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1 **Giant landslide triggerings and paleoprecipitations in the Central Western Andes: the Aricota**  
2 **rockslide dam (South Peru)**

3

4 Fabrizio Delgado <sup>1,2</sup>, Swann Zerathe <sup>2 \*</sup>, Laurence Audin <sup>2</sup>, Stéphane Schwartz <sup>2</sup>, Carlos Benavente <sup>3</sup>,  
5 Julien Carcaillet <sup>2</sup>, Didier L. Bourlès <sup>4</sup>, ASTER Team <sup>4,#</sup>.

6

7 <sup>1</sup> Especialidad Ingeniería Geológica, Facultad de Ciencias e Ingeniería. Pontificia Universidad Católica  
8 del Perú, Av. Universitaria 1801, San Miguel, Lima 15088, Perú.

9 <sup>2</sup> Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre, 38000 Grenoble,  
10 France

11 <sup>3</sup> Instituto Geológico, Minero y Metalúrgico INGEMMET, Av. Canadá 1470, Lima, Perú

12 <sup>4</sup> Aix-Marseille Univ., CNRS, IRD, Coll. France, UM 34 CEREGE, Technopôle de l'Environnement Arbois-  
13 Méditerranée, BP80, 13545 Aix-en-Provence, France

14 # Georges Aumaître and Karim Keddadouche

15

16 \* *Corresponding author: S Zerathe*

17 *Tel.:+33 4 76 51 40 74*

18 *E-mail address: swann.zerathe@ird.fr*

19

20 **Abstract**

21 The central part of the Western Andes holds an exceptional concentration of giant paleolandslides  
22 involving very large volumes of rock material ( $v > \text{km}^3$ ). While those gravitational slope failures are  
23 interpreted consensually as an erosional response to the geodynamic activity of the Andes (relief  
24 formation and tectonic activity), the question of their triggering mechanisms remains enigmatic. To  
25 clarify the respective roles of climatic versus seismic forcing on the Andean landslides, new temporal  
26 constraints on paleo movements are essential. Here, we focus on one of those giant slope failures,

27 the Aricota giant landslide that damned the Locumba valley in southern Peru. We conducted  
28 fieldwork, high-resolution DEM analysis and cosmogenic nuclide dating to decipher its development  
29 history and failure mechanisms. Our results point to the occurrence of two successive rockslide  
30 events. A giant failure mobilizing a rock volume of ca. 2 km<sup>3</sup> first produced a dam at 17.9 ± 0.7 ka.  
31 Considering its height of ca. 600 m, the Aricota rockslide dam is one of the five largest landslide  
32 dams. At 12.1 ± 0.2 ka, a second event produced ca. 0.2 km<sup>3</sup> of material, and the rock-avalanche  
33 debris spread out over the dam. As the chronology of those two events is pointing to the two main  
34 paleoclimatic pluvial periods in this region (Heinrich Stadial 1a and Younger Dryas), we favor the  
35 interpretation of a climatic forcing. At a regional scale, the concomitant aggradation of alluvial  
36 terraces and fan systems along the nearby valleys highlights higher regional erosion, sediments  
37 supply and mass-wasting events during those paleoprecipitation events and strengthens this  
38 conclusion.

39

#### 40 **Keywords**

41 Giant landslide dam; Central Western Andes; <sup>10</sup>Be dating; Triggering factors

42

#### 43 **1. Introduction**

44 The Western flank of the Central Andes (south Peru - north Chile) holds one of the most exceptional  
45 concentrations of giant landslides worldwide (Crosta et al., 2014). Those gravitational instabilities  
46 mobilize large volume of rock material (> 10<sup>9</sup> m<sup>3</sup>), with debris propagation over long distance (> 10<sup>3</sup>  
47 m) affecting the Western Cordillera from elevations between 4500 m to sea level (e.g. Wörner et al.,  
48 2002; Strasser and Schlunegger, 2005; Pinto et al., 2008; Crosta et al., 2014). This Andean area is  
49 particularly active geodynamically, related to the long-term convergence between the Nazca and the  
50 South America plates. The global shortening is associated with the relief construction, producing  
51 instantaneous deformation (crustal seismicity) coupled with long-term processes of surface uplift

52 and volcanism (Thouret et al., 2017; Benavente et al., 2017). In this region, the large-scale landsliding  
53 is suspected to be an efficient relief erosion mechanism at regional scale (Mather et al., 2014).  
54 Additionally, the Western Andean flank presents a climatic setting marked by a dominant hyper-  
55 aridity persisting at least since 20 million years (e.g. Dunai et al., 2005). This particular climate  
56 environment, with very low denudation rates (typically 1 - 10 mm.kyr<sup>-1</sup>; Nishiizumi et al., 2005;  
57 Madella et al., 2018), allows the local preservation of landscape over hundreds of thousands years  
58 (e.g. Zerathe et al., 2017). This offers a unique opportunity to track gravitational slope processes over  
59 a temporal scale currently unknown, close to the timing of the orogen evolution (Hermanns et al.,  
60 2001).

61 On the other hand, the development of such giant landslides in a desert environment raise the  
62 question of their triggering conditions and failure mechanisms. In the literature, this question is  
63 largely debated with two main opposite views implying seismicity versus climatic controls (Moreiras  
64 and Sepúlveda, 2015). For examples, McPhillips et al. (2014) suggest that at a millennial-scale, the  
65 record of landslides activity in the Andes is mainly consistent with earthquake trigger, whereas  
66 Margirier et al. (2015) identified a correlation between the activity phases of a giant paleolandslide  
67 (Chuquibamba, south Peru) and wet climatic events on the Altiplano. As pointed by Moreiras and  
68 Sepúlveda (2015), in order to push away the limit of this debate and to decipher the respective role  
69 of each forcing, new temporal constraints on giant Andean paleolandslides are required. Indeed,  
70 while numerous giant landslides have been identified along the western Andean flank (Audin and  
71 Bechir, 2006; Crosta et al., 2014), the great majority of them have not been dated yet. In this context,  
72 the cosmogenic nuclide dating, applied to either landslide scarps or boulders, is specifically pertinent  
73 to constrain the timing of slope evolution (Zerathe et al., 2017; Crosta et al., 2017).

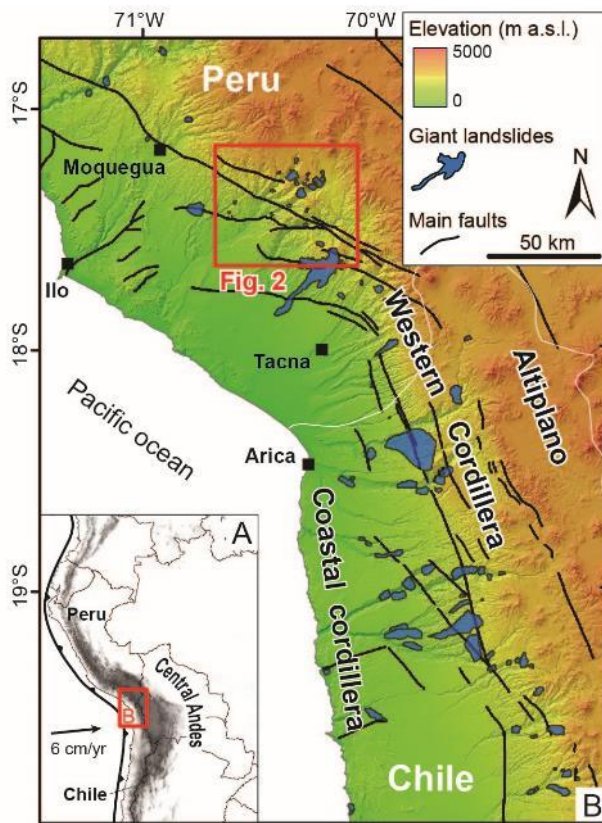
74 In this paper, we combined geomorphological analysis based on high resolution Pléiades DEMs and  
75 geochronological dating using <sup>10</sup>Be produced within quartz minerals (in situ-produced <sup>10</sup>Be) in order  
76 to document the chronology and to determine the context in which the Aricota giant rockslide dam  
77 (Central Western Andes, South Peru) occurred.

78

## 79 2. Geological context and landslide setting

80 The study area is located in the South Peru at  $\sim 17^{\circ}\text{S}$  latitude, along the Western flank of the Central  
81 Andean Cordillera (Figure 1), where ongoing subduction of the Nazca Plate occurs with a  
82 convergence velocity of about  $62 \text{ mm}\cdot\text{yr}^{-1}$  (e.g. Villegas-Lanza et al., 2016). The geomorphology of  
83 this region is contrasted and shows from West to East: (1) a coastal cordillera with a maximum  
84 elevation of 1000 m a.s.l., (2) the Western Cordillera with elevations comprised between 1000 and  
85 4500 m a.s.l., and (3) the Altiplano plateau reaching 5000 m a.s.l.. This western flank of the Andes is  
86 carved by deep valleys and canyons related to a regional uplift (e.g. Thouret et al., 2007; Schildgen et  
87 al., 2009 ; Gunnell et al., 2010 and references therein). The Western Cordillera is affected by  
88 westward major thrusts (Figure 1) oriented parallel to the subduction trench (Hall et al., 2012;  
89 Benavente et al., 2017). The timing and the processes involved in the creation of the Andean relief in  
90 this region are still debated. Sempere et al. (2008) propose a rapid uplift of about 2.5 km since the  
91 Late Miocene (11 to 6 Ma) in response to a large-scale mantle delamination. Armijo et al. (2015)  
92 propose that the topography was controlled by crustal thickening during the Paleogene (50 to 30 Ma)  
93 in response to the tectonic shortening of the Central Andes. This process is responsible for aridity  
94 increase of the Atacama Desert during the Neogene (Evenstar et al., 2015). Recently, Thouret et al.  
95 (2017) provide a compilation of  $^{40}\text{Ar}/^{39}\text{Ar}$  and U/Pb dating of ignimbrite deposit covering this region,  
96 which helped to decipher the canyon incision chronology. Their dataset suggest that uplift was  
97 gradual over the past 25 Ma and accelerated after 9 Ma. The valley incisions start around 11–9 Ma  
98 and accelerate between 5 and 4 Ma. Pleistocene uplift rates of  $0.2$  to  $0.4 \text{ mm}\cdot\text{yr}^{-1}$  have been derived  
99 from cosmogenic dating (Hall et al., 2012), and interpreted as a combination of tectonic shortening  
100 along steep westvergent faults of the western flank and isostatic responses to fluvial erosion  
101 associated with large scale landslide processes. The same conclusion is reached by Viveen and  
102 Schlunegger (2018) showing uplift at the Quaternary time scale in the Moquegua region. However, at

103 the scale of the Peruvian forearc, their conclusions open other perspectives showing possible  
104 alternating phases of compressional and transtensional tectonics during the Cenozoic.



105  
106 **Figure 1 : Morpho-tectonic context of the Central Western Andes and location of the study area. Hillshade**  
107 **and elevation are produced using the ASTER DEM (resolution 30 m). Main faults are reported from *Hall et al.***  
108 **(2012), *Armijo et al. (2015)* and *Benavente et al. (2017)*. The database of giant landslides is compiled from**  
109 ***Audin and Bechir (2006)*, *Crosta et al. (2014)*; *Mather et al. (2014)*, *Zerathe et al. (2017)* and adding personal**  
110 **mapping from this study.**

111  
112 The progressive Cenozoic onset of the Andean relief acted as an important topographic barrier  
113 impeding the cross of cloud currents and precipitation from the Amazonian basin (*Houston and*  
114 *Hartley, 2003*). As a result, hyper-arid conditions have developed and still currently prevail in the so-  
115 called Atacama Desert, along the Western Central Andes, allowing for long-term preservation of  
116 landscapes (up to several millions of years, e.g. *Dunai et al., 2005*). As contrasting with this long-term  
117 dry climate, the flank of Western Central Andes, between latitudes 17°S and 20°S, holds an  
118 exceptional concentration of some of the largest landslides identified at the Earth surface (Figure 1).

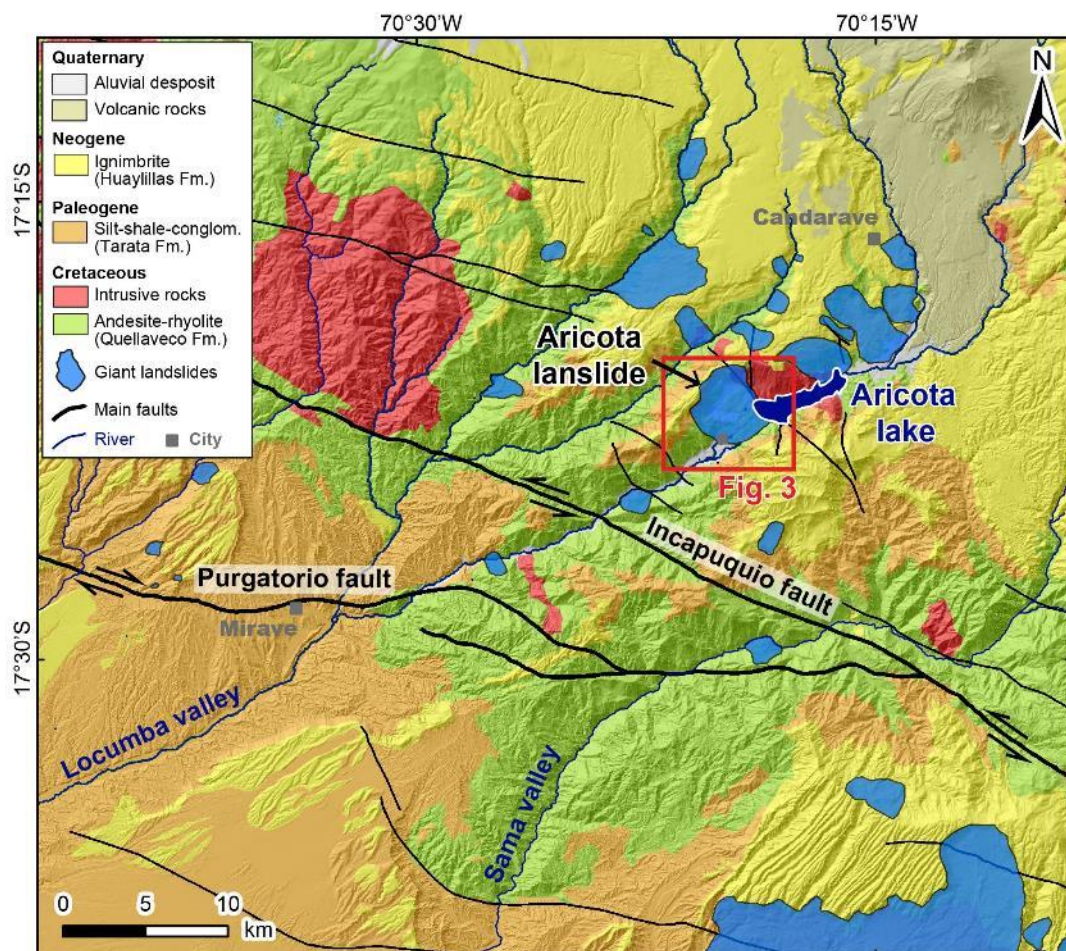
119 The imprint of those giant landslides have been progressively identified and mapped since a decade  
120 (e.g. [Audin and Bechir, 2006](#); [Crosta et al., 2014](#)). From North to South, some impressive examples  
121 among others are: the Chuquibamba landslide - 40 km<sup>3</sup> ([Margirier et al., 2015](#); [Thouret et al., 2017](#)),  
122 the Caquilluco landslide - 15 km<sup>3</sup> ([Zerathe et al., 2017](#)), the Lluta Landslide - 26 km<sup>3</sup> ([Wörner et al.,](#)  
123 [2002](#) ; [Strasser and Schlunegger, 2005](#)), the Minimini landslide -  $v > 5$  km<sup>3</sup>, the Latagualla landslide - 5.4  
124 km<sup>3</sup> ([Pinto et al., 2008](#)) or the Magnifico landslide - 0.2 km<sup>3</sup> ([Mather et al., 2014](#); [Crosta et al., 2017](#)).  
125 Only few of those giant landslides have been precisely dated (e.g. [Zerathe et al., 2017](#); [Crosta et al.,](#)  
126 [2017](#)). Paleo-climatic variations and/or active tectonic and seismicity are considered both as possible  
127 factors of forcing. However, mainly because of the lack precise of chronological constraints on these  
128 events, there is no consensus to date about the reason of their triggerings ([McPhillips et al., 2014](#);  
129 [Margirier et al., 2015](#)).

130 In this paper, we focus on one of those giant landslides, the Aricota rockslide dam. It developed in  
131 the middle of the Locumba valley whose basin extends across the whole Western Cordillera, from the  
132 Altiplano down to Pacific Ocean. The Aricota rockslide generated a large dam in the Locumba valley,  
133 forming a 6 km-long lake. The lithology observed around the valley is dominated by volcano-  
134 sedimentary rocks (Figure 2). The Aricota rockslide affects geological series that are almost  
135 horizontal. From the valley bottom to the plateau, we observe the following stratigraphic cross  
136 section: Cretaceous andesite and rhyolite of the Quellaveco formation, Paleogene silt and shales  
137 of the Tarata formation and Neogene ignimbrite of the Huaylillas formation unconformably  
138 covering the former (Figure 2). The Cretaceous layers are cut by intrusive granite at the north-east of  
139 the Aricota landslide zone. Neotectonic faults activities have been described recently south-west of  
140 the Aricota landslide, mainly along the Incapuquio fault system and the Purgatorio fault ([Hall et al.,](#)  
141 [2012](#); [Benavente et al., 2017](#)). The Incapuquio fault system is a sub-vertical lineament of ~400 km in  
142 length with a northwest-southeast trending direction and accommodates left lateral transpressive  
143 displacement. The Purgatorio fault accommodates right lateral transpressive displacement which has

144 produced at least two ruptures during the last thousands years with superficial offsets of several  
145 meters (Benavente et al., 2017).

146 On the Aricota rockslide dam site, two hydroelectric plants, "Aricota I and II" (35 MW) were built in  
147 1967. The continuous pumping of water caused a drop of the lake level of ~100 m in the last 50  
148 years, which allow studying paleo shorelines revealed by diatomite deposits (Placzek et al., 2001).  
149 Placzek et al. (2001) obtained radiocarbon calibrated ages ranging between ca. 300 and 7000 yr B.P.,  
150 pointing to high lake levels around 6100 yr B.P. and 1700-1300 yr B.P. and giving a minimum age of  
151 ca. 7 ka for the rockslide-dam emplacement. They identified in the morphology the existence of two  
152 successive failure events. However, the precise chronology of this landslide, the failure and triggering  
153 mechanisms remain unknown yet.

154



155



156 *Figure 2 : Geological settings around the Aricota landslide (see frame location on Figure 1). The geological*  
157 *map is adapted from INGEMMET (2011) and draped above hillshade produced using the TanDEM-X DEM*  
158 *(resolution 12 m). Quaternary crustal faults are reported (e.g. Incapuquio-Purgatorio fault system; Hall et al.,*  
159 *2012; Benavente et al., 2017). Giant landslides reported were mapped during this study.*

160

### 161 **3. Methods**

#### 162 *3.1. Pléiades DEM elaboration and mapping*

163 To identify and map the structures and deposits associated to the Aricota giant rockslide activity, we  
164 combine geomorphic and tectonic observations based on field data, analyses of high-resolution  
165 Digital Elevation Model (DEM) and Google Earth images. A high-resolution DEM was derived from  
166 two stereo images acquired by the Pléiades satellites on October 2015. The full resolution of these  
167 optical images is 0.7 m and their orientation was assessed using the Rational Polynomial Coefficient  
168 (RPC) provided in their ancillary data. We generated the DEM using the open source software Ames  
169 Stereo Pipeline (ASP) developed by NASA (Broxton and Edwards, 2008) and followed the three-step  
170 procedure. First, each image was map-projected using the low-resolution (30 m) SRTM DEM. Then  
171 the two images were bundle-adjusted based on automatically extracted tie points, before finding the  
172 disparities. The third step involved finding the intersection of all the rays coming from the  
173 homologous points of the image pair. This step leads to a point cloud of the surface topography,  
174 which is then converted onto a 2-m resolution grid (Figure 3A). Field campaigns were conducted in  
175 2014 and 2015 to (1) validate the observations/interpretations made about the different deposits  
176 and related events within the landslide mass, and (2) to sample boulders and scarps for cosmogenic  
177 nuclide surface exposure dating.

178

#### 179 *3.2. Cosmogenic nuclide surface exposure dating*

180 In order to determine the ages of the different events that occurred on the Aricota landslide area, a  
181 sampling strategy was designed according to our geomorphological mapping. Seventeen samples

182 were selected (Figure 3B). In order to constrain an accurate long-term and local denudation rate, one  
183 sample (AR1) was taken on the eroding surface (presumed at steady state) that is located on the  
184 plateau above the landslide scarp at ca. 3700 m a.s.l.. Three samples (AR3, AR4 and AR5) were  
185 extracted from the free-face of two preserved sub vertical scarps (bedrock). Thirteen samples were  
186 extracted from boulders distributed all over the landslide mass, including six samples (AR14 to AR21)  
187 from the main dam and seven others (AR6 to AR12, and AR27 to AR29) from a rock-avalanche  
188 deposit located on top of the dam (Figure 3B). A last boulder, AR29, has been taken tentatively to  
189 estimate past variations of the Aricota lake level (Figure 3B). Indeed, despite belonging  
190 morphologically to the rock-avalanche deposit, this boulder stands at an elevation that is of about 40  
191 m below the pre-1967 lake level (date of artificial lake lowering by pumping). In other words, before  
192 1967, tens of meters of water, sufficient to protect quasi-completely the AR29 boulder from cosmic  
193 ray primary and secondary particles, were covering it. Thus, any concentration measured in this  
194 sample might represent periods of past lake level drop that would be large enough to allow exposing  
195 the AR29 boulder to cosmic ray particles (at ten meters depth, the cosmogenic nuclide production  
196 rates are less than 0.2% that at the surface, [Gosse and Phillips, 2001](#)).

197 In general, we paid special attention to select boulders whose height and length were higher than 2  
198 m and with no trace of post-deposition toppling, nor large desquamations. Elevation, latitude and  
199 longitude were recorded with a handheld GPS. Pictures of the boulders are provided in the  
200 supplementary material.

201 Sample preparation and  $^{10}\text{Be}$  chemical extraction were achieved following routine procedure, which  
202 is detailed in the supplementary information, at the GTC Plateform, ISTERre laboratory (Grenoble,  
203 France).  $^{10}\text{Be}/^9\text{Be}$  measurements were performed at the French AMS National Facility, located at  
204 CEREGE in Aix-en-Provence ([Arnold et al., 2013](#)).  $^{10}\text{Be}/^9\text{Be}$  ratios were calibrated against the in-house  
205 standard STD-11, using an assigned  $^{10}\text{Be}/^9\text{Be}$  ratio of  $(1.191 \pm 0.013) \times 10^{-11}$  ([Braucher et al., 2015](#)).  
206 Uncertainties on  $^{10}\text{Be}$  concentrations (reported as  $1\sigma$ ) are calculated according to the standard error  
207 propagation method using the quadratic sum of the relative errors and include a conservative 0.5%

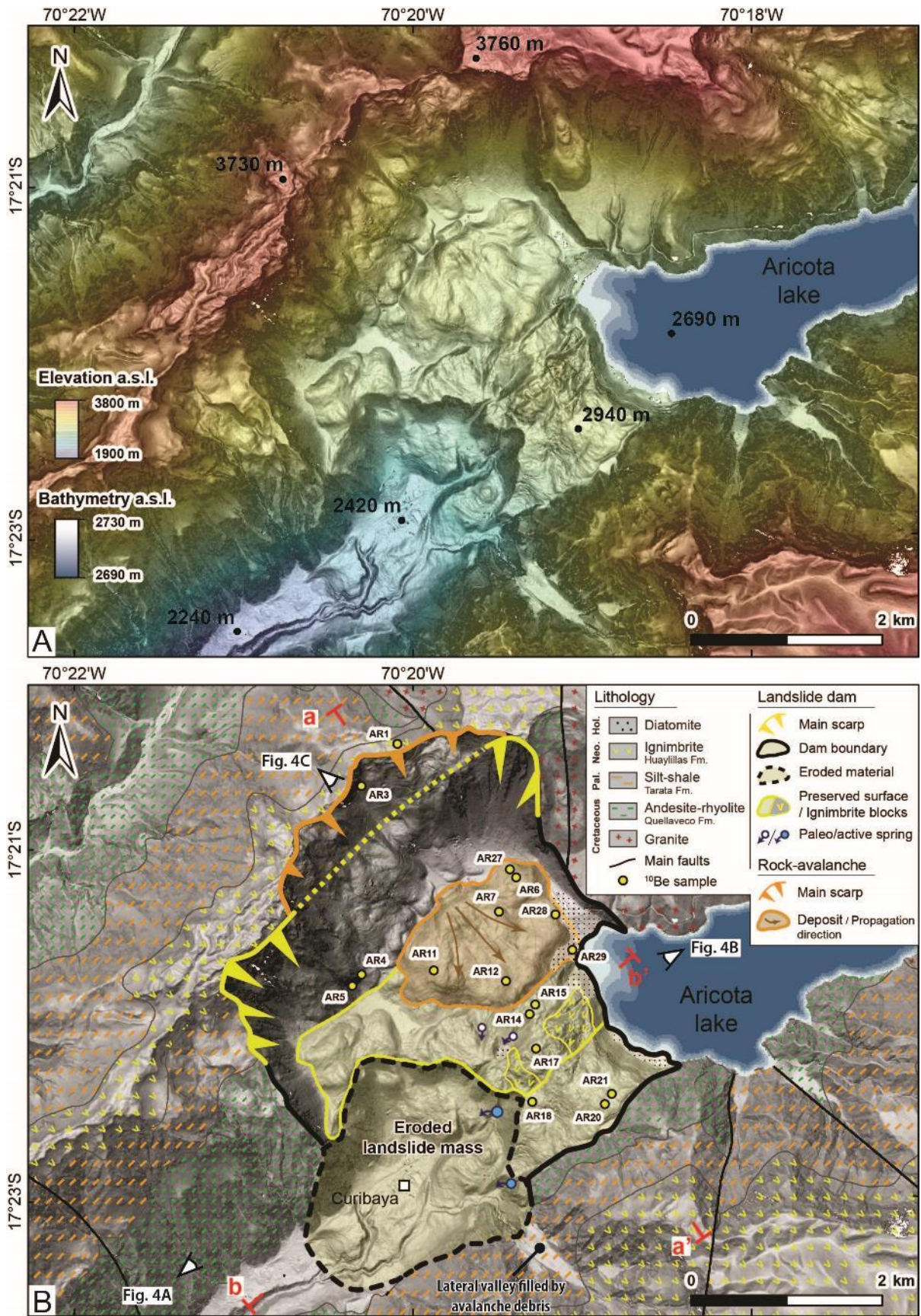
208 external machine uncertainty (Arnold et al., 2010), a 1.08% uncertainty on the certified standard  
209 ratio, a  $1\sigma$  uncertainty associated to the mean of the standard ratio measurements during the  
210 measurement cycles, a  $1\sigma$  statistical error on counted events and the uncertainty associated with the  
211 chemical and analytical blank correction.

212 Denudation rates and exposure durations were both calculated using the MATLAB<sup>®</sup>-based  
213 CRONUScalc program, developed by Marrero et al. (2016). We applied a globally calibrated <sup>10</sup>Be  
214 spallation production rate of  $4.09\pm 0.35$  at.gr<sup>-1</sup>.yr<sup>-1</sup> (sea level and high latitude; Borchers et al., 2016)  
215 which was scaled at the geographical and altitudinal location of each sampling site using the LSD  
216 scaling scheme (SF; Lifton et al., 2014; see details in the supplementary information).

217 We initially calculated long-term denudation rates for this area. As this will be detailed in the  
218 following results, in addition to the dedicated sample AR1, two other samples (AR14 and AR15) were  
219 considered for denudation rates calculation.

220 Finally, exposure duration calculations were performed considering this locally constrained  
221 denudation rate. Both analytical and total uncertainties ( $1\sigma$ ) are reported. Analytical age  
222 uncertainties (i.e. internal) include uncertainties of the measured <sup>10</sup>Be concentrations (Table 1,  
223 supplementary data), pressure ( $\pm 5$  hPa), sample thickness ( $\pm 1$  cm), shielding factor ( $\pm 0.01$ ),  
224 denudation rate ( $\pm 0.4$  mm.ka<sup>-1</sup>) and attenuation length ( $\pm 10$  gr.cm<sup>-2</sup>). Total age uncertainties (i.e.  
225 external) include contributions from the analytical method and production rate uncertainty (Marrero  
226 et al., 2016). All results are presented in Table 1 (supplementary data).

227



228

229

230

Figure 3 : The Aricota giant landslide (see frame location on Figure 2). (A) Raw hillshade and elevation image derived from high resolution (2 m) Pléiades DEM (see text for details). The bathymetry of the Aricota lake

231 *(resolution 1 m) has been provided by the company EGESUR. (B) Geomorphological map of the Aricota*  
232 *landslide showing the two failure events. The first and main event that generated the dam in the valley is*  
233 *mapped in yellow. Note the regressive erosion affecting southwestern part of the slipped mass and the infill*  
234 *of the secondary valley located at the southern center of the map. The second event, a rock-avalanche that*  
235 *have affected the main scarp of the first event, is depicted in orange. Yellow points correspond to samples*  
236 *extracted for <sup>10</sup>Be cosmic ray exposure dating (1 above the landslide scarp, 3 on the free face of the landslide*  
237 *scarp and 13 on boulders distributed over the landslide mass). Outside of the landslide area, the geology is*  
238 *the same as Figure 3.*

239

## 240 **4. Results and interpretations**

### 241 *4.1. Landslide morphology*

242 The failure of the Aricota giant rockslide has left a spectacular morphological imprint in the Locumba  
243 valley and has deeply modified the surrounding landscapes (Figure 3 and Figure 4A). It generated a  
244 natural dam of about 600 m of height impounding a lake of  $\sim 0.8 \text{ km}^3$  with a length of  $\sim 6 \text{ km}$  (Aricota  
245 lake) and produced a large scar of about 4 km of width along the northern flank of the valley (Figure  
246 3A). As it is visible on the Figure 3A, the main scarp intercepts a plateau, corresponding to a paleo  
247 ignimbrite surface (Huayllillas formation, Figure 2), at an elevation of ca. 3700 m a.s.l.. According to  
248 the geomorphological description proposed by Placzek et al. (2001), two successive deposits can be  
249 distinguished in the rockslide mass. The dam itself and a subsequent rock-avalanche deposit  
250 overlying its northern part. The whole destabilized area extends over  $\sim 3 \text{ km}$  of length towards the  
251 south until the opposite valley slope.

252 We observe in the central part of the dam a continuous lithological succession, locally fractured,  
253 composed from bottom to top by the Huayllillas ignimbrites (Figure 5A), overlying the metasediment  
254 (silts-shales) and pyroclastics of the Tarata formation. This lithological succession is comparable with  
255 the one outcropping along the stable valley slopes (Figure 4). On southern extremity of the dam (i.e.  
256 the most distal part), we observe a dominance of andesite from the Quellaveco formation (Figure  
257 3B), derived from the lower most layer of the original slope, with a high degree of deconstruction,

258 also mixing all the other lithologies (Figure 4B). According to those observations, the dam was likely  
259 produced during a first large and “in mass” rockslide failure that have the whole valley flank.

260 The western side of the dam (downstream side) shows a large amphitheater (Figure 3A), affected by  
261 gullies and landslides with scarps of several hundred meters in length (Figure 6A). Water seeping is  
262 also observable at the base of the dam (see location of current and paleo springs on Figure 3B). We  
263 interpret this morphology as regressive erosion processes affecting the dam due to its steep  
264 topography and to the high level of rock fracturing produced during the rockslide propagation. On  
265 the opposite Locumba valley flank (southern flank), our DEM (Figure 3A) highlights a flat and perched  
266 surface, at the same elevation than the Aricota dam (ca. 2700-2800 m a.s.l.), infilling a small lateral  
267 valley (Figure 4C). This morphology suggests that the former dam reached this area before being  
268 eroded.

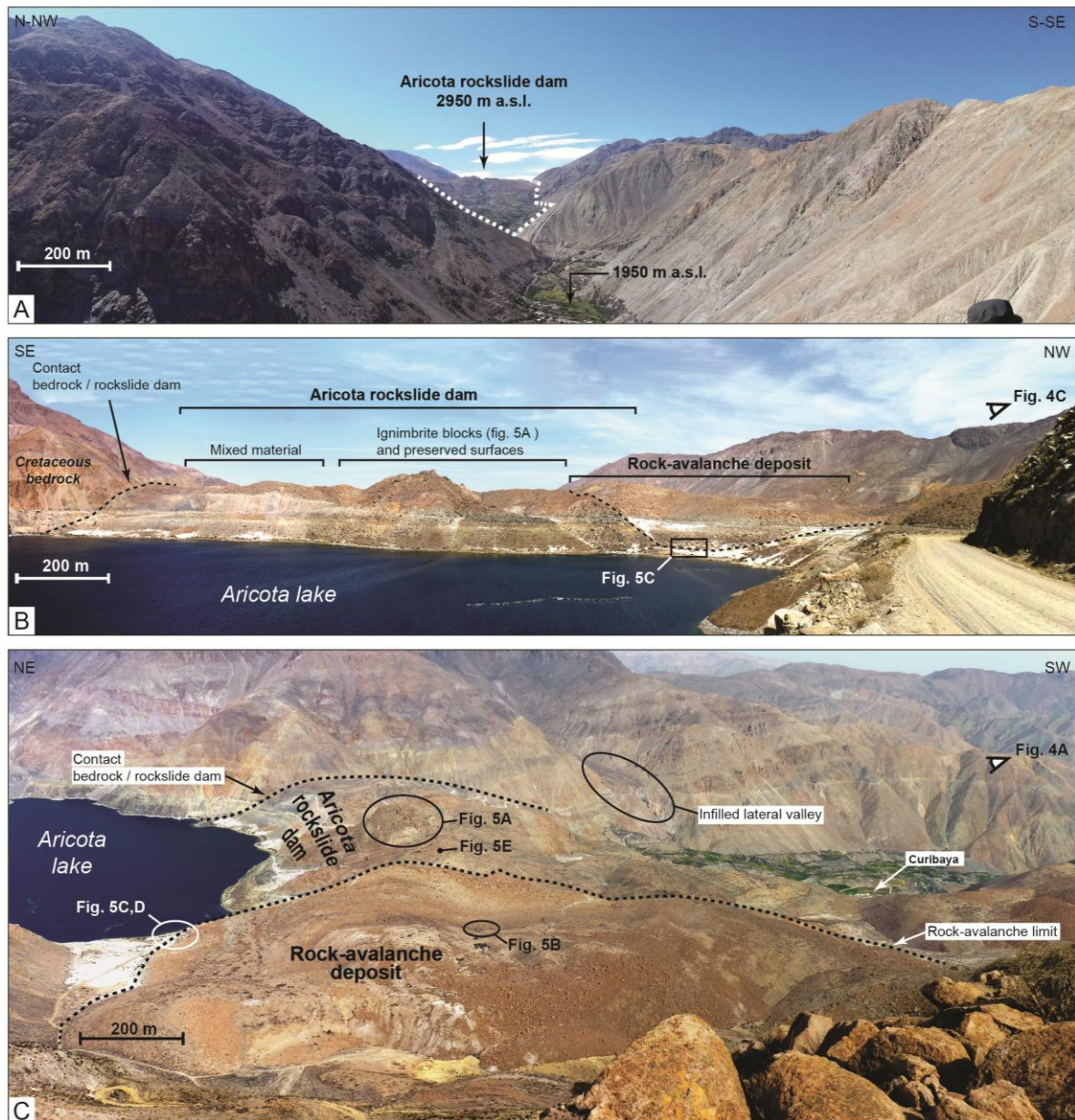
269 Postulating that before the rockslide triggering, the valley had a typical v-shaped morphology (as the  
270 adjacent ones, Figure 4A) we reconstructed a pre-failure topography. Then taking into account the  
271 strike and dip of the main scarp, we estimate a volume of ca.  $2\pm 0.3$  km<sup>3</sup> for the Aricota rockslide dam,  
272 which includes an estimation of the volume eroded since it emplaced.

273 On its northern part, the dam is covered by a secondary rock-avalanche deposit constituting a  
274 circular lobe of debris of 800 m of radius (Figure 3A). The contact between the dam and this rock-  
275 avalanche deposit is delineated on the DEM by a slope break (Figure 3). On the field, it corresponds  
276 to a clear contact between a chaotic deposit of blocs of thickness of 60 to 100 m overlying the oldest  
277 dam surface. Taking into account the area covered by the rock-avalanche and its mean thickness; we  
278 estimated a volume  $\sim 0.2$  km<sup>3</sup> for this second event. Above this rock-avalanche deposit, we observe a  
279 high cliff of more than 200 m of elevation, cutting through the intercalations of silts and shales from  
280 the Tarata formation (Figure 6C). This cliff crosscuts morphologically the main scarp left by the first  
281 failure over a width of  $\sim 3$  km (Figure 3B and Figure 6A) inducing a regression toward the north of  
282 about 600-700 m.

283 Two types of structures can be distinguished in the rock-avalanche deposit. The firsts ones  
284 correspond to radial structures in the morphology (Figure 3A), which directions point mainly toward  
285 the southeast. They are interpreted as an indication of the main direction of debris propagation  
286 toward the southeast. The second types of structures are concentric and are revealed by several  
287 bands of colors (black, brown and white) that are alternating in the deposit (Figure 4C and Figure 6A).  
288 Those colors correspond to different lithology of boulders. Indeed, from the northern to the southern  
289 part of the deposit, we can recognize boulders of ignimbrite and weathered material from the  
290 Huayllilas formation, followed by alignment of black silt-shale boulders from the Tarata formation  
291 (e.g. Figure 5B) and finally very large boulders (up to 25 m in length) of andesitic breccia from the  
292 Quellaveco formation. The eastern side of the rock-avalanche deposit is composed of granitic  
293 boulders such as they outcrop above and along the top of the scarp (Figure 3B). At the front of the  
294 rock-avalanche deposit (Figure 6A), we observed an outcrop of weathered yellow material that  
295 originates from the middle part of the upper slope (Figure 6D).

296 As a whole, those morphologies and such spatial distribution of boulders indicate that the former  
297 lithological succession of the slope was not mixed during the rock-avalanche and debris transport.  
298 The failure mode probably follows a translational failure allowing the bottom part of the slope to be  
299 projected in the distal part of the deposit.

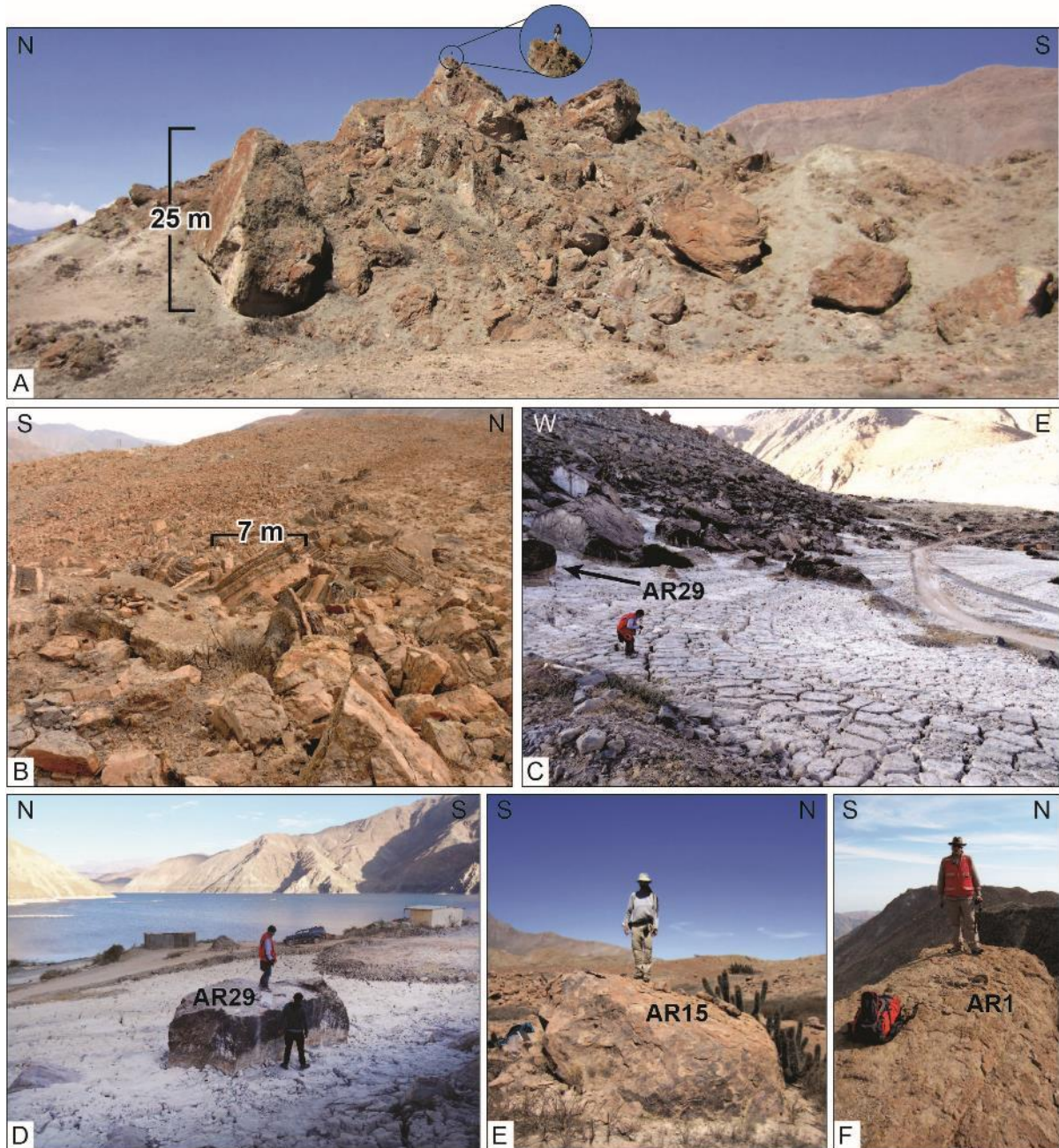
300



301  
 302 **Figure 4 : Panoramic views illustrating the main structures of the Aricota giant landslide area. (A) Panoramic**  
 303 **view from the downstream part of the Locumba valley (see location on Figure 4C). Note the general V-shape**  
 304 **of the valley and the contact between the giant Aricota rockslide and the flank underlined by a dotted white**  
 305 **line. (B) Westward view taken from the road along the lake (see location on Figure 3B) and showing the dam**  
 306 **generated by the first giant event. Along the dam, two bodies can be discriminated. On the central part, pre-**  
 307 **landslide topographic surfaces and large ignimbrite blocks are preserved (see also Figure 5A). On the south-**  
 308 **eastern part, mixed and highly deformed material are outcropping. Rock-avalanche deposits overly the top**  
 309 **the rockslide dam. (C) Southward view of the whole landslide area taken from the top of the scarp (see**

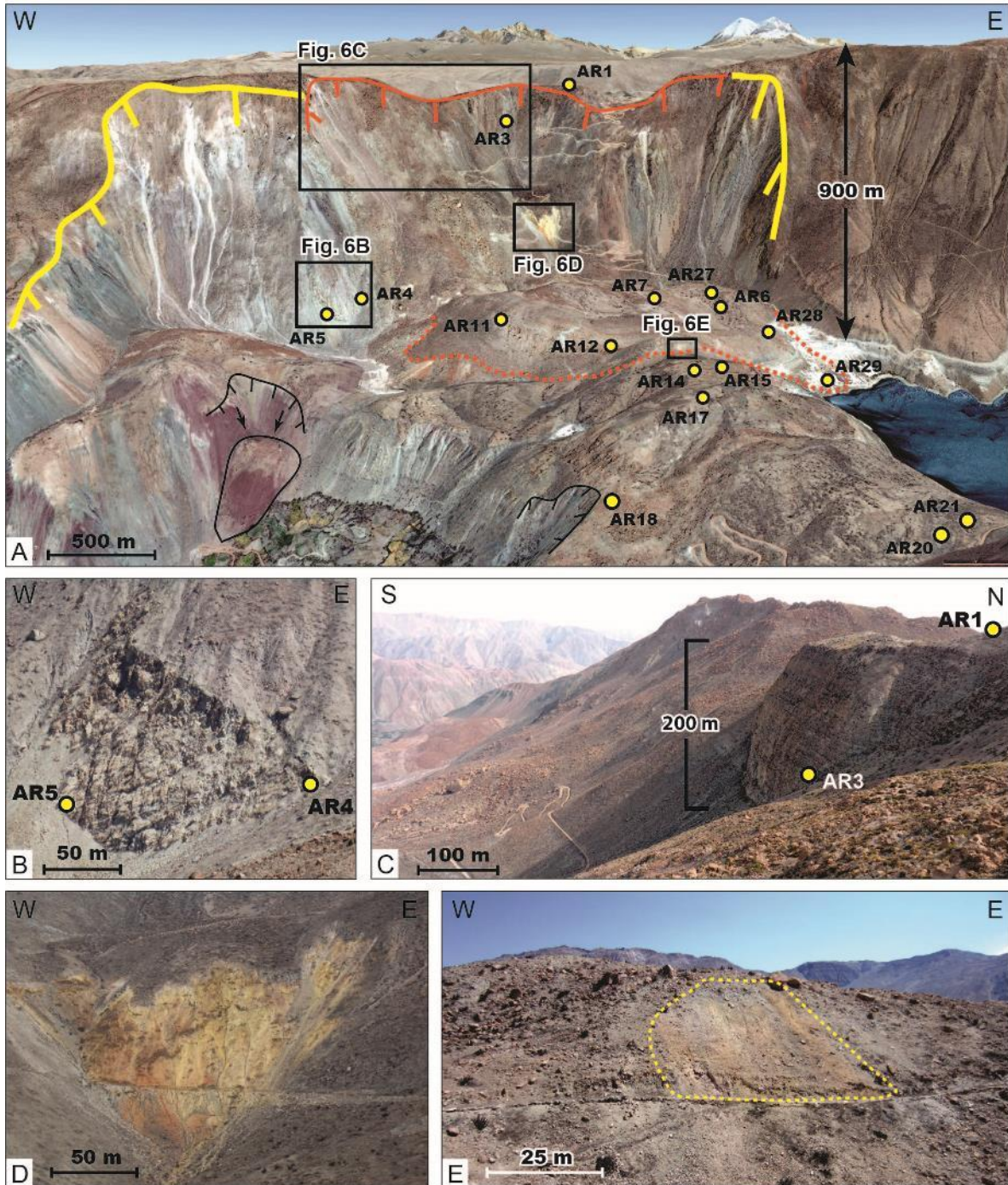


310 location on Figure 4B). Note on the opposite Locumba valley flank, the lateral valley infilled by accumulation  
 311 of deposits reflecting its obstruction by the main Aricota rockslide dam.  
 312



313  
 314 **Figure 5: Detailed morphologies of the Aricota landslide. (A) Preserved large ignimbrite boulders**  
 315 **outcropping in the central part of the rockslide dam. (B) Large boulders from the Tarata formation (bedded**  
 316 **silt and shales) aligned in the rock-avalanche deposit. (C) Boulders of the rock-avalanche partially covered by**  
 317 **diatomite. This zone was immersed before the hydroelectric lake drop. (D) Boulder (AR29) sampled to**  
 318 **tentatively tract the paleo-lake level variations. (E) Boulder of sample AR15. (F) Ignimbrite surface located on**

319 *the plateau at the top of landslide scarp and sampled to estimate the long-term local denudation rate (see*  
 320 *location on Figure 3B). On all pictures, see the persons for scale and their location on Figure 4.*  
 321



322  
 323 **Figure 6 : Main scarp morphologies of the Aricota landslide. (A) 3D view of the Aricota landslide area (Google**  
 324 **Earth). The scarp of the rockslide dam (first event) is depicted in yellow while the rock-avalanche scarp**  
 325 **(second event) is in orange. Dashed orange line highlights the boundary of the rock-avalanche deposit. Small**

326 *landslides (in black) affect the southwestern slope of the rockslide dam. (B) Preserved scarp surface of the*  
327 *first failure event and location of samples AR4 and AR5. (C) Vertical scarp generated by the second failure*  
328 *event and cutting through alternating silts and black shales of the Tarata formation. Sample AR3 was*  
329 *extracted from the scarp toe. See also location of the sample AR1 at the top of the slope, dedicated to*  
330 *constrain long-term denudation rate. (D) Layer corresponding to a regional paleo weathering profile*  
331 *interbedded in Cretaceous series. (E) Same weathered material (yellow) reworked and transported by the*  
332 *rock-avalanche.*

333

#### 334 4.2. Denudation rate and exposure duration results

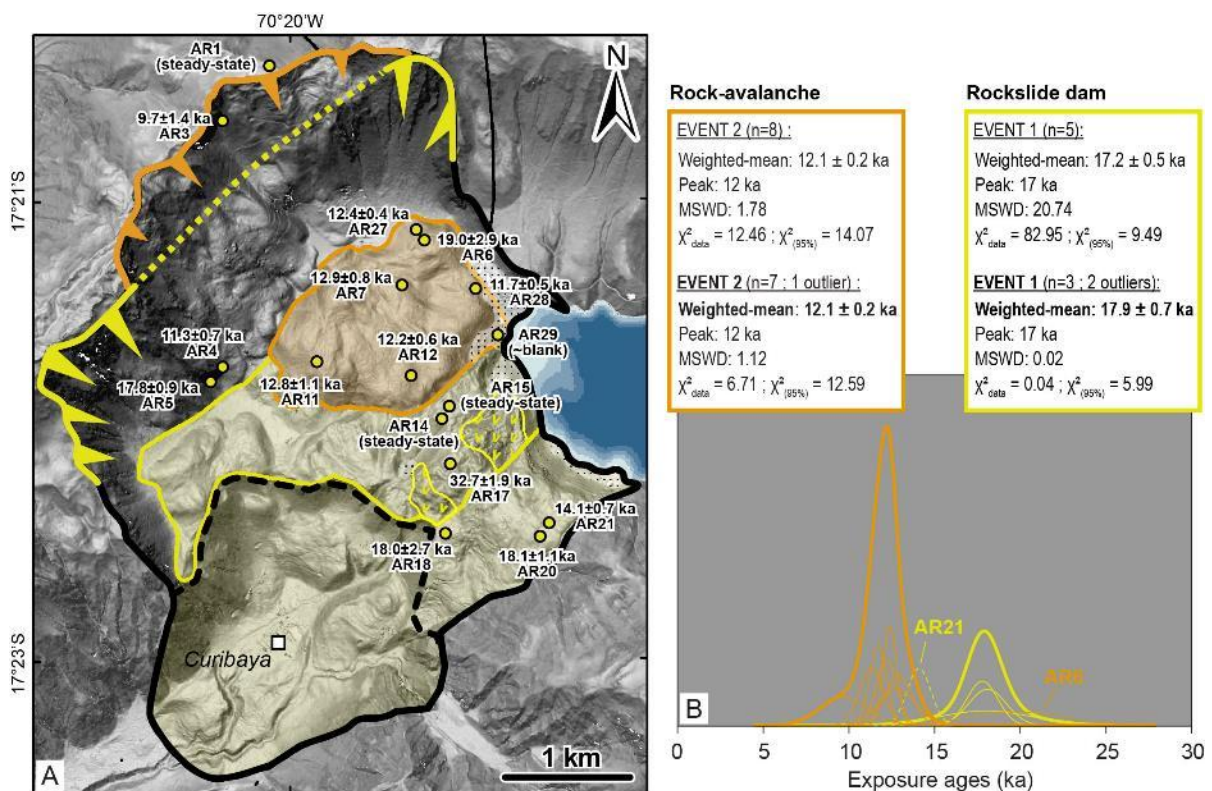
335 Denudation rate and exposure durations derived from  $^{10}\text{Be}$  data are reported in Table 1  
336 (supplementary data). As previously mentioned, our first objective was to constrain the local  
337 denudation rate of the Aricota landslide area in order to derive accurate exposure durations. The  
338 sample AR1, extracted on the ignimbritic plateau for this purpose, provided a high concentration of  
339  $38.00 \pm 1.36 \times 10^5 \text{ at.g}^{-1}$ . This indicates a saturation of  $^{10}\text{Be}$ , i.e. a steady state, which is reached after an  
340 exposure duration greater than 1 Ma (Gosse and Phillips, 2001) at this latitude and elevation (17°S  
341 and ca. 3700 m a.s.l.) and corresponds to a denudation rate of  $3.1 \pm 0.6 \text{ mm.ka}^{-1}$ . Unexpectedly two  
342 other samples, AR14 and AR15, taken at the top of the Aricota rockslide dam also provided steady-  
343 state concentrations of  $43.78 \pm 1.42 \times 10^5$  and  $50.49 \pm 1.47 \times 10^5 \text{ at.g}^{-1}$ , corresponding respectively to  
344 denudation rates of  $2.6 \pm 0.5$  and  $2.2 \pm 0.4 \text{ mm.ka}^{-1}$ . The presence of those steady-state surfaces in the  
345 main rockslide body suggests that a part of the original topography of the plateau was preserved  
346 during the mass movement. The implications of that result for the understanding of the failure  
347 typology will be more specifically discussed hereafter. All agreeing within uncertainties, those three  
348 denudation rates success a chi-2 test (1.39/5.99 (95%) and belong to the same population whose  
349 weighted mean is  $2.6 \pm 0.4 \text{ mm.ka}^{-1}$  (uncertainty attached is 1 sigma weighted standard deviation).  
350 Exposure durations were then calculated using this mean denudation rate. In general, as shown on  
351 the Figure 7B, exposure durations obtained are in good agreement with the geomorphological

352 settings and they allow discriminating the two successive events that occurred on the Aricota  
353 landslide. In the following, the exposure durations are reported with one sigma internal uncertainty.  
354 The youngest exposure durations correspond to boulders of the rock-avalanche deposits,  
355 corresponding to the second event. Five exposure durations over six (samples AR7, AR11, AR12,  
356 AR27 and AR28) range between  $11.7\pm 0.5$  and  $12.8\pm 1.1$  ka (Table 1 (supplementary data) and Figure  
357 7B). The sample AR6 ( $19.0\pm 2.9$  ka) is the only one age of this lobe of deposit falling out of this range,  
358 and for which we suspect likely inheritance. Comparing with exposure durations of ca. 12-13 ka, the  
359 excess of  $^{10}\text{Be}$  concentration in this sample would be about  $1\times 10^5$   $\text{at}\cdot\text{g}^{-1}$ . Along a depth profile that is  
360 theoretically at the equilibrium, and considering the denudation and the production rate conditions  
361 of the plateau (mean denudation rate of  $2.6\pm 0.4$   $\text{mm}\cdot\text{ka}^{-1}$ , "infinite" time, and production scaling of  
362 sample AR1), this concentration would be achieved at depth of 4 to 6 m. It is thus probable that the  
363 boulder AR19 comes from this pre-failure depth location and then was deposited in the debris with  
364 non-zero initial  $^{10}\text{Be}$  concentration, giving an apparent older exposure duration. The sample AR3,  
365 picked at the foot of the vertical scarp located directly above the debris lobe (Figure 6A and C),  
366 provided an exposure duration of  $9.7\pm 1.4$  ka, not significantly different from the previous ones  
367 considering the uncertainties. It confirms the relation between this secondary scarp and the rock-  
368 avalanche deposits.

369 Finally, the sample AR4, that was extracted from the northern part of the scarp presented on Figure  
370 6B (see also location on Figure 3B), provided an exposure duration of  $11.3\pm 0.7$  ka that also agree  
371 with the one's previously listed. It is likely that the rock-avalanche failure has rejuvenated this side of  
372 the main scarp during its propagation. A probability density plot including all those samples (Figure  
373 7B) highlights a unimodal distribution (chi-2 test (95%): 6.71/12.59), the weighted mean of which is  
374  $12.1\pm 0.7$  ka (uncertainty attached is 1 sigma weighted standard deviation). Considered or not, the  
375 AR4 and AR6 samples do not affect the result (Figure 7B).

376 Exposure durations obtained from the five samples picked on the dam area (AR5, AR17, AR18, AR20,  
377 AR21), and its corresponding scarp, are significantly older. They range between  $14.1\pm 0.7$  and

378 32.7±1.9 ka (Table 1, supplementary data). The probability density distribution provided on Figure 7B  
 379 shows that three of those ages (AR5, AR18 and AR20) agree within uncertainties (chi-2 test (95%):  
 380 0.04/5.99) and point to a weighted mean of 17.9±0.7 ka. Inheritance is inferred in the sample AR17  
 381 (32.7±1.9 ka) leading to a significantly older apparent exposure duration than the mean duration.  
 382 This is fairly concordant with the fact that (1) the sample AR17 was extracted on boulders close to  
 383 the samples AR14 and AR15 at steady state, and (2) all those samples are all standing in an area of  
 384 preserved surface (Figure 3B and Figure 7) representing pre-landslide topography.  
 385 The <sup>10</sup>Be concentration of sample AR21 (14.1±0.7 ka) leads to a significantly younger apparent  
 386 exposure duration. We interpret this younger apparent age as the consequence of a desquamation  
 387 process of the boulder surface following the typical onion-skin weathering of the Atacama desert.  
 388

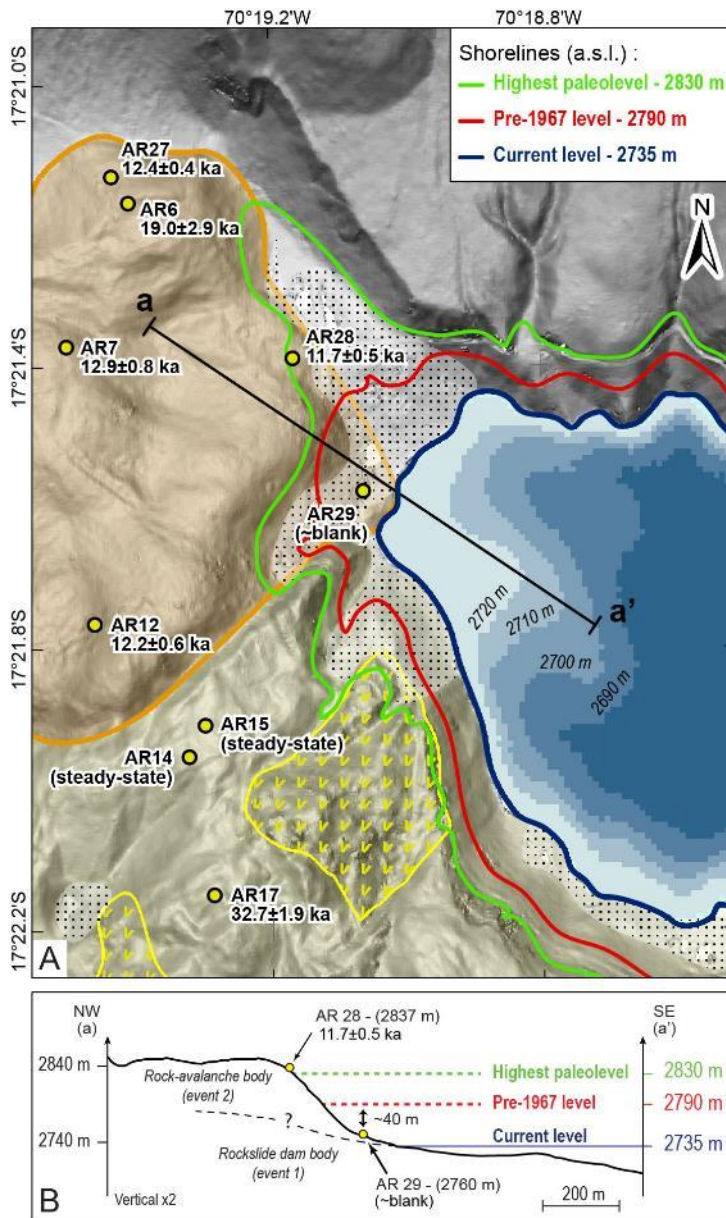


389  
 390 **Figure 7 : Exposure durations results on the Aricota giant landslide. (A) Landslide map and sample ages (1  $\sigma$**   
 391 **internal uncertainty, Table 1, supplementary data). Legend is the same as Figure 3B. (B) Probability density**  
 392 **plot and statistics over exposure durations (1  $\sigma$  internal uncertainty, Table 1, supplementary data). Yellow**  
 393 **curves and orange curves correspond to the rockslide dam (event 1) and the rock-avalanche (event 2),**

394 *respectively. Thin lines correspond to individual exposure durations. Dashed lines refer to exposure durations*  
395 *interpreted as outliers (see text for details). Exposure duration from sample AR17 ( $32.7 \pm 1.9$  ka) is considered*  
396 *as an outlier (out of frame). Thick curves refer to the summed probability density function for each event*  
397 *(excluding outliers).*

398

399 We measured in the sample AR29 (Figure 5C and D) a  $^{10}\text{Be}/^9\text{Be}$  ratio of  $0.56 \pm 0.08 \times 10^{-14}$  that is  
400 equivalent to the corresponding blank value for this run ( $0.52 \pm 0.23 \times 10^{-14}$ , Table 1, supplementary  
401 data). This means that the  $^{10}\text{Be}$  concentration in this sample is close to the detection limit, implying  
402 an exposure duration close to zero. The Figure 8 shows the morphological context of the boulder  
403 AR29. It stands at an elevation of 2760 m, while the pre-1967 level was at 2790 m and the highest  
404 level deduced from diatomite deposit (Placzek et al., 2001) was estimated at ca. 2830 m (Figure 8B).  
405 As this boulder belongs morphologically to the second event (mean age of deposition is  $12.1 \pm 0.7$  ka),  
406 its very low  $^{10}\text{Be}$  concentration suggests that during the rock-avalanche, the boulder likely fell directly  
407 in deep water, thus shielded from the incident cosmic ray particles up to now.



408

409 **Figure 8 : Morphological context around the sample AR29. (A) Geomorphological map of the north-eastern**  
 410 **part of the Aricota dam showing the location of the sample AR29 and the main variations of the Aricota lake**  
 411 **shorelines (the probable highest paleo-lake level was reconstructed according to diatomite deposits (Placzek**  
 412 **et al., 2001)). (B) Topographic profile extracted from the Pléiades DEM (see location on Figure 8B). The**  
 413 **legend of the landslide morphologies is the same as Figure 3B.**

414

## 415 5. Discussion

416 Most of the large landslides identified in the Central Western Andes, including the Aricota landslide,  
 417 have developed along the flank of deeply incised canyons (Figure 1; e.g. Crosta et al., 2014; Thouret

418 [et al., 2017](#)). In those canyons, the incision can locally exceed 1500 meters ([Thouret et al., 2017](#))  
419 suggesting that the topography is probably the first preconditioning factor for those giant  
420 gravitational failures. The same conclusions were made by [Strasser and Schlunegger \(2005\)](#), and  
421 [Wörner et al. \(2002\)](#) regarding the Lluta landslide. The deep incision of those canyons is the result of  
422 the peculiar conditions prevailing along the Central Western Andes since several millions of years  
423 ([Schlunegger et al., 2006](#); [García et al., 2011](#); [Gunnell et al., 2010](#); [Bissig and Riquelme, 2010](#); [Jeffery](#)  
424 [et al., 2013](#)). It is first related to the uplift of the region since the Cenozoic (e.g. [Schildgen et al., 2009](#);  
425 [Thouret et al., 2007](#)). Second, it is related to the specific climate condition marked by a long lasting  
426 hyper-aridity affecting all the Central Western Andean flank (Atacama desert) until elevations of  
427 about 3000 m a.s.l., and, on the other hand, precipitations from the easterlies that reached the  
428 upper part of the western watersheds (Altiplano and Western Cordillera). Indeed, after [Huffman et](#)  
429 [al. \(2007\)](#), while current mean precipitation are ~0 mm/yr along the coast and the Western  
430 Cordillera, about 800 mm/yr of precipitation in average are recorded on the Altiplano. This rain  
431 shadow effect started possibly at 12/10 Ma (e.g. [Insel et al., 2012](#); [Rech et al., 2019](#)). This way, while  
432 the western flank of the Andes remains hyper-arid, the upper catchments collect a significant  
433 amount of water, flowing then throughout the Cordillera toward the Pacific ([Litty et al., 2017](#)). This  
434 discharge has maintained a constant incision in the valleys thus contributing to maintain very steep  
435 canyon flanks and critical topographic wedges highly prone to large-scale landslide failure ([Thouret et](#)  
436 [al., 2017](#)). As it was globally reported by [Korup et al. \(2007\)](#), and locally by [Wörner et al. \(2002\)](#) in the  
437 Lluta valley, this suggests that the critical relief (see also [Blöthe et al., 2015](#)) that can be close, or  
438 even beyond, to its proposed upper strength limit may be one of the primary factor controlling the  
439 development of large landslides in the Andean canyons.

440 In the Locumba valley, the gravitational failure of the canyon flank was deep and large enough to  
441 produce a massive dam generating upstream a lake more than 6 km long. As shown by our  
442 morphological analysis, two successive failure events occurred at the Aricota site (Figure 3 and Figure  
443 9). A first main event, of rockslide typology, created the dam and then a second event occurred, of

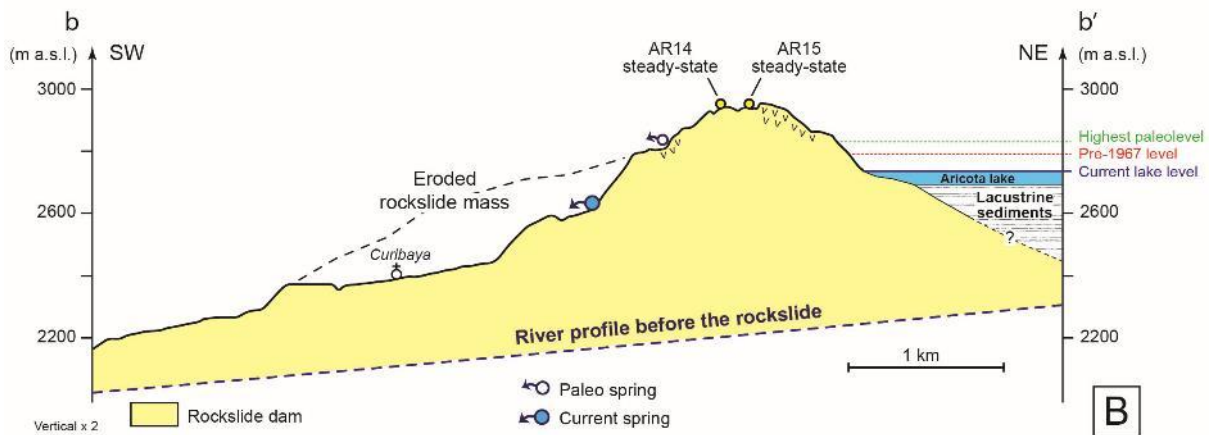
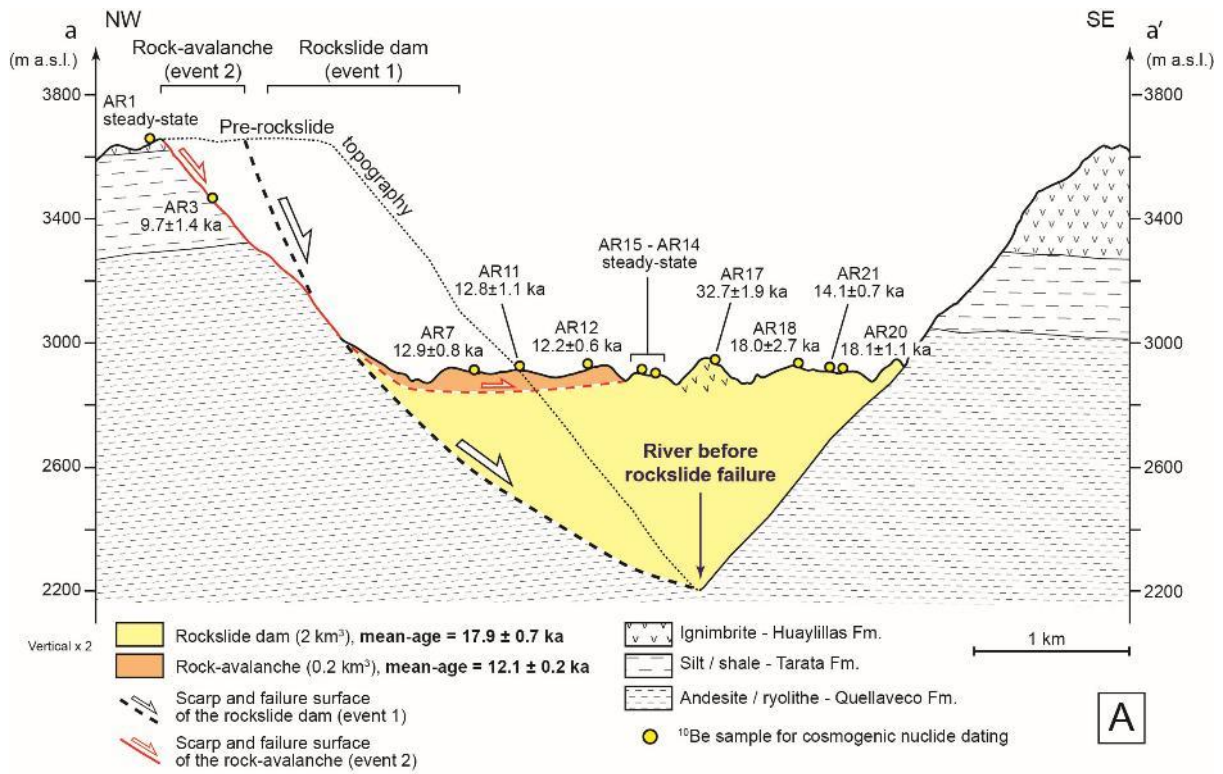


444 rock-avalanche typology, which deposits spread out on top of the first ones, reinforcing the initial  
445 dam. Taking into account the height of the dam (~600 m), its volume ( $2\pm 0.3 \text{ km}^3$ ) and the pre-  
446 landslide valley morphology, we propose that the first event (rockslide dam) has affected the  
447 ignimbritic plateau over a maximal width of 400-500 m (Figure 9A). The failure allowed the collapse  
448 of a part of this plateau originally located at ca. 3650 m a.s.l.. Ignimbritic rock volume outcrops at the  
449 present-day at the top of the rockslide dam at ca. 2900 m a.s.l. (Figure 9A). Translational movements  
450 probably dominated the failure type as the vertical distribution of the stratigraphy is preserved in the  
451 dam. This morphological characteristic has been already described in various study cases of large  
452 slope destabilizations (Shreve, 1968; Strom, 2006; Humair et al., 2013). According to the classification  
453 of Hermanns et al. (2011), the distribution of the Aricota landslide deposits in the Locumba valley  
454 corresponds to a type “IV a” in plan view. Indeed, the run-out of the debris was long enough (~3 km)  
455 to reach the opposite valley flank and to dam a small tributary valley (Figure 3). As shown on the  
456 geological cross-section Figure 9A, along a cross-valley profile, the deposit profile is roughly flat and  
457 symmetric to the original valley profile. This would correspond to a type “i” of cross-valley profile in  
458 the classification of Hermanns et al. (2011). The cross-section of the landslide deposit, parallel to the  
459 valley (Figure 9B), highlights the large thickness of the dam (600 m) and shows similarities with the  
460 type “2” of the along-valley profile classification of rockslide dams that is associated with a large lake  
461 (Hermanns et al., 2011). The great depth of the failure surface and the confined setting of the  
462 original Locumba valley may explain the high thickness of the deposit (Figure 9B).

463 As shown on Figure 10, comparing with the compilation of landslide dams established by Korup et al.  
464 (2004), the Aricota rockslide dam stands among the largest worldwide. To explore the geotechnical  
465 stability of this dam, we compiled the two indexes developed by Casagli and Ermini (1999). They are  
466 based on geomorphometric parameters of the site: (1) the Blockage Index  $I_b = \log(V_D * A_C^{-1})$  and  
467 (2) the Impoundment Index  $I_i = \log(V_D * V_L^{-1})$ , where  $V_D$  and  $V_L$  are the volumes of the rockslide  
468 dam and the lake [in  $\text{m}^3$ ], respectively, and  $A_C$  is catchment area upstream of the blockage [in  $\text{km}^2$ ].  
469 The values obtained for the Aricota rockslide dam are  $I_b = 6$  and  $I_i = 3.4$  (taking  $V_D = 2 * 10^9 \text{ m}^3$ ,  $A_C =$

470 1600 km<sup>2</sup> and  $V_L = 8 \cdot 10^5 \text{ m}^3$  (Placzek et al., 2001) indicating the stability of the site. Indeed Korup et  
471 al. (2004) shown that below  $I_b = 2$  no landslide-dammed lakes formed, whereas unstable lakes form  
472 at  $I_b < 4$  and that impoundments with  $I_b > 7$  have remained stable. Similarly, sites where  $I_i > 1$  have all  
473 retained existing lakes, whereas locations with  $I_i < 1$  comprise both stable and unstable landslide  
474 dams. Since the dam emplacement, the progressive infilling of the lake by lacustrine sediments  
475 (Figure 9B) have also decreased the water volume and therefore reduced the pressure imposed to  
476 the dam. More generally, megatsunami is another hazard potentially linked to mountain lakes (either  
477 natural, landslide dam or artificial lakes) that can be triggered by slope failures around the lake  
478 (Hermanns et al., 2004). Taking into account the steep slope around the Aricota lake, this hazard  
479 cannot be excluded and deserve to be studied.

480



481

482 **Figure 9: Interpretative cross-sections of the Aricota giant landslide. See locations on Figure 3B. (A)**

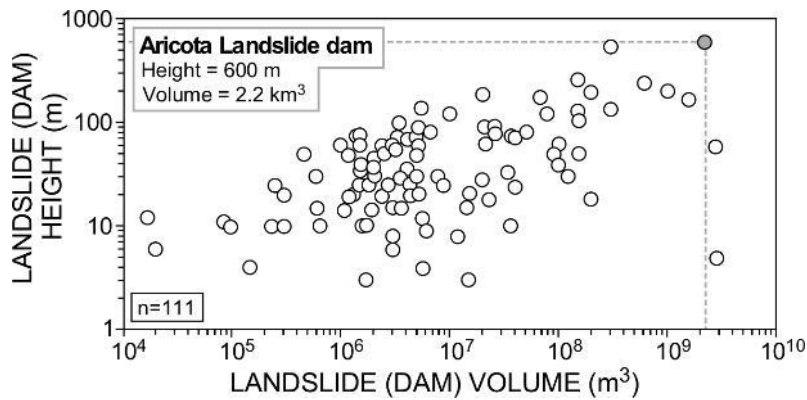
483 **Perpendicular to the Locumba valley. The pre-landslide topography, before the first event, is reconstructed**

484 **considering the volume estimation of the rockslide dam and interpolating the slope of the valley flanks.**

485 **Samples for <sup>10</sup>Be cosmic ray exposure dating are projected on the cross-section. (B) Parallel to the Locumba**

486 **valley. The pre-landslide dam river profile is indicated.**

487



488

489 **Figure 10 : Worldwide compilation of landslide dams modified from Korup et al. (2004) showing the relations**  
 490 **between the landslide volumes and heights (n is the number of landslides of the database). The Aricota**  
 491 **landslide (grey circle) stands within the 3 largest landslide dams and the highest height reported worldwide.**

492

493 In the case of large landslide processes, Glade and Crozier (2005), or Hermanns et al. (2006)  
 494 introduce that both preparatory factors (static and dynamic) and triggering factors are often  
 495 interdependent and play crucial role in the slope failure evolution. In our study the geomorphological  
 496 observations combined with cosmogenic nuclide dating obtained on the Aricota landslide area show  
 497 clearly two stages of destabilization at  $17.9 \pm 0.7$  ka and  $12.1 \pm 0.2$  ka, corresponding to the main  
 498 rockslide dam event and to the secondary rock-avalanche, respectively (Figure 9A). This timing of  
 499 events provides a frame to discuss the nature of forcings that may have triggered the two landslide  
 500 failures. However, we do not have any constraints to discuss the preparatory phases and their  
 501 related factors, thus the following discussion focuses on triggering factors only.

502 According to the literature, most of the contemporaneous, or historical landslide dams, have been  
 503 triggered by earthquakes. Some of the most impressive cases are the Usoy landslide (volume = 2.4  
 504 km<sup>3</sup>, impounding a lake of a 17 km<sup>3</sup>), triggered in 1911 by an earthquake of Mw7.7 (Ambraseys and  
 505 Bilham, 2012), the Tortum landslide (0.18 km<sup>3</sup>) in Turkey (Duman, 2009), or the numerous landslide  
 506 dams in southeastern Italy which triggered by earthquakes of intensity VII to X during the 17<sup>th</sup>  
 507 (Nicoletti and Parise, 2002). In the Andes, mostly in the NW Argentina, numerous paleo-landslide

508 dams were reported and attributed also to past earthquakes (Wayne, 1999; Hermanns and  
509 Schellenberger, 2008; Moreiras et al., 2015).

510 Considering that the Aricota landslide is located in a tectonically active region, with two large crustal  
511 fault systems (Incapuquio and Purgatorio faults) located from 10 to 20 km south of the landslide  
512 (Figure 2), a coseismic triggering of the Aricota landslide failures is probable. Indeed, Benavente et al.  
513 (2017) revealed Holocene seismotectonic activity of the Purgatorio fault, showing at least two  
514 ruptures of ~3 and ~2 m of vertical offset at the surface, equivalent to  $>M_w7$  shallow seismic events.  
515 However, even if those faults represent high seismogenic potential in the close field of the landslide,  
516 it does not exist for the moment any paleoseismic records as old as the Aricota landslide failures that  
517 would corroborate a coseismic trigger. Another observation is that several landslides, including the  
518 Aricota ones, seem to cluster spatially on the hanging wall of the Incapuquio fault (transpressive  
519 senestral, Figure 2). Similarly to what was reported by Gorum et al. (2011) in the Sichuan after the  
520 2008 Wenchuan earthquake, such a landslide distribution could reflect a coseismic “hanging wall”  
521 effect. Indeed, Gorum et al. (2011) noticed that most of the landslides triggered during the  
522 Wenchuan earthquake occurred on the hanging wall block of the Wenchuan-Maowen fault. This  
523 massive landslide triggering was interpreted as a site effect and a probable amplification of ground  
524 motion in this area (Chiou and Youngs, 2014). Over the long-term, a higher concentration of slope  
525 failures on the hanging wall of the Incapuquio fault (Figure 2) can be interpreted also as the effect of  
526 the river incision into the uplifting block, which may have increased and steepened the relief there.

527 On the other hand, several studies reported that in northwestern Argentinian Andes many landslide  
528 producing dammed lakes may have formed during wet periods (e.g. Trauth et al., 2003). Moreiras  
529 and Sepúlveda (2015) provide an up-to-date inventory of mega paleolandslides in the Central Andes  
530 at 32-34°S and discuss traditional hypotheses used to explain landslide occurrences. Whereas  
531 earthquakes have been widely proposed as the main triggering mechanism of the Chilean slope  
532 failures, paleoclimatic conditions are considered as the main cause of mega-landslides in Argentina.  
533 However, Moreiras and Sepúlveda (2015) also insist on the fact that local evidences and geological

534 records of those wetter periods are often lacking. On our study area at 17°S, it is striking to note the  
535 synchronicity between the chronic of failures of the Aricota landslide and the two latest humid  
536 periods recorded at the scale of the Central Altiplano since 20 ka, pointing to a potential climatic  
537 control on the Aricota landslide triggering. Those humid periods, documented since the 80 S' (e.g.  
538 [Blodgett et al., 1997](#)), are characterized mainly by two major expansions of the Altiplano lakes: the  
539 Tauca (18.5-14.5 ka) and the Coipasa (12.8-11 ka) phases ([Placzek et al., 2013](#)), during the Heinrich  
540 Stadial 1a and the Younger Dryas, respectively. Recently [Martin et al. \(2018\)](#) explored in details the  
541 past climate conditions during the Tauca phase by simultaneously reconstructing the fluctuations of  
542 lake levels and glacier advances in the Altiplano region. They found that during this period, on the  
543 northwestern edge of the Altiplano and the upper Locumba basin, the paleoprecipitations were  
544 amplified by 2 to 3 times compared to the present day precipitation. At a regional scale, the  
545 occurrence of such drastic increases of the paleoprecipitation is corroborated also by the  
546 concomitant aggradation of alluvial terraces and fan systems on valley floors along the western  
547 Peruvian margin. For instance, in the Majes river, located at about 300 km northwest to the Locumba  
548 valley, [Steffen et al. \(2010\)](#) pointed to the occurrence of major periods of aggradation at ca. 20 ka  
549 and between 12–8 ka. In the Moquegua valley (50 km northwest to Aricota), [Keefer et al. \(2003\)](#)  
550 reported the existence of extensive flood and debris flow deposits dated between 12 and 8.4 ka, and  
551 at least ten severe events that took place between 38 and 13 ka. At a larger scale along the western  
552 margin of the Andes in Peru, [Litty et al. \(2017\)](#) highlighted changes in precipitations patterns during  
553 the last 100 ka through shifts of the sediment provenance. In the Pisco valley, 700 km northwest to  
554 the Locumba valley, [Steffen et al. \(2009\)](#) and [Bekaddour et al. \(2014\)](#) conclude that phases of  
555 sediment aggradation and accumulation were triggered by shifts toward a more humid climate  
556 conditions during the Tauca paleolakes maximal expansions.

557 As a summary, several lines of evidences point toward significant increase of paleoprecipitation  
558 regime along the Central Western Andes during the periods 18.5-14.5 ka and 12.8-11 ka ([Placzek et](#)  
559 [al., 2013](#)). Given the correlation between those wet events and the timing of the Aricota landslide

560 (17.9±0.7 ka and 12.1±0.2 ka, Figure 7); we tentatively propose that the generation of catastrophic  
561 mass movements in the Locumba valley was firstly climatically driven. Prolonged periods of increased  
562 precipitation may have reduced thresholds for slope instabilities by increasing water content in the  
563 unstable masses, decreasing the effective friction over the sliding planes, and eroding slope foots  
564 because of higher river discharge.

565

## 566 **6. Conclusions**

567 In this paper, we provide a geomorphological analysis and dating of the Aricota giant landslide,  
568 located in the Central Western Cordillera of southern Peru (17° S). Our results indicate the  
569 occurrence of two successive events. A giant failure producing a rockslide dam occurred first at 17.9  
570 ± 0.7 ka. This first destabilization event mobilized a rock volume of ca. 2 km<sup>3</sup> and affected the  
571 northern flank of the Locumba valley. As shown by the presence of large preserved ignimbrite blocks  
572 overlying mixed and fragmented material in the dam, this first failure event was “in mass”. It  
573 generated an impressive dam in the main valley with a height of about 600 m, impounding a lake of  
574 approximately 6 km long upstream that remains until today. At 12.1 ± 0.2 ka, a second event of  
575 destabilization cross-cutting the initial scarp produced a rock-avalanche of ca. 0.2 km<sup>3</sup> which debris  
576 spread out at the top of the northern part of the dam formed by the first event. The chronology of  
577 those two events of destabilization is compatible with the main paleoclimatic events of this region  
578 during the Heinrich Stadial 1a and the Younger Dryas, both characterized by paleoprecipitation  
579 increases. Furthermore, aggradation of alluvial terraces and fan systems are concomitant along the  
580 valley floors of the western Peruvian margin highlighting higher regional erosion, sediments supply  
581 and mass-wasting events during those two periods. This temporal correlation suggests that the  
582 climate has played a preponderant role on the triggering of the Aricota landslide. However,  
583 additional and/or concomitant effect of crustal earthquakes on the landslide initiation cannot be  
584 ruled out considering the seismotectonic setting of this Andean region. Future studies related to  
585 paleoseismicity would help to clarify this debated question. At the scale of the Central Andes,

586 although numerous giant paleolandslides are recognized on its western arid flank, their  
587 understanding still suffers of a lack of time constraints, either in term of climatic events or in term of  
588 their individual geomorphic description.

589

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605

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Figure 1 (Color)

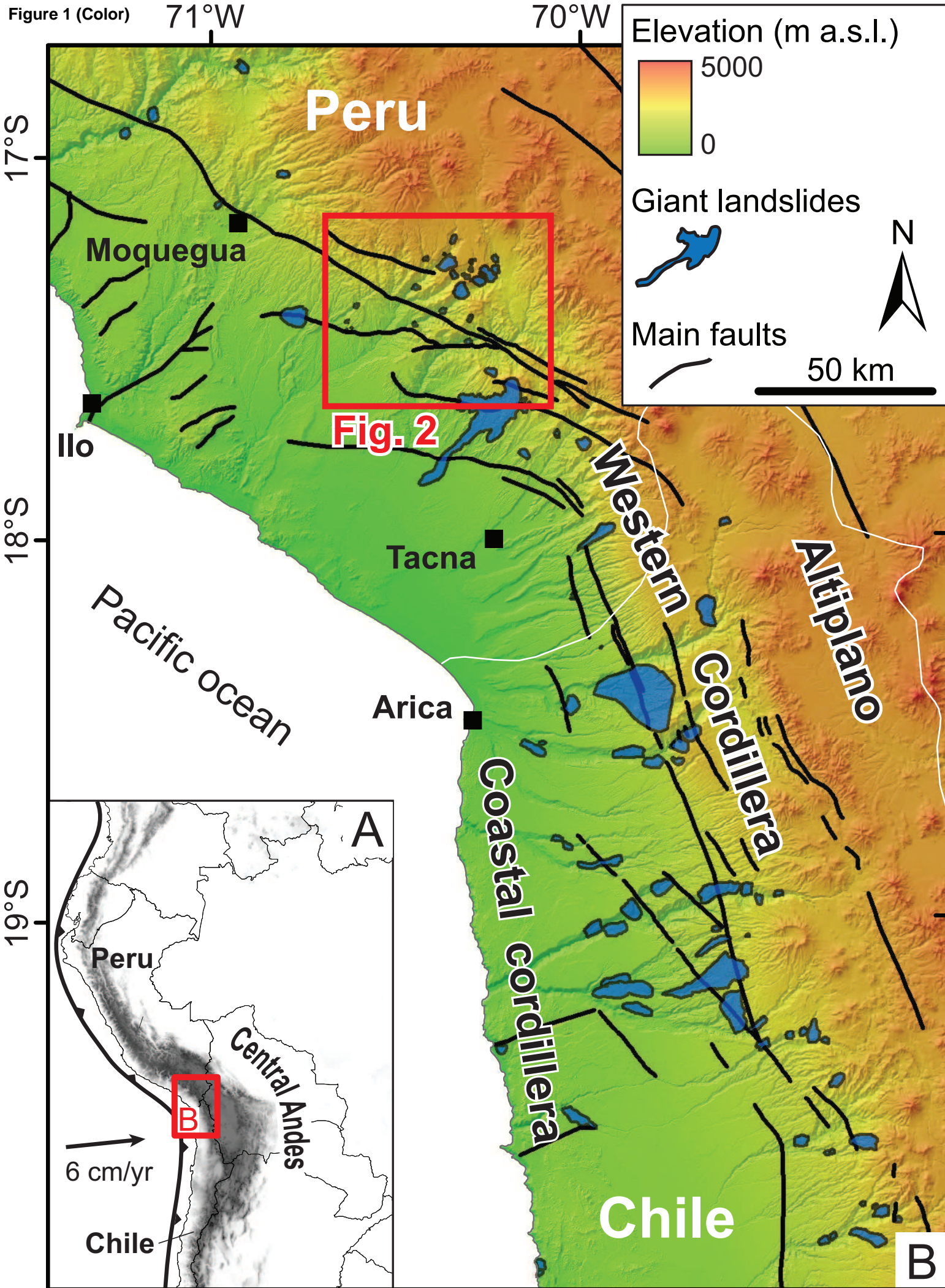


Figure 2 (Color)

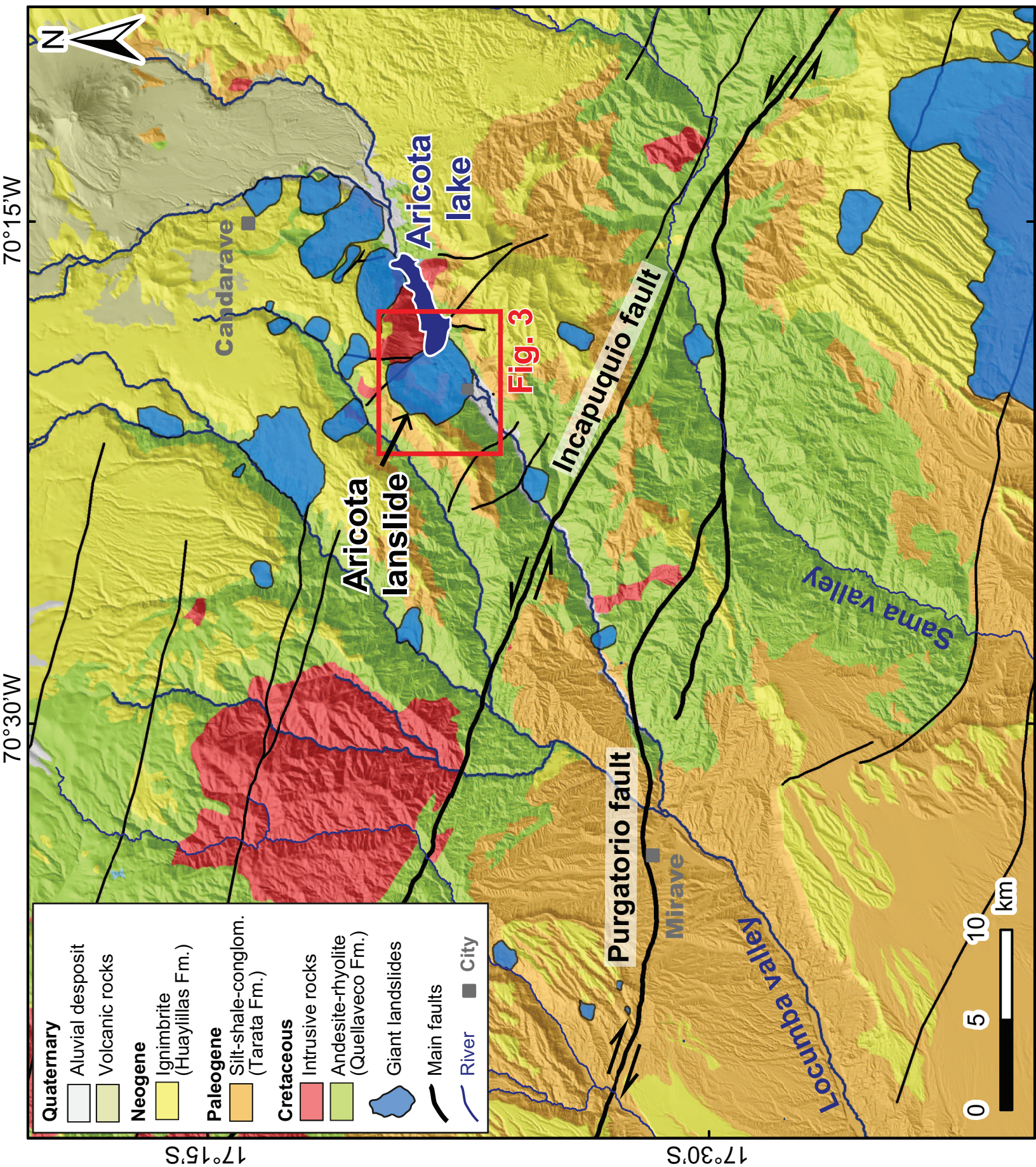


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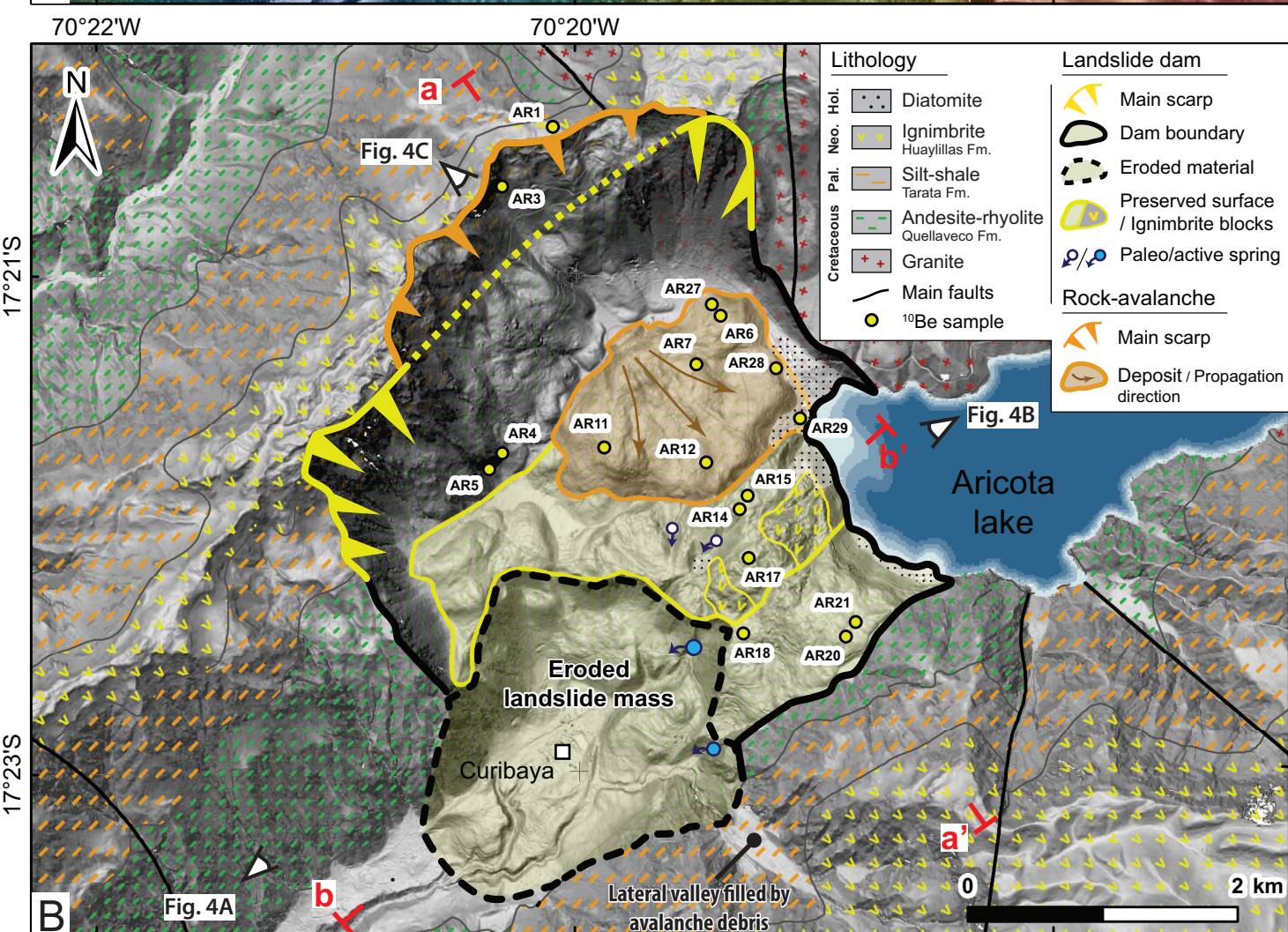
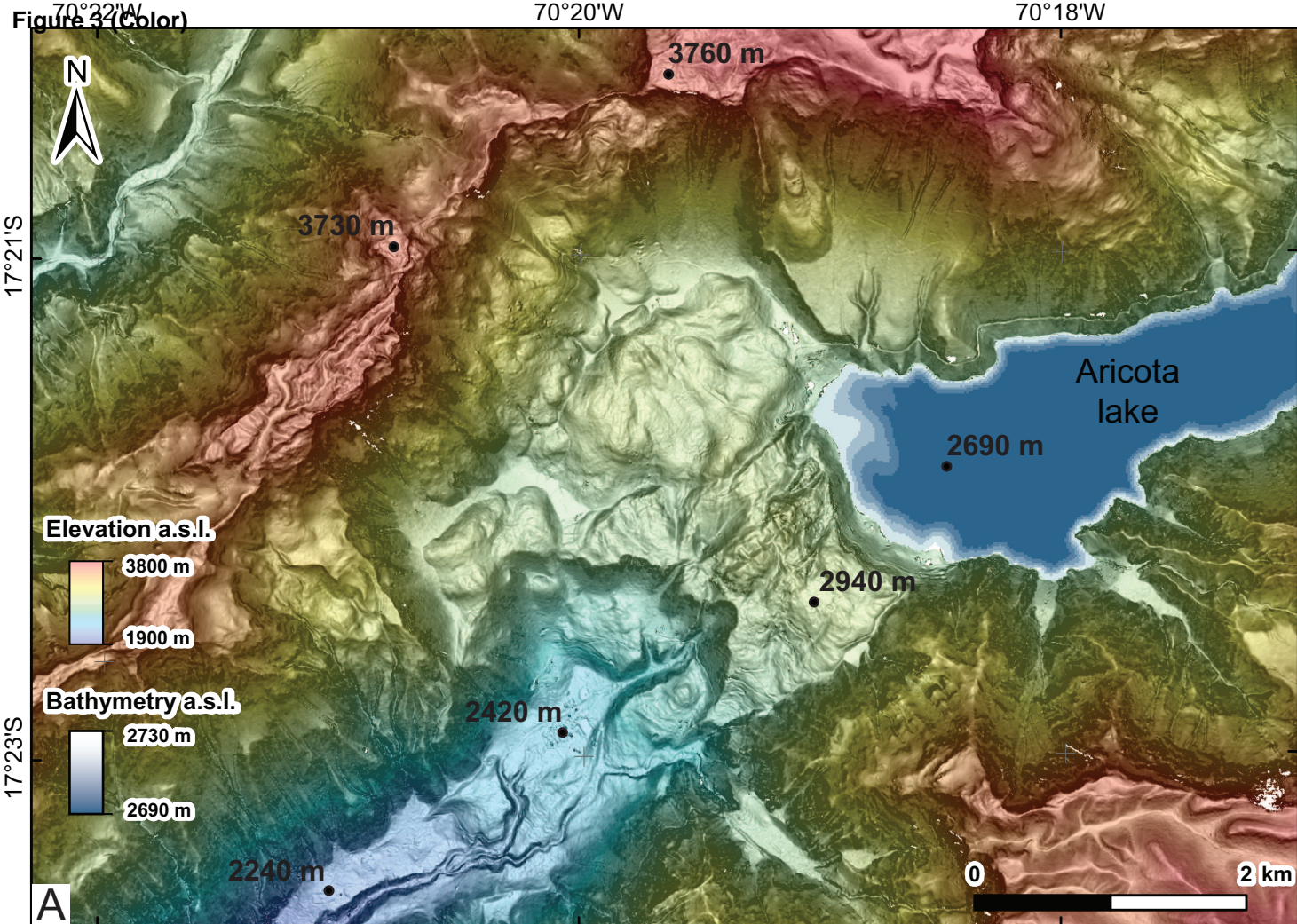


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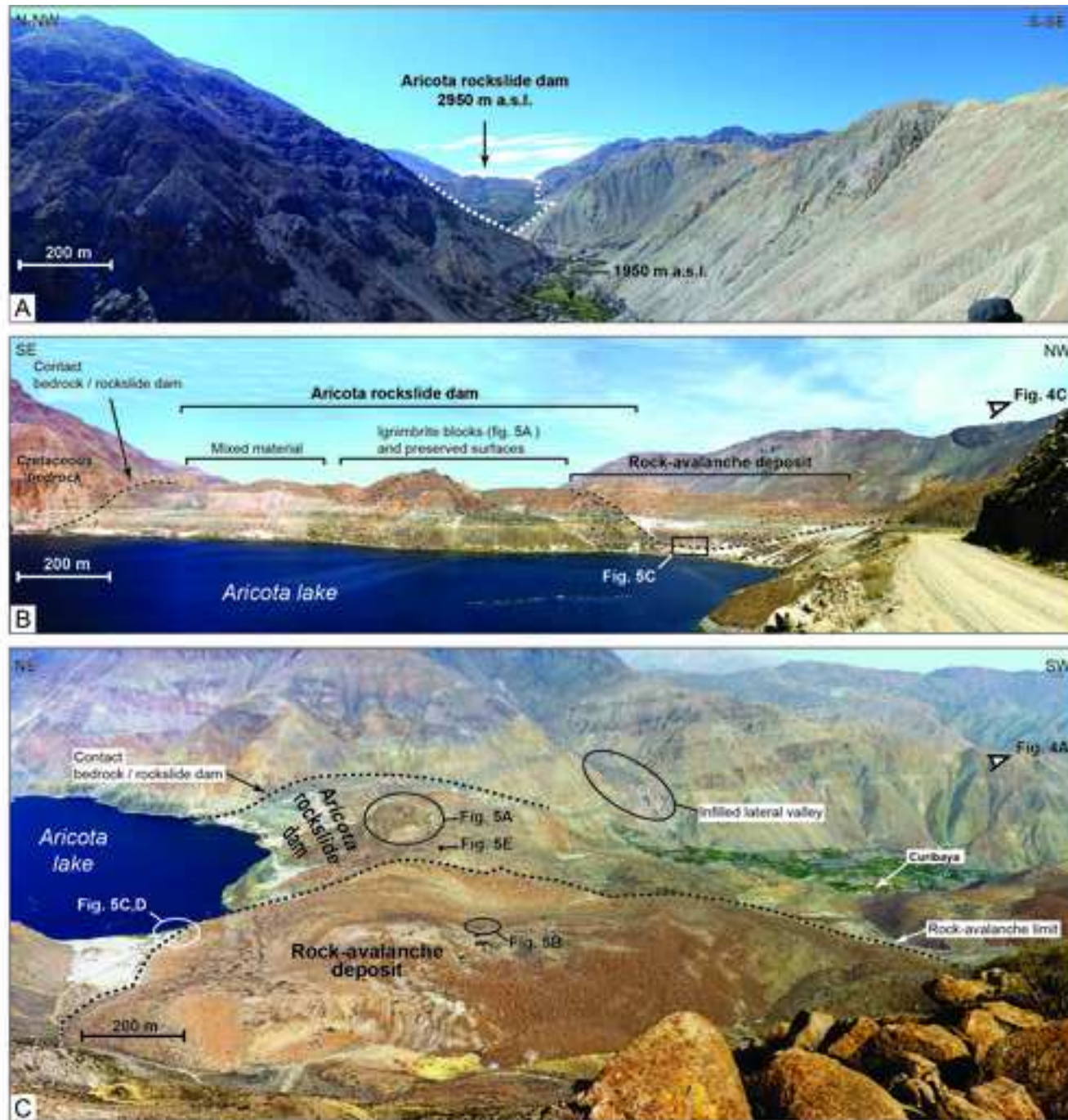
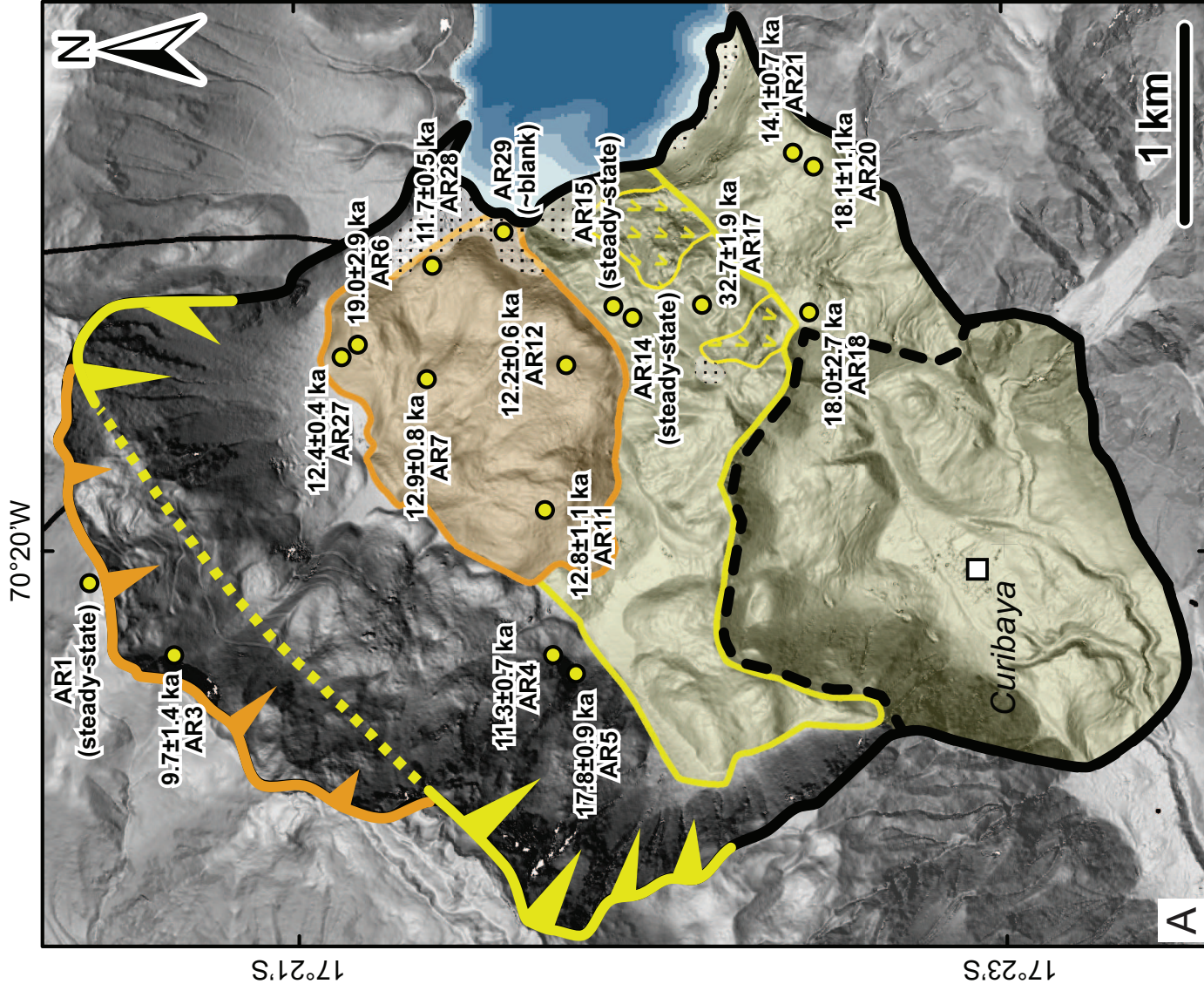


Figure 5 (Color)  
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Figure 7 (Color)



### Rock-avalanche

#### EVENT 2 (n=8):

Weighted-mean:  $12.1 \pm 0.2$  ka

Peak: 12 ka

MSWD: 1.78

$\chi^2_{\text{data}} = 12.46$  ;  $\chi^2_{(95\%)} = 14.07$

#### EVENT 2 (n=7 ; 1 outlier):

Weighted-mean:  $12.1 \pm 0.2$  ka

Peak: 12 ka

MSWD: 1.12

$\chi^2_{\text{data}} = 6.71$  ;  $\chi^2_{(95\%)} = 12.59$

### Rockslide dam

#### EVENT 1 (n=5):

Weighted-mean:  $17.2 \pm 0.5$  ka

Peak: 17 ka

MSWD: 20.74

$\chi^2_{\text{data}} = 82.95$  ;  $\chi^2_{(95\%)} = 9.49$

#### EVENT 1 (n=3 ; 2 outliers):

Weighted-mean:  $17.9 \pm 0.7$  ka

Peak: 17 ka

MSWD: 0.02

$\chi^2_{\text{data}} = 0.04$  ;  $\chi^2_{(95\%)} = 5.99$

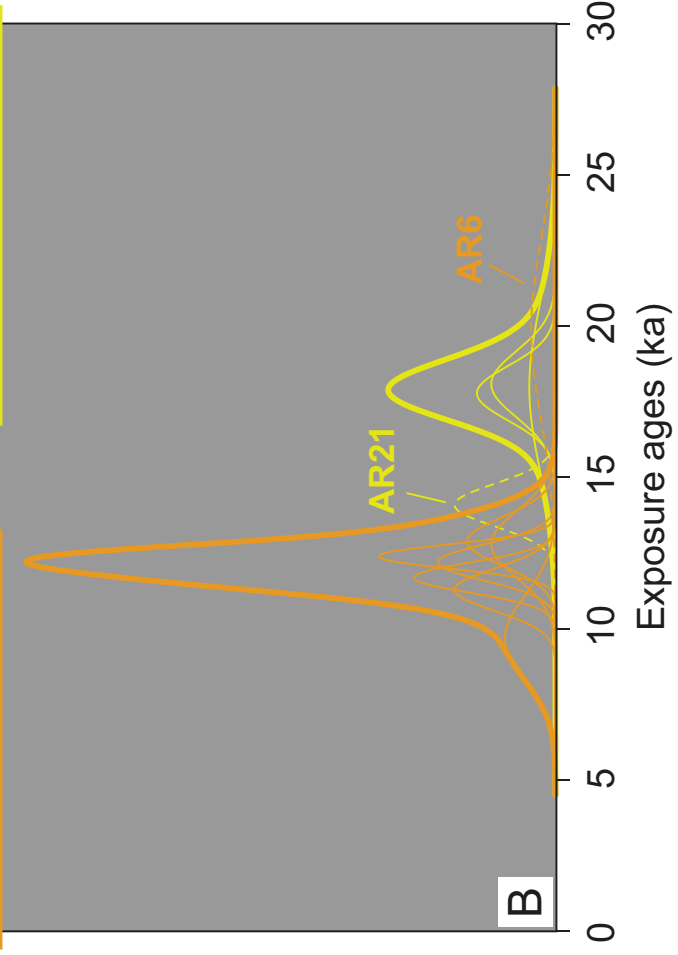
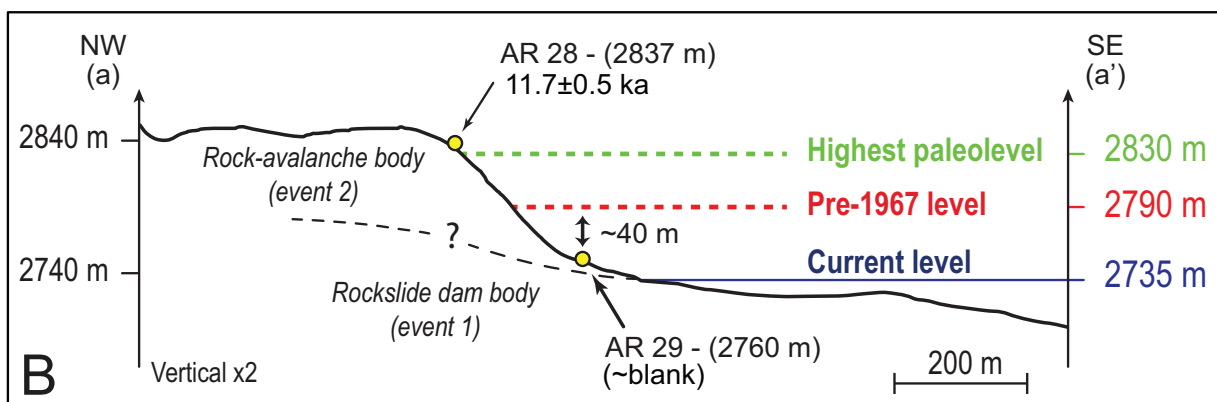
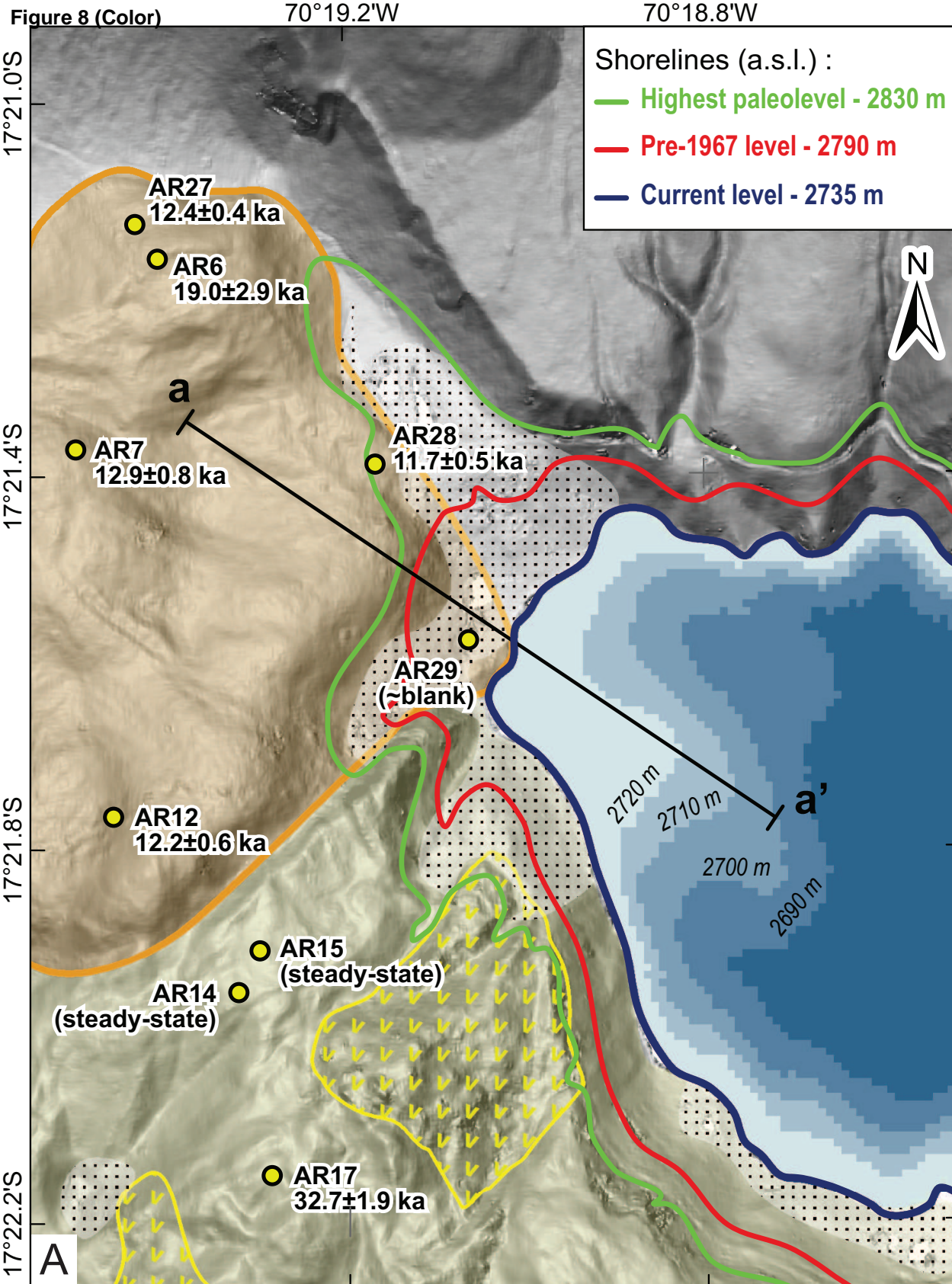


Figure 8 (Color)



**Figure 9 (Color)**

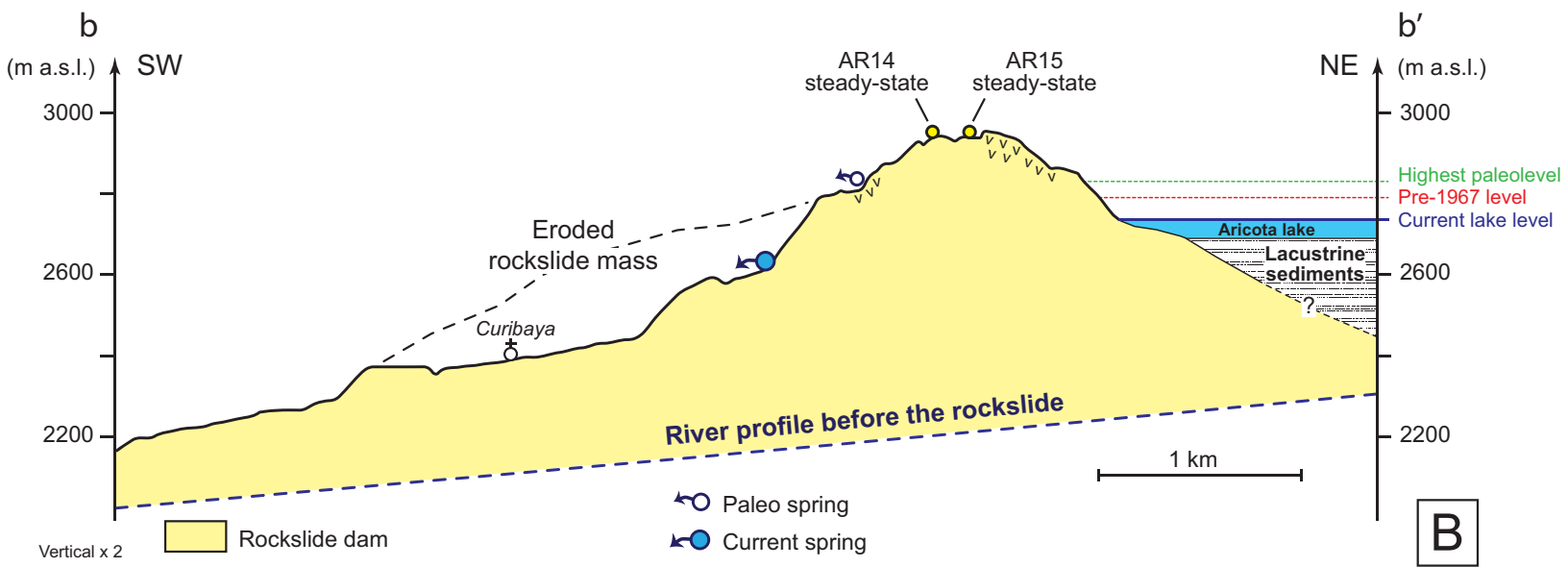
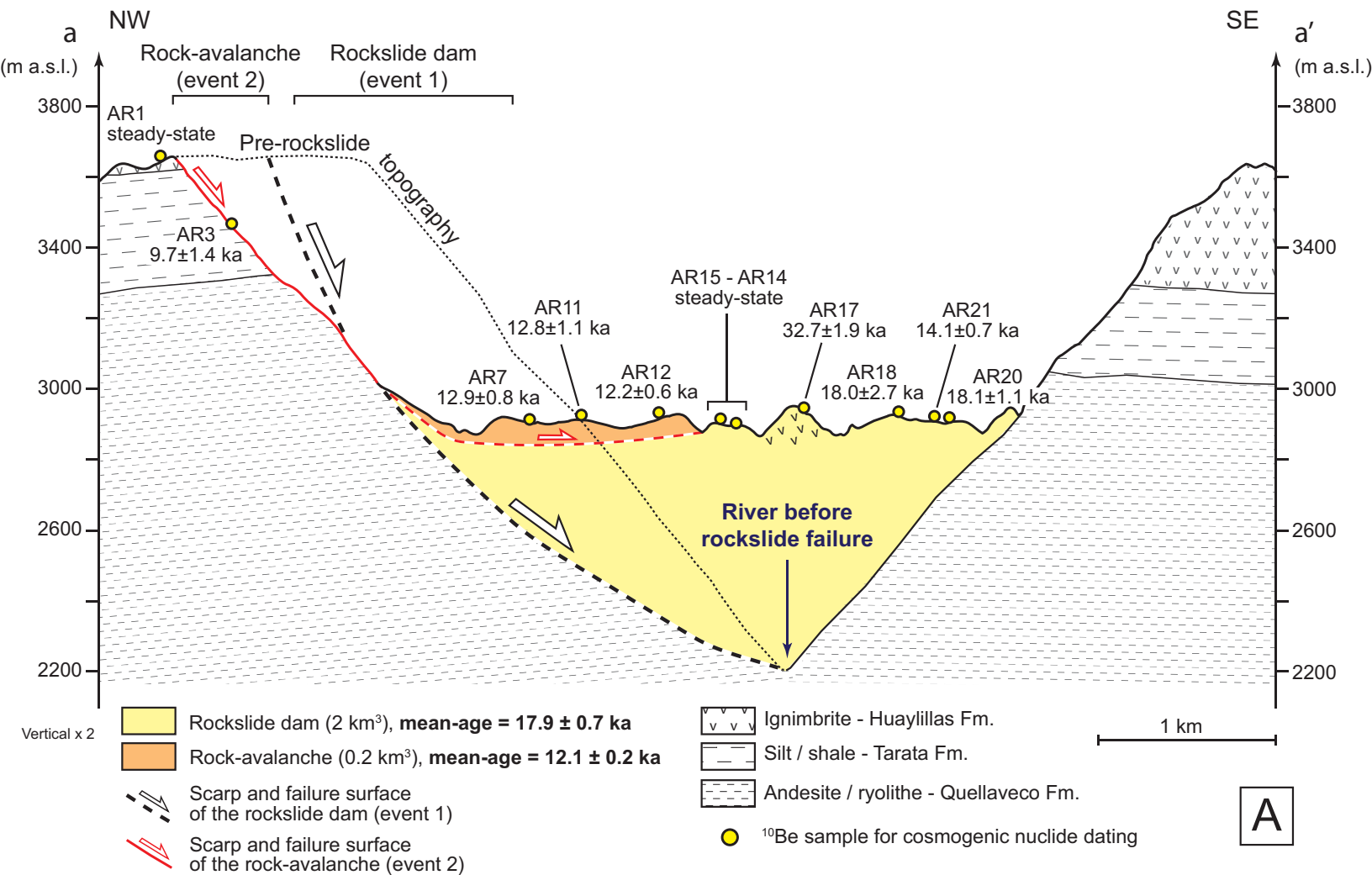




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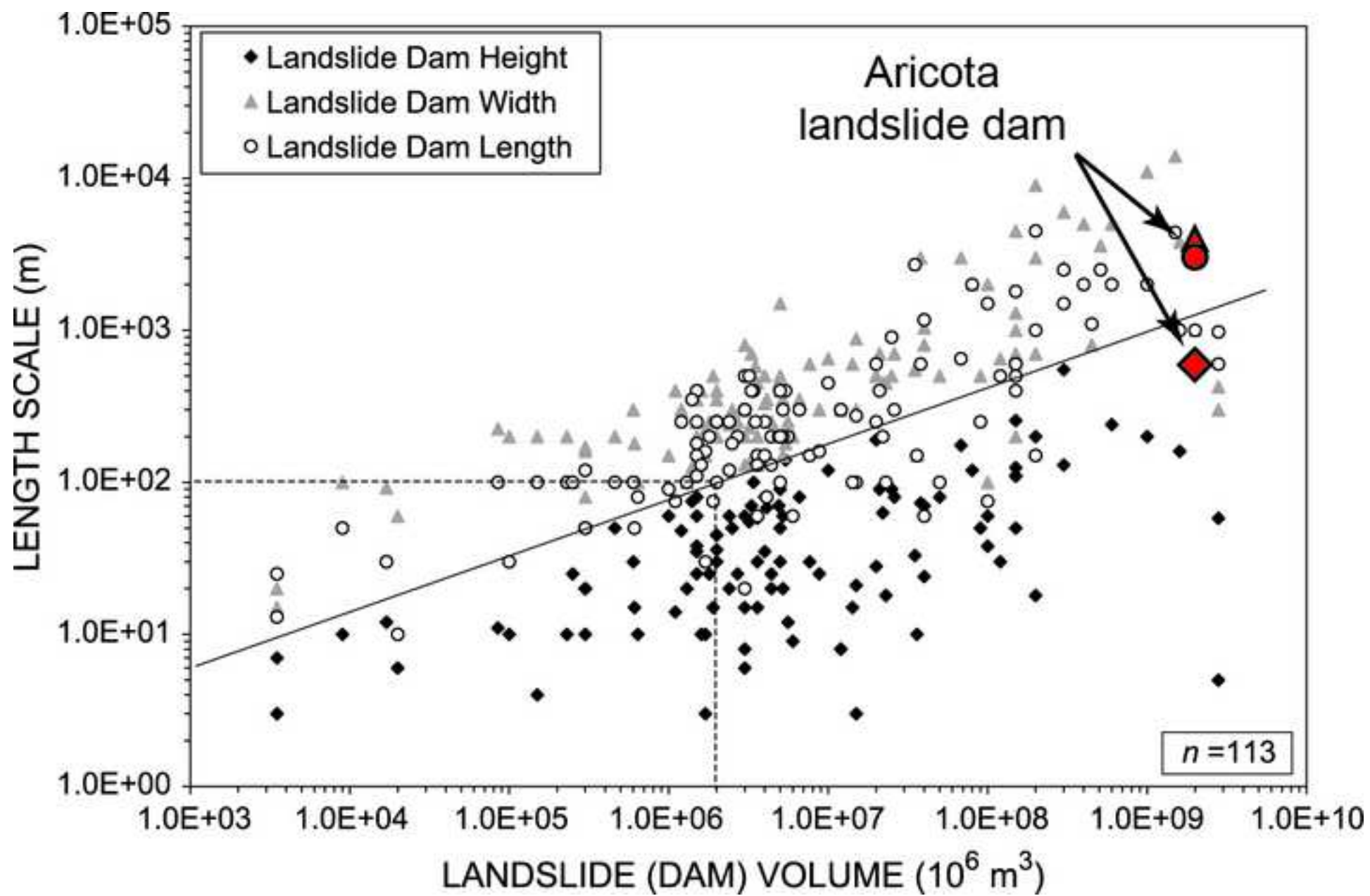


Figure 6 (Color)

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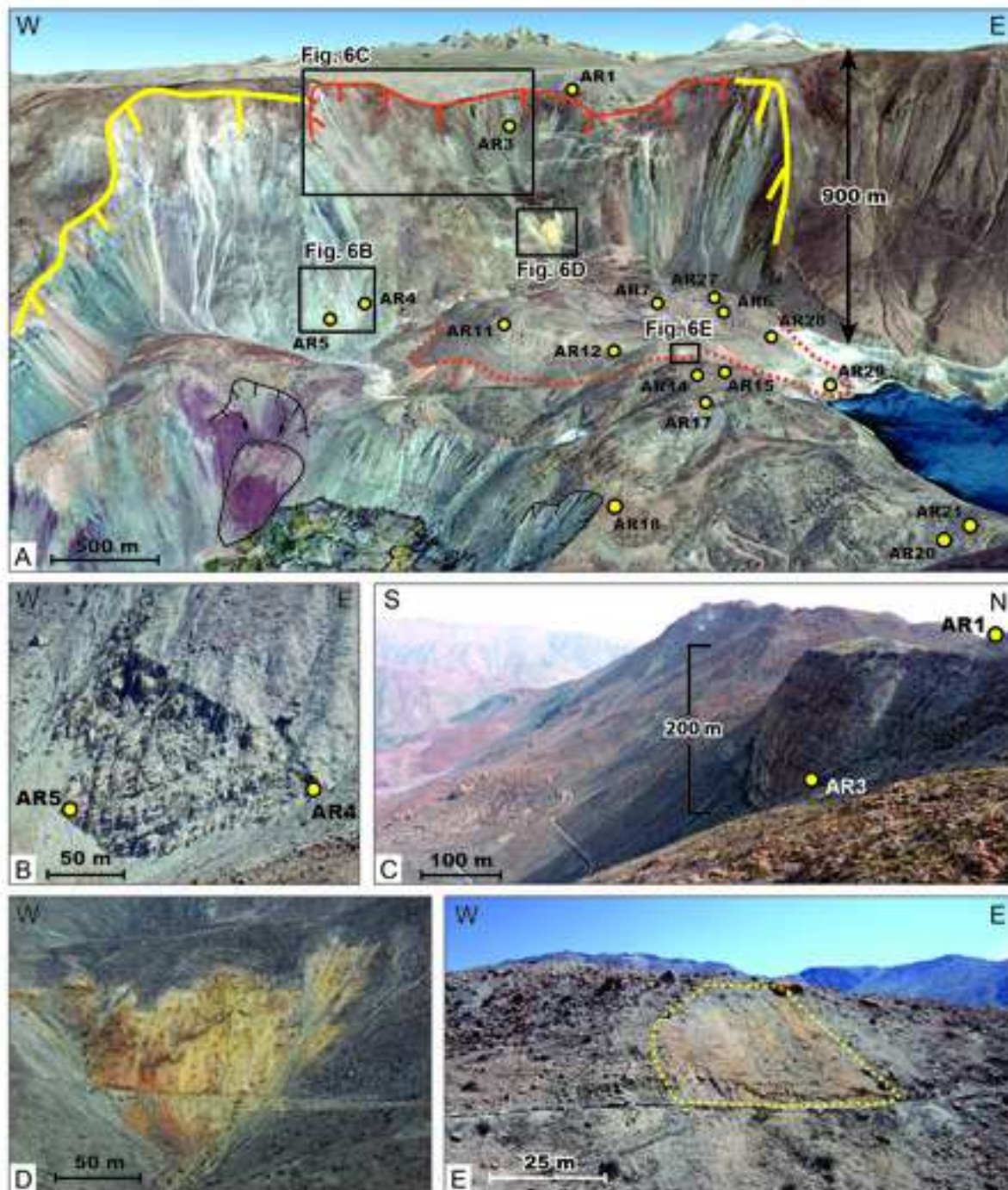


Figure 1 (Greyscale)  
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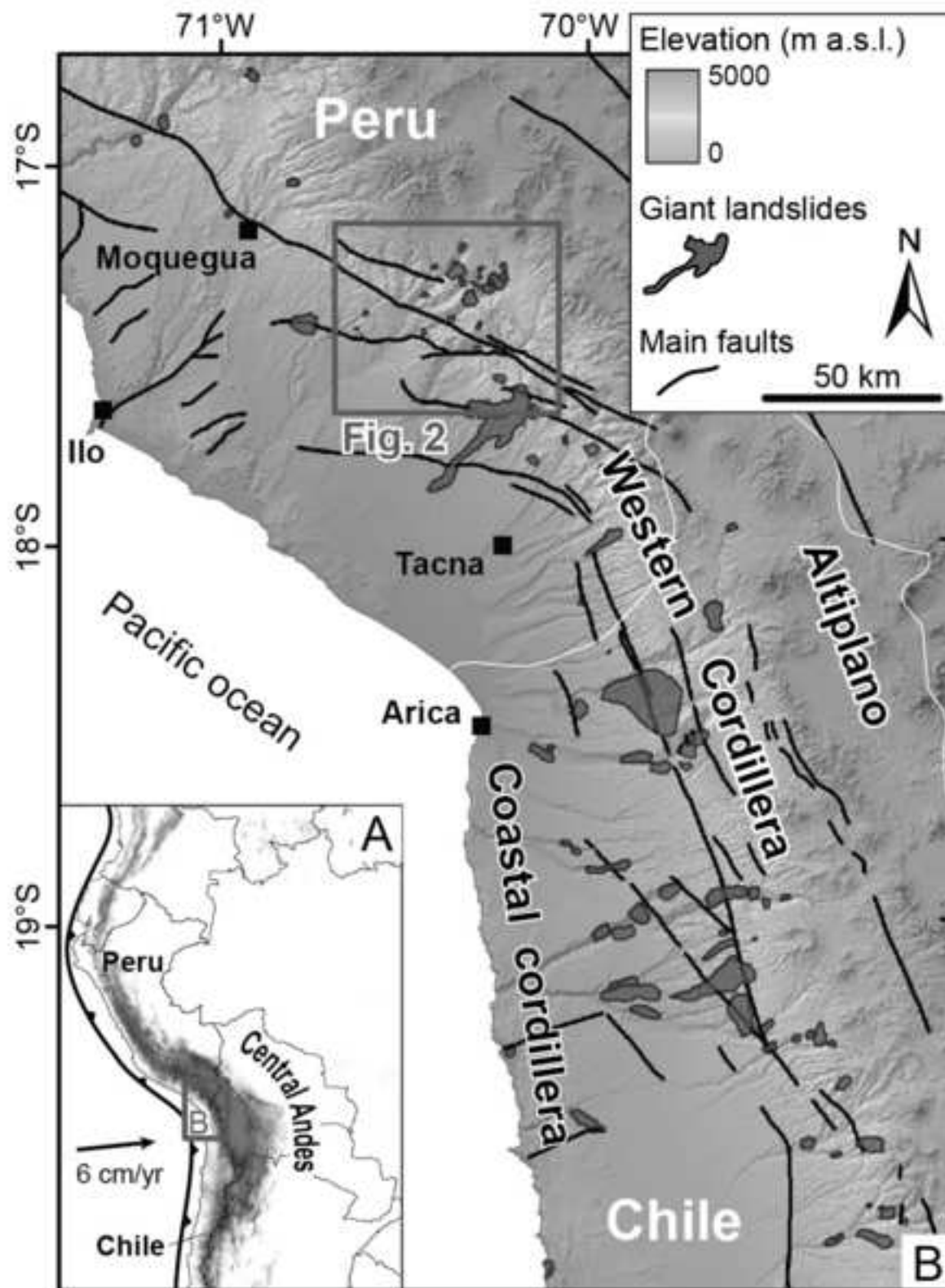


Figure 2 (Greyscale)

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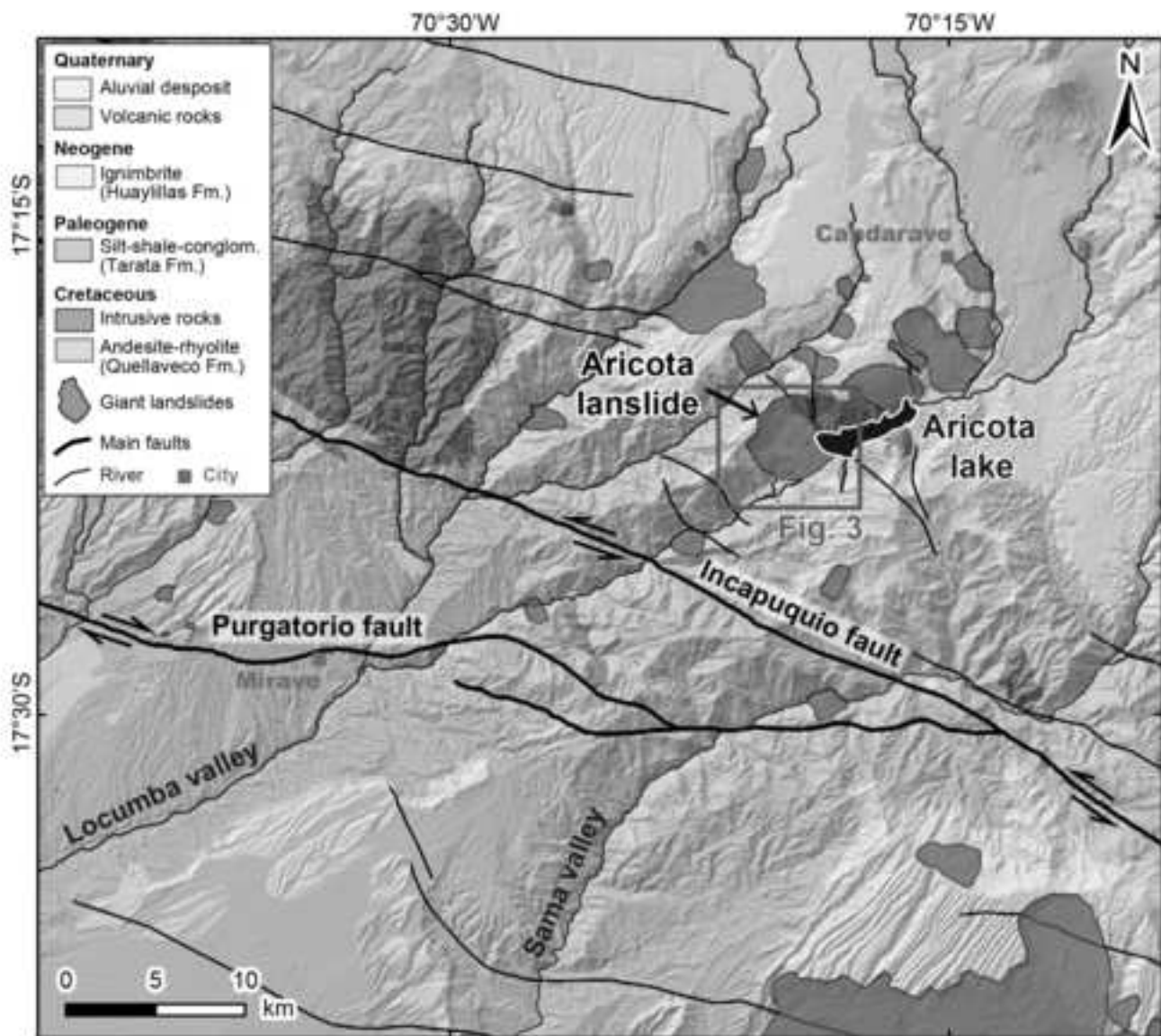


Figure 3 (Greyscale)

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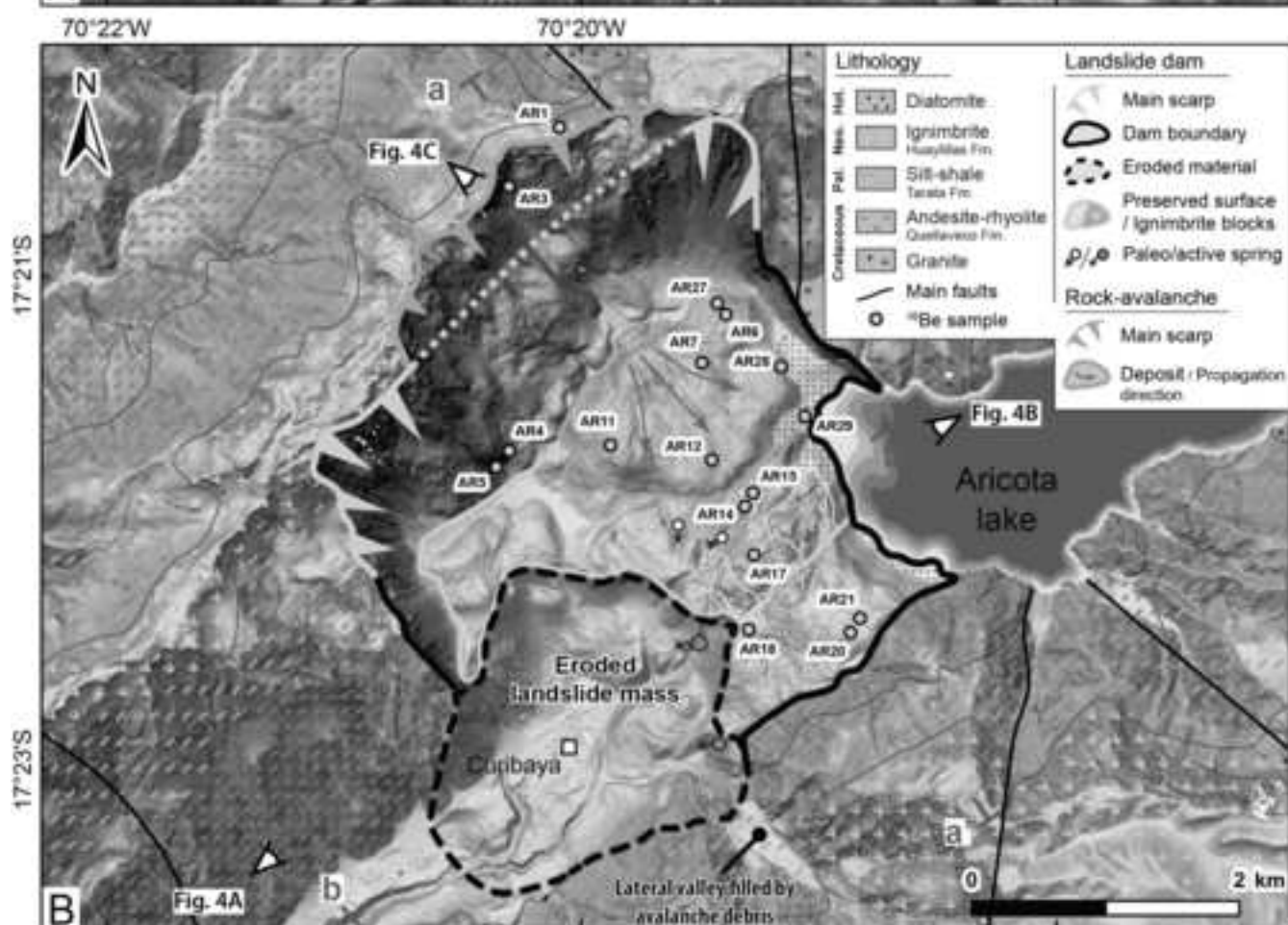
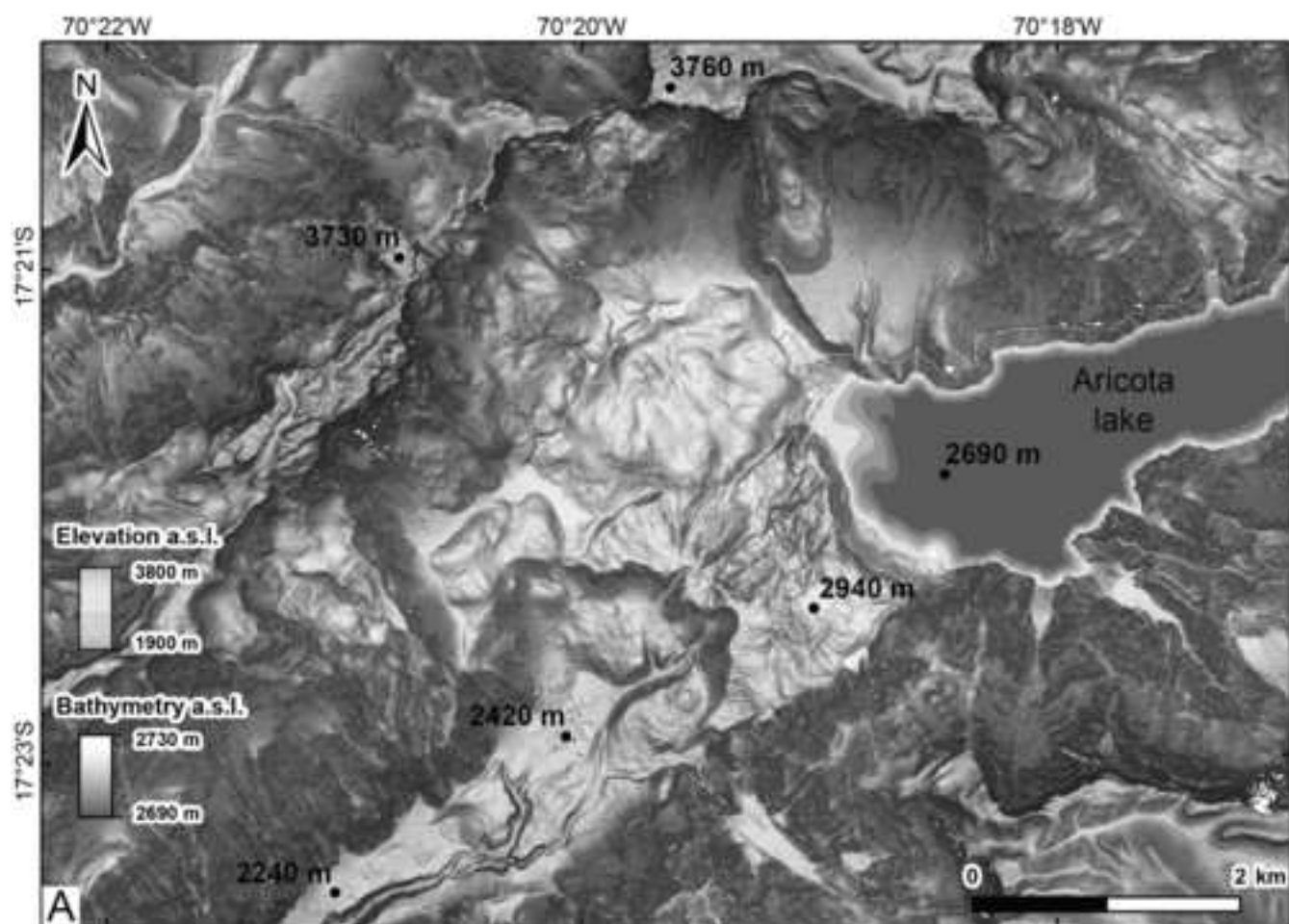


Figure 4 (Greyscale)  
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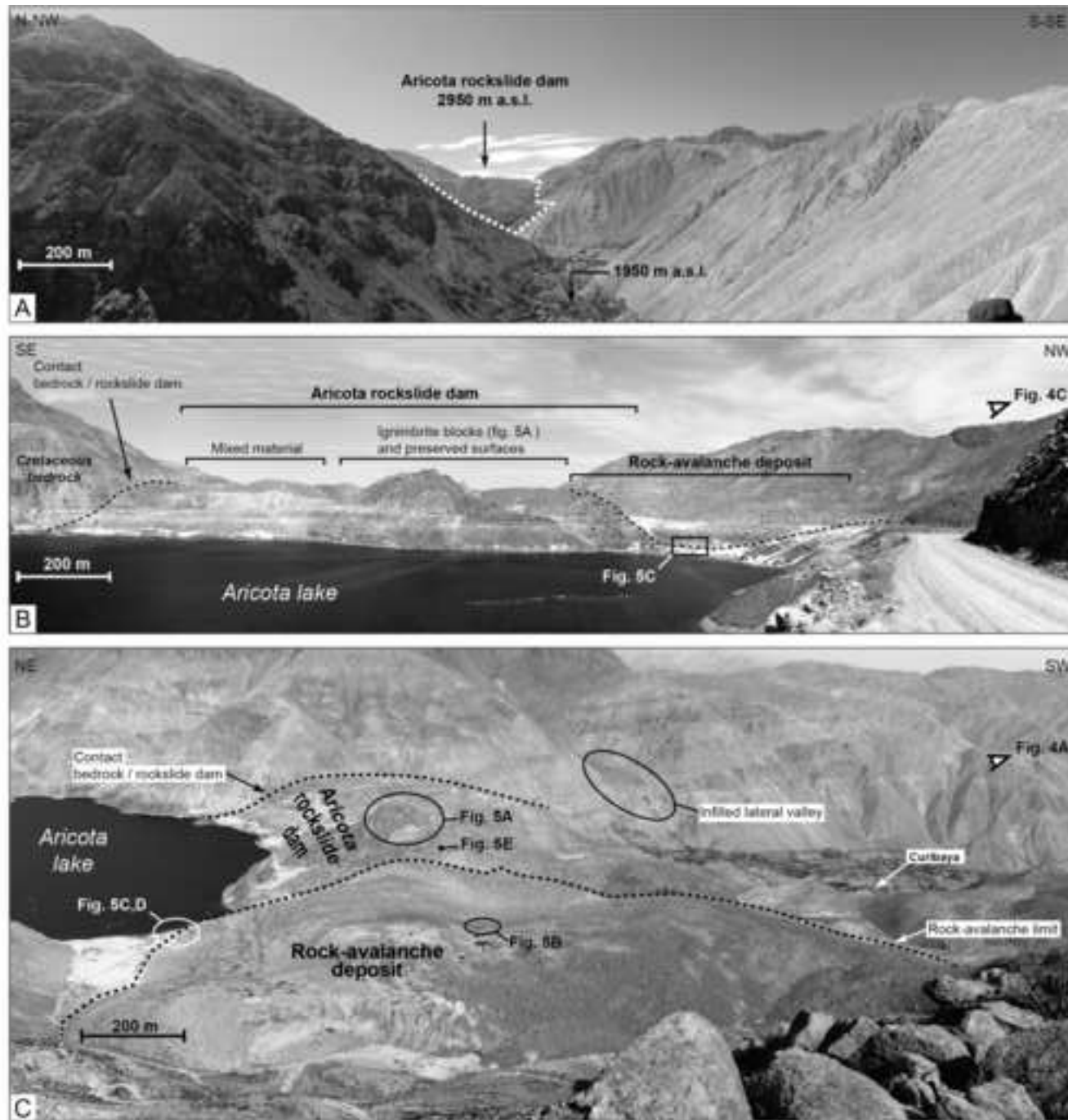


Figure 5 (Greyscale)  
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Figure 6 (Greyscale)  
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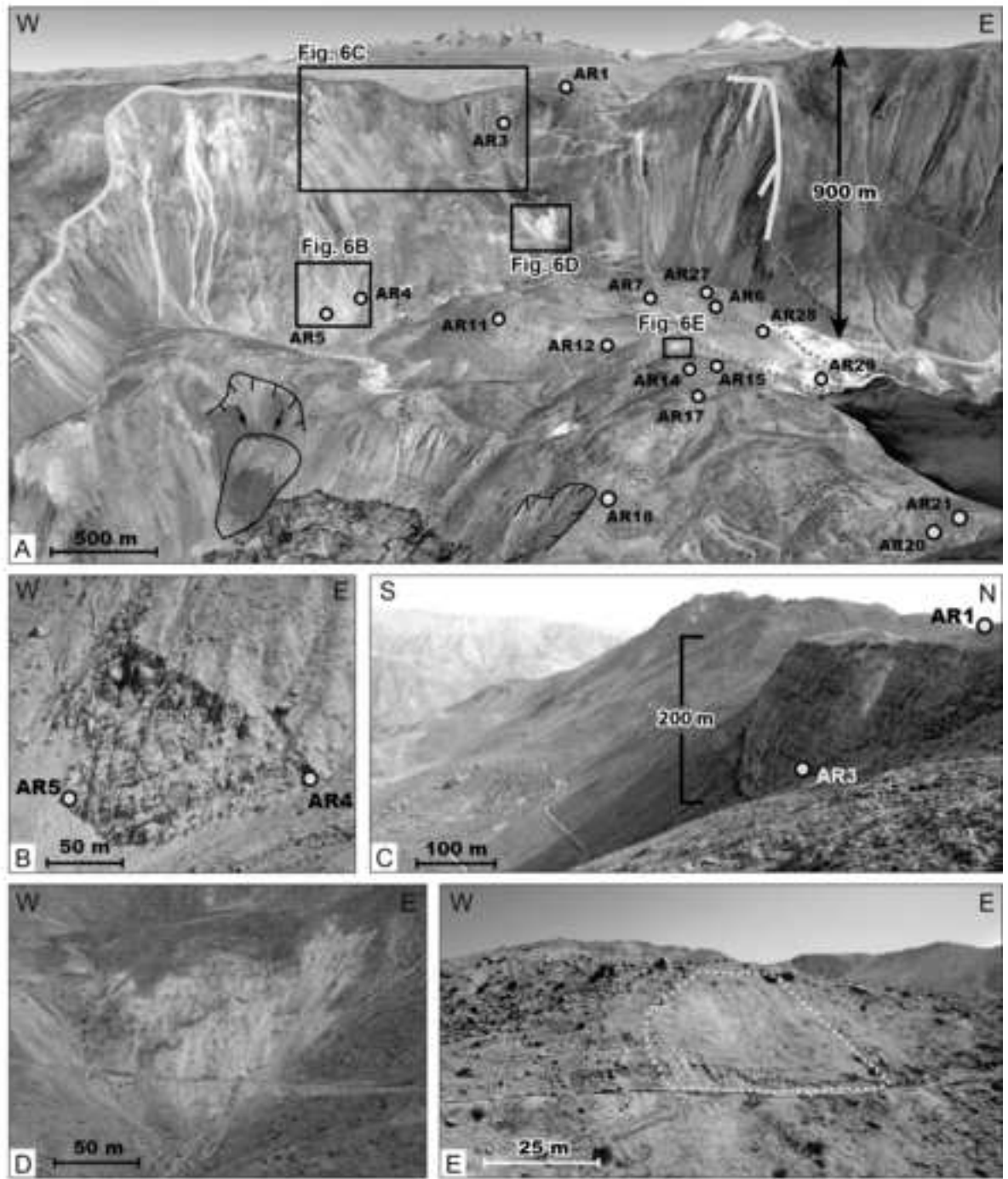
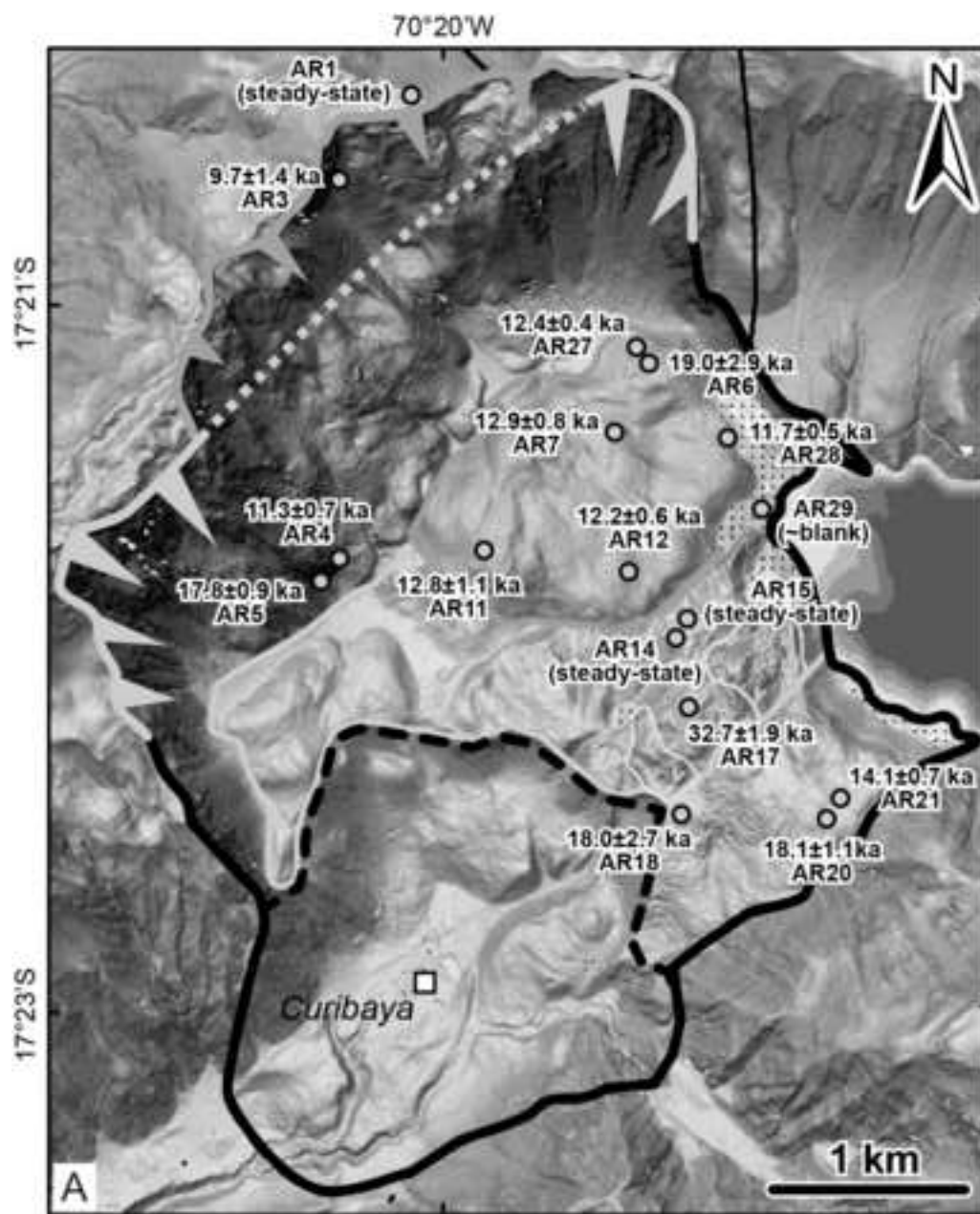




Figure 7 (Greyscale)  
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### Rock-avalanche

#### EVENT 2 (n=8):

Weighted-mean:  $12.1 \pm 0.2$  ka  
 Peak: 12 ka  
 MSWD: 1.78  
 $\chi^2_{data} = 12.46$ ;  $\chi^2_{(95\%)} = 14.07$

#### EVENT 2 (n=7; 1 outlier):

Weighted-mean:  $12.1 \pm 0.2$  ka  
 Peak: 12 ka  
 MSWD: 1.12  
 $\chi^2_{data} = 6.71$ ;  $\chi^2_{(95\%)} = 12.59$

### Rockslide dam

#### EVENT 1 (n=5):

Weighted-mean:  $17.2 \pm 0.5$  ka  
 Peak: 17 ka  
 MSWD: 20.74  
 $\chi^2_{data} = 82.95$ ;  $\chi^2_{(95\%)} = 9.49$

#### EVENT 1 (n=3; 2 outliers):

Weighted-mean:  $17.9 \pm 0.7$  ka  
 Peak: 17 ka  
 MSWD: 0.02  
 $\chi^2_{data} = 0.04$ ;  $\chi^2_{(95\%)} = 5.99$

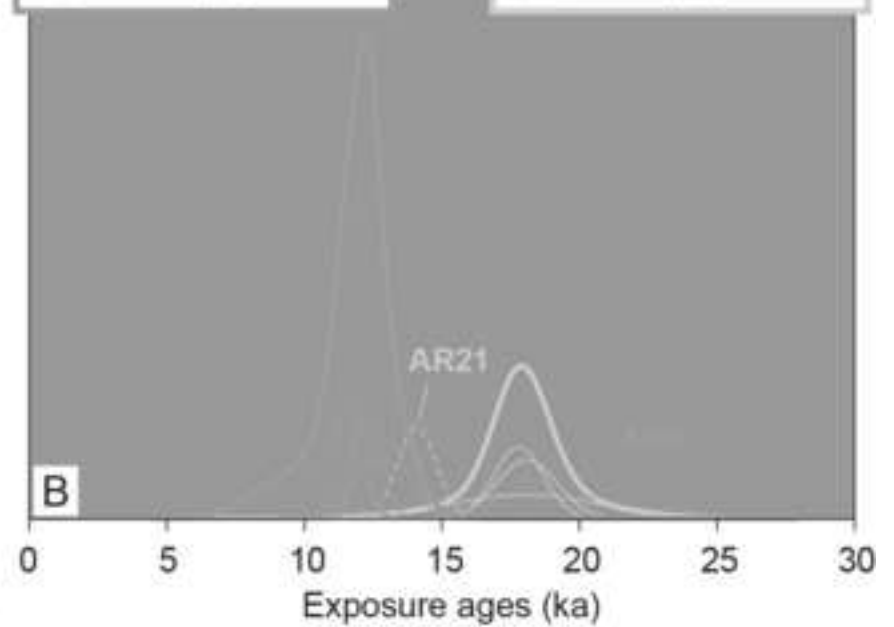


Figure 8 (Greyscale)

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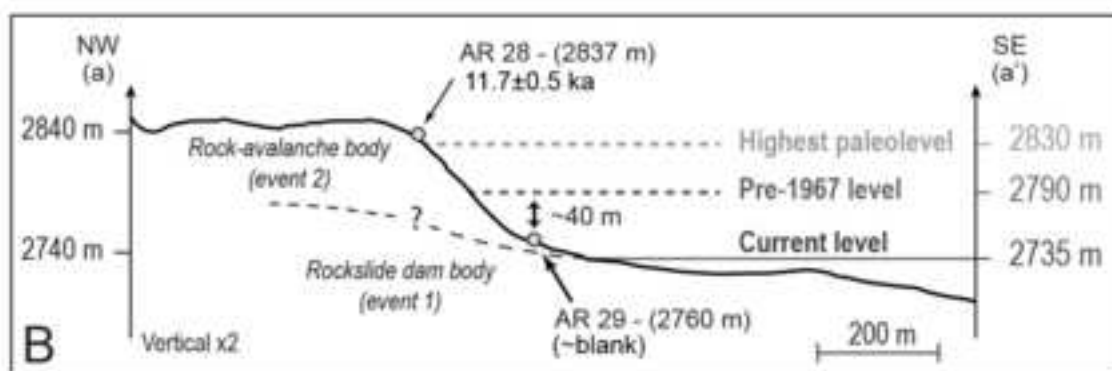
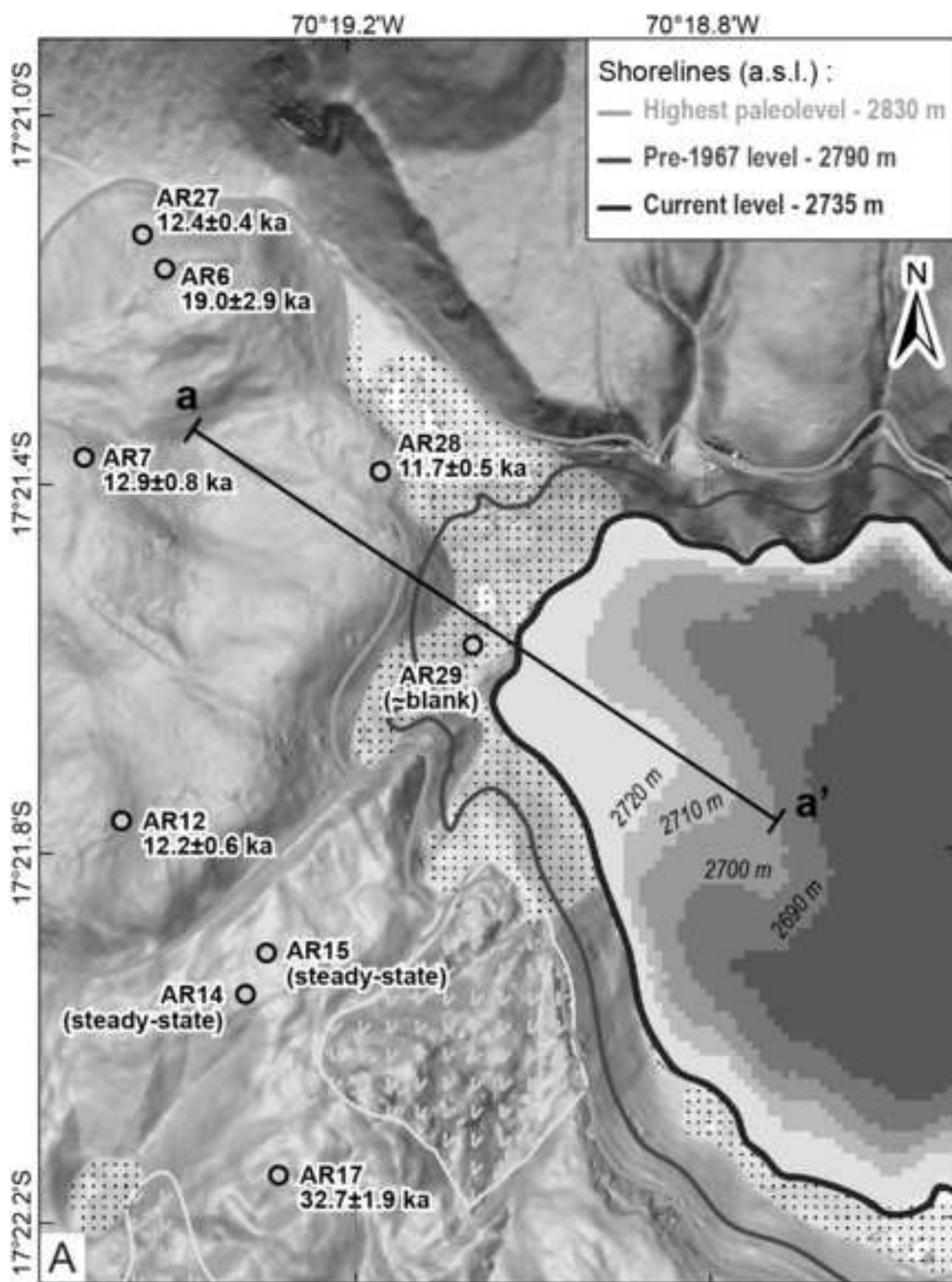


Figure 9 (Greyscale)

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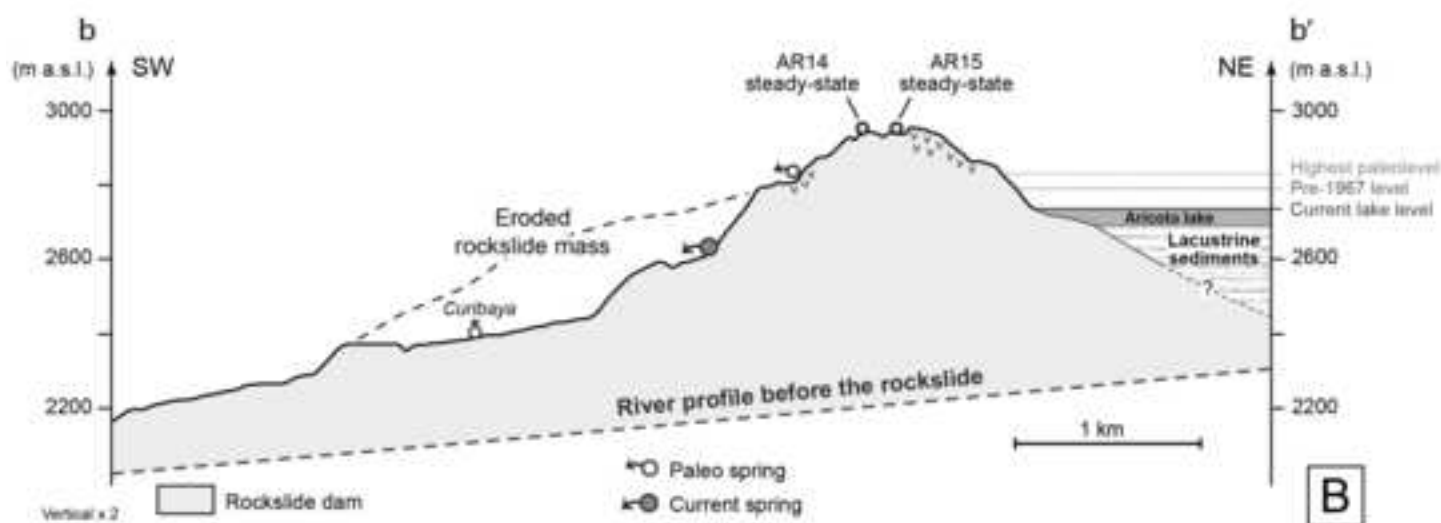
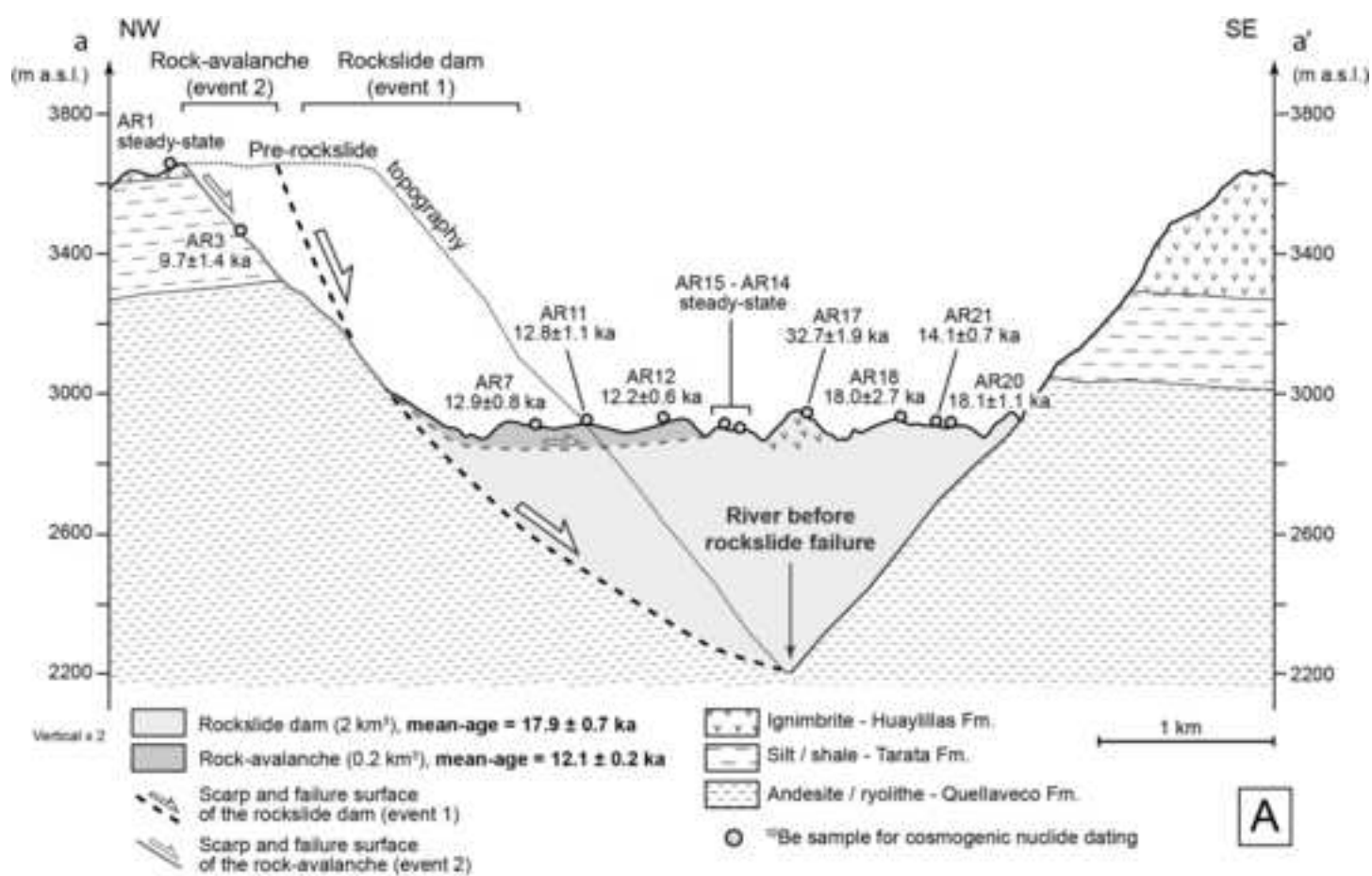


Figure 10 (Greyscale)  
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