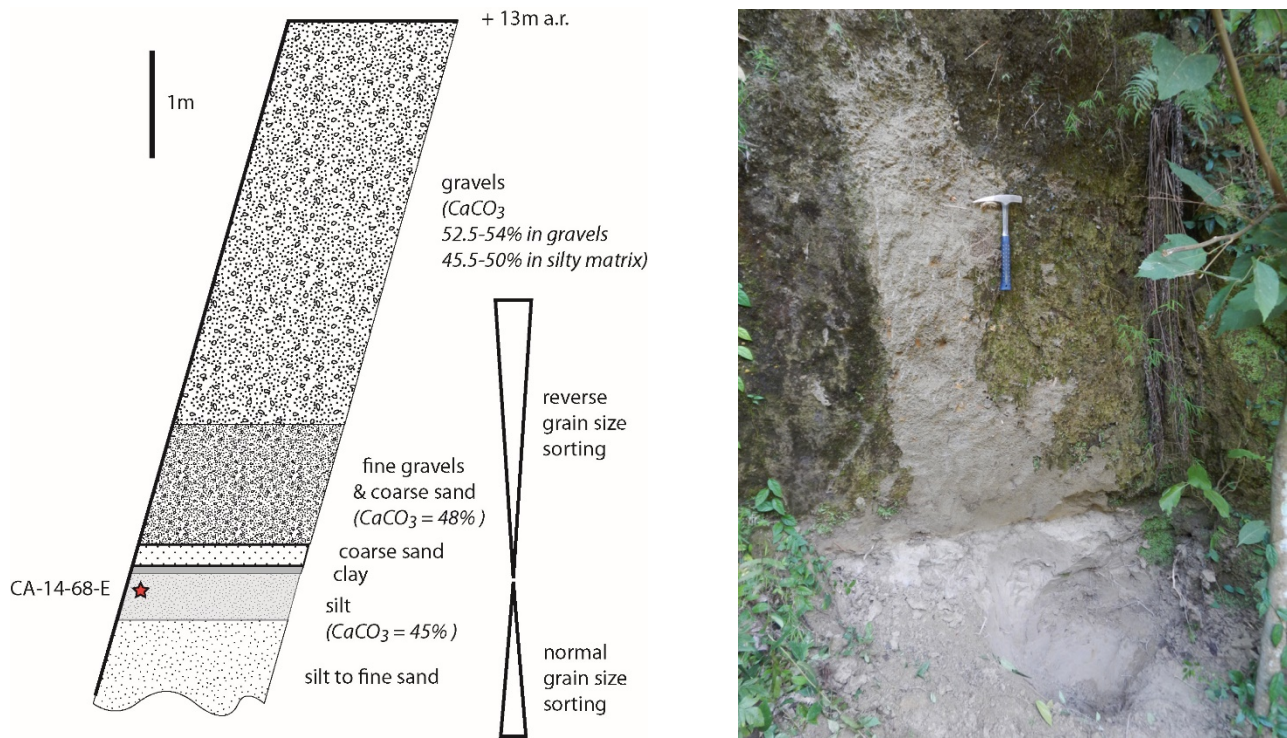
In the center of Pokhara valley, most facies are well stratified conglomeratic alluvium made of alternation of relatively well sorted TSS gravels or pebbles (Figure SI-9-1-b and c) of variable median size ( $0.5\text{cm} < D_{50} < 5\text{cm}$ ). The clasts are subangular to subrounded and are commonly imbricated (Figure SI-9-1-d). The contacts between the layers are mostly planar, without presenting any major unconformity surfaces, except at a few places where small channel reincision by a few meters can be observed (Figure SI-9-1-e). If typical proximal debris-flow units with poorly sorted and matrix-supported material were not observed in the Pokhara basin, layers made of unsorted homometric material (Figure SI-9-1-f), clast- to matrix-supported, suggest clast transport by competent or hyperconcentrated flows. Even in its upstream part (Figure SI-9-1-a), south of Karuwa, a majority of the facies correspond to dominant stratified alluvium, interlayered with a minority of debris-flow-like units. The sorting increases downstream both in the clast and matrix-supported facies.

We interpret these planar conglomeratic units to reflect rapid aggradation during turbulent, sediment-laden flows, with successions of debris floods, sheet and hyperconcentrated flows (Blair and McPherson, 2009), and alluvial reworking. The dominance of sediment-laden or hyperconcentrated require an initial sediment source reach in fine fraction. Finally, it has to be noted that the clasts as well the silty matrix of the conglomerate units display carbonate content very similar to the average material of the Sabche rockslide breccia (fig. 4).

## **B. Narayangad terrace**

The Pokhara conglomeratic formation can be tracked at least down to the Himalayan front, just north of the city of Narayangad (see loc. "N" on fig. 1). There, the remnant of a peculiar fill deposit observed at a few meters above the present river on the left bank of the Narayani river in a somehow sheltered environment. This unit contrasts strongly with the other terrace deposits of the Narayani at that place as much on the level of its much finer granulometry as on the level of its composition much richer in carbonates. This unit presents two sequences of opposite grading but with constant  $\text{CaCO}_3$  content (Figure SI-9-2),: a basal unit with normal grading unit terminated by very fine silts is overlain in continuity by an inverse grading sequence that ranges from coarse sand to gravel clast-supported conglomerates made of small subangular, sorted, but unstratified, dark limestone gravels of similar composition as Pokhara conglomerates. We interpret such particular stratigraphic order as a deposition first of a suspended sediment laden front, likely generated just in front of the rock-avalanche, followed by aggradation of the fine pebble load that travelled more slowly as a debris or dense flow. Nevertheless the scarcity of these remnants of units indicates that after the deposition of the sequence, the Narayani river was able to recover rapidly and to wash its banks of these ~10-15 m deposits of fine conglomerates, except very locally. A microscopic charcoal or organic debris (C14-68-E) was found at the middle of the silty sequence, and is synchronous of the upper Seti rock avalanche and onset of the filling of Pokhara basin (fig. 2b).





**Figure SI-9-2:** Micro-conglomerate deposit north of Narayangad (site N on fig.1)

### C: Volume of deposited Pokhara type sediments

The volume of conglomerates in the Pokhara and upper Seti valley was estimated to reach  $\sim 5$  to  $\sim 7$   $\text{km}^3$  (refs. 30, 36) over a distance of 70 km. Further downstream, the volume of deposited Pokhara sediment was estimated by considering the present geometry of the valley and a sediment filling assuming a linearly decreasing thickness from Pokhara to the Gangetic plain, based on our field measurements: 60 m in the southern Pokhara basin, 20 m at the confluence of the Seti with the Trisuli, 13 m at Narayangad (site “N” on fig. 1b), and 3-5 m at the GR2 borehole (site “G” on fig. 1a). In the Gangetic plain, the long and narrow lobe raised on top of the mega-fan (blue-colored in Extended Data fig.10) was assumed to correspond to the deposition of sediments preferentially derived from the rockslide.

Between the southern part of the Pokhara basin and Naryangad (site “N”), the deposited volume is  $\sim 1$   $\text{km}^3$ . Between Naryangad and the MFT (most frontal thrust), in the Chitwan dun (piggy-back basin), an additional volume of  $\sim 2$   $\text{km}^3$  of fine gravels and sands could have been deposited. Downstream of the MFT, the lobe deposited at the top in the Narayani mega-fan has represents a volume of sediment of  $\sim 6$   $\text{km}^3$  ( $L \times W \times H \approx 120 \text{ km} \times 12 \text{ km} \times 4 \text{ m}$ ). As a whole, 15  $\text{km}^3$  of sediments might have been deposited between Pokhara and the Narayani megafan, that is, considering a porosity of 30% of the sediments,  $\leq 50\%$  of the initial rock volume. The other half was presumably exported further downstream as suspended load like most Himalayan sediments that end up in the Bengal Fan<sup>39</sup>.

It has to be noted that we assume above that the downstream units were not fed by the re-erosion of the upstream conglomerates. The synchronism of the sediment at Narayangad (downstream site “N”) with the initial granular avalanche in the most upstream part supports such hypothesis.

### D: Proportion of Sabche material in the Gandak river after the rockslide

The carbonate-rich lobe of the Narayani fan displays variable carbonate concentration between 30 and 60%, but on average it remains slightly lower than the Sabche breccia and Pokhara conglomerate. This likely arises from mixing with background supply of sediments issued from the whole Narayani catchment.

Considering the average carbonate concentrations of around 55, 40, and 10% for breccia material, sediments in the carbonate-rich lobe of the Narayani fan (upper units of GR2), and mean Narayani sediments (in GR1, lower GR2 cores or sandy fraction of modern sediments) respectively, it is shown that the carbonate-rich lobe of the Narayani was corresponding to the mixing of two volumes of Sabche debris and one volume of background Narayani sediments. Following the Annapurna IV collapse, the input of Sabche

material would have tripled the Narayani sediment flux compared to average values. In order to evacuate  $\sim 15 \text{ km}^3$  (the total rockslide volume minus the breccia remaining in the Sabche cirque and the deposited part along the middle and lower Seti respectively) of breccia material out of the mountain range at Narayangad, such a situation could have persisted  $\sim 150 \text{ yr}$ , which seems to confirm accelerated erosion of the Sabche deposit over a period of 100 yr following the summit collapse.

## SI-10: 14C dating of the various organic debris (wood pieces and charcoals) samples of this study

The pdf associated to the mean age for Karuwa and the basal Pokhara conglomerates (Fig. 2) were calculated by computing the uncertainty-weighted average of the 14C raw radiocarbon ages (8 dating for each mean age), before applying the calibration curve of IntCal 13 (ref. 54).

Lab.No	Sample ID	Lat [°N]	Lon [°E]	Elevation [m asl]	Material	stratigraphic setting	Radiocarbon age [y BP]	Calibrated age
<b>Karuwa debris flow</b>								
SacA-41772	CA-14-59	28° 23.24'	83° 58.51'	1460	wood	base of the granular avalanche breccia	950 ± 30	1085 AD ± 47
SacA-43078	CA-14-58	28° 23.24'	83° 58.51'	1460	wood	base of the granular avalanche breccia	840 ± 30	1199 AD ± 29
SacA-48072	CA-16-5-C	28° 23.24'	83° 58.51'	1460	bark	base of the granular avalanche breccia	830 ± 30	1208 AD ± 30
SacA-46539	CA-16-5-D	28° 23.24'	83° 58.51'	1460	monocots type stem	base of the granular avalanche breccia	870 ± 30	1139 AD ± 61
SacA-48073	CA-16-5-D	Replicate					895 ± 30	1125 AD ± 52
SacA-48714	CA-16-7	28° 23.25'	83° 58.43'	1530	wood (root)	paleosoil buried by the granular avalanche breccia	835 ± 30	1212 AD ± 30
SacA-46541	CA-16-8-B	28° 23.25'	83° 58.43'	1530	small branch	base of the granular avalanche breccia	935 ± 35	1094 AD ± 48
SacA-48715	CA-16-8-E	28° 23.25'	83° 58.43'	1530	small branch	base of the granular avalanche breccia	825 ± 30	1229 AD ± 22
<b>Pokhara basin</b>								
SacA-41776	CA-13-245	28° 6.62'	84° 7.18'	588	small tree trunk	Paleosoil buried by the Pokhara Fm	740 ± 30	1261 AD ± 15
SacA-41777	CA-13-246	28° 6.64'	84° 7.19'	605	charcoal	Paleosoil buried by the Pokhara Fm	940 ± 30	1090 AD ± 46
SacA-43080	CA-13-246-B	28° 6.64'	84° 7.19'	605	charcoal	Paleosoil buried by the Pokhara Fm	955 ± 30	1082 AD ± 47
SacA-41773	CA-14-63-B	28° 8.05'	84° 5.70'	640	charcoal	Thin sand layer at the top of Pokhara Fm	1940 ± 30	57 AD ± 33
SacA-43079	CA-14-64-A	28° 7.17'	84° 6.31'	612	charcoal	Paleosoil buried by the Pokhara Fm	940 ± 30	1090 AD ± 46
SacA-41774	CA-14-64-B	28° 7.17'	84° 6.31'	612	charcoal	Paleosoil buried by the Pokhara Fm	940 ± 30	1090 AD ± 46
SacA-41775	CA-14-66	28° 5.60'	84° 4.53'	547	charcoal	Paleosoil buried by the Pokhara Fm	3375 ± 35	1678 BC ± 45
SacA-46544	CA-16-27	28° 5.57'	84° 3.89'	549	wood	slackwater deposits at tributary damming	870 ± 30	1139 AD ± 61
<b>Narayangad</b>								
WHOI-133624	CA-14-68E	27°42.83'	84°26.03'	198	Micro-charcoal	Silt layer at the base of fine conglomerates	885 ± 25	1126 AD ± 60

**Table SI-10-1:** Details of the samples of the organic debris found at Karuwa, in Pokhara basin and Narayangad, and dated by 14C AMS dating. Several charcoals, in particular CA-14-63B and CA-14-66 in paleosoils buried by the Pokhara conglomeratic formation, are clearly too old and suggest either long residence time in the soil (CA-14-66) or reworking (CA-14-63B).

SampleID	River	ref.	Latitude	Longitude	Sample elevation	Material	Pokhara Fm top elevation	Elevation of the Seti river	Age (calibrated 14C age AD)		
									mediane (P <sub>50%</sub> )	P <sub>2.5%</sub>	P <sub>97.5%</sub>
			(°N)	(°E)	(m asl)		(m asl)	(m asl)			
BIJ02	Bijaypur	36	28.219	84.029	820	Humic Silt	828	710	1246	1167	1290
PH02C	Phusre	36	28.18	83.968	730	Leaves	773	680	1193	1046	1269
PHUSRE03	Phusre	36	28.183	83.951	740	Charcoal	773	680	1098	1016	1205
SARA1-1	Saraudi	36	28.096	84.029	541	Wood	560	490	1265	1215	1298
MADHI2	Magdi	36	28.015	84.117	495	Charcoal	500	438	1061	990	1155
<b>PH6</b>	Phusre	36	28.175	83.976	703	Wood	773	680	1160	1038	1224
<b>Phusre010</b>	Phusre	36	28.175	83.982	706	Wood	773	680	1170	1043	1241
<b>Phusre012</b>	Phusre	36	28.175	83.982	698	Leaves	773	680	1232	1169	1270
<b>Phusre013</b>	Phusre	36	28.175	83.982	696	Wood	773	680	1199	1058	1262
<b>Phusre14</b>	Phusre	36	28.175	83.982	701	Charcoal	773	680	1219	1163	1264
PhusreFa	Phusre	36	28.185	83.958	728	Charcoal	773	680	1106	1033	1204
PRE14C1	Phusre	36	28.184	83.934	748	Charcoal	773	680	1347	1298	1410
KBP03	Bijaypur	36	28.218	84.027	825	Wood	828	710	1289	1263	1388
TAL02	Tal	36	28.117	84.105	583	Wood	623	530	1214	1161	1264
TAL05	Tal	36	28.117	84.105	614	Wood	623	530	1099	1025	1165
Anpu02	Anpu	36	28.109	84.116	591	Humic Silt	618	530	1097	1024	1155
KBP02	Bijaypur	37	28.218	84.027	825	Humic Silt	828	710	1176	1045	1250
<b>Phusre11</b>	Phusre	37	28.175	83.982	698	Wood	773	680	1186	1049	1256
Tal01	Tal	37	28.117	84.105	585	Humic Silt	623	530	1224	1165	1265
14CANpu11	Anpu	37	28.108	84.114	590	Charcoal	618	530	1099	1025	1165
<b>14CANpu01</b>	Anpu	37	28.111	84.105	556	Leaves	618	530	1186	1049	1256
14CANpu16	Anpu	37	28.11	84.12	592	Charcoal	618	530	1214	1161	1264
BIJ03	Bijaypur	37	28.219	84.029	820	Humic Silt	828	710	1299	1270	1390
<b>Ph6u_14C</b>	Phusre	37	28.176	83.977	704	Wood	773	680	1113	1037	1207
EBGcc01	Anpu	37	28.111	84.12	609	Charcoal	618	530	698	656	769
PhTree1	Phusre	38	28.183	83.953	725	tree trunk	773	680	1232	1169	1270
PhTree2	Phusre	38	28.183	83.953	725	tree trunk	773	680	1272	1223	1295
AnpuTrib	Anpu	38	28.118	84.105	587	tree trunk	623	530	1209	1157	1264
AnpuTree1	Anpu	38	28.111	84.12	601	tree trunk	618	530	1242	1190	1279
AnpuTree2	Anpu	38	28.11	84.122	608	tree trunk	618	530	1240	1189	1277
AnpuTree3	Anpu	38	28.111	84.121	591	tree trunk	618	530	1228	1168	1266
AnpuTree4	Anpu	38	28.111	84.121	591	tree trunk	618	530	1199	1058	1262
AnpuTree5	Anpu	38	28.11	84.12	592	tree trunk	618	530	1224	1165	1265
CA-14-63-B	upper Begnas	this study	28.1342	84.0950	640	charcoal in sand lense	640	560	62	-20	130
CA-14-64-A	Rupa	this study	28.1195	84.1052	612	charcoal in paleosoil	623	532	1098	1025	1160
CA-14-64-B	Rupa	this study	28.1195	84.1052	612	charcoal in paleosoil	623	532	1098	1025	1160
CA-14-66	Seti Majuwa	this study	28.0933	84.0755	547	charcoal in paleosoil	585	507	-1669	-1753	-1549
CA-13-245	Anpu	this study	28.1103	84.1197	588	small tree trunk base	618	530	1270	1224	1291
CA-13-246	Anpu	this study	28.1107	84.1198	605	charcoal in paleosoil	618	530	1098	1025	1160
CA-13-246B	Anpu	this study	28.1107	84.1198	605	charcoal in paleosoil	618	530	1096	1022	1155
CA-16-27	Rudi	this study	28.0929	84.0649	549	wood	580	500	1176	1045	1250

**Table SI-10-2: Published 14C dating (dated by AMS) of the various organic debris samples of the Pokhara conglomeratic formation, including their location and their elevation as well as that of the Seti and the top of the Pokhara formation used in fig.2b. The sample names in bold correspond to the most basal ones, used in fig.2a.**



**Table SI-11-2:** Sample information, AMS measurement results, and calculated  $^{36}\text{Cl}$  and chlorine concentrations and concentration of Ca measured at ICP-AES (inductively coupled plasma atomic emission spectrometry). Exposure ages calculated with Online Chronus Calculator ([http://hess.ess.washington.edu/math/index\\_dev.html](http://hess.ess.washington.edu/math/index_dev.html)). Reported analytical uncertainties include uncertainties in AMS counting statistics, the isotopic ratios of the standards, and on the blank chemical measurements, an external AMS error of 0.5% (Arnold et al., 2010), and the uncertainties associated with the cosmogenic nuclide half-lives. External uncertainties include the uncertainties associated with the cosmogenic nuclide production rates, the sample thickness, the estimated surface and snow shielding.

Sample Name	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	H <sub>2</sub> O	Cl	B	Sm	Gd	U	Th	Cr	Li
	%	%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
CA13-260	9.65	0.09	1.80	0.76	0.01	2.36	45.49	0.41	0.51	0.43	10	9	0.92	0.75	0.69	2.60	4.3	5.2
CA13-261	31.12	0.26	4.79	0.89	0.02	2.09	31.64	1.11	1.16	0.79	10	22	2.07	1.71	1.49	8.13	15.3	12.8
CA13-262	13.70	0.13	2.52	0.81	0.02	2.53	42.45	0.65	0.70	0.49	10	12	1.60	1.29	0.84	3.66	7.2	6.2
CA13-263	15.83	0.19	3.60	1.00	0.02	2.65	40.65	0.58	1.12	0.61	10	17	2.45	1.95	0.81	5.22	14.5	11.3
CA13-264	15.62	0.19	3.70	1.18	0.02	1.80	41.05	0.55	1.03	0.65	10	36	2.13	1.80	0.70	5.54	16.5	9.8
CA13-265	45.41	0.44	8.57	2.84	0.03	3.03	19.02	1.21	2.58	1.31	25	46	4.21	3.49	1.55	11.9	33.2	23

**Table SI-11-3:** Bulk rocks geochemical composition of the 6 blocks sampled at the top of the relic surface of the rockslide deposit: Major and trace elements composition measured by ICP-MS (SARM, CRPG).

## SI-12: Infra-red stimulated luminescence (IRSL) measurements and results on sheared breccia deposits

Breccia samples were first sawed in subdued light conditions to remove the exposed outer rock surfaces. Samples were then dissolved in HCl, and the silicate fraction was treated using H<sub>2</sub>O<sub>2</sub> (30%) and sieved to coarse sand fraction before density separation with LST to isolate K-feldspar fraction (d<2.58). K-feldspar separates were settled on 10-mm diameter stainless steel discs for subsequent luminescence analyses. About 50 g of bulk sample was saved (external breccia surface) and sent to Actlabs or SARM-CRPG for ICP analysis to quantify U, Th and K contents (Table SI-8-1). Final dose rate determination, using grain size range and estimated water content, were obtained through the Dose Rate and Age Calculator<sup>59</sup> (DRAC).

All conventional luminescence measurements were carried out using TL/OSLDA-20 Risø readers, equipped with a calibrated <sup>90</sup>Sr/<sup>90</sup>Y beta source (reader dose rate ~0.1Gy/s; Institute of Earth Surface Dynamics, University of Lausanne, Switzerland). Luminescence signals were detected using an EMI 9235QA photomultiplier tube, in the blue region through a Schott BG-39 filter for IRSL measurements. We used the post-IR IRSL protocol<sup>60</sup>, applying first a preheat treatment at 250°C for 60s before a single-aliquot regenerative-dose (SAR) protocol (Murray & Wintle 2000) with a first IRSL stimulation at 50 °C (100 s, IR50) followed by a second IRSL stimulation at 225 °C (100 s, pIR225). For all the samples, residual doses and dose recovery ratios were quantified. Dose–response curves were constructed using an exponential+linear fitting (with recycling ratios within 15% of unity and recuperation within 10% of the natural dose were used as acceptance criteria for the single-aliquot data).

We used the Luminescence R package (Kreutzer et al. 2012) to quantify the Central Age Model (CAM) for all samples<sup>61</sup>, and based on the overdispersion in De distributions we also calculated a Minimum Age Model (MAM) for sample CA-13-283 (ref. 61). Fading rates (g<sub>2days</sub>) were measured following Auclair et al. (2003) (Figure SI-12-1). Final fading-corrected ages were calculated following ref. 62 fading correction procedure (Table SI-12-2).

Sample	Coordinates (WGS84, °N/°E, and elevation, m a.s.l.)	Radionuclide concentration <sup>1</sup>			Grain size range <sup>2</sup> (µm)	Total dose rate <sup>3</sup> (Gy ka <sup>-1</sup> )
		U (ppm)	Th (ppm)	K (%)		
CA-13-273	28.5058; 84.0001 3410	1.69±0.06	10.8±0.38	1.82±0.06	90-180	3.83±0.21
CA-13-274	28.5058; 84.0001 3410	1.64±0.06	10.3±0.36	1.90±0.07	90-180	3.85±0.21
CA-13-283	28.5055; 83.9999 3405	2.15±0.08	12.6±0.44	2.04±0.07	180-250	4.39±0.17

**Table SI-12-1.** Details of dose-rate calculations for IRSL dating.

Samples were collected at the base of the breccia deposit (see Extended Data Figs. 2 and 6) but this was rapidly incised after deposition. To account for this, a 0.25 Gy dose has been subtracted for post-deposition exposure to cosmic rays.

<sup>1</sup>Radionuclide concentrations were quantified on bulk samples using ICP at Actlabs (CA-13-273/-274) and at SARM-CRPG (CA-13-283).

<sup>2</sup>Coarse-grain fraction of 90-180 µm was isolated for samples CA-13-273 and CA-13-274, and of 180-250 µm for CA-13-283, to ensure material abundance for IRSL measurements.

<sup>3</sup>Dose rate calculations were performed with DRAC<sup>59</sup>, assuming water content of 2±2%, an internal K-content of 12.5±0.5% (Huntley and Baril, 1997) and an alpha efficiency value of 0.15±0.05 (Balescu and Lamothe, 1994).

Sample (aliquots)	Signal	Dose recovery ratio <sup>1</sup>	residuals <sup>1</sup> (Gy)	CAM <sup>2</sup> uncorrected D <sub>e</sub> (Gy)	OD <sup>2</sup> (%)	MAM <sup>3</sup> uncorrected D <sub>e</sub> (Gy)	Fading <sup>4</sup> g <sub>2days</sub> (%/decade)	CAM or MAM* fading-corrected age (ka)
CA-13-273 (17)	IR50	0.94±0.04	0.57	84.2±9.0	9.2	/	1.40±0.48	31.9±4.3
	pIR225	0.90±0.03	2.27	156.7±25.8	15.0	/	0.58±0.34	34.6±4.1
CA-13-274 (17)	IR50	0.94±0.04	0.57	90.5±8.8	8.0	/	1.47±0.75	64.4±7.4
	pIR225	0.91±0.03	2.26	155.8±26.0	15.3	/	0.63±0.28	48.1±2.5
CA-13-283 (60)	IR50	0.88±0.02	0.25	7.5±2.2	28.7	5.2±0.6	1.37±0.64	1.21±0.23*
	pIR225	0.86±0.02	0.27	8.7±2.9	32.3	6.2±1.0	0.59±0.39	1.50±0.30*

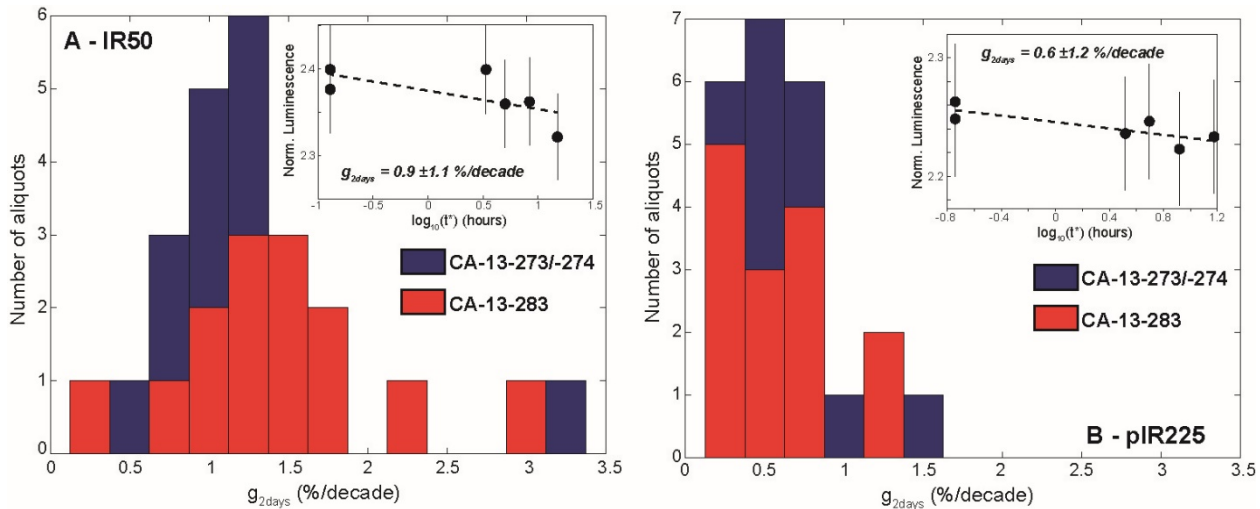
**Table SI-12-2.** IRSL dating of the base of the breccia deposit (see Extended Data Figs. 2d and 6) on small-aliquots, using feldspar infra-red luminescence at 50°C (IR50) and post-infra-red infra-red luminescence at 225°C (pIR225) signals. Analytical details and measurement protocols are given in supplementary text.

<sup>1</sup>Dose recovery ratios have been calculated for each individual sample and using a given dose of 60Gy for 5 aliquots. Residuals have been estimated for 4 aliquots per sample, with an additional 0.25 Gy to account for post-deposition cosmic-ray exposure following rapid breccia incision.

<sup>2</sup>De = Equivalent doses, CAM = Central Age Model, OD = overdispersion of D<sub>e</sub> distribution<sup>61</sup>.

<sup>3</sup>MAM = Minimum Age Model<sup>61</sup> (MAM-3). It was applied for D<sub>e</sub> distributions with OD > 25%, i.e. for sample CA-13-283. Sigma-b ( $\sigma_b$ ) values of 0.085 and 0.152 were used for IR50 and pIR225 signals, respectively, based on OD values for CA-13-273/-274 samples. No MAM was run for CA-13-273/-274, due to the low OD in the D<sub>e</sub> distribution (Fig. SI-12-1).

<sup>4</sup>Fading measurements have been performed on 12-14 aliquots per sample to evaluate the variability in fading rates for IR50 and pIR225 signals (Fig. SI-12-1).



**Fig. SI-12-1.** Fading rate (g<sub>2days</sub> values) distributions for K-feldspar IR50 (A) and pIRIR225 (B) signals. Insets show representative examples of fading measurements. Fading rate distributions illustrate similar behaviour between CA-13-273, -274 and -283.



### SI-13: Carbonate content

Total carbonate (*Table SI-13-1*) content was measured by phosphoric acid dissolution at 70°C on a gas-bench coupled to a MAT253 spectrometer using internal concentration standards. Concentrations are expressed in equivalent CaCO<sub>3</sub> wt% and the overall uncertainty is ± 2% relative.

Sample	Sample Type	Lithology	river / location	Latitude	Longitude	distance from Sabche divide	CaCO <sub>3</sub>
				(°N)	(°E)	(km)	%
<b>Rivers</b>							
<i>Seti &amp; downstream (Trisuli, Narayani)</i>							
HF 10	sand (bank)	sand	Seti Kh. North of Pokhara	28.4200	83.9921	19	56.0
CA-13-232	sand (bank)	sand	Seti Kh. North of Pokhara	28.3219	83.9573	30	29.4
CA-13-233	sand (bank)	silt	Seti Kh. North of Pokhara	28.3219	83.9573	30	48.5
HF 11	sand (bank)	sand	Seti Khola	28.3015	83.9429	36	44.0
LO 313	sand (bank)	sand	Seti Khola	28.1274	84.0836	69.5	44.4
MO 305	Suspended Load	silt	Seti Khola	28.0500	84.0700	78.5	47.0
CA-14-72	sand (bank)	sand	Seti Khola	27.8273	84.4662	142	11.0
LO 303	sand (bank)	sand	Seti Khola	27.8255	84.4635	142	24.7
CA 11133	sand (bank)	sand	Seti Khola	27.8292	84.4667	142	17
CA13-251	sand (bank)	sand	lower Trisuli	27.7564	84.4638	157.3	8.2
CA-14-67	sand (bank)	sand	Narayani	27.7022	84.4262	166.5	9.18
LO 309	sand (bank)	sand	Narayani	27.7020	84.4260	166.5	14.7
NAG 48	sand (bank)	sand	Narayani	27.7020	84.4260	166.5	13.8
LO 741	sand (bank)	sand	Narayani	27.7020	84.4260	166.5	15.0
CA 11-140	sand (bank)	sand	Narayani	27.7020	84.4260	166.5	9.19
<i>Narayani</i>	sand (mean)	sand	Narayani @ Narayangad	27.7020	84.4260	166.5	12.4
	(std)						2.9
<i>Narayani</i>	Suspended load (average 2010 monsoon)	silt	Narayani @ Narayangad	27.7020	84.4260	166.5	16.4
	(std)						3.9
CA 11305	sand (bank)	sand	Narayani	26.8598	84.2098	337	9.3
CA 11306A	sand (bank)	Bank	Narayani	27.2059	83.9300	284	10.1
CA 11306B	sand (bank)	Bank	Narayani	27.2059	83.9300	284	7.8
CA 11306D	sand (bank)	Bank	Narayani	27.2059	83.9300	284	7.9
CA 11307	sand (bank)	Bank	Narayani	27.1215	84.0609	301	9.4
CA 11308	sand (bank)	Bank	Narayani	26.6890	84.4333	369	11.2
<b>Main Tributaries</b>							
CA-13-237	sand (bank)	sand	Mardi Khola	28.2996	83.9267	38	7.9
CA-13-238	sand (bank)	sand	Madi Khola	28.2341	84.0868	113	2.4
CA-13-239	silt (bank)	silt	Madi Khola	28.2243	84.0592	113	4.2
CA-13-247	sand (bank)	sand	Madi Khola	27.9783	84.2600	113	3.64
LO 305	sand (bank)	sand	Trisuli	27.8180	84.4640	144	3.2

LO 307	sand (bank)	sand	Kali Gandaki	27.7486	84.4194	161	12.3
CA11136	sand (bank)	sand	Kali Gandaki	27.7486	84.4194	161	21.2
CA-13-126	sand (bank)	sand	Kali Gandaki	27.7486	84.4194	161	15.6
CA-13-128	sand (bank)	sand	Kali Gandaki	27.7486	84.4194	161	17.9
<b>Breccia (Sabche rockslide deposit)</b>							
CA-13-270	breccia	matrix	Sabche cirque _ base of deposit	28.5061	83.9999	5	48.6
CA-13-275	sediment in gully	sand	Sabche cirque _ base of deposit	28.5039	83.9996	5	65.1
							66.7
CA13-275 A	sediment in gully	clast	Sabche cirque _ base of deposit	28.5039	83.9996	5	15.9
CA13-275 B	sediment in gully	clast	Sabche cirque _ base of deposit	28.5039	83.9996	5	99.0
CA13-275 C	sediment in gully	clast	Sabche cirque _ base of deposit	28.5039	83.9996	5	82.6
CA13-275 D	sediment in gully	clast	Sabche cirque _ base of deposit	28.5039	83.9996	5	87.7
CA-13-280		mixed clasts	Sabche cirque _ base of deposit	28.5056	83.9999	5	79.2
CA13-280 A	breccia	mixed clasts	Sabche cirque _ base of deposit	28.5056	83.9999	5	58.7
CA13-280 B	breccia	mixed clasts	Sabche cirque _ base of deposit	28.5056	83.9999	5	75.1
CA-13-281		matrix	Sabche cirque _ base of deposit	28.5056	83.9999	5	41.2
CA13-281 A	breccia	clast	Sabche cirque _ base of deposit	28.5056	83.9999	5	55.6
CA13-281 B	breccia	clast	Sabche cirque _ base of deposit	28.5056	83.9999	5	20.8
CA13-281 C	breccia	clast	Sabche cirque _ base of deposit	28.5056	83.9999	5	88.5
CA13-281 D	breccia	clast	Sabche cirque _ base of deposit	28.5056	83.9999	5	71.0
<b>Breccia (upper Seti rock avalanche deposit)</b>							
CA-14-57	avalanche deposit (top)	matrix	upper Seti Kh. _ Nanhe spur	28.4112	83.9871	21	55.9
CA-14-56	fluid injection vein	greenish part	upper Seti Kh. _ Karuwa	28.3870	83.9751	24	42.9
		pinkish part					43.8
		whitish part					19.8
CA-14-60	breccia of light tone clasts		upper Seti Kh. _ Karuwa	28.3870	83.9751	24	46.5
							41.3
CA-16-9	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3875	83.9738	24	21.8
CA-16-10	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3875	83.9738	24	27.4
CA-16-11	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3875	83.9738	24	35.4

CA-16-12	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3875	83.9738	24	33.2
		gravels					39.9
CA-16-13	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3875	83.9738	24	29.7
CA-16-14	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3875	83.9738	24	55.9
CA-16-15	avalanche deposit (base)	light tone gravels	upper Seti Kh. _ Karuwa	28.3875	83.9738	24	39.6
		dark gravels					33.3
		matrix					41.5
CA-16-17	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3873	83.9750	24	32.3
CA-16-18	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3873	83.9750	24	45.5
		light tone gravels					26.9
		dark gravels					13.6
CA-16-19	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3873	83.9750	24	30.3
CA-16-20	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3869	83.9750	24	30.9
CA-16-4	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3846	83.9757	24.5	38.2
CA-16-21	avalanche deposit (base)	matrix	upper Seti Kh. _ Karuwa	28.3828	83.9754	24.8	28.6
CA-16-2	avalanche deposit (middle height)	gravels	upper Seti Kh. _ Karuwa	28.3806	83.9733	25	59.8
		matrix				25	68.3
CA-16-3	avalanche deposit (middle height)	matrix	upper Seti Kh. _ Karuwa	28.3825	83.9732	25	70.5
CA-16-22	avalanche deposit (middle height)	matrix	upper Seti Kh.	28.3594	83.9571	29	59.6
CA-13-234	avalanche deposit (middle height)	matrix	Seti Kh. _ North of Pokhara	28.3203	83.9567	34	28.2
CA-14-62	isolated breccia remnant	matrix	Seti Kh. _ South of Pokhara	28.1229	84.0849	68.5	40.3
<b>Pokhara formation</b>							
CA-19-18	conglomerate	gravels	upper Seti Kh. _ Karuwa	28.3860	83.9750	24	32.7
CA19-18_A	conglomerate	individual gravel	upper Seti Kh. _ Karuwa	28.3860	83.9750	25	14.3
CA19-18_B	conglomerate	individual gravel	upper Seti Kh. _ Karuwa	28.3860	83.9750	25	75.0
CA19-18_C	conglomerate	individual gravel	upper Seti Kh. _ Karuwa	28.3860	83.9750	25	58.0
CA19-18_D	conglomerate	individual gravel	upper Seti Kh. _ Karuwa	28.3860	83.9750	25	74.4
CA-16-24	conglomerate	gravels	upper Seti Kh.	28.3591	83.9566	29	59.1
		matrix				29	52.7
CA-13-236	conglomerate		Seti Kh. _ north of Pokhara	28.3096	83.9406	37	58.5
CA-14-61	fine conglomerate	matrix	Seti Kh. _ north of Pokhara	28.1340	84.0731	66.3	55.7

CA-13-240	slackwater deposit	silt	Seti Kh. _ south of Pokhara	28.1088	84.1151	70	58.1
						70	57.1
						70	58.9
CA-13-241	unstratified angular clasts unit	gravels	Seti Kh. _ south of Pokhara	28.1083	84.1156	70	63.1
						70	62.2
		matrix				70	59.9
						70	58.6
						70	62.6
						70	62.5
CA-14-65	unstratified angular clasts unit	matrix	Seti Kh.	28.0933	84.0755	73	63.7
CA-16-30	upper part of Pokhara Fm	silt	Seti Kh. _ south of Pokhara basin	28.0926	84.0688	73.5	55.1
CA-16-31	unstratified angular clasts unit	matrix	Seti Kh. _ south of Pokhara	28.0182	84.0967	83	53.8
CA-13-249	fine conglomerate		lower Trisuli	27.7564	84.4638	157.3	51.5
						157.3	52.8
CA-13-252	fine conglomerate	gravels	Narayani at Narayangad	27.7137	84.4339	164	54.5
						164	58.4
		matrix				164	50.4
						164	50.4
CA-14-69	conglomerate	matrix	Narayani at Narayangad	27.7140	84.4339	164	45.6
		mixed gravels				164	52.5
CA14-69_A	conglomerate	gravel	Narayani at Narayangad	27.7140	84.4339	164	79.1
CA14-69_B	conglomerate	gravel	Narayani at Narayangad	27.7140	84.4339	164	38.7
CA14-69_C	conglomerate	gravel	Narayani at Narayangad	27.7140	84.4339	164	65.2
CA14-69_D	conglomerate	gravel	Narayani at Narayangad	27.7140	84.4339	164	68.7
CA14-69_E	conglomerate	gravel	Narayani at Narayangad	27.7140	84.4339	164	10.5
CA-14-70	coarse sand unit	sand	Narayani at Narayangad	27.7140	84.4339	164	48.6
						164	47.5
CA-14-71	silty unit	silt	Narayani at Narayangad	27.7140	84.4339	164	45.3
						164	45.2
<b>pit near GR2 core (Gandak fan)</b>							
GR2 16-5	sediment @ -2.85m below surface	sand	Dudahi (India)	26.8161	84.1458	337	73.1
GR2 16-6	sediment @ -2.45m below surface	fine sand	-	-	-	337	32.5
GR2 16-7	sediment @ -2m below surface	micaceous sand	-	-	-	337	18.5
GR2 16-8	sediment @ -1.7m below surface	silt / fine sand	-	-	-	337	33.7

GR2 16-9	sediment @ -1.2m below surface	silt / fine sand	-	-	-	337	41.9
GR2 16-2	sediment @ -0.9m below surface	silt / fine sand	-	-	-	337	36.6
GR2 16-10	sediment @ -0.65m below surface	silt	-	-	-	337	44.4
<b>TSS Rocks</b>							
CA-13-260	block on surface of rockslide deposit	Sombre Fm (Silurian)	Seti (upper)	28.5352	84.0274		90.7
							86.6
							85.6
CA-13-261	block on surface of rockslide deposit	Sombre Fm (Silurian)	Seti (upper)	28.5359	84.0271		48.7
							44.9
							48.7
CA-13-265	block on surface of rockslide deposit	Sombre Fm (Silurian)	Seti (upper)	28.5394	84.0297		41.3
							40.7
CA-14-29	morainic block	Sombre Fm (Silurian)	Upper Marsyandi	28.6069	84.0525		62.4
CA-14-32	morainic block	Sombre Fm (Silurian)	Upper Marsyandi	28.6042	84.0516		41.4
							40.5
CA-14-36	glacial striated surface	lower Nilgiri Fm (ordovicien)	Upper Marsyandi	28.6012	84.0508		49.0
							51.3
CA-14-38	morainic block	Sombre Fm (Silurian)	Upper Marsyandi	28.5977	84.0510		59.3
CA-14-40	morainic block	Sombre Fm (Silurian)	Upper Marsyandi	28.5957	84.0513		88.1
CA-14-44	morainic block	Sombre Fm (Silurian)	Upper Marsyandi	28.5985	84.0563		81.9
UM-18-3	bedrock	annapurna lm (cambrien)	Upper Marsyandi	28.5590	84.2220		58.0
UM-18-4	bedrock	annapurna lm (cambrien)	Upper Marsyandi	28.5758	84.1870		55.2
UM-18-8	bedrock	top of annapurna lm (cambrien)	Upper Marsyandi	28.5905	84.1949		59.8
UM-18-10	bedrock	top of annapurna lm (cambrien)	Upper Marsyandi	28.5923	84.1949		60.9
UM-18-11	bedrock	lower Nilgiri Fm (ordovicien)	Upper Marsyandi	28.6029	84.1742		78.6
UM-18-12	bedrock	Nilgiri Fm (ordovicien)	Upper Marsyandi	28.6105	84.1514		32.0
UM-18-13	bedrock	top of Nilgiri Fm (Silurian)	Upper Marsyandi	28.6252	84.1331		56.2

**Table SI-13-1:** Summary of the CaCO<sub>3</sub> content of Sabche rockslide deposit, related sediments further downstream, modern river sediment of the area, and of the Silurian to Cambrian TSS units typical of rockslide source.

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