Geomorphology

Gravitational slope processes triggered by past earthquakes on the Western Cantabrian Mountains (Sierra de la Sobia, Northern Spain)

--Manuscript Draft--

Comment on Ms. Ref. No.: GEOMOR-10601 *by F.J. Fernández et al.*

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Dear Markus,

The few minor errors found in the revised version by the reviewers of our Ms have been corrected.

We hope you will find it suitable for publication in Geomorphology.

Best regards,

FJ Fernández

In addition, we provide a marked-up manuscript version showing the few minor errors corrected (highlighted in red).

Paleo-earthquakes M6+ triggered rock- avalanches in the Western Cantabrian Mountains.

Kinematic of active faults being consistent with a horizontal N-S compression.

Slopes of the depletion zones become unstable with horizontal seismic ground > 0.10 g.

Dynamic fragmentation is not fractal and change in block size ca 1 m.

Sierra de la Sobia is a linear mountain range of arcuate shape, located West of the Cantabrian Mountains. The long-lived crustal León Fault runs along its western hillslope, and its trace is partially covered by multiple rock-avalanches. Here we discuss if recurrent paleo-earthquakes in the M6+ range could have acted as the triggering factor for rock-avalanches in a region where the historical and instrumental seismic records only include seismic events up to Ms 4.6. Evidence concurring with a coseismic origin includes: (i) kinematic of current minor transverse and parallel faults to Sierra de la Sobia being consistent with a horizontal North-South compression of the Cantabrian Arc; (ii) slopes of the depletion zones that would become unstable if horizontal seismic ground rose 0.10–0.15 g; and (iii) block size-reduction by dynamic fragmentation creating block size distribution with fractal dimension, ranging between 2.24 and 2.70. U/Th dating of seven calcite precipitates coating the blocks of cemented rock-avalanche deposits suggesting that cementation has taken place in multiple episodes since MIS-9a. Neotectonics of Sierra de la Sobia are expressed in subtle changes in relief after extremely rapid co-seismic events, with average recurrence intervals much longer than the time covered by the regional historical and instrumental period.

1 **Gravitational slope processes triggered by past earthquakes on the Western**

2 **Cantabrian Mountains (Sierra de la Sobia, Northern Spain)**

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10 **Abstract**

11 Sierra de la Sobia is a linear mountain range of arcuate shape, located West of the

12 Cantabrian Mountains. The long-lived crustal León Fault runs along its western hillslope,

13 and its trace is partially covered by multiple rock-avalanches. Here we discuss if recurrent

14 paleo-earthquakes in the M6+ range could have acted as the triggering factor for rock-

15 avalanches in a region where the historical and instrumental seismic records only include

16 seismic events up to Ms 4.6. Evidence concurring with a coseismic origin includes: (i)

17 kinematic of current minor transverse and parallel faults to Sierra de la Sobia being

18 consistent with a horizontal North-South compression of the Cantabrian Arc; (ii) slopes

19 of the depletion zones that would become unstable if horizontal seismic ground rose 0.10–

20 0.15 g; and (iii) block size-reduction by dynamic fragmentation creating block size

21 distribution with fractal dimension, ranging between 2.24 and 2.70. U/Th dating of seven

22 calcite precipitates coating the blocks of cemented rock-avalanche deposits suggesting

that cementation has taken place in multiple episodes since MIS-9a. Neotectonics of Sierra de la Sobia are expressed in subtle changes in relief after extremely rapid co-seismic events, with average recurrence intervals much longer than the time covered by the regional historical and instrumental period.

1. Introduction

The Cantabrian Arc (CA), also known as Ibero-Armorican Arc (Lefort, 1989), is the largest structure of the Variscan orogeny in Western Europe. The CA deformed an initially linear foreland thrust and fold belt, formally defined as the Cantabrian Zone (CZ; Lotze, 1945) in the latest Stephanian to the earliest Permian (Weil et al., 2001). Later, the CA also controlled the reactivation of the basement during the Alpine cycle, when the Cantabrian Mountains were raised (Gallastegui et al., 2016). Alpine deformation produced the inversion of the northern Iberian plate, and it migrated and decreased progressively from the Pyrenees, westward to the CA (Fig. 1A). Alpine sedimentation ceased after the Late Oligocene (Álvarez-Marron et al., 1997), and Alpine exhumation of the central part of the Cantabrian Mountains occurred from 39 to 29 Ma, at a rate of 2.4–3 mm yr^{-1} (Fillon et al., 2016). Little is known about the post-Oligocene tectonics of the Cantabrian Mountains due to the scarcity of Tertiary outcrops, the limited size of surficial formations formed since the late Quaternary glaciations, and the later slope dynamics controlled by fluvial incision (Menéndez-Duarte et al., 2007; Rodríguez-Rodríguez et al., 2015). Consequently, we might wonder if evidence of Quaternary deformation exists in the Cantabrian Mountains, and what traces correspond to active landscape processes.

Nowadays, northern Iberia is considered a passive margin, hundreds of kilometres away from the interaction of the Nubia Plate with the Iberian microplate. This overall tectonic setting engenders a stress field in the Iberian Peninsula, characterized by a predominately NNW to NW trending maximum horizontal stress (SHmax; de Vicente et al., 2008; Custódio et al., 2015). In this context, the Cantabrian Mountains are considered a seismically active shallow crust (Delavaud et al., 2012) with earthquakes of low to moderate magnitude (Stich et al., 2020). During the 2015–2017 instrumental period, the CZ recorded 40 seismic events of surface wave magnitude (Ms)>2 at depths of between 9 and 18 km at the intersection between the León and Ventaniella faults and the biggest recorded was an Ms 3.7 event (Fig. 1B; López- Fernández et al., 2018). The León Fault is a breaching fault (Alonso et al., 2009) buckled by the CA, and cut northwards by the younger Permo-Triassic right-lateral Ventaniella Fault. Large submarine avalanche deposits have recently been found, along with the northwest offshore extension of the Ventaniella Fault-scarp (Fernández-Viejo et al., 2014), near to the location of the historical earthquakes of 1522 and 1861 (Fig. 1B). East-west trending uplifted wave-cut platforms extend along the Cantabrian coastline for more than 400 km, tectonically uplifted since at least 1–2 Ma (Álvarez-Marrón et al., 2008).

These tectonic geomorphology imprints might result from the ongoing slow convergence and inversion extending along the Cantabrian coast, where the CA may reactivate. To test this hypothesis, we studied the recent tectonic geomorphology of Sierra de la Sobia, a Carboniferous limestone mountain range of arcuate shape, buckled according to the curvature of the CA to the west of the Ventaniella Fault. The northern branch of the León Fault lies along the western flank of Sierra de la Sobia (Figs. 1B and 1C), and an unusually high number of rock-avalanches never previously described or analysed overlie the fault trace. In 1996 an earthquake of Ms 4.1 (Fig. 1B) struck the Villa de Sub village on the

southern slope of Sierra de la Sobia, triggering a rock-fall. North-westward, El Canto district was built atop the most massive rock-avalanche, composed of several superposed deposits. The higher parts of this avalanche still represent a severe risk for the citizens of Entrago and La Plaza. Moreover, an early cemented deposit accumulated about 600 m east of Sobrevilla has its origin in a rockfall from the deposit. The number of tension cracks easily visible on Google Earth suggest that more rockfalls are likely to happen. In addition, a reverse fault superposing Carboniferous limestone onto cemented talus scree deposits has also been described (Fernández et al., 2018). At first sight, Sierra de la Sobia is among the best places to shed new light on the Quaternary tectonic geomorphology in the CZ.

2. Regional setting

Sierra de la Sobia is in the eastern nappe of the Somiedo Unit (Figs. 1B, C; Alonso et al., 2009). From a geomorphological standpoint, it is an arcuate mountain range ~16 km long and 2-5 km wide with a Range Level of Summits (RLS) dipping 1.5° northward (Figs. 2, 3, 4 and 5). It is formed by a continuously well-exposed outcrop of Carboniferous limestone. The highest elevations of these mountains are south of Sierra de la Sobia, at the Ubiña Massif with peaks 400 m higher than the regional-RLS. It is noteworthy that the León Fault is bent around the Ubiña Peak (2417 m), accordingly with CA orocline and such a footwall corner gives relief to a syntaxial shape (Fig. 2). Carboniferous limestone overrides the Lower Cretaceous cover south of the Ubiña Peak, evidencing the Alpine reactivation of the León Fault (Alonso et al., 2007). The long-lived León Fault has been active in different tectonic cycles, and it remains seismically active (Fig. 1B; López- Fernández et al., 2018).

2.1 Variscan structure

95   The Paleozoic basement of the Sobia Nappe involves an ~2500 m and a 500 m-thick syn-

96   orogenic sequence (Fig. 3; Marcos and Pulgar, 1982). During the Variscan orogeny the

97   oldest thrusts, such as the Sobia, Tameza, and Somiedo, accommodated most of the

98   shortening in deep levels (Figs. 1C and 3). Upwards, the shortening was accommodated

99   stratigraphically by fault-propagation folds, like the Caranga Antiform (Figs. 3 and 4B;

100   Bulnes and Aller, 2002). It consists of a stack of at least three thrusts of Ordovician

101   quartzite and sandstone formed to facilitate accommodation for shortening northwards

102   due to the presence of lateral thrust ramps (Bastida and Castro, 1988).

103   Later, the León Fault cut the sequence, superposing the Somiedo and the Tameza Nappes

104   onto the Sobia Nappe (Fig. 1C). The primary displacement of the León Thrust occurred

105   before the CA, and kinematic markers indicate an ENE transport direction (Alonso et al.,

106   2009). Since the CA bends the León Fault, it trends along with two main strikes N30ºW

107   and N100ºE, respectively, from the Ubiña Massif (Fig. 2). Its North-Western termination

108   consists of a splay fault formed by three main segments. The Marabio Segment-Fault

109   (MSF; Figs. 1C, 2, 4) is the longest at 48 km, its trace being partially covered by rock

110   avalanches triggered along the western flank of Sierra de la Sobia.

111   **3. Materials and methods**

112   The geology of Sierra de la Sobia was entirely reviewed based on the latest regional study

113   (Alonso et al., 2009) and the analysis of previous geological maps of the northern and

114   eastern areas (Bastida and Castro, 1988; Bulnes, 1994), and the online version of the

115   continuous digital geological map of the CZ, scale 1:50,000 (Merino-Tomé et al., 2011).

116   This map differentiates the unconformable Quaternary, Tertiary, and Stephanian outcrops

117   from the Paleozoic underlying basement, as well as the Variscan mechanical contact from

118   the latterly developed structures (Fig. 3). Quaternary deposits and fracture networks

119   within the limestone massif have been tracked from fieldwork and ortho-photographs,

120   scale 1:50,000 (PNOA series, IGN). Due to the difficulties inherent to discriminating

121   Quaternary faults from other earlier Cenozoic faults, both have been grouped as "late

122   faults" when cut-off relationships with the earlier Variscan faults can be established.

123   However, most of these later faults do not show relative displacements at our working

124   scale, because fault slips are frequently <10 m.

125   A selection of nine rock-avalanches was quantitatively characterized. The vertical drop

126   (H) measures the difference in height between the crown of the depletion zone and the

127   toe of the accumulation body, and the length (L) is the horizontal distance between both

128   points. The rock-avalanche volume was estimated multiplying its surface area by the

129   mean thickness of the accumulation body. The average thickness of rock-avalanche

130   deposits was indirectly estimated as half of the possible maximum thickness of the

131   deposit, calculated from the topographic expression of the accumulation body.

132   Analyses of Block Size Distribution (BSD) were completed in four representative

133   deposits of rock-avalanches using high-resolution drone imagery to compile maps of

134   block sizes >10 cm. Ortho-photographs were acquired from a drone, ATYGES FV-8,

135   using pre-planned flight lines of the mapped areas and geo-referenced with a GPS,

136   LEYCA GS14 GNSS. The fractal dimension (*D,* Epstein, 1947) was calculated in such

137   deposits easily, using the BSD of >14k blocks as the slope of the lineal fit in log

138   frequency/log equivalent radius diagrams; they were plotted showing 20 bins per order

139   of magnitude. The shape parameter *S* calculated as $S = \frac{4\pi A}{P^2}$ (1) (Fernández et al., 2005),

140   where the area *A* and perimeter *P* of wedges were measured in pixel^2 and pixel,

141   respectively. Wedges <20 pixel^2 were removed. *S* is not wedge-size dependent, and

142   ranges between 1 (wedge-shape is a perfect circle) and 0 as irregularities of the wedge-

143   shape increase. Block size measures by the radii equivalent (r_i) of each block, where $r_i =$

144     $\sqrt{\frac{(A+P)}{\pi}}$ (2).

145   The rock mechanics of the residual slope were analysed where the rupture scarps were

146   mapped. Slope stability was calculated based on over 350 measurements of joint and fault

147   plain orientations using the advanced computational tools for geometrical, kinematical,

148   and mechanical analysis of the Dips 7.0, Rocplane, and Swedge programs, respectively.

149   Mechanical discontinuities were heuristically classified as: (i) bedding planes (S_0); (ii)

150   faults parallel (F_p) or transverse (F_r) to the range trend; and (iii) joints parallel (J_p) or

151   transverse (J_r) to the range trend. Joints transverse to the range were subdivided according

152   to the direction and angle of dip in: (i) <30º dip angle northwards (J_{r1}); (ii) >50º angle

153   northwards ($J_{r1'}$); (iii) <30º dip angle southwards (J_{r2}); (iv) >50º angle southwards ($J_{r2'}$).

154   Calcite cements, interfusing blocks and pebbles in the oldest rock-avalanches were

155   collected at eight sampling localities and treated in the laboratory to extract the calcite for

156   U/Th dating. Five of the eight samples processed exhibited calcitic cement pure enough

157   for radiometric analysis. Calcite crystals were selected under the microscope to minimize

158   detrital contamination from detrital fine sediment matrix. U/Th dating was completed at

159   the University of Minnesota by Inductively Coupled Plasma Mass Spectrometry (ICP-

160   MS) as described by Shen et al. (2002). Sample RB_02 was replicated by sample RB_9

161   and sample RB_03 by sample RB_10 by the U/Th facility at the Institute of Earth

162   Sciences Jaume Almera (ICTJA-CSIC; Barcelona). The replicates provided purer calcite

163   cements which reduced the age uncertainties previously obtained, likely due to a Th

164   excess of detrital origin. The chemical separation and purification of the radioisotopes

165   followed Bischoff et al. (1988). The isotope electrode position followed Talvitie (1972)

166 and was modified following Hallstadius (1984). Age calculations were based on

167 Rosenbauer (1991). Results are compiled in Table 3.

168 **4. Results**

169 Three structural domains have been distinguished in Sierra de la Sobia. The northern

170 domain extends southward to the Marabio Mountain Pass. The MSF outcrops within the

171 Westphalian shale, superposing the Teverga coal basin (Middle and Upper Westphalian

172 formations in Figs. 3 and 4) onto the Sobia Nappe. The Tameza Thrust and MS converge

173 progressively northwards (Fig. 3). The western hillslope of Sierra de la Sobia is separated

174 by >1 km of MS-trace (Fig. 4B), and it lacks rock-avalanches. Minor parallel faults trend

175 NNE, and transverse faults define three sets trending NE, E, and SE. A reverse parallel-

176 fault superposes Carboniferous limestone westward onto recently cemented talus-scree

177 deposits, with up to 6 m net slip (Fernández et al., 2018). A fault splay also cuts the

178 Caranga fault-propagation anticline (Figs. 3, 4B, and 6). It shows a reverse displacement

179 with anticlockwise rotation from SW to S. The kinematic agrees with the Alpine

180 inversion, but also with the NNW-trend of the current regional SHmax. The stress

181 inversion obtained for Sierra de la Sobia, after excluding some of the latest transverse

182 fault kinematics that gave inconsistent solutions, gives a similar SHmax, and the

183 limestone outcrop has a joint fracture network with similar strikes to faults belonging to

184 this domain (Fig. 6).

185 The hinge domain extends southward from Marabio Pass to Sobrevilla (Fig. 3). The

186 arcuate MSF-trace lies progressively closer to the western hillslope of Sierra de la Sobia.

187 The slope has a convex shape and has recorded several rock-avalanches. The limestone

188 outcrops' width decreases progressively as the curvature of the arcuate range increases

189 (Fig. 3). Deformation has been accommodated by normal faults that transect the hinge of

190 the range, some of them cut MSF. Southward, MSF is covered by the Entrago rock-

191   avalanche. The outcrop of limestone is strongly fractured, and the fracture network is

192   formed by joint sets parallel to the main fault strikes (Fig. 6).

193   The southern domain extends from the Entrago to the Villa de Sub rock-avalanches (Fig.

194   3). The South-Western hillslope of the range between the Entrago and the Carrea rock-

195   avalanches is a structural form controlled by the orientation of the limestone bedding and

196   MSF. Both mechanical discontinuities run parallel to the slope, and dip in the same

197   direction but are more pronounced than the slope. Parallel faults run SE, with transverse

198   faults and fractures defining three sets trending N, NE, and E, respectively (Fig. 6). The

199   periclinal structure of the Sobia Nappe is exposed on the southern hillslope of Sierra de

200   la Sobia (Fig. 3). The structure consists of folds related to Variscan thrusts in the lateral

201   ramp of the Sobia Nappe and with a transport direction north-eastward. The León Fault

202   thrusts out of sequence towards the NE and accumulates a total displacement of ~9 km in

203   the section shown in Fig. 1C (Alonso et al., 2009). This lateral ramp was shifted 45ºNW

204   during the Alpine inversion.

205   More recently, the current re-tightening of the Sobia Nappe was accommodated by right-

206   lateral faults (N150ºE-strike). The trace of these faults runs parallel to the Taja Fault

207   segment throughout the southern hillslope of Sierra de la Sobia. Additionally, several

208   active faults trending E-W have exposed their respective fault scarps and have been

209   mapped on the junction of the splay between the Trobaniello Fault segment and the MSF.

210   Most of them are small (widths <7 km) with relative movement frequently attenuated

211   laterally and accommodated by the thickly fractured surficial network of the limestone

212   massif (Fig. 6).

213   Restoration of an eventual continuous RLS-line before its segmentation along the

214   northern and hinge domains of the range results in an extension of ~300 m southward by

215   right-lateral faults N150ºE-strike, and potentially by faults trending E-W (Fig. 6). The

216 current re-tightening of the arc described by the hinge domain of Sierra de la Sobia has

217 been measured, assuming that the extension of the western convex hillslope was created

218 by tangential longitudinal folding (Ramsay, 1967). The finite neutral surface is on

219 longitudinal section A (Fig. 3) and runs along the RLS (Fig 4). The result is an

220 incremental longitudinal strain e_i= 0.031 that produces a strain ellipse on the outer arc of

221 aspect ratio R= 1.42 (Fig. 6), therefore an angular extension of 3.32º along the western

222 convex hillslope. However, the kinematics of the current faults suggest that the parallel

223 shear could be progressively more significant toward the northern and southern domains

224 respectively, according to the orientation of their finite strain ellipses (Fig. 6).

4.1. Rock-avalanche geometry

226 Multiple rock-avalanche deposits are within the hinge and southern domains of Sierra de

227 la Sobia (Figs. 3 and 6). The largest occurred on the south-western hillslope, and the

228 smallest on the southern hillslope of the mountain range. Frequently, rock-avalanches

229 result from the superposition of multiple destabilizing events. Rock-avalanches in the

230 vicinity of Villa de Sub could have been triggered by a recent re-activation of the right-

231 lateral faults of N150ºE-strike (Fig. 6).

232 The geometry and volume estimated for the nine selected rock-avalanche deposits were

233 compared with their respective source areas (Table 1). All these proxies have a reasonable

234 correlation. Avalanches with deposit-volumes >3x10^6 m^3 have similar vertical drops of

235 ~0.7 km on average, whereas avalanches with deposit-volumes <3x10^6 m^3 have lower

236 vertical drops. Assumptions used in the estimation of areas and volumes result in both

237 being undervalued. This misrepresentation is significant for the source area because the

238 rupture surfaces are usually on high, steep hillslopes. For instance, the rupture scarp of

239 Cueva Güerta is above vertical crags at the outlet of the Páramo River canyon (cross-

240 section D, Fig.4). A maximum depth of ~65 m has been measured at this deposit,

241 anomalously high compared to other deposits due to its confinement between the crags

242 of the Páramo River canyon (Table 1; Fig. 3). Geometrical features of the most

243 representative rock-avalanches have allowed the distinguishing of two types relative to

244 size. A detailed analysis of BSD and rock slope mechanics are presented for the rock-

245 avalanches of the Entrago and Carrea (largest) and the Villa de Sub and Cueva Güerta

246 (smallest).

247 **4.2. Structural control and BSD analysis of selected rock-avalanches**

248 The Entrago rock-avalanche is at the boundary between the hinge and southern domains.

249 Its source area lies between 800 and 1100 m above the villages of Entrago and La Plaza

250 (Fig. 7). Rock-slope failure occurred by direct toppling and planar slides, triggered in

251 multiple events. Roughly mapped rupture scars define a triangular planar surface of ~70

252 ha dipping 68º toward N71ºW. The crown of the avalanche is bound by a right-lateral

253 fault N19ºE-strike (Fig. 8). The southern fault tip has 72 m of horizontal strike. The

254 conical accumulation zone (40.75 ha) extends down to the Teverga River. It slopes to

255 ~47ºNW and the landslide accumulation consists of four superposed minor deposits: an

256 earth flow overlaid by three conic bodies of block accumulations (early, middle, and

257 recent) that still preserve their transverse ridges (Fig. 7). The fracture pattern mapped in

258 the depletion zone of this rock-avalanche (Figs. 6 and 7) allowed the outlining of 612

259 wedges (Fig. 9). A bi-modal BSD is observed, with two size-fractions of wedges. The

260 fine fraction includes wedges with diameters of <20 m, mostly on the rock-buttress failure

261 and usually of triangular shape. However, a large proportion of wedges are rhomboidal.

262 The major axis of the rhomboids is parallel to the active fault (N19ºE-strike). In contrast,

263 the wedges of the fine fraction show an anticlockwise rotation (Fig. 9B), with uniform

264 dispersion onto the rupture slope. Rotation is a consequence of the slight obliquity

265 between the wedge orientation and the rupture plane (Fig. 10). The diagram of *S* against

266 the wedge eccentricity shows small differences between both fractions (Fig. 9C). Wedges

267 of eccentricity 2.5 have $S=0.64$ if triangular or $S=0.46$ when rhomboidal. Wedges run out

268 from the depletion zone, and consequently their roundness tends to increase as indicated

269 by parameter S and their eccentricity. Diagram C (Fig. 9) shows both effects, the

270 difference in shape of each fraction size, and the effect of incipient sliced wedges within

271 the unstable residual relief.

272 The total range of block size r_i is <10 cm to >10 m. However, pebbles <20 cm were not

273 considered in the analysis because of their unrealistic statistical significance. The size

274 distribution of 4805 blocks (the total outlined blocks within the accumulation zone) is

275 presented in a frequency histogram of the normal distribution (Fig. 11A). BSD is not

276 fractal, with a slope change in the best fit regression line of the corresponding log

277 (frequency)-log (radius) histograms at block radius $r_k \sim 1$ m (Fig. 11B). The block sizes

278 $r_k > 1$ m yield $D=2.35$, the usual fractal dimension of limestone fault-rocks and the damage

279 zone of strike-slip and extensional fault zones (Storti et al., 2003). Conversely, the block

280 sizes $r_k < 1$ m yield $D=1.42$, a value frequently observed in small grain size fractions of

281 cataclastic fault rocks (Keulen et al., 2007). Both have an eccentricity of ~1.9 and yield

282 $S \sim 0.65$ ($r_k > 1$ m) and $S \sim 0.68$ ($r_k < 1$ m; Fig. 12B), accordingly with increasing block

283 roundness. A comparative BSD analysis between the three overlapped bodies has allowed

284 us to understand the specific contribution of each rock-avalanche outbreak to the total

285 BSD. ~1400 blocks in each body were analysed, and all show normal distributions (aspect

286 ratio ~0.7). It therefore follows that the early deposit yields a D value that compares better

287 than the latest rock avalanches with the BSD of the total accumulation zone (Fig. 11C).

288 Moreover, D appears time dependent. So, the fractal dimension in large blocks reduces

289 as the relative age of the deposit increases (Fig. 11D-F). Consequently, BSD becomes

290 fractal in the early deposit because the slope rupture at r_k is highly attenuated (Fig. 11F).

291 South of the Entrago rock-avalanche, there are two accumulation bodies of limestone

292 blocks above the villages of Sobrevilla and Carrea, between 650 and 1200 m (Figs. 7, 12

293 and 13). They correspond to medium sized rock-avalanches (Table 1). The current active

294 right-lateral faults that triggered both avalanches are trending NNE and NE respectively,

295 and their kinematics are accommodate the extension along the outer arc as the curvature

296 of the mountain range increases (Fig. 6). These faults create a downthrown block with

297 200 m of maximum vertical slip (longitudinal section A in Fig. 4) with maximum strike

298 separations raised in their respective southern tips. Both faults displace the MSF trace,

299 which cut out of sequence an earlier Variscan thrust, possibly the Tameza Thrust (Fig.

300 1C). The early cemented deposit accumulated about 600 m east of Sobrevilla has its origin

301 in a rockfall (Fig. 13). The number of tension cracks easily visible on Google Earth

302 suggest that more rockfalls are likely to happen.

303 The southern hillslope of Sierra de la Sobia presented three small rock-avalanches: Villa

304 de Sub, Sabariegos, and Busbigre (Table 1). The structure consists of an asymmetric

305 cuspate-lobate anticline-syncline of N-shape folding related to two faults (Fig. 3 and

306 cross-section D in Fig. 4). The Sobia Syncline is a Variscan fault propagation fold related

307 to the Sobia Thrust and then thrust out sequence by the León Fault toward the NE (Fig.

308 4; Alonso et al., 2009). The cuspate anticline is an ESE-verging fault-propagation fold

309 related to a small back thrust that crops out upslope of Villa de Sub (Fig. 14). The structure

310 probably formed to accommodate the tightening within the MSF footwall (Fig. 15 and

311 cross-section D in Fig. 4). Since the Alpine inversion, the structure of the southern domain

312 tilted northward ~30°. The occurrence of small rock-avalanches seems to be related to

313 Quaternary deformation. The rock-avalanches are controlled by penetrative vertical

314 planes (J_{p1}) trending N125-150°E, parallel to the general trend of the most significant

315 structures (Fig. 3). Some fractures have sub-horizontal slickenlines according to right-

316   lateral kinematics (F_{p1}), and they control the rupture scarps of rock-avalanches. Such local

317   kinematics are consistent with the whole kinematic model proposed for Sierra de la Sobia

318   (Fig. 6). The main accumulation of the Villa de Sub rock-avalanche has three overlapped

319   deposits, with the lowest composed of calcite-coated limestone blocks. The middle and

320   upper deposits have two overlapped fans. Additional blocks were incorporated during the

321   last instability events with little change in the fan shape (Fig. 15A): a rock-fall triggered

322   in 2004, synchronously with an earthquake of Ms 2; and a co-seismic 4.1 Ms rock-fall in

323   1996 (Fig. 1B). BSD of the Villa de Sub rock-avalanche is not fractal, with a slope change

324   also at block radius r_k~1 m (Fig. 12A). The block sizes r_k>1 m yield D=2.53 (R^2=0.92 to

325   the fitted regression line). Conversely, the block sizes r_k<1 m yield D=1.25 (R^2=0. 98).

326   Both sizes have similar low eccentricity of ~1.6 and roundness of S~0.73 (Fig. 12B)

327   respectively, with a relatively lower vertical drop of rock-fall and a lower impact

328   compared to larger rock-avalanches (Table 1).

329   Finally, a small rock-avalanche located at the northern entrance of Cueva Güerta at the

330   spring of Foz de la Estruchura has been analysed in detail. Most accumulation bodies

331   triggered along this canyon are confined by two opposite facing crags that bound the

332   narrow course of the river. Both the cave conduits and the river course lie parallel,

333   trending N-S along the damage zone of the MSF (Fig. 14). BSD in the accumulation body

334   of Cueva Güerta is not fractal, with a slope change also at r_k<1 m (Fig. 12A). The block

335   sizes r_k>1 m yield D=2.70. Conversely, the block sizes r_k<1 m yield D=0.54, but with low

336   confidence. Both sizes have a low eccentricity of ~1.6, but the coarse fraction includes

337   less rounded blocks (S~0.68), than the finer fraction (S~0.72). The coarse fraction has the

338   highest D among the populations analysed in Sierra de la Sobia. It shows lower particle

339   fragmentation (higher D) than the other unconfined accumulation bodies. Low

14

340   fragmentation is consistent with a progressive increment of relatively fine blocks towards

341   the top of the confined accumulation, caused by gravity selection.

342   **4.3. Slope stability analysis**

343   The stability models for all the slopes analysed assumed a conservative friction angle of

344   35° on the joint surfaces. The slope stability above the Entrago rock-avalanche was

345   analysed based on the orientation of 85 fractures measured along the rupture scarp,

346   controlled by the right-lateral fault of N19°E-strike. The mechanical instability of the

347   rupture scarp was evaluated under different dynamic failure modes (Fig. 10). Visual

348   estimates indicate <6% risk for planar sliding, <16% direct toppling risk for joint sets $J_{r1'}$

349   and $J_{r2'}$, <16% flexural toppling risk for joint sets J_{r1} and <13% wedge sliding risk.

350   Although the dynamic analysis gives a low risk of instability, the slope records at least

351   four superposed landslide deposits (Fig. 7). The models have a slope safety factor of <1.3

352   only when running with horizontal peak ground accelerations (PGA)>0.10-0.15 g, within

353   the prediction of the 2013 European Seismic Hazard Map for north-western Iberia

354   (Giardini et al., 2014).

355   84 mechanical discontinuities (25 S_0, 3 F_r, 1 F_p, 23 J_p, 18 J_{r1}, 6 $J_{r1'}$, 6 J_{r2} and 2 $J_{r2'}$)

356   measured on the rupture plane of the Carrea rock-avalanche have been considered for the

357   slope stability analysis. The fracture pattern lies parallel to both the Variscan thrusts and

358   an active transverse fault, and a rupture slope with dip direction 237/50 is considered for

359   the stability models. Considering these surface conditions there is a 0% risk for flexural

360   toppling, <4% risk for planar sliding, <11% risk for direct toppling and wedge sliding.

361   All these models indicate slightly higher safety factors than for the Entrago rock-

362   avalanche, even though a safety factor of <1.3 may arise with horizontal PGA>0.15 g.

15

363 123 mechanical discontinuities (45 S_0, 1 F_r, 7 F_p, 35 J_p, 23 J_{r1}, 8 $J_{r1'}$, 1 J_{r2} and 3 $J_{r2'}$)

364 measured on the rupture plane of Villa de Sub were considered for the slope stability

365 analysis. A penetrative fracture pattern lies parallel to the active right-lateral fault and

366 normal to the S_0 trend. The rupture slope modelled has a 173/80 dip direction and tilts

367 opposite to S_0. The dynamic analysis gives risks of <8% for flexural toppling, <9% for

368 planar sliding, <24 % for direct toppling and <19% for wedge sliding. The models

369 provided lower safety factors than for the Entrago rock-avalanche, even though a safety

370 factor of <1.3 may arise with horizontal PGA>0.10 g.

371 Only a dynamical slope stability analysis has been carried on the external Cueva Güerta

372 avalanche. 52 discontinuities (5 S_0, 8 F_r, 18 F_p, 6 J_p, 9 J_{r1}, 1 $J_{r1'}$, 4 J_{r2}, and 1 $J_{r2'}$) measured

373 around the north cave entrance were considered in the slope stability analysis. Two planes

374 with dip directions 20/90 and 87/90 define the rupture slope, and consequently two

375 dynamic analyses of the respective slope stability risk have been considered. These

376 indicate risks of <14 and 25% for flexural toppling, <8 and 14% for planar sliding, <21

377 and 27% for direct toppling, and <24 and 26% for wedge sliding, with dip directions

378 20/90 and 87/90 respectively. Slope stability models created with the dip direction 87/90

379 give lower safety factors than those for 20/90. Both models have lower safety factors than

380 any other rock-avalanche case studies, even though >1.3 has been obtained for all rupture

381 slopes modelled in this work.

382 **4.4. Timing of rock-avalanche events**

383 Calcite coating the blocks within the oldest calcareous rock-avalanche of the Entrago

384 deposit was successfully dated in samples RB_5, RB_6, and RB_7 (Fig. 7, Table 2).

385 Samples RB_5 and RB_6 taken along the transverse frontal ridge of the conical cemented

386 deposit, yielded ages of 13.7±0.9 and 278.3±32.9 ka coeval to marine isotope stages MIS-

387   1 and MIS-9a, respectively. Sample RB_7 from the toe of the deposit, yields 194.3±70.2

388   ka, indicating cementation during MIS-7a.

389   In the case of the Sobrevilla deposit, a minimum U/Th age of ~100 ka has been reported

390   (Fig. 13; Rodríguez-Pérez, 2012). Sample RB_2 taken at the accumulation body of the

391   Carrea avalanche yields an age of 58.8±14.6 ka, coeval to MIS 3-4 (Table 2), while RB_9

392   yields a minimum age of 38.3±2.8 ka, coeval to MIS 3 (Table 3). Based on the U/Th

393   dates, the Sobrevilla rock-avalanche occurred earlier than the Carrea rock-avalanche, but

394   later than the main event that caused the Entrago rock-avalanche. Radiometric ages are

395   consistent with the evolution of the BSD observed between the three overlapped deposits

396   in the avalanche. So, the Carrea rock-avalanche has BSD with a sharper slope break than

397   the Entrago one (Fig. 12A). The blocks within the accumulation body are also more

398   irregular than those in the Entrago avalanche, as shown by parameter S (Fig. 12B).

399   Sample RB_03 taken from a calcite cement coating a block at the Cueva Güerta rock

400   failed to provide a reliable age (Table 2). A replica of that sample, RB_10, yields a

401   minimum age of 9.9±1.2 ka (Table 3). Based on the U/Th results, Cueva Güerta is the

402   youngest dated rock-avalanche until now in Sierra de la Sobia. Its bi-log frequency-size

403   diagram shows a greater slope rupture between the two block fractions (Fig. 12A).

404   According to the tendency observed between the diagrams in the Entrago rock-avalanche

405   (Figs. 11D, E, and F), the slope rupture (Fig. 12A) is also consistent with the young age

406   obtained in the Cueva Güerta avalanche.

407   **5. Discussion**

408   The impact of our results is discussed below, addressing the following: 1) current

409   tectonics in Sierra de la Sobia; 2) origin and recurrence of rock-avalanches; 3) Quaternary

410   geomorphological evolution of the landscape.

5.1 Current tectonics in Sierra de la Sobia

The kinematic analysis of active faults, as well as their slip inversion, is consistent with a re-tightening by horizontal shortening accordingly with a N-S trending SH_{max} (Fig. 6). Current strain gave rise to the stretching along the western outer arc of the range, throughout the activation of strike-slip faults but also reverse and minor normal-scissor faults that accommodate deformation at the surface. In contrast, at depth, this intensely fractured zone is probably linked to the León Fault as indicated by the fracture network, the fault trends and their distribution compared to the trace of the León Fault. However, some of the minor active faults also displace the main trace of the León Fault (Figs. 3 and 4). These structural features might raise questions about the current activity of this fault. However, we have observed that current tectonics related to the León Fault likely triggered the slope failures recurrently, both in the outer arc of Sierra de la Sobia and along the whole southern branch of this fault (Figs. 1B and 2). Moreover, several low seismic signals have recently been recorded at a depth of ~15 km near the intersection of the León and Ventaniella Faults (López- Fernández et al., 2018). Therefore, we consider that the most recent minor faults showing cut off relationships with the León Fault trace are a consequence of the growth fracture density along the main fault trace and the dissipation of the current differential stress along such new fault planes.

The summit elevation in Sierra de la Sobia progressively increases southwards, showing a constant slope of 1.5° from 1350-1776 m (Saleras peak; Figs. 2 and 5). The restored section A (Fig. 4) has given a maximum current extension of 300 m of the outer arc of the range. The progressive uplift of the range southward led to the reactivation of the Variscan lateral ramp and the development of several high angle faults trending E-W at the junction between the MSF and the Trobaniello segment fault (Fig. 6). Finally, the current brittle strain partition in the southern domain of Sierra de la Sobia accommodated

436   right-lateral minor faults N150ºE-strike as well as other conjugated faults that likely

437   caused smaller avalanches (Fig. 6). The larger avalanches triggered northward suggest

438   that Quaternary seismicity is higher in the hinge domain of Sierra de la Sobia and

439   diminishes southward.

440   It is reasonable to extend the current tectonics of Sierra de la Sobia to CZ, as a working

441   hypothesis. Because this arcuate mountain range lies parallel to the León Fault, the fault

442   trace eastward prolonged according to CA orocline (Fig.1), and along the whole trace of

443   the León Fault has recorded rock-avalanches and complex flows like those described

444   above (Fig. 2). Moreover, CZ has other active structures that support this statement. One

445   is the Variscan Tineo Thrust, westward of the Cenozoic basin of Oviedo. This trends NE-

446   SW accordingly with the CA, and it was reactivated, thrusting over Cenozoic sediments

447   south-eastward (Fig. 1B; Pulgar et al., 1999). Another case is the Boinás Thrust (Fig. 1B;

448   de Vicente Muñoz et al., 2007). It trends parallel to the Tineo Thrust but back thrusts

449   north-westward 350 m. The Tineo Thrust and the reverse fault described in the Marabio

450   Pass (Fig. 6; Fernández et al., 2018) have the same kinematics. In both cases, tectonics

451   seem to accommodate the deformation after the unfolding limb section of regional

452   Variscan folds parallel to the CA by horizontal shortening parallel to their respective axes

453   accordingly with the regional trends of SH_{max} (de Vicente et al., 2008; Custódio et al.,

454   2015). Eastward, the fault junction between the León and Ventaniella faults (Fig. 1B)

455   recorded recent low-magnitude earthquakes (López- Fernández et al., 2018). The

456   clustering of earthquakes along these faults coincides spatially at depth with the transition

457   zone. The seismicity of the Ventaniella fault is fragmented, having only moderate seismic

458   records at the northern onshore segment and south of the fault's junction, whereas the

459   central segment is aseismic.

460　　CA is divided into two tectonic units by the Ventaniella Fault. The current deformation

461　　in the western tectonic unit appears controlled by the arcuate shape of the orocline.

462　　Normal faults accommodate stretching, parallel to the arc. Strike-slip faults transverse to

463　　the arc accommodate the N-S shortening, and back-thrusts towards the outer-arc

464　　accommodate the subsequent migration of the neutral surface predicted for the

465　　longitudinal tangential folding mechanism (Fig. 1B). Variscan and Alpine structures east

466　　of the Ventaniella Fault have a linear trend E-W and they can accommodate the current

467　　regional SH_{max} easily with straight displacement southward. However, because the CA

468　　controls the Quaternary reactivation, deformation is partitioned in transtensive basins

469　　controlled by right faults trending NW-SE parallel to the Ventaniella Fault. Finally,

470　　according to the crustal thickness variation, the aseismic central segment might be

471　　interpreted as the current strain rate, progressing more efficiently toward the flanks of the

472　　orocline than in its core (Díaz et al., 2016; Díaz and Gallart, 2009).

473　　The topography of the crust-mantle boundary is also interpreted as evidence of a passive

474　　margin (Cadenas et al., 2018; Fernández-Viejo et al., 2000; López-Fernández et al., 2020)

475　　or as the earliest initiation of ocean-continent subduction (Álvarez-Marron et al., 1997;

476　　Ayarza et al., 2004; Díaz and Gallart, 2009; Gallastegui et al., 2016). In our opinion,

477　　surface topographic features such as marine terraces are not only dependent on the crust

478　　thickness as postulated in López-Fernández et al. (2020) but also on the elastic thickness

479　　of the whole lithosphere (Burov and Diament, 1995; François et al., 2013). It is

480　　noteworthy that the Quaternary kinematics of the active fault analysed in Sierra de la

481　　Sobia consist of tangential deformation (Fig. 6), although normal faulting is associated

482　　with isostatic balance in passive margins (Conway-Jones et al., 2019; Pederson et al.,

483　　2002). The reverse and strike-slip fault kinematics prevail against the current normal

484　　faults, mostly locate radially to the outer-arc at the hinge domain of Sierra de la Sobia.

485 Most of the active fault mapped along the Cantabrian wave-cut paleo-platform by

486 Álvarez-Marrón et al. (2008) indicate consistent kinematics with our study area.

5.2 Rock-avalanches: origin and recurrence

488 Rock fragmentation, weathering, climatic factors, and geomorphological factors, during the

489 withdrawal of glaciers and associated debuttressing have been described as the triggers of large

490 rock-avalanches (Ambrosi and Crosta, 2011; Ballantyne et al., 2014; Turcotte, 1986).

491 Additionally, in many rock-avalanches, seismicity is the main triggering factor: avalanches

492 triggered by recent (Wasowski et al., 2021) or historical earthquakes (Martin et al., 2014; Zeng et

493 al., 2020) or polyphase rock-avalanches that are consistent with sedimentological paleoseismic

494 records (Grämiger et al., 2016).

495 Slope failure analyses demonstrate that under static conditions the main rupture scarps of

496 the rock-avalanches on the Sierra de la Sobia are mechanically stable (Fig.10) and

497 consequently differential stress must be increased for dynamic fragmentation. Moreover,

498 the BSD analysis shows $r_k > 1$ m for all the rock-avalanche deposits yield D ranging

499 between 2.24 and 2.70 (Table 1), into the usual range of dynamic fragmentation (Storti et

500 al., 2003). Therefore, similar two-stage breakage dynamic processes caused the block

501 fragmentation within all rock-avalanches: (i) dynamic and ballistic fragmentation from

502 the aftershock rupture scarp; and (ii) fragmentation by wear and attrition from the scar

503 slope to the accumulation body, causing the BSD-homogenization within the block size

504 fractions $r_i < 1$ m. The block size at the slope change (r_k) seems to represent a change in

505 the dominant fragmentation mechanism from (i) to (ii). D variations can be interpreted

506 because of the percentage weight of fine to coarse fragments in each respective fraction.

507 So, decreasing particle fragmentation occurred in confined accumulation bodies only

508 because the surface of the accumulation body is considered for the BSD analysis (see

509 methods), where the percentage weight of fine fragments is higher than at the bottom.

510   Consequently, D for $Logr_k > 1$ is higher in the accumulation body of Cueva Güerta

511   compared to other avalanches (Fig. 12, Table 1). Selection can also be evaluated

512   indirectly by the difference of the roundness versus eccentricity between the fine and

513   coarse fractions of each BSD (Fig. 12B). More selection is expected at the top of the

514   accumulation body than at the tip. For instance, the BSD of Carrea avalanche shows the

515   greatest segregation because only the top sector of the accumulation body is considered,

516   whereas in other avalanches the whole accumulation body is well exposed and

517   consequently used for BSD analysis. This feature is also consistent with the relative ages

518   inferred from BSD. The accumulation body of the largest avalanches is composed of

519   several superposed deposits of horizontal conic shape, where the most recent deposit is

520   located at the top of the accumulation body. The detailed BSD of the Entrago avalanche

521   shows a progressive attenuation of the $logr_k$-slope rupture as the relative age of the BSD

522   deposit increases (Fig. 11). If the BSD of the analysed avalanches is compared, according

523   to this criterion, Entrago is the oldest rock-avalanche in the Sierra de la Sobia and Cueva

524   Güerta the youngest (Fig. 12A). This relative chronology is consistent with the U/Th ages

525   obtained from the coated calcite blocks sampled in these accumulation bodies (Tables 2

526   and 3).

527   At least three superposed deposits of blocks have been differentiated at the map-scale on

528   the massive avalanches of Sierra de la Sobia (Figs. 7 and 13), along a fault segment ~4.5

529   km length, suggesting that such avalanches record the same seismic events. Moreover,

530   co-seismic rock-falls have been recorded near Villa de Sub (Fig. 14). However,

531   destructive to very destructive events, ranging between VIII to X in the environmental

532   seismic intensity scale (Michetti et al., 2007) could be inferred accordingly, with: (i) the

533   offset and length of the active faults; (ii) the evaluated tectonic uplift and subsidence

534   (Figs. 3, 4, 6); (iii) the length and width of the ground cracks and the reach of slope

movements (Figs. 7, 13, 14, Table 1); and (iv) the affected area and type of record (Reicherter et al., 2009). Recently, the empirical power-law relationships between the total volume of the avalanche and the seismic magnitude (Keefer, 1999) were validated (Croissant et al., 2017). However, this approach is challenging to apply in this study area because it is impossible to evaluate which avalanche volume corresponds to each paleoseismic event. Also, for short-term recurrence, the total volume could decrease as the rupture scarp becomes more stable during aftershocks. Currently, the slope stability analyses indicate that a horizontal PGA ranging between 0.10-0.15 g is required to disrupt such scarps again. Sierra de la Sobia experiences moderate seismicity, characterized by frequent Ms<6 events, because of its geodynamic setting (Álvarez-Marron et al., 1997; Ayarza et al., 2004; Díaz and Gallart, 2009; Gallastegui et al., 2016). In this context, the largest earthquakes generated in the past might occur within recurrence intervals much longer than the period covered by both the historical and instrumental local records (Fig. 1B) and could be conditioned by the reactivation of the long-lived crustal León Fault at a slow slip rate during the re-tightening of the CA under NNW-SSE compression. Further work is necessary for insight into the standard log $r_k= 1$ for all the BSDs analysed (Fig. 12A). Samples have been collected from the non-cemented rock-avalanches at Entrago and Carrea to broaden the chronological framework presented here by ^{36}Cl cosmic-ray exposure dating. The accurate date of the latest avalanche-events might help forecast future massive earthquakes in the region.

Based on the oldest calcite cement, a reference age of 278.3±32.9 ka is inferred for the oldest cementation episode affecting the Entrago deposit, and hence a minimum age for the oldest rock-avalanche event. Subsequent avalanche cementation occurred thereafter, spanning the last 200 ka, potentially conditioned by Quaternary climate changes. Calcite growth took place preferentially during the interglacials, and during the warm periods

560   that bounded the MIS-3 glacial advance of the Cantabrian Mountains (Rodríguez-

561   Rodríguez et al., 2015).

562   **5.3 Quaternary geomorphological evolution of the landscape**

563   The western hillslope of the Sierra de la Sobia is a structural form controlled by the

564   arcuate orientation of the limestone bedding and MSF. Compression of this mountain

565   range according to the current regional NNW SH_{max} (de Vicente et al., 2008; Custódio et

566   al., 2015) triggered several rock-avalanches with recurrent avenues along the Quaternary

567   period. This active tectonic process strongly conditioned the geomorphology of the

568   Teverga Valley.

569   In this period, the incision rate of the Páramo River may have accelerated as suggested

570   by the cuspate shape of the river valley throughout the Foz de la Estrechura canyon (Fig.

571   14). The current course is incised ca 30 m from the paleo-epiphreatic sediment deposited

572   on the upper entrance of Cueva Güerta. The current phreatic level runout ca 100 m below

573   the paleo-phreatic level is defined along the low gradient of the longest gallery in this

574   cave (Ferreras et al., 2015). However, the accumulation of the rock avalanche confined

575   at the spring of the canyon did not dam the stream. This is because, at that time, the flow

576   of water was underground, and its runout was at a deeper level.

577   Downstream is the old village of Fresneu, which was destroyed on June the 25th 1522.

578   Canon Tirso de Avilés of Oviedo Cathedral tells of an earthquake event, after which a

579   new village was built at the current site (Fig. 14). Moreover, the Entrago avalanche

580   dammed the Val de Cazana, Taja and Páramo Rivers (Fig. 3), deviated the resultant course

581   of the Teverga River at the entrance of the Val de Cerezales canyon, and developed the

582   only floodplains present in this valley (Fig. 7).

583 A detailed analysis of this river sub-basin extended to the whole Nalón basin that would

584 give new insights into understanding the Quaternary geomorphology and tectonics of the

585 Cantabrian Mountains is currently underway.

586 **6. Conclusions**

587 The Quaternary reactivation of minor faults lying along the MSF-trace has

588 accommodated ~300 m uplift of the summits in Sierra de la Sobia. Their slip inversion is

589 consistent with a current N-S trend of the SH_{max} that contributes to the re-tightening of

590 this arcuated mountain range and the stretch of its outer arc also ~300 m by longitudinal

591 tangential deformation.

592 The largest rock-avalanches are distributed along the hinge domain of Sierra de la Sobia,

593 while the smallest are in the southern domain. The sizes of rock-accumulation bodies are

594 proportional to the corresponding vertical drop. BSDs of the accumulation bodies are not

595 fractal. The largest block size fractions (r_i>1 m) have slope D-values ranging between

596 2.70 and 2.24, whereas the block size fractions r_i <1 m have lower D-values.

597 The mechanical slope stability analysis of relevant rupture scarps reported safety factors

598 >1.3 under static boundary conditions. However, all rupture scarps become unstable if

599 horizontal seismic acceleration rises 0.10-0.15 g.

600 Chronological U/Th data obtained from calcium carbonate cements bounding limestone

601 blocks in the Entrago, Carrea and Cueva Güerta rock-avalanches suggest recurrent

602 instability events for at least the last 300 ka, with episodic cementation occurring during

603 the last five interglacials.

604 Geomorphological and structural data gathered on the western flank of Sierra de la Sobia

605 reveal unambiguously a clear relationship between current tectonics and recurrent

606 catastrophic rock-avalanches.

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800

Figure and table captions

802 Fig. 1: (A) Overview map of NW Spain presenting the evidence for the main Alpine exhumation

803 phase in the Cantabrian Mountain and Basque-Cantabrian Basin. (B) Geological map of the

804 Cantabrian Zone. Available seismic records are indicated with stars, and the trace of the

805 geological section (C). Inset shows the location of Fig. 2. The Somiedo (SoT) and Sobia (ST)

806 thrusts.

807 Fig. 2: Aerial image of Sierra de la Sobia and Macizo de Ubiña. Main segments of the northern

808 León Fault sector, rock-avalanches and the highest summits are highlighted (orange lines). The

809 orange arrow shows the NNW trends of the current regional maximum horizontal stress (SHmax;

810 de Vicente et al. 2008).

811 Fig. 3: Geological map of the Sobia Nappe showing the relationships between rock-avalanche,

812 Quaternary sediments, mechanical contacts and relief. Traces of the geological section

813 represented in Fig. 4 are also shown.

814 Fig. 4: Longitudinal-section (A) and three cross-sections (B, C, and D) to Sierra de la Sobia.

815 Traces of the transversal cross-sections and the range level of summits (RLS) line are located on

816 the longitudinal-section A.

817 Fig. 5: Panoramic view of a 15km-long segment of Sierra de la Sobia, including the hinge and

818 southern domains. Carboniferous limestone outcrop exposes MS, thrusting out of sequence the

819 earliest Variscan syncline and thrust. Minor normal and strike-slip faults cut the MS-trace, also

820 folded by the Foz de la Estrechura anticline, southward. RLS have small steps controlled by the

821 vertical slip of both later-normal and strike-slip faults as the mountain chain increases in height

822 southward (see also Fig. 4A).

823 Fig. 6: Structural map of Sierra de la Sobia showing the relationship between the León Fault, the

824 latest faults and the fracture network imposed on the limestone massif. The stereonet plots

825 represent the equal area and lower hemisphere projections of fault planes and slickenlines. Arrows

826 represent the direction of displacement inferred from slickenlines. Blue lines and symbols

827   represent fault segments reactivated during the Quaternary and their respective kinematics.

828   Orange finite strain ellipse is scaled to R=1.42, strain ellipse orientation is consistent with the

829   kinematic of most current active faults.

830   Fig. 7: Detailed geomorphological map of the Gradura and Entrago rock-avalanches including

831   earth flow, slope dynamic and river deposits. Stars show the location of U/Th samples.

832   Fig. 8: Entrago rock-avalanche. (A) Details of the rupture scarp where a rotational rockslide (rock

833   slump) rests atop. The Sobia spire is a buttress 125 m in height separated by less than 50 m from

834   the rupture scarp. A huge rock-topple was triggered at the southern scarp tip. Note that

835   discontinuities have the same pattern into the rupture scarp than in the rock-slump. (B) Behind

836   the Sobia spire a transverse fault N5ºE-strike with slickenlines indicating sub-horizontal right-

837   lateral displacement (North is on the left-hand side) is exposed.

838   Figure 9: Dynamic analysis of slope instability risk considering four failure modes for the rupture

839   scarp of Entrago. Flexural toppling analysis following Goodman (1989) and direct toppling

840   following Hudson and Harrison (1997). Pole planes are plotted in lower hemispheres and equal

841   angle stereonets. Contour density at constant intervals of 0.7%.

842   Fig. 10: Shape-fabric analysis of the depletion zone for the Entrago rock-avalanche (612 wedges).

843   (A) Diagram showing the size frequency (black line) and the area percentage (dashed line) versus

844   wedge size. (B) Histogram showing the frequency of the orientation of the major ellipse inscribed

845   in each wedge. Fine fraction (white bars) of wedges was sketched from the thickly fractured rock-

846   slump of the unstable residual relief (Fig. 7A) and it preserves the same orientation than the coarse

847   fraction (black bars). (C) Shape parameter (S; Fernández et al., 2005) versus eccentricity diagram.

848   Triangular wedges, defined by the intersection of joint sets, dominate within the fine fraction

849   (white dot), and rhomboidal wedges dominate within the coarse fraction (black dot). Error bars

850   represent standard deviations.

851   Fig. 11: Block size analysis of the Entrago rock-avalanche. (A) Histogram of equivalent radii

852   (dm) for the whole accumulation body (4805 blocks). (B) Log-log plot of frequency versus

853   equivalent radius (20 bins per order of magnitude). The slope of the fitting lines yields two *D*-

854   values which intersect at r_k. (C) Histogram of equivalent radii (dm) for the three superimposed

855   bodies mapped (Fig. 7). (D) Log-log plot of frequency versus equivalent radius for the earliest,

856   (E) middle and (D) the apical bodies.

857   Fig. 12: Shape-fabric analysis of blocks for the four accumulation bodies studied in detail. (A)

858   Log-log plot of frequency versus equivalent radius (20 bins per order of magnitude). The slope

859   of the fitting lines yields two *D*-values which intersect at r_k. (B) Shape parameter (S; Fernández

860   et al., 2005) versus eccentricity diagram. Error bars are their respective standard deviations. Block

861   sizes plotted for each fine fraction is larger than $Log(r_i)=0.5$ (dm).

862   Fig. 13: Detailed geomorphological map of the Sobrevilla and Carrea rock-avalanches (left and

863   right, respectively). Start indicates the location of U/Th samples.

864   Fig. 14: Detailed geomorphological map of rock-avalanches occurred at Fresneu, Cueva Güerta,

865   Villa de Sub, Sabariegos and Busbigre. Stars indicate the location of U/Th samples of calcite

866   cements coating the blocks of the Cueva Güerta rock-avalanche deposit. Cave plan view modified

867   after Ferreras et al. (2015).

868   Fig. 15: South-Eastern Sierra de la Sobia. Villa de Sub is located down hillslope at the tip of the

869   accumulation body. (A) Geology sketched onto the picture highlights the effect of the current

870   right-lateral faults (F_{p1}) and fold-related onto the back-thrust structure of the basement. One of

871   such fault is the rupture plane of the Villa de Sub rock-avalanche. (B) The picture shows the

872   regular and penetrative joint set J_{p1} associated with faults F_{p1}. Limestone bedding surfaces (S_0)

873   dip in the opposite direction to the SE hillslope, enhancing the risk for direct toppling. Width of

874   view is ~500 m in A, and ~50 m in B.

875   Table 1: Geometrical features of rock-avalanches located at the northern domain (Marabio); the

876   hinge domain (Gradura, Entrago and Sobrevilla); and the southern domain of Sierra de la Sobia

877   (Carrea, Cueva Güerta, Villa de Sub, Sabariegos and Busbigre). Sites are in Figs. 3 and 5. H is

878   the vertical drop and L is the length of fall. H/L ratio is the Fahrböschung parameter of Heim

879   (1932) and ϕ is the corresponding angle. Dimension fractal (*D*) for the block size distribution

880   (BSD) within the accumulation bodies are obtained from the slope line fit yield values $> r_k$ (Fig.

881   12 A).

882   Table 2 U/Th isotopic compositions and [230]Th ages for samples analysed by α-spectrometry.

883   Analytical errors are 2σ of the mean. Samples, UTM coordinates ETRS-89, 29T.

884   Table 3: U/Th isotopic compositions and [230]Th ages for samples analysed by Alpha spectrometry.

885   Analytical errors are 2σ. UTM coordinates ETRS-89, 29T.

1   **Gravitational slope processes triggered by past earthquakes on the Western**

2   **Cantabrian Mountains (Sierra de la Sobia, Northern Spain)**

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10 **Abstract**

11 Sierra de la Sobia is a linear mountain range of arcuate shape, located West of the

12 Cantabrian Mountains. The long-lived crustal León Fault runs along its western hillslope,

13 and its trace is partially covered by multiple rock-avalanches. Here we discuss if recurrent

14 paleo-earthquakes in the M6+ range could have acted as the triggering factor for rock-

15 avalanches in a region where the historical and instrumental seismic records only include

16 seismic events up to Ms 4.6. Evidence concurring with a coseismic origin includes: (i)

17 kinematic of current minor transverse and parallel faults to Sierra de la Sobia being

18 consistent with a horizontal North-South compression of the Cantabrian Arc; (ii) slopes

19 of the depletion zones that would become unstable if horizontal seismic ground rose 0.10–

20 0.15 g; and (iii) block size-reduction by dynamic fragmentation creating block size

21 distribution with fractal dimension, ranging between 2.24 and 2.70. U/Th dating of seven

22 calcite precipitates coating the blocks of cemented rock-avalanche deposits suggesting

that cementation has taken place in multiple episodes since MIS-9a. Neotectonics of Sierra de la Sobia are expressed in subtle changes in relief after extremely rapid co-seismic events, with average recurrence intervals much longer than the time covered by the regional historical and instrumental period.

1. Introduction

The Cantabrian Arc (CA), also known as Ibero-Armorican Arc (Lefort, 1989), is the largest structure of the Variscan orogeny in Western Europe. The CA deformed an initially linear foreland thrust and fold belt, formally defined as the Cantabrian Zone (CZ; Lotze, 1945) in the latest Stephanian to the earliest Permian (Weil et al., 2001). Later, the CA also controlled the reactivation of the basement during the Alpine cycle, when the Cantabrian Mountains were raised (Gallastegui et al., 2016). Alpine deformation produced the inversion of the northern Iberian plate, and it migrated and decreased progressively from the Pyrenees, westward to the CA (Fig. 1A). Alpine sedimentation ceased after the Late Oligocene (Álvarez-Marron et al., 1997), and Alpine exhumation of the central part of the Cantabrian Mountains occurred from 39 to 29 Ma, at a rate of 2.4–3 mm yr^{-1} (Fillon et al., 2016). Little is known about the post-Oligocene tectonics of the Cantabrian Mountains due to the scarcity of Tertiary outcrops, the limited size of surficial formations formed since the late Quaternary glaciations, and the later slope dynamics controlled by fluvial incision (Menéndez-Duarte et al., 2007; Rodríguez-Rodríguez et al., 2015). Consequently, we might wonder if evidence of Quaternary deformation exists in the Cantabrian Mountains, and what traces correspond to active landscape processes.

Nowadays, northern Iberia is considered a passive margin, hundreds of kilometres away from the interaction of the Nubia Plate with the Iberian microplate. This overall tectonic setting engenders a stress field in the Iberian Peninsula, characterized by a predominately NNW to NW trending maximum horizontal stress (SHmax; de Vicente et al., 2008; Custódio et al., 2015). In this context, the Cantabrian Mountains are considered a seismically active shallow crust (Delavaud et al., 2012) with earthquakes of low to moderate magnitude (Stich et al., 2020). During the 2015–2017 instrumental period, the CZ recorded 40 seismic events of surface wave magnitude (Ms)>2 at depths of between 9 and 18 km at the intersection between the León and Ventaniella faults and the biggest recorded was an Ms 3.7 event (Fig. 1B; López- Fernández et al., 2018). The León Fault is a breaching fault (Alonso et al., 2009) buckled by the CA, and cut northwards by the younger Permo-Triassic right-lateral Ventaniella Fault. Large submarine avalanche deposits have recently been found, along with the northwest offshore extension of the Ventaniella Fault-scarp (Fernández-Viejo et al., 2014), near to the location of the historical earthquakes of 1522 and 1861 (Fig. 1B). East-west trending uplifted wave-cut platforms extend along the Cantabrian coastline for more than 400 km, tectonically uplifted since at least 1–2 Ma (Álvarez-Marrón et al., 2008).

These tectonic geomorphology imprints might result from the ongoing slow convergence and inversion extending along the Cantabrian coast, where the CA may reactivate. To test this hypothesis, we studied the recent tectonic geomorphology of Sierra de la Sobia, a Carboniferous limestone mountain range of arcuate shape, buckled according to the curvature of the CA to the west of the Ventaniella Fault. The northern branch of the León Fault lies along the western flank of Sierra de la Sobia (Figs. 1B and 1C), and an unusually high number of rock-avalanches never previously described or analysed overlie the fault trace. In 1996 an earthquake of Ms 4.1 (Fig. 1B) struck the Villa de Sub village on the

southern slope of Sierra de la Sobia, triggering a rock-fall. North-westward, El Canto district was built atop the most massive rock-avalanche, composed of several superposed deposits. The higher parts of this avalanche still represent a severe risk for the citizens of Entrago and La Plaza. Moreover, an early cemented deposit accumulated about 600 m east of Sobrevilla has its origin in a rockfall from the deposit. The number of tension cracks easily visible on Google Earth suggest that more rockfalls are likely to happen. In addition, a reverse fault superposing Carboniferous limestone onto cemented talus scree deposits has also been described (Fernández et al., 2018). At first sight, Sierra de la Sobia is among the best places to shed new light on the Quaternary tectonic geomorphology in the CZ.

2. Regional setting

Sierra de la Sobia is in the eastern nappe of the Somiedo Unit (Figs. 1B, C; Alonso et al., 2009). From a geomorphological standpoint, it is an arcuate mountain range ~16 km long and 2-5 km wide with a Range Level of Summits (RLS) dipping 1.5º northward (Figs. 2, 3, 4 and 5). It is formed by a continuously well-exposed outcrop of Carboniferous limestone. The highest elevations of these mountains are south of Sierra de la Sobia, at the Ubiña Massif with peaks 400 m higher than the regional-RLS. It is noteworthy that the León Fault is bent around the Ubiña Peak (2417 m), accordingly with CA orocline and such a footwall corner gives relief to a syntaxial shape (Fig. 2). Carboniferous limestone overrides the Lower Cretaceous cover south of the Ubiña Peak, evidencing the Alpine reactivation of the León Fault (Alonso et al., 2007). The long-lived León Fault has been active in different tectonic cycles, and it remains seismically active (Fig. 1B; López- Fernández et al., 2018).

2.1 Variscan structure

95   The Paleozoic basement of the Sobia Nappe involves an ~2500 m and a 500 m-thick syn-

96   orogenic sequence (Fig. 3; Marcos and Pulgar, 1982). During the Variscan orogeny the

97   oldest thrusts, such as the Sobia, Tameza, and Somiedo, accommodated most of the

98   shortening in deep levels (Figs. 1C and 3). Upwards, the shortening was accommodated

99   stratigraphically by fault-propagation folds, like the Caranga Antiform (Figs. 3 and 4B;

100 Bulnes and Aller, 2002). It consists of a stack of at least three thrusts of Ordovician

101 quartzite and sandstone formed to facilitate accommodation for shortening northwards

102 due to the presence of lateral thrust ramps (Bastida and Castro, 1988).

103 Later, the León Fault cut the sequence, superposing the Somiedo and the Tameza Nappes

104 onto the Sobia Nappe (Fig. 1C). The primary displacement of the León Thrust occurred

105 before the CA, and kinematic markers indicate an ENE transport direction (Alonso et al.,

106 2009). Since the CA bends the León Fault, it trends along with two main strikes N30ºW

107 and N100ºE, respectively, from the Ubiña Massif (Fig. 2). Its North-Western termination

108 consists of a splay fault formed by three main segments. The Marabio Segment-Fault

109 (MSF; Figs. 1C, 2, 4) is the longest at 48 km, its trace being partially covered by rock

110 avalanches triggered along the western flank of Sierra de la Sobia.

111 **3. Materials and methods**

112 The geology of Sierra de la Sobia was entirely reviewed based on the latest regional study

113 (Alonso et al., 2009) and the analysis of previous geological maps of the northern and

114 eastern areas (Bastida and Castro, 1988; Bulnes, 1994), and the online version of the

115 continuous digital geological map of the CZ, scale 1:50,000 (Merino-Tomé et al., 2011).

116 This map differentiates the unconformable Quaternary, Tertiary, and Stephanian outcrops

117 from the Paleozoic underlying basement, as well as the Variscan mechanical contact from

118 the latterly developed structures (Fig. 3). Quaternary deposits and fracture networks

119 within the limestone massif have been tracked from fieldwork and ortho-photographs,

120 scale 1:50,000 (PNOA series, IGN). Due to the difficulties inherent to discriminating

121 Quaternary faults from other earlier Cenozoic faults, both have been grouped as "late

122 faults" when cut-off relationships with the earlier Variscan faults can be established.

123 However, most of these later faults do not show relative displacements at our working

124 scale, because fault slips are frequently <10 m.

125 A selection of nine rock-avalanches was quantitatively characterized. The vertical drop

126 (H) measures the difference in height between the crown of the depletion zone and the

127 toe of the accumulation body, and the length (L) is the horizontal distance between both

128 points. The rock-avalanche volume was estimated multiplying its surface area by the

129 mean thickness of the accumulation body. The average thickness of rock-avalanche

130 deposits was indirectly estimated as half of the possible maximum thickness of the

131 deposit, calculated from the topographic expression of the accumulation body.

132 Analyses of Block Size Distribution (BSD) were completed in four representative

133 deposits of rock-avalanches using high-resolution drone imagery to compile maps of

134 block sizes >10 cm. Ortho-photographs were acquired from a drone, ATYGES FV-8,

135 using pre-planned flight lines of the mapped areas and geo-referenced with a GPS,

136 LEYCA GS14 GNSS. The fractal dimension (*D,* Epstein, 1947) was calculated in such

137 deposits easily, using the BSD of >14k blocks as the slope of the lineal fit in log

138 frequency/log equivalent radius diagrams; they were plotted showing 20 bins per order

139 of magnitude. The shape parameter S calculated as $S = \frac{4\pi A}{P^2}$ (1) (Fernández et al., 2005),

140 where the area A and perimeter P of wedges were measured in pixel^2 and pixel,

141 respectively. Wedges <20 pixel^2 were removed. S is not wedge-size dependent, and

142 ranges between 1 (wedge-shape is a perfect circle) and 0 as irregularities of the wedge-

143   shape increase. Block size measures by the radii equivalent (r_i) of each block, where $r_i =$

144    $\sqrt{\frac{(A+P)}{\pi}}$ (2).

145   The rock mechanics of the residual slope were analysed where the rupture scarps were

146   mapped. Slope stability was calculated based on over 350 measurements of joint and fault

147   plain orientations using the advanced computational tools for geometrical, kinematical,

148   and mechanical analysis of the Dips 7.0, Rocplane, and Swedge programs, respectively.

149   Mechanical discontinuities were heuristically classified as: (i) bedding planes (S_0); (ii)

150   faults parallel (F_p) or transverse (F_r) to the range trend; and (iii) joints parallel (J_p) or

151   transverse (J_r) to the range trend. Joints transverse to the range were subdivided according

152   to the direction and angle of dip in: (i) <30º dip angle northwards (J_{r1}); (ii) >50º angle

153   northwards ($J_{r1'}$); (iii) <30º dip angle southwards (J_{r2}); (iv) >50º angle southwards ($J_{r2'}$).

154   Calcite cements, interfusing blocks and pebbles in the oldest rock-avalanches were

155   collected at eight sampling localities and treated in the laboratory to extract the calcite for

156   U/Th dating. Five of the eight samples processed exhibited calcitic cement pure enough

157   for radiometric analysis. Calcite crystals were selected under the microscope to minimize

158   detrital contamination from detrital fine sediment matrix. U/Th dating was completed at

159   the University of Minnesota by Inductively Coupled Plasma Mass Spectrometry (ICP-

160   MS) as described by Shen et al. (2002). Sample RB_02 was replicated by sample RB_9

161   and sample RB_03 by sample RB_10 by the U/Th facility at the Institute of Earth

162   Sciences Jaume Almera (ICTJA-CSIC; Barcelona). The replicates provided purer calcite

163   cements which reduced the age uncertainties previously obtained, likely due to a Th

164   excess of detrital origin. The chemical separation and purification of the radioisotopes

165   followed Bischoff et al. (1988). The isotope electrode position followed Talvitie (1972)

166 and was modified following Hallstadius (1984). Age calculations were based on

167 Rosenbauer (1991). Results are compiled in Table 3.

168 **4. Results**

169 Three structural domains have been distinguished in Sierra de la Sobia. The northern

170 domain extends southward to the Marabio Mountain Pass. The MSF outcrops within the

171 Westphalian shale, superposing the Teverga coal basin (Middle and Upper Westphalian

172 formations in Figs. 3 and 4) onto the Sobia Nappe. The Tameza Thrust and MS converge

173 progressively northwards (Fig. 3). The western hillslope of Sierra de la Sobia is separated

174 by >1 km of MS-trace (Fig. 4B), and it lacks rock-avalanches. Minor parallel faults trend

175 NNE, and transverse faults define three sets trending NE, E, and SE. A reverse parallel-

176 fault superposes Carboniferous limestone westward onto recently cemented talus-scree

177 deposits, with up to 6 m net slip (Fernández et al., 2018). A fault splay also cuts the

178 Caranga fault-propagation anticline (Figs. 3, 4B, and 6). It shows a reverse displacement

179 with anticlockwise rotation from SW to S. The kinematic agrees with the Alpine

180 inversion, but also with the NNW-trend of the current regional SHmax. The stress

181 inversion obtained for Sierra de la Sobia, after excluding some of the latest transverse

182 fault kinematics that gave inconsistent solutions, gives a similar SHmax, and the

183 limestone outcrop has a joint fracture network with similar strikes to faults belonging to

184 this domain (Fig. 6).

185 The hinge domain extends southward from Marabio Pass to Sobrevilla (Fig. 3). The

186 arcuate MSF-trace lies progressively closer to the western hillslope of Sierra de la Sobia.

187 The slope has a convex shape and has recorded several rock-avalanches. The limestone

188 outcrops' width decreases progressively as the curvature of the arcuate range increases

189 (Fig. 3). Deformation has been accommodated by normal faults that transect the hinge of

190 the range, some of them cut MSF. Southward, MSF is covered by the Entrago rock-

191 avalanche. The outcrop of limestone is strongly fractured, and the fracture network is

192 formed by joint sets parallel to the main fault strikes (Fig. 6).

193 The southern domain extends from the Entrago to the Villa de Sub rock-avalanches (Fig.

194 3). The South-Western hillslope of the range between the Entrago and the Carrea rock-

195 avalanches is a structural form controlled by the orientation of the limestone bedding and

196 MSF. Both mechanical discontinuities run parallel to the slope, and dip in the same

197 direction but are more pronounced than the slope. Parallel faults run SE, with transverse

198 faults and fractures defining three sets trending N, NE, and E, respectively (Fig. 6). The

199 periclinal structure of the Sobia Nappe is exposed on the southern hillslope of Sierra de

200 la Sobia (Fig. 3). The structure consists of folds related to Variscan thrusts in the lateral

201 ramp of the Sobia Nappe and with a transport direction north-eastward. The León Fault

202 thrusts out of sequence towards the NE and accumulates a total displacement of ~9 km in

203 the section shown in Fig. 1C (Alonso et al., 2009). This lateral ramp was shifted 45ºNW

204 during the Alpine inversion.

205 More recently, the current re-tightening of the Sobia Nappe was accommodated by right-

206 lateral faults (N150ºE-strike). The trace of these faults runs parallel to the Taja Fault

207 segment throughout the southern hillslope of Sierra de la Sobia. Additionally, several

208 active faults trending E-W have exposed their respective fault scarps and have been

209 mapped on the junction of the splay between the Trobaniello Fault segment and the MSF.

210 Most of them are small (widths <7 km) with relative movement frequently attenuated

211 laterally and accommodated by the thickly fractured surficial network of the limestone

212 massif (Fig. 6).

213 Restoration of an eventual continuous RLS-line before its segmentation along the

214 northern and hinge domains of the range results in an extension of ~300 m southward by

215 right-lateral faults N150ºE-strike, and potentially by faults trending E-W (Fig. 6). The

216   current re-tightening of the arc described by the hinge domain of Sierra de la Sobia has

217   been measured, assuming that the extension of the western convex hillslope was created

218   by tangential longitudinal folding (Ramsay, 1967). The finite neutral surface is on

219   longitudinal section A (Fig. 3) and runs along the RLS (Fig 4). The result is an

220   incremental longitudinal strain e_i= 0.031 that produces a strain ellipse on the outer arc of

221   aspect ratio R= 1.42 (Fig. 6), therefore an angular extension of 3.32º along the western

222   convex hillslope. However, the kinematics of the current faults suggest that the parallel

223   shear could be progressively more significant toward the northern and southern domains

224   respectively, according to the orientation of their finite strain ellipses (Fig. 6).

225   **4.1. Rock-avalanche geometry**

226   Multiple rock-avalanche deposits are within the hinge and southern domains of Sierra de

227   la Sobia (Figs. 3 and 6). The largest occurred on the south-western hillslope, and the

228   smallest on the southern hillslope of the mountain range. Frequently, rock-avalanches

229   result from the superposition of multiple destabilizing events. Rock-avalanches in the

230   vicinity of Villa de Sub could have been triggered by a recent re-activation of the right-

231   lateral faults of N150ºE-strike (Fig. 6).

232   The geometry and volume estimated for the nine selected rock-avalanche deposits were

233   compared with their respective source areas (Table 1). All these proxies have a reasonable

234   correlation. Avalanches with deposit-volumes >3x10^6 m^3 have similar vertical drops of

235   ~0.7 km on average, whereas avalanches with deposit-volumes <3x10^6 m^3 have lower

236   vertical drops. Assumptions used in the estimation of areas and volumes result in both

237   being undervalued. This misrepresentation is significant for the source area because the

238   rupture surfaces are usually on high, steep hillslopes. For instance, the rupture scarp of

239   Cueva Güerta is above vertical crags at the outlet of the Páramo River canyon (cross-

240   section D, Fig.4). A maximum depth of ~65 m has been measured at this deposit,

10

241 anomalously high compared to other deposits due to its confinement between the crags

242 of the Páramo River canyon (Table 1; Fig. 3). Geometrical features of the most

243 representative rock-avalanches have allowed the distinguishing of two types relative to

244 size. A detailed analysis of BSD and rock slope mechanics are presented for the rock-

245 avalanches of the Entrago and Carrea (largest) and the Villa de Sub and Cueva Güerta

246 (smallest).

247 **4.2. Structural control and BSD analysis of selected rock-avalanches**

248 The Entrago rock-avalanche is at the boundary between the hinge and southern domains.

249 Its source area lies between 800 and 1100 m above the villages of Entrago and La Plaza

250 (Fig. 7). Rock-slope failure occurred by direct toppling and planar slides, triggered in

251 multiple events. Roughly mapped rupture scars define a triangular planar surface of ~70

252 ha dipping 68º toward N71ºW. The crown of the avalanche is bound by a right-lateral

253 fault N19ºE-strike (Fig. 8). The southern fault tip has 72 m of horizontal strike. The

254 conical accumulation zone (40.75 ha) extends down to the Teverga River. It slopes to

255 ~47ºNW and the landslide accumulation consists of four superposed minor deposits: an

256 earth flow overlaid by three conic bodies of block accumulations (early, middle, and

257 recent) that still preserve their transverse ridges (Fig. 7). The fracture pattern mapped in

258 the depletion zone of this rock-avalanche (Figs. 6 and 7) allowed the outlining of 612

259 wedges (Fig. 9). A bi-modal BSD is observed, with two size-fractions of wedges. The

260 fine fraction includes wedges with diameters of <20 m, mostly on the rock-buttress failure

261 and usually of triangular shape. However, a large proportion of wedges are rhomboidal.

262 The major axis of the rhomboids is parallel to the active fault (N19ºE-strike). In contrast,

263 the wedges of the fine fraction show an anticlockwise rotation (Fig. 9B), with uniform

264 dispersion onto the rupture slope. Rotation is a consequence of the slight obliquity

265 between the wedge orientation and the rupture plane (Fig. 10). The diagram of *S* against

266   the wedge eccentricity shows small differences between both fractions (Fig. 9C). Wedges

267   of eccentricity 2.5 have $S=0.64$ if triangular or $S=0.46$ when rhomboidal. Wedges run out

268   from the depletion zone, and consequently their roundness tends to increase as indicated

269   by parameter S and their eccentricity. Diagram C (Fig. 9) shows both effects, the

270   difference in shape of each fraction size, and the effect of incipient sliced wedges within

271   the unstable residual relief.

272   The total range of block size r_i is <10 cm to >10 m. However, pebbles <20 cm were not

273   considered in the analysis because of their unrealistic statistical significance. The size

274   distribution of 4805 blocks (the total outlined blocks within the accumulation zone) is

275   presented in a frequency histogram of the normal distribution (Fig. 11A). BSD is not

276   fractal, with a slope change in the best fit regression line of the corresponding log

277   (frequency)-log (radius) histograms at block radius $r_k \sim 1$ m (Fig. 11B). The block sizes

278   $r_k>1$ m yield $D=2.35$, the usual fractal dimension of limestone fault-rocks and the damage

279   zone of strike-slip and extensional fault zones (Storti et al., 2003). Conversely, the block

280   sizes $r_k<1$ m yield $D=1.42$, a value frequently observed in small grain size fractions of

281   cataclastic fault rocks (Keulen et al., 2007). Both have an eccentricity of ~1.9 and yield

282   $S\sim0.65$ ($r_k>1$ m) and $S\sim0.68$ ($r_k<1$ m; Fig. 12B), accordingly with increasing block

283   roundness. A comparative BSD analysis between the three overlapped bodies has allowed

284   us to understand the specific contribution of each rock-avalanche outbreak to the total

285   BSD. ~1400 blocks in each body were analysed, and all show normal distributions (aspect

286   ratio ~0.7). It therefore follows that the early deposit yields a D value that compares better

287   than the latest rock avalanches with the BSD of the total accumulation zone (Fig. 11C).

288   Moreover, D appears time dependent. So, the fractal dimension in large blocks reduces

289   as the relative age of the deposit increases (Fig. 11D-F). Consequently, BSD becomes

290   fractal in the early deposit because the slope rupture at r_k is highly attenuated (Fig. 11F).

South of the Entrago rock-avalanche, there are two accumulation bodies of limestone blocks above the villages of Sobrevilla and Carrea, between 650 and 1200 m (Figs. 7, 12 and 13). They correspond to medium sized rock-avalanches (Table 1). The current active right-lateral faults that triggered both avalanches are trending NNE and NE respectively, and their kinematics are accommodate the extension along the outer arc as the curvature of the mountain range increases (Fig. 6). These faults create a downthrown block with 200 m of maximum vertical slip (longitudinal section A in Fig. 4) with maximum strike separations raised in their respective southern tips. Both faults displace the MSF trace, which cut out of sequence an earlier Variscan thrust, possibly the Tameza Thrust (Fig. 1C). The early cemented deposit accumulated about 600 m east of Sobrevilla has its origin in a rockfall (Fig. 13). The number of tension cracks easily visible on Google Earth suggest that more rockfalls are likely to happen.

The southern hillslope of Sierra de la Sobia presented three small rock-avalanches: Villa de Sub, Sabariegos, and Busbigre (Table 1). The structure consists of an asymmetric cuspate-lobate anticline-syncline of N-shape folding related to two faults (Fig. 3 and cross-section D in Fig. 4). The Sobia Syncline is a Variscan fault propagation fold related to the Sobia Thrust and then thrust out sequence by the León Fault toward the NE (Fig. 4; Alonso et al., 2009). The cuspate anticline is an ESE-verging fault-propagation fold related to a small back thrust that crops out upslope of Villa de Sub (Fig. 14). The structure probably formed to accommodate the tightening within the MSF footwall (Fig. 15 and cross-section D in Fig. 4). Since the Alpine inversion, the structure of the southern domain tilted northward ~30º. The occurrence of small rock-avalanches seems to be related to Quaternary deformation. The rock-avalanches are controlled by penetrative vertical planes (J_{p1}) trending N125-150ºE, parallel to the general trend of the most significant structures (Fig. 3). Some fractures have sub-horizontal slickenlines according to right-

316   lateral kinematics (F_{p1}), and they control the rupture scarps of rock-avalanches. Such local

317   kinematics are consistent with the whole kinematic model proposed for Sierra de la Sobia

318   (Fig. 6). The main accumulation of the Villa de Sub rock-avalanche has three overlapped

319   deposits, with the lowest composed of calcite-coated limestone blocks. The middle and

320   upper deposits have two overlapped fans. Additional blocks were incorporated during the

321   last instability events with little change in the fan shape (Fig. 15A): a rock-fall triggered

322   in 2004, synchronously with an earthquake of Ms 2; and a co-seismic 4.1 Ms rock-fall in

323   1996 (Fig. 1B). BSD of the Villa de Sub rock-avalanche is not fractal, with a slope change

324   also at block radius r_k~1 m (Fig. 12A). The block sizes r_k>1 m yield D=2.53 (R^2=0.92 to

325   the fitted regression line). Conversely, the block sizes r_k<1 m yield D=1.25 (R^2=0. 98).

326   Both sizes have similar low eccentricity of ~1.6 and roundness of S~0.73 (Fig. 12B)

327   respectively, with a relatively lower vertical drop of rock-fall and a lower impact

328   compared to larger rock-avalanches (Table 1).

329   Finally, a small rock-avalanche located at the northern entrance of Cueva Güerta at the

330   spring of Foz de la Estruchura has been analysed in detail. Most accumulation bodies

331   triggered along this canyon are confined by two opposite facing crags that bound the

332   narrow course of the river. Both the cave conduits and the river course lie parallel,

333   trending N-S along the damage zone of the MSF (Fig. 14). BSD in the accumulation body

334   of Cueva Güerta is not fractal, with a slope change also at r_k<1 m (Fig. 12A). The block

335   sizes r_k>1 m yield D=2.70. Conversely, the block sizes r_k<1 m yield D=0.54, but with low

336   confidence. Both sizes have a low eccentricity of ~1.6, but the coarse fraction includes

337   less rounded blocks (S~0.68), than the finer fraction (S~0.72). The coarse fraction has the

338   highest D among the populations analysed in Sierra de la Sobia. It shows lower particle

339   fragmentation (higher D) than the other unconfined accumulation bodies. Low

340   fragmentation is consistent with a progressive increment of relatively fine blocks towards

341   the top of the confined accumulation, caused by gravity selection.

342   **4.3. Slope stability analysis**

343   The stability models for all the slopes analysed assumed a conservative friction angle of

344   35º on the joint surfaces. The slope stability above the Entrago rock-avalanche was

345   analysed based on the orientation of 85 fractures measured along the rupture scarp,

346   controlled by the right-lateral fault of N19ºE-strike. The mechanical instability of the

347   rupture scarp was evaluated under different dynamic failure modes (Fig. 10). Visual

348   estimates indicate <6% risk for planar sliding, <16% direct toppling risk for joint sets $J_{r1'}$

349   and $J_{r2'}$, <16% flexural toppling risk for joint sets J_{r1} and <13% wedge sliding risk.

350   Although the dynamic analysis gives a low risk of instability, the slope records at least

351   four superposed landslide deposits (Fig. 7). The models have a slope safety factor of <1.3

352   only when running with horizontal peak ground accelerations (PGA)>0.10-0.15 g, within

353   the prediction of the 2013 European Seismic Hazard Map for north-western Iberia

354   (Giardini et al., 2014).

355   84 mechanical discontinuities (25 S_0, 3 F_r, 1 F_p, 23 J_p, 18 J_{r1}, 6 $J_{r1'}$, 6 J_{r2} and 2 $J_{r2'}$)

356   measured on the rupture plane of the Carrea rock-avalanche have been considered for the

357   slope stability analysis. The fracture pattern lies parallel to both the Variscan thrusts and

358   an active transverse fault, and a rupture slope with dip direction 237/50 is considered for

359   the stability models. Considering these surface conditions there is a 0% risk for flexural

360   toppling, <4% risk for planar sliding, <11% risk for direct toppling and wedge sliding.

361   All these models indicate slightly higher safety factors than for the Entrago rock-

362   avalanche, even though a safety factor of <1.3 may arise with horizontal PGA>0.15 g.

363   123 mechanical discontinuities (45 S_0, 1 F_r, 7 F_p, 35 J_p, 23 J_{r1}, 8 $J_{r1'}$, 1 J_{r2} and 3 $J_{r2'}$)

364   measured on the rupture plane of Villa de Sub were considered for the slope stability

365   analysis. A penetrative fracture pattern lies parallel to the active right-lateral fault and

366   normal to the S_0 trend. The rupture slope modelled has a 173/80 dip direction and tilts

367   opposite to S_0. The dynamic analysis gives risks of <8% for flexural toppling, <9% for

368   planar sliding, <24 % for direct toppling and <19% for wedge sliding. The models

369   provided lower safety factors than for the Entrago rock-avalanche, even though a safety

370   factor of <1.3 may arise with horizontal PGA>0.10 g.

371   Only a dynamical slope stability analysis has been carried on the external Cueva Güerta

372   avalanche. 52 discontinuities (5 S_0, 8 F_r, 18 F_p, 6 J_p, 9 J_{r1}, 1 $J_{r1'}$, 4 $J_{r2,}$ and 1 $J_{r2'}$) measured

373   around the north cave entrance were considered in the slope stability analysis. Two planes

374   with dip directions 20/90 and 87/90 define the rupture slope, and consequently two

375   dynamic analyses of the respective slope stability risk have been considered. These

376   indicate risks of <14 and 25% for flexural toppling, <8 and 14% for planar sliding, <21

377   and 27% for direct toppling, and <24 and 26% for wedge sliding, with dip directions

378   20/90 and 87/90 respectively. Slope stability models created with the dip direction 87/90

379   give lower safety factors than those for 20/90. Both models have lower safety factors than

380   any other rock-avalanche case studies, even though >1.3 has been obtained for all rupture

381   slopes modelled in this work.

382   **4.4. Timing of rock-avalanche events**

383   Calcite coating the blocks within the oldest calcareous rock-avalanche of the Entrago

384   deposit was successfully dated in samples RB_5, RB_6, and RB_7 (Fig. 7, Table 2).

385   Samples RB_5 and RB_6 taken along the transverse frontal ridge of the conical cemented

386   deposit, yielded ages of 13.7±0.9 and 278.3±32.9 ka coeval to marine isotope stages MIS-

387   1 and MIS-9a, respectively. Sample RB_7 from the toe of the deposit, yields 194.3±70.2

388   ka, indicating cementation during MIS-7a.

389   In the case of the Sobrevilla deposit, a minimum U/Th age of ~100 ka has been reported

390   (Fig. 13; Rodríguez-Pérez, 2012). Sample RB_2 taken at the accumulation body of the

391   Carrea avalanche yields an age of 58.8±14.6 ka, coeval to MIS 3-4 (Table 2), while RB_9

392   yields a minimum age of 38.3±2.8 ka, coeval to MIS 3 (Table 3). Based on the U/Th

393   dates, the Sobrevilla rock-avalanche occurred earlier than the Carrea rock-avalanche, but

394   later than the main event that caused the Entrago rock-avalanche. Radiometric ages are

395   consistent with the evolution of the BSD observed between the three overlapped deposits

396   in the avalanche. So, the Carrea rock-avalanche has BSD with a sharper slope break than

397   the Entrago one (Fig. 12A). The blocks within the accumulation body are also more

398   irregular than those in the Entrago avalanche, as shown by parameter S (Fig. 12B).

399   Sample RB_03 taken from a calcite cement coating a block at the Cueva Güerta rock

400   failed to provide a reliable age (Table 2). A replica of that sample, RB_10, yields a

401   minimum age of 9.9±1.2 ka (Table 3). Based on the U/Th results, Cueva Güerta is the

402   youngest dated rock-avalanche until now in Sierra de la Sobia. Its bi-log frequency-size

403   diagram shows a greater slope rupture between the two block fractions (Fig. 12A).

404   According to the tendency observed between the diagrams in the Entrago rock-avalanche

405   (Figs. 11D, E, and F), the slope rupture (Fig. 12A) is also consistent with the young age

406   obtained in the Cueva Güerta avalanche.

407   **5. Discussion**

408   The impact of our results is discussed below, addressing the following: 1) current

409   tectonics in Sierra de la Sobia; 2) origin and recurrence of rock-avalanches; 3) Quaternary

410   geomorphological evolution of the landscape.

5.1 Current tectonics in Sierra de la Sobia

The kinematic analysis of active faults, as well as their slip inversion, is consistent with a re-tightening by horizontal shortening accordingly with a N-S trending SH_{max} (Fig. 6). Current strain gave rise to the stretching along the western outer arc of the range, throughout the activation of strike-slip faults but also reverse and minor normal-scissor faults that accommodate deformation at the surface. In contrast, at depth, this intensely fractured zone is probably linked to the León Fault as indicated by the fracture network, the fault trends and their distribution compared to the trace of the León Fault. However, some of the minor active faults also displace the main trace of the León Fault (Figs. 3 and 4). These structural features might raise questions about the current activity of this fault. However, we have observed that current tectonics related to the León Fault likely triggered the slope failures recurrently, both in the outer arc of Sierra de la Sobia and along the whole southern branch of this fault (Figs. 1B and 2). Moreover, several low seismic signals have recently been recorded at a depth of ~15 km near the intersection of the León and Ventaniella Faults (López- Fernández et al., 2018). Therefore, we consider that the most recent minor faults showing cut off relationships with the León Fault trace are a consequence of the growth fracture density along the main fault trace and the dissipation of the current differential stress along such new fault planes.

The summit elevation in Sierra de la Sobia progressively increases southwards, showing a constant slope of 1.5º from 1350-1776 m (Saleras peak; Figs. 2 and 5). The restored section A (Fig. 4) has given a maximum current extension of 300 m of the outer arc of the range. The progressive uplift of the range southward led to the reactivation of the Variscan lateral ramp and the development of several high angle faults trending E-W at the junction between the MSF and the Trobaniello segment fault (Fig. 6). Finally, the current brittle strain partition in the southern domain of Sierra de la Sobia accommodated

436   right-lateral minor faults N150ºE-strike as well as other conjugated faults that likely

437   caused smaller avalanches (Fig. 6). The larger avalanches triggered northward suggest

438   that Quaternary seismicity is higher in the hinge domain of Sierra de la Sobia and

439   diminishes southward.

440   It is reasonable to extend the current tectonics of Sierra de la Sobia to CZ, as a working

441   hypothesis. Because this arcuate mountain range lies parallel to the León Fault, the fault

442   trace eastward prolonged according to CA orocline (Fig.1), and along the whole trace of

443   the León Fault has recorded rock-avalanches and complex flows like those described

444   above (Fig. 2). Moreover, CZ has other active structures that support this statement. One

445   is the Variscan Tineo Thrust, westward of the Cenozoic basin of Oviedo. This trends NE-

446   SW accordingly with the CA, and it was reactivated, thrusting over Cenozoic sediments

447   south-eastward (Fig. 1B; Pulgar et al., 1999). Another case is the Boinás Thrust (Fig. 1B;

448   de Vicente Muñoz et al., 2007). It trends parallel to the Tineo Thrust but back thrusts

449   north-westward 350 m. The Tineo Thrust and the reverse fault described in the Marabio

450   Pass (Fig. 6; Fernández et al., 2018) have the same kinematics. In both cases, tectonics

451   seem to accommodate the deformation after the unfolding limb section of regional

452   Variscan folds parallel to the CA by horizontal shortening parallel to their respective axes

453   accordingly with the regional trends of SH_{max} (de Vicente et al., 2008; Custódio et al.,

454   2015). Eastward, the fault junction between the León and Ventaniella faults (Fig. 1B)

455   recorded recent low-magnitude earthquakes (López- Fernández et al., 2018). The

456   clustering of earthquakes along these faults coincides spatially at depth with the transition

457   zone. The seismicity of the Ventaniella fault is fragmented, having only moderate seismic

458   records at the northern onshore segment and south of the fault's junction, whereas the

459   central segment is aseismic.

460   CA is divided into two tectonic units by the Ventaniella Fault. The current deformation

461   in the western tectonic unit appears controlled by the arcuate shape of the orocline.

462   Normal faults accommodate stretching, parallel to the arc. Strike-slip faults transverse to

463   the arc accommodate the N-S shortening, and back-thrusts towards the outer-arc

464   accommodate the subsequent migration of the neutral surface predicted for the

465   longitudinal tangential folding mechanism (Fig. 1B). Variscan and Alpine structures east

466   of the Ventaniella Fault have a linear trend E-W and they can accommodate the current

467   regional SH_{max} easily with straight displacement southward. However, because the CA

468   controls the Quaternary reactivation, deformation is partitioned in transtensive basins

469   controlled by right faults trending NW-SE parallel to the Ventaniella Fault. Finally,

470   according to the crustal thickness variation, the aseismic central segment might be

471   interpreted as the current strain rate, progressing more efficiently toward the flanks of the

472   orocline than in its core (Díaz et al., 2016; Díaz and Gallart, 2009).

473   The topography of the crust-mantle boundary is also interpreted as evidence of a passive

474   margin (Cadenas et al., 2018; Fernández-Viejo et al., 2000; López-Fernández et al., 2020)

475   or as the earliest initiation of ocean-continent subduction (Álvarez-Marron et al., 1997;

476   Ayarza et al., 2004; Díaz and Gallart, 2009; Gallastegui et al., 2016). In our opinion,

477   surface topographic features such as marine terraces are not only dependent on the crust

478   thickness as postulated in López-Fernández et al. (2020) but also on the elastic thickness

479   of the whole lithosphere (Burov and Diament, 1995; François et al., 2013). It is

480   noteworthy that the Quaternary kinematics of the active fault analysed in Sierra de la

481   Sobia consist of tangential deformation (Fig. 6), although normal faulting is associated

482   with isostatic balance in passive margins (Conway-Jones et al., 2019; Pederson et al.,

483   2002). The reverse and strike-slip fault kinematics prevail against the current normal

484   faults, mostly locate radially to the outer-arc at the hinge domain of Sierra de la Sobia.

485 Most of the active fault mapped along the Cantabrian wave-cut paleo-platform by

486 Álvarez-Marrón et al. (2008) indicate consistent kinematics with our study area.

5.2 Rock-avalanches: origin and recurrence

488 Rock fragmentation, weathering, climatic factors, and geomorphological factors, during the

489 withdrawal of glaciers and associated debuttressing have been described as the triggers of large

490 rock-avalanches (Ambrosi and Crosta, 2011; Ballantyne et al., 2014; Turcotte, 1986).

491 Additionally, in many rock-avalanches, seismicity is the main triggering factor: avalanches

492 triggered by recent (Wasowski et al., 2021) or historical earthquakes (Martin et al., 2014; Zeng et

493 al., 2020) or polyphase rock-avalanches that are consistent with sedimentological paleoseismic

494 records (Grämiger et al., 2016).

495 Slope failure analyses demonstrate that under static conditions the main rupture scarps of

496 the rock-avalanches on the Sierra de la Sobia are mechanically stable (Fig.10) and

497 consequently differential stress must be increased for dynamic fragmentation. Moreover,

498 the BSD analysis shows $r_k>1$ m for all the rock-avalanche deposits yield D ranging

499 between 2.24 and 2.70 (Table 1), into the usual range of dynamic fragmentation (Storti et

500 al., 2003). Therefore, similar two-stage breakage dynamic processes caused the block

501 fragmentation within all rock-avalanches: (i) dynamic and ballistic fragmentation from

502 the aftershock rupture scarp; and (ii) fragmentation by wear and attrition from the scar

503 slope to the accumulation body, causing the BSD-homogenization within the block size

504 fractions $r_i <1$ m. The block size at the slope change (r_k) seems to represent a change in

505 the dominant fragmentation mechanism from (i) to (ii). D variations can be interpreted

506 because of the percentage weight of fine to coarse fragments in each respective fraction.

507 So, decreasing particle fragmentation occurred in confined accumulation bodies only

508 because the surface of the accumulation body is considered for the BSD analysis (see

509 methods), where the percentage weight of fine fragments is higher than at the bottom.

510   Consequently, D for $\mathrm{Logr_k}{>}1$ is higher in the accumulation body of Cueva Güerta

511   compared to other avalanches (Fig. 12, Table 1). Selection can also be evaluated

512   indirectly by the difference of the roundness versus eccentricity between the fine and

513   coarse fractions of each BSD (Fig. 12B). More selection is expected at the top of the

514   accumulation body than at the tip. For instance, the BSD of Carrea avalanche shows the

515   greatest segregation because only the top sector of the accumulation body is considered,

516   whereas in other avalanches the whole accumulation body is well exposed and

517   consequently used for BSD analysis. This feature is also consistent with the relative ages

518   inferred from BSD. The accumulation body of the largest avalanches is composed of

519   several superposed deposits of horizontal conic shape, where the most recent deposit is

520   located at the top of the accumulation body. The detailed BSD of the Entrago avalanche

521   shows a progressive attenuation of the $\mathrm{logr_k}$-slope rupture as the relative age of the BSD

522   deposit increases (Fig. 11). If the BSD of the analysed avalanches is compared, according

523   to this criterion, Entrago is the oldest rock-avalanche in the Sierra de la Sobia and Cueva

524   Güerta the youngest (Fig. 12A). This relative chronology is consistent with the U/Th ages

525   obtained from the coated calcite blocks sampled in these accumulation bodies (Tables 2

526   and 3).

527   At least three superposed deposits of blocks have been differentiated at the map-scale on

528   the massive avalanches of Sierra de la Sobia (Figs. 7 and 13), along a fault segment ~4.5

529   km length, suggesting that such avalanches record the same seismic events. Moreover,

530   co-seismic rock-falls have been recorded near Villa de Sub (Fig. 14). However,

531   destructive to very destructive events, ranging between VIII to X in the environmental

532   seismic intensity scale (Michetti et al., 2007) could be inferred accordingly, with: (i) the

533   offset and length of the active faults; (ii) the evaluated tectonic uplift and subsidence

534   (Figs. 3, 4, 6); (iii) the length and width of the ground cracks and the reach of slope

movements (Figs. 7, 13, 14, Table 1); and (iv) the affected area and type of record (Reicherter et al., 2009). Recently, the empirical power-law relationships between the total volume of the avalanche and the seismic magnitude (Keefer, 1999) were validated (Croissant et al., 2017). However, this approach is challenging to apply in this study area because it is impossible to evaluate which avalanche volume corresponds to each paleoseismic event. Also, for short-term recurrence, the total volume could decrease as the rupture scarp becomes more stable during aftershocks. Currently, the slope stability analyses indicate that a horizontal PGA ranging between 0.10-0.15 g is required to disrupt such scarps again. Sierra de la Sobia experiences moderate seismicity, characterized by frequent Ms<6 events, because of its geodynamic setting (Álvarez-Marron et al., 1997; Ayarza et al., 2004; Díaz and Gallart, 2009; Gallastegui et al., 2016). In this context, the largest earthquakes generated in the past might occur within recurrence intervals much longer than the period covered by both the historical and instrumental local records (Fig. 1B) and could be conditioned by the reactivation of the long-lived crustal León Fault at a slow slip rate during the re-tightening of the CA under NNW-SSE compression. Further work is necessary for insight into the standard log r_k= 1 for all the BSDs analysed (Fig. 12A). Samples have been collected from the non-cemented rock-avalanches at Entrago and Carrea to broaden the chronological framework presented here by ^{36}Cl cosmic-ray exposure dating. The accurate date of the latest avalanche-events might help forecast future massive earthquakes in the region.

Based on the oldest calcite cement, a reference age of 278.3±32.9 ka is inferred for the oldest cementation episode affecting the Entrago deposit, and hence a minimum age for the oldest rock-avalanche event. Subsequent avalanche cementation occurred thereafter, spanning the last 200 ka, potentially conditioned by Quaternary climate changes. Calcite growth took place preferentially during the interglacials, and during the warm periods

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560 that bounded the MIS-3 glacial advance of the Cantabrian Mountains (Rodríguez-
561 Rodríguez et al., 2015).

562 **5.3 Quaternary geomorphological evolution of the landscape**

563 The western hillslope of the Sierra de la Sobia is a structural form controlled by the
564 arcuate orientation of the limestone bedding and MSF. Compression of this mountain
565 range according to the current regional NNW SH_{max} (de Vicente et al., 2008; Custódio et
566 al., 2015) triggered several rock-avalanches with recurrent avenues along the Quaternary
567 period. This active tectonic process strongly conditioned the geomorphology of the
568 Teverga Valley.

569 In this period, the incision rate of the Páramo River may have accelerated as suggested
570 by the cuspate shape of the river valley throughout the Foz de la Estrechura canyon (Fig.
571 14). The current course is incised ca 30 m from the paleo-epiphreatic sediment deposited
572 on the upper entrance of Cueva Güerta. The current phreatic level runout ca 100 m below
573 the paleo-phreatic level is defined along the low gradient of the longest gallery in this
574 cave (Ferreras et al., 2015). However, the accumulation of the rock avalanche confined
575 at the spring of the canyon did not dam the stream. This is because, at that time, the flow
576 of water was underground, and its runout was at a deeper level.

577 Downstream is the old village of Fresneu, which was destroyed on June the 25th 1522.
578 Canon Tirso de Avilés of Oviedo Cathedral tells of an earthquake event, after which a
579 new village was built at the current site (Fig. 14). Moreover, the Entrago avalanche
580 dammed the Val de Cazana, Taja and Páramo Rivers (Fig. 3), deviated the resultant course
581 of the Teverga River at the entrance of the Val de Cerezales canyon, and developed the
582 only floodplains present in this valley (Fig. 7).

583   A detailed analysis of this river sub-basin extended to the whole Nalón basin that would

584   give new insights into understanding the Quaternary geomorphology and tectonics of the

585   Cantabrian Mountains is currently underway.

586   **6. Conclusions**

587   The Quaternary reactivation of minor faults lying along the MSF-trace has

588   accommodated ~300 m uplift of the summits in Sierra de la Sobia. Their slip inversion is

589   consistent with a current N-S trend of the SH_{max} that contributes to the re-tightening of

590   this arcuated mountain range and the stretch of its outer arc also ~300 m by longitudinal

591   tangential deformation.

592   The largest rock-avalanches are distributed along the hinge domain of Sierra de la Sobia,

593   while the smallest are in the southern domain. The sizes of rock-accumulation bodies are

594   proportional to the corresponding vertical drop. BSDs of the accumulation bodies are not

595   fractal. The largest block size fractions (r_i>1 m) have slope D-values ranging between

596   2.70 and 2.24, whereas the block size fractions r_i <1 m have lower D-values.

597   The mechanical slope stability analysis of relevant rupture scarps reported safety factors

598   >1.3 under static boundary conditions. However, all rupture scarps become unstable if

599   horizontal seismic acceleration rises 0.10-0.15 g.

600   Chronological U/Th data obtained from calcium carbonate cements bounding limestone

601   blocks in the Entrago, Carrea and Cueva Güerta rock-avalanches suggest recurrent

602   instability events for at least the last 300 ka, with episodic cementation occurring during

603   the last five interglacials.

604   Geomorphological and structural data gathered on the western flank of Sierra de la Sobia

605   reveal unambiguously a clear relationship between current tectonics and recurrent

606   catastrophic rock-avalanches.

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800

Figure and table captions

802 Fig. 1: (A) Overview map of NW Spain presenting the evidence for the main Alpine exhumation

803 phase in the Cantabrian Mountain and Basque-Cantabrian Basin. (B) Geological map of the

804 Cantabrian Zone. Available seismic records are indicated with stars, and the trace of the

805 geological section (C). Inset shows the location of Fig. 2. The Somiedo (SoT) and Sobia (ST)

806 thrusts.

807 Fig. 2: Aerial image of Sierra de la Sobia and Macizo de Ubiña. Main segments of the northern

808 León Fault sector, rock-avalanches and the highest summits are highlighted (orange lines). The

809 orange arrow shows the NNW trends of the current regional maximum horizontal stress (SHmax;

810 de Vicente et al. 2008).

811 Fig. 3: Geological map of the Sobia Nappe showing the relationships between rock-avalanche,

812 Quaternary sediments, mechanical contacts and relief. Traces of the geological section

813 represented in Fig. 4 are also shown.

814 Fig. 4: Longitudinal-section (A) and three cross-sections (B, C, and D) to Sierra de la Sobia.

815 Traces of the transversal cross-sections and the range level of summits (RLS) line are located on

816 the longitudinal-section A.

817 Fig. 5: Panoramic view of a 15km-long segment of Sierra de la Sobia, including the hinge and

818 southern domains. Carboniferous limestone outcrop exposes MS, thrusting out of sequence the

819 earliest Variscan syncline and thrust. Minor normal and strike-slip faults cut the MS-trace, also

820 folded by the Foz de la Estrechura anticline, southward. RLS have small steps controlled by the

821 vertical slip of both later-normal and strike-slip faults as the mountain chain increases in height

822 southward (see also Fig. 4A).

823 Fig. 6: Structural map of Sierra de la Sobia showing the relationship between the León Fault, the

824 latest faults and the fracture network imposed on the limestone massif. The stereonet plots

825 represent the equal area and lower hemisphere projections of fault planes and slickenlines. Arrows

826 represent the direction of displacement inferred from slickenlines. Blue lines and symbols

827   represent fault segments reactivated during the Quaternary and their respective kinematics.

828   Orange finite strain ellipse is scaled to R=1.42, strain ellipse orientation is consistent with the

829   kinematic of most current active faults.

830   Fig. 7: Detailed geomorphological map of the Gradura and Entrago rock-avalanches including

831   earth flow, slope dynamic and river deposits. Stars show the location of U/Th samples.

832   Fig. 8: Entrago rock-avalanche. (A) Details of the rupture scarp where a rotational rockslide (rock

833   slump) rests atop. The Sobia spire is a buttress 125 m in height separated by less than 50 m from

834   the rupture scarp. A huge rock-topple was triggered at the southern scarp tip. Note that

835   discontinuities have the same pattern into the rupture scarp than in the rock-slump. (B) Behind

836   the Sobia spire a transverse fault N5ºE-strike with slickenlines indicating sub-horizontal right-

837   lateral displacement (North is on the left-hand side) is exposed.

838   Figure 9: Dynamic analysis of slope instability risk considering four failure modes for the rupture

839   scarp of Entrago. Flexural toppling analysis following Goodman (1989) and direct toppling

840   following Hudson and Harrison (1997). Pole planes are plotted in lower hemispheres and equal

841   angle stereonets. Contour density at constant intervals of 0.7%.

842   Fig. 10: Shape-fabric analysis of the depletion zone for the Entrago rock-avalanche (612 wedges).

843   (A) Diagram showing the size frequency (black line) and the area percentage (dashed line) versus

844   wedge size. (B) Histogram showing the frequency of the orientation of the major ellipse inscribed

845   in each wedge. Fine fraction (white bars) of wedges was sketched from the thickly fractured rock-

846   slump of the unstable residual relief (Fig. 7A) and it preserves the same orientation than the coarse

847   fraction (black bars). (C) Shape parameter (S; Fernández et al., 2005) versus eccentricity diagram.

848   Triangular wedges, defined by the intersection of joint sets, dominate within the fine fraction

849   (white dot), and rhomboidal wedges dominate within the coarse fraction (black dot). Error bars

850   represent standard deviations.

851   Fig. 11: Block size analysis of the Entrago rock-avalanche. (A) Histogram of equivalent radii

852   (dm) for the whole accumulation body (4805 blocks). (B) Log-log plot of frequency versus

853 equivalent radius (20 bins per order of magnitude). The slope of the fitting lines yields two *D*-

854 values which intersect at r_k. (C) Histogram of equivalent radii (dm) for the three superimposed

855 bodies mapped (Fig. 7). (D) Log-log plot of frequency versus equivalent radius for the earliest,

856 (E) middle and (D) the apical bodies.

857 Fig. 12: Shape-fabric analysis of blocks for the four accumulation bodies studied in detail. (A)

858 Log-log plot of frequency versus equivalent radius (20 bins per order of magnitude). The slope

859 of the fitting lines yields two *D*-values which intersect at r_k. (B) Shape parameter (S; Fernández

860 et al., 2005) versus eccentricity diagram. Error bars are their respective standard deviations. Block

861 sizes plotted for each fine fraction is larger than $Log(r_i)=0.5$ (dm).

862 Fig. 13: Detailed geomorphological map of the Sobrevilla and Carrea rock-avalanches (left and

863 right, respectively). Start indicates the location of U/Th samples.

864 Fig. 14: Detailed geomorphological map of rock-avalanches occurred at Fresneu, Cueva Güerta,

865 Villa de Sub, Sabariegos and Busbigre. Stars indicate the location of U/Th samples of calcite

866 cements coating the blocks of the Cueva Güerta rock-avalanche deposit. Cave plan view modified

867 after Ferreras et al. (2015).

868 Fig. 15: South-Eastern Sierra de la Sobia. Villa de Sub is located down hillslope at the tip of the

869 accumulation body. (A) Geology sketched onto the picture highlights the effect of the current

870 right-lateral faults (F_{p1}) and fold-related onto the back-thrust structure of the basement. One of

871 such fault is the rupture plane of the Villa de Sub rock-avalanche. (B) The picture shows the

872 regular and penetrative joint set J_{p1} associated with faults F_{p1}. Limestone bedding surfaces (S_0)

873 dip in the opposite direction to the SE hillslope, enhancing the risk for direct toppling. Width of

874 view is ~500 m in A, and ~50 m in B.

875 Table 1: Geometrical features of rock-avalanches located at the northern domain (Marabio); the

876 hinge domain (Gradura, Entrago and Sobrevilla); and the southern domain of Sierra de la Sobia

877 (Carrea, Cueva Güerta, Villa de Sub, Sabariegos and Busbigre). Sites are in Figs. 3 and 5. H is

878 the vertical drop and L is the length of fall. H/L ratio is the Fahrböschung parameter of Heim

879   (1932) and ϕ is the corresponding angle. Dimension fractal (D) for the block size distribution

880   (BSD) within the accumulation bodies are obtained from the slope line fit yield values $> r_k$ (Fig.

881   12 A).

882   Table 2 U/Th isotopic compositions and ^{230}Th ages for samples analysed by α-spectrometry.

883   Analytical errors are 2σ of the mean. Samples, UTM coordinates ETRS-89, 29T.

884   Table 3: U/Th isotopic compositions and ^{230}Th ages for samples analysed by Alpha spectrometry.

885   Analytical errors are 2σ. UTM coordinates ETRS-89, 29T.

Table_01

Rock avalanche	H (km)	L (km)	ϕ (degrees)	Deposit Width (km)	Source area (km²)	Deposit area (km²)	Deposit Depth (m)	Volume (× 10⁶ m³)	D-BSD (fractal)
Marabio	0.41	1.28	18	0.15	0.0247	0.0715	20	0.07	
Gradura	0.56	0.84	34	0.27	0.1278	0.1698	12	2.03	
Entrago	0.71	1.16	31	0.65	0.1232	0.4315	29	12.5	2.35
Sobrevilla	0.71	1.79	29	0.64	0.1570	0.2268	25	5.67	
Carrea	0.68	1.57	23	0.19	0.1157	0.1312	25	3.28	2.56
Cueva Güerta	0.07	0.07	45	0.07	0.0007	0.0043	30	0.13	2.70
Villa de Sub	0.25	0.39	33	0.11	0.0122	0.0219	5	0.11	2.24
Sabariegos	0.27	0.81	18	0.17	0.0121	0.0325	10	0.16	
Busbigre	0.21	0.53	22	0.10	0.0153	0.0299	5	0.07	
Mean	0.43	0.88	28	0.26	0.0654	0.1244	21.22	2.68	
Standard deviation	±0.24	±0.49	±9	±0.23	±0.0634	±0.1378	±17.07	±4.16	
Total					0.5887	1.1194		24.15	

Table_02   Click here to access/download;Table;Table_02.docx ≛

Sample ID	RB_03	RB_05	RB_02	RB_07	RB_06
Weight (g)	0.3498	0.3471	0.3548	0.3532	0.3603
Coord. X	739331.12	736360.02	739319.66	736458.12	736281.16
Coord. Y	4778755.92	4784219.02	4781901.94	4784017.74	4784023.89
Altitude (m.a.s.l)	673.49	445.91	1083.06	492.02	471.67
Rock avalanche	Cueva Güerta	Entrago	Carrea	Entrago	Entrago
^{238}U (ppb)	36.1 ± 0.1	125.7 ± 0.2	441.2 ± 0.9	398.2 ± 1.1	1296.7 ± 6.9
^{232}Th (ppt)	17970 ± 360	2786 ± 56	68918 ± 2123	87155 ± 4086	66395 ± 1575
$\delta^{234}U_{Measured}$ [a]	102.2 ± 2.7	-2.2 ± 2.5	2.4 ± 1.6	19.7 ± 2.1	6.7 ± 3.1
$[^{230}Th/^{238}U]_{Activity}$ [b]	0.20 ± 0.04	0.123 ± 0.006	0.44 ± 0.07	0.86 ± 0.09	0.93 ± 0.02
$[^{230}Th/^{232}Th]$ [c]	7 ± 2	91 ± 5	47 ± 8	63 ± 8	300 ± 10
Age Uncorrected (yr)	21519 ± 5822	14317 ± 791	63452 ± 14821	200834 ± 75643	279791 ± 33327
$\delta^{234}U_{initial}$ corrected	104 ± 4	-2 ± 3	3 ± 2	34 ± 8	15 ± 7
Age corrected [b,d] **(yr)**	7561 ± 11216	13669 ± 910	58823 ± 14577	194345 ± 70211	278312 ± 32868
Quaternary stage	Holocene	Late Pleistocene	Late Pleistocene	Middle Pleistocene	Middle Pleistocene
MIS stage	1	1	3	7a	9a
After glacial-(ka)	Termination I-14	Termination I-14	Termination II-130	Termination III-243	Termination IV-337

Table_03

Sample ID	RB_10	RB_09
Weight (g)	19.81	17.16
Coord. X	739331.12	739620.8
Coord. Y	4778755.92	4781818.74
Rock avalanche	Cueva Güerta	Carrea
Altitude (m.a.s.l)	673.49	673.49
^{238}U (ppm)	0.05	0.16
^{232}Th (ppm)	0.01	0.02
$^{234}U/^{238}U$	1.24+/-0.08	0.93+/-0.03
$^{230}Th/^{232}Th$	7.266+/-2.211	8.317+/-1.240
$^{230}Th/^{234}U$	0.09+/-0.01	0.30+/-0.02
Nominal date (years BP)	9945+1222/-1209	38327+2890/-2820
Quaternary stage	Holocene	Late Pleistocene
MIS stage	1	3
After Glacial-(ka)	Termination I-14	Termination II-130

Figure_01

Click here to access/download;Figure (Color);Fig_01.tif ⬇

A

Modified after:
(1) Grove et al., 2010
(2) Martín González et al., 2011
(3) Alonso et al., 2009
(4) Pedreira et al., 2015

Iberian massif

No Alpine phase of exhumation (1,2)

Oviedo

Cantabrian Mountains

Cantabrian Frontal Thrust (3,4)

Cantabrian sea

Basque-cantabrian Basin

Duero Basin

- Quaternary
- Cenozoic
- Oligocene - Miocene
- Paleocene - Eocene
- Lw. Cretaceous / Up.Cretaceous
- Jurassic - Lw. Cretaceous
- Permian - Triassic
- Proterozoic - Paleozoic basement

B

Modified after Alonso et al., 2009

WEST-ASTURIAN LEONESE ZONE

CANTABRIAN ZONE

▲ Historical seismic events
★ Ms 4.6 (04/04/1950)
★ Ms 4.1 (12/10/1996)

Seismic Intensity scale MSK
★ VI
★ V
☆ IV
☆ III
☆ undetermined

(IGN and USGS historic files)

✳ Rock avalanches and/or complex flows related to León Fault

1861 1552
1877

GIJON

Cantabrian sea

Ventaniella Fault

OVIEDO

Figure 2

López-Fernández et al. (2018)

León Fault

43° 20'

43° 00'

- Stephanian
- Upper Westphalian
- Lower and Middle Carboniferous
- Silurian and Devonian
- Lower Cambrian to Lower Ordovician
- Lower Cambrian
- Precambrian
- Permian-Mesozoic and Tertiary cover

— Variscan Thrusts
— Alpine Thrusts
— León Fault

0   5   50 km

C

Alonso et al., 2009

SW

TS   MS   ToS   PT   NE

SoT   TT   ST

km
0
-5
-10

SOLE   THRUST   OF   THE CANTABRIAN ZONE

0   5   20 km

Breaching Thrusts
(León Fault: TS Taja segment, MS: Marabio segment. ToS: Trobaniello segment; PT: Pajares Thrust)
Earlier Thrusts (SoT: Somiedo Thrust; TT: Tameza Thrust; ST: Sobia Thrust)

Figure_02

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Caldoveiror (1351 m)

N175°E

Marabio segment-fault

El Ouviu (1357 m)

Fig. 3

Fig. 7

Sierra de la Sobia

La Sobia (1406 m)

(1507 m)

Fig. 13

Taja segment-fault

Fig. 14

Salinas (1376 m)

Trobaniello segment-fault

León Fault

Ubiña Massif

main rock avalanches

10 km

Figure_03

Figure_03

Legend (right):

- Unconformable Cenozoic a- Quaternary
- Unconformable Stephanian

Paleozoic basement

- Sama Group
- Lena Group
- Middle and Upper Westphalian formations
- Lower and Middle Carboniferous formations (except Uppermost Westphalian terrigenous formations) and Candamo Formation
- Devonian except uppermost Famenian Formation (Rañeces, Moniello, Naranco Formations)
- Lower to Upper Cambrian, Lower Ordovician and Silurian Formations (Láncara, Oville, Barrios, Formigoso and San Pedro Formations)

Legend (lower left):

- Bedding strike and dip
- Normal stratigraphic contact
- Unconformable contact
- Trace of layer
- Trace of syncline
- Trace of anticline
- Variscan thrust
- Minor fault
- León Fault
- Late reverse fault
- Late minor fault
- ★ Main rock avalanche
- Transection (**Fig. 4**)
- Longitudinal section (**Fig. 4**)

0 1 2 3 km

Labels on map: Marabio, Gradura, Entrago, Sobrevilla, Carrea, Cueva Güerta, Villa de Sub, Tala river, Val de Gezano river

743000 744000 745000 UTM
4775000 4776000 4775000

Figure_04

A | NNE — Northern domain SSW | — Hinge domain | NW — Southern domain SE |

B — Marabio Gradura — Teverga river canyon — Sobrevilla — C — Carrea — D

B | W — A — Caranga antiform — E

C | WSW — Siella A — ENE

D | SW — Páramo river canyon — Solpicu — A — NE

Fig.15

The Sobia Nappe (Somiedo Unit, Cantabrian Zone)

Trace of layer
Normal contact
Variscan mechanical contact
León Fault-segments: TS: Taja segment; MS: Marabio segment; ToS: Trobaniello segment
Current active minor faults
Thrust with kinematic sense normal to the section
Right lateral and left lateral | faults

5 km

Figure_05

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Figure_06

Click here to access/download;Figure (Color);Fig_06.tif ⬇

Faults parallel to the Arc(F$_p$)

Faults resolved: 15/16
Misfit angle:39.6°

Faults transverse to the Arc (F$_t$)

Faults resolved: 6/16

Fault strike

N = 32
Maximum = 1.5

(1) Fernández et al. (2018)

Main rock
avalanche

León Fault

Fracture joint
network

Late
fault kinematics

1 km

Figure_08

Click here to access/download;Figure (Color);Fig_08.tif ⬇

A

Sobia spire

125 m

B

Rock topple

Rock slump

Rock avalanche

B

Figure_09

Click here to access/download;Figure (Color);Fig_9.tif ⬇

Planar Sliding

Lateral limits: 20°
Critical fracture: 5 (5.88%)

Wedge Sliding

Fracture sets N:

◇	Fp	1
×	Fr	5
△	Jp	16
⬥	Jr1	18
▽	Jr1'	13
◻	Jr2	13
◁	Jr2'	7
⊙	S0	12

◻ Critical intersection

• Intersection

Intersection count: 3568
Critical intersection: 493 (12.30%)

Flexural Toppling

Lateral limits: 25°
Critical flexural plane : 13 (15.29%)

Direct Toppling

Lateral limits: 25°
Critical direct intersection: 170 (4.76%)
Critical oblique intersection: 436 (12.22%)
Critical base plane : 13 (15.29%)

Figure_13

Click here to access/download;Figure (Color);Fig_13.tif ⬇

Legend:

- Layer trace
- Fracturation pattern
- Thrust
- Minor faults
- Rupture scarp
- RB_X ☆ U-Th sample
- R_2012 ⭐ U-Th sampled *after* Rodríguez-Pérez (2012)
- 500 m

- Middle and Upper Westphalian formations
- Lower and Middle Carboniferous formations
- Rock-avalanche deposits:
  - a - Recent
  - b - Middle
  - c - Early (cemented deposits)
- Earth flow
- Morraine
- Talus scree deposits

Figure_14   Click here to access/download;Figure (Color);Fig_14.tif ⬇

Legend:

- Layer trace
- Fracturation pattern
- Thrust
- Minor fault
- Unconformable Stephanian rocks
- Middle and Upper Westphalian formations
- Lower and Middle Carboniferous formations
- Devonian formations
- Silurian and Lower Ordovician formations
- a — Rock-avalanche deposits: a-recent
- b — b-early
- Talus scree deposits
- Rupture scarp
- Cueva Güerta (cave plane view)
- Páramo stream (seasonal activity)
- Ponor ephemeral stream
- Springs
- RB_X — U-Th sample
- Recent rock-fall date (11-1-2004)
- 500 m

Labels on map: Fresneu, RB_3; RB_10, Páramo river, Saleris, Busbigre, Sabariegos, Villa de Sub, (11-1-2004), N

Figure_15

Click here to access/download;Figure (Color);Fig_15.tif ⬇

A

Backthrust
frontal folds axes

Fold axes
parallel to F_{p1}

270°

114°

90°

Maximum density = 6.32
N = 12 fold axis

180°

F_{p1}_N125-150°E

Villa de Sub

Rock avalanche

Barcaliente Fm.
Alba Fm.
Candamo Fm.
Naranco Fm.

B

F_{p1}_N150°E

S_0_N30°E

S_0_N30°E

S_0_N30°E

Figure_10

Click here to access/download;Figure (Greyscale);Fig_10.tif

Figure_12

A

Entrago:
● Log rk>1 fraction
○ Log rk<1 fraction
N: 4805

Carrea:
■ Log rk>1 fraction
□ Log rk<1 fraction
N: 1172

Cueva Güerta:
◆ Log rk>1 fraction
◇ Log rk<1 fraction
N: 646

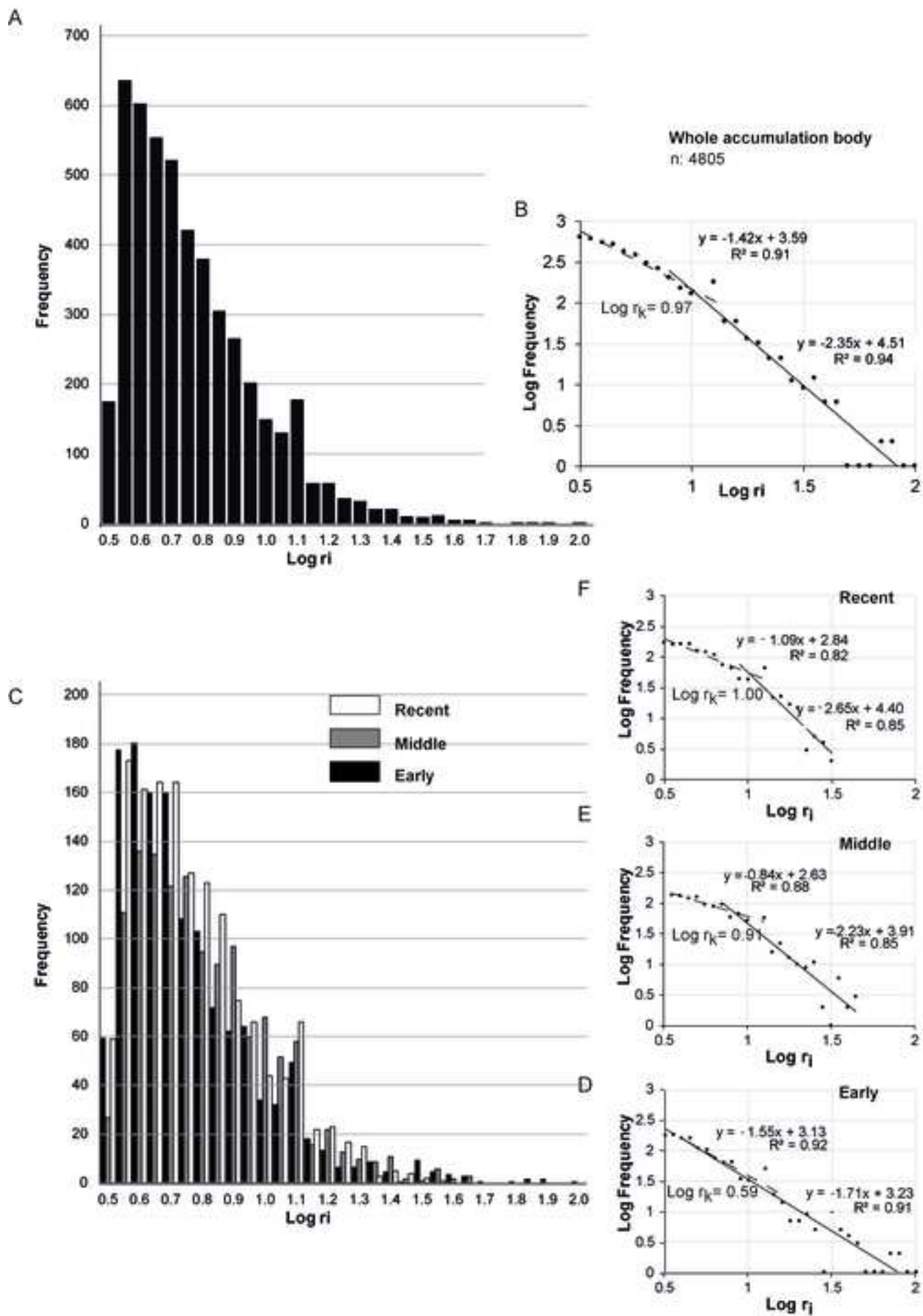Villa de Sub:
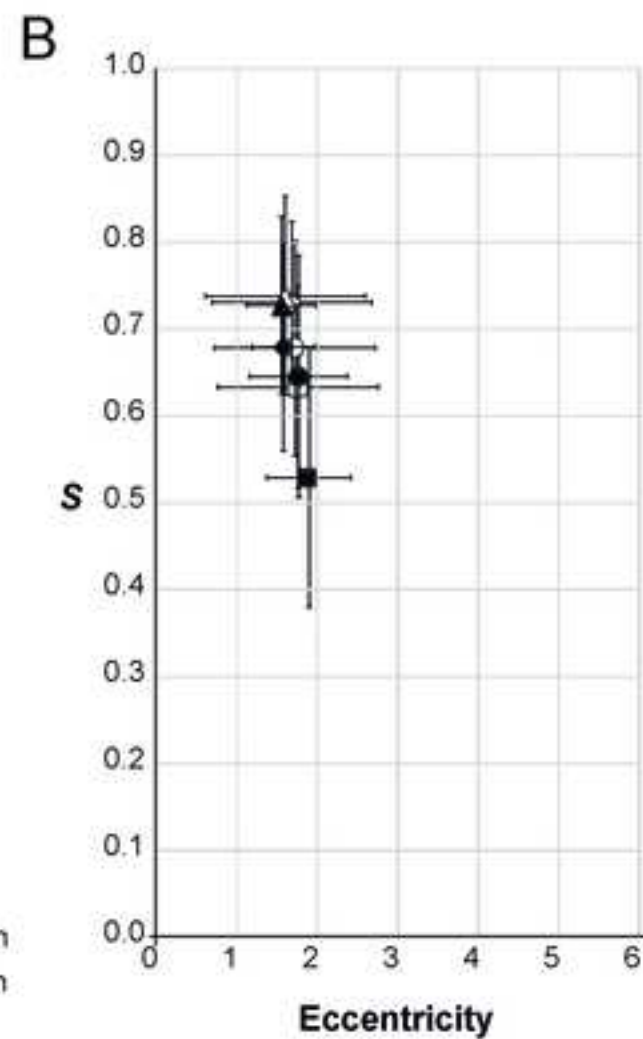▲ Log rk>1 fraction
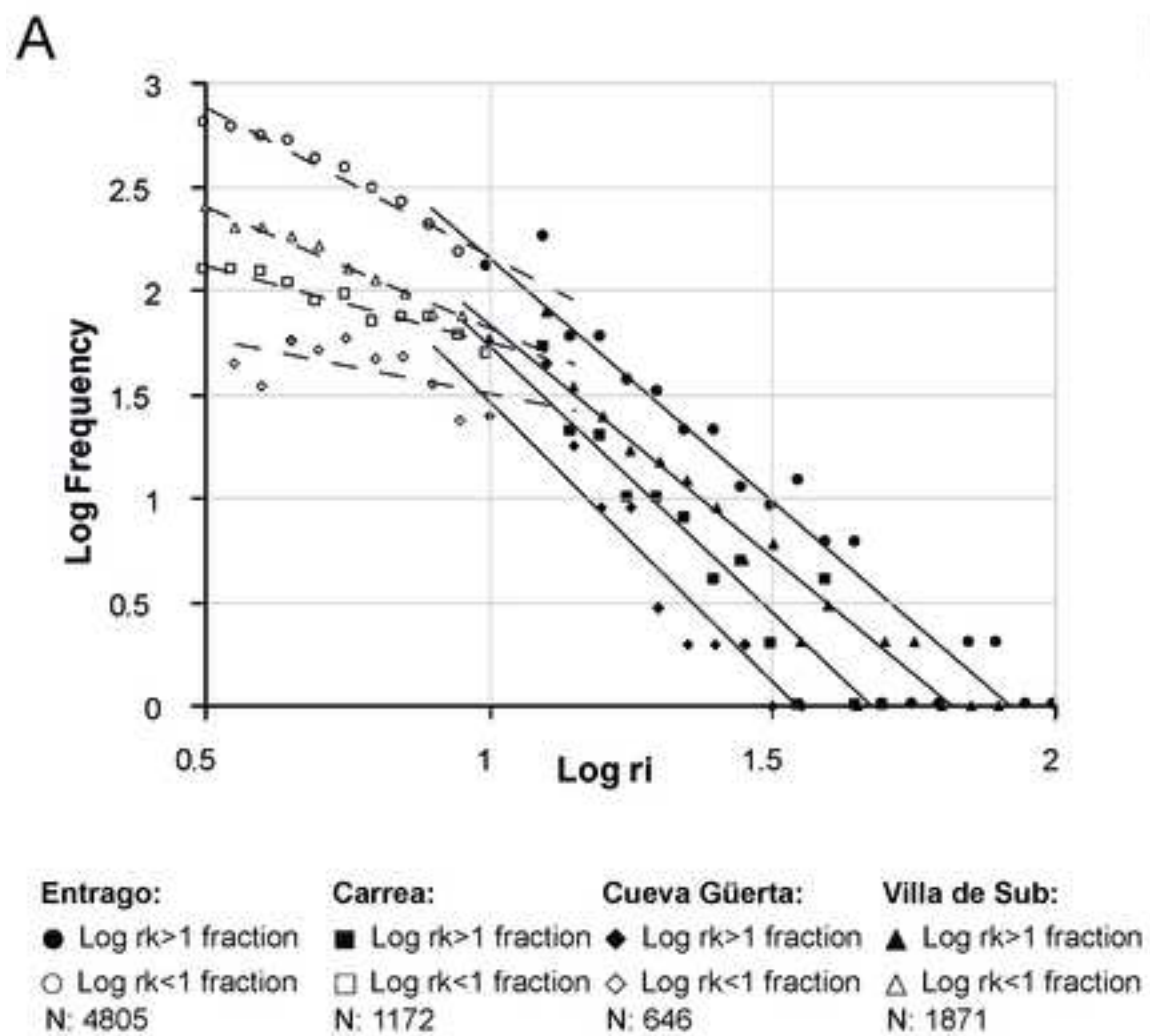△ Log rk<1 fraction
N: 1871

B

Author declaration

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We wish to draw the attention of the Editor to the following facts, which may be considered as potential conflicts of interest, and to significant financial contributions to this work:

The nature of potential conflict of interest is described below:

X No conflict of interest exists.

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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