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New evidence for large earthquakes on the Central Iran plateau: Paleoseismology of the Anar fault

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3 1 **New evidence for large earthquakes on the Central Iran plateau: Paleoseismology**
4 **of the Anar fault**
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40
41 23

42
43
44 24 **Abstract**
45
46

47 25 The Central Iran plateau appears aseismic during the last few millenniums based on
48 26 instrumental and historical seismic records. Nevertheless, it is sliced by several strike-slip
49 27 faults that are hundreds kilometres-long. These faults display along-strike, horizontal offsets
50 28 of intermittent gullies that suggest the occurrence of earthquakes in the Holocene.
51 29 Establishing this is crucial for accurately assessing the regional seismic hazard. The first
52 30 paleoseismic study performed on the 200-km-long, NS striking Anar fault shows that this
53 31 right-lateral fault hosted three large ($M_w \approx 7$) earthquakes during the Holocene or possibly
54 32 Uppermost Pleistocene for the older one. These three seismic events are recorded within a
55 33 sedimentary succession, which is not older than 15 ka, suggesting an average recurrence of at

1
2
3 34 most 5 ka. The six OSL ages available provide additional constraints and allow estimating
4
5 35 that the three earthquakes have occurred within the following time intervals: 4.4 ± 0.8 ka,
6
7 36 6.8 ± 1 ka, and 9.8 ± 2 ka. The preferred age of the more recent event, ranging between 3600 yrs
8
9 37 and 5200 yrs, suggests that the fault is approaching the end of its seismic cycle and the city of
10
11 38 Anar could be under the threat of a destructive earthquake in the near future. Additionally, our
12
13 39 results confirm a previous minimum slip rate estimate of 0.8 ± 0.1 mm/yr for the Anar
14
15 40 fault indicating the westernmost prominent right-lateral faults of the Central Iran
16
17 41 plateau are characterized by slip rates close to 1 mm/yr. These faults, which have
18
19 42 repeatedly produced destructive earthquakes with large magnitudes and long
20
21 43 recurrence interval of several thousands of years during the Holocene, show that the
22
23 44 Central Iran plateau does not behave totally as a rigid block and that its moderate
24
25 45 internal deformation is nonetheless responsible for a significant seismic hazard.

26 46

27 28 47 **Introduction**

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30
31 48 The Central Iran Plateau is a wide region experiencing low GPS deformation rates
32
33 49 and is commonly described as a rigid block (e.g., Jackson & McKenzie, 1984; Vernant et
34
35 50 al., 2004). The region (Figure 1) is nonetheless sliced by several strike-slip faults with
36
37 51 clear morphological traces (Walker & Jackson, 2004; Meyer et al., 2006; Meyer & Le
38
39 52 Dortz, 2007) that contrast with the very few earthquakes recorded in the region
40
41 53 (Ambraseys & Jackson, 1998). Destructive earthquakes have occurred close to or along
42
43 54 the Lut faulted borders only, and, according to the historical and instrumental records
44
45 55 (Ambraseys & Melville, 1982; Ambraseys & Jackson, 1998), the prominent right-lateral
46
47 56 strike-slip faults inland remained quiescent for millennia. Although the absence of
48
49 57 historical record of earthquakes in remote and uninhabited desert does not mean an
50
51 58 absence of earthquakes, knowledge of the behaviour of such faults and assessment of
52
53 59 the regional seismic hazard requires paleoseismic studies and depends on the selection
54
55 60 of suitable trenching sites. This is the case for the region of the Dehshir and Anar faults.
56
57 61 While a recent paleoseismic study stated the occurrence of large and infrequent
58
59 62 earthquakes on the Dehshir fault (Nazari et al., 2009; Fattahi et al., 2010), the seismic
60
63 63 behaviour of the Anar fault is still to be assessed.

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2
3 64 The Anar fault is a 200-km-long NS strike-slip fault located nearby 55°E, in the
4
5 65 middle of the Central Iran Plateau (Figure 1). The northern part of the fault is located
6
7 66 within a mountainous region where several closely spaced splays cut across the Kuh-e
8
9 67 Kharanaq range. The southern portion of the fault runs along the Kuh-e Bafq range and cuts
10
11 68 right across the western piedmont of the range and across the Anar salt flat. The fault goes
12
13 69 through the populated city of Anar and further bends eastwards to reactivate a thrust fault
14
15 70 to the south. According to ^{10}Be cosmic ray exposure (CRE) and optically-stimulated
16
17 71 luminescence (OSL) dating of cumulative offset of alluvial fans, the southern portion of the
18
19 72 fault slips at a minimum rate of 0.8 mm/year (Le Dortz et al., 2009). Both the sharpness
20
21 73 of these cumulative offsets and the absence of along fault microseismicity suggest these
22
23 74 offsets have accrued through large and infrequent earthquakes rather than by creeping.
24
25 75 At a few places, the offset of small gullies that ranges between 2.5 and 3.5 m (Figure 2)
26
27 76 may be interpreted as the amount of coseismic slip during the last earthquake but clear
28
29 77 evidence for a continuous and distinctive surface break is missing. Trenching appears
30
31 78 therefore necessary to document earthquakes and access the Recent seismic history of
32
33 79 the fault.
34

80

81 **Site selection and trench stratigraphy**

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37
38 82 We scrutinized the fault on Quickbird satellite imagery and in the field to select
39
40 83 the most favourable place to conduct paleoseismic investigations. The selected site is
41
42 84 located 35 km north of the city of Anar along a very clear portion of the N175°E fault
43
44 85 trace that is highlighted by an E-facing scarp (Figure 3). This fault scarp is readily seen
45
46 86 cutting across numerous rills and ephemeral streams that incise a fan surface
47
48 87 characterized by a subdued bar-and-swale morphology. The abandoned alluvial fan
49
50 88 surface comprises a loose desert pavement of varnished clasts separated by sandy-silty
51
52 89 material. The smooth scarp has a minimum height of 35 cm near the excavation (Figure
53
54 90 3b). South of the trench site, the scarp height increases progressively to reach one meter
55
56 91 where small streams, which have been dammed and channelled along the fault,
57
58 92 rejuvenate this scarp. North of the trench site, the scarp height also increases, but the
59
60 93 streams are wider and deeper than to the south and have been able to maintain their
94
95 94 courses to flow across the fault trace. At the trench site, the possibility of damming small
95
96 95 intermittent streams during the emplacement of the fan material is high and the

1
2
3 96 possibility of subsequent erosion low, maximizing the chances to record the earthquakes
4
5 97 coeval with alluvial aggradation and subsequent colluvial deposition. The next
6
7 98 paragraphs report the observations gathered at the selected site, where trenching
8
9 99 allowed us to distinguish three unambiguous events.

10
11 100 The eastern tip of the excavated trench is located about 5 km west of the Kuh-e
12
13 101 Bafq range at 31.1953°N; 55.1536°E, and 1544-m-altitude above sea level (Figures 1 and
14
15 102 3b). The trench strikes N85°E, it has a 28-m-length, a depth between 4.3 and 4.7 m, and
16
17 103 a width of some 1.5 m (Figures 3, 4, and 5). Trench walls expose a total deposit thickness
18
19 104 of 5.9 m with fairly flat, 0.1-to 1-m-thick beds that correspond to medium-distal, alluvial
20
21 105 fan facies. Trench stratigraphy is relatively straightforward as these beds are continuous
22
23 106 and easily correlated across the fault zone located approximately in the middle of the
24
25 107 trench (Figure 5). Overall the beds found in the trench are composed of sands and
26
27 108 gravels mixed with variable amounts of silt and clay, these deposits correspond mostly
28
29 109 to a debris-flow dominated alluvial fan. Although debris-flows and sheet-floods appears
30
31 110 to dominate, sediment dynamics is not easy to determine precisely for each bed due to
32
33 111 the medium-distal deposit conditions.

34 112 A total of 17 units have been defined in the excavated trench (see Table 1 and
35
36 113 Figures 4 and 5). The uppermost part of the trench, approximately the last meter, is
37
38 114 made of the thinner units 13 to 17 containing smaller pebbles than the alluvial units 1 to
39
40 115 8 and an almost clay-free matrix contrary to the units 9 to 11. This last meter hence is
41
42 116 made of runoff deposits. The only evidence for a significant break in alluvial
43
44 117 sedimentation is the ≈ 0.15 -m-thick, gypsiferous calcrete that is located toward the top of
45
46 118 unit 11. This latter unit and units 9 and 10 correspond to reddish brown, mud-
47
48 119 dominated debris flows. OSL was used to date the alluvial layers seen in the trench.

49 120

50 121 **OSL dating**

51
52 122 Six lenses of fine sandy-silts intercalated between fanglomerates at various depths
53
54 123 below the surface were sampled for OSL in opaque tubes (Figure 5). The Single Aliquot
55
56 124 Regeneration (SAR) protocol (e.g.; Murray and Wintle, 2000) was employed for the
57
58 125 Equivalent dose (D_e) measurement once quartz had been extracted and cleaned from each
59
60 126 sample. The analytical procedures employed are identical to that applied to similar samples

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2
3 127 from the neighbouring Sabzevar, Doruneh, and Dehshir faults (Fattahi et al, 2006; 2007;
4 128 2010; Le Dortz et al., 2011). In order to make all data consistent, three samples with ages that
5 129 were previously published in Le Dortz et al. (2009), including one sample collected
6 130 approximately 8 km farther north (OSL-2 on Figure 1 and in Table 2), have been refined in
7 131 the light of procedural development outlined by Fattahi et al. (2010). Table 2 provides the
8 132 relevant information for OSL ages in years from present (2010) with 1 sigma errors.

133 Initial attempts to use single grains for De determination failed due to the dimness of
134 OSL signal. As a result, De measurements were undertaken on 9.6-mm-diameter aliquots
135 containing approximately 1500-2000 grains. Whilst normally this might result in averaging
136 out of any multiple dose component within a sample, here it is assumed that for these dim
137 samples the luminescence signal from each aliquot was produced by a relatively few number
138 of bright grains and thus may be considered as almost measuring at single grain level.
139 Therefore, the De distribution of the single aliquot De measurements is considered to be
140 almost a true reflection of the actual De distribution within a sample. For samples showing
141 unimodal, apparently normally distributed De's with a low over-dispersion (Ant-I and Ant-IV
142 in Table 2), which are interpreted as having had the OSL signal reset (bleached) prior to
143 burial, Central Age Model (CAM) was employed for calculation purposes. For the remaining
144 samples (Ant-II, Ant-III, Ant-V, Ant-VI and OSL-2 in Table 2), the depositional setting, field
145 sedimentary logs, and the scatter of the replicate aliquot De data indicated that prior to burial,
146 full resetting (bleaching) of the OSL signal had not taken place and/or that the sediments had
147 undergone some post-depositional disturbance (Bateman et al., 2007). Indeed, the small size
148 of the catchment area at the trench site, less than 20 km², is indicative of a rapid transport
149 before the emplacement of the fan (Le Dortz et al., 2009). The great majority of the Anar
150 trench deposits come from high-discharge depositional events with limited surface exposure,
151 which favour partial bleaching (Rittenour, 2008). As a consequence, Finite Mixture Model
152 (FMM; Roberts et al. 2000) was used where samples showed skewed, scattered, or
153 multimodal distributions and the dominant De component was used for age calculations (as in
154 Fattahi et al., 2010). This approach yielded ages in accordance with site stratigraphy except
155 for sample Ant-III whose age was too young. This sample has exhibited the highest over-
156 dispersion value (51%, Table 2) of all measured samples and three De component were
157 extracted by FMM for this sample, the highest representing 30% of the signal and the smallest
158 47%. It is possible to get an age that fits with stratigraphy using the higher two De
159 components extracted using FMM, corresponding to ages of 7.3±0.5 ka and 10.7±0.8 ka,

1
2
3 160 respectively. However, there are no good reasons to accept components representing only
4
5 161 23% or 30% of the data over the 47% of the data incorporated into the dominant smallest
6
7 162 FMM component. The latter cannot be ignored on the basis of partial bleaching as it has a
8
9 163 lower D_e and is unlikely to represent post-depositional disturbance as it is the dominant D_e
10
11 164 component but also based on observed bedding within the unit. However, unlike most other
12
13 165 samples studied, Ant-III was sampled actually on a stratigraphic boundary (between units 8
14
15 166 and 9). As the dose-rate for this sample is based only on the activity from unit 9, a difference
16
17 167 in the gamma radiation dose received from unit 8 might help explain the apparent under-
18
19 168 estimation of age based on the lowest FFM D_e component. Unfortunately field-based gamma-
20
21 169 spectrometer readings or material for analyzing the radioactive elements within unit 8 were
22
23 170 not available to test this and so the age of Ant-III has not been included within the subsequent
24
25 171 site interpretation. Thus, the ages of the trench units have been constrained based on only five
26
27 172 OSL ages (Ant-I, Ant-II, Ant-IV, Ant-V, and Ant-VI).

27 173

30 174 **Ages of trench units**

31
32 175 The samples collected within the trench define a time range spanning from 5.8 to
33
34 176 14.9 ka. The oldest age Ant-I (13.6 ± 1.3 ka) stands at the bottom of the trench and
35
36 177 belongs to one of the oldest stratigraphic units (unit 2), it indicates that all the trench
37
38 178 units should be younger than 15 ka. As the youngest OSL sample Ant-VI (6.2 ± 0.4 ka) is
39
40 179 located at 0.8 m below the surface (unit 14), these ages define a maximum time interval
41
42 180 between 0 and 14.9 ka and a minimum one between 6.6 and 12.3 ka, indicating the
43
44 181 trench deposits aggraded during the uppermost Marine Isotopic Stage 2 (MIS-2 \approx 12-
45
46 182 22 ka) and part, or the entirety of MIS-1. The age of the fan surface at the trench site
47
48 183 appears poorly constrained between 0 and 6.6 ka.

49
50 184 A proxy to the surface age may be obtained by estimating average sedimentation
51
52 185 rates. Assuming this fan surface is still active, the whole 5.9 m of sedimentary units seen
53
54 186 in the trench should have been aggraded during the last 14.9 or 12.3 ka at an overall
55
56 187 sedimentation rate ranging between 0.4 and 0.48 mm/yr. Deposit thicknesses above the
57
58 188 samples Ant-I (13.6 ± 1.3 ka) and Ant-II (12.4 ± 0.6 ka) yield slightly lower rates ranging
59
60 189 between 0.28 and 0.36 mm/yr. Conversely, if one assumes the top of the fan surface was
190
abandoned just after 6.6 ka, the oldest possibility for the youngest sample (Ant-VI), the

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2
3 191 sedimentation rate may have reached 1 mm/yr. These two extreme hypotheses raise the
4
5 192 problem of the abandonment age of the alluvial fan at the precise location where the
6
7 193 trench was excavated. The refined age of OSL-2 (10.1 ± 0.6 ka versus 11.8 ± 6.5 ka in Le
8
9 194 Dortz et al., 2009), which is sampled some 8 km north of the trench (see location on
10
11 195 Figure 1, see also Figures 4a and 7 in Le Dortz et al., 2009) at 0.8 m below the surface of
12
13 196 another fan on the riser of a ≈ 4.5 m incised dry stream, suggests its surface was
14
15 197 abandoned some 9-10 ka ago at this site while the fan surface at the trench site cannot
16
17 198 be older than 6.6 ka. These ages are in agreement with the late Pleistocene and Holocene
18
19 199 regional climate scenario, for the central and eastern Iran, as recently proposed by
20
21 200 Walker & Fattahi (2011). In fact, the satellite image in the vicinity of the trench site
22
23 201 (Figure 3a) shows this location corresponds to an area where the fan surface has been
24
25 202 exceptionally preserved from the backward erosion of deeply incised dry streams.
26
27 203 Therefore, the late aggradation on the fan surface at the trench site (~ 1544 m a.s.l.),
28
29 204 resulting from surface runoff, lasted until more recently than some 8 km further north
30
31 205 on a more proximal alluvial fan (~ 1748 m a.s.l.) where Le Dortz et al. (2009) collected
32
33 206 the sample OSL-2. In conclusion, the best estimate for the aggradation rate of the trench
34
35 207 sediments is provided by the depth difference of 3.3 m between Ant-I (13.6 ± 1.3 ka) and
36
37 208 Ant-VI (6.2 ± 0.4 ka) samples, this rate ranges between 0.36 and 0.58 mm/yr.
38
39 209 Interestingly, this rate is comparable to the late Pleistocene-Holocene aggradation rates
40
41 210 derived from alluvial sediments in similar deposition settings at southwestern Nebraska,
42
43 211 Negev desert and Central Iran plateau (Daniels et al., 2003; Guralnik et al., 2011;
44
45 212 Schmidt et al., 2011). Consequently, the best averaged net sedimentation rate, if
46
47 213 meaningful in such environment, amounts to 0.47 ± 0.11 mm/yr suggesting that the final
48
49 214 aggradation of the trench units ended between 3.6 and 5.2 ka to the west of the fault
50
51 215 zone and approximately one thousand years later to the east of the fault zone. The
52
53 216 abandonment age of the fan surface at the trench site (4.4 ± 0.8 ka) is comparable with
54
55 217 late Holocene drought cycles at 4.2 ka, proposed by Staubwasser et al. (2003) to the
56
57 218 southeast of the Persian Gulf.

219

220 **Seismic event identification**

221 The surface geomorphology, particularly, the characteristics of the fault scarp,
222 detailed geological and structural analyses of the trench walls (bed unconformities,

1
2
3 223 sealed fault strands, and fissure fills or sand-blows), and restoration of the trench log
4
5 224 permit to trace three individual event horizons that correlate with three destructive past
6
7 225 earthquakes, which ruptured the ground surface. The evidence for these three seismic
8
9 226 events, which are labelled A, B, and C from the youngest to the oldest, is presented
10
11 227 below.

12
13 228 **Event A**, the youngest event is responsible for the 35-cm-high, E-facing scarp,
14
15 229 which is observed at the surface in the vicinity of the trench (Figures 3b and 3c). The
16
17 230 trench log shows this scarp is located above a nearly 1-m-wide, steep faulted zone
18
19 231 associated with an E-facing flexure of the upper trench units; i.e., downthrown to the
20
21 232 east (Figure 5). Units 16 and 17 are not observed west of the fault zone nor warped
22
23 233 eastward. They rest unconformably on unit 15 dipping about 25°E (Figure 6), hence
24
25 234 indicating the faulting and flexuring deformation postdate unit 15 and predate units 16
26
27 235 and 17. As there are no significant thickness differences of the upper trench units on
28
29 236 both sides of the fault zone, the faulting and flexuring deformation appear to result from
30
31 237 a sudden and discrete slipping event on the fault zone instead of a continuous shear; i.e.,
32
33 238 creep slip (Figure 7-step 1). Inasmuch as the upper trench units are seen faulted up to
34
35 239 unit 15, the discrete slipping event should relate to an earthquake that ruptured the
36
37 240 surface producing the scarp. The event horizon of this earthquake locates on the top
38
39 241 boundary of unit 15, so that it stands between this latter and units 16 and 17 to the east
40
41 242 of the fault and corresponds approximately with the present-day topographic surface to
42
43 243 the west of the fault. This suggests that the western block has been slightly eroded as
44
45 244 well as partly concealed by units 16 and 17 so that its present-day height
46
47 245 underestimates its original height at the time of the earthquake (Figure 7-step 2). Then,
48
49 246 unit 17 is a local sag pond deposit caused by event A.

50
51 247 Backstripping of event A suggests its vertical throw is of some 60 cm (Figure 7-
52
53 248 step 3), confirming that the 35-cm high scarp at the surface has been partly degraded.
54
55 249 Taking into account the Anar fault is dominantly a strike-slip fault (Figure 2), the 60 cm
56
57 250 of vertical displacement should be associated with at least a couple of meters of right-
58
59 251 lateral displacement. Then, the magnitude of event A should be at least on the order of
60
252 M_w 7. The age of event A is poorly constrained as the uppermost OSL sample (Ant-VI),
253
254 which is at 0.8-m-depth, comes from unit 14. This indicates only that event A is younger
than 6.6 ka. Tentatively, the sediment thickness, which stands between the sample Ant-

1
2
3 255 VI and the event horizon of event A, may be used to propose a rough estimate of the
4
5 256 youngest possible age for this seismic event based on the aggradation rate between Ant-
6
7 257 VI and Ant-I. Since aggradation of unit 15 ended between 3600 and 5200 years (see
8
9 258 previous section) event A should not be younger than 3600 years and might be as old as
10
11 259 5200 years. This time interval will be considered as the preferred age of event A in the
12
13 260 following discussion.

14
15 261 **Event B**, the penultimate event, is easily determined from analysis of the trench
16
17 262 walls. Several filled fissures (unit 12), which postdate unit 11 and predate unit 13, are
18
19 263 seen (Figures 5 and 7-step 4). A careful analysis of these filled fissures permits to
20
21 264 conclude they correspond indeed to either open cracks or sand-blows (Figures 8a and
22
23 265 8b). It is possible to observe these features formed suddenly as they disrupt the hard
24
25 266 gypsiferous calcrete (e.g., Figure 8b), which is located in the top part of unit 11. Thus, the
26
27 267 interface between units 11 and 13 corresponds to the event horizon of event B. The
28
29 268 backstripping analysis of the trench log (Figure 7), removing the effects of event A and
30
31 269 the units aggraded between events A and B, allow reconstructing the event B horizon
32
33 270 just after the penultimate earthquake (Figure 7-step 4). This reconstruction suggests
34
35 271 that the rupture of event B should have occurred on two parallel fault strands of the
36
37 272 Anar fault zone, totalling a vertical throw of some 40 cm, distributed into 25 cm on the
38
39 273 eastern strand and 15 cm on the western one. Thus, the penultimate earthquake appears
40
41 274 to have a vertical throw close to that of the last one, hence a magnitude lightly
42
43 275 comparable with the one of event A. The age of event B is well constrained by three OSL
44
45 276 ages (Ant-V, -IV, and -VI) and bracketed between 5.8 ka and 7.8 ka yielding an average
46
47 277 age of 6.8 ± 1 ka for this earthquake (Figure 9).

48
49 278 **Event C**, the oldest seismic event, can be safely identified on the trench walls.
50
51 279 Evidence for a third earthquake rests on the facts that lower trench units (5 to 8) exhibit
52
53 280 higher vertical throws than middle ones (9 to 11). Different reconstructions have been
54
55 281 tested to restore the trench lower units, the best fit is obtained when considering the
56
57 282 interface between units 8 and 9 as the event horizon of a surface rupturing earthquake
58
59 283 (Figure 7-step 6). This reconstruction favours that event C ruptured along the eastern
60
284 fault strand with a vertical displacement of about 25 cm. Nevertheless, this vertical
285 displacement is poorly constrained and higher estimates might be obtained according to
286 the amount of erosion chosen (dashed line on Figure 7-step 6). Even if this vertical

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2
3 287 throw is poorly determined and appears smaller than the ones of the subsequent
4
5 288 earthquakes, this does not imply a much smaller magnitude as the amount of coseismic
6
7 289 vertical displacement is highly variable along a strike-slip fault (e.g., Barka, 1996; Barka
8
9 290 et al., 2002). The age of event C is not well constrained, it occurred prior to the OSL age
10
11 291 of sample Ant-V (7.1 ± 0.7 ka) and after that of Ant-II (12.4 ± 0.6 ka) so that it is bracketed
12
13 292 within the interval between 6.4 and 13 ka, with a minimum interval of 4 ka (Figure 9).
14
15 293 We have investigated the possibility for a fourth event in the lowermost part of the
16
17 294 trench (Figure 5). However, the lowermost units (1 to 4) cannot be followed on the
18
19 295 eastern side of the trench precluding the possibility to document an additional event.

20 296

21 22 23 297 **Discussion and Conclusions**

24
25
26 298 Due to the reduced size of the surface sag pond, a 3D trench exploration was not
27
28 299 undertaken at the trench site so that the slip per event was not directly measurable for
29
30 300 the three identified seismic events, A, B, and C. Accounting for the lack of morphological
31
32 301 segmentation along the Anar fault (Le Dortz et al., 2009) and the excavation of a single
33
34 302 trench, there are no possibilities to calculate confidently any magnitude. The restored
35
36 303 vertical throws per event suggest only that the related magnitudes are more likely on
37
38 304 the order of $M_w \approx 7$ (see previous section). The right-lateral offsets observed at the
39
40 305 surface (Figures 2 and 3a) permit to reinforce this inference. Deeply incised intermittent
41
42 306 streams are seen offset by 8 ± 0.5 m (Le Dortz et al., 2009 and Figure 3a) while several
43
44 307 weakly incised small dry gullies show offsets of 3 ± 0.5 m only (Figure 2). Considering
45
46 308 these lower offsets were more likely formed during the most recent earthquake, they
47
48 309 provide the best estimate for the coseismic horizontal slip of event A. Such a coseismic
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50 310 slip at the surface agrees with a magnitude close to 7. Thus the higher offsets, which are
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52 311 only observed where the alluvial surface is older, should represent the cumulative
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54 312 horizontal slip of the last three events that are seen in the trench. Therefore, the three
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56 313 events, which are observed within the trench to the north of Anar city, should have had
57
58 314 slip per event on the order of 3 m, suggesting they are of similar magnitudes.

59
60 315 Overall, the new data presented in this paper give evidence for at least three
316 seismic events of similar sizes on the Anar fault (Figure 9). OSL age of Ant-I sample
317 indicates that the aggradation of the trench units did not started much before 14.9 ka or

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2
3 318 to the latest by 12.3 ka. Since only 3 events have occurred during the last 15 ka, this
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5 319 provides a rough estimate of at most 5 ka for the average maximum time interval
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7 320 between two earthquakes. The youngest age possibility may reduce this average time
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9 321 interval between two earthquakes to ≈ 4 ka. Considering the best estimates of average
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11 322 ages for the three seismic events A, B, and C are: 4.4 ± 0.8 ka, 6.8 ± 1 ka, and 9.7 ± 3.3 ka,
12
13 323 respectively (Figure 9), the time interval between two subsequent earthquakes is ill-
14
15 324 defined and might vary significantly. Nevertheless, the average ages for events A, B, and
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17 325 C indicate that the intervals between two subsequent earthquakes should be of 2400
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19 326 and 2900 years between events A-B and B-C, respectively. As the elapsed time since the
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21 327 last earthquake is 3600 years at least and 5200 years at most, this suggests we are
22
23 328 getting close to the end of the seismic cycle and may anticipate a destructive earthquake
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25 329 for the Anar city in the near future.

26 330 Finally, the cumulative offset of 8 ± 0.5 m (Le Dortz et al., 2009) postdating fan
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28 331 aggradation and the refined age of fan abandonment given by OSL-2 sample
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30 332 (10.1 ± 0.6 ka) confirms a minimum slip rate estimate of 0.8 ± 0.1 mm/yr for the Anar
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32 333 fault. Then, the westernmost prominent right-lateral faults of the Central Iran plateau,
33
34 334 namely the Dehshir and Anar faults, which are active though void of historical and
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36 335 instrumental earthquakes, are characterized by slip rates close to 1 mm/yr (Le Dortz et
37
38 336 al., 2009 and 2011). Such faults have repeatedly produced destructive earthquakes with
39
40 337 large magnitudes ($M_w \approx 7$) and long recurrence interval of several thousands of years
41
42 338 during the Holocene (Nazari et al., 2009; Fattahi et al., 2010 and this paper). This
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44 339 demonstrates that the Central Iran plateau does not behave totally as a rigid block and
45
46 340 that its moderate internal deformation is nonetheless responsible for a significant
47
48 341 seismic hazard.

49 342

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17 356 **References**

- 19
20 357 Ambraseys, N. & Melville, C., 1982. A history of Persian earthquakes. Cambridge
21
22 358 University Press.
- 23
24
25 359 Ambraseys, N.N. & Jackson, J.A, 1998. Faulting associated with historical and recent
26
27 360 earthquakes in the Eastern Mediterranean region. *Geophys. J. Int.* , 133, 390-406.
- 28
29
30 361 Barka, A.A., 1996. Slip distribution along the North Anatolian Fault associated with the
31
32 362 large earthquakes of the period 1939 to 1967. *Bull. Seismol. Soc. Am.*, 86 (5), 1238-
33
34 363 1254.
- 35
36 364 Barka, A.A., Akyüz, H.S., Altunel, E., Sunal, G., Çakir, Z., Dikbas, A., Yerli, B., Armijo, R.,
37
38 365 Meyer, B., De Chabalier, J.B., Rockwell, T., Dolan, J.R., Hartleb, R., Dawson, T.,
39
40 366 Christofferson, S., Tucker, A., Fumal, T., Langridge, R., Stenner, H., Lettis, W.,
41
42 367 Bachhuber, J. & W. Page, 2002. The Surface Rupture and Slip Distribution of the 17
43
44 368 August 1999 Izmit Earthquake (M 7.4), North Anatolian Fault. *Bull. Seismol. Soc. Am.*,
45
46 369 92, 43-60.
- 47
48 370 Bateman, M.D., Boulter, C.H., Carr, A.S., Frederick, C.D., Peter, D. & M. Wilder, 2007.
49
50 371 Preserving the palaeoenvironmental record in Drylands: Bioturbation and its
51
52 372 significance for luminescence derived chronologies. *Sedimentary Geology*, 195(1-2),
53
54 373 5-19.
- 55
56
57 374 Daniels, J.M., 2003. Floodplain aggradation and pedogenesis in a semiarid environment.
58
59 375 *Geomorphology*, 56, 225-242.
- 60
376 Fattahi, M., Walker, R., Hollingsworth, J., Bahroudi, A., Nazari, H., Talebian, M., Armitage,

- 1
2
3 377 S., Stokes, S., 2006. Holocene slip-rate on the Sabzevar thrust fault, NE Iran,
4
5 378 determined using Optically-stimulated Luminescence (OSL). *Earth and*
6
7 379 *Planetary Science Letters*, 245, 673-684.
8
9
10 380 Fattahi, M., Walker, R.T., Khatib, M.M., Dolati, A. & A. Bahroudi, 2007. Slip-rate estimate
11
12 381 and past earthquakes on the Doruneh fault, eastern Iran. *Geophy. J. Int.*, 168,
13
14 382 691-709.
15
16 383 Fattahi, M., Nazari, H., Bateman, M.D., Meyer, B., Sébrier, M., Talebian, M., Le Dortz, K.,
17
18 384 Foroutan, M., Ahmadi Givi, F. & M. Ghorashi, 2010. Refining the OSL age of the
19
20 385 last earthquake on the Dheshir fault, Central Iran. *Quaternary Geochronology*, 5,
21
22 386 286-292, doi:10.1016/j.quageo.2009.04.005.
23
24
25 387 Guralnik, B., Matmon, A., Avni, Y., Porat, N., Fink, D., 2011. Constraining the evolution of
26
27 388 river terraces with integrated OSL and cosmogenic nuclide data. *Quaternary*
28
29 389 *Geochronology*, 6, 22-32.
30
31
32 390 Jackson, J. & D. McKenzie, 1984. Active tectonics of the Alpine-Himalayan Belt between
33
34 391 western Turkey and Pakistan. *Geophys. J. R. Astron. Soc.*, 77, 185-264.
35
36 392 Le Dortz, K., Meyer, B., Sébrier, M., Nazari, H., Braucher, R., Fattahi, M., Benedetti, L.,
37
38 393 Foroutan, M., Siame, L., Bourles, D., Talebian, M., Bateman, M.D. & Ghorashi, M.,
39
40 394 2009. Holocene right-slip rate determined by cosmogenic and OSL dating on the
41
42 395 Anar fault, Central Iran. *Geophys. J. Int.*, 179, 700-710.
43
44
45 396 Le Dortz, K., B. Meyer, M. Sébrier, R. Braucher, H. Nazari, L. Benedetti, M. Fattahi, D.
46
47 397 Bourles, M. Foroutan, L. Siame, A. Rashidi, & M. Bateman, 2011. Dating inset
48
49 398 terraces and offset fans along the Dehshir fault combining cosmogenic and OSL
50
51 399 methods. *Geophys. J. Int.*, 185, 1147-1174.
52
53 400 Meyer, B., Mouthereau, F., Lacombe, O. & P. Agard, 2006. Evidence of Quaternary activity
54
55 401 along the Deshir Fault, *Geophy. J. Int.*, 164, 192-201.
56
57
58 402 Meyer, B. & K. Le Dortz, 2007. Strike-slip kinematics in Central and Eastern Iran :
59
60 403 estimating fault slip-rates averaged over the Holocene, *Tectonics*, 26, TC5009,
404
doi:10.1029/2006TC002073.

- 1
2
3 405 Murray, A.S. & A.G. Wintle, 2000. Luminescence dating of quartz using an improved
4
5 406 single-aliquot regenerative-dose protocol., *Radiation Measurements*, 32, 57-73.
6
7
8 407 Nazari, H., M. Fattahi, B. Meyer, M. Sébrier, M. Talebian, M. Foroutan, K. Le Dortz, M. D.
9
10 408 Bateman & M. Ghorashi, 2009. First evidence for large earthquakes on the
11
12 409 Deshir Fault, Central Iran Plateau. *Terra Nova*, 21, 417–426.
13
14
15 410 Rittenour, T.M., 2008. Luminescence dating of fluvial deposits: applications to
16
17 411 geomorphic, palaeoseismic and archaeological research. *Boreas*, 37, 613-635.
18
19
20 412 R.G. Roberts, R.F. Galbraith, H. Yoshida, G.M. Laslett, J.M. Olley, 2000. Distinguishing dose
21
22 413 populations in sediment mixtures: a test of single-grain optical dating
23
24 414 procedures using mixtures of laboratory-dosed quartz. *Radiation Measurements*,
25
26 415 32 , 459-465.
27
28 416 Schmidt, A., Quigley, M., Fattahi, M., Azizi, Gh., Maghsoudi, M. and H. Fazeli, 2011.
29
30 417 Holocene settlement shifts and palaeoenvironments on the Central Iranian Plateau:
31
32 418 investigating linked systems. *The Holocene*, 21 (4), 583-595,
33
34 419 DOI:10.1177/0959683610385961.
35
36 420 Staubwasser, M., Sirocko, F., Grootes, P.M. and M. Segl, 2003. Climate change at the 4.2 ka
37
38 421 BP termination of the Indus valley civilization and Holocene south Asian monsoon
39
40 422 variability. *Geophys. Res. Lett.*, 30(8), 1425, doi:10.1029/2002GL016822.
41
42
43 423 Vernant, P., Nilforoushan, F., Hatzfeld, D., Abbassi, M.R., Vigny, C., Masson, F., Nankali, H.,
44
45 424 Martinod, J., Ashtiani, A., Bayer, R., Tavakoli, F. & J. Chéry, 2004. Present-day
46
47 425 crustal deformation and plate kinematics in the Middle East constrained by GPS
48
49 426 measurements in Iran and northern Oman. *Geophys. J. Int.*, 157, 381-398.
50
51
52 427 Walker, R. & M. Fattahi, 2011. A framework of Holocene and Late Pleistocene
53
54 428 environmental change in eastern Iran inferred from the dating of periods of
55
56 429 alluvial fan abandonment, river terracing, and lake deposition, *Quaternary*
57
58 430 *Science Reviews*, 30, 1256-1271, doi:10.1016/j.quascirev.2011.03.004.
59
60 431 Walker, R. & J. Jackson, 2004. Active tectonics and late Cenozoic strain distribution in
432
432 central and eastern Iran, *Tectonics*, 23, TC5010, doi:10.1029/2003TC001529.

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Figure captions

Figure 1. Landsat mosaic of the Anar fault area. White squares for location of photograph in Figure 2, Quickbird extract in Figure 3, and location of OSL-2 sampling site. Upper right inset locates the area within a simplified seismotectonic map of Iran. K, D, A, KB, N and G, respectively for Kashan, Dehshir, Anar, Kuh Banan, Nayband, and Gowk faults.

Figure 2. Field photograph of the Anar fault (vertical arrows, top panel) taken towards the north from 31.2764°N and 55.1304°E with emphasis on a 3 m right-lateral offset rill (horizontal arrow, bottom panel).

Figure 3. (a) Quickbird imagery of the Anar fault trace (red arrows) centred on the paleoseismological site (rectangle). Circle indicates the 8 ± 0.5 m cumulative dextral-offset riser described as site 1 in Le Dortz et al. (2009). (b) Topographic DGPS map (top) and profiles (bottom) of the paleoseismological site. Contour interval is 5 cm (survey data not tied to absolute elevation). The smooth and subdued E-facing fault scarp is indicated by a red overprint and the location of the trench by a rectangle. Violet and green dots locate the DGPS data points used for the topographic profiles. (c) Field photograph, looking south, of the E-facing fault scarp. The upper part of the southern trench wall is in the foreground. Three white labels that are 1-m spaced show scale on trench wall.

Figure 4. Composite photomosaic of the sediments exposed in the Anar trench excavation, with top four meters (between 11 and 12 meters) east and bottom two meters (between 19 and 20 meters) west of the main fault zone (a), and corresponding stratigraphic log of the units with vertical positions of dated samples (b). Numbers indicate units described in detail in Table 1. Three event horizons (EH-A, -B and -C) are shown as thick black lines (see text for discussion). Stars locate the positions (see exact location in Figure 5) of the six samples with OSL ages given (c).

Figure 5. (Top) Photomosaic of southern trench wall (see Figure 3 for location). (Bottom) Corresponding log, with labels marking the stratigraphic units. Faults and fractures are shown with red and dashed red lines, respectively. Short black lines

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3 463 represent bedding of sedimentary layers. Event horizons discussed in text are labelled
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5 464 as EH-A, EH-B and EH-C. Labelled black stars locate the OSL samples. Sample Ant-I,
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7 465 collected west of the fault zone at 4.1-m-deep within unit 2, yields an age of 13.6 ± 1.3 ka.
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9 466 Sample Ant-II, collected east of the fault zone at 4.2-m-deep within unit 5, yields an age
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11 467 of 12.4 ± 0.6 ka. Sample Ant-III, collected at 1.5-m-deep in a sandy lens of unit 9, yields a
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13 468 poorly constrain ages between 11.5 and 3.3 ka. Sample Ant-IV, collected at 1.5-m-deep at
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15 469 the base of a fissure filled with eolian and runoff sand deposits within unit 12, yields an
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17 470 age of 6.2 ± 0.6 ka. Sample Ant-V, collected at 1-m-deep within unit 11, yields an age of
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19 471 7.1 ± 0.7 ka. Sample Ant-VI, collected at 0.8-m-deep in a sandy lens within unit 14, yields
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21 472 an age of 6.2 ± 0.4 ka.

22 473 **Figure 6.** Photomosaic (top) and interpretation (bottom) of the main faulted
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24 474 zone showing evidence for the most recent earthquake (event A). Units 11 to 15,
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26 475 affected by faulting, are warped downward, while undeformed units 16 and 17 lie
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28 476 unconformably atop. Faults and tiny fractures are shown as red and dashed red lines,
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30 477 respectively.

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32 478 **Figure 7.** Schematic view of possible restoration of trench log showing sequence
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34 479 of faulting and depositional phases from present-day (step 1) to prior to the oldest
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36 480 paleoearthquake (step 7). The trench log has been simplified for clarity. Dashed black
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38 481 lines show inferred ground surface prior to the erosion. Step 1) is present-day situation.
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40 482 Step 2) is E-facing fault scarp formed during the most recent earthquake. Step 3) is
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42 483 restoration of the ground surface to its position prior to event A showing a vertical
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44 484 displacement of about 60 cm created by faulting on the eastern branch. Step 4) is the
45
46 485 penultimate earthquake denoted by open fissures and cracks formed near the main
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48 486 faulted zone. Sand-blows also emplaced in both sides and away of the main faulted zone.
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50 487 Step 5) is restoration of the ground surface to its position prior to event B showing
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52 488 vertical displacement created during penultimate earthquake on the eastern and
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54 489 western fault branches about 25 and 15 cm, respectively. Step 6) is the oldest
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56 490 earthquake, it has produced some surficial fissures within downthrown (eastern) block
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58 491 and a 25-cm-height E-facing fault scarp. Step 7) is restoration of the ground surface to its
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60 492 position prior to event C, showing a vertical displacement of about 25 cm.

493 **Figure 8.** Evidence for the penultimate earthquake (event B) encountered in a
494
fissure fill and a liquefaction feature (sand-blow) at 16 and 22 meters of the trench log,

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3 495 respectively. Red lines correspond to tiny cracks postdating the penultimate earthquake.
4
5 496 (a) Photomosaic of fissure filled with eolian sands and silts and interpretative sketch.
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7 497 The fissure is ~85-cm-deep and up to ~55-cm-wide, tapering downward through unit 9.
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9 498 Colours denote stratigraphy as shown in Figures 4 and 5. The material at the base of the
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11 499 fissure includes a collapsed piece from sidewall and grades into interbedded sand and
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13 500 silt layers. The fissure is sealed by a grey, well-stratified, surficial runoff deposit (unit
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15 501 13). (b) Photomosaic and interpretative sketch of a sand-blow (unit 12) made of sandy
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17 502 material of unit 8 injected into and deforming units 9 and 11. Hydraulic fractures,
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19 503 vertical and oblique alignments of dragged sands and gravels deform the host sediments
20
21 504 close to the liquefaction pillar.

22 505 **Figure 9.** Five well-constrained OSL ages place bounds on the ages of the three
23
24 506 paleoearthquakes (A, B, and C) identified in the Anar trench exposure. Light grey areas
25
26 507 represent the maximum time windows for the past earthquakes, dark grey pointing the
27
28 508 minimum time window for event C. For event A, hatched domain shows the preferred
29
30 509 time interval of the earthquake (4.4 ± 0.8 ka). Colour codes are similar to units shown in
31
32 510 Figures 4 and 5. Question mark illustrates the ambiguity due to the lack of ages in units
33
34 511 postdating the most recent earthquake (16 and 17).

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36 512
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38 513 **Table 1.** Detailed description of the units observed in the trench excavated across the
39
40 514 Anar fault, corresponding stratigraphic column and log are shown in Figures 4 and 5,
41
42 515 respectively.

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45 517 **Table 2.** Calculated OSL ages on the Anar samples with their parameters. Ages have
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47 518 been calculated for quartz grains with size ranging between 90 and 150 microns.

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520 Table 1

521	522	Unit	Detailed Stratigraphic Explanation
523	17		Light grey to cream, poorly stratified, silty sand with some angular gravels (20%, 0.5-2 cm).
524	16		Light cream, fairly stratified, medium consolidated, angular gravels (60%, 0.5-6 cm), with sand and silt matrix and some gypsiferous cementation.
525			
526	15		Buff to light grey, well stratified, medium consolidated, angular gravels (50%, 0.5-10 cm), with sand and silt matrix and some gypsiferous cementation.
527			
528	14		Grey to buff grey, thinly stratified, medium consolidated sand and angular granules (0.5-4 cm) with cross-bedding.
529			
530	13		Grey, well stratified, medium to well consolidated, coarse sand with angular granules and few pebbles (30%, 0.2-6 cm). The unit bottom is erosive and rests both on units 12 and 11.
531			
532	12		Light cream to grey, sandy fissure fills and sand-blows.
533	11		Brown to olive cream, roughly stratified, medium to well consolidated, silts and sands with some channels of angular gravels (40%, 0.1-4 cm). The top exhibits a hard gypsiferous calcrete.
534			
535	10		Cream to grey, fairly stratified, poorly consolidated, coarse sands and angular gravels (50%, 0.1-3 cm) with sandy-silty matrix and some cross-bedding.
536			
537	9		Reddish brown to brownish grey, non-stratified, semi-consolidated coarse sand, with clayish silt matrix, including some channels of angular gravels (90%, 2-15 cm) with silt matrix.
538			
539	8		Cream to brownish grey, fairly stratified, well consolidated, angular granules and pebbles (60%, 0.2-3 cm), with silty sand matrix, including some small cobbles and traces of sulfate calcrete within the coarser levels.
540			
541	7		Grey to brownish grey, poorly stratified, poorly sorted angular pebbles (70%, 0.5-10 cm), with sandy silt matrix.
542			
543	6		Cream to brown, fairly stratified, angular granules and pebbles (80%, 0.2-4 cm), with silty sand matrix, including some sparse big cobbles and silty sand lenses.
544			
545	5		Buff to light grey, fairly stratified, loose silt and sand.
546	4		Grey to light grey, poorly stratified, well sorted, silty sands with some cross-bedding and gravelly lenses.
547	3		Grey, fairly stratified, well consolidated, medium to well sorted, coarse angular gravels (90%, 0.5-10 cm) with silty sand matrix, including some sparse bigger cobbles and clayish silty sand lenses.
548			
549	2		Grey, stratified, loose, silty sand, with some cross-bedding.
550	1		Grey, poorly stratified, well consolidated, angular pebbles (>20%, 0.5-3 cm) with silty sand matrix.
551			

552 Table 2

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Sample	Latitude ° N	Longitude ° E	Depth (m)	Water (%)	K (%)	U (%)	Th (%)	Annual dose rate (Gy/ka)	over- dispersion (%)	Skewness	CAM De (Gy)	FMM De (Gy)	Age (ka)
Ant-I (OSL1-b)*	31.1952	55.1534	4.1	2	0.93±0.03	1.16±0.05	4.0±0.1	1.64±0.05	24	0.69	22.3±1.90		13.6±1.3 ^a
Ant-II	31.1952	55.1534	4.2	0.4	0.77±0.03	0.97±0.05	3.4±0.1	1.42±0.04	27	4.09	16.1±0.90	17.5±0.47	12.4±0.6 ^b
Ant-III	31.1952	55.1534	1.7	1.1	0.97±0.01	1.23±0.05	4.3±0.1	1.75±0.04	51	2.1	9.7±1.09	6.1±0.24	3.5±0.2 ^b
Ant-IV	31.1952	55.1534	1.5	0.6	0.94±0.01	1.44±0.05	3.7±0.1	1.78±0.14	20	0.01	11.0±0.61		6.2±0.6 ^a
Ant-V	31.1952	55.1534	1.0	0.3	0.99±0.01	1.72±0.05	4.2±0.1	1.96±0.14	25	0.35	13.5±0.90	13.9±0.70	7.1±0.7 ^b
Ant-VI (OSL1-a)*	31.1952	55.1534	0.8	0.6	1.21±0.01	1.60±0.05	5.9±0.1	2.20±0.05	42	0.94	11.6±1.39	13.7±0.56	6.2±0.4 ^c
OSL-2	31.2697	55.1337	0.8	1.1	1.06±0.01	1.33±0.05	4.0±0.1	1.90±0.05	41	2.39	20.1±2.16	19.3±0.76	10.1±0.6 ^c

554

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^a Age based on De determined using Central Age Model (CAM; Galbraith et al., 1999).

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^b Age based on De determined using the dominant component of Finite Mixture Modeling (FMM; Roberts et al., 2000).

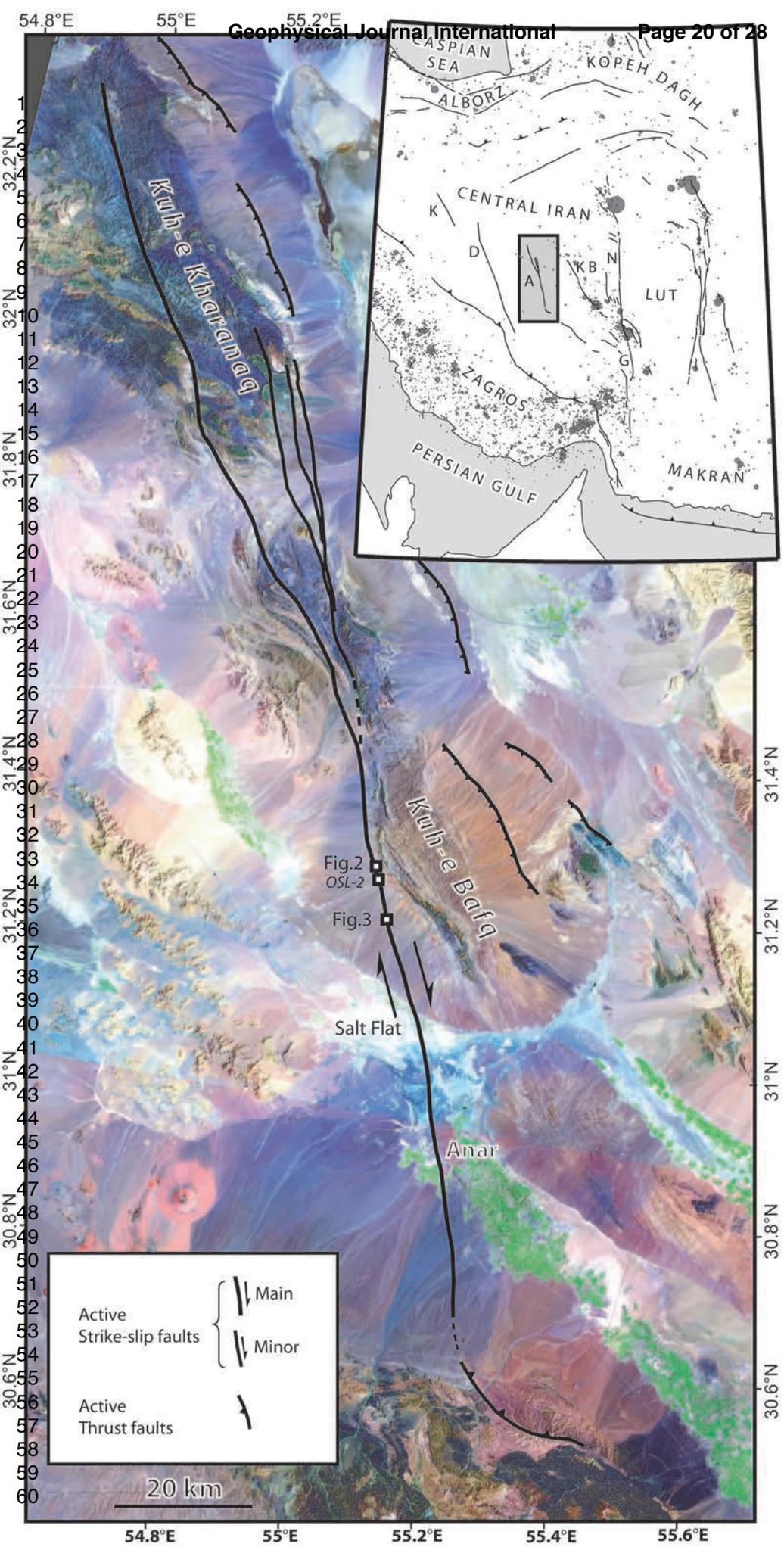
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^c Age previously published, now refined using Finite Mixture Modeling (FMM; Roberts et al., 2000).

558

* Parenthesis contains the sample label used by Le Dortz et al. (2009)

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54.8°E
55°E
55.2°E
55.4°E
55.6°E
32.2°N
32.0°N
31.8°N
31.6°N
31.4°N
31.2°N
31.0°N
30.8°N
30.6°N

32.2°N
32.0°N
31.8°N
31.6°N
31.4°N
31.2°N
31.0°N
30.8°N
30.6°N

Active Strike-slip faults
Main
Minor
Active Thrust faults

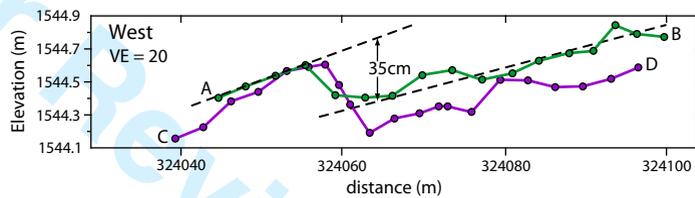
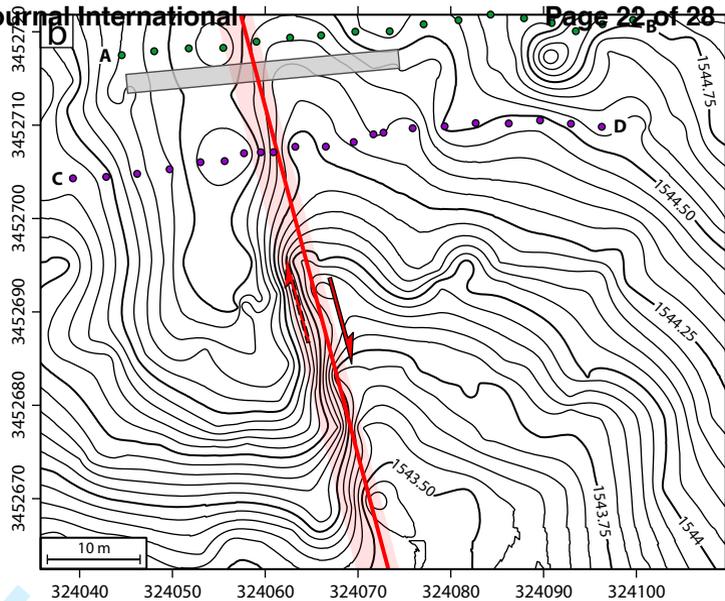
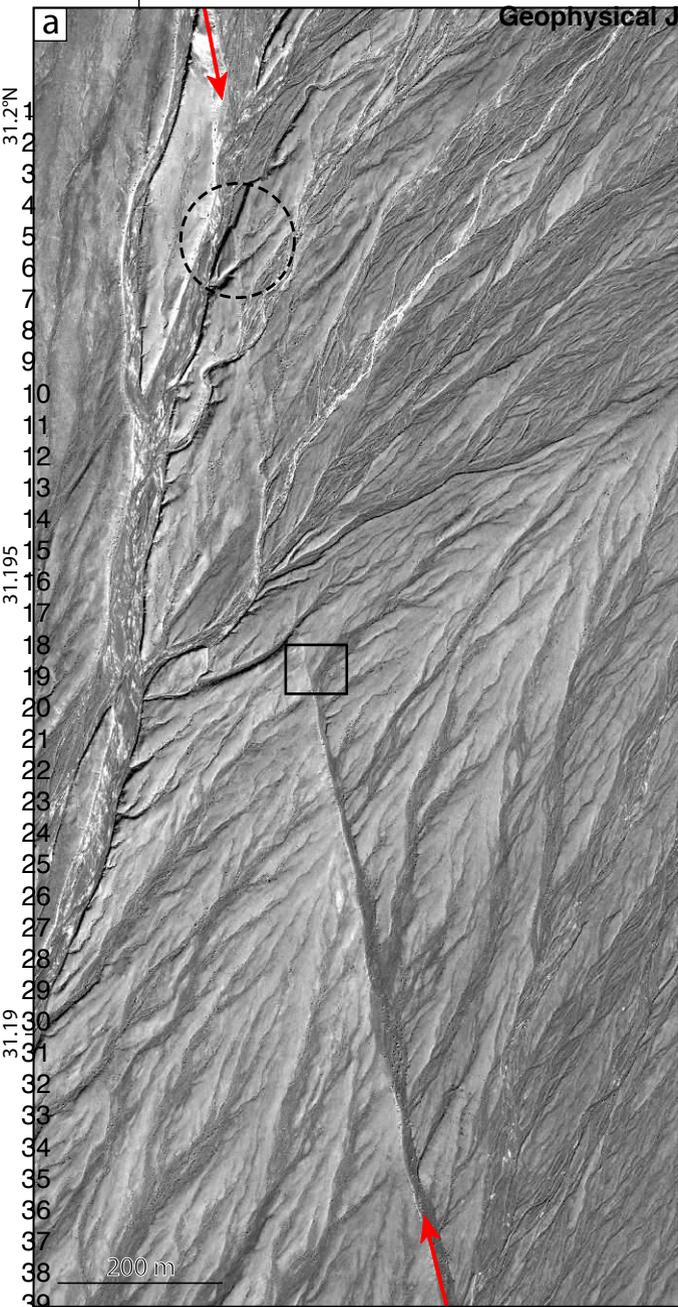
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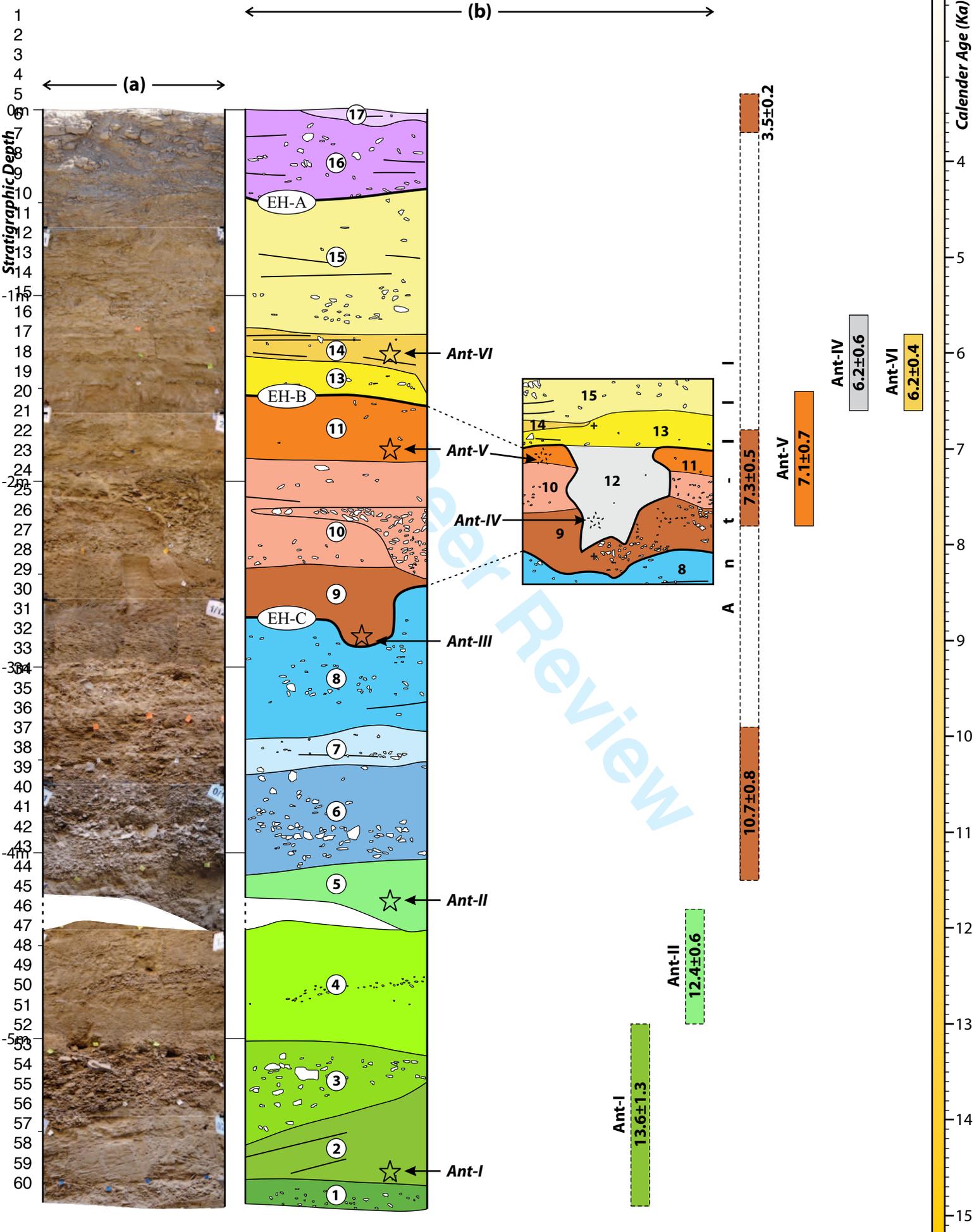
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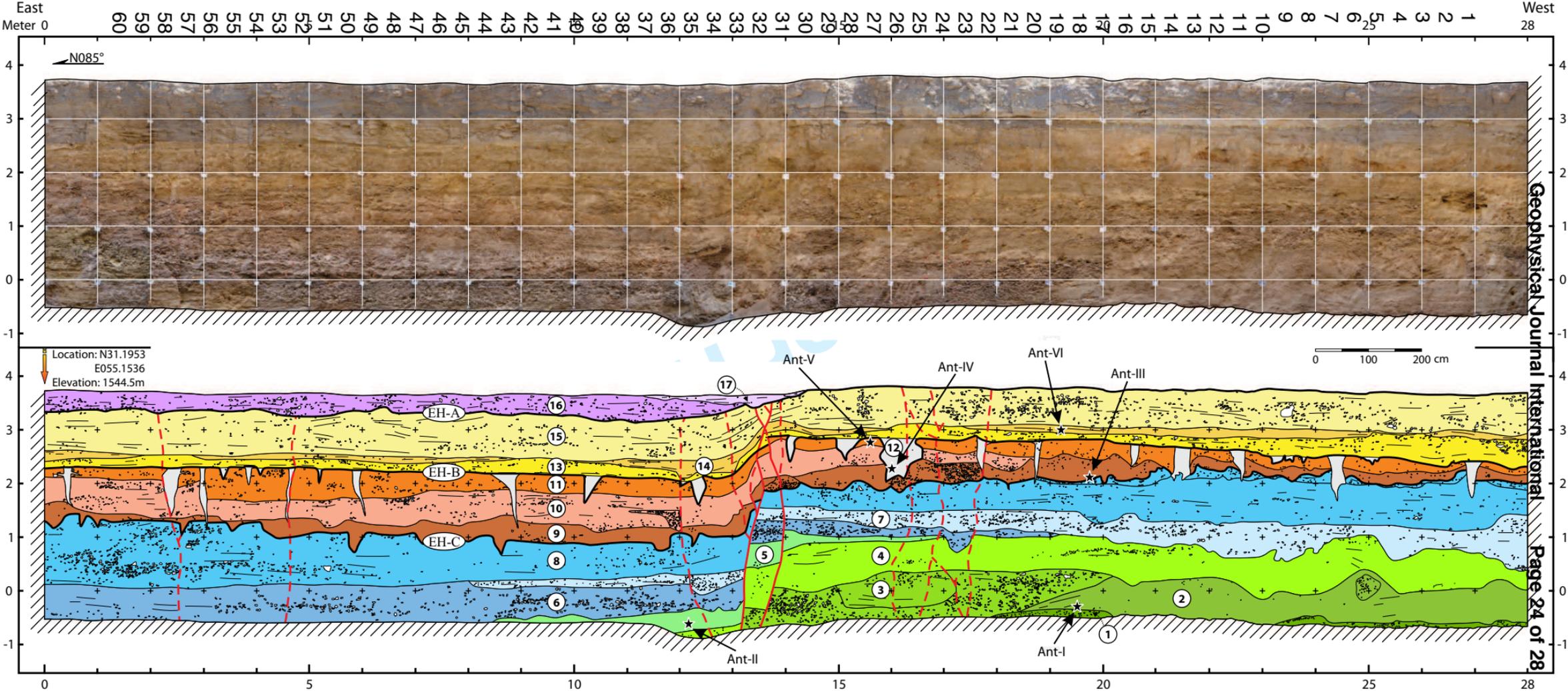


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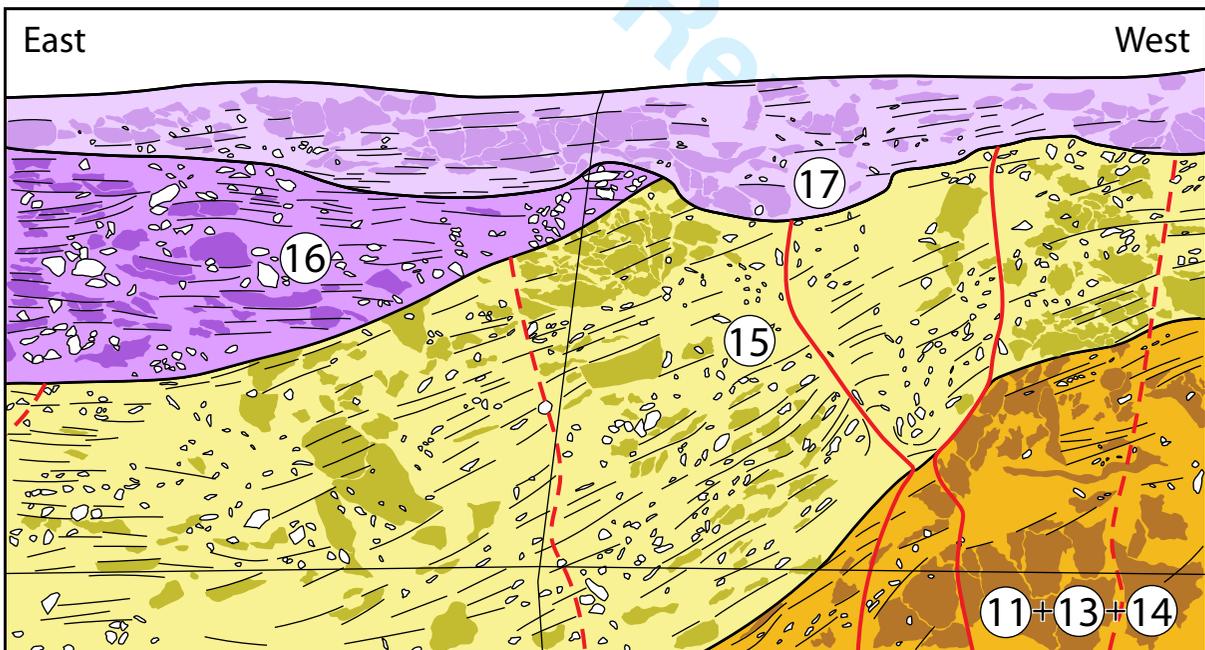
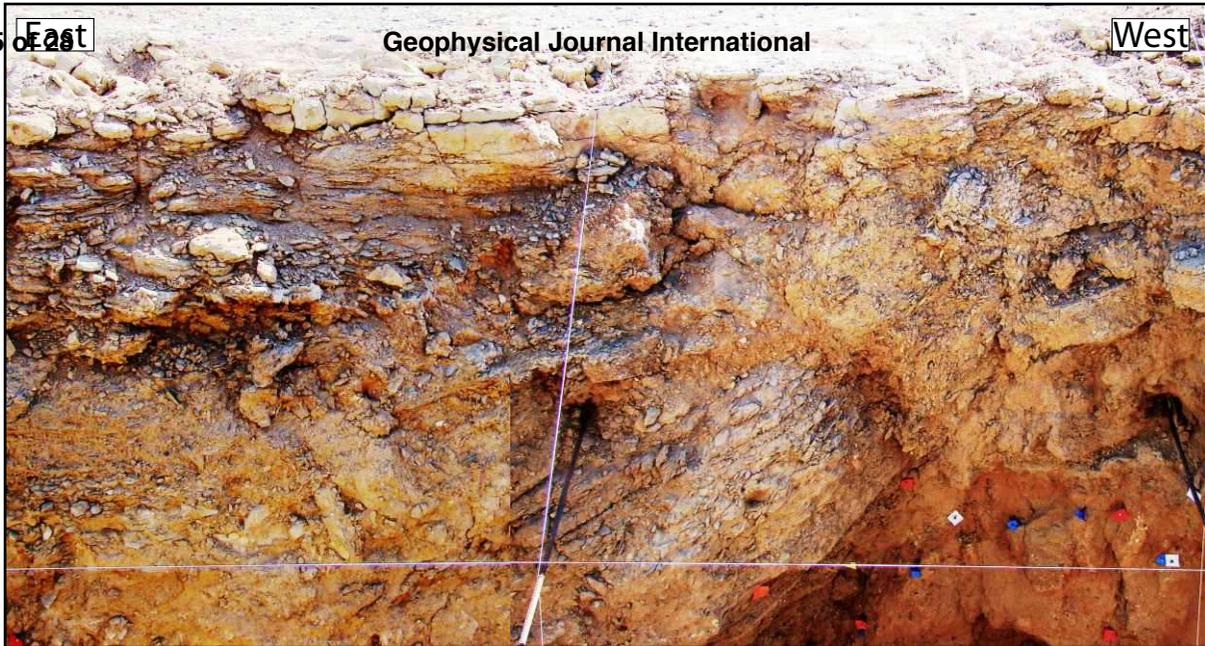


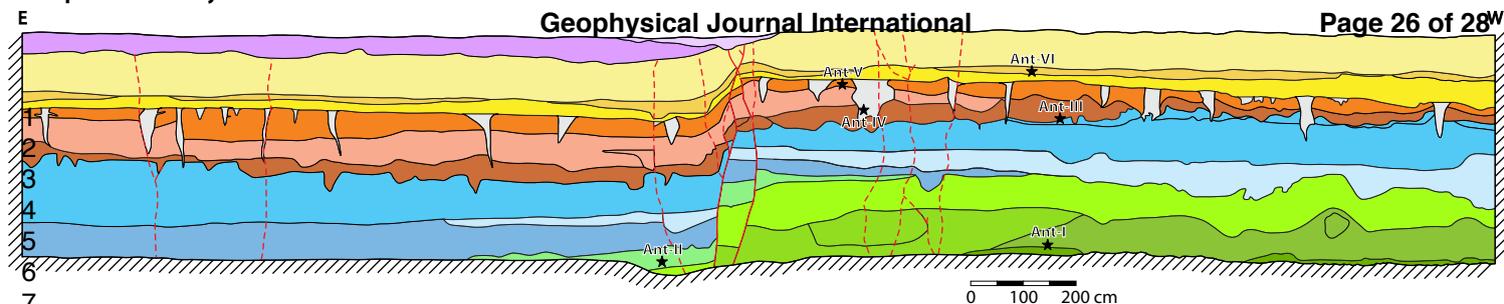




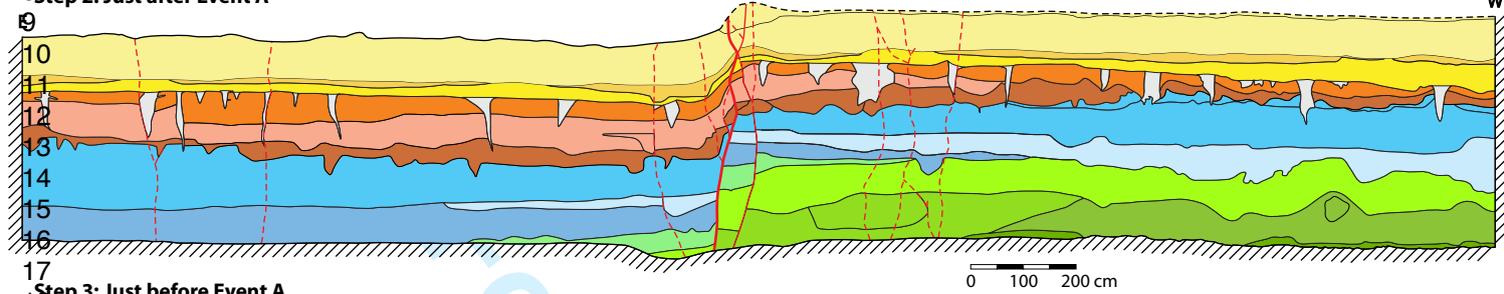


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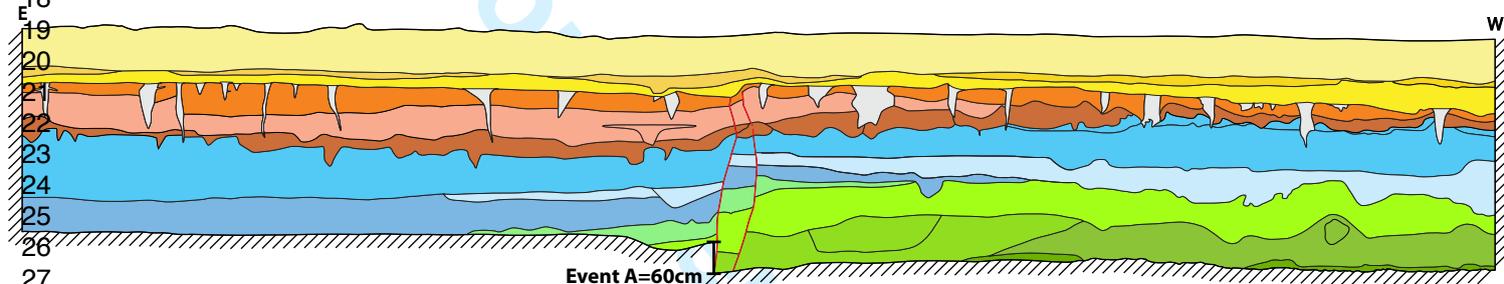




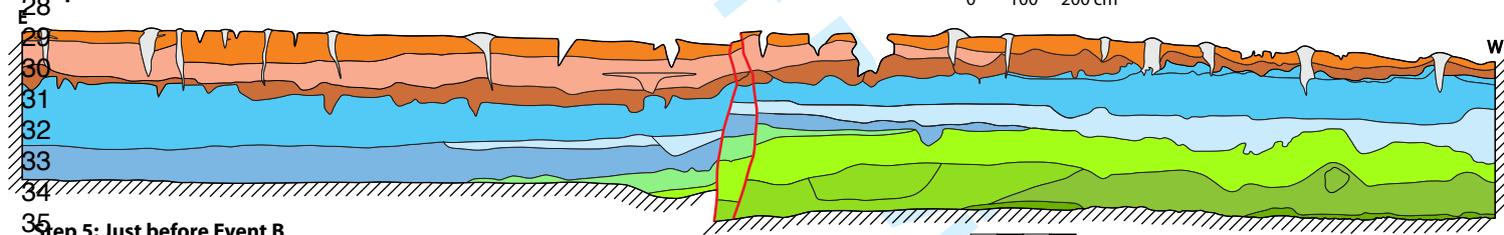
Step 2: Just after Event A



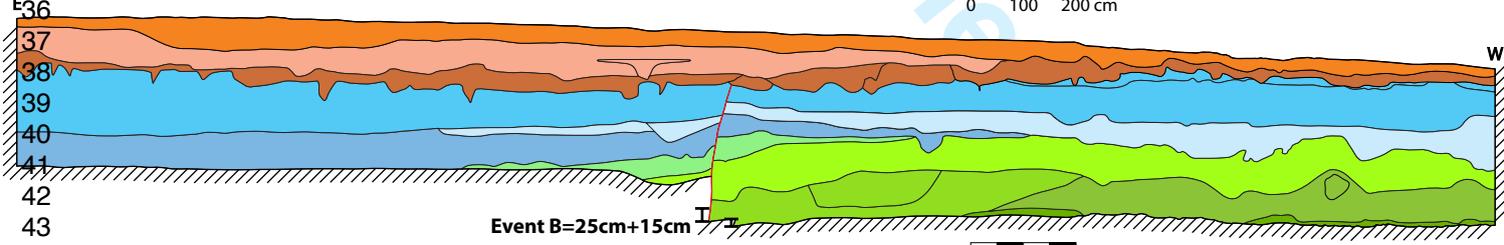
Step 3: Just before Event A



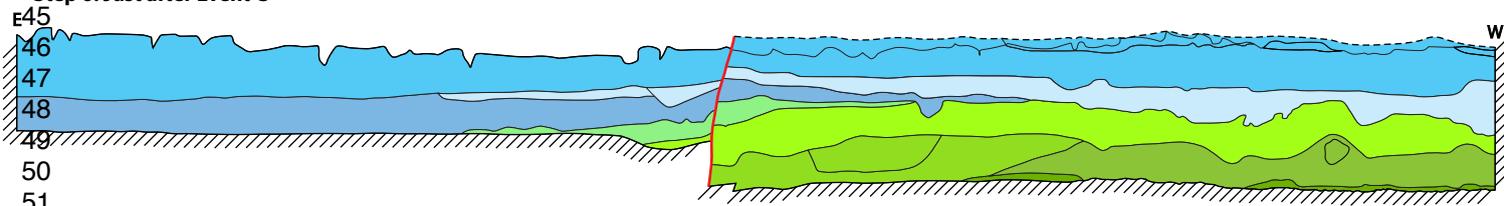
Step 4: Just after Event B



Step 5: Just before Event B



Step 6: Just after Event C



Step 7: Just before Event C

