

Geomorphology

Quaternary landscape evolution in a tectonically active rift basin (paleo-lake Mweru, south-central Africa)

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Highlights

- Explores existence of a Quaternary paleo-lake Mweru, SW East African rift system
- Applies exposure ages of knickpoints, fault analyses and geomorphic investigations
- Cosmogenic nuclides retrieve a landscape history of burial, exposure and denudation
- Faulting and lake-river knickpoints indicate a paleo-lake level at ~1200 m asl
- Lake dynamics linked to recurring neotectonics and regional climate variation

Abstract

Located between the Northern Province of Zambia and the southeastern Katanga Province of the Democratic Republic of Congo, Lakes Mweru and Mweru Wantipa are part of the southwest extension of the East African Rift System (EARS). Fault analysis reveals that, since the Miocene, movements along the active Mweru-Mweru Wantipa Fault System (MMFS) have been largely responsible for the reorganization of the landscape and the drainage patterns across the western branch of the EARS. To investigate the spatial and temporal patterns of fluvial-lacustrine landscape development, we determined in-situ cosmogenic ^{10}Be and ^{26}Al using Accelerator Mass Spectrometry. A total of twenty-six quartzitic bedrock samples were collected from knickpoints across the Mporokoso Plateau (south of Lake Mweru) and the eastern part of the Kundelungu Plateau (north of Lake Mweru). Samples from the Mporokoso Plateau and close to the MMFS provide evidence of temporary burial. By contrast, surfaces located far from the MMFS appear to have remained uncovered since their initial exposure as they show consistent ^{10}Be and ^{26}Al exposure ages ranging up to ~830 ka. Reconciliation of the observed burial patterns with morphotectonic and stratigraphic analysis reveals the existence of an extensive paleo-lake during the Pleistocene. Through hypsometric analyses of the dated knickpoints, the potential maximum water level of the paleo-lake is constrained to ~1200 m asl. High denudation rates (up to ~40 mm ka^{-1}) along the eastern Kundelungu Plateau suggest that footwall uplift, resulting from normal faulting, caused rapid river incision, thereby controlling paleo-lake drainage. The complex exposure histories recorded by ^{10}Be and ^{26}Al may be explained because of lake water-level fluctuations caused by active normal faulting along the MMFS coupled with intense climate variations across southeastern Africa.

1 Quaternary landscape evolution in a tectonically active rift basin (paleo- 2 lake Mweru, south-central Africa)

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20 **Keywords:** Landscape evolution; Morphotectonic Analysis; Terrestrial cosmogenic
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- 23 • Explores existence of a Quaternary paleo-lake Mweru, SW East African rift system
- 24 • Applies exposure ages of knickpoints, fault analyses and geomorphic investigations,
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- 30 — Applies cosmogenic nuclide dating, fault analysis and geomorphic investigations
- 31 — Cosmogenic data show spatial-temporal patterns of burial, exposure and denudation

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- 32 — Faulting and lake river knickpoints indicate a paleo lake level at ~1200 m asl
- 33 — Lake development linked to active faulting and regional SE Africa climate variation
- 34 ● ¹⁰Be and ²⁶Al dating reveals an extended paleo lake Mweru during the Quaternary
- 35 ● Morphotectonic analysis indicate a paleo lake level at ~1200 m asl
- 36 ● Two waterfalls have exceptionally high minimum exposure ages of 524 and 833 ka
- 37 ● Normal faulting forces increased river incision NW of paleo lake Mweru
- 38 ● Striking differences in denudation rates among the surrounding plateaus

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40 Abstract

41 Located between the Northern Province of Zambia and the southeastern Katanga Province of
42 the Democratic Republic of Congo, Lakes Mweru and Mweru Wantipa are part of the southwest
43 extension of the East African Rift System (EARS). Fault analysis reveals that, since the
44 Miocene, ~~the~~ movements ~~at~~ along the active Mweru-Mweru Wantipa Fault System (MMFS)
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46 across the western branch of the EARS. ~~In order to~~ To investigate the spatial and temporal
47 patterns of fluvial-lacustrine landscape development, we determined in-situ cosmogenic ^{10}Be
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56 knickpoints, the potential maximum water level of the paleo-lake is constrained to ~1200 m asl.
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58 footwall uplift, resulting from normal faulting, caused ~~fast~~ rapid river incision, thereby
59 controlling paleo-lake drainage. The complex exposure histories recorded ~~by~~ ^{10}Be and ^{26}Al
60 may be explained ~~as a result of~~ because of lake water-level fluctuations caused by active normal
61 faulting along the MMFS coupled with intense climate variations across southeastern Africa.

62 1. Introduction

63 The East African Rift System (EARS) is one of Earth's best studied active intracontinental
64 rifts (e.g., Ebinger, 1989; Delvaux, 1991; Delvaux et al., 1992; Ring, 1994; Schlüter, 1997;
65 Chorowicz, 2005; Braile et al., 2006; Stamps et al., 2008; Macgregor, 2015). The combination
66 of the EARS length (> 3,000 km) and longevity (active throughout the Neogene, ~25 Ma)
67 provides a unique opportunity to study the evolution of continental rifting; from initial crustal
68 break-up (via normal faulting) to incipient oceanic rifting and, eventually, the opening of future
69 oceans. Overall, the EARS can be considered to have had a dominant control on the landscape
70 evolution of eastern Africa during the last ~30 Ma (e.g., Chorowicz, 1989, 2005; Macgregor,
71 2015). The northern and central parts of the EARS have been previously investigated and
72 linkages between tectonic activity, climatic variations and (paleo) lake formation have been
73 established (Bergner et al., 2009). However, there are limited constraints on the landscape
74 evolution of the Western Branch of the EARS.

75 The interplay of faulting, climatic and fluvial processes have resulted in the development
76 of a series of lakes that extend over a thousand kilometers along the EARS (Fig. 1 inset). The
77 existence of large and deep paleo-lakes within the Western Branch during the Plio-Pleistocene
78 (e.g. paleo-lakes Turkana, Edward-Albert, Obweruka, Bangweulu, Magadi, Thamalakane and
79 Tanganyika) is well established (Williamson, 1978; Hillaire-Marcel et al., 1986; Burrough and
80 Thomas, 2008; Cotterill and de Wit, 2011; Danley et al., 2012; Cohen et al., 2016).

81 Our study area lies to the southwest of Lake Tanganyika, straddling the border between the
82 Democratic Republic of Congo (DRC; Katanga Province) and Zambia (Northern Province; Fig.
83 1). This area (Lake Mweru) is part of the ~~fast-spreading~~~~fast-spreading~~ Western Branch of the
84 EARS, and it is characterized by an ENE-WSW trending basin-and-range topography that
85 intersects the Tanganyika Rift System perpendicularly (Fig. 1). These typical horst and graben
86 structures formed due to normal faulting along the Mweru-Mweru Wantipa Fault System

87 (MMFS) and are the seismically most active faults of central east Africa. Two of these graben
88 structures host the high-altitude present-day lakes of Lake Mweru (917 m asl) and Lake Mweru
89 Wantipa (932 m asl; Delvaux and Barth, 2010; Daly et al., 2020). The lakes are bounded to the
90 northwest and southeast by two high plateaus, Kundelungu and Mporokoso, respectively
91 (Mondeguer et al., 1989; Tack et al., 2003; Daly et al., 2020; Fig. 1).

92 Active faulting has been proposed previously as one of the key controls in shaping of river
93 catchments and the landscape southwest of Tanganyika (Gumbrecht et al., 2001; Haddon and
94 McCarthy, 2005; Flügel et al., 2017; Daly et al., 2020). However, detailed geomorphological
95 and tectonic studies in the area remain scarce, with much of the literature having focused on
96 first-order physiographic characteristics of the rift to infer tectonic correlations between these
97 structures and the EARS (e.g., Mohr, 1974; Tiercelin et al., 1988; Mondeguer et al., 1989;
98 Strecker et al., 1990; Delvaux, 1991; Chorowicz, 2005; Kipata et al., 2013). Yet knickpoint
99 creation is not only correlated with tectonic activity (normal faulting) and differential
100 denudation, but may also be associated with changes in base-level and sea-level, as well as
101 climatic variations (Whipple and Tucker, 1999; Whipple et al., 2000). It has been argued that
102 climatic extremes within such ~~fast-spreading~~ fast-spreading rifts may have played a key role in
103 controlling lake-level fluctuations (Lavayssiere et al., 2019). The paleo-lakes Manonga
104 (Tanzania) and Obweruka (Uganda) are considered primary examples of climate-controlled
105 lakes in the EARS (Harrison, et al., 1996; Van Damme and Pickford, 2003). However, without
106 geochronologic dates to constrain landscape evolution rates in the Western Branch, determining
107 the controlling factors acting on the landscape remains challenging. A secondary, albeit key,
108 consideration of this study is that large knickpoints are important biogeographic controls, acting
109 as natural barriers to species dispersal, especially fish. These landforms often result in divergent
110 evolution between upstream and downstream populations of biota (Cotterill and de Wit, 2011;

111 Schwarzer et al., 2011). Thus, direct age estimates of knickpoints may inform on
112 biogeographical histories of the region.

113 Dixey (1944) inferred a “greater” Lake Mweru based primarily on lacustrine deposits that
114 are abandoned at ~1030 m asl, about 100 m higher than the present-day lake level. Moreover,
115 Bos et al. (1995, 2006) suggested that patches of sands along the present-day Zambian (southern
116 and southeastern) shores of Lake Mweru may indicate a migration of the Luapula River (Fig.
117 1). This is evidenced by sedimentary deposits that lie more to the west than its current position
118 (Bos et al., 1995). Several studies propose that the initial Lake Mweru formed a large
119 impoundment that extended over the lower part of the Northern Province of Zambia. No
120 fieldwork and/or geomorphological analysis have hitherto explored the precise extent and
121 duration of a larger paleo-lake Mweru (Dixey, 1946; Bos et al., 1995; Cotterill and de Wit,
122 2011).

123 This study attempts to identify and, where possible, quantify key factors and mechanisms
124 that control the landscape evolution proximal to Lake Mweru. By doing so, we aim to test
125 whether a precursor of Lake Mweru formed a big impoundment, inundating a larger portion of
126 the Northern Province of Zambia at its lower elevations. Collectively, our study aims to explore
127 the impact of normal fault growth on the formation of the paleo-lake and the drainage around
128 the present-day Lake Mweru by combining tectonic and geomorphologic analyses of the study
129 area with the application of terrestrial cosmogenic nuclides to dating and the magnitude of
130 denudation by combining tectonic and geomorphologic analysis of the study area with terrestrial
131 cosmogenic nuclides dating method. By interpreting a network of surface exposure dates of key
132 landforms (river knickpoints, fault scarps, and river bedsriverbeds) across the two high plateaus
133 (Mporokoso and Kundelungu Plateaus) that surround and delimit the current lake, we deduce
134 the age of formation of the paleo-lake. By doing so, we constrain the extent and depth of the
135 paleo-lake Mweru and estimate its life span, andspan and explore possible mechanisms that

136 reduced its Pleistocene high stand. Direct geochronological derivations of the timing of the
137 onset of the paleo-lake - and its tenure - contribute new information toward resolving the
138 landscape evolution of the southwestern part of the Western Branch. Moreover, constraining
139 the tenure of this Late Cenozoic depocenter reveals important information relating to the
140 drainage evolution of the Congo-Kalahari Watershed during the Pleistocene (Flügel et al., 2015,
141 2017).

142 2. Geomorphic and Geologic Setting

143 The MMFS has a length of ~ 400 km, a width of ~ 200 km and is divided into eastern and
144 western parts. The eastern part is characterized by an elongated ENE-WSW trend, almost
145 perpendicular to the NW-SE trend of the Mpulungu basin (southern Lake Tanganyika; Tiercelin
146 and Lezzar, 2002). Small and parallel grabens form shallow depressions, characterized by
147 wetland environments (Mondeguer et al., 1989). To the west, two major troughs with NNE-
148 SSW trend form the two main shallow lakes (Lakes Mweru and Mweru Wantipa). The majority
149 of the faults follow a NNE-SSW trend, while few faults that mainly confine the end of the basins
150 have a vertical trend of WNW-ESE (Mondeguer et al., 1989). The deviation in the fault trend
151 near the Mpulungu basin results from the competency ~~contrast with~~ ~~of~~ the relatively stable
152 Bangweulu ~~block~~ Block (Mondeguer et al., 1989; Fig. 1). The rotation of the extension direction
153 reactivated earlier dip-slip faults, since strain accumulated in the same pre-Pleistocene inherited
154 crustal structures (Ring, 1994; Morley, 2002; Saria et al., 2014). Furthermore, earthquake fault
155 plane solutions from the area indicate an extensional displacement around the WNW axis
156 (Delvaux and Barth, 2010). Recent modeling studies suggest that the extension direction
157 changes from ~60° to 90°, while a left-lateral motion is applied on two domains with NE-E
158 oriented weaknesses in between them (Molnar et al., 2019 and references therein).

159 Lake Mweru (situated at ~9° S and ~29° E) forms part of the south-eastern extension of
160 the Congo Basin, being fed from the south by the Luapula River and drained to the northwest

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161 by the Luvua River (Fig. 1). The drainage of the Lake Mweru sub-basin is mostly sub-dendritic,
162 representing the interaction of rivers flowing on Precambrian basement and regional faulting
163 (Deffontaines and Chorowicz, 1991, Flügel et al., 2015). The extensive delta of the Luapula
164 River suggests rapid denudation of the high plateaus between Lake Mweru and Lake
165 Bangweulu (Fig. 1). In addition, the accumulation of Quaternary sediments with a thickness of
166 400 m unconformably overlying the Neoproterozoic basement (Bos et al., 2006; Daly et al.,
167 2020) can be interpreted as further evidence of rapid denudation of the surrounding highlands.
168 Quaternary sediments are absent from Kilwa Island, a Neoproterozoic clastic rock outcrop,
169 north of the delta (Shudofsky, 1985; Tiercelin and Lezzar, 2002; Daly et al., 2020). In the north,
170 the outflowing Luvua River runs through a steep valley path with several large waterfalls,
171 suggesting rapid incision (Flügel et al., 2017). The Kalungwishi River, a major tributary, feeds
172 Lake Mweru from the east. This river drains its own highland sub-basin and has several large
173 knickpoints on its course. The inflowing rivers allow the lake to maintain a surface area of ~
174 5100 km² ~~year-round~~year-round (Bos et al., 2006).

175 Along the eastern shore of Lake Mweru, a ~~an~~ ~10 m high beach terrace indicates an actively
176 uplifted coastline controlled by a long major fault line (Fault 16 in Fig. 1) across the southern
177 borders of the Kundelungu Plateau (Daly et al., 2020). The southeastern border of the lake is
178 delimited by a major fault (Fault 23 in Fig. 1) parallel to the trend of the Mporokoso Plateau,
179 creating Lake Mweru that is 27 m at its deepest (Bos et al., 2006). This rectangular lake is
180 surrounded by uplifted rift margins, ~~and with~~ the lake geometry and bathymetry ~~is being~~
181 controlled by ~~subsided~~ basins subsidence. The structural control of this setting is described in
182 further detail below.

183 Southeast of Lake Mweru, a large basin of sub-horizontal sedimentary cover (Mporokoso
184 Plateau) is developed onto the Archean-Paleoproterozoic cratonic Bangweulu ~~block~~Block
185 (Mondeguer et al., 1989; De Waele et al., 2009; Fig. 1). The Mporokoso Plateau consists mostly

186 of undeformed fluvial and lacustrine sediments (De Waele and Fitzsimons, 2007). Unrug (1984)
187 characterized the Mporokoso Plateau as the late Palaeoproterozoic to late Mesoproterozoic pre-
188 Katangan succession to the northwest and northeast of the Bangweulu Block. A thick
189 sedimentary bedrock succession, called the Kundelungu Plateau, forms the half graben structure
190 that delimits the lake to the northwest (Fig 1). The Kundelungu Plateau is a part of the larger
191 Neoproterozoic (<883 Ma to ~573 Ma; Master et al., 2005) Katangan Supergroup, ~~and it~~
192 ~~consists of comprising~~ carbonatic-carbonate and siliciclastic sequences which were deposited in
193 a wider basin. The bedded red sand- and siltstones of the Kundelungu Plateau are exposed at
194 the northwest corner of Lake Mweru due to incision along the Luvua River (Kipata et al., 2013).

195 The interplay of faulting and erosion in the broader Lake Mweru region has resulted in two
196 relatively flat but vertically offset surfaces: the Lake Mweru valley bottom and the surrounding
197 plateaus. In general terms, the valley bottom (~ 900 m asl) is approximately 600 m lower than
198 the flat plateau tops (~ 1500 m asl). The amagmatic character of the tectonism, combined with
199 an indistinct sedimentation sequence across the southwestern extension of the EARS, does not
200 allow precise dating of the initiation of faulting in the study area. The formation of the extended
201 denudational surface of the Central African Plateau is estimated at around late Miocene to early
202 Pliocene times (Daly et al., 2020). The absence of Neogene sedimentation across the Central
203 African basin suggests that the tectonic activity must have been initiated after, or during, the
204 uplift of the Central African Plateau, thereby constraining the onset of the MMFS to the late
205 Pliocene - early Pleistocene (~2.6 Ma; Daly et al., 2020).

206 **3. Material and Methods**

207 *3.1. Sampling and Sample Grouping*

208 In this study, we aim to provide temporal control to derive rates for landscape evolution.
209 We focus on surface exposure dating of geomorphic markers using two cosmogenic
210 radionuclides (^{10}Be , ^{26}Al ; the intended inclusion of stable ^{21}Ne did not provide meaningful

211 results, see Appendix). ~~In order to~~To ensure sufficient sample material (i.e., quartz) to undertake
212 surface exposure dating, the field sampling mostly targeted bedrock quartzites due to their
213 abundance in quartz. Sampling sites were located at or near waterfalls (knickpoints) as these
214 are sites of exposed rock and considered key features in a river's development. Samples were
215 taken from two broader areas, the Mporokoso Plateau and the northeastern Lake Mweru (Fig
216 1). Twenty-one samples, from seven waterfalls, were collected across the Mporokoso Plateau
217 (Table 1), mostly from vertical or subvertical (45-90°) surfaces (Fig. 2A), downstream of the
218 present-day knickpoint position. Where possible, samples were also taken from the waterfalls
219 themselves to determine the minimum exposure age of the knickpoint at its current position
220 (Fig. 2B, 2C). Dating two or more samples at different distances from the present knickpoint
221 enables us, in principle, to estimate knickpoint retreat rates (Fig. A1). ~~In order to~~To determine
222 maximum denudation rates, samples from horizontal surfaces (from above and below the
223 knickpoints) were also collected (Table 1; Fig. 2B).

224 Five additional quartz-rich samples were obtained from the northwest shore of Lake Mweru:
225 two from horizontal and two from vertical surfaces located along river channels (Fig. 2D) and
226 one directly from the fault that bounds the MMFS to the north (Fig. 2E). See Table 1 for sample
227 information and the Appendix (Fig. A1) for a more detailed description of the sampling process.

228 Based on their location relative to the MMFS, we subdivide our samples into three main
229 groups: Group A samples are from south and southeast of Lake Mweru within the MMFS,
230 Group B samples are from southeast of Lake Mweru but situated outside the MMFS, and Group
231 C samples derive from north of Lake Mweru, along the northern margin of the MMFS (Table
232 1; Fig. 1).

233 3.1.1. Group A

234 The ~25 m high Kundabikwa Waterfalls (elevation ~1043 m asl) have incised quartzitic
235 bedrock to form one of the two main knickpoints along the Kalungwishi River. Three pairs of

236 vertical and horizontal samples (KUN01/02, KUN03/04 and KUN05/06) were taken from the
237 right bank at different distances downstream of the present waterfalls. An additional sample
238 (KUN07) was collected from the ~~river bank~~riverbank immediately above the waterfalls.

239 The Lumangwe Waterfall (~1159 m asl), located ca. 37 km upstream of the Kundabikwa
240 Waterfalls, forms the most prominent knickpoint along the Kalungwishi River, with a height of
241 ~40 m and a width of ~160 m (Fig. 2C). At Lumangwe Waterfall, the main bedrock is
242 interbedded quartzite, with layers of red siltstones. Due to the vegetation density and the large
243 amount of water, sampling this waterfall was challenging. Therefore, only one siltstone sample
244 from a vertical face (LUM01) and a pair of quartzitic samples from vertical (LUM02) and
245 horizontal (LUM03) surfaces were taken. Due to the very low amount of appropriately sized
246 quartz grains, LUM01 could not be analyzed.

247 The cascade of the Ntumbachushi Waterfalls (~1160 m asl) is about 30 m high and is located
248 on the Ng'ona River. Three samples were collected from these waterfalls, of which NTU01 and
249 NTU03 were taken from the right vertical bank downstream of the current knickpoint, while
250 NTU02 was collected above NTU01 from the corresponding horizontal bank.

251 The Mumbuluma Waterfalls (~1186 m asl) are situated on the Mumbuluma River and
252 cascade down over two discrete steps. They will be denoted Mumbuluma I Waterfalls hereafter
253 to distinguish them from the equally named waterfall on the Luongo River (section 3.1.2).
254 MUM01 and MUM04 were collected from a vertical and a horizontal surface, respectively, of
255 the top cascade, while the samples MUM02 (horizontal) and MUM03 (vertical) were taken
256 from the lower step of the waterfalls.

257 3.1.2. Group B

258 The Lupupa Waterfall is located on the Mukubwe River and has a height of approximately
259 90 m. The highest set of cascades is located at about 1360 m asl. Due to difficulties associated

260 with the steepness of the waterfall, we only managed to collect one sample (LUP01) close to
261 the top of the vertical cliff.

262 The Luongo River is one of the dominant rivers of the Northern Province in Zambia. We
263 collected two samples from inclined surfaces of the Mumbuluma Waterfall (hereafter denoted
264 Mumbuluma II to distinguish it from the falls on the Mumbuluma River; section 3.1.1.), which
265 lies at ~1370 m asl with ~10 m height.

266 The Lunzua Waterfalls form a series of cascades along the Lunzua River. The waterfalls
267 are close to the town of Mpulungu at the southern shore of Lake Tanganyika (Fig. 1) and are
268 situated at ~1300 m asl. Two vertical samples (LUZ01 and LUZ02) were collected from the
269 banks of the Lunzua River downstream of the cascades.

270 3.1.3. *Group C*

271 Due to the extreme inaccessibility of waterfalls caused mainly by vegetation along the
272 northwestern side of Lake Mweru, no samples from waterfalls were collected in that area.
273 Rather, they were taken from ~~river beds~~riverbeds and banks comprising mostly quartzitic
274 bedrock. MWE01 derived from an almost vertical (80°) face that forms the surface expression
275 of a normal fault scarp (Fig. 1; Fig. 2E). Two samples (ME04, ME05) were collected from the
276 vertical walls of the gorge along the Luvua River, close to where it discharges from Lake Mweru
277 (Fig. 1; Fig. 2D). The samples ME06 and ME09 were collected from horizontal bank surfaces
278 along the Misefwe and Lwilwa rivers, two small tributaries northwest of Lake Mweru.

279 3.2. *Sample Processing*

280 Samples were crushed and sieved to 250–500 µm. Quartz grains were separated by the
281 standard methods of heavy liquid and Frantz magnetic separation (Kohl and Nishiizumi, 1992).
282 ~~In order to~~To dissolve all non-quartz minerals, samples were treated with dilute HCl and H₂SiF₆
283 (Brown et al., 1991). Afterwards, HF was used to remove any contribution of meteoric ¹⁰Be by

284 partially dissolving the quartz grains. A small fraction from each sample (~2 g) was kept for
285 ^{21}Ne analyses, while the remaining ~25-50 g were used for ^{10}Be and ^{26}Al analyses. Preparation
286 and processing of the samples took place at the Helmholtz-Zentrum Dresden-Rossendorf
287 (HZDR) following a modified version of the method described by Merchel and Herpers (1999)
288 and at the University of Potsdam following the sample preparation manual of the UC Santa
289 Barbara Cosmogenic Nuclide Preparation Facility
290 (http://www.geog.ucsb.edu/~bodo/pdf/bookhagen_chemSeparation_UCSB.pdf), which is
291 based on modifications of previous studies (e.g., Kohl and Nishiizumi, 1992; von Blanckenburg
292 et al., 2004). The samples from the Kundabikwa Waterfalls (KUN) were prepared at HZDR,
293 while the rest of the samples were prepared at University of Potsdam. For the radionuclide
294 extraction, a known amount (~0.3 mg) of ^9Be carrier was added to each sample, whilst ~1 mg
295 Al carrier was added only to the blank samples (Table A1). Concentrated HF was used for
296 digestion of the samples. After evaporation of the HF and the addition of HClO_4 , ICP-AES
297 (Inductively Coupled Plasma Atomic Emission Spectroscopy) or ICP-MS (Inductively Coupled
298 Plasma Mass Spectrometry) measurements were done from aliquots, which were dissolved in
299 HCl, in order to quantify the total Al concentration (Appendix Table A1). Be and Al were
300 separated via ion exchange columns and precipitated as hydroxides. The last step before the
301 target pressing was the ignition to oxides (900-1000 °C). Be isotope ratios were measured by
302 Accelerator Mass Spectrometry (AMS) at the DREAMS facility of HZDR (Rugel et al., 2016;
303 Table 2) and the National Laboratory of Age Determination of the Norwegian University of
304 Science and Technology (NTNU), Trondheim (Seiler et al., 2018; Table 2). Al isotope ratio
305 measurements were performed at HZDR (Rugel et al., 2016; Table 2) and at the French national
306 facility Accélérateur pour les Sciences de la Terre, Environnement, Risques (ASTER,
307 CEREGE, Aix-en-Provence; Arnold et al., 2010; Table 2). All processing values are provided
308 in the Appendix (Table A1) and are one to three orders of magnitude lower than sample values.

309 3.3. Calculation of Exposure and Burial Ages and Denudation Rates

310 Waterfalls are dynamic systems that undergo geomorphological changes through time. The
311 rate at which knickpoints migrate upstream along a river is dependent on a combination of
312 lithology, elevation, morphology, climatic conditions, and tectonic activity (Howard et al.,
313 1994; Whipple and Tucker, 1999; Whipple et al., 2000; Brocklehurst, 2010). Their complexity
314 means waterfalls can be a challenge to date, even with cosmogenic nuclides. Nevertheless,
315 useful parameters such as denudation rates, periods of burial, minimum exposure ages and
316 sequential exposure can be estimated for knickpoints and their surrounding landscape.

317 To calculate exposure ages and denudation rates, sea level high latitude (SLHL) spallogenic
318 production rates of 4.01 atoms g⁻¹ a⁻¹ for ¹⁰Be and 27.93 atoms g⁻¹ a⁻¹ for ²⁶Al were used
319 (Borchers et al., 2016). Minimum ages and maximum denudation rates were calculated with
320 CosmoCalc 3.0 (Vermeesch, 2007), using Lal (1991) scaling factors and default values for all
321 parameters except the SLHL production rates. The density used for the calculations is 2.65 g
322 cm⁻³ for all samples. Values were corrected according to sample thickness (1-10 cm) and
323 geometric shielding. All ¹⁰Be/⁹Be ratios were normalized to the in-house standard material
324 “SMD-Be-12” with a weighted mean value of $(1.704 \pm 0.030) \times 10^{-12}$ (Akhmadaliev et al., 2013).
325 The “SMD-Be-12” has been cross-calibrated to the NIST SRM 4325 standard, which has a
326 ¹⁰Be/⁹Be ratio of $(2.79 \pm 0.03) \times 10^{-11}$ (Nishiizumi et al., 2007). ²⁶Al/²⁷Al ratios measured at
327 DREAMS were normalized to the in-house standard “SMD-Al-11”, with a ²⁶Al/²⁷Al ratio of
328 $(9.66 \pm 0.14) \times 10^{-12}$ (Rugel et al., 2016), while the Al ratios measured at ASTER were
329 normalized to “SM-Al-11” with a ²⁶Al/²⁷Al ratio of $(7.401 \pm 0.064) \times 10^{-12}$ (Arnold et al., 2010).
330 Both Al standards are traceable via cross-calibration to the same primary standards (MB04-A,
331 MB04-B, MB04-D) from a ²⁶Al round-robin exercise (Merchel and Bremser, 2004). For
332 samples with ¹⁰Be and ²⁶Al ages agreeing within error limits, error-weighted mean ages were
333 also calculated.

334 Since the attenuation length of terrestrial cosmogenic nuclide (TCN) production is smaller
335 at low angles than in a vertical direction (Dunne et al., 1999), the TCN concentration decreases
336 faster perpendicularly beneath an inclined surface than beneath a horizontal surface. This ~~has~~
337 ~~to~~must be taken into account when calculating denudation rates of inclined or vertical surfaces
338 and, therefore, a slope dependent correction (Hermanns et al., 2004) was applied to such
339 surfaces.

340 In general, discordance between ^{10}Be and ^{26}Al ages may be due to long exposure (when ^{26}Al
341 production equals decay, i.e. after a few ^{26}Al half-lives), denudation which has not been taken
342 into account, or shielding from cosmic rays after initial exposure (e.g. Lal, 1991; Gosse and
343 Phillips, 2001; Goethals et al., 2009). To reveal complex exposure histories, ^{10}Be concentrations
344 can be plotted against $^{26}\text{Al}/^{10}\text{Be}$ ratios. In such two-nuclide plots, samples which lie between
345 the “steady state denudation line” and the “constant exposure line” have experienced simple
346 exposure histories, i.e. a combination of surface exposure and denudation. In contrast, samples
347 plotting beneath the steady state field indicate burial after initial exposure. The calculation of
348 burial ages (Lal, 1991) is based on the assumption that a surface has once been irradiated by
349 cosmic rays up to steady ~~state, and state and~~ was later buried until the present. This assumption
350 is obviously not correct in our study, as all samples were taken from presently exposed surfaces.
351 If such samples indicate burial, they must have been re-exposed sometime in the past, and only
352 minimum burial ages can be calculated from them.

353 3.4. Normal Fault Analysis

354 We used a Shuttle Radar Topography Mission (SRTM) digital surface model (DSM),
355 Google EarthTM imagery, and the ArcGIS software (version 10.6) to map the traces of 63 normal
356 faults in the area, from west of Lake Mweru to the southern shorelines of Lake Tanganyika (Fig.
357 1). This area largely includes faults of the MMFS, while at its eastern edge it comprises elements
358 of the EAR (Fig. 1).

359 We focused our analysis on two fault parameters that, collectively, provide important
360 information on the fault system's activity and growth: the fault length (L) and the fault
361 displacement (D). Fault length represents an important parameter in estimating the seismic
362 potential (including earthquake magnitude and single-event displacement) on each studied fault
363 (Wells and Coppersmith, 1994; Wesnousky, 2008). It should be noted that several of the
364 identified faults contain numerous parallel or sub-parallel strands (e.g. faults 30, 38, 44, 46, 49,
365 etc. in Fig. 1) or along-strike segments (e.g. 1, 2, 7, 16, 43, etc.) which are either hard or soft
366 linked (Walsh and Watterson, 1991). Here, these elements are thought to represent a single
367 coherent fault that ruptures along its entirety; however, it remains possible that individual
368 earthquakes rupture these faults or fault segments only partially. The maximum vertical
369 displacement (or throw) on each normal fault derives by averaging numerous (>10) scarp height
370 measurements from fault perpendicular topographic profiles collected proximal to the fault's
371 centre. Fault lengths and displacements represent direct measurements drawn on the DSM and
372 are presented in Table A2 together with the faults' geometries. Indirect earthquake attributes
373 (e.g. earthquake magnitude, average recurrence interval, etc.) associated with each studied fault
374 derive from Wells and Coppersmith's (1994) and Wesnousky's (2008) empirical relations and
375 are also included in Table A2 (see caption of Table A2 in the Appendix for details).

376 Measurement of active fault lengths and displacements can be subject to significant
377 uncertainties (Wesnousky, 2008; Mouslopoulou et al., 2012; Nicol et al., 2016a, 2020a). This
378 is because fault scarps are prone to denudation and/or burial, especially at fault tips, where
379 displacements are often too small to be detected with conventional mapping methods (such as
380 aerial photo or DSM analysis, field mapping, etc.; Begg and Mouslopoulou, 2010). In this study,
381 fault lengths and displacements should be considered as minimum values as fault scarps of < 2
382 m are not resolvable on the available DSM, and also because fault scarps of any size may be
383 partly or entirely modified by denudation and/or burial (see Nicol et al., 2020a for detailed
384 discussion on sampling biases). Rifting across the MMFS is thought to have initiated at about

385 2.6 Ma (late Pliocene-early Pleistocene; Tiercelin and Lezzar, 2002; Molnar et al., 2019; Daly
386 et al., 2020), thus, fault displacement rates are calculated over this time-period (~2.6 Ma) (Table
387 A2).

388 3.5. Digital Topography Analyses

389 We analyzed selected domains of the 30-m NASADEM (NASA JPL, 2020). We have
390 delineated the catchment of Lake Mweru using standard procedures implemented in
391 TopoToolbox (Schwanghart and Scherler, 2014). Elevation lows (pits) were filled, a
392 hydrological-corrected DEM has been calculated, and the catchment extents were visually
393 verified. Our catchment extent, using the higher resolution NASADEM data, is similar to that
394 calculated in the HydroBASINs dataset (Lehner and Grill, 2013). The catchment extent was
395 used to extract the hypsometric curve, showing the surface area for each elevation bin. Further,
396 we identified river knickpoints using previously published approaches (Neely et al., 2017). This
397 entailed deriving longitudinal river profiles, converting them to Chi coordinates, and identifying
398 knickpoint lips and bases based on positive or negative distance above a best-fit Chi profile
399 (Neely et al., 2017). Chi profiles are area-normalized profiles where the distance coordinate has
400 been normalized by an averaged river profile following an exponential function (Perron and
401 Royden, 2012). The resulting profile, when in steady state, will follow a straight line. We
402 analyze profile deviation above and below an averaged line to identify knickpoints. More
403 detailed analysis steps are described in Neely et al. (2017). ~~In order to~~To avoid small
404 knickpoints and remove noise inherent in the DEM, we focus on knickpoints with magnitudes
405 (i.e., distances from the average Chi profile line) exceeding 30 m. Field observations suggest
406 that major waterfalls associated with past lake-level highstands are generally higher than 30 m.

407 4. Results

408 We present our results as three components, starting with the determinations of the
409 terrestrial cosmogenic nuclides. Second, the findings of tectonics analyses are reported,

410 summarizing the fault geometries and kinematics of the faulted topography. Third, we present
411 a geomorphic analysis of northeast Zambia and the adjacent Katanga Province. In the
412 subsequent section 5 we will focus on reconstructed scenarios informed from the TCN results,
413 which are classified according to respective landscape history, including ~~elevation~~elevation,
414 and contrasting tectonic regimes.

415 4.1. Terrestrial Cosmogenic Nuclides

416 While the ^{10}Be and ^{26}Al results indicate extended periods of burial for many samples (see
417 section 4.1.1.), there is no straightforward way to interpret the ^{21}Ne data along with ^{10}Be and
418 ^{26}Al . Due to their inconclusive nature, we do not discuss them further but present and describe
419 them in the Appendix (Table A3 and Fig. A3, A4). Below we present the ^{10}Be and ^{26}Al results
420 (shown in Table 2) by sample groups.

421 4.1.1. ^{10}Be and ^{26}Al minimum exposure ages

422 4.1.1.1. Group A

423 Vertical samples KUN01 and KUN04 from Kundabikwa Waterfalls yield ^{10}Be minimum
424 ages of ~510 and ~580 ka, respectively, while ^{26}Al minimum ages are younger, ~240 and ~360
425 ka. The horizontal samples KUN03, KUN05 and KUN07 show consistently younger minimum
426 ^{10}Be ages than the vertical samples (~320-370 ka) and ^{26}Al minimum ages in a similar range
427 (~170-360 ka). The horizontal KUN02 (^{10}Be : ~150 ka; ^{26}Al : ~80 ka) and vertical KUN06 (^{10}Be :
428 ~90 ka; ^{26}Al : ~70 ka) samples show much younger minimum ages compared to the other
429 Kundabikwa samples. The Lumangwe Waterfall samples LUM02 and LUM03 yielded
430 minimum ^{10}Be ages of ~230 and ~200 ka, respectively, and minimum ^{26}Al ages of ~180 and
431 ~190 ka. One vertical sample from Ntumbachushi Waterfall (NTU01) yielded a very young
432 minimum ^{10}Be and ^{26}Al mean age of ~20 ka. The ^{10}Be minimum age of the horizontal sample
433 NTU02 is similar to those derived from the horizontal surface proximal to the Kundabwika
434 Waterfalls (~380 ka) while its ^{26}Al age (~340 ka) is slightly younger. NTU03, which was

435 derived from a vertical surface, returns much younger ^{10}Be and ^{26}Al minimum ages of ~110 and
436 ~100 ka, respectively. The samples MUM01 (vertical) and MUM04 (horizontal) from the top
437 cascade of the Mumbuluma I Waterfalls yield minimum ^{10}Be ages of ~70 and ~110 ka,
438 respectively, while ^{26}Al minimum ages are slightly younger (~60 and ~90 ka). The horizontally
439 positioned sample MUM02 shows minimum ages of ^{10}Be (~270 ka) and ^{26}Al (~240 ka) which
440 are older than for the vertical sample MUM03 (~110 and ~100 ka, respectively).

441 4.1.1.2. Group B

442 For the single sample collected from Lupupa Waterfall, the minimum ^{10}Be and ^{26}Al ages
443 are in excellent agreement at a mean of 42.4 ± 1.1 ka. The Mumbuluma II Waterfall sample
444 LUO01 yields a minimum ^{10}Be and ^{26}Al mean age of 76.8 ± 2.2 ka, which is an order of
445 magnitude younger than the exceptionally old minimum mean age of LUO02 of 833 ± 17 ka.
446 Sample LUZ01, taken within a narrow river gorge of the Lunzua River, shows a minimum ^{10}Be
447 and ^{26}Al mean age of 524 ± 12 ka. LUZ02 was collected only about 2.4 m below the top surface
448 and yields a mean age of 102.2 ± 2.7 ka.

449 4.1.1.3. Group C

450 Sample MWE01 yielded minimum ^{10}Be and ^{26}Al ages which are in agreement at 7.79 ± 0.60
451 ka. Samples ME04 and ME05 return minimum ^{10}Be and ^{26}Al mean ages of 12.29 ± 0.81 ka and
452 11.56 ± 0.72 ka, respectively, while ME06 and ME09 yielded minimum ^{10}Be and ^{26}Al mean ages
453 of 42.8 ± 1.6 and 45.7 ± 2.0 ka, respectively.

454 4.1.2. Maximum denudation rates

455 For several samples that derive from Groups B and C, maximum denudation rates are also
456 reported (Table 3). Samples from the eastern part of the Kundelungu Plateau yield maximum
457 denudation rates ranging from ~15 to ~40 mm ka^{-1} (samples MWE01, ME04, ME05, ME06 and
458 ME09), while denudation rates associated with the Mporokoso Plateau are much lower and
459 range from ~0.4 to ~6 mm ka^{-1} (samples LUO01, LUO02, LUZ01 and LUZ02). Even though

460 the denudation rates reported in this study are local ones, they indicate general differences in
461 denudation history of both studied plateaus.

462 4.2. *Tectonic Analysis*

463 4.2.1. *Fault kinematics and scaling relationships*

464 We mapped 63 lineaments that we interpreted to represent the surface expressions of active
465 normal faulting at depth (Fig. 1; Appendix Table A2). Fifty-three faults are located within the
466 MMFS, while ten are located within the Mpulungu basin (southern Lake Tanganyika). The
467 faults in the southern MMFS strike NE-SW while the northeast section of the fault system
468 swings its strike clockwise to an ENE-WSW orientation (Table A2), intersecting, at high angles
469 ($\sim 90^\circ$), the NW to SW trending normal faults around Lake Tanganyika. Fault lengths (L) in our
470 dataset range from 12 km to 168 km, whereas maximum vertical fault displacements (D) range
471 from 10 m to 700 m (Fig. 3A). Fault displacement rates (DR) are typically low, ranging from
472 0.004 mm a^{-1} to 0.27 mm a^{-1} (Fig. 3C). This, in turn, corresponds to an average earthquake
473 recurrence for the faults in the MMFS of $\sim 120 \text{ ka}$ (Table A2). In order to understand the impact
474 of normal faulting on the formation of the past and current landscape proximal to Lake Mweru,
475 we explore the D-L relationship on the 53 normal faults in the MMFS (Table A2).

476 The D-L relation may provide important information on the growth and scaling properties
477 of faults (Fig. 3; Walsh and Watterson, 1988; Bilham and Bodin, 1992; Cowie and Scholz,
478 1992; Schlische et al., 1996; Kim and Sanderson, 2005; Schultz et al., 2008; Nicol et al., 2010,
479 2020a). The graphs in Figures 3A and 3C indicate a positive D-L and DR-L relationship for the
480 faults in the MMFS, suggesting that larger faults have accommodated more displacement and
481 have moved faster than smaller faults (Nicol et al., 1997, 2005). Similar graphs, which indicate
482 positive relationships between fault displacements/displacement rates and length, have been
483 recorded on several other active and inactive fault systems globally (Kim and Sanderson, 2005;
484 Mouslopoulou et al., 2009; Nicol et al., 2020a, b). Despite the overall positive D-L trend for

485 most fault systems globally, the D values at a given L value and the slope of the best-fit line in
486 these graphs may vary between fault systems (but also between different sampling periods in
487 the same fault system), with the slope typically ranging from 0.5 to 1.5 (Schlische et al., 1996;
488 Walsh et al., 2002; Kim and Sanderson, 2005; Nicol et al., 2010; Torabi and Berg, 2011, Nicol
489 et al., 2020b). This variability in the D-L scaling may be due to biases arising from the time-
490 window of observation, the age of the faulted horizons, the strain accommodated by each fault
491 system, the mechanical properties of the faulted rocks and/or the degree of fault interactions
492 (Watterson et al., 1996; Bailey et al., 2005; Mouslopoulou et al., 2009; Nicol et al., 2010;
493 Rotevatn et al., 2019).

494 To better understand the growth of the faults in the MMFS with respect to other fault
495 systems globally, we have plotted their D-L trend against a global dataset of inactive normal
496 faults (Fig. 3D; Nicol et al., 2016c and references therein). Comparison shows that the faults in
497 the MMFS plot in agreement with the global dataset occupying, however, the lower part of the
498 global population (slopes of ~ 0.92 vs. ~ 0.99 , respectively; Fig. 3D). To explore further the
499 growth of the faults in Africa, we have also plotted in Figure 3D the single-event displacement
500 rupture lengths from a global compilation of historic normal fault earthquakes (Wesnousky,
501 2008). As expected, single earthquakes clearly plot below the average trend of the global dataset
502 (including the MMFS), their slope is significantly less than 1 (~ 0.3) and their scatter greater
503 than that of the global dataset (R^2 values of 0.25 vs. 0.85; Fig. 3D). These features collectively
504 suggest that each fault in the MMFS has accommodated numerous earthquakes, the number of
505 which scales with fault length.

506 The approximate number of earthquakes accommodated by each fault in the MMFS,
507 together with their earthquake magnitude and recurrence interval, has been calculated using
508 Wesnousky's (2008) scaling relationships (Table A2). First, we calculate the single event
509 displacement (SED) for each fault in the MMFS from the fault length (L) and subsequently the
510 earthquake recurrence interval on each fault (Table A2). The recurrence interval is subsequently

511 used, in conjunction with the 2.6 Ma displacement rate (time-period that rifting is thought to
512 have initiated), to estimate the number of earthquakes accommodated by each fault (Table A2
513 and Fig. A2). We find that the faults in the MMFS ~~have~~are likely to have accommodated ~2,000
514 ground-rupturing earthquakes since the rift's onset (~35 events per fault), with earthquake
515 magnitudes ranging from M6.7 to M7.2 (Table A2 and Figure A2).

516 4.2.2. *Faulted topography*

517 To explore the relationship between the faulted topography, the available TCN ages and
518 the current extents of Lakes Mweru and Mweru Wantipa, we generated five rift-perpendicular
519 topographic profiles (Fig. 4) and one rift-parallel profile (Fig. 5). The profiles 1-3, across the
520 southern MMFS and the modern Lake Mweru, reveal a strongly asymmetric rift (Fig. 4A-C).
521 To characterize the distribution of strain along the rift, we have calculated the cumulative throw
522 across the five profiles illustrated in Figure 4. Furthermore, to better visualize the landscape
523 when rifting in the area was about to commence, we subtracted from the identified faults the
524 throw measured along the topographic profiles 1-8 (Fig. 6), that is the displacement accrued on
525 each fault since the initiation of faulting at 2.6 Ma.

526 Our analysis shows a three-fold increase in the cumulative throw, trending northeastwards
527 along the rift (from ~800 m across profile 1 to ~2180 m across profile 5), with the southeast
528 dipping faults having accommodated almost twice as much displacement (4550 m) compared
529 to the northwest dipping faults (2690 m; Fig. 4). The dominance of the southeast dipping faults
530 is persistent along the entire length of the MMFS, where these faults appear to have locally
531 (e.g., see profile 5) accommodated up to 4 times more throw compared to the northwest dipping
532 faults. The northeastward increase in extension, which is manifested by the greater number of
533 active faults and the more confined rift axis, is not surprising as the MMFS at its northernmost
534 extension approaches (and intersects) the fast spreading ($\sim 1 \text{ mm a}^{-1}$) EARS (Fig. 1; Fernandes
535 et al., 2004; Calais et al., 2006; Omenda et al., 2016).

536 Topographic analysis suggests that the faults which are largely responsible for the
537 formation of the modern landscape within the MMFS are faults 8, 9, 16, 17, 23 and 28 in the
538 south, and faults 38, 40, 46 and 48 in the north. The profile along Lake Mweru (profile 6 in Fig.
539 5) reveals a shallow topographic basin (within <100 m from the modern lake) which is bounded
540 at its northern side by the Kundelungu Plateau and to the south by steep hilly country formed
541 by sediments of the Luapula River's delta (Fig. 4A). Profile 7 runs along Lake Mweru Wantipa
542 and displays the high topographic relief between the Mporokoso Plateau and the Mpulungu
543 basin, while profile 8 reveals the impact of normal faulting on the landscape associated with the
544 Kundelungu Plateau (Fig. 6). These profiles are discussed in detail in Section 6.

545 4.3. *Geomorphic Analysis*

546 We identified a total of 61 river knickpoints from individual stream profiles that
547 corroborate the paleo-shoreline observation (Fig. 7A). In a second step, we analyzed the
548 hypsometry of the Lake Mweru catchment to delineate the impact of paleo-lake Mweru on the
549 elevation distribution. The hypsometric curve of the catchment (Fig. 7B, blue and black lines)
550 reveals large areas characterized by gentle slopes, which we interpret to correspond to areas
551 confining the paleo-lake Mweru. They all lie at elevations between 920-930 m asl, 990-1100 m
552 asl and 1170-1190 m asl, which align with the sampled waterfalls at 1050 and 1160 m asl. We
553 observe additional areas with low slopes at varying elevations, but focus our analyses on the
554 most prominent elevations. We have furthermore excluded slope angles above 3° to better show
555 terrain associated with lake-erosion processes (Fig. 7B, blue line). In the same elevation
556 framework, we plot the number of knickpoints observed at a specific elevation. Knickpoints
557 cluster at specific elevations and delineate the remnant paleo-shorelines in a more refined spatial
558 pattern, indicating three abandoned shorelines at elevations of ~925 m asl, ~1000 m asl and
559 ~1180 m asl, respectively (Fig. 7B).

560 **5. Reconstructed Scenarios for the Principal Sets of TCN Results**

561 Overall, our TCN samples record a pattern of temporary burial over parts of the region
562 studied. As discussed earlier (Section 1), stratigraphic evidence suggests that during the
563 Pleistocene the study area hosted an enlarged lake, approximately 130 km wide and 300 km
564 long (~40,000 km²), centered around the (much smaller) present-day Lake Mweru (~5000 km²).
565 TCN production is completely blocked (except for some minor production by muons) when a
566 surface is ≥ 10 m below the lake level. Therefore, interpreting the Plio–Pleistocene tectonic
567 history of ~~south-central~~south-central Africa, we suggest that the burial patterns recorded by our
568 samples most likely reflect the existence of a paleo-lake that inundated a much larger
569 depocenter.

570 *5.1. Group A*

571 ~~The majority of~~Most of the samples from Group A indicate burial (Fig. 1; Fig. 8). A few
572 significant age discrepancies arising from samples collected from a single waterfall are also
573 evident. The fact that all waterfalls in Group A are located within the MMFS and at elevations
574 <1200 m asl (that is, significantly lower than Group B samples which are all located >1200 m
575 asl) indicates that faulting and uplift may have played an important role in the burial of the
576 landscape. Below we discuss separately the likely exposure scenarios for each waterfall in
577 Group A.

578 *5.1.1. Kundabikwa Waterfalls*

579 Samples from the Kundabikwa Waterfalls indicate burial over a continuous period for at
580 least 250 ka (Fig. 8A). The significantly younger minimum exposure ages (Section 4.1.1.) of
581 samples KUN02 and KUN06 probably indicate enhanced surface denudation or
582 rockfalls/landslides (e.g. mechanical failure of exposed rock outcrop leading to fresh exposure).
583 In addition, two of the three pairs of samples (KUN01/KUN02 and KUN03/KUN04) indicate
584 older ¹⁰Be and ²⁶Al minimum ages (Table 2) for the vertical face compared to the top horizontal

585 surface. The fact that the top horizontal surface (KUN02, KUN03 and KUN05) of the area is
586 younger than the vertical sections (KUN01, KUN04) is intriguing and requires further
587 examination.

588 Based on the relative ^{10}Be and ^{26}Al minimum age estimates, we reconstruct the complex
589 exposure-burial history of Kundabikwa Waterfalls and paleo-lake Mweru over six sequential
590 stages (Fig. 9). The pre-lake stage (T1) represents the initial state of the river. In order to record
591 a burial ~~signal~~signal, the studied surfaces must have been exposed prior to burial. ~~Thus~~Thus,
592 the knickpoint must have already existed during stage T1. The vertical faces of the banks are
593 gradually exposed through sequential knickpoint retreat. During this stage, channel denudation
594 dominates. The denudation rate is relatively low on the top-horizontal surface. Most
595 geomorphologic characteristics from this stage are assumed to have been erased by today. The
596 second stage (T2) is defined by the onset of the lake-level rise (flooding). Water starts to cover
597 the vertical ~~river banks~~riverbanks. Denudation decreases as the base-level increases, leading to
598 slower knickpoint migration. Denudation is minimal (but probably not zero) as the top
599 horizontal surfaces are flooded and lake sedimentation initiates. During T3, the lake reaches its
600 greatest depth. Water and sediments now shield the sampled surfaces from cosmic ray
601 irradiation, entirely blocking ^{10}Be and ^{26}Al production. Lacustrine sedimentation occurs mostly
602 on the horizontal surfaces. The lake-level is now the base-level, resulting in the interruption of
603 denudation.

604 Denudation recommences with the onset of lake drainage and associated drop of the water-
605 level (stage T4). Localized denudation occurs on the sediment-covered horizontal surfaces
606 while the vertical faces remain under water, with TCN production still being absent for all
607 submerged areas. Consequent to paleo-lake outflow (T5) via the Luvua River, regional
608 denudation of the sediments that blanket the horizontal surfaces occurs. This period of new
609 equilibrium may have been characterized by low energy environments, which can be described,

610 for example, as a changing complex of small wetlands, oxbow lakes and meandering channel
611 systems, similar to the current situation in the upper reaches of ~~present-day~~present-day Lake
612 Mweru. Lacustrine sediments are now confined to the top horizontal banks, as in the channel
613 the sediments are eroded. The subsequent lowering of base level as the lake drains sees the
614 rejuvenation of the waterfalls. In the last stage (T6), ~~the majority of~~most of the lacustrine
615 sediments have been removed from all surfaces and the top horizontal surfaces are re-exposed
616 and TCN production resumes. Back- and downwearing of the vertical bank faces leads to further
617 denudation of the bedrock surfaces. We note that gradual rising and lowering of the lake's
618 water-level between stages T2 and T4 should have lasted thousands or even tens of thousands
619 of years in order to induce a detectable difference between the cosmogenic nuclide
620 concentrations of different (horizontal vs. vertical) sampled surfaces. Indeed, previous studies
621 of other paleo-lakes have revealed long-term lake fluctuations spanning time-intervals from 2
622 to >20 ka (Masters et al., 1991; Gamrod, 2009; Shuman et al., 2009; Trauth et al., 2010).

623 5.1.2. Lumangwe Waterfall

624 According to Figure 8B, ~~the~~ sample LUM03 does not show an unequivocal burial signal, in
625 contrast to LUM02 that clearly underwent ~~clearly~~ a complex exposure history. One possible
626 explanation is that LUM02 (1150 m asl) was covered by lake water, while LUM03 (1159 m
627 asl) was not (or it was only slightly covered so the cosmogenic nuclide production did not stop
628 completely). Such a scenario implies that the Lumangwe cascades marked the eastern shore of
629 the paleo-lake. Another possibility is that the LUM02 rock face was covered by a recent
630 landslide or rockfall. ~~However~~However, no physical evidence of such an event can be found,
631 suggesting that if it did occur, the Kalungwishi River has subsequently removed any such
632 debris. A minimum burial time of 300 ka is estimated for LUM02 (Fig. 8B).

633 5.1.3. *Ntumbachushi Waterfalls*

634 Samples NTU01 and NTU02 do not indicate a clear burial signal. The weathered profile of
635 the NTU01 surface and the very young minimum ^{10}Be and ^{26}Al mean age (~20 ka) most likely
636 indicate a recent rockfall. Although NTU03 does indicate burial of ~400 ka (Fig. 8C), this age
637 is questionable due to the young minimum ^{10}Be and ^{26}Al ages (~100 and ~80 ka, respectively)
638 that derive from the same sample and which, coupled with the highly weathered and fractured
639 nature of the sampled surface, make it unlikely to record an ancient pre-lake stage.

640 5.1.4. *Mumbuluma I Waterfalls (Mumbuluma River)*

641 All results from [the](#) Mumbuluma I falls indicate a clear burial signal at 1σ confidence level,
642 though not at 2σ (Fig. 8D). The top cascade yields younger minimum ^{10}Be ages (MUM01,
643 MUM04) than the second cascade downstream (MUM02, MUM03), suggesting that the lower
644 waterfall formed before the top one. Also, the top horizontal surface (MUM04; minimum ^{10}Be
645 age 113 ka) seems to have undergone more intense denudation than the lower surface (MUM02;
646 271 ka). A rockfall may explain the young minimum ^{10}Be age of the vertical sample MUM01
647 (~70 ka). The approximate minimum burial time of the area is ~350 ka (Fig. 8D), an age which
648 is in good agreement with the duration of burial recorded at [the](#) Lumangwe falls.

649 5.2. *Group B*

650 Samples in Group B date waterfalls which are situated outside the MMFS (Fig. 1). ^{10}Be and
651 ^{26}Al minimum ages are in good agreement for most samples, indicating that these surfaces have
652 not been buried since their initial exposure (Fig. 10). Thus, it appears that these locations were
653 not flooded by the paleo-lake. Minimum exposure ages and maximum denudation rates within
654 this group are discussed below.

655 5.2.1. *Lupupa Waterfall*

656 LUP01 shows very young minimum ^{10}Be and ^{26}Al ages, which probably do not reflect the
657 actual age of the waterfall but a rockfall event. For such recent events, no burial signal is
658 expected (Fig. 10A).

659 5.2.2. *Mumbuluma II Waterfall (Luongo River)*

660 Both samples from the Luongo's Mumbuluma II Waterfall are from sub-vertical (45° - 50°)
661 surfaces and show no clear ^{10}Be - ^{26}Al burial signal (Fig. 10B). This cascade was formed on a
662 bedrock contact between quartzites and sandstones. The development of the cascade is clearly
663 controlled by differential denudation between the overlying softer sandstone and the harder
664 quartzite. Maximum denudation rates of $\sim 6 \text{ mm ka}^{-1}$ for the sandstone (LUO01) and of ~ 0.4
665 mm ka^{-1} for the quartzite (LUO02) are calculated (Table 3). The large difference in the
666 denudation rates of the two lithologies further highlights the role of differential denudation in
667 the formation of this cascade. Sample LUO02 plots exactly on the no denudation line in Figure
668 5b, indicating a minimum ^{10}Be and ^{26}Al mean exposure age of $833 \pm 17 \text{ ka}$. This age, which is
669 the oldest recorded minimum exposure age among the studied waterfalls, indicates a very old
670 formation age of the Mumbuluma II knickpoint. It is worth mentioning that this is an
671 exceptionally old age for an inclined surface located within the zone of an actively incising river
672 channel.

673 5.2.3. *Lunzua Waterfalls*

674 Both samples from Lunzua Waterfalls show no ^{10}Be - ^{26}Al burial signal (Fig. 10C). LUZ01
675 yields a very old minimum age for a vertical surface, which indicates that it was constantly
676 exposed since at least $524 \pm 12 \text{ ka}$. In terms of a steady denudation rate, this age would
677 correspond to a local rate of receding of the rock face (in horizontal direction) of $\sim 0.4 \text{ mm ka}^{-1}$.
678 LUZ02 yields a much younger minimum ^{10}Be and ^{26}Al mean age ($102.2 \pm 2.7 \text{ ka}$). It is unclear

679 whether the age difference between the two samples reflects the retreat of the waterfall or is just
680 due to more intense denudation near the top.

681 5.3. *Group C*

682 Samples from the northwest side of Lake Mweru (Group C) were located at lower elevations
683 than those from groups A and B and their minimum ^{10}Be and ^{26}Al ages are distinctly younger
684 and more comparable to one another (Table 2). The sample that derives from a vertical surface
685 of the fault no. 16 (MWE01; Fig. 1) implies a fast but steady denudation rate of $\sim 40 \text{ mm ka}^{-1}$
686 (Table 3) or a rockfall on the fault surface $< 10 \text{ ka}$ ago. Additionally, two further samples (ME04,
687 ME05) from vertical sections along the Luvua River show rather young minimum ^{10}Be and ^{26}Al
688 mean ages (12.29 ± 0.81 and $11.56 \pm 0.72 \text{ ka}$, respectively). As the paleo-lake Mweru was drained
689 via the Luvua River, during the Pleistocene (Cotterill and de Wit, 2011), it is possible that these
690 young ages reflect rockfall events or steady and fast incision, but obviously they do not
691 represent the age of paleo-lake drainage. Fast denudation of the northeastern section of the
692 Kundelungu Plateau is further supported by two samples which were collected from horizontal
693 surfaces along the Misefwe and Lwilwa rivers (ME06 and ME09; Fig. 1), yielding maximum
694 ^{10}Be denudation rates of $\sim 16 \text{ mm ka}^{-1}$ (Table 3). In summary, Group C samples show no ^{10}Be -
695 ^{26}Al burial signals and relatively young minimum ages due to recent rockfalls and/or fast
696 eroding surfaces (Fig. 11; Tables 2, 3). However, these young ages do not contradict the
697 assumed extension of the paleo-lake Mweru over this section of the Kundelungu Plateau.
698 Rather, they suggest that pre paleo-lake surfaces have not been preserved due to faster
699 denudation. Such rates could be related to a potential uplifting caused by the activity of fault
700 no. 16 (Fig. 1). Further investigation of this activity is required.

701 6. Discussion

702 Our results explore the landscape evolution of the Mweru rift system, the southwest
703 extension of the EARS, since the late Neogene. The establishment of paleo-lake Mweru

704 initiated a new drainage network feeding the paleo-lake until the penultimate capture of this
705 depocenter by an Upper Congo headwater. Here we discuss the implications of these new
706 insights with respect to the southward and westward propagation of rifting.

707 *6.1. Onset of Active Faulting and the Formation of the Paleo-Lake Mweru*

708 Rifting in the study area is thought to have commenced by at least ~2.6 Ma (Tiercelin and
709 Lezzar, 2002; Decrée et al., 2010; Molnar et al., 2019; Daly et al., 2020). Overall, analysis of
710 the faulted topography within the MMFS reveals that individual faults have played a pivotal
711 role in forming the two depressions that host the Lakes Mweru and Mweru Wantipa. Active
712 faulting and associated footwall uplift ~~is~~are also responsible for the wide ridge that extends
713 today between the two lakes (Fig. 1). The landscape reconstruction through subtraction of the
714 2.6 Ma fault throws (Fig. 6) displays a mild relief across the extended area of the MMFS,
715 revealing that the landscape was similar to the flat East African erosion surface. During the
716 early Pleistocene, the average topographic altitude was formerly higher, though it is possible
717 that the relative height difference between the Kundelungu and Mporokoso Plateaus has not
718 changed significantly since the onset of rifting. A low energy environment, such as a shallow
719 wetland, and associated meandering rivers probably extended over this landscape, which was
720 related to the extensive and relatively long-lived paleo-Chambeshi drainage system (Cotterill,
721 2005).

722 The southern part of the MMFS (profiles 1 and 6; Fig. 6A, 6F) hosts deltaic deposits
723 associated with the Luapula River (Fig. 1). The primary faults that bound the depression that
724 hosts ~~today~~Lake Mweru today to the west are (from south to north) faults 8, 9, 10 and 16 (Fig.
725 1). The total throw on these southeast dipping faults is ~640 m as opposed to the 200 m of
726 cumulative throw recorded on the northwest dipping faults (i.e., 23 and 28) that bound this
727 depression to the southeast. This geometry reveals a highly asymmetric rift tilted to the
728 southeast. Profiles in Figure 6A and 6F suggest that faults 8 and 23 contributed drastically to

729 the lowering of the landscape between the two horsts by a total throw of ~700 m. During the
730 early Pleistocene, the southern part of the Mporokoso Plateau was about 250 m lower than the
731 Kundelungu Plateau. It is known that during this period, the Luapula River captured the paleo-
732 Chambeshi River, which led to the ~~present day~~present-day linkage between the Bangweulu and
733 Mweru lakes (Cotterill, 2003, 2005). This interpretation, which is not described by the tectonic
734 analysis presented here, suggests that the proto-Luapula River was flowing southward towards
735 Lake Bangweulu (as suggested previously; Cotterill, 2005, 2006; Cotterill and de Wit, 2011;
736 Moore et al., 2012). The onset of tectonic activity, together with the southward knickpoint
737 retreat of the proto-Luapula River, may have contributed to the separation of the previously
738 topographically connected Mporokoso and Kundelungu Plateaus.

739 Moving northwards, to profiles 2 and 6 (Figs. 6B, 6F), the elevation difference between
740 the two shoulders of the rift is more distinct. The southeast dipping faults of the Kundelungu
741 Plateau sum a total throw of almost 800 m, while faults along the Mporokoso Plateau have a
742 total throw of ~300 m. It appears that the Mporokoso Plateau stood around 1400-1500 m asl
743 during the late Pliocene. The basement of the lake was clearly higher than today, standing at
744 ~1000 m asl, while the Kundelungu Plateau maintained its high elevation at ~1700 m asl. Faults
745 9, 16, 23, 24, 28 and 32 were the main contributors of downfaulting. In this area, the wetland
746 was deeper (Kilwa Island did not exist) and the clastic bedrock was the main dominant rock
747 type of the wetland's bottom. According to profiles 3 and 6 (Figs. 6C, 6F), the local average
748 altitude of the landscape was lower, reaching the highest point of ~1350 m asl on the
749 Kundelungu Plateau. The maximum altitude of the Mporokoso Plateau was ~1250 m asl,
750 minimizing the elevational difference between the two shoulders of the rift. The total throw of
751 the southeast dipping faults is ~500 m, while the northwest dipping faults' total displacement
752 is 400 m, creating an almost symmetric section in a generally asymmetric structure. Considering
753 Figure 6C, the reconstructed landscape during the early Pleistocene had a relatively low relief.

754 Both these plateaus seem to have had an approximately similar local height (~1400 m asl), and
755 the lowest point was probably close to the ~~present-day~~present-day location of the Kundabwika
756 Waterfalls, which was controlled by Fault 44.

757 Cotterill (2006) discussed the possibility that part of the Kalungwishi River, today flowing
758 north, was redirected from the south, as the Kalungwishi River was formerly a major headwater
759 of the proto-Luongo River (Fig. 1). Geobiological estimates of evolutionary events can be
760 applied from the genomic record of extant fishes. These estimates of speciation events confer
761 an independent chronology of these drainage links (Cotterill and de Wit, 2011). A pertinent
762 example is the Early Pleistocene speciation of a killifish, *Nothobranchius ostergaardi*, confined
763 within the eastern Mweru Wantipa basin; this species diverged from 0.46 to 1.11 Ma from its
764 closest living relatives, which today occur south of the Congo-Zambezi watershed (van der
765 Merwe et al., 2021). Their origin is attributed to the breakup of the paleo-Chambeshi River, and
766 this event overlaps with independent pulses of fish speciation within the Mweru graben, as well
767 as TCN dates constraining the tenure of paleo-lake Mweru. The onset of the MMFS (deepening
768 of the paleo-lake Mweru) then disrupted the paleo-drainage of the Luongo-Kalungwishi system,
769 contributing gradually to its disconnection from the paleo-Chambeshi drainage (Cotterill, 2006;
770 Cotterill and de Wit, 2011).

771 Compared to Lake Mweru (917 m asl), Lake Mweru Wantipa stands at a higher elevation
772 (932 m asl), and it is characterized by a high relief landscape. According to profiles 4 and 5
773 (Fig. 4), the total throw of the southeast dipping faults along the Kundelungu Plateau reaches
774 up to 1720 m, while the northeast dipping faults have a maximum total throw of 460 m. Despite
775 the approximately four-fold difference of the throw measured on the southeast and northwest
776 faults, the rift here does not appear to be strongly asymmetric. This can be rationalized if we
777 consider that the former faults are distributed across a distance of ~140 km whereas the latter
778 ones span only 10 km across the rift's shoulder. From a geomorphological ~~point of~~

779 ~~view~~perspective, the Mweru Wantipa depression hosts the seismically most active structures of
780 the Southwestern Extension of the EARS (Daly et al., 2020). This is also supported by the DEM
781 fault analysis that suggests a denser fault network of fresh discontinuous traces between the
782 Lakes Mweru Wantipa and Tanganyika. The extended landscape around the modern Lake
783 Mweru Wantipa during the early Pleistocene was also characterized by high relief, while the
784 base of the wetland was standing at ~1150 m asl (Fig. 6D). The Kundelungu Plateau was
785 standing at a maximum altitude of > 2000 m asl, while the Mporokoso Plateau had a maximum
786 elevation of ~1900 m asl (Fig. 6E). The modern lowlands (cross ~~hachure~~hatching in the east in
787 Fig. 12) on the borders between Lake Mweru Wantipa and the Mpulungu basin have currently
788 an average elevation <1200 m asl. During the Pleistocene (Fig. 6G), the elevation was just ~50
789 m higher, with the lowest point ~1200 m asl. However, this elevation difference was sufficient
790 to prevent the merging of paleo-lake Mweru and paleo-lake Tanganyika and suggests that these
791 lakes have never been linked.

792 The western margin of the paleo-lake was defined by the long and high Kundelungu
793 Plateau. The depression (cross ~~hachure~~hatching in the west in Fig. 12) that separates the main
794 part of the plateau from its eastern continuity did not exist during the Pleistocene. Based on
795 Figure 6H, the two parts of the plateau were connected, and the average elevation of the linking
796 crest was ~1400 m. Faults 16a and 17 downfaulted the intervening landscape by ~200 m,
797 resulting in the separation of the southwestern and northeastern sections of the Kundelungu
798 Plateau. There is no evidence of a sudden tectonic event that created this depression, so we
799 assume that it was dominated by gradual lowering of the landscape due to normal faulting and
800 denudation activity across the Kundelungu Plateau, as implied also by the TCN data.

801 Interestingly, the transition from Pliocene to Pleistocene (2.6 Ma) is characterized by a
802 major climatic change in the southern hemisphere, from warm and humid conditions to
803 aridification until 1.8 Ma, which is invoked as a driver of contraction and expansion of the lakes

804 (Cohen et al., 1997). The lakes that were already flooded since ~3.6 Ma experienced
805 contractions around 1.1 Ma (Cohen et al., 1997). Lavayssiere et al. (2019) reported that Lake
806 Tanganyika dried down to the point it was divided into three contracted paleo-lakes, limited
807 within the sub basins of the rift, which possibly caused fish speciation. The lake levels were
808 restored gradually until 550 ka, while fluctuations in levels occurred, possibly linked to
809 alterations in Pleistocene paleo-climates (Cohen et al., 1997; Trauth et al., 2005, 2010;
810 Lavayssiere et al., 2019). Indeed, TCN dating suggests water level fluctuations across the paleo-
811 lake Mweru during the Pleistocene (Section 5.1.1.), which attests to complex interactions
812 between past climates and tectonics.

813 6.2. The Drainage of Paleo-Lake Mweru

814 At Kundabikwa Waterfalls, three samples (KUN01, 02, 03) yield burial ages of ~1 Ma (Fig.
815 8A). The minimum burial ages of the other four samples (KUN04, 05, 06, 07) are lower (~500
816 ka). This may be explained by a higher contribution of post-burial production, which shifts data
817 points in the two-nuclide plot (Fig. 8A) from the burial area towards the steady-state field again.
818 Therefore, it is the oldest burial age among all samples that provides a minimum estimate for
819 the time the Kundabikwa Waterfalls have been covered, i.e. >1 Ma. Indeed, it is possible that
820 the paleo-lake Mweru existed much longer than that. If the lake (including the various lake
821 fluctuations) actually lasted more than ~2 Ma, essentially all ^{26}Al present in a sample today
822 would have been produced after the drainage of the paleo-lake (as the half-life of ^{26}Al is 705 ka
823 and after three half-lives almost 90% will have decayed; Norris et al., 1983). Under such an
824 assumption, the highest minimum ^{26}Al age of all samples showing burial would provide a time
825 constraint for when the paleo-lake was drained to a level below the elevation of the waterfalls.
826 Sample KUN04 of the Kundabikwa Waterfalls records the highest ^{26}Al minimum age among
827 all samples that indicate burial, constraining the timing of lake drainage to ~350 ka (i.e. middle
828 Pleistocene). Variable denudation and tectonic rates within the study area can explain the

829 observed variations in minimum ages between different locations. Nevertheless, all samples
830 from Group A are consistent with an inferred lake drainage at ~200-400 ka, with age differences
831 most likely representing lake level fluctuations.

832 The reconstruction of key features that formed the landscape at ~350 ka is required to
833 determine potential waterways allowing for the drainage, and consequent lowering, of the
834 paleo-lake. To achieve this, we calculated, assuming constant displacement rates over these
835 timescales (Mouslopoulou et al. 2009), the throw accrued on each fault since 350 ka and we
836 subsequently subtracted it from its total displacement (Table A2). The modified faulted
837 topography is assessed via profiles 1-8 (cross sections in Fig. 1), the results of which are
838 illustrated in Figure A5 in the Appendix. The restored topography at 350 ka reveals minor,
839 albeit crucial, readjustments that appear to have impacted on the size of the paleo-lake.
840 According to the profiles in Figure 4, faults 8, 9 and 16 are the largest displacement faults that
841 formed the asymmetrical half-graben structure that hosted the paleo-lake. Faults 16a and 17
842 also contributed to the formation of the depression west of present-day Lake Mweru and across
843 the Kundelungu Plateau (Fig. A5c). This depression might have played a key role in the
844 lowering of the paleo-lake's water level as it aided its tapping to the west (Fig. 12). Faster
845 denudation rates in the north (~40 mm ka⁻¹; Group C) compared to the south (~6 mm ka⁻¹;
846 Groups A, B) were forced by footwall uplift across Fault 16, resulting in fast incision along the
847 northward flowing Luvua River (Fig. 1).

848 Dramatic lake level fluctuations have been reported throughout the late Pleistocene (14-450
849 ka) across Lake Tanganyika, Lake Malawi and the southwest extension of the EARS, which are
850 related to tectonic factors and/or aridification periods (Danley et al., 2012; Ivory et al., 2016).

851 From 450 to 350 ka, a regional ~~dropping lowering~~ of the temperature and ~~the global sea level~~ is
852 directly correlated with the low stand of the lake levels across the Western Branch (Bakker and
853 Mercer, 1986). In addition, a major dry period across the Congo basin occurred between ~270

Commented [A4]: You do mean sea level don't you and not lake level?

Commented [A5R4]: Indeed yes. Sea leve it is.

854 and 180 ka, resulting in an additional lowering of the water level (Gasse et al., 1989). The
855 evidence for the drainage of paleo-lake Mweru based on ^{10}Be and ^{26}Al data, together with
856 tectonic analyses and the evidence for intensive climatic variation during the Pleistocene,
857 indicate a gradual shrinking of the paleo-lake rather than a sudden tectonic event. The outflow
858 of the paleo-lake through the Luvua River was most likely one of the main events that drained
859 the lake (Dixey, 1944; Bos et al., 2006; Goodier et al., 2011; Cotterill and de Wit, 2011; Fig.
860 1). However, evaporation, especially in arid periods, may have further accelerated contraction
861 of the paleo-lake, notably across the vast, shallow depression located between the two sections
862 of the Kundelungu Plateau (Fig. 12).

863 6.3. Paleo-Lake Mweru During the Late Neogene-Quaternary

864 Assuming that the paleo-lake Mweru ~~lasted~~existed for a minimum of ~2 Ma, the burial
865 ages constrain its formation to the late Pliocene-early Pleistocene. This assumption is supported
866 by the high species endemism of the extant fish fauna of Lake Mweru (Cotterill, 2005; Meier
867 et al., 2019). More specifically, recent molecular clock analyses have estimated respective
868 timings of origin of several radiations of endemic fish clades (Family Cichlidae) confined
869 within Lake Mweru. Four of these clades have evolved diverse species flocks, whose origins
870 are estimated at 270–350, 430–560, 270–940, and 720–940 ka, constrained by a molecular clock
871 calibrated for the Cichlidae (Meier et al., 2019). Thus, depending on the applied calibration
872 scheme, the mean genetic divergence of the most common recent ancestors provides a date of
873 0.27-1.04 Ma and their actual speciation dates (i.e. timing of completed lineage divergence)
874 was likely more recent (Meier et al., 2019). The second line of geobiotic evidence comprises
875 the “Mweru Complex” of killifishes, genus *Nothobranchius*. The timing of radiation of its seven
876 species is significant, because their ecology confines them within the floodplains that formed
877 after the shrinkage of the larger lake. The independently constrained molecular clock of

878 *Nothobranchius* estimates the origin of this complex between 0.48 and 1.01 Ma (van der Merwe
879 et al., 2021).

880 Our data inform a schematic map that estimates the maximum size of the paleo-lake Mweru
881 through the Pleistocene (Fig. 12). The maximum lake level is constrained via TCN dating at
882 1200 m asl, while the minimum level should be the elevation of the Kundabikwa Waterfalls
883 (~1050 m asl). The estimate of a 1200 m asl lake level is supported by the hypsometric and
884 knickpoint analysis (~1180 m asl). The Lumangwe and Ntumbachushi Waterfalls are assumed
885 to represent the eastern shorelines of this paleo-lake. This inference is confirmed by the heights
886 of the dominant knickpoints at the same elevation mapped throughout the catchment (Fig. 7).
887 The southern border of the paleo-lake likely coincided closely with the Mumbuluma I waterfalls
888 which, together with preliminary molecular phylogenetic analyses (Cotterill, 2004, 2005),
889 suggest that the southern section of the Kundelungu Plateau was connected with the Mporokoso
890 Plateau during the Pliocene (and prior to the formation of the Luapula River; Tack et al., 2003;
891 Cotterill and de Wit, 2011; Guillocheau et al., 2015).

892 Red siltstones from the Kundelungu Plateau are possibly correlated with the upper red beds
893 of the Luapula Beds, implying that the Luapula River eroded the once connected Kundelungu
894 and Mporokoso Plateaus (Abraham, 1959; Thieme, 1971). The western bank of the paleo-lake
895 is defined by the Kundelungu Plateau that rises to ~1700 m asl. Paleo-lake Mweru was likely
896 connected to the Mweru Wantipa wetlands as suggested by the relationships of
897 *Pseudocrenilabrus* (family: Cichlidae) species from these two waterbodies (Egger et al., 2015).
898 However, it appears unlikely that it was linked with the Mpulungu graben of Lake Tanganyika
899 due to the highly distinct fish fauna of these two lakes. This is in agreement with Dixey (1944,
900 1946), who proposed that the Lakes Mweru and Mweru Wantipa were once connected, a
901 hypothesis re-affirmed by Cotterill and de Wit (2011). Finally, the northern banks are defined

902 by the edge of the extensive plateau between the Mweru Wantipa wetlands and Lake
903 Tanganyika (Fig. 12).

904 **7. Conclusions**

905 Terrestrial cosmogenic nuclides results coupled with tectonic and digital topographic
906 analyses reveal the existence of a large paleo-lake Mweru. This paleo lake exceeded the sizes
907 of the present-day Lakes Mweru and Mweru Wantipa. We identified the following evidence for
908 lake size and timing:

909 As estimated previously, our results indicate the onset of the paleo-lake at around 2.6 Ma.
910 The timing of lake existence is consistent with the phylogenetic molecular clock analyses of
911 endemic fish species, which also constrain the formation of the paleo-lake at the late Pliocene -
912 early Pleistocene. Formation of this lake is correlated with the onset of the Mweru-Mweru
913 Wantipa Fault System in the Early Pleistocene and likely established an estimated maximum
914 shoreline at ~1200 m asl. The extent of the paleo-lake was also identified by river knickpoint
915 and hypsometric analysis to constrain its paleo-shorelines at ~1180 m.

916 Intense normal faulting and associated footwall uplift at the northwestern paleo-lake
917 boundary must have forced fast river incision in the eastern section of the Kundelungu Plateau.
918 In contrast, two exceptionally old minimum ^{10}Be and ^{26}Al exposure ages of 524 and 833 ka
919 were obtained from vertical/sub-vertical surfaces besides active river courses across the
920 Mporokoso Plateau, possibly reflecting the actual exposure ages of these surfaces. These ages
921 illustrate the stability of the plateau, which is also reflected by the low maximum denudation
922 rates (~ 0.4 to ~ 6 mm ka^{-1}). The deepening/flooding of the paleo-lake, which was probably due
923 to the active extension and associated normal faulting, continued at least until the Middle
924 Pleistocene (~ 350 ka), resulting in complex exposure histories observed at the knickpoints on
925 the Mporokoso Plateau.

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1358 **Figure Captions**

1359 Figure 1: Morphotectonic map of the Mweru-Mweru Wantipa Fault System (MMFS) in the
1360 southern East African Rift System. Normal faults are indicated by black lines while ticks
1361 indicate downfaulted side. Numbers next to each fault correspond to entries in Table A2 in the
1362 Appendix. Red lines indicate topographic profiles presented in Figures 4, 5 and 6. Green circles,
1363 yellow triangles and blue squares indicate sampling locations of the three different sampling
1364 groups. Inset shows location of study area in Africa. KUN: Kundabikwa Waterfalls; LUM:
1365 Lumangwe Waterfall; NTU: Ntumbachushi Waterfalls; MUM: Mumbuluma I Waterfalls; LUP:
1366 Lupupa Waterfall; LUO: Mumbuluma II Waterfall; LUZ: Lunzua Waterfalls.

1367 Figure 2: A) Sampling of KUN01 from a vertical face on the banks of Kalungwishi River,
1368 downstream of Kundabikwa Waterfalls, Zambia; B) Sampling of bedrock (MUM04) directly
1369 from the horizontal surface of the knickpoint at Mumbuluma I Waterfalls, Zambia; C) View of
1370 Lumangwe Waterfall, Zambia; D) Sample location of ME09, Lwilwa River, DRC; E) Sampling
1371 of MWE01 from the face of fault 16, DRC.

1372 Figure 3: A) Log-log plot illustrating the relationship between topographic fault length and total
1373 displacement for the faults in the MMFS (grey circles) and the Mpulungu basin (southern
1374 Tanganyika Fault System; black circles). B) Same as (a) but illustrating separately the NW
1375 dipping (circles) and the SE dipping (triangles) faults in the MMFS. C) Log-log plot illustrating
1376 the relationship between topographic fault length and the displacement rate for the faults in the
1377 MMFS (grey circles) and the Mpulungu basin (black circles). D) Global dataset of displacement
1378 vs. fault length (shaded area; Nicol et al., 2016b). Black circles show data for the same faults
1379 as in Figure 3A while white triangles represent single-event displacement rupture lengths for
1380 historical earthquakes (Wesnousky, 2008). Least squares lines of best fit and R2 values are also
1381 indicated for each dataset.

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1382 Figure 4: Five topographic profiles approximately perpendicular to the trend of the MMFS (for
1383 locality of the profiles see Figure 1). The SE dipping faults are indicated with red lines while
1384 the NW dipping faults with blue lines. Sample locations are indicated with yellow circles.
1385 Numbers with F next to faults correspond to numbered faults in Figure 1 and entries in Table
1386 A2 in the Appendix. Plain numbers next to the faults indicate the throw (m) of the respective
1387 fault. The total fault throw as well as the throw of the NW (blue) and SE (red) dipping faults
1388 are indicated on each profile. Blue dashed line indicates the potential water level of the paleo-
1389 lake Mweru.

1390 Figure 5: Topographic profile along the trend of the MMFS. See Figure 1 for profile location
1391 and Figure 4 for explanations.

1392 Figure 6: Reconstructed landscape based on the topographic profiles presented in Figures 4 and
1393 5 and two additional profiles (Profiles 7 and 8) which are depicted in Figure 1. Subtracted throw
1394 resulted assuming a constant fault displacement rate (see Table A2 for values) during the last
1395 2.6 Ma. Dashed black lines represent the current landscape. Grey dashed line indicates the
1396 approximate elevation of the reconstructed landscape about 2.6 Ma (rift's onset), while black
1397 solid line is the average elevation of the reconstructed landscape. The SE dipping faults are
1398 indicated by red triangles while blue circles indicate the NW dipping faults. The SW dipping
1399 faults are presented as green rhombuses, while yellow squares show the NE dipping faults.

1400 Figure 7: A) Locations of river knickpoints for the Lake Mweru catchment. Symbol colours
1401 indicate knickpoint elevations and symbol sizes show knickpoint magnitudes (lips minus base
1402 elevation). Only river knickpoints with elevations between 900 and 1200 m asl are shown. Note
1403 the clustering of river knickpoints at ~925 (dark blue), ~1000, and ~1180 m asl that correspond
1404 to paleo-shorelines of paleo-lake Mweru. B) Hypsometric curve of Lake Mweru derived from
1405 a 30 m SRTM DEM (NASA JPL, 2020). All grid cells within the Lake Mweru catchment were
1406 binned into 10 m elevation bins and their respective surface areas were calculated (black line).

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1407 The elevations were filtered to only show hillslope angles $< 3^\circ$ (blue line). Note the two
1408 distinctive peaks at ~925 m asl and ~1180 m asl that show the elevations of the paleo-lake
1409 Mweru. Knickpoint elevation shows a high number of river knickpoints at paleo-lake shorelines
1410 (only river knickpoints with at least 30 m offset are shown).

1411 Figure 8: Two-nuclide diagrams showing ^{10}Be concentrations (atoms/g, corrected for total
1412 shielding and scaled to common elevation) versus $^{26}\text{Al}/^{10}\text{Be}$ ratios for samples of Group A. The
1413 black dashed line indicates the “steady state denudation line” and the solid black line the
1414 “constant exposure line” (e.g. Lal, 1991). Red lines show the temporal evolution of data at
1415 constant denudation rates and subsequent burial. Green lines indicate duration of burial under
1416 the assumption that samples were first exposed and later completely buried until present.
1417 Samples are indicated with black error ellipses (1σ shown). Underlined labels indicate samples
1418 taken from vertical surfaces. A) Kundabikwa Waterfalls; B) Lumangwe Waterfall; C)
1419 Ntumbachushi Waterfalls; D) Mumbuluma I Waterfalls.

1420 Figure 9: Schematic figure of successive landscape stages of Kalungwishi River at Kundabikwa
1421 Waterfalls and paleo-lake Mweru. T1: Initial river state with waterfall already in place. T2:
1422 Onset of paleo-lake Mweru below Kundabikwa Waterfalls. Areas downstream of the knickpoint
1423 are covered with water and sediment, while denudation at and upstream of the waterfalls is
1424 reduced due to lower energy environment. T3: Full establishment of paleo-lake Mweru resulting
1425 in water cover and sediment deposition on top horizontal surfaces. T4: Drainage of the paleo-
1426 lake, resulting in exposure of areas above the knickpoint with concomitant incision of lacustrine
1427 sediments at the waterfalls and deposition of these sediments into the remaining lake below the
1428 waterfalls. T5: Paleo-lake Mweru is completely drained and sediments deposited during T3 and
1429 T4 are removed through regional denudation, resulting in differential bedrock exposure. T6:
1430 Present day river course with limited sedimentary cover and ongoing down- and backwearing
1431 through increased denudation.

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1432 Figure 10: Two-nuclide diagrams showing ^{10}Be concentrations (atoms/g) versus $^{26}\text{Al}/^{10}\text{Be}$
1433 ratios for samples of Group B. See Figure 8 for explanations. A) Lupupa Waterfall; B)
1434 Mumbuluma II Waterfall (Luongo River); C) Lonzua Waterfalls.

1435 Figure 11: Two-nuclide diagram showing ^{10}Be concentration (atoms/g) versus $^{26}\text{Al}/^{10}\text{Be}$ ratios
1436 for samples of Group C. See Figure 8 for explanations.

1437 Figure 12: Schematic representation of the possible maximum extent of paleo-lake Mweru
1438 during the Plio-Pleistocene (see blue contour at 1200 m asl). Shaded areas represent
1439 reconstructed paleo-topography that was present during the Plio-Pleistocene.

1 **Quaternary landscape evolution in a tectonically active rift basin (paleo-** 2 **lake Mweru, south-central Africa)**

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20 **Keywords:** Landscape evolution; Morphotectonic Analysis; Terrestrial cosmogenic
21 nuclides; East African Rift System.

22 **Highlights**

- 23 • Explores existence of a Quaternary paleo-lake Mweru, SW East African rift system
- 24 • Applies exposure ages of knickpoints, fault analyses and geomorphic investigations
- 25 • Cosmogenic nuclides retrieve a landscape history of burial, exposure and denudation
- 26 • Faulting and lake-river knickpoints indicate a paleo-lake level at ~1200 m asl
- 27 • Lake dynamics linked to recurring neotectonics and regional climate variation

28

29 **Abstract**

30 Located between the Northern Province of Zambia and the southeastern Katanga Province of
31 the Democratic Republic of Congo, Lakes Mweru and Mweru Wantipa are part of the southwest
32 extension of the East African Rift System (EARS). Fault analysis reveals that, since the
33 Miocene, movements along the active Mweru-Mweru Wantipa Fault System (MMFS) have
34 been largely responsible for the reorganization of the landscape and the drainage patterns across
35 the western branch of the EARS. To investigate the spatial and temporal patterns of fluvial-
36 lacustrine landscape development, we determined in-situ cosmogenic ^{10}Be and ^{26}Al using
37 Accelerator Mass Spectrometry. A total of twenty-six quartzitic bedrock samples were collected
38 from knickpoints across the Mporokoso Plateau (south of Lake Mweru) and the eastern part of
39 the Kundelungu Plateau (north of Lake Mweru). Samples from the Mporokoso Plateau and
40 close to the MMFS provide evidence of temporary burial. By contrast, surfaces located far from
41 the MMFS appear to have remained uncovered since their initial exposure as they show
42 consistent ^{10}Be and ^{26}Al exposure ages ranging up to ~ 830 ka. Reconciliation of the observed
43 burial patterns with morphotectonic and stratigraphic analysis reveals the existence of an
44 extensive paleo-lake during the Pleistocene. Through hypsometric analyses of the dated
45 knickpoints, the potential maximum water level of the paleo-lake is constrained to ~ 1200 m asl.
46 High denudation rates (up to ~ 40 mm ka^{-1}) along the eastern Kundelungu Plateau suggest that
47 footwall uplift, resulting from normal faulting, caused rapid river incision, thereby controlling
48 paleo-lake drainage. The complex exposure histories recorded by ^{10}Be and ^{26}Al may be
49 explained because of lake water-level fluctuations caused by active normal faulting along the
50 MMFS coupled with intense climate variations across southeastern Africa.

51 **1. Introduction**

52 The East African Rift System (EARS) is one of Earth's best studied active intracontinental
53 rifts (e.g., Ebinger, 1989; Delvaux, 1991; Delvaux et al., 1992; Ring, 1994; Schlüter, 1997;
54 Chorowicz, 2005; Braile et al., 2006; Stamps et al., 2008; Macgregor, 2015). The combination
55 of the EARS length (> 3,000 km) and longevity (active throughout the Neogene, ~25 Ma)
56 provides a unique opportunity to study the evolution of continental rifting; from initial crustal
57 break-up (via normal faulting) to incipient oceanic rifting and, eventually, the opening of future
58 oceans. Overall, the EARS can be considered to have had a dominant control on the landscape
59 evolution of eastern Africa during the last ~30 Ma (e.g., Chorowicz, 1989, 2005; Macgregor,
60 2015). The northern and central parts of the EARS have been previously investigated and
61 linkages between tectonic activity, climatic variations and (paleo) lake formation have been
62 established (Bergner et al., 2009). However, there are limited constraints on the landscape
63 evolution of the Western Branch of the EARS.

64 The interplay of faulting, climatic and fluvial processes have resulted in the development
65 of a series of lakes that extend over a thousand kilometers along the EARS (Fig. 1 inset). The
66 existence of large and deep paleo-lakes within the Western Branch during the Plio-Pleistocene
67 (e.g. paleo-lakes Turkana, Edward-Albert, Obweruka, Bangweulu, Magadi, Thamalakane and
68 Tanganyika) is well established (Williamson, 1978; Hillaire-Marcel et al., 1986; Burrough and
69 Thomas, 2008; Cotterill and de Wit, 2011; Danley et al., 2012; Cohen et al., 2016).

70 Our study area lies to the southwest of Lake Tanganyika, straddling the border between the
71 Democratic Republic of Congo (DRC; Katanga Province) and Zambia (Northern Province; Fig.
72 1). This area (Lake Mweru) is part of the fast-spreading Western Branch of the EARS, and it is
73 characterized by an ENE-WSW trending basin-and-range topography that intersects the
74 Tanganyika Rift System perpendicularly (Fig. 1). These typical horst and graben structures
75 formed due to normal faulting along the Mweru-Mweru Wantipa Fault System (MMFS) and

76 are the seismically most active faults of central east Africa. Two of these graben structures host
77 the high-altitude present-day lakes of Lake Mweru (917 m asl) and Lake Mweru Wantipa (932
78 m asl; Delvaux and Barth, 2010; Daly et al., 2020). The lakes are bounded to the northwest and
79 southeast by two high plateaus, Kundelungu and Mporokoso, respectively (Mondeguer et al.,
80 1989; Tack et al., 2003; Daly et al., 2020; Fig. 1).

81 Active faulting has been proposed previously as one of the key controls in shaping of river
82 catchments and the landscape southwest of Tanganyika (Gumbrecht et al., 2001; Haddon and
83 McCarthy, 2005; Flügel et al., 2017; Daly et al., 2020). However, detailed geomorphological
84 and tectonic studies in the area remain scarce, with much of the literature having focused on
85 first-order physiographic characteristics of the rift to infer tectonic correlations between these
86 structures and the EARS (e.g., Mohr, 1974; Tiercelin et al., 1988; Mondeguer et al., 1989;
87 Strecker et al., 1990; Delvaux, 1991; Chorowicz, 2005; Kipata et al., 2013). Yet knickpoint
88 creation is not only correlated with tectonic activity (normal faulting) and differential
89 denudation, but may also be associated with changes in base-level and sea-level, as well as
90 climatic variations (Whipple and Tucker, 1999; Whipple et al., 2000). It has been argued that
91 climatic extremes within such fast-spreading rifts may have played a key role in controlling
92 lake-level fluctuations (Lavayssiere et al., 2019). The paleo-lakes Manonga (Tanzania) and
93 Obweruka (Uganda) are considered primary examples of climate-controlled lakes in the EARS
94 (Harrison, et al., 1996; Van Damme and Pickford, 2003). However, without geochronologic
95 dates to constrain landscape evolution rates in the Western Branch, determining the controlling
96 factors acting on the landscape remains challenging. A secondary, albeit key, consideration of
97 this study is that large knickpoints are important biogeographic controls, acting as natural
98 barriers to species dispersal, especially fish. These landforms often result in divergent evolution
99 between upstream and downstream populations of biota (Cotterill and de Wit, 2011; Schwarzer

100 et al., 2011). Thus, direct age estimates of knickpoints may inform on biogeographical histories
101 of the region.

102 Dixey (1944) inferred a “greater” Lake Mweru based primarily on lacustrine deposits that
103 are abandoned at ~1030 m asl, about 100 m higher than the present-day lake level. Moreover,
104 Bos et al. (1995, 2006) suggested that patches of sands along the present-day Zambian (southern
105 and southeastern) shores of Lake Mweru may indicate a migration of the Luapula River (Fig.
106 1). This is evidenced by sedimentary deposits that lie more to the west than its current position
107 (Bos et al., 1995). Several studies propose that the initial Lake Mweru formed a large
108 impoundment that extended over the lower part of the Northern Province of Zambia. No
109 fieldwork and/or geomorphological analysis have hitherto explored the precise extent and
110 duration of a larger paleo-lake Mweru (Dixey, 1946; Bos et al., 1995; Cotterill and de Wit,
111 2011).

112 This study attempts to identify and, where possible, quantify key factors and mechanisms
113 that control the landscape evolution proximal to Lake Mweru. By doing so, we aim to test
114 whether a precursor of Lake Mweru formed a big impoundment, inundating a larger portion of
115 the Northern Province of Zambia at its lower elevations. Collectively, our study aims to explore
116 the impact of normal fault growth on the formation of the paleo-lake and the drainage around
117 the present-day Lake Mweru by combining tectonic and geomorphologic analyses of the study
118 area with the application of terrestrial cosmogenic nuclides to dating and the magnitude of
119 denudation. By interpreting a network of surface exposure dates of key landforms (river
120 knickpoints, fault scarps, and riverbeds) across the two high plateaus (Mporokoso and
121 Kundelungu Plateaus) that surround and delimit the current lake, we deduce the age of
122 formation of the paleo-lake. By doing so, we constrain the extent and depth of the paleo-lake
123 Mweru and estimate its life span and explore possible mechanisms that reduced its Pleistocene
124 high stand. Direct geochronological derivations of the timing of the onset of the paleo-lake -

125 and its tenure - contribute new information toward resolving the landscape evolution of the
126 southwestern part of the Western Branch. Moreover, constraining the tenure of this Late
127 Cenozoic depocenter reveals important information relating to the drainage evolution of the
128 Congo-Kalahari Watershed during the Pleistocene (Flügel et al., 2015, 2017).

129 **2. Geomorphic and Geologic Setting**

130 The MMFS has a length of ~ 400 km, a width of ~ 200 km and is divided into eastern and
131 western parts. The eastern part is characterized by an elongated ENE-WSW trend, almost
132 perpendicular to the NW-SE trend of the Mpulungu basin (southern Lake Tanganyika; Tiercelin
133 and Lezzar, 2002). Small and parallel grabens form shallow depressions, characterized by
134 wetland environments (Mondeguer et al., 1989). To the west, two major troughs with NNE-
135 SSW trend form the two main shallow lakes (Lakes Mweru and Mweru Wantipa). The majority
136 of the faults follow a NNE-SSW trend, while few faults that mainly confine the end of the basins
137 have a vertical trend of WNW-ESE (Mondeguer et al., 1989). The deviation in the fault trend
138 near the Mpulungu basin results from the competency contrast with the relatively stable
139 Bangweulu Block (Mondeguer et al., 1989; Fig. 1). The rotation of the extension direction
140 reactivated earlier dip-slip faults, since strain accumulated in the same pre-Pleistocene inherited
141 crustal structures (Ring, 1994; Morley, 2002; Saria et al., 2014). Furthermore, earthquake fault
142 plane solutions from the area indicate an extensional displacement around the WNW axis
143 (Delvaux and Barth, 2010). Recent modeling studies suggest that the extension direction
144 changes from ~60° to 90°, while a left-lateral motion is applied on two domains with NE-E
145 oriented weaknesses in between them (Molnar et al., 2019 and references therein).

146 Lake Mweru (situated at ~9° S and ~29° E) forms part of the south-eastern extension of
147 the Congo Basin, being fed from the south by the Luapula River and drained to the northwest
148 by the Luvua River (Fig. 1). The drainage of the Lake Mweru sub-basin is mostly sub-dendritic,
149 representing the interaction of rivers flowing on Precambrian basement and regional faulting

150 (Deffontaines and Chorowicz, 1991, Flügel et al., 2015). The extensive delta of the Luapula
151 River suggests rapid denudation of the high plateaus between Lake Mweru and Lake
152 Bangweulu (Fig. 1). In addition, the accumulation of Quaternary sediments with a thickness of
153 400 m unconformably overlying the Neoproterozoic basement (Bos et al., 2006; Daly et al.,
154 2020) can be interpreted as further evidence of rapid denudation of the surrounding highlands.
155 Quaternary sediments are absent from Kilwa Island, a Neoproterozoic clastic rock outcrop,
156 north of the delta (Shudofsky, 1985; Tiercelin and Lezzar, 2002; Daly et al., 2020). In the north,
157 the outflowing Luvua River runs through a steep valley path with several large waterfalls,
158 suggesting rapid incision (Flügel et al., 2017). The Kalungwishi River, a major tributary, feeds
159 Lake Mweru from the east. This river drains its own highland sub-basin and has several large
160 knickpoints on its course. The inflowing rivers allow the lake to maintain a surface area of ~
161 5100 km² year-round (Bos et al., 2006).

162 Along the eastern shore of Lake Mweru, a ~10 m high beach terrace indicates an actively
163 uplifted coastline controlled by a long major fault line (Fault 16 in Fig. 1) across the southern
164 borders of the Kundelungu Plateau (Daly et al., 2020). The southeastern border of the lake is
165 delimited by a major fault (Fault 23 in Fig. 1) parallel to the trend of the Mporokoso Plateau,
166 creating Lake Mweru that is 27 m at its deepest (Bos et al., 2006). This rectangular lake is
167 surrounded by uplifted rift margins, with the lake geometry and bathymetry being controlled by
168 basin subsidence. The structural control of this setting is described in further detail below.

169 Southeast of Lake Mweru, a large basin of sub-horizontal sedimentary cover (Mporokoso
170 Plateau) is developed onto the Archean-Paleoproterozoic cratonic Bangweulu Block
171 (Mondeguer et al., 1989; De Waele et al., 2009; Fig. 1). The Mporokoso Plateau consists mostly
172 of undeformed fluvial and lacustrine sediments (De Waele and Fitzsimons, 2007). Unrug (1984)
173 characterized the Mporokoso Plateau as the late Palaeoproterozoic to late Mesoproterozoic pre-
174 Katangan succession to the northwest and northeast of the Bangweulu Block. A thick

175 sedimentary bedrock succession, called the Kundelungu Plateau, forms the half graben structure
176 that delimits the lake to the northwest (Fig 1). The Kundelungu Plateau is a part of the larger
177 Neoproterozoic (<883 Ma to ~573 Ma; Master et al., 2005) Katangan Supergroup, comprising
178 carbonate and siliciclastic sequences which were deposited in a wider basin. The bedded red
179 sand- and siltstones of the Kundelungu Plateau are exposed at the northwest corner of Lake
180 Mweru due to incision along the Luvua River (Kipata et al., 2013).

181 The interplay of faulting and erosion in the broader Lake Mweru region has resulted in two
182 relatively flat but vertically offset surfaces: the Lake Mweru valley bottom and the surrounding
183 plateaus. In general terms, the valley bottom (~ 900 m asl) is approximately 600 m lower than
184 the flat plateau tops (~ 1500 m asl). The amagmatic character of the tectonism, combined with
185 an indistinct sedimentation sequence across the southwestern extension of the EARS, does not
186 allow precise dating of the initiation of faulting in the study area. The formation of the extended
187 denudational surface of the Central African Plateau is estimated at around late Miocene to early
188 Pliocene times (Daly et al., 2020). The absence of Neogene sedimentation across the Central
189 African basin suggests that the tectonic activity must have been initiated after, or during, the
190 uplift of the Central African Plateau, thereby constraining the onset of the MMFS to the late
191 Pliocene - early Pleistocene (~2.6 Ma; Daly et al., 2020).

192 **3. Material and Methods**

193 *3.1. Sampling and Sample Grouping*

194 In this study, we aim to provide temporal control to derive rates for landscape evolution.
195 We focus on surface exposure dating of geomorphic markers using two cosmogenic
196 radionuclides (^{10}Be , ^{26}Al ; the intended inclusion of stable ^{21}Ne did not provide meaningful
197 results, see Appendix). To ensure sufficient sample material (i.e., quartz) to undertake surface
198 exposure dating, the field sampling mostly targeted bedrock quartzites due to their abundance
199 in quartz. Sampling sites were located at or near waterfalls (knickpoints) as these are sites of

200 exposed rock and considered key features in a river's development. Samples were taken from
201 two broader areas, the Mporokoso Plateau and the northeastern Lake Mweru (Fig 1). Twenty-
202 one samples, from seven waterfalls, were collected across the Mporokoso Plateau (Table 1),
203 mostly from vertical or subvertical (45-90°) surfaces (Fig. 2A), downstream of the present-day
204 knickpoint position. Where possible, samples were also taken from the waterfalls themselves to
205 determine the minimum exposure age of the knickpoint at its current position (Fig. 2B, 2C).
206 Dating two or more samples at different distances from the present knickpoint enables us, in
207 principle, to estimate knickpoint retreat rates (Fig. A1). To determine maximum denudation
208 rates, samples from horizontal surfaces (from above and below the knickpoints) were also
209 collected (Table 1; Fig. 2B).

210 Five additional quartz-rich samples were obtained from the northwest shore of Lake Mweru:
211 two from horizontal and two from vertical surfaces located along river channels (Fig. 2D) and
212 one directly from the fault that bounds the MMFS to the north (Fig. 2E). See Table 1 for sample
213 information and the Appendix (Fig. A1) for a more detailed description of the sampling process.

214 Based on their location relative to the MMFS, we subdivide our samples into three main
215 groups: Group A samples are from south and southeast of Lake Mweru within the MMFS,
216 Group B samples are from southeast of Lake Mweru but situated outside the MMFS, and Group
217 C samples derive from north of Lake Mweru, along the northern margin of the MMFS (Table
218 1; Fig. 1).

219 3.1.1. *Group A*

220 The ~25 m high Kundabikwa Waterfalls (elevation ~1043 m asl) have incised quartzitic
221 bedrock to form one of the two main knickpoints along the Kalungwishi River. Three pairs of
222 vertical and horizontal samples (KUN01/02, KUN03/04 and KUN05/06) were taken from the
223 right bank at different distances downstream of the present waterfalls. An additional sample
224 (KUN07) was collected from the riverbank immediately above the waterfalls.

225 The Lumangwe Waterfall (~1159 m asl), located ca. 37 km upstream of the Kundabikwa
226 Waterfalls, forms the most prominent knickpoint along the Kalungwishi River, with a height of
227 ~40 m and a width of ~160 m (Fig. 2C). At Lumangwe Waterfall, the main bedrock is
228 interbedded quartzite, with layers of red siltstones. Due to the vegetation density and the large
229 amount of water, sampling this waterfall was challenging. Therefore, only one siltstone sample
230 from a vertical face (LUM01) and a pair of quartzitic samples from vertical (LUM02) and
231 horizontal (LUM03) surfaces were taken. Due to the very low amount of appropriately sized
232 quartz grains, LUM01 could not be analyzed.

233 The cascade of the Ntumbachushi Waterfalls (~1160 m asl) is about 30 m high and is located
234 on the Ng'ona River. Three samples were collected from these waterfalls, of which NTU01 and
235 NTU03 were taken from the right vertical bank downstream of the current knickpoint, while
236 NTU02 was collected above NTU01 from the corresponding horizontal bank.

237 The Mumbuluma Waterfalls (~1186 m asl) are situated on the Mumbuluma River and
238 cascade down over two discrete steps. They will be denoted Mumbuluma I Waterfalls hereafter
239 to distinguish them from the equally named waterfall on the Luongo River (section 3.1.2).
240 MUM01 and MUM04 were collected from a vertical and a horizontal surface, respectively, of
241 the top cascade, while the samples MUM02 (horizontal) and MUM03 (vertical) were taken
242 from the lower step of the waterfalls.

243 3.1.2. Group B

244 The Lupupa Waterfall is located on the Mukubwe River and has a height of approximately
245 90 m. The highest set of cascades is located at about 1360 m asl. Due to difficulties associated
246 with the steepness of the waterfall, we only managed to collect one sample (LUP01) close to
247 the top of the vertical cliff.

248 The Luongo River is one of the dominant rivers of the Northern Province in Zambia. We
249 collected two samples from inclined surfaces of the Mumbuluma Waterfall (hereafter denoted
250 Mumbuluma II to distinguish it from the falls on the Mumbuluma River; section 3.1.1.), which
251 lies at ~1370 m asl with ~10 m height.

252 The Lunzua Waterfalls form a series of cascades along the Lunzua River. The waterfalls
253 are close to the town of Mpulungu at the southern shore of Lake Tanganyika (Fig. 1) and are
254 situated at ~1300 m asl. Two vertical samples (LUZ01 and LUZ02) were collected from the
255 banks of the Lunzua River downstream of the cascades.

256 *3.1.3. Group C*

257 Due to the extreme inaccessibility of waterfalls caused mainly by vegetation along the
258 northwestern side of Lake Mweru, no samples from waterfalls were collected in that area.
259 Rather, they were taken from riverbeds and banks comprising mostly quartzitic bedrock.
260 MWE01 derived from an almost vertical (80°) face that forms the surface expression of a
261 normal fault scarp (Fig. 1; Fig. 2E). Two samples (ME04, ME05) were collected from the
262 vertical walls of the gorge along the Luvua River, close to where it discharges from Lake Mweru
263 (Fig. 1; Fig. 2D). The samples ME06 and ME09 were collected from horizontal bank surfaces
264 along the Misefwe and Lwilwa rivers, two small tributaries northwest of Lake Mweru.

265 *3.2. Sample Processing*

266 Samples were crushed and sieved to 250–500 µm. Quartz grains were separated by the
267 standard methods of heavy liquid and Frantz magnetic separation (Kohl and Nishiizumi, 1992).
268 To dissolve all non-quartz minerals, samples were treated with dilute HCl and H₂SiF₆ (Brown
269 et al., 1991). Afterwards, HF was used to remove any contribution of meteoric ¹⁰Be by partially
270 dissolving the quartz grains. A small fraction from each sample (~2 g) was kept for ²¹Ne
271 analyses, while the remaining ~25-50 g were used for ¹⁰Be and ²⁶Al analyses. Preparation and

272 processing of the samples took place at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR)
 273 following a modified version of the method described by Merchel and Herpers (1999) and at
 274 the University of Potsdam following the sample preparation manual of the UC Santa Barbara
 275 Cosmogenic Nuclide Preparation Facility
 276 (http://www.geog.ucsb.edu/~bodo/pdf/bookhagen_chemSeparation_UCSB.pdf), which is
 277 based on modifications of previous studies (e.g., Kohl and Nishiizumi, 1992; von Blanckenburg
 278 et al., 2004). The samples from the Kundabikwa Waterfalls (KUN) were prepared at HZDR,
 279 while the rest of the samples were prepared at University of Potsdam. For the radionuclide
 280 extraction, a known amount (~0.3 mg) of ⁹Be carrier was added to each sample, whilst ~1 mg
 281 Al carrier was added only to the blank samples (Table A1). Concentrated HF was used for
 282 digestion of the samples. After evaporation of the HF and the addition of HClO₄, ICP-AES
 283 (Inductively Coupled Plasma Atomic Emission Spectroscopy) or ICP-MS (Inductively Coupled
 284 Plasma Mass Spectrometry) measurements were done from aliquots, which were dissolved in
 285 HCl, in order to quantify the total Al concentration (Appendix Table A1). Be and Al were
 286 separated via ion exchange columns and precipitated as hydroxides. The last step before the
 287 target pressing was the ignition to oxides (900-1000 °C). Be isotope ratios were measured by
 288 Accelerator Mass Spectrometry (AMS) at the DREAMS facility of HZDR (Rugel et al., 2016;
 289 Table 2) and the National Laboratory of Age Determination of the Norwegian University of
 290 Science and Technology (NTNU), Trondheim (Seiler et al., 2018; Table 2). Al isotope ratio
 291 measurements were performed at HZDR (Rugel et al., 2016; Table 2) and at the French national
 292 facility Accélérateur pour les Sciences de la Terre, Environnement, Risques (ASTER,
 293 CEREGE, Aix-en-Provence; Arnold et al., 2010; Table 2). All processing values are provided
 294 in the Appendix (Table A1) and are one to three orders of magnitude lower than sample values.

295 3.3. Calculation of Exposure and Burial Ages and Denudation Rates

296 Waterfalls are dynamic systems that undergo geomorphological changes through time. The
297 rate at which knickpoints migrate upstream along a river is dependent on a combination of
298 lithology, elevation, morphology, climatic conditions, and tectonic activity (Howard et al.,
299 1994; Whipple and Tucker, 1999; Whipple et al., 2000; Brocklehurst, 2010). Their complexity
300 means waterfalls can be a challenge to date, even with cosmogenic nuclides. Nevertheless,
301 useful parameters such as denudation rates, periods of burial, minimum exposure ages and
302 sequential exposure can be estimated for knickpoints and their surrounding landscape.

303 To calculate exposure ages and denudation rates, sea level high latitude (SLHL) spallogenic
304 production rates of 4.01 atoms $\text{g}^{-1} \text{a}^{-1}$ for ^{10}Be and 27.93 atoms $\text{g}^{-1} \text{a}^{-1}$ for ^{26}Al were used
305 (Borchers et al., 2016). Minimum ages and maximum denudation rates were calculated with
306 CosmoCalc 3.0 (Vermeesch, 2007), using Lal (1991) scaling factors and default values for all
307 parameters except the SLHL production rates. The density used for the calculations is 2.65 g
308 cm^{-3} for all samples. Values were corrected according to sample thickness (1-10 cm) and
309 geometric shielding. All $^{10}\text{Be}/^9\text{Be}$ ratios were normalized to the in-house standard material
310 “SMD-Be-12” with a weighted mean value of $(1.704 \pm 0.030) \times 10^{-12}$ (Akhmadaliev et al., 2013).
311 The “SMD-Be-12” has been cross-calibrated to the NIST SRM 4325 standard, which has a
312 $^{10}\text{Be}/^9\text{Be}$ ratio of $(2.79 \pm 0.03) \times 10^{-11}$ (Nishiizumi et al., 2007). $^{26}\text{Al}/^{27}\text{Al}$ ratios measured at
313 DREAMS were normalized to the in-house standard “SMD-Al-11”, with a $^{26}\text{Al}/^{27}\text{Al}$ ratio of
314 $(9.66 \pm 0.14) \times 10^{-12}$ (Rugel et al., 2016), while the Al ratios measured at ASTER were
315 normalized to “SM-Al-11” with a $^{26}\text{Al}/^{27}\text{Al}$ ratio of $(7.401 \pm 0.064) \times 10^{-12}$ (Arnold et al., 2010).
316 Both Al standards are traceable via cross-calibration to the same primary standards (MB04-A,
317 MB04-B, MB04-D) from a ^{26}Al round-robin exercise (Merchel and Bremser, 2004). For
318 samples with ^{10}Be and ^{26}Al ages agreeing within error limits, error-weighted mean ages were
319 also calculated.

320 Since the attenuation length of terrestrial cosmogenic nuclide (TCN) production is smaller
321 at low angles than in a vertical direction (Dunne et al., 1999), the TCN concentration decreases
322 faster perpendicularly beneath an inclined surface than beneath a horizontal surface. This must
323 be taken into account when calculating denudation rates of inclined or vertical surfaces and,
324 therefore, a slope dependent correction (Hermanns et al., 2004) was applied to such surfaces.

325 In general, discordance between ^{10}Be and ^{26}Al ages may be due to long exposure (when ^{26}Al
326 production equals decay, i.e. after a few ^{26}Al half-lives), denudation which has not been taken
327 into account, or shielding from cosmic rays after initial exposure (e.g. Lal, 1991; Gosse and
328 Phillips, 2001; Goethals et al., 2009). To reveal complex exposure histories, ^{10}Be concentrations
329 can be plotted against $^{26}\text{Al}/^{10}\text{Be}$ ratios. In such two-nuclide plots, samples which lie between
330 the “steady state denudation line” and the “constant exposure line” have experienced simple
331 exposure histories, i.e. a combination of surface exposure and denudation. In contrast, samples
332 plotting beneath the steady state field indicate burial after initial exposure. The calculation of
333 burial ages (Lal, 1991) is based on the assumption that a surface has once been irradiated by
334 cosmic rays up to steady state and was later buried until the present. This assumption is
335 obviously not correct in our study, as all samples were taken from presently exposed surfaces.
336 If such samples indicate burial, they must have been re-exposed sometime in the past, and only
337 minimum burial ages can be calculated from them.

338 *3.4. Normal Fault Analysis*

339 We used a Shuttle Radar Topography Mission (SRTM) digital surface model (DSM),
340 Google EarthTM imagery, and the ArcGIS software (version 10.6) to map the traces of 63 normal
341 faults in the area, from west of Lake Mweru to the southern shorelines of Lake Tanganyika (Fig.
342 1). This area largely includes faults of the MMFS, while at its eastern edge it comprises elements
343 of the EAR (Fig. 1).

344 We focused our analysis on two fault parameters that, collectively, provide important
345 information on the fault system's activity and growth: the fault length (L) and the fault
346 displacement (D). Fault length represents an important parameter in estimating the seismic
347 potential (including earthquake magnitude and single-event displacement) on each studied fault
348 (Wells and Coppersmith, 1994; Wesnousky, 2008). It should be noted that several of the
349 identified faults contain numerous parallel or sub-parallel strands (e.g. faults 30, 38, 44, 46, 49,
350 etc. in Fig. 1) or along-strike segments (e.g. 1, 2, 7, 16, 43, etc.) which are either hard or soft
351 linked (Walsh and Watterson, 1991). Here, these elements are thought to represent a single
352 coherent fault that ruptures along its entirety; however, it remains possible that individual
353 earthquakes rupture these faults or fault segments only partially. The maximum vertical
354 displacement (or throw) on each normal fault derives by averaging numerous (>10) scarp height
355 measurements from fault perpendicular topographic profiles collected proximal to the fault's
356 centre. Fault lengths and displacements represent direct measurements drawn on the DSM and
357 are presented in Table A2 together with the faults' geometries. Indirect earthquake attributes
358 (e.g. earthquake magnitude, average recurrence interval, etc.) associated with each studied fault
359 derive from Wells and Coppersmith's (1994) and Wesnousky's (2008) empirical relations and
360 are also included in Table A2 (see caption of Table A2 in the Appendix for details).

361 Measurement of active fault lengths and displacements can be subject to significant
362 uncertainties (Wesnousky, 2008; Mouslopoulou et al., 2012; Nicol et al., 2016a, 2020a). This
363 is because fault scarps are prone to denudation and/or burial, especially at fault tips, where
364 displacements are often too small to be detected with conventional mapping methods (such as
365 aerial photo or DSM analysis, field mapping, etc.; Begg and Mouslopoulou, 2010). In this study,
366 fault lengths and displacements should be considered as minimum values as fault scarps of < 2
367 m are not resolvable on the available DSM, and also because fault scarps of any size may be
368 partly or entirely modified by denudation and/or burial (see Nicol et al., 2020a for detailed
369 discussion on sampling biases). Rifting across the MMFS is thought to have initiated at about

370 2.6 Ma (late Pliocene-early Pleistocene; Tiercelin and Lezzar, 2002; Molnar et al., 2019; Daly
371 et al., 2020), thus, fault displacement rates are calculated over this time-period (~2.6 Ma) (Table
372 A2).

373 3.5. *Digital Topography Analyses*

374 We analyzed selected domains of the 30-m NASADEM (NASA JPL, 2020). We have
375 delineated the catchment of Lake Mweru using standard procedures implemented in
376 TopoToolbox (Schwanghart and Scherler, 2014). Elevation lows (pits) were filled, a
377 hydrological-corrected DEM has been calculated, and the catchment extents were visually
378 verified. Our catchment extent, using the higher resolution NASADEM data, is similar to that
379 calculated in the HydroBASINS dataset (Lehner and Grill, 2013). The catchment extent was
380 used to extract the hypsometric curve, showing the surface area for each elevation bin. Further,
381 we identified river knickpoints using previously published approaches (Neely et al., 2017). This
382 entailed deriving longitudinal river profiles, converting them to Chi coordinates, and identifying
383 knickpoint lips and bases based on positive or negative distance above a best-fit Chi profile
384 (Neely et al., 2017). Chi profiles are area-normalized profiles where the distance coordinate has
385 been normalized by an averaged river profile following an exponential function (Perron and
386 Royden, 2012). The resulting profile, when in steady state, will follow a straight line. We
387 analyze profile deviation above and below an averaged line to identify knickpoints. More
388 detailed analysis steps are described in Neely et al. (2017). To avoid small knickpoints and
389 remove noise inherent in the DEM, we focus on knickpoints with magnitudes (i.e., distances
390 from the average Chi profile line) exceeding 30 m. Field observations suggest that major
391 waterfalls associated with past lake-level highstands are generally higher than 30 m.

392 4. Results

393 We present our results as three components, starting with the determinations of the
394 terrestrial cosmogenic nuclides. Second, the findings of tectonics analyses are reported,

395 summarizing the fault geometries and kinematics of the faulted topography. Third, we present
396 a geomorphic analysis of northeast Zambia and the adjacent Katanga Province. In the
397 subsequent section 5 we will focus on reconstructed scenarios informed from the TCN results,
398 which are classified according to respective landscape history, including elevation, and
399 contrasting tectonic regimes.

400 *4.1. Terrestrial Cosmogenic Nuclides*

401 While the ^{10}Be and ^{26}Al results indicate extended periods of burial for many samples (see
402 section 4.1.1.), there is no straightforward way to interpret the ^{21}Ne data along with ^{10}Be and
403 ^{26}Al . Due to their inconclusive nature, we do not discuss them further but present and describe
404 them in the Appendix (Table A3 and Fig. A3, A4). Below we present the ^{10}Be and ^{26}Al results
405 (shown in Table 2) by sample groups.

406 *4.1.1. ^{10}Be and ^{26}Al minimum exposure ages*

407 *4.1.1.1. Group A*

408 Vertical samples KUN01 and KUN04 from Kundabikwa Waterfalls yield ^{10}Be minimum
409 ages of ~510 and ~580 ka, respectively, while ^{26}Al minimum ages are younger, ~240 and ~360
410 ka. The horizontal samples KUN03, KUN05 and KUN07 show consistently younger minimum
411 ^{10}Be ages than the vertical samples (~320-370 ka) and ^{26}Al minimum ages in a similar range
412 (~170-360 ka). The horizontal KUN02 (^{10}Be : ~150 ka; ^{26}Al : ~80 ka) and vertical KUN06 (^{10}Be :
413 ~90 ka; ^{26}Al : ~70 ka) samples show much younger minimum ages compared to the other
414 Kundabikwa samples. The Lumangwe Waterfall samples LUM02 and LUM03 yielded
415 minimum ^{10}Be ages of ~230 and ~200 ka, respectively, and minimum ^{26}Al ages of ~180 and
416 ~190 ka. One vertical sample from Ntumbachushi Waterfall (NTU01) yielded a very young
417 minimum ^{10}Be and ^{26}Al mean age of ~20 ka. The ^{10}Be minimum age of the horizontal sample
418 NTU02 is similar to those derived from the horizontal surface proximal to the Kundabwika
419 Waterfalls (~380 ka) while its ^{26}Al age (~340 ka) is slightly younger. NTU03, which was

420 derived from a vertical surface, returns much younger ^{10}Be and ^{26}Al minimum ages of ~110 and
421 ~100 ka, respectively. The samples MUM01 (vertical) and MUM04 (horizontal) from the top
422 cascade of the Mumbuluma I Waterfalls yield minimum ^{10}Be ages of ~70 and ~110 ka,
423 respectively, while ^{26}Al minimum ages are slightly younger (~60 and ~90 ka). The horizontally
424 positioned sample MUM02 shows minimum ages of ^{10}Be (~270 ka) and ^{26}Al (~240 ka) which
425 are older than for the vertical sample MUM03 (~110 and ~100 ka, respectively).

426 4.1.1.2. *Group B*

427 For the single sample collected from Lupupa Waterfall, the minimum ^{10}Be and ^{26}Al ages
428 are in excellent agreement at a mean of 42.4 ± 1.1 ka. The Mumbuluma II Waterfall sample
429 LUO01 yields a minimum ^{10}Be and ^{26}Al mean age of 76.8 ± 2.2 ka, which is an order of
430 magnitude younger than the exceptionally old minimum mean age of LUO02 of 833 ± 17 ka.
431 Sample LUZ01, taken within a narrow river gorge of the Lunzua River, shows a minimum ^{10}Be
432 and ^{26}Al mean age of 524 ± 12 ka. LUZ02 was collected only about 2.4 m below the top surface
433 and yields a mean age of 102.2 ± 2.7 ka.

434 4.1.1.3. *Group C*

435 Sample MWE01 yielded minimum ^{10}Be and ^{26}Al ages which are in agreement at 7.79 ± 0.60
436 ka. Samples ME04 and ME05 return minimum ^{10}Be and ^{26}Al mean ages of 12.29 ± 0.81 ka and
437 11.56 ± 0.72 ka, respectively, while ME06 and ME09 yielded minimum ^{10}Be and ^{26}Al mean ages
438 of 42.8 ± 1.6 and 45.7 ± 2.0 ka, respectively.

439 4.1.2. *Maximum denudation rates*

440 For several samples that derive from Groups B and C, maximum denudation rates are also
441 reported (Table 3). Samples from the eastern part of the Kundelungu Plateau yield maximum
442 denudation rates ranging from ~15 to ~40 mm ka^{-1} (samples MWE01, ME04, ME05, ME06 and
443 ME09), while denudation rates associated with the Mporokoso Plateau are much lower and
444 range from ~0.4 to ~6 mm ka^{-1} (samples LUO01, LUO02, LUZ01 and LUZ02). Even though

445 the denudation rates reported in this study are local ones, they indicate general differences in
446 denudation history of both studied plateaus.

447 4.2. Tectonic Analysis

448 4.2.1. *Fault kinematics and scaling relationships*

449 We mapped 63 lineaments that we interpreted to represent the surface expressions of active
450 normal faulting at depth (Fig. 1; Appendix Table A2). Fifty-three faults are located within the
451 MMFS, while ten are located within the Mpulungu basin (southern Lake Tanganyika). The
452 faults in the southern MMFS strike NE-SW while the northeast section of the fault system
453 swings its strike clockwise to an ENE-WSW orientation (Table A2), intersecting, at high angles
454 ($\sim 90^\circ$), the NW to SW trending normal faults around Lake Tanganyika. Fault lengths (L) in our
455 dataset range from 12 km to 168 km, whereas maximum vertical fault displacements (D) range
456 from 10 m to 700 m (Fig. 3A). Fault displacement rates (DR) are typically low, ranging from
457 0.004 mm a^{-1} to 0.27 mm a^{-1} (Fig. 3C). This, in turn, corresponds to an average earthquake
458 recurrence for the faults in the MMFS of $\sim 120 \text{ ka}$ (Table A2). In order to understand the impact
459 of normal faulting on the formation of the past and current landscape proximal to Lake Mweru,
460 we explore the D-L relationship on the 53 normal faults in the MMFS (Table A2).

461 The D-L relation may provide important information on the growth and scaling properties
462 of faults (Fig. 3; Walsh and Watterson, 1988; Bilham and Bodin, 1992; Cowie and Scholz,
463 1992; Schlische et al., 1996; Kim and Sanderson, 2005; Schultz et al., 2008; Nicol et al., 2010,
464 2020a). The graphs in Figures 3A and 3C indicate a positive D-L and DR-L relationship for the
465 faults in the MMFS, suggesting that larger faults have accommodated more displacement and
466 have moved faster than smaller faults (Nicol et al., 1997, 2005). Similar graphs, which indicate
467 positive relationships between fault displacements/displacement rates and length, have been
468 recorded on several other active and inactive fault systems globally (Kim and Sanderson, 2005;
469 Mouslopoulou et al., 2009; Nicol et al., 2020a, b). Despite the overall positive D-L trend for

470 most fault systems globally, the D values at a given L value and the slope of the best-fit line in
471 these graphs may vary between fault systems (but also between different sampling periods in
472 the same fault system), with the slope typically ranging from 0.5 to 1.5 (Schlische et al., 1996;
473 Walsh et al., 2002; Kim and Sanderson, 2005; Nicol et al., 2010; Torabi and Berg, 2011, Nicol
474 et al., 2020b). This variability in the D-L scaling may be due to biases arising from the time-
475 window of observation, the age of the faulted horizons, the strain accommodated by each fault
476 system, the mechanical properties of the faulted rocks and/or the degree of fault interactions
477 (Watterson et al., 1996; Bailey et al., 2005; Mouslopoulou et al., 2009; Nicol et al., 2010;
478 Rotevatn et al., 2019).

479 To better understand the growth of the faults in the MMFS with respect to other fault
480 systems globally, we have plotted their D-L trend against a global dataset of inactive normal
481 faults (Fig. 3D; Nicol et al., 2016c and references therein). Comparison shows that the faults in
482 the MMFS plot in agreement with the global dataset occupying, however, the lower part of the
483 global population (slopes of ~ 0.92 vs. ~ 0.99 , respectively; Fig. 3D). To explore further the
484 growth of the faults in Africa, we have also plotted in Figure 3D the single-event displacement
485 rupture lengths from a global compilation of historic normal fault earthquakes (Wesnousky,
486 2008). As expected, single earthquakes clearly plot below the average trend of the global dataset
487 (including the MMFS), their slope is significantly less than 1 (~ 0.3) and their scatter greater
488 than that of the global dataset (R^2 values of 0.25 vs. 0.85; Fig. 3D). These features collectively
489 suggest that each fault in the MMFS has accommodated numerous earthquakes, the number of
490 which scales with fault length.

491 The approximate number of earthquakes accommodated by each fault in the MMFS,
492 together with their earthquake magnitude and recurrence interval, has been calculated using
493 Wesnousky's (2008) scaling relationships (Table A2). First, we calculate the single event
494 displacement (SED) for each fault in the MMFS from the fault length (L) and subsequently the
495 earthquake recurrence interval on each fault (Table A2). The recurrence interval is subsequently

496 used, in conjunction with the 2.6 Ma displacement rate (time-period that rifting is thought to
497 have initiated), to estimate the number of earthquakes accommodated by each fault (Table A2
498 and Fig. A2). We find that the faults in the MMFS are likely to have accommodated ~2,000
499 ground-rupturing earthquakes since the rift's onset (~35 events per fault), with earthquake
500 magnitudes ranging from M6.7 to M7.2 (Table A2 and Figure A2).

501 *4.2.2. Faulted topography*

502 To explore the relationship between the faulted topography, the available TCN ages and
503 the current extents of Lakes Mweru and Mweru Wantipa, we generated five rift-perpendicular
504 topographic profiles (Fig. 4) and one rift-parallel profile (Fig. 5). The profiles 1-3, across the
505 southern MMFS and the modern Lake Mweru, reveal a strongly asymmetric rift (Fig. 4A-C).
506 To characterize the distribution of strain along the rift, we have calculated the cumulative throw
507 across the five profiles illustrated in Figure 4. Furthermore, to better visualize the landscape
508 when rifting in the area was about to commence, we subtracted from the identified faults the
509 throw measured along the topographic profiles 1-8 (Fig. 6), that is the displacement accrued on
510 each fault since the initiation of faulting at 2.6 Ma.

511 Our analysis shows a three-fold increase in the cumulative throw, trending northeastwards
512 along the rift (from ~800 m across profile 1 to ~2180 m across profile 5), with the southeast
513 dipping faults having accommodated almost twice as much displacement (4550 m) compared
514 to the northwest dipping faults (2690 m; Fig. 4). The dominance of the southeast dipping faults
515 is persistent along the entire length of the MMFS, where these faults appear to have locally
516 (e.g., see profile 5) accommodated up to 4 times more throw compared to the northwest dipping
517 faults. The northeastward increase in extension, which is manifested by the greater number of
518 active faults and the more confined rift axis, is not surprising as the MMFS at its northernmost
519 extension approaches (and intersects) the fast spreading (~1 mm a⁻¹) EARS (Fig. 1; Fernandes
520 et al., 2004; Calais et al., 2006; Omenda et al., 2016).

521 Topographic analysis suggests that the faults which are largely responsible for the
522 formation of the modern landscape within the MMFS are faults 8, 9, 16, 17, 23 and 28 in the
523 south, and faults 38, 40, 46 and 48 in the north. The profile along Lake Mweru (profile 6 in Fig.
524 5) reveals a shallow topographic basin (within <100 m from the modern lake) which is bounded
525 at its northern side by the Kundelungu Plateau and to the south by steep hilly country formed
526 by sediments of the Luapula River's delta (Fig. 4A). Profile 7 runs along Lake Mweru Wantipa
527 and displays the high topographic relief between the Mporokoso Plateau and the Mpulungu
528 basin, while profile 8 reveals the impact of normal faulting on the landscape associated with the
529 Kundelungu Plateau (Fig. 6). These profiles are discussed in detail in Section 6.

530 4.3. Geomorphic Analysis

531 We identified a total of 61 river knickpoints from individual stream profiles that
532 corroborate the paleo-shoreline observation (Fig. 7A). In a second step, we analyzed the
533 hypsometry of the Lake Mweru catchment to delineate the impact of paleo-lake Mweru on the
534 elevation distribution. The hypsometric curve of the catchment (Fig. 7B, blue and black lines)
535 reveals large areas characterized by gentle slopes, which we interpret to correspond to areas
536 confining the paleo-lake Mweru. They all lie at elevations between 920-930 m asl, 990-1100 m
537 asl and 1170-1190 m asl, which align with the sampled waterfalls at 1050 and 1160 m asl. We
538 observe additional areas with low slopes at varying elevations, but focus our analyses on the
539 most prominent elevations. We have furthermore excluded slope angles above 3° to better show
540 terrain associated with lake-erosion processes (Fig. 7B, blue line). In the same elevation
541 framework, we plot the number of knickpoints observed at a specific elevation. Knickpoints
542 cluster at specific elevations and delineate the remnant paleo-shorelines in a more refined spatial
543 pattern, indicating three abandoned shorelines at elevations of ~925 m asl, ~1000 m asl and
544 ~1180 m asl, respectively (Fig. 7B).

545 **5. Reconstructed Scenarios for the Principal Sets of TCN Results**

546 Overall, our TCN samples record a pattern of temporary burial over parts of the region
547 studied. As discussed earlier (Section 1), stratigraphic evidence suggests that during the
548 Pleistocene the study area hosted an enlarged lake, approximately 130 km wide and 300 km
549 long (~40,000 km²), centered around the (much smaller) present-day Lake Mweru (~5000 km²).
550 TCN production is completely blocked (except for some minor production by muons) when a
551 surface is ≥ 10 m below the lake level. Therefore, interpreting the Plio–Pleistocene tectonic
552 history of south-central Africa, we suggest that the burial patterns recorded by our samples most
553 likely reflect the existence of a paleo-lake that inundated a much larger depocenter.

554 *5.1. Group A*

555 Most of the samples from Group A indicate burial (Fig. 1; Fig. 8). A few significant age
556 discrepancies arising from samples collected from a single waterfall are also evident. The fact
557 that all waterfalls in Group A are located within the MMFS and at elevations <1200 m asl (that
558 is, significantly lower than Group B samples which are all located >1200 m asl) indicates that
559 faulting and uplift may have played an important role in the burial of the landscape. Below we
560 discuss separately the likely exposure scenarios for each waterfall in Group A.

561 *5.1.1. Kundabikwa Waterfalls*

562 Samples from the Kundabikwa Waterfalls indicate burial over a continuous period for at
563 least 250 ka (Fig. 8A). The significantly younger minimum exposure ages (Section 4.1.1.) of
564 samples KUN02 and KUN06 probably indicate enhanced surface denudation or
565 rockfalls/landslides (e.g. mechanical failure of exposed rock outcrop leading to fresh exposure).
566 In addition, two of the three pairs of samples (KUN01/KUN02 and KUN03/KUN04) indicate
567 older ¹⁰Be and ²⁶Al minimum ages (Table 2) for the vertical face compared to the top horizontal
568 surface. The fact that the top horizontal surface (KUN02, KUN03 and KUN05) of the area is

569 younger than the vertical sections (KUN01, KUN04) is intriguing and requires further
570 examination.

571 Based on the relative ^{10}Be and ^{26}Al minimum age estimates, we reconstruct the complex
572 exposure-burial history of Kundabikwa Waterfalls and paleo-lake Mweru over six sequential
573 stages (Fig. 9). The pre-lake stage (T1) represents the initial state of the river. In order to record
574 a burial signal, the studied surfaces must have been exposed prior to burial. Thus, the knickpoint
575 must have already existed during stage T1. The vertical faces of the banks are gradually exposed
576 through sequential knickpoint retreat. During this stage, channel denudation dominates. The
577 denudation rate is relatively low on the top-horizontal surface. Most geomorphologic
578 characteristics from this stage are assumed to have been erased by today. The second stage (T2)
579 is defined by the onset of the lake-level rise (flooding). Water starts to cover the vertical
580 riverbanks. Denudation decreases as the base-level increases, leading to slower knickpoint
581 migration. Denudation is minimal (but probably not zero) as the top horizontal surfaces are
582 flooded and lake sedimentation initiates. During T3, the lake reaches its greatest depth. Water
583 and sediments now shield the sampled surfaces from cosmic ray irradiation, entirely blocking
584 ^{10}Be and ^{26}Al production. Lacustrine sedimentation occurs mostly on the horizontal surfaces.
585 The lake-level is now the base-level, resulting in the interruption of denudation.

586 Denudation recommences with the onset of lake drainage and associated drop of the water-
587 level (stage T4). Localized denudation occurs on the sediment-covered horizontal surfaces
588 while the vertical faces remain under water, with TCN production still being absent for all
589 submerged areas. Consequent to paleo-lake outflow (T5) via the Luvua River, regional
590 denudation of the sediments that blanket the horizontal surfaces occurs. This period of new
591 equilibrium may have been characterized by low energy environments, which can be described,
592 for example, as a changing complex of small wetlands, oxbow lakes and meandering channel
593 systems, similar to the current situation in the upper reaches of present-day Lake Mweru.

594 Lacustrine sediments are now confined to the top horizontal banks, as in the channel the
595 sediments are eroded. The subsequent lowering of base level as the lake drains sees the
596 rejuvenation of the waterfalls. In the last stage (T6), most of the lacustrine sediments have been
597 removed from all surfaces and the top horizontal surfaces are re-exposed and TCN production
598 resumes. Back- and downwearing of the vertical bank faces leads to further denudation of the
599 bedrock surfaces. We note that gradual rising and lowering of the lake's water-level between
600 stages T2 and T4 should have lasted thousands or even tens of thousands of years in order to
601 induce a detectable difference between the cosmogenic nuclide concentrations of different
602 (horizontal vs. vertical) sampled surfaces. Indeed, previous studies of other paleo-lakes have
603 revealed long-term lake fluctuations spanning time-intervals from 2 to >20 ka (Masters et al.,
604 1991; Gamrod, 2009; Shuman et al., 2009; Trauth et al., 2010).

605 *5.1.2. Lumangwe Waterfall*

606 According to Figure 8B, sample LUM03 does not show an unequivocal burial signal, in
607 contrast to LUM02 that clearly underwent a complex exposure history. One possible
608 explanation is that LUM02 (1150 m asl) was covered by lake water, while LUM03 (1159 m
609 asl) was not (or it was only slightly covered so the cosmogenic nuclide production did not stop
610 completely). Such a scenario implies that the Lumangwe cascades marked the eastern shore of
611 the paleo-lake. Another possibility is that the LUM02 rock face was covered by a recent
612 landslide or rockfall. However, no physical evidence of such an event can be found, suggesting
613 that if it did occur, the Kalungwishi River has subsequently removed any such debris. A
614 minimum burial time of 300 ka is estimated for LUM02 (Fig. 8B).

615 *5.1.3. Ntumbachushi Waterfalls*

616 Samples NTU01 and NTU02 do not indicate a clear burial signal. The weathered profile of
617 the NTU01 surface and the very young minimum ^{10}Be and ^{26}Al mean age (~ 20 ka) most likely
618 indicate a recent rockfall. Although NTU03 does indicate burial of ~ 400 ka (Fig. 8C), this age

619 is questionable due to the young minimum ^{10}Be and ^{26}Al ages (~100 and ~80 ka, respectively)
620 that derive from the same sample and which, coupled with the highly weathered and fractured
621 nature of the sampled surface, make it unlikely to record an ancient pre-lake stage.

622 *5.1.4. Mumbuluma I Waterfalls (Mumbuluma River)*

623 All results from the Mumbuluma I falls indicate a clear burial signal at 1σ confidence level,
624 though not at 2σ (Fig. 8D). The top cascade yields younger minimum ^{10}Be ages (MUM01,
625 MUM04) than the second cascade downstream (MUM02, MUM03), suggesting that the lower
626 waterfall formed before the top one. Also, the top horizontal surface (MUM04; minimum ^{10}Be
627 age 113 ka) seems to have undergone more intense denudation than the lower surface (MUM02;
628 271 ka). A rockfall may explain the young minimum ^{10}Be age of the vertical sample MUM01
629 (~70 ka). The approximate minimum burial time of the area is ~350 ka (Fig. 8D), an age which
630 is in good agreement with the duration of burial recorded at the Lumangwe falls.

631 *5.2. Group B*

632 Samples in Group B date waterfalls which are situated outside the MMFS (Fig. 1). ^{10}Be and
633 ^{26}Al minimum ages are in good agreement for most samples, indicating that these surfaces have
634 not been buried since their initial exposure (Fig. 10). Thus, it appears that these locations were
635 not flooded by the paleo-lake. Minimum exposure ages and maximum denudation rates within
636 this group are discussed below.

637 *5.2.1. Lupupa Waterfall*

638 LUP01 shows very young minimum ^{10}Be and ^{26}Al ages, which probably do not reflect the
639 actual age of the waterfall but a rockfall event. For such recent events, no burial signal is
640 expected (Fig. 10A).

641 5.2.2. *Mumbuluma II Waterfall (Luongo River)*

642 Both samples from the Luongo's Mumbuluma II Waterfall are from sub-vertical (45°-50°)
643 surfaces and show no clear ^{10}Be - ^{26}Al burial signal (Fig. 10B). This cascade was formed on a
644 bedrock contact between quartzites and sandstones. The development of the cascade is clearly
645 controlled by differential denudation between the overlying softer sandstone and the harder
646 quartzite. Maximum denudation rates of $\sim 6 \text{ mm ka}^{-1}$ for the sandstone (LUO01) and of ~ 0.4
647 mm ka^{-1} for the quartzite (LUO02) are calculated (Table 3). The large difference in the
648 denudation rates of the two lithologies further highlights the role of differential denudation in
649 the formation of this cascade. Sample LUO02 plots exactly on the no denudation line in Figure
650 5b, indicating a minimum ^{10}Be and ^{26}Al mean exposure age of $833 \pm 17 \text{ ka}$. This age, which is
651 the oldest recorded minimum exposure age among the studied waterfalls, indicates a very old
652 formation age of the Mumbuluma II knickpoint. It is worth mentioning that this is an
653 exceptionally old age for an inclined surface located within the zone of an actively incising river
654 channel.

655 5.2.3. *Lunzua Waterfalls*

656 Both samples from Lunzua Waterfalls show no ^{10}Be - ^{26}Al burial signal (Fig. 10C). LUZ01
657 yields a very old minimum age for a vertical surface, which indicates that it was constantly
658 exposed since at least $524 \pm 12 \text{ ka}$. In terms of a steady denudation rate, this age would
659 correspond to a local rate of receding of the rock face (in horizontal direction) of $\sim 0.4 \text{ mm ka}^{-1}$.
660 LUZ02 yields a much younger minimum ^{10}Be and ^{26}Al mean age ($102.2 \pm 2.7 \text{ ka}$). It is unclear
661 whether the age difference between the two samples reflects the retreat of the waterfall or is just
662 due to more intense denudation near the top.

663 5.3. *Group C*

664 Samples from the northwest side of Lake Mweru (Group C) were located at lower elevations
665 than those from groups A and B and their minimum ^{10}Be and ^{26}Al ages are distinctly younger

666 and more comparable to one another (Table 2). The sample that derives from a vertical surface
667 of the fault no. 16 (MWE01; Fig. 1) implies a fast but steady denudation rate of $\sim 40 \text{ mm ka}^{-1}$
668 (Table 3) or a rockfall on the fault surface $< 10 \text{ ka}$ ago. Additionally, two further samples (ME04,
669 ME05) from vertical sections along the Luvua River show rather young minimum ^{10}Be and ^{26}Al
670 mean ages (12.29 ± 0.81 and $11.56 \pm 0.72 \text{ ka}$, respectively). As the paleo-lake Mweru was drained
671 via the Luvua River, during the Pleistocene (Cotterill and de Wit, 2011), it is possible that these
672 young ages reflect rockfall events or steady and fast incision, but obviously they do not
673 represent the age of paleo-lake drainage. Fast denudation of the northeastern section of the
674 Kundelungu Plateau is further supported by two samples which were collected from horizontal
675 surfaces along the Misefwe and Lwilwa rivers (ME06 and ME09; Fig. 1), yielding maximum
676 ^{10}Be denudation rates of $\sim 16 \text{ mm ka}^{-1}$ (Table 3). In summary, Group C samples show no ^{10}Be -
677 ^{26}Al burial signals and relatively young minimum ages due to recent rockfalls and/or fast
678 eroding surfaces (Fig. 11; Tables 2, 3). However, these young ages do not contradict the
679 assumed extension of the paleo-lake Mweru over this section of the Kundelungu Plateau.
680 Rather, they suggest that pre paleo-lake surfaces have not been preserved due to faster
681 denudation. Such rates could be related to a potential uplifting caused by the activity of fault
682 no. 16 (Fig. 1). Further investigation of this activity is required.

683 **6. Discussion**

684 Our results explore the landscape evolution of the Mweru rift system, the southwest
685 extension of the EARS, since the late Neogene. The establishment of paleo-lake Mweru
686 initiated a new drainage network feeding the paleo-lake until the penultimate capture of this
687 depocenter by an Upper Congo headwater. Here we discuss the implications of these new
688 insights with respect to the southward and westward propagation of rifting.

689 *6.1. Onset of Active Faulting and the Formation of the Paleo-Lake Mweru*

690 Rifting in the study area is thought to have commenced by at least ~2.6 Ma (Tiercelin and
691 Lezzar, 2002; Decrée et al., 2010; Molnar et al., 2019; Daly et al., 2020). Overall, analysis of
692 the faulted topography within the MMFS reveals that individual faults have played a pivotal
693 role in forming the two depressions that host the Lakes Mweru and Mweru Wantipa. Active
694 faulting and associated footwall uplift are also responsible for the wide ridge that extends today
695 between the two lakes (Fig. 1). The landscape reconstruction through subtraction of the 2.6 Ma
696 fault throws (Fig. 6) displays a mild relief across the extended area of the MMFS, revealing that
697 the landscape was similar to the flat East African erosion surface. During the early Pleistocene,
698 the average topographic altitude was formerly higher, though it is possible that the relative
699 height difference between the Kundelungu and Mporokoso Plateaus has not changed
700 significantly since the onset of rifting. A low energy environment, such as a shallow wetland,
701 and associated meandering rivers probably extended over this landscape, which was related to
702 the extensive and relatively long-lived paleo-Chambeshi drainage system (Cotterill, 2005).

703 The southern part of the MMFS (profiles 1 and 6; Fig. 6A, 6F) hosts deltaic deposits
704 associated with the Luapula River (Fig. 1). The primary faults that bound the depression that
705 hosts Lake Mweru today to the west are (from south to north) faults 8, 9, 10 and 16 (Fig. 1).
706 The total throw on these southeast dipping faults is ~640 m as opposed to the 200 m of
707 cumulative throw recorded on the northwest dipping faults (i.e., 23 and 28) that bound this
708 depression to the southeast. This geometry reveals a highly asymmetric rift tilted to the
709 southeast. Profiles in Figure 6A and 6F suggest that faults 8 and 23 contributed drastically to
710 the lowering of the landscape between the two horsts by a total throw of ~700 m. During the
711 early Pleistocene, the southern part of the Mporokoso Plateau was about 250 m lower than the
712 Kundelungu Plateau. It is known that during this period, the Luapula River captured the paleo-
713 Chambeshi River, which led to the present-day linkage between the Bangweulu and Mweru

714 lakes (Cotterill, 2003, 2005). This interpretation, which is not described by the tectonic analysis
715 presented here, suggests that the proto-Luapula River was flowing southward towards Lake
716 Bangweulu (as suggested previously; Cotterill, 2005, 2006; Cotterill and de Wit, 2011; Moore
717 et al., 2012). The onset of tectonic activity, together with the southward knickpoint retreat of
718 the proto-Luapula River, may have contributed to the separation of the previously
719 topographically connected Mporokoso and Kundelungu Plateaus.

720 Moving northwards, to profiles 2 and 6 (Figs. 6B, 6F), the elevation difference between
721 the two shoulders of the rift is more distinct. The southeast dipping faults of the Kundelungu
722 Plateau sum a total throw of almost 800 m, while faults along the Mporokoso Plateau have a
723 total throw of ~300 m. It appears that the Mporokoso Plateau stood around 1400-1500 m asl
724 during the late Pliocene. The basement of the lake was clearly higher than today, standing at
725 ~1000 m asl, while the Kundelungu Plateau maintained its high elevation at ~1700 m asl. Faults
726 9, 16, 23, 24, 28 and 32 were the main contributors of downfaulting. In this area, the wetland
727 was deeper (Kilwa Island did not exist) and the clastic bedrock was the main dominant rock
728 type of the wetland's bottom. According to profiles 3 and 6 (Figs. 6C, 6F), the local average
729 altitude of the landscape was lower, reaching the highest point of ~1350 m asl on the
730 Kundelungu Plateau. The maximum altitude of the Mporokoso Plateau was ~1250 m asl,
731 minimizing the elevational difference between the two shoulders of the rift. The total throw of
732 the southeast dipping faults is ~500 m, while the northwest dipping faults' total displacement
733 is 400 m, creating an almost symmetric section in a generally asymmetric structure. Considering
734 Figure 6C, the reconstructed landscape during the early Pleistocene had a relatively low relief.
735 Both these plateaus seem to have had an approximately similar local height (~1400 m asl), and
736 the lowest point was probably close to the present-day location of the Kundabwika Waterfalls,
737 which was controlled by Fault 44.

738 Cotterill (2006) discussed the possibility that part of the Kalungwishi River, today flowing
739 north, was redirected from the south, as the Kalungwishi River was formerly a major headwater
740 of the proto-Luongo River (Fig. 1). Geobiological estimates of evolutionary events can be
741 applied from the genomic record of extant fishes. These estimates of speciation events confer
742 an independent chronology of these drainage links (Cotterill and de Wit, 2011). A pertinent
743 example is the Early Pleistocene speciation of a killifish, *Nothobranchius ostergaardi*, confined
744 within the eastern Mweru Wantipa basin; this species diverged from 0.46 to 1.11 Ma from its
745 closest living relatives, which today occur south of the Congo-Zambezi watershed (van der
746 Merwe et al., 2021). Their origin is attributed to the breakup of the paleo-Chambeshi River, and
747 this event overlaps with independent pulses of fish speciation within the Mweru graben, as well
748 as TCN dates constraining the tenure of paleo-lake Mweru. The onset of the MMFS (deepening
749 of the paleo-lake Mweru) then disrupted the paleo-drainage of the Luongo-Kalungwishi system,
750 contributing gradually to its disconnection from the paleo-Chambeshi drainage (Cotterill, 2006;
751 Cotterill and de Wit, 2011).

752 Compared to Lake Mweru (917 m asl), Lake Mweru Wantipa stands at a higher elevation
753 (932 m asl), and it is characterized by a high relief landscape. According to profiles 4 and 5
754 (Fig. 4), the total throw of the southeast dipping faults along the Kundelungu Plateau reaches
755 up to 1720 m, while the northeast dipping faults have a maximum total throw of 460 m. Despite
756 the approximately four-fold difference of the throw measured on the southeast and northwest
757 faults, the rift here does not appear to be strongly asymmetric. This can be rationalized if we
758 consider that the former faults are distributed across a distance of ~140 km whereas the latter
759 ones span only 10 km across the rift's shoulder. From a geomorphological perspective, the
760 Mweru Wantipa depression hosts the seismically most active structures of the Southwestern
761 Extension of the EARS (Daly et al., 2020). This is also supported by the DEM fault analysis
762 that suggests a denser fault network of fresh discontinuous traces between the Lakes Mweru

763 Wantipa and Tanganyika. The extended landscape around the modern Lake Mweru Wantipa
764 during the early Pleistocene was also characterized by high relief, while the base of the wetland
765 was standing at ~1150 m asl (Fig. 6D). The Kundelungu Plateau was standing at a maximum
766 altitude of > 2000 m asl, while the Mporokoso Plateau had a maximum elevation of ~1900 m
767 asl (Fig. 6E). The modern lowlands (cross hatching in the east in Fig. 12) on the borders between
768 Lake Mweru Wantipa and the Mpulungu basin have currently an average elevation <1200 m
769 asl. During the Pleistocene (Fig. 6G), the elevation was just ~50 m higher, with the lowest point
770 ~1200 m asl. However, this elevation difference was sufficient to prevent the merging of paleo-
771 lake Mweru and paleo-lake Tanganyika and suggests that these lakes have never been linked.

772 The western margin of the paleo-lake was defined by the long and high Kundelungu
773 Plateau. The depression (cross hatching in the west in Fig. 12) that separates the main part of
774 the plateau from its eastern continuity did not exist during the Pleistocene. Based on Figure 6H,
775 the two parts of the plateau were connected, and the average elevation of the linking crest was
776 ~1400 m. Faults 16a and 17 downfaulted the intervening landscape by ~200 m, resulting in the
777 separation of the southwestern and northeastern sections of the Kundelungu Plateau. There is
778 no evidence of a sudden tectonic event that created this depression, so we assume that it was
779 dominated by gradual lowering of the landscape due to normal faulting and denudation activity
780 across the Kundelungu Plateau, as implied also by the TCN data.

781 Interestingly, the transition from Pliocene to Pleistocene (2.6 Ma) is characterized by a
782 major climatic change in the southern hemisphere, from warm and humid conditions to
783 aridification until 1.8 Ma, which is invoked as a driver of contraction and expansion of the lakes
784 (Cohen et al., 1997). The lakes that were already flooded since ~3.6 Ma experienced
785 contractions around 1.1 Ma (Cohen et al., 1997). Lavayssiere et al. (2019) reported that Lake
786 Tanganyika dried down to the point it was divided into three contracted paleo-lakes, limited
787 within the sub basins of the rift, which possibly caused fish speciation. The lake levels were

788 restored gradually until 550 ka, while fluctuations in levels occurred, possibly linked to
789 alterations in Pleistocene paleoclimates (Cohen et al., 1997; Trauth et al., 2005, 2010;
790 Lavayssiere et al., 2019). Indeed, TCN dating suggests water level fluctuations across the paleo-
791 lake Mweru during the Pleistocene (Section 5.1.1.), which attests to complex interactions
792 between past climates and tectonics.

793 6.2. The Drainage of Paleo-Lake Mweru

794 At Kundabikwa Waterfalls, three samples (KUN01, 02, 03) yield burial ages of ~1 Ma (Fig.
795 8A). The minimum burial ages of the other four samples (KUN04, 05, 06, 07) are lower (~500
796 ka). This may be explained by a higher contribution of post-burial production, which shifts data
797 points in the two-nuclide plot (Fig. 8A) from the burial area towards the steady-state field again.
798 Therefore, it is the oldest burial age among all samples that provides a minimum estimate for
799 the time the Kundabikwa Waterfalls have been covered, i.e. >1 Ma. Indeed, it is possible that
800 the paleo-lake Mweru existed much longer than that. If the lake (including the various lake
801 fluctuations) actually lasted more than ~2 Ma, essentially all ^{26}Al present in a sample today
802 would have been produced after the drainage of the paleo-lake (as the half-life of ^{26}Al is 705 ka
803 and after three half-lives almost 90% will have decayed; Norris et al., 1983). Under such an
804 assumption, the highest minimum ^{26}Al age of all samples showing burial would provide a time
805 constraint for when the paleo-lake was drained to a level below the elevation of the waterfalls.
806 Sample KUN04 of the Kundabikwa Waterfalls records the highest ^{26}Al minimum age among
807 all samples that indicate burial, constraining the timing of lake drainage to ~350 ka (i.e. middle
808 Pleistocene). Variable denudation and tectonic rates within the study area can explain the
809 observed variations in minimum ages between different locations. Nevertheless, all samples
810 from Group A are consistent with an inferred lake drainage at ~200-400 ka, with age differences
811 most likely representing lake level fluctuations.

812 The reconstruction of key features that formed the landscape at ~350 ka is required to
813 determine potential waterways allowing for the drainage, and consequent lowering, of the
814 paleo-lake. To achieve this, we calculated, assuming constant displacement rates over these
815 timescales (Mouslopoulou et al. 2009), the throw accrued on each fault since 350 ka and we
816 subsequently subtracted it from its total displacement (Table A2). The modified faulted
817 topography is assessed via profiles 1-8 (cross sections in Fig. 1), the results of which are
818 illustrated in Figure A5 in the Appendix. The restored topography at 350 ka reveals minor,
819 albeit crucial, readjustments that appear to have impacted on the size of the paleo-lake.
820 According to the profiles in Figure 4, faults 8, 9 and 16 are the largest displacement faults that
821 formed the asymmetrical half-graben structure that hosted the paleo-lake. Faults 16a and 17
822 also contributed to the formation of the depression west of present-day Lake Mweru and across
823 the Kundelungu Plateau (Fig. A5c). This depression might have played a key role in the
824 lowering of the paleo-lake's water level as it aided its tapping to the west (Fig. 12). Faster
825 denudation rates in the north (~40 mm ka⁻¹; Group C) compared to the south (~6 mm ka⁻¹;
826 Groups A, B) were forced by footwall uplift across Fault 16, resulting in fast incision along the
827 northward flowing Luvua River (Fig. 1).

828 Dramatic lake level fluctuations have been reported throughout the late Pleistocene (14-450
829 ka) across Lake Tanganyika, Lake Malawi and the southwest extension of the EARS, which are
830 related to tectonic factors and/or aridification periods (Danley et al., 2012; Ivory et al., 2016).
831 From 450 to 350 ka, a regional lowering of the temperature and global sea level is directly
832 correlated with the low stand of the lake levels across the Western Branch (Bakker and Mercer,
833 1986). In addition, a major dry period across the Congo basin occurred between ~270 and 180
834 ka, resulting in an additional lowering of the water level (Gasse et al., 1989). The evidence for
835 the drainage of paleo-lake Mweru based on ¹⁰Be and ²⁶Al data, together with tectonic analyses
836 and the evidence for intensive climatic variation during the Pleistocene, indicate a gradual

837 shrinking of the paleo-lake rather than a sudden tectonic event. The outflow of the paleo-lake
838 through the Luvua River was most likely one of the main events that drained the lake (Dixey,
839 1944; Bos et al., 2006; Goodier et al., 2011; Cotterill and de Wit, 2011; Fig. 1). However,
840 evaporation, especially in arid periods, may have further accelerated contraction of the paleo-
841 lake, notably across the vast, shallow depression located between the two sections of the
842 Kundelungu Plateau (Fig. 12).

843 6.3. Paleo-Lake Mweru During the Late Neogene-Quaternary

844 Assuming that the paleo-lake Mweru existed for a minimum of ~2 Ma, the burial ages
845 constrain its formation to the late Pliocene-early Pleistocene. This assumption is supported by
846 the high species endemism of the extant fish fauna of Lake Mweru (Cotterill, 2005; Meier et
847 al., 2019). More specifically, recent molecular clock analyses have estimated respective timings
848 of origin of several radiations of endemic fish clades (Family Cichlidae) confined within Lake
849 Mweru. Four of these clades have evolved diverse species flocks, whose origins are estimated
850 at 270–350, 430–560, 270–940, and 720–940 ka, constrained by a molecular clock calibrated
851 for the Cichlidae (Meier et al., 2019). Thus, depending on the applied calibration scheme, the
852 mean genetic divergence of the most common recent ancestors provides a date of 0.27-1.04 Ma
853 and their actual speciation dates (i.e. timing of completed lineage divergence) was likely more
854 recent (Meier et al., 2019). The second line of geobiotic evidence comprises the “Mweru
855 Complex” of killifishes, genus *Nothobranchius*. The timing of radiation of its seven species is
856 significant, because their ecology confines them within the floodplains that formed after the
857 shrinkage of the larger lake. The independently constrained molecular clock of *Nothobranchius*
858 estimates the origin of this complex between 0.48 and 1.01 Ma (van der Merwe et al., 2021).

859 Our data inform a schematic map that estimates the maximum size of the paleo-lake Mweru
860 through the Pleistocene (Fig. 12). The maximum lake level is constrained via TCN dating at
861 1200 m asl, while the minimum level should be the elevation of the Kundabikwa Waterfalls

862 (~1050 m asl). The estimate of a 1200 m asl lake level is supported by the hypsometric and
863 knickpoint analysis (~1180 m asl). The Lumangwe and Ntumbachushi Waterfalls are assumed
864 to represent the eastern shorelines of this paleo-lake. This inference is confirmed by the heights
865 of the dominant knickpoints at the same elevation mapped throughout the catchment (Fig. 7).
866 The southern border of the paleo-lake likely coincided closely with the Mumbuluma I waterfalls
867 which, together with preliminary molecular phylogenetic analyses (Cotterill, 2004, 2005),
868 suggest that the southern section of the Kundelungu Plateau was connected with the Mporokoso
869 Plateau during the Pliocene (and prior to the formation of the Luapula River; Tack et al., 2003;
870 Cotterill and de Wit, 2011; Guillocheau et al., 2015).

871 Red siltstones from the Kundelungu Plateau are possibly correlated with the upper red beds
872 of the Luapula Beds, implying that the Luapula River eroded the once connected Kundelungu
873 and Mporokoso Plateaus (Abraham, 1959; Thieme, 1971). The western bank of the paleo-lake
874 is defined by the Kundelungu Plateau that rises to ~1700 m asl. Paleo-lake Mweru was likely
875 connected to the Mweru Wantipa wetlands as suggested by the relationships of
876 *Pseudocrenilabrus* (family: Cichlidae) species from these two waterbodies (Egger et al., 2015).
877 However, it appears unlikely that it was linked with the Mpulungu graben of Lake Tanganyika
878 due to the highly distinct fish fauna of these two lakes. This is in agreement with Dixey (1944,
879 1946), who proposed that the Lakes Mweru and Mweru Wantipa were once connected, a
880 hypothesis re-affirmed by Cotterill and de Wit (2011). Finally, the northern banks are defined
881 by the edge of the extensive plateau between the Mweru Wantipa wetlands and Lake
882 Tanganyika (Fig. 12).

883 **7. Conclusions**

884 Terrestrial cosmogenic nuclides results coupled with tectonic and digital topographic
885 analyses reveal the existence of a large paleo-lake Mweru. This paleo lake exceeded the sizes

886 of the present-day Lakes Mweru and Mweru Wantipa. We identified the following evidence for
887 lake size and timing:

888 As estimated previously, our results indicate the onset of the paleo-lake at around 2.6 Ma.
889 The timing of lake existence is consistent with the phylogenetic molecular clock analyses of
890 endemic fish species, which also constrain the formation of the paleo-lake at the late Pliocene -
891 early Pleistocene. Formation of this lake is correlated with the onset of the Mweru-Mweru
892 Wantipa Fault System in the Early Pleistocene and likely established an estimated maximum
893 shoreline at ~1200 m asl. The extent of the paleo-lake was also identified by river knickpoint
894 and hypsometric analysis to constrain its paleo-shorelines at ~1180 m.

895 Intense normal faulting and associated footwall uplift at the northwestern paleo-lake
896 boundary must have forced fast river incision in the eastern section of the Kundelungu Plateau.
897 In contrast, two exceptionally old minimum ^{10}Be and ^{26}Al exposure ages of 524 and 833 ka
898 were obtained from vertical/sub-vertical surfaces besides active river courses across the
899 Mporokoso Plateau, possibly reflecting the actual exposure ages of these surfaces. These ages
900 illustrate the stability of the plateau, which is also reflected by the low maximum denudation
901 rates (~ 0.4 to ~ 6 mm ka^{-1}). The deepening/flooding of the paleo-lake, which was probably due
902 to the active extension and associated normal faulting, continued at least until the Middle
903 Pleistocene (~ 350 ka), resulting in complex exposure histories observed at the knickpoints on
904 the Mporokoso Plateau.

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1333 **Figure Captions**

1334 Figure 1: Morphotectonic map of the Mweru-Mweru Wantipa Fault System (MMFS) in the
1335 southern East African Rift System. Normal faults are indicated by black lines while ticks
1336 indicate downfaulted side. Numbers next to each fault correspond to entries in Table A2 in the
1337 Appendix. Red lines indicate topographic profiles presented in Figures 4, 5 and 6. Green circles,
1338 yellow triangles and blue squares indicate sampling locations of the three different sampling
1339 groups. Inset shows location of study area in Africa. KUN: Kundabikwa Waterfalls; LUM:
1340 Lumangwe Waterfall; NTU: Ntumbachushi Waterfalls; MUM: Mumbuluma I Waterfalls; LUP:
1341 Lupupa Waterfall; LUO: Mumbuluma II Waterfall; LUZ: Lunzua Waterfalls.

1342 Figure 2: A) Sampling of KUN01 from a vertical face on the banks of Kalungwishi River,
1343 downstream of Kundabikwa Waterfalls, Zambia; B) Sampling of bedrock (MUM04) directly
1344 from the horizontal surface of the knickpoint at Mumbuluma I Waterfalls, Zambia; C) View of
1345 Lumangwe Waterfall, Zambia; D) Sample location of ME09, Lwilwa River, DRC; E) Sampling
1346 of MWE01 from the face of fault 16, DRC.

1347 Figure 3: A) Log-log plot illustrating the relationship between topographic fault length and total
1348 displacement for the faults in the MMFS (grey circles) and the Mpulungu basin (southern
1349 Tanganyika Fault System; black circles). B) Same as (a) but illustrating separately the NW
1350 dipping (circles) and the SE dipping (triangles) faults in the MMFS. C) Log-log plot illustrating
1351 the relationship between topographic fault length and the displacement rate for the faults in the
1352 MMFS (grey circles) and the Mpulungu basin (black circles). D) Global dataset of displacement
1353 vs. fault length (shaded area; Nicol et al., 2016b). Black circles show data for the same faults
1354 as in Figure 3A while white triangles represent single-event displacement rupture lengths for
1355 historical earthquakes (Wesnousky, 2008). Least squares lines of best fit and R² values are also
1356 indicated for each dataset.

1357 Figure 4: Five topographic profiles approximately perpendicular to the trend of the MMFS (for
1358 locality of the profiles see Figure 1). The SE dipping faults are indicated with red lines while
1359 the NW dipping faults with blue lines. Sample locations are indicated with yellow circles.
1360 Numbers with F next to faults correspond to numbered faults in Figure 1 and entries in Table
1361 A2 in the Appendix. Plain numbers next to the faults indicate the throw (m) of the respective
1362 fault. The total fault throw as well as the throw of the NW (blue) and SE (red) dipping faults
1363 are indicated on each profile. Blue dashed line indicates the potential water level of the paleo-
1364 lake Mweru.

1365 Figure 5: Topographic profile along the trend of the MMFS. See Figure 1 for profile location
1366 and Figure 4 for explanations.

1367 Figure 6: Reconstructed landscape based on the topographic profiles presented in Figures 4 and
1368 5 and two additional profiles (Profiles 7 and 8) which are depicted in Figure 1. Subtracted throw
1369 resulted assuming a constant fault displacement rate (see Table A2 for values) during the last
1370 2.6 Ma. Dashed black lines represent the current landscape. Grey dashed line indicates the
1371 approximate elevation of the reconstructed landscape about 2.6 Ma (rift's onset), while black
1372 solid line is the average elevation of the reconstructed landscape. The SE dipping faults are
1373 indicated by red triangles while blue circles indicate the NW dipping faults. The SW dipping
1374 faults are presented as green rhombuses, while yellow squares show the NE dipping faults.

1375 Figure 7: A) Locations of river knickpoints for the Lake Mweru catchment. Symbol colours
1376 indicate knickpoint elevations and symbol sizes show knickpoint magnitudes (lips minus base
1377 elevation). Only river knickpoints with elevations between 900 and 1200 m asl are shown. Note
1378 the clustering of river knickpoints at ~925 (dark blue), ~1000, and ~1180 m asl that correspond
1379 to paleo-shorelines of paleo-lake Mweru. B) Hypsometric curve of Lake Mweru derived from
1380 a 30 m SRTM DEM (NASA JPL, 2020). All grid cells within the Lake Mweru catchment were
1381 binned into 10 m elevation bins and their respective surface areas were calculated (black line).
1382 The elevations were filtered to only show hillslope angles $< 3^\circ$ (blue line). Note the two
1383 distinctive peaks at ~925 m asl and ~1180 m asl that show the elevations of the paleo-lake
1384 Mweru. Knickpoint elevation shows a high number of river knickpoints at paleo-lake shorelines
1385 (only river knickpoints with at least 30 m offset are shown).

1386 Figure 8: Two-nuclide diagrams showing ^{10}Be concentrations (atoms/g, corrected for total
1387 shielding and scaled to common elevation) versus $^{26}\text{Al}/^{10}\text{Be}$ ratios for samples of Group A. The
1388 black dashed line indicates the “steady state denudation line” and the solid black line the
1389 “constant exposure line” (e.g. Lal, 1991). Red lines show the temporal evolution of data at
1390 constant denudation rates and subsequent burial. Green lines indicate duration of burial under
1391 the assumption that samples were first exposed and later completely buried until present.

1392 Samples are indicated with black error ellipses (1σ shown). Underlined labels indicate samples
1393 taken from vertical surfaces. A) Kundabikwa Waterfalls; B) Lumangwe Waterfall; C)
1394 Ntumbachushi Waterfalls; D) Mumbuluma I Waterfalls.

1395 Figure 9: Schematic figure of successive landscape stages of Kalungwishi River at Kundabikwa
1396 Waterfalls and paleo-lake Mweru. T1: Initial river state with waterfall already in place. T2:
1397 Onset of paleo-lake Mweru below Kundabikwa Waterfalls. Areas downstream of the knickpoint
1398 are covered with water and sediment, while denudation at and upstream of the waterfalls is
1399 reduced due to lower energy environment. T3: Full establishment of paleo-lake Mweru resulting
1400 in water cover and sediment deposition on top horizontal surfaces. T4: Drainage of the paleo-
1401 lake, resulting in exposure of areas above the knickpoint with concomitant incision of lacustrine
1402 sediments at the waterfalls and deposition of these sediments into the remaining lake below the
1403 waterfalls. T5: Paleo-lake Mweru is completely drained and sediments deposited during T3 and
1404 T4 are removed through regional denudation, resulting in differential bedrock exposure. T6:
1405 Present day river course with limited sedimentary cover and ongoing down- and backwearing
1406 through increased denudation.

1407 Figure 10: Two-nuclide diagrams showing ^{10}Be concentrations (atoms/g) versus $^{26}\text{Al}/^{10}\text{Be}$
1408 ratios for samples of Group B. See Figure 8 for explanations. A) Lupupa Waterfall; B)
1409 Mumbuluma II Waterfall (Luongo River); C) Lunzua Waterfalls.

1410 Figure 11: Two-nuclide diagram showing ^{10}Be concentration (atoms/g) versus $^{26}\text{Al}/^{10}\text{Be}$ ratios
1411 for samples of Group C. See Figure 8 for explanations.

1412 Figure 12: Schematic representation of the possible maximum extent of paleo-lake Mweru
1413 during the Plio-Pleistocene (see blue contour at 1200 m asl). Shaded areas represent
1414 reconstructed paleo-topography that was present during the Plio-Pleistocene.

Table 1: Sampling details for samples from Northern Province, Zambia and Katanga Province, Democratic Republic of Congo. Total shielding factor includes surface dip, horizon shielding and self shielding.

Name	Latitude ° S	Longitude ° E	Elevation (m)	Surface Dip (°)	Average Thickness (cm)	Total Shielding Factor
<i>Kundabikwa Waterfalls, Kalungwishi River, Zambia</i>						
KUN01	9.21207	29.30468	1037	90	2.5	0.49
KUN02	9.21201	29.30470	1043	0	2.5	0.97
KUN03	9.20947	29.30399	1043	0	2.5	0.98
KUN04	9.20949	29.30403	1039	90	2.5	0.49
KUN05	9.20824	29.30189	1034	0	7	0.94
KUN06	9.20849	29.30184	1030	90	2	0.49
KUN07	9.21781	29.30395	1030	0	2.5	0.98
<i>Lumangwe Waterfall, Kalungwishi River, Zambia</i>						
LUM02	9.54023	29.38688	1150	86	2.5	0.53
LUM03	9.54027	29.38696	1159	0	2.5	0.98
<i>Ntumbachushi Waterfalls, Ngona River, Zambia</i>						
NTU01	9.85439	28.94402	1157	75	2.5	0.65
NTU02	9.85421	28.94397	1157	5	2.5	0.88
NTU03	9.85481	28.94346	1167	90	2.5	0.49
<i>Mumbuluma I Waterfalls, Mumbuluma River, Zambia</i>						
MUM01	10.93031	28.73533	1182	90	2.5	0.49
MUM02	10.93544	28.73293	1178	0	2.5	0.98
MUM03	10.92980	28.73502	1177	90	8.5	0.46
MUM04	10.93012	28.73532	1186	0	2.5	0.98
<i>Lupupa Waterfall, Mukubwe River, Zambia</i>						
LUP01	9.27355	29.78074	1361	90	2.5	0.49
<i>Mumbuluma II Waterfall, Luongo River, Zambia</i>						
LUO01	10.10907	29.57566	1371	45	2.5	0.90
LUO02	10.10732	29.57449	1339	50	7.5	0.76
<i>Lunzua Waterfalls, Lunzua River, Zambia</i>						
LUZ01	8.91501	31.15994	1258	90	2.5	0.45
LUZ02	8.91686	31.16070	1303	90	2.5	0.48
<i>Luvua River, D.R.Congo</i>						
ME04	8.48340	28.88423	937	90	2	0.49
ME05	8.48366	28.88371	985	90	5	0.54
<i>Musefwe River, D.R. Congo</i>						
ME06	8.72807	28.68353	992	0	1	0.98
<i>Lwilwa River, D.R. Congo</i>						
ME09	8.82977	28.56613	1030	0	2	0.98
<i>Fault scarp sample, D.R. Congo</i>						
MWE01	8.74980	28.65532	1035	80	7.5	0.56

Table 2: ^{10}Be and ^{26}Al concentrations and minimum exposure ages (T_{10} , T_{26}) based thereon. Asterisk (*) indicates samples collected from vertical or subvertical surfaces. All uncertainties presented are 1σ . They include: measurement uncertainty (statistical), standard uncertainty (certification), reproducibility of standard analyses, carrier uncertainties. Age uncertainties do not include errors of production rates and scaling. See text for details on production rates and scaling method used. AMS labs where analyses were performed: D= HZDR, Dresden, Germany; T= NTNU, Trondheim, Norway; C= ASTER, CEREGE, Aix-en-Provence, France.

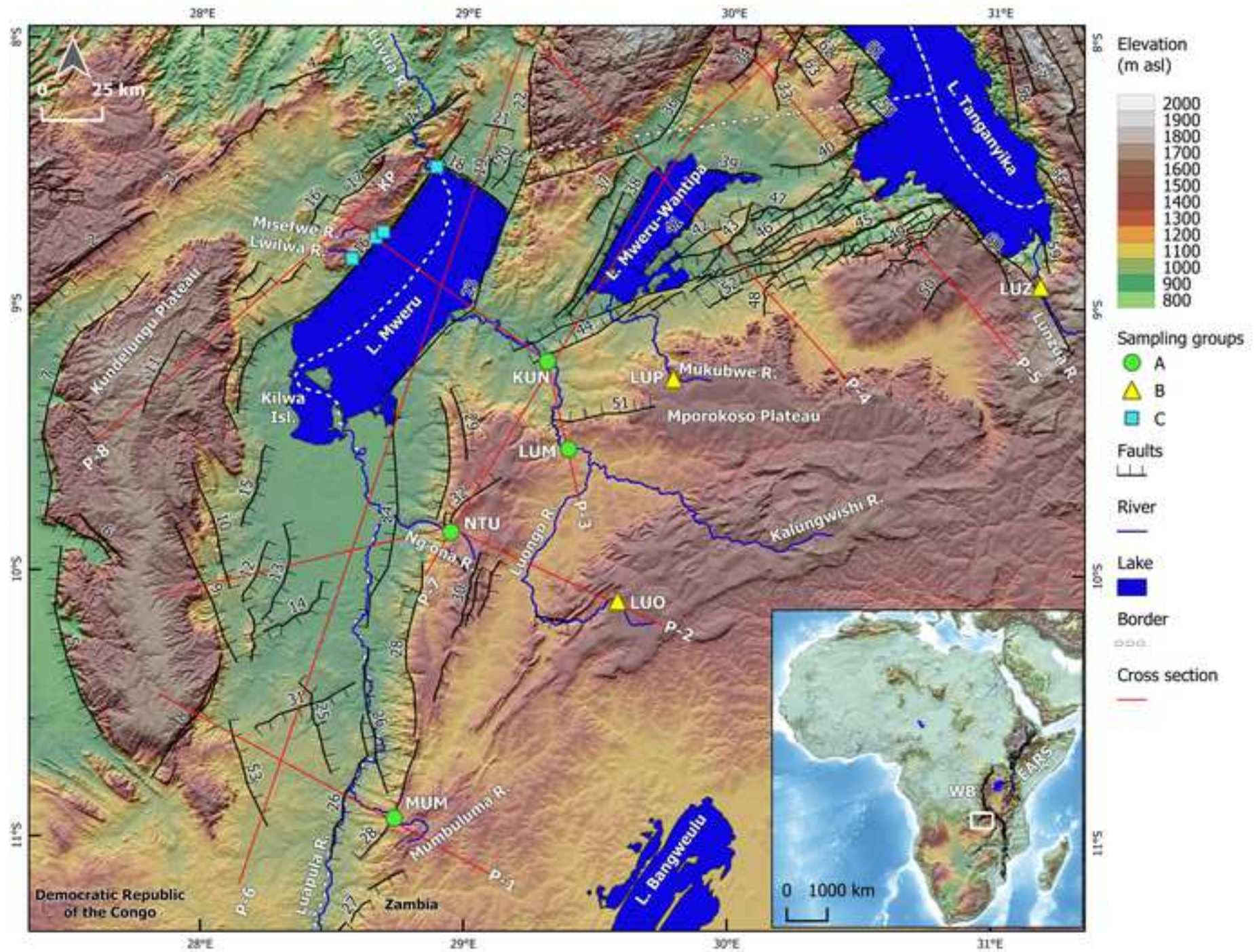
Name	^{10}Be (10^6 atoms g^{-1})	T_{10} (ka)	^{10}Be AMS	^{26}Al (10^6 atoms g^{-1})	T_{26} (ka)	^{26}Al AMS
<i>Group A</i>						
KUN01*	1.178±0.024	514±11	D	4.03±0.15	244.0±9.1	D
KUN02	0.725±0.015	145.1±3.0	D	2.91±0.11	82.1±3.2	D
KUN03	1.751±0.035	367.3±7.4	D	5.81±0.22	169.2±6.3	D
KUN04*	1.305±0.027	577±12	D	5.63±0.23	360±15	D
KUN05	1.491±0.030	326.5±6.6	D	7.59±0.28	240.9±9.0	D
KUN06*	0.2400±0.0055	94.6±2.2	D	1.256±0.060	70.2±3.3	D
KUN07	1.570±0.032	329.3±6.7	D	8.07±0.30	360±13	D
LUM02*	0.657±0.025	225.4±8.6	T	3.64±0.26	181±13	C
LUM03	1.074±0.028	198.2±5.1	T	6.93±0.30	186.9±8.0	C
NTU01*	0.0820±0.0032	21.70±0.85	D	0.525±0.056	19.6±2.1	C
NTU02	1.754±0.046	376.0±9.8	T	10.43±0.58	335±19	C
NTU03*	0.2806±0.0076	100.4±2.7	D	1.52±0.12	77.3±5.9	C
MUM01*	0.1986±0.0059	68.9±2.0	D	1.25±0.07	61.5±3.5	C
MUM02	1.479±0.035	271.1±6.5	D	8.77±0.41	236±11	C
MUM03*	0.3054±0.0082	113.8±3.0	D	1.91±0.12	101.8±6.5	C
MUM04	0.643±0.016	112.8±2.8	D	3.78±0.17	94.6±4.3	C
<i>Group B</i>						
LUP01*	0.1385±0.0041	42.5±1.3	D	0.957±0.062	41.6±2.7	C
LUO01	0.484±0.019	81.0±3.2	T	3.06±0.13	72.7±3.1	C
LUO02	3.441±0.080	830±19	T	20.72±0.97	844±40	C
LUZ01*	1.306±0.033	533±13	T	7.88±0.36	499±23	C
LUZ02*	0.309±0.010	102.6±3.4	T	2.128±0.091	101.5±4.3	C
<i>Group C</i>						
ME04*	0.0292±0.0024	12.1±1.0	T	0.216±0.023	12.6±1.4	C
ME05*	0.0294±0.0024	10.72±0.88	T	0.258±0.024	13.2±1.2	C
ME06	0.2136±0.0080	42.8±1.6	T	1.506±0.071	42.7±2.0	C
ME09	0.2270±0.0079	44.5±1.5	T	1.69±0.10	46.9±2.9	C
MWE01*	0.0249±0.0026	7.89±0.81	T	0.173±0.020	7.67±0.90	C

Table 3: ^{10}Be and ^{26}Al maximum erosion rates (ϵ_{10} , ϵ_{26}) obtained for samples of Groups B and C. All uncertainties presented are 1σ .

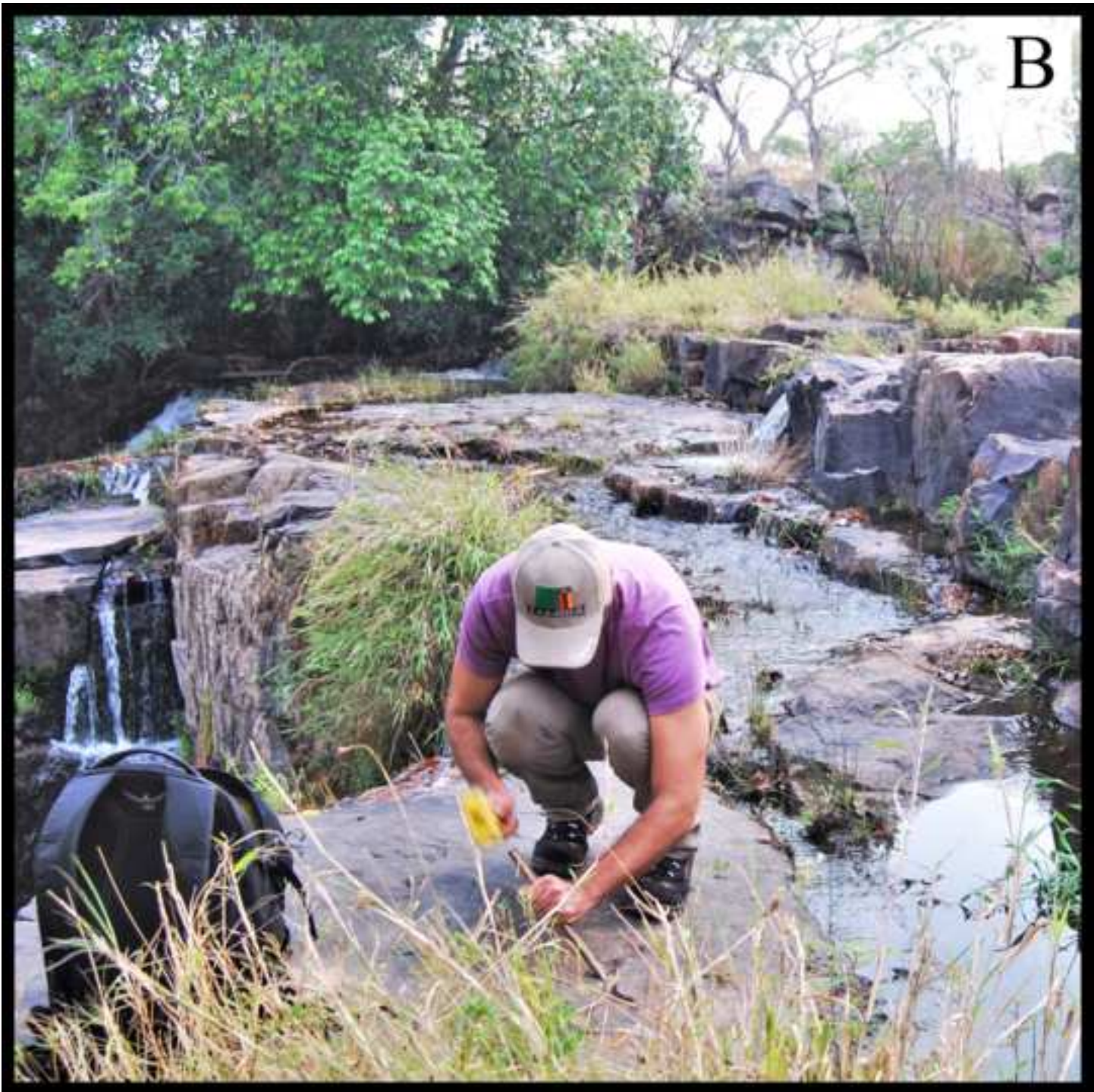
Name	Dip angle ($^\circ$)	ϵ_{10} (mm ka^{-1})	ϵ_{26} (mm ka^{-1})
LUO01	45	5.65±0.22	6.39±0.27
LUO02	50	0.4016±0.0094	0.317±0.015
LUZ01	90	0.3906±0.0099	0.375±0.017
LUZ02	90	2.367±0.079	2.40±0.10
ME04	90	22.6±1.9	22.6±2.4
ME05	90	25.4±2.1	21.3±2.0
ME06	0	15.96±0.60	16.42±0.77
ME09	0	15.26±0.53	14.79±0.91
MWE01	80	39.2±4.0	41.9±4.9

Figure (Color)

[Click here to access/download;Figure \(Color\);Figure 1.jpeg](#)

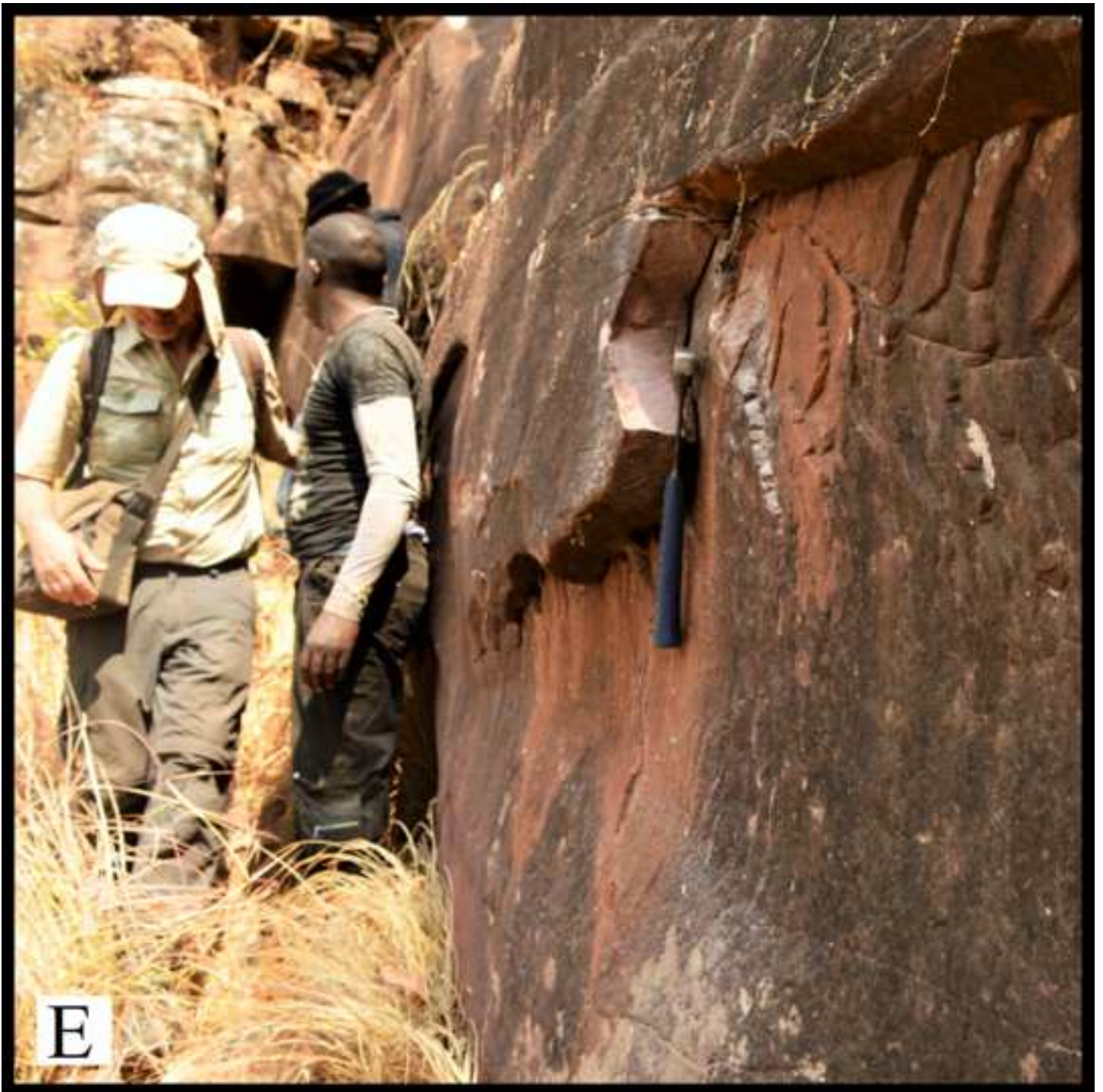


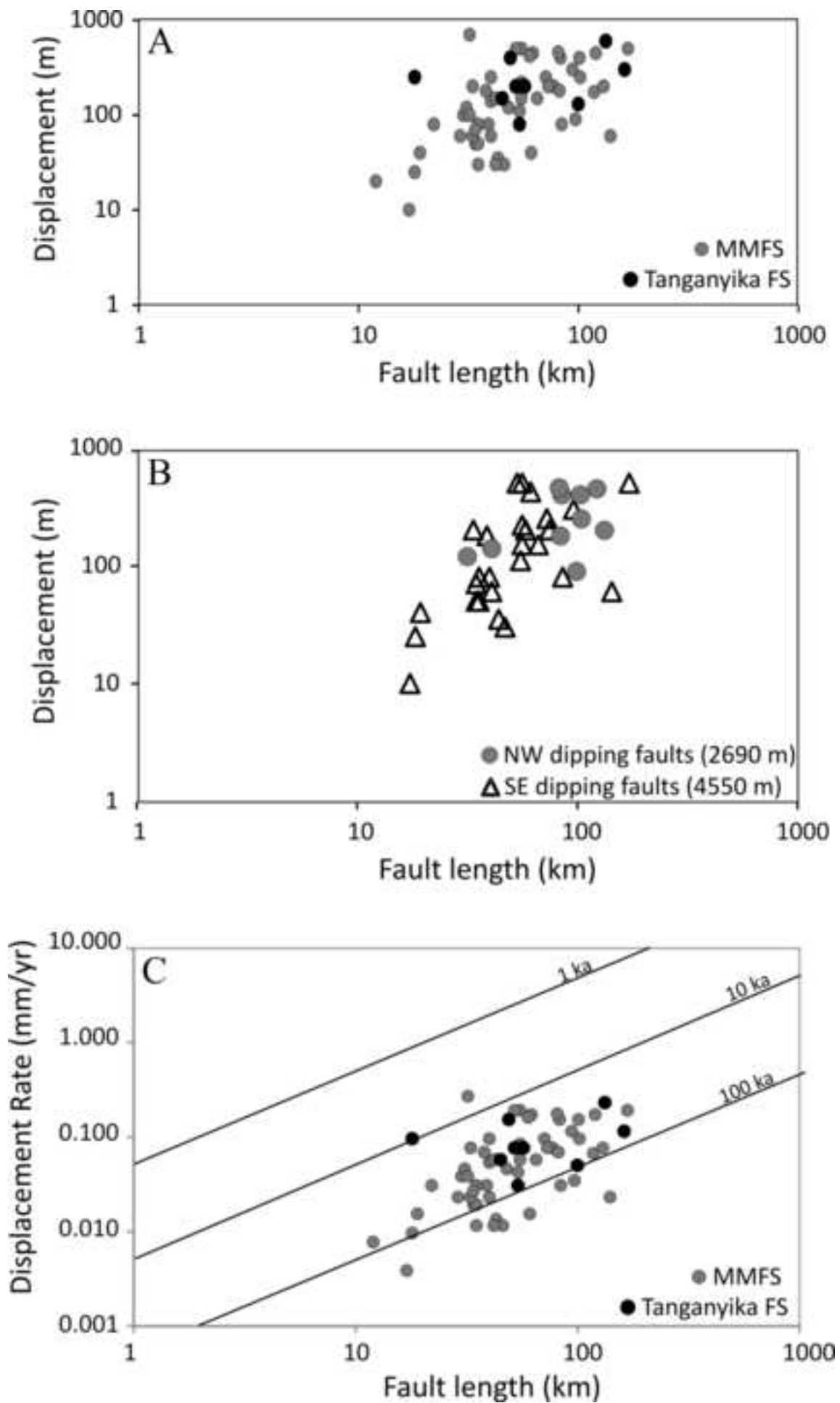


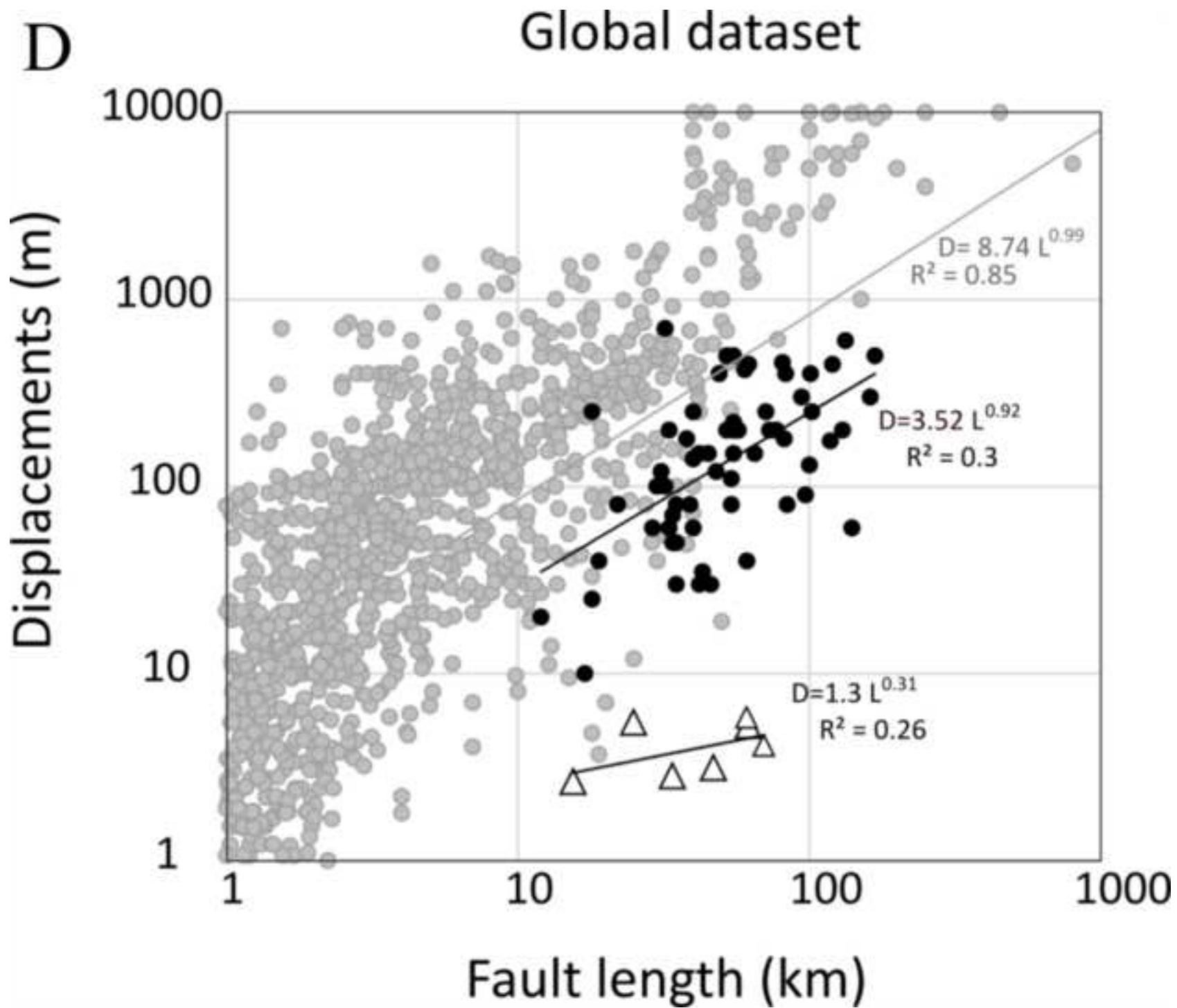


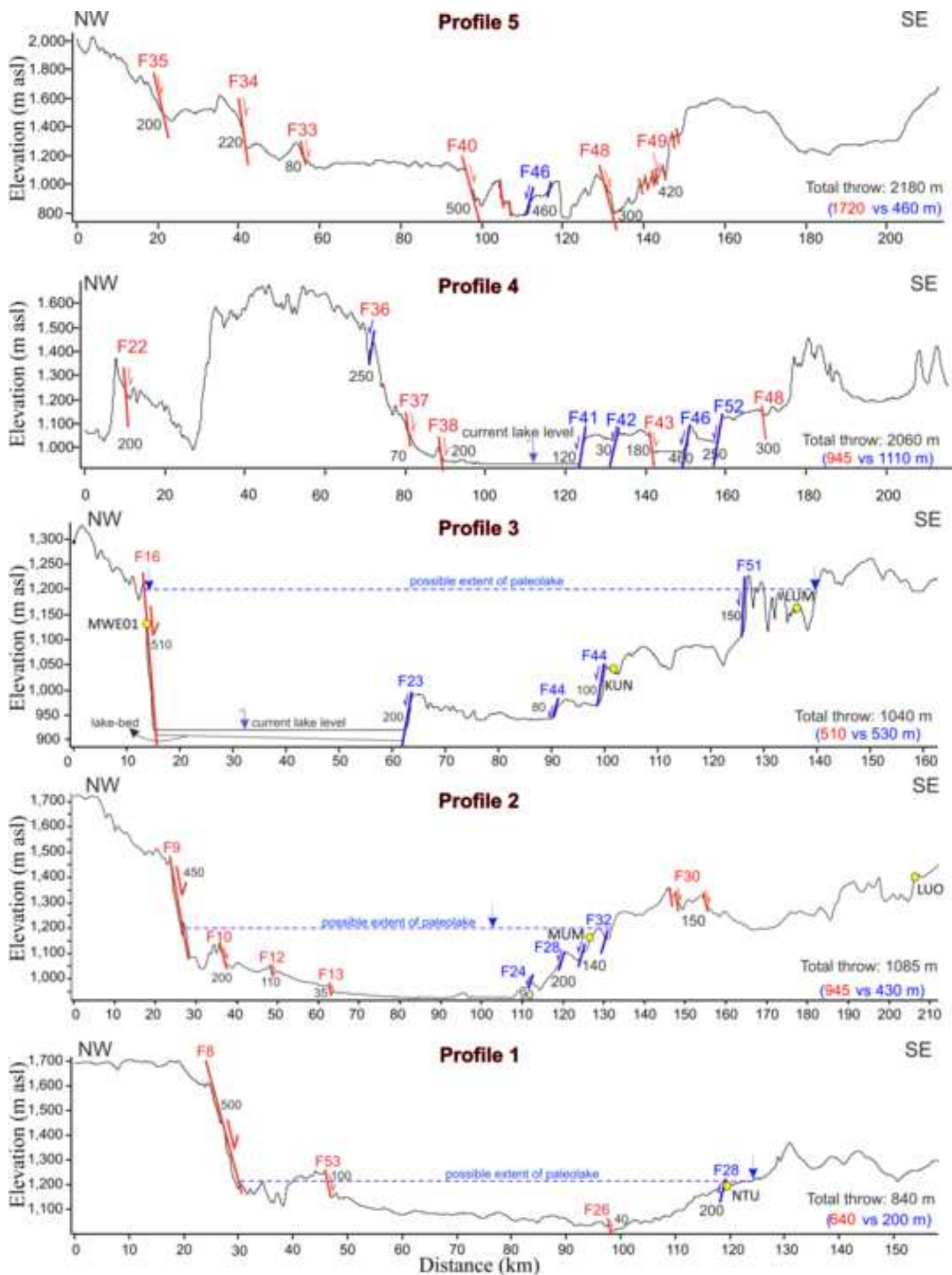


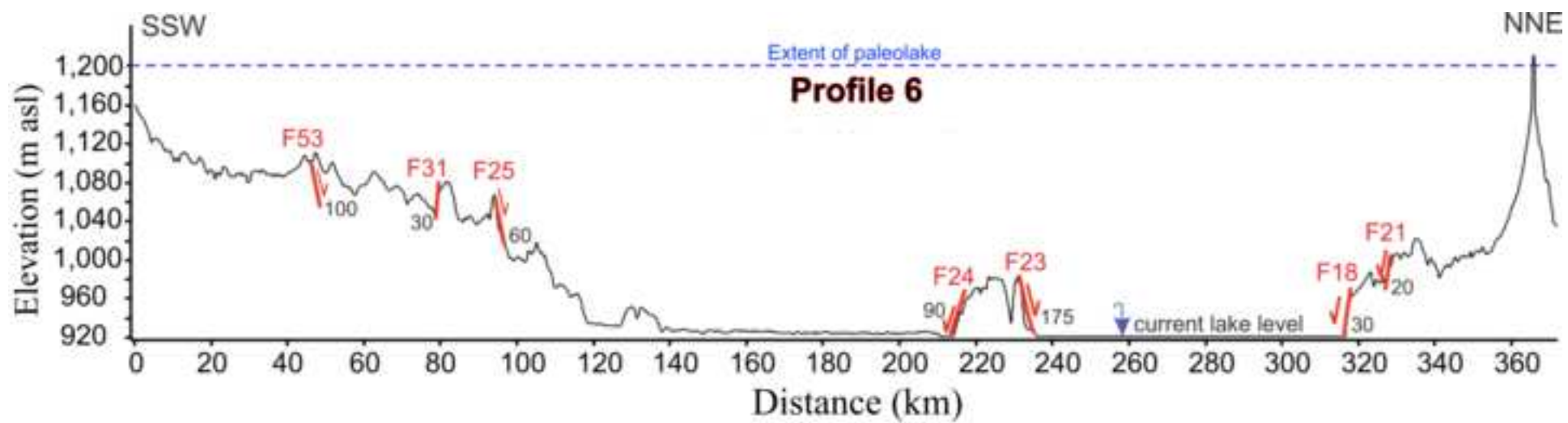


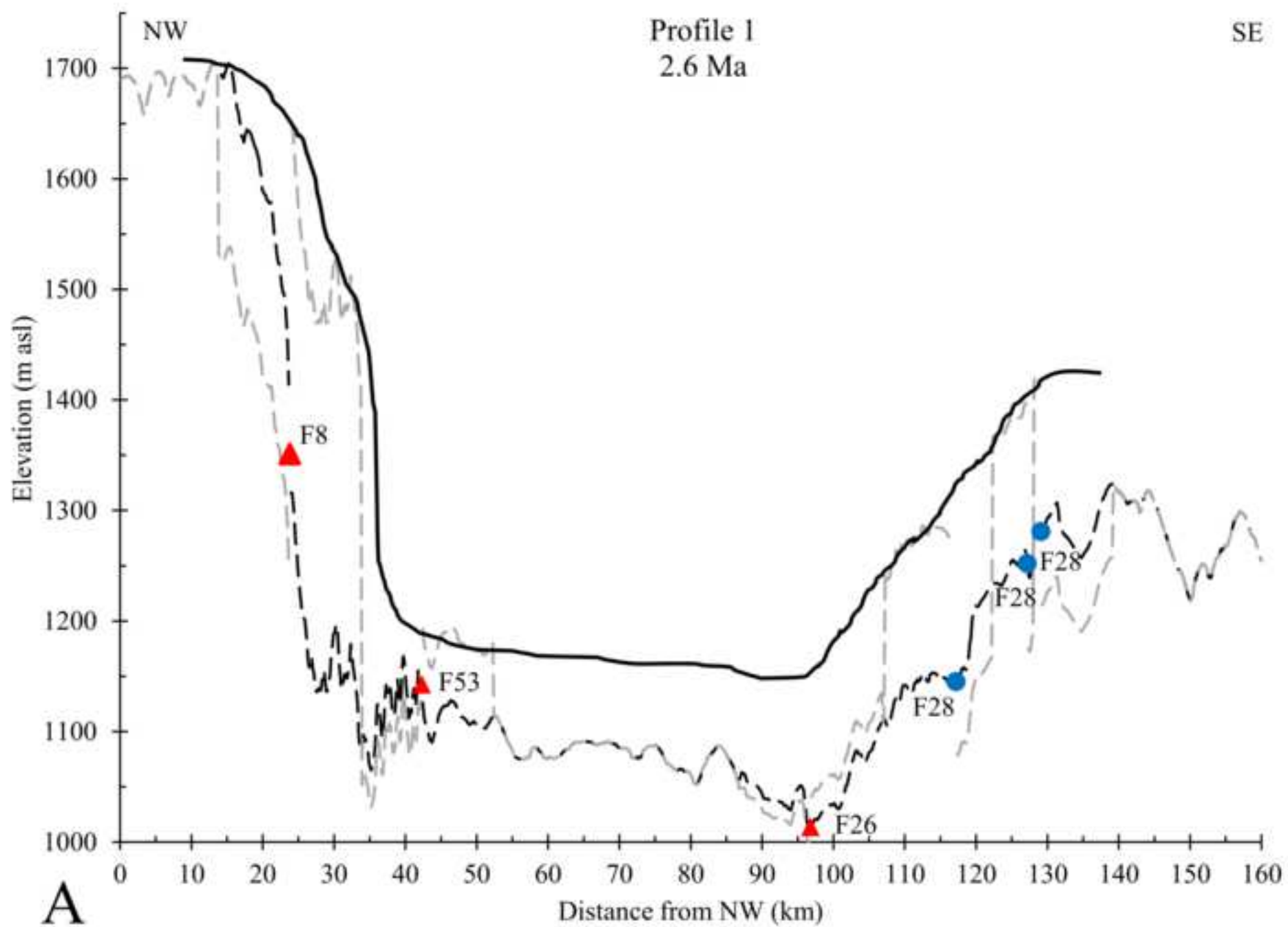


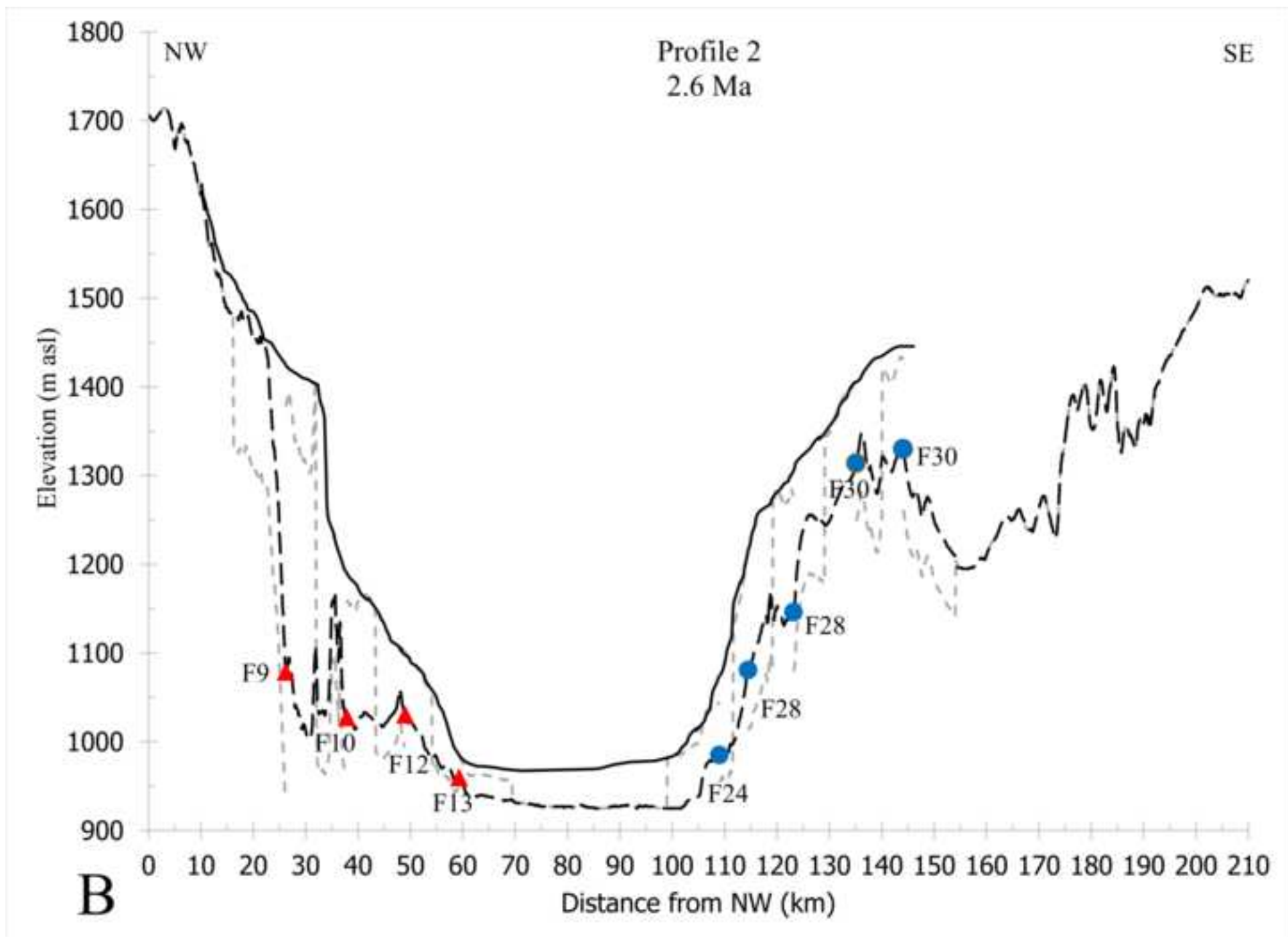


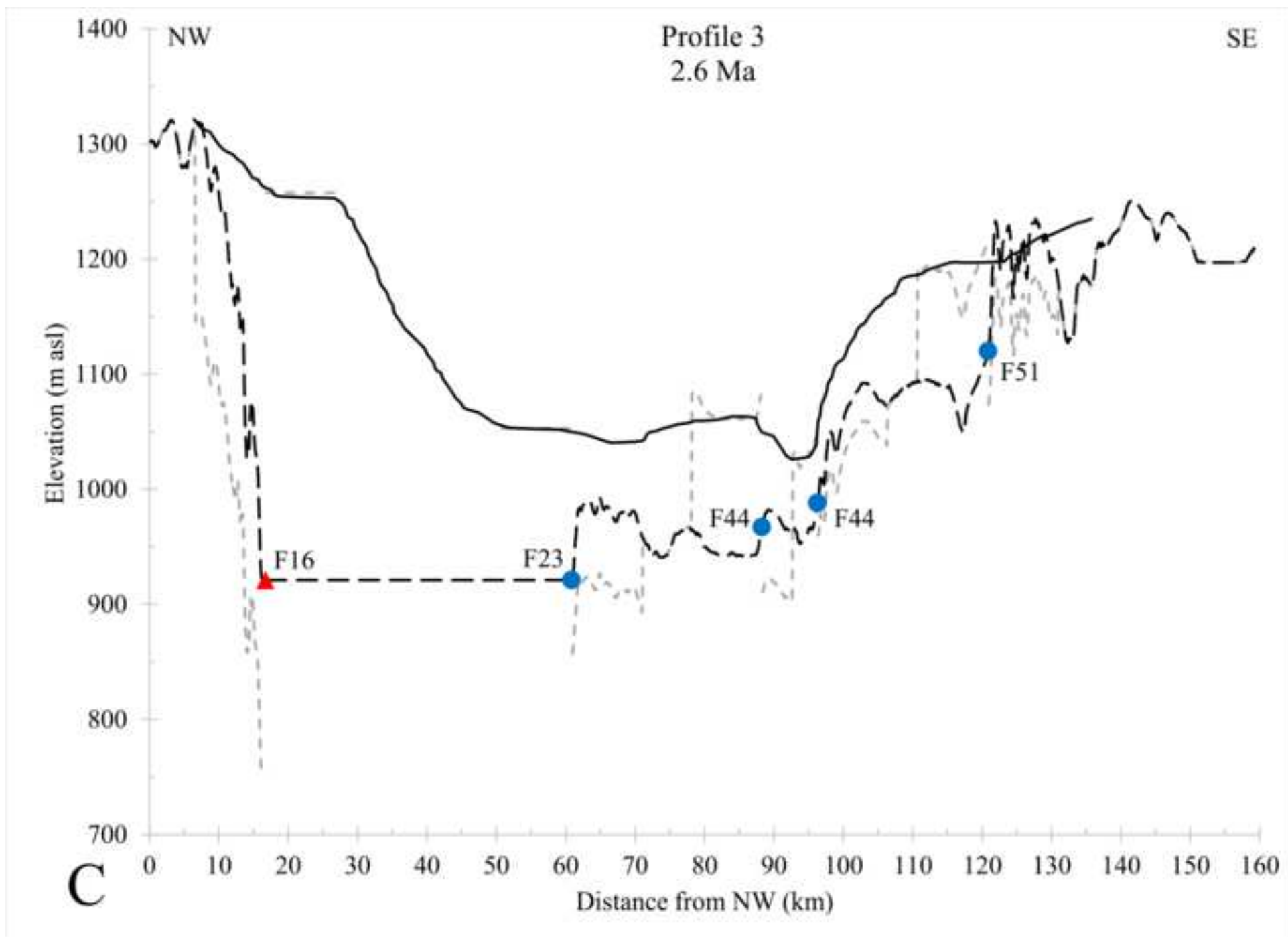


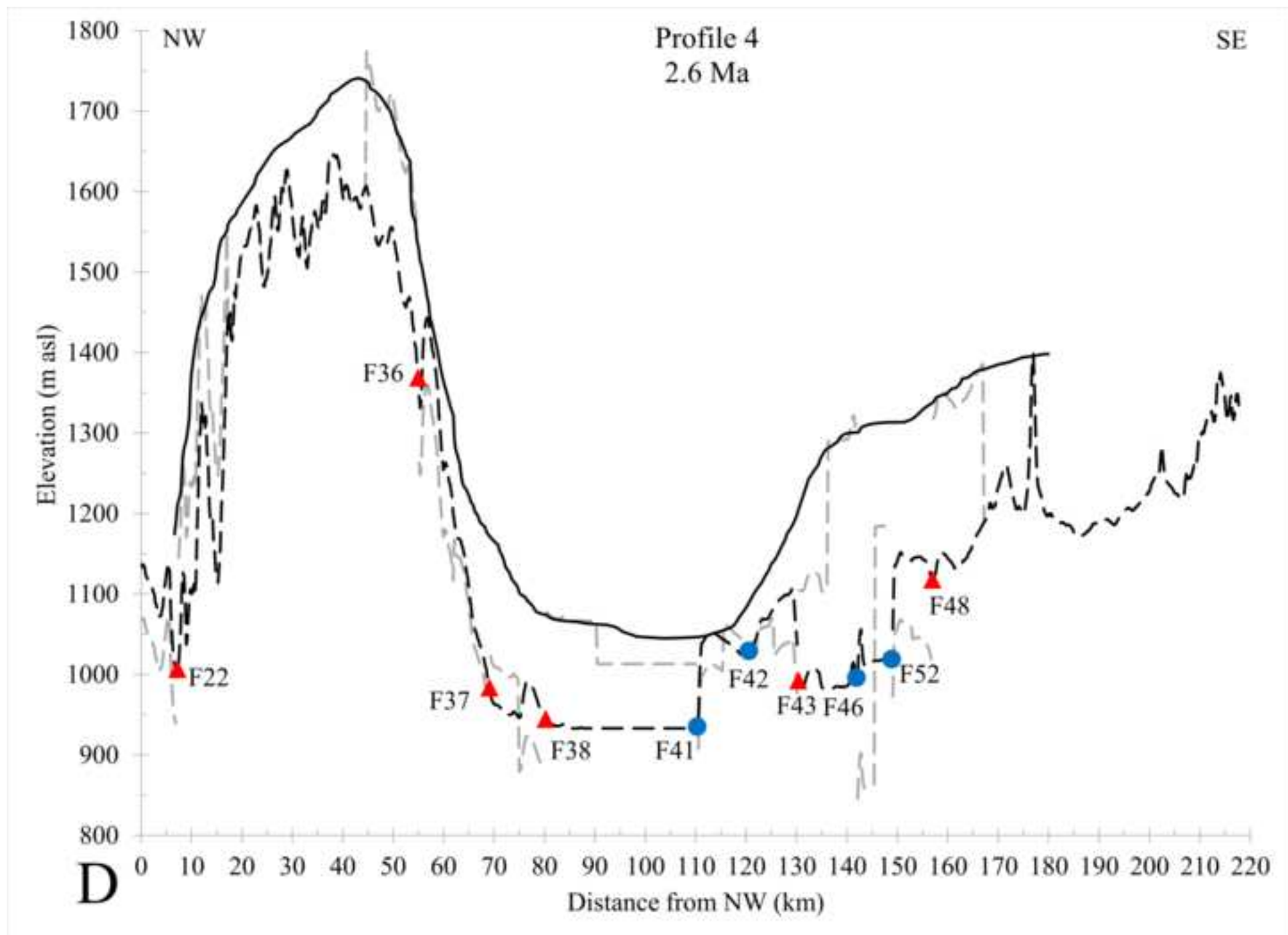


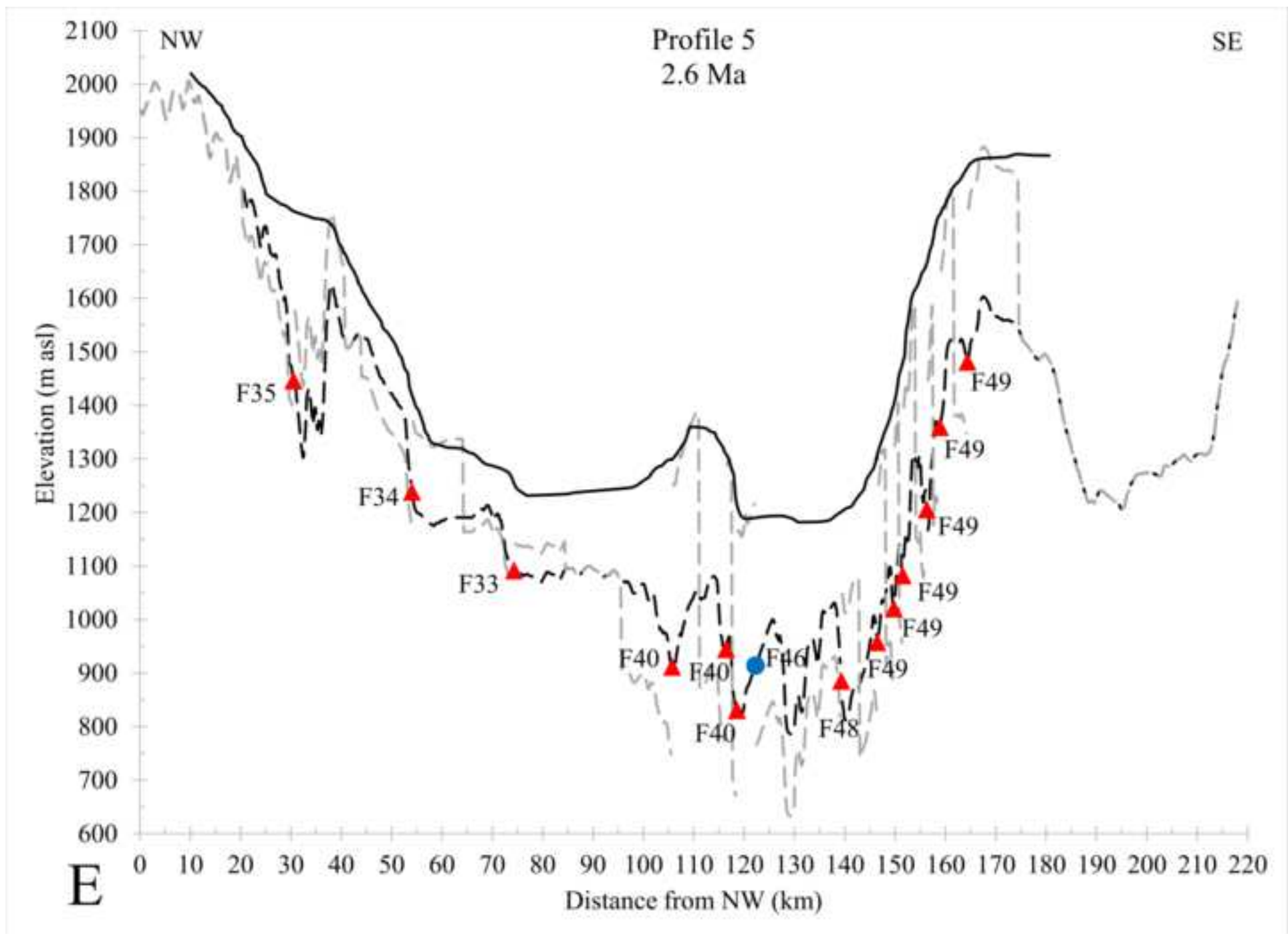


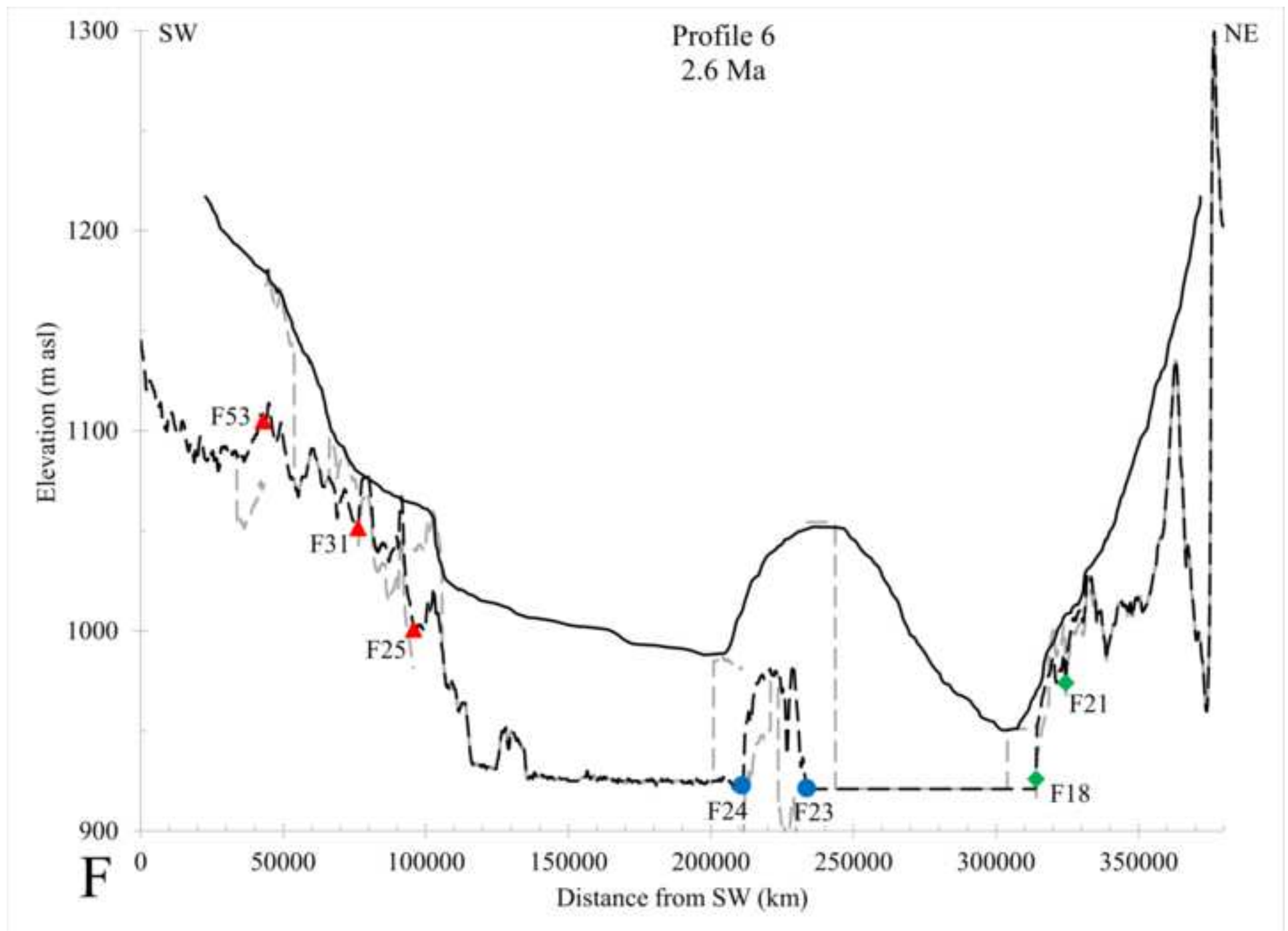


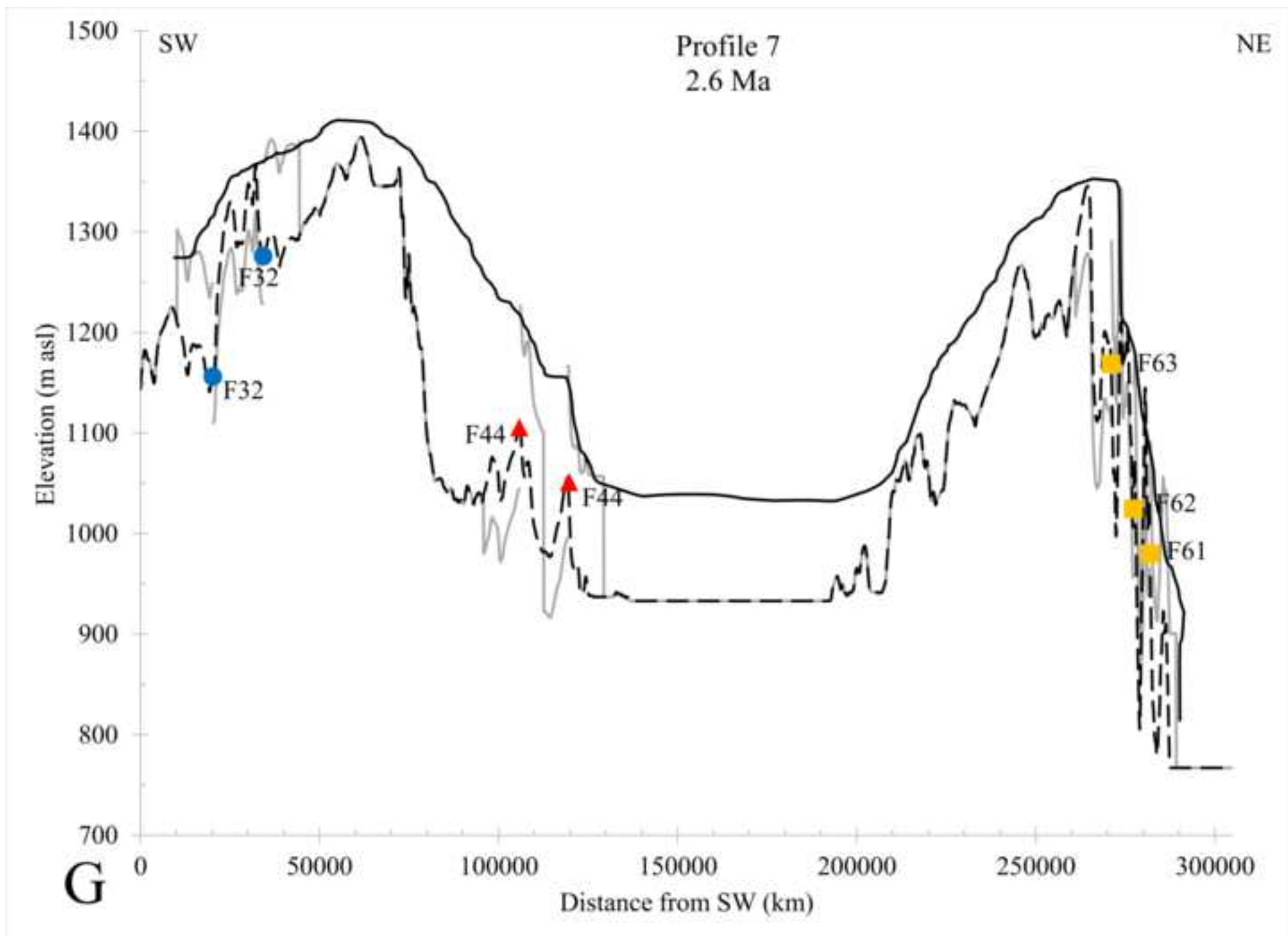


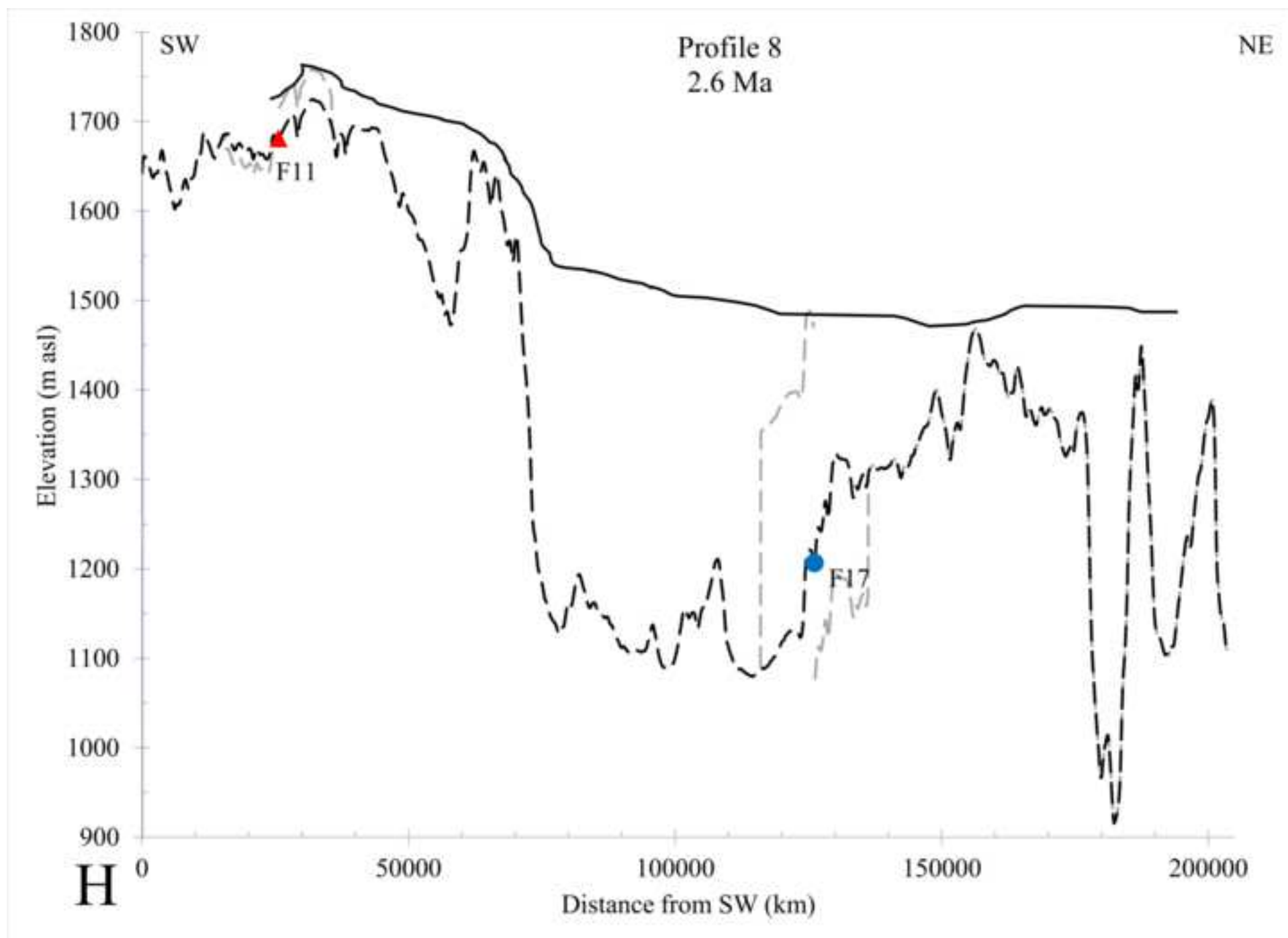


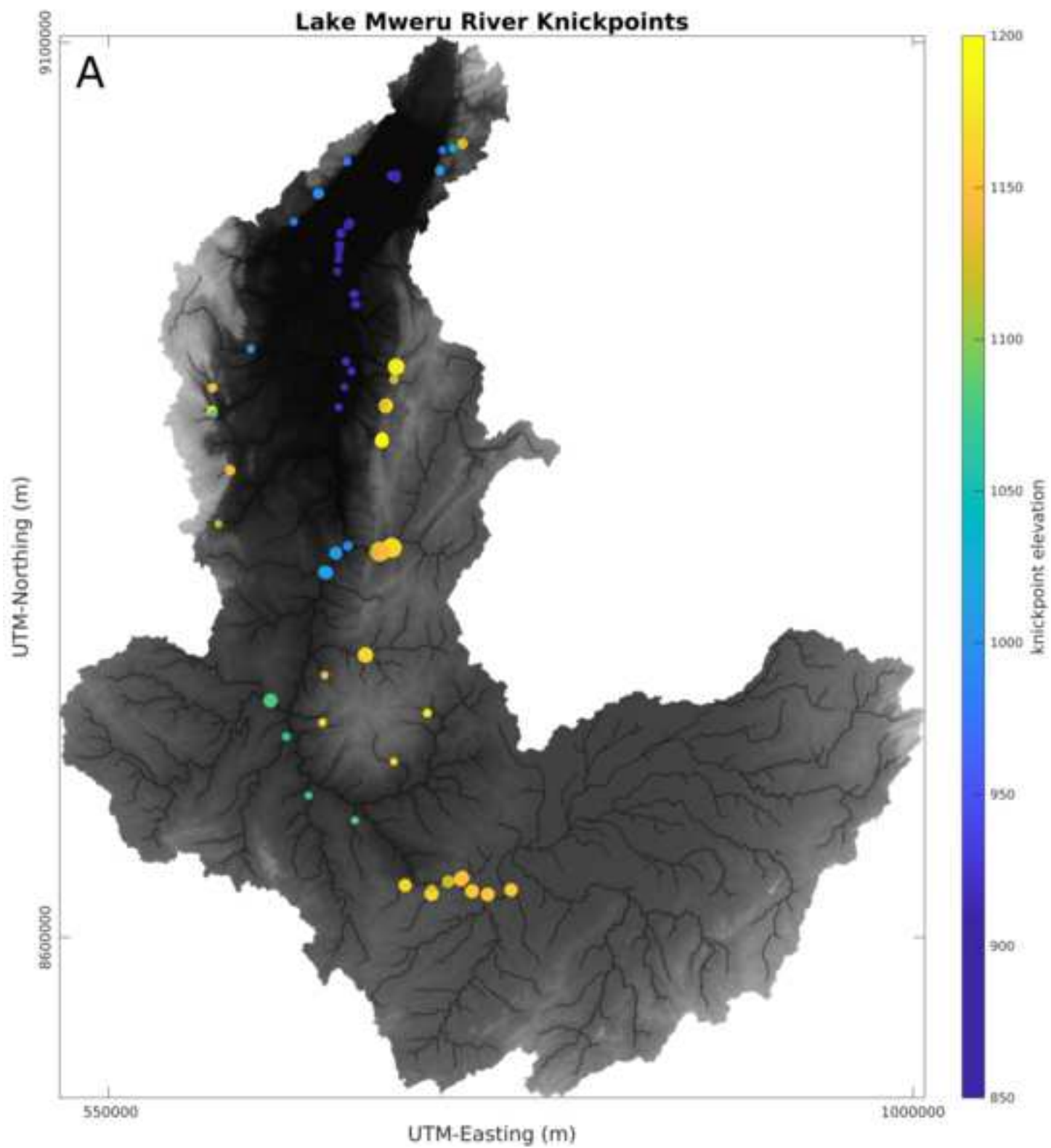


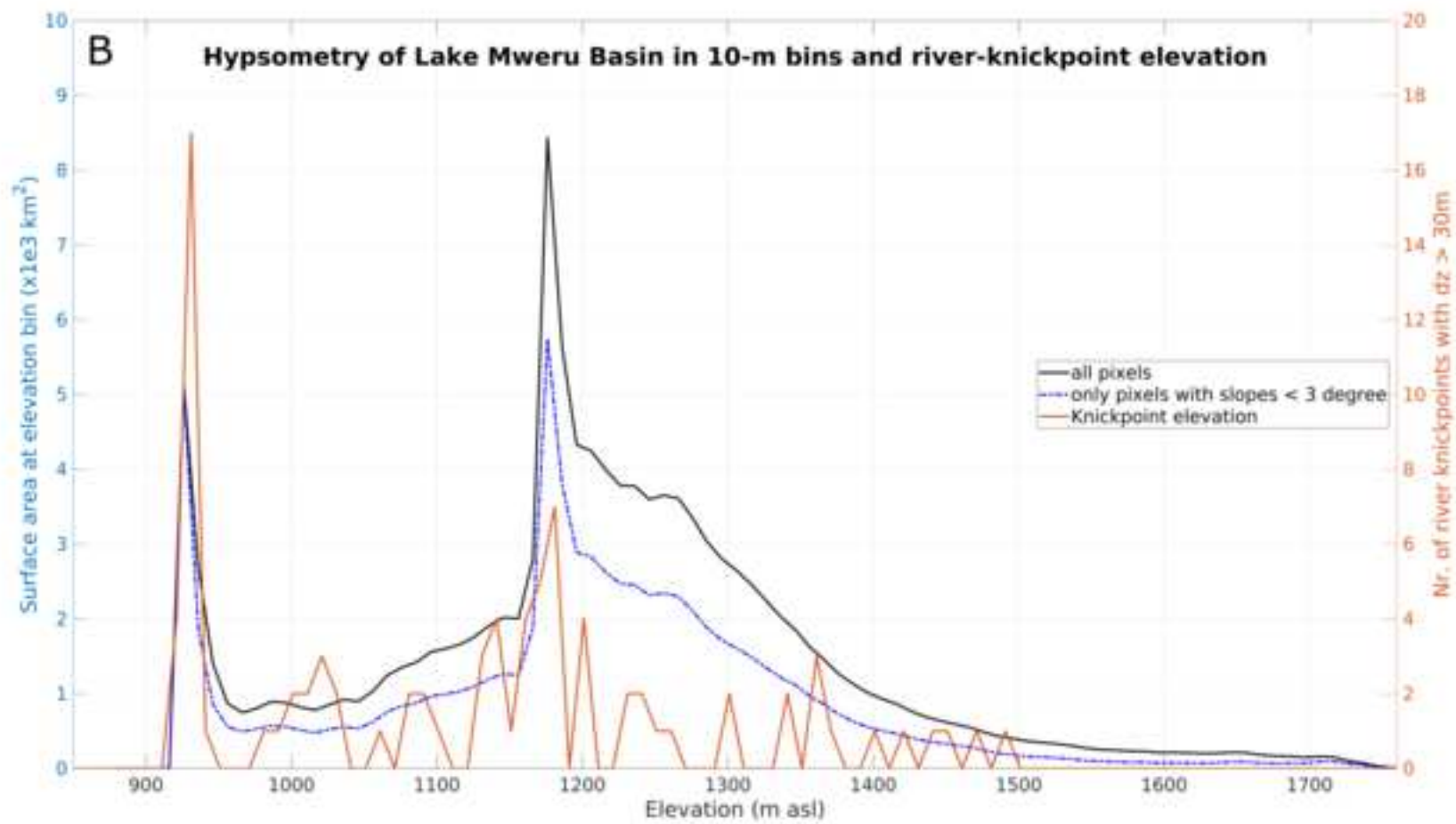


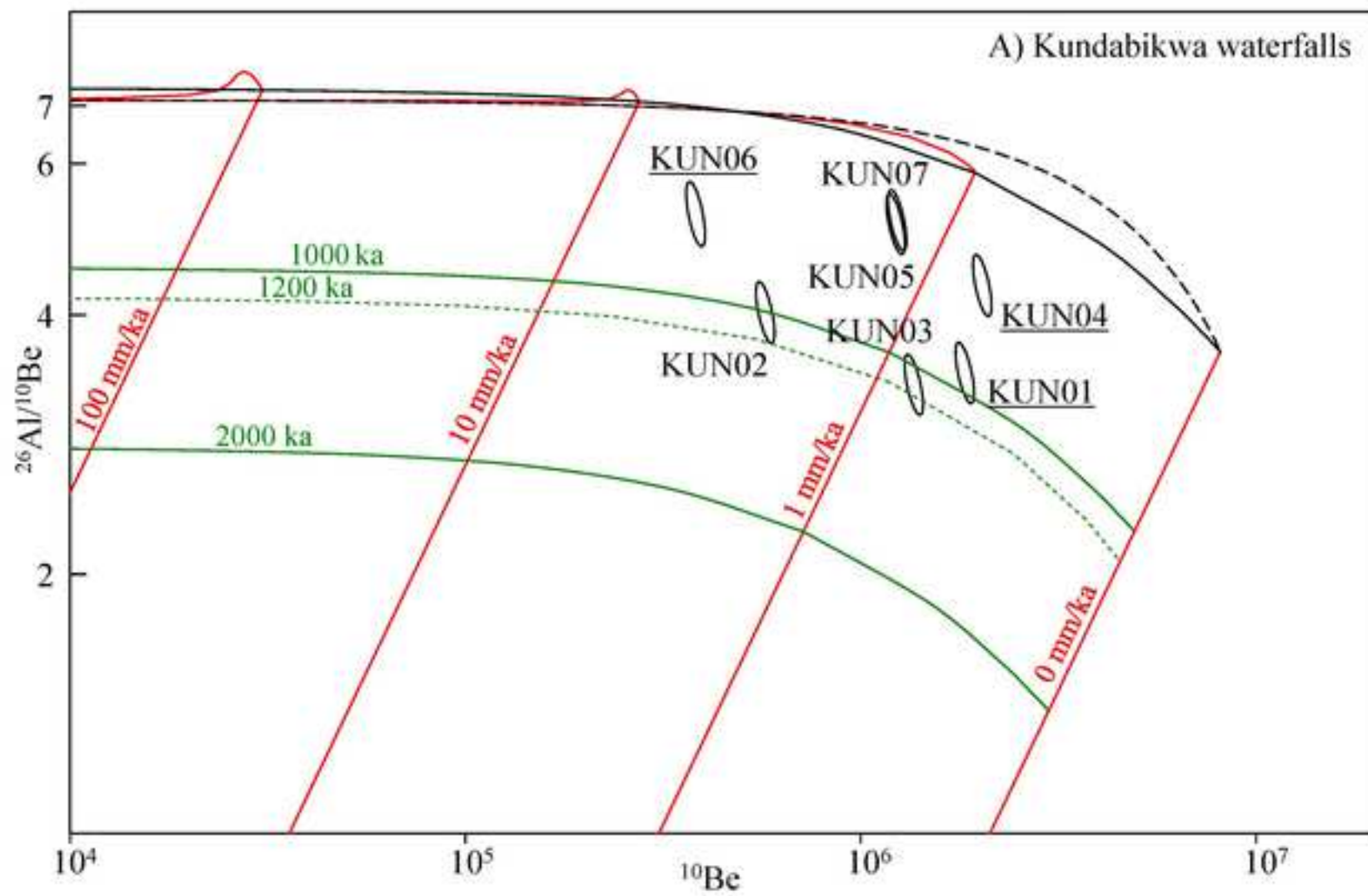


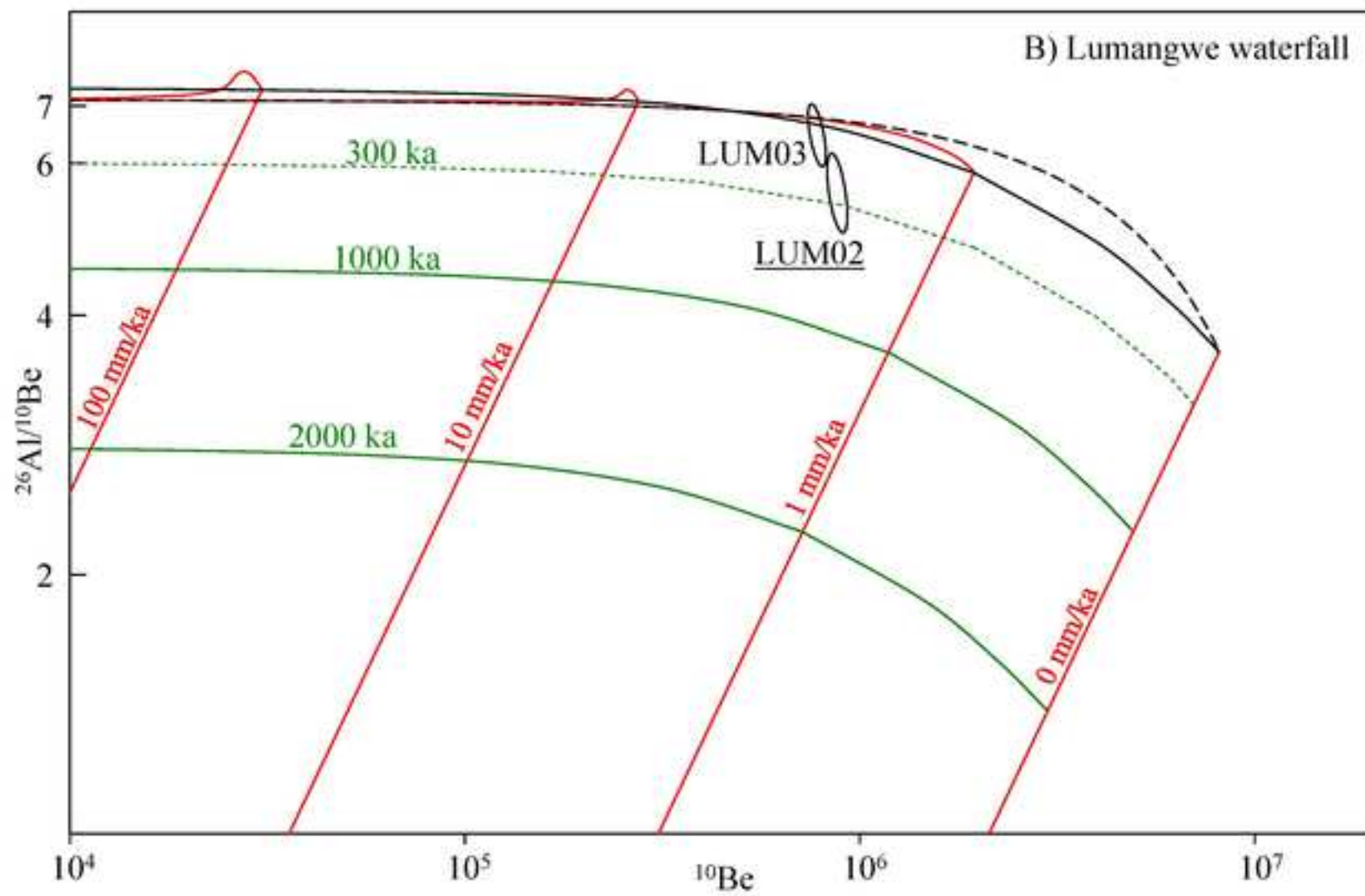


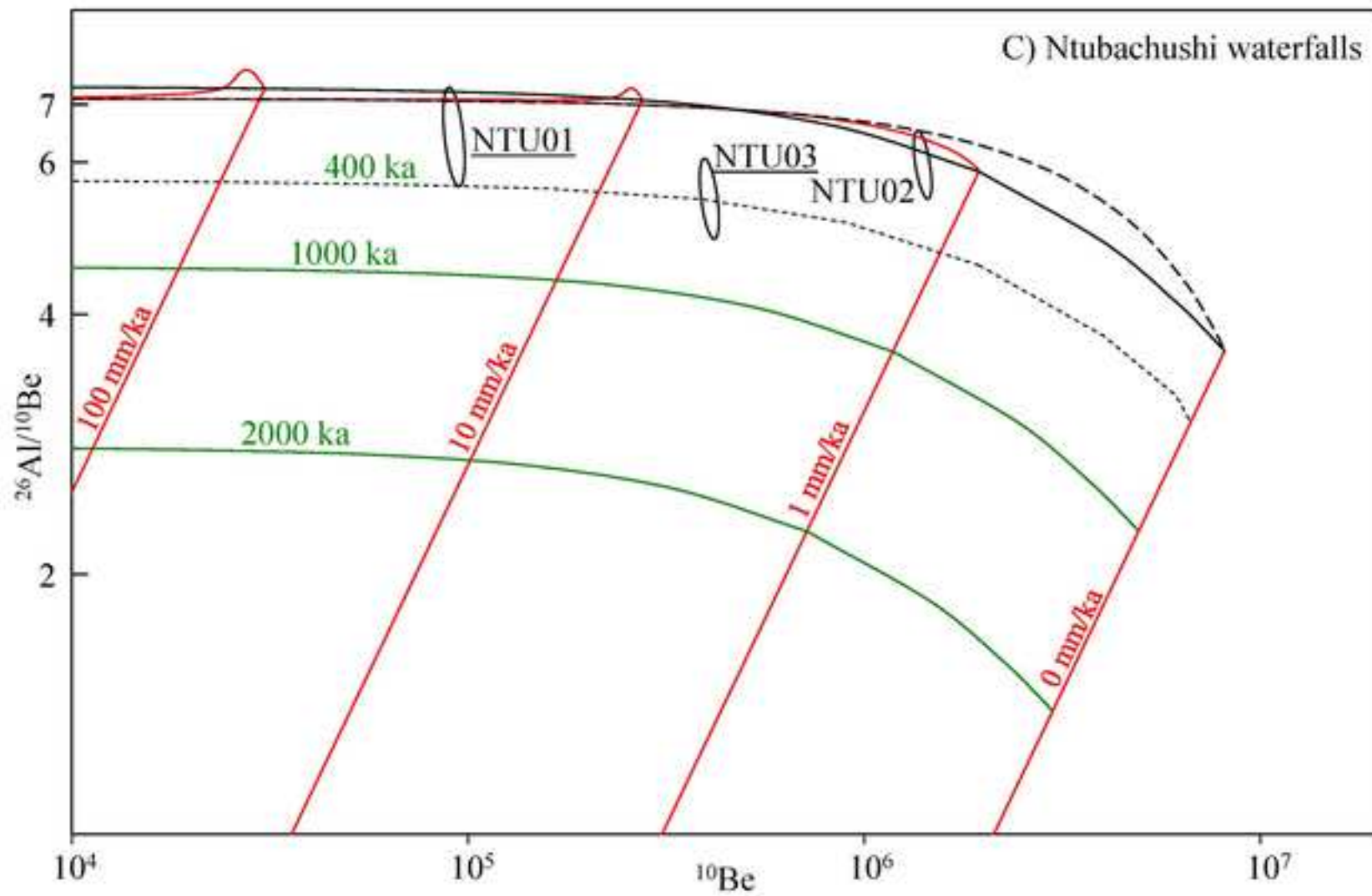


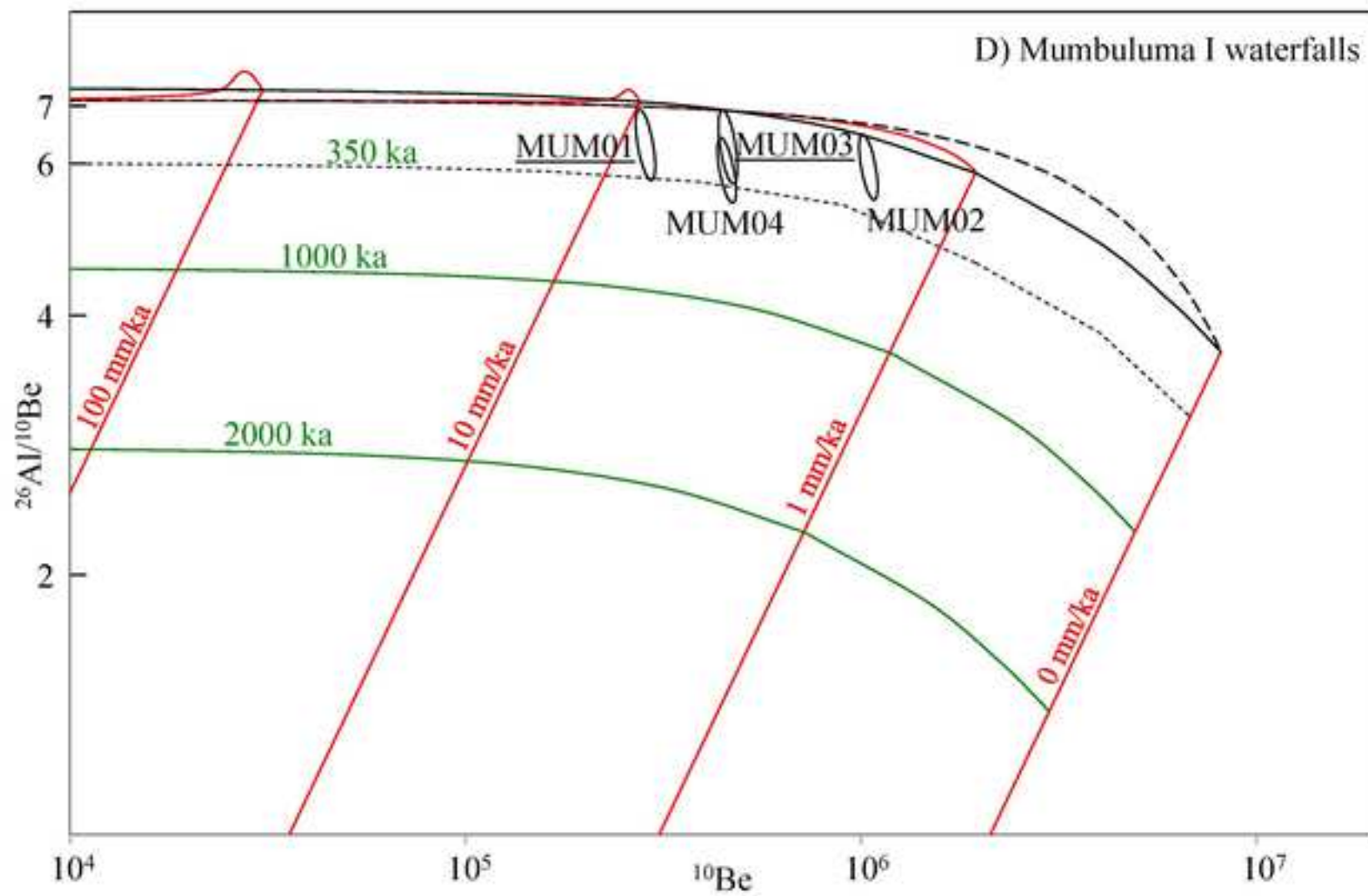


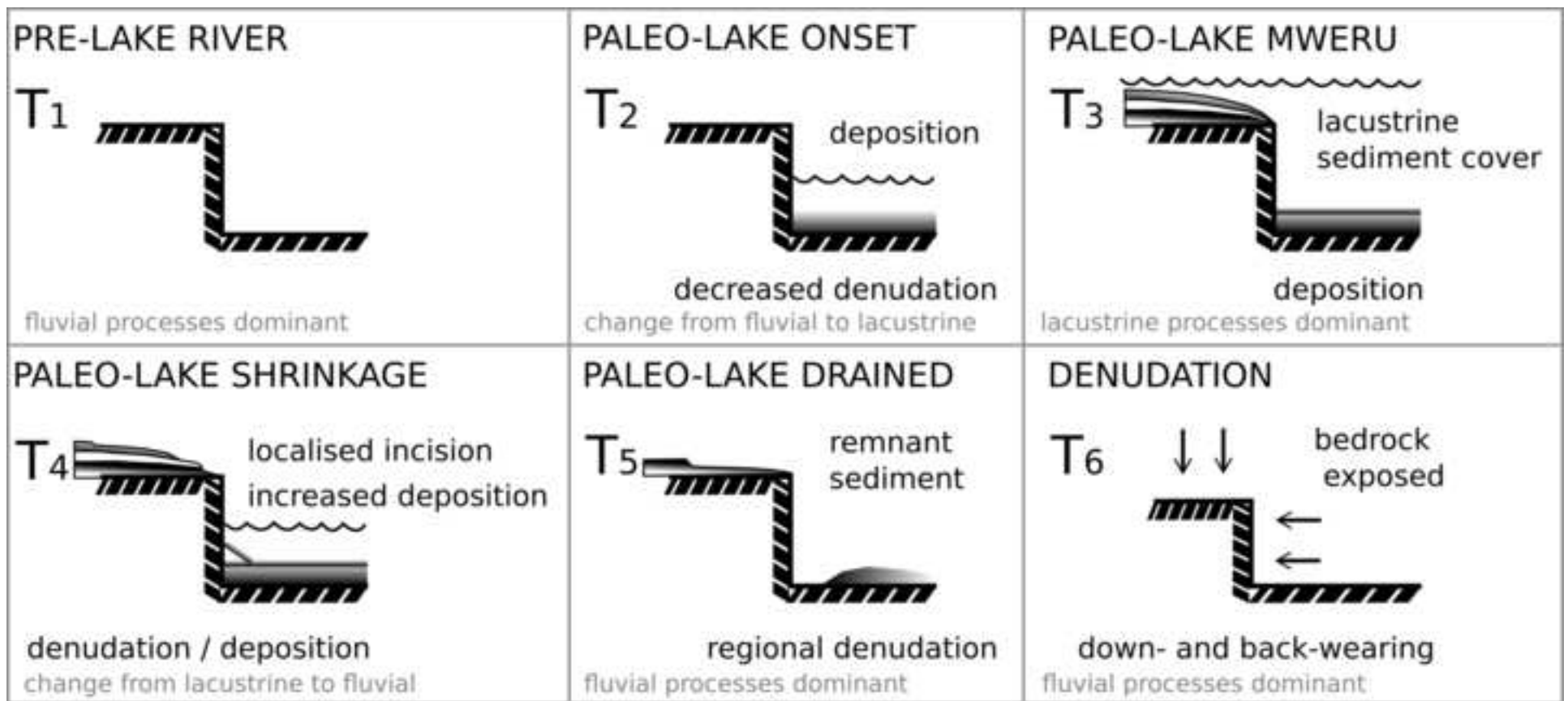


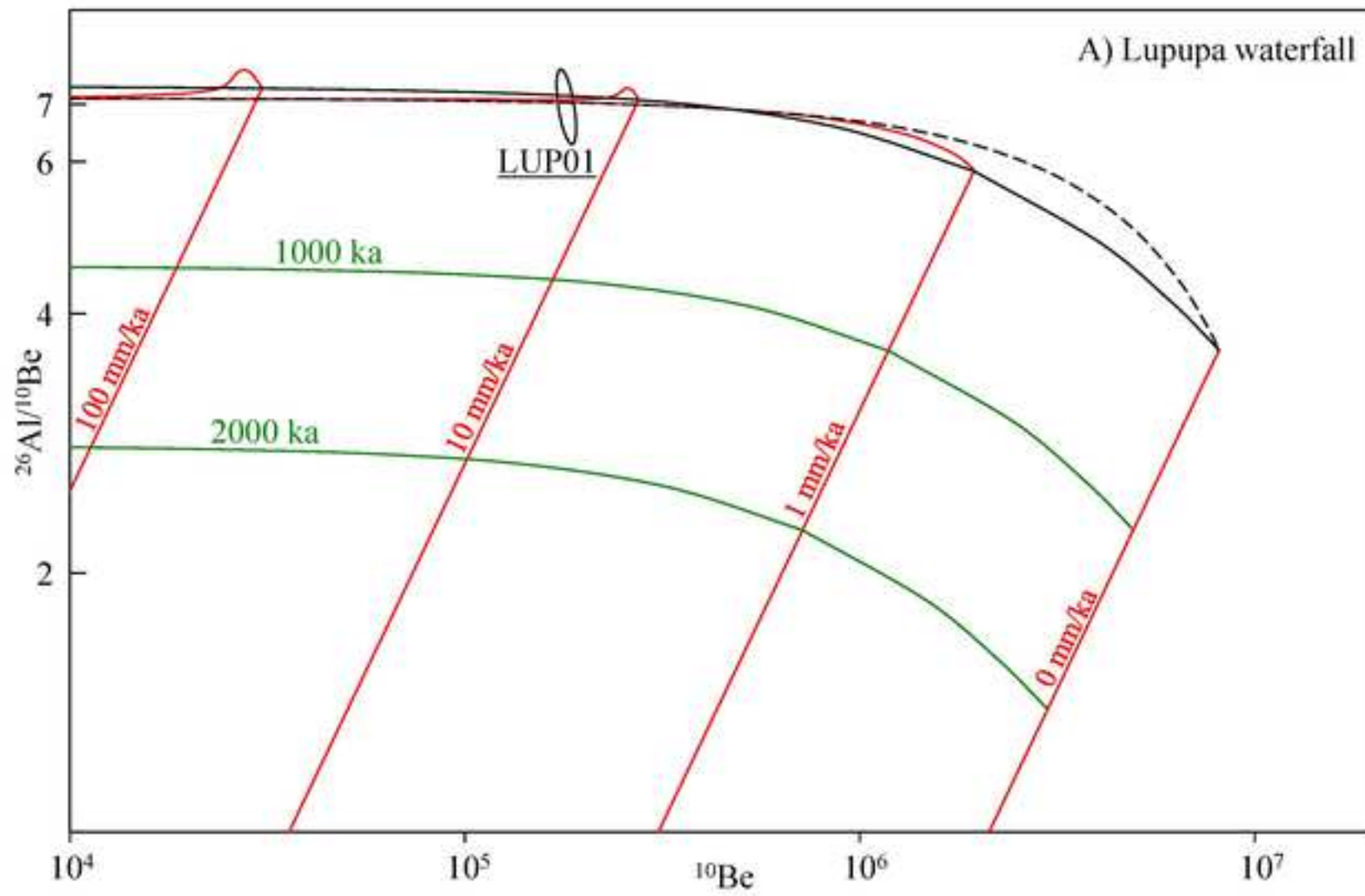


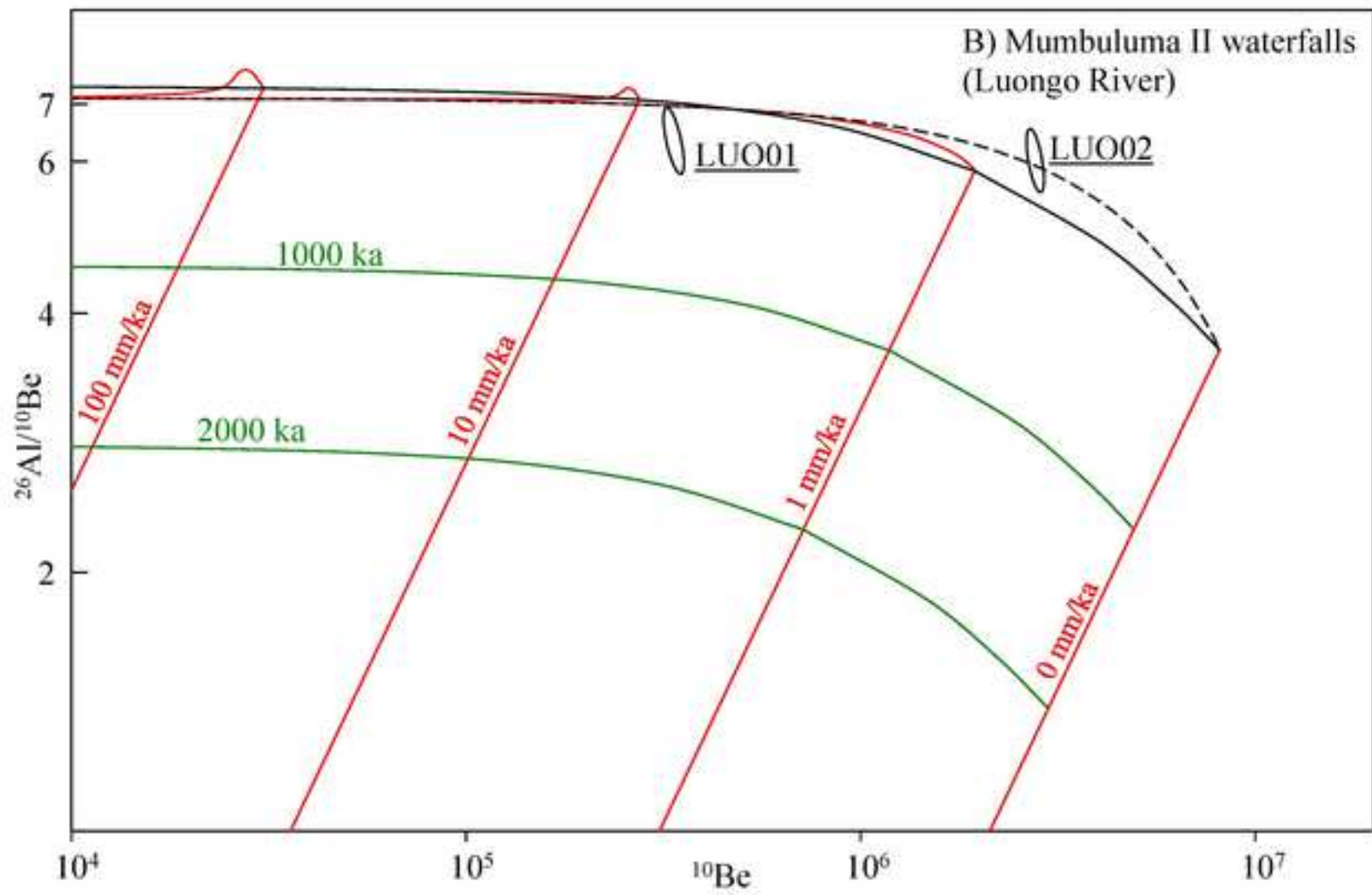


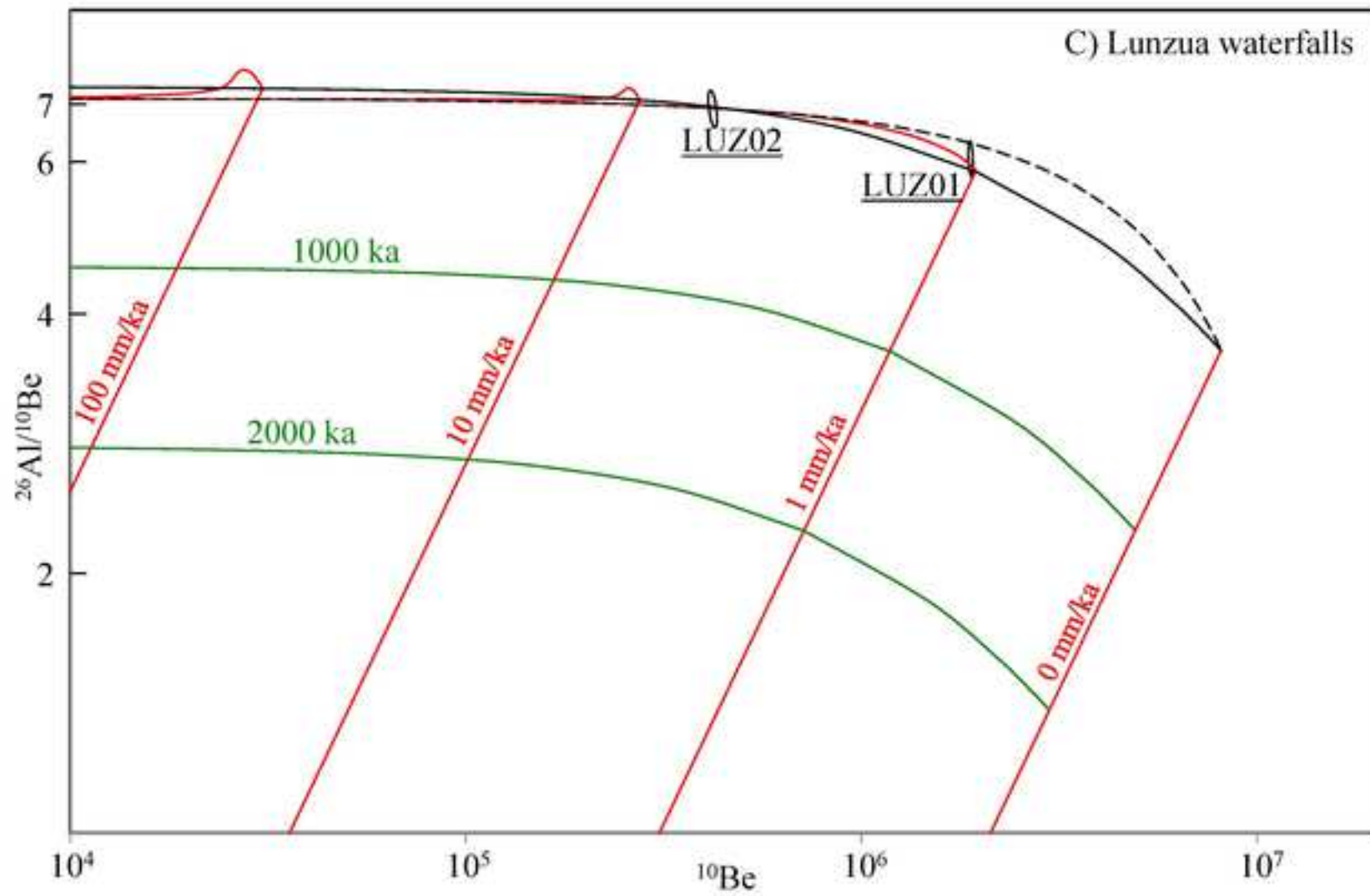


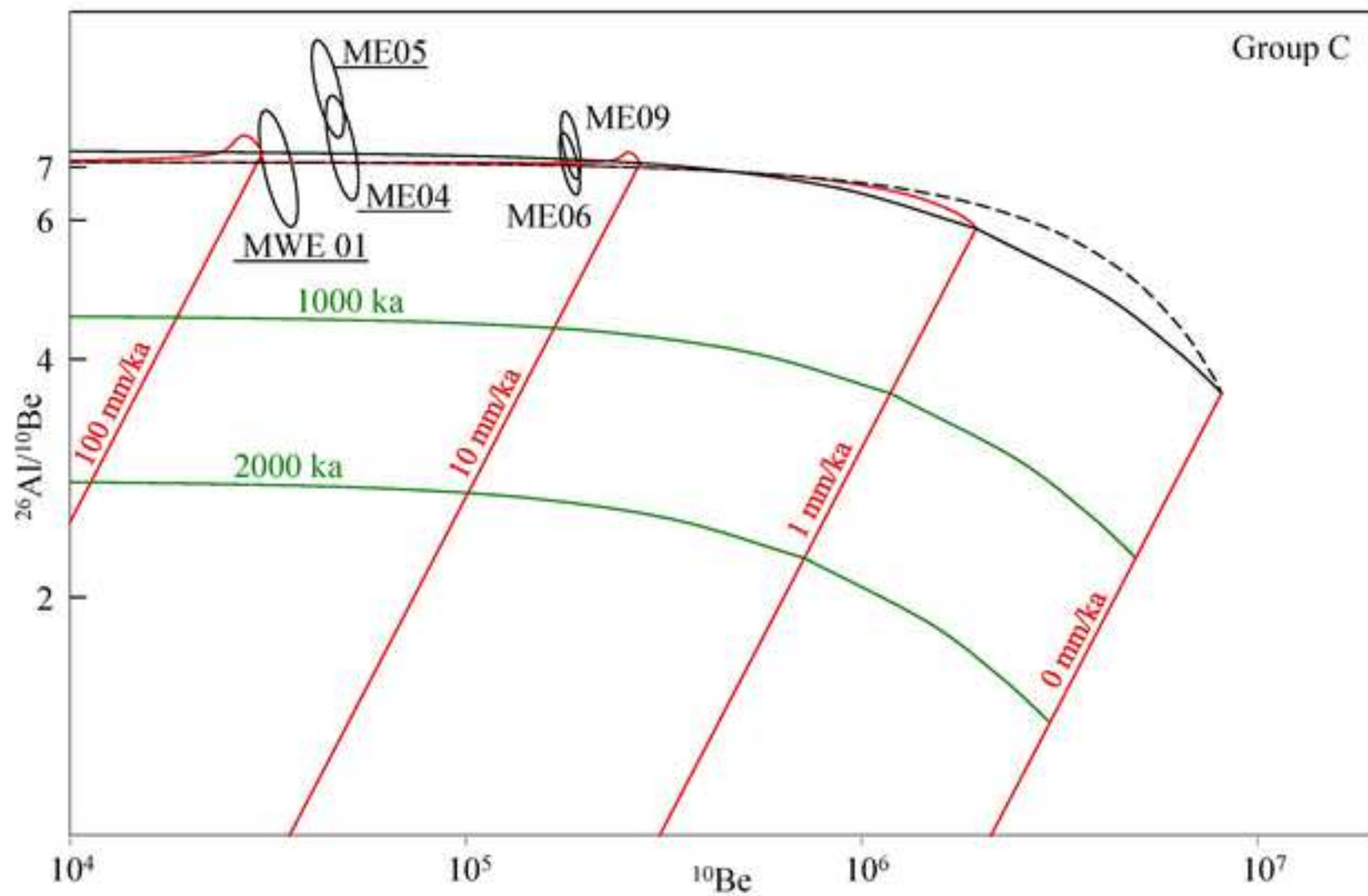












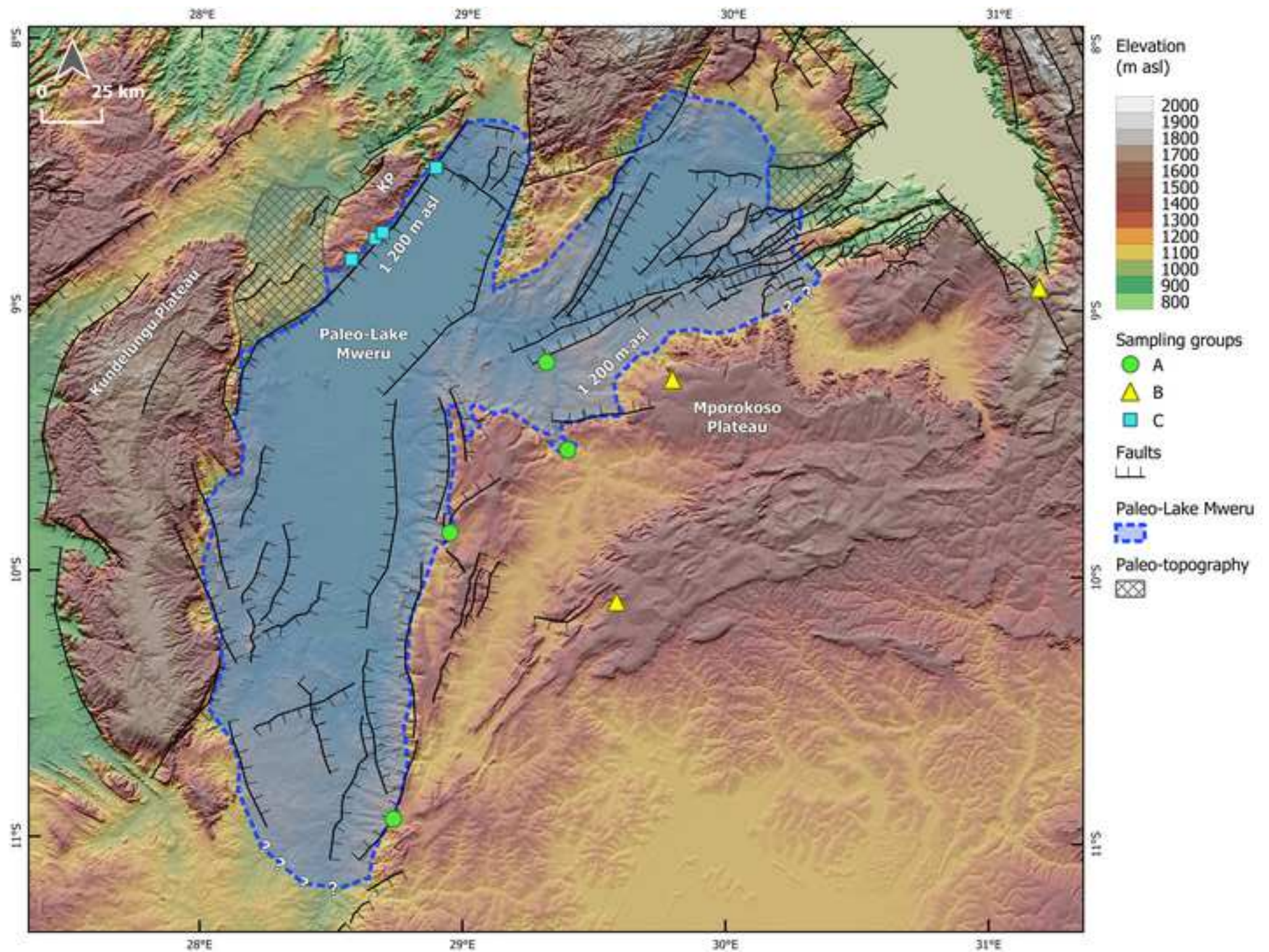
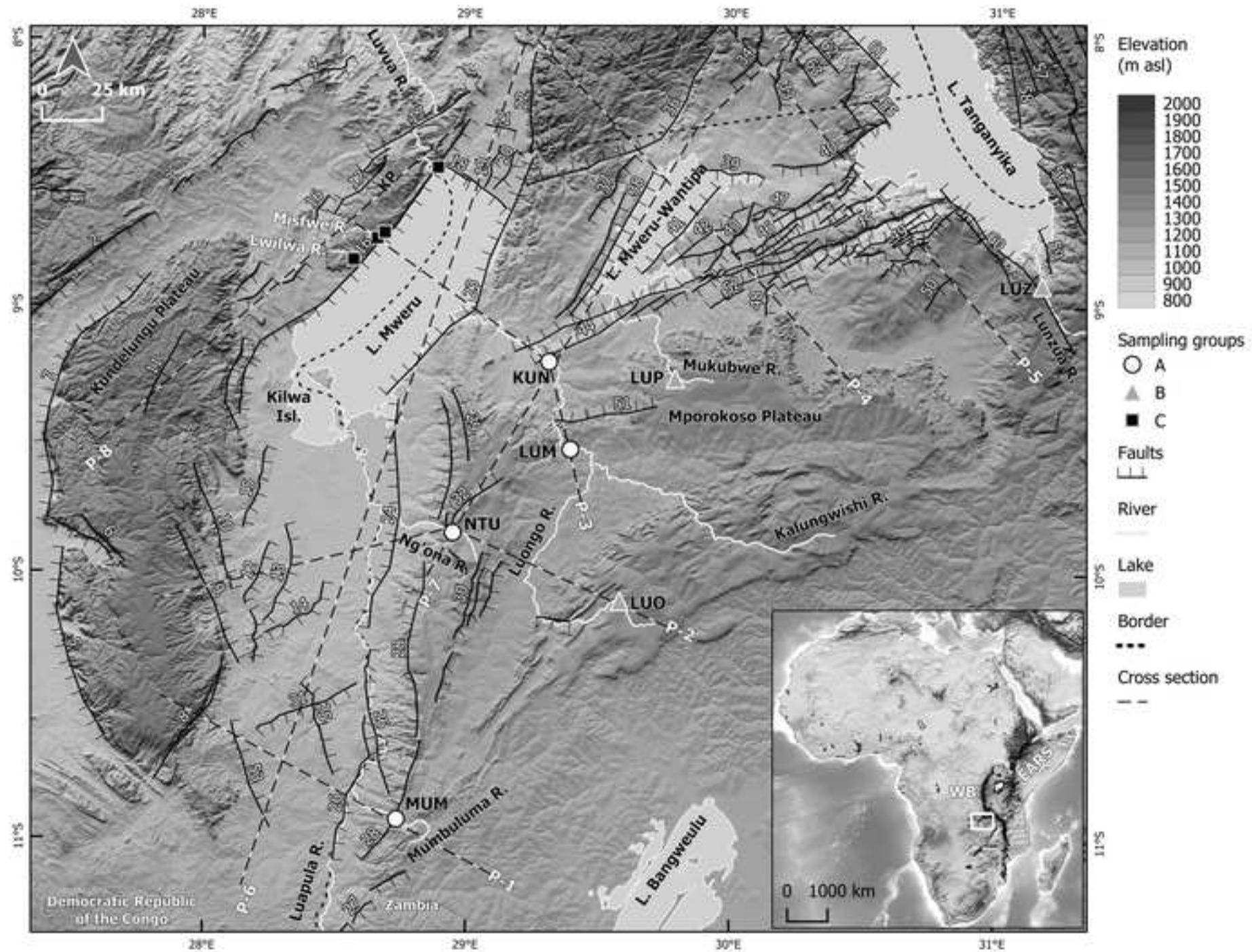
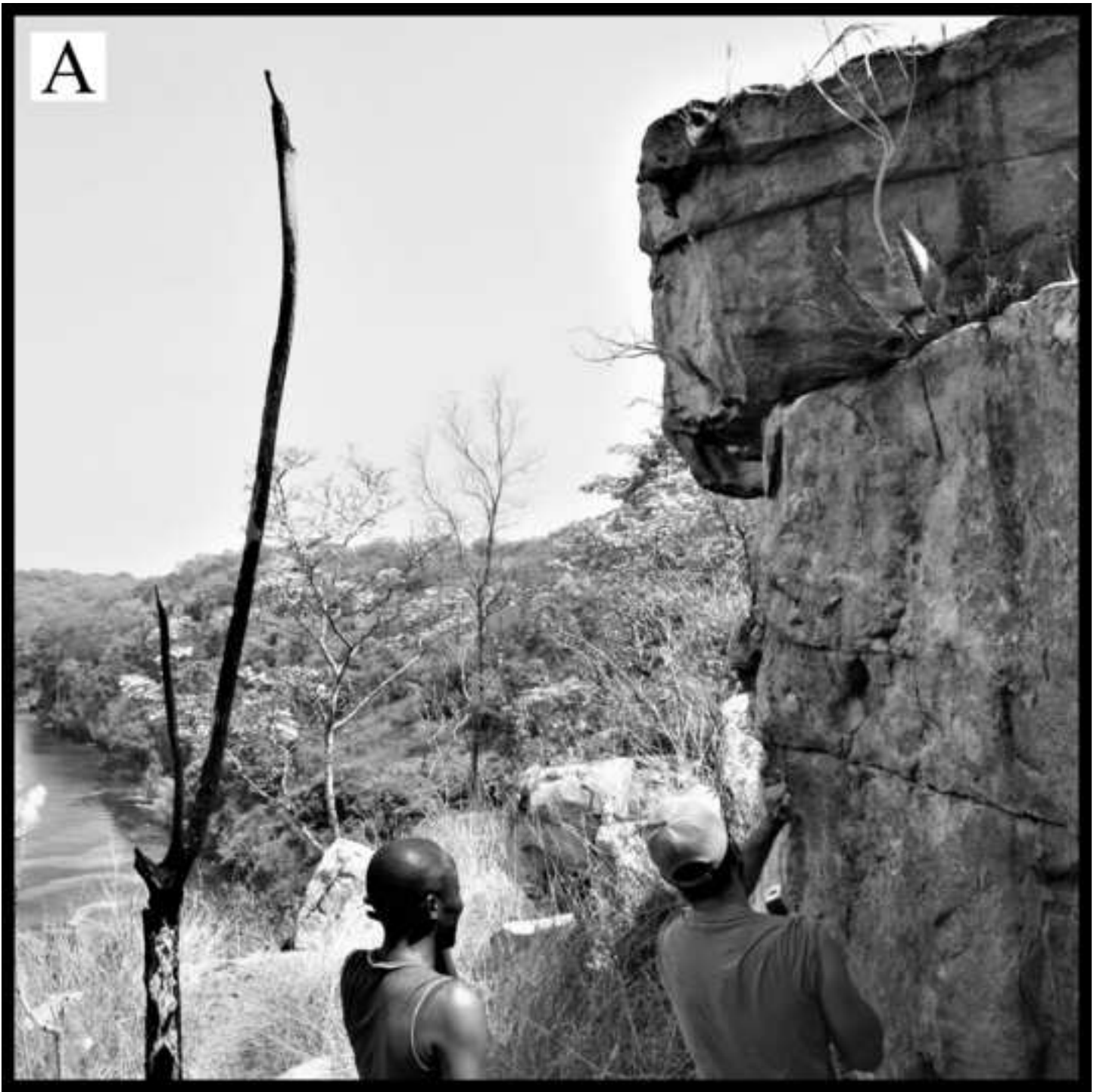
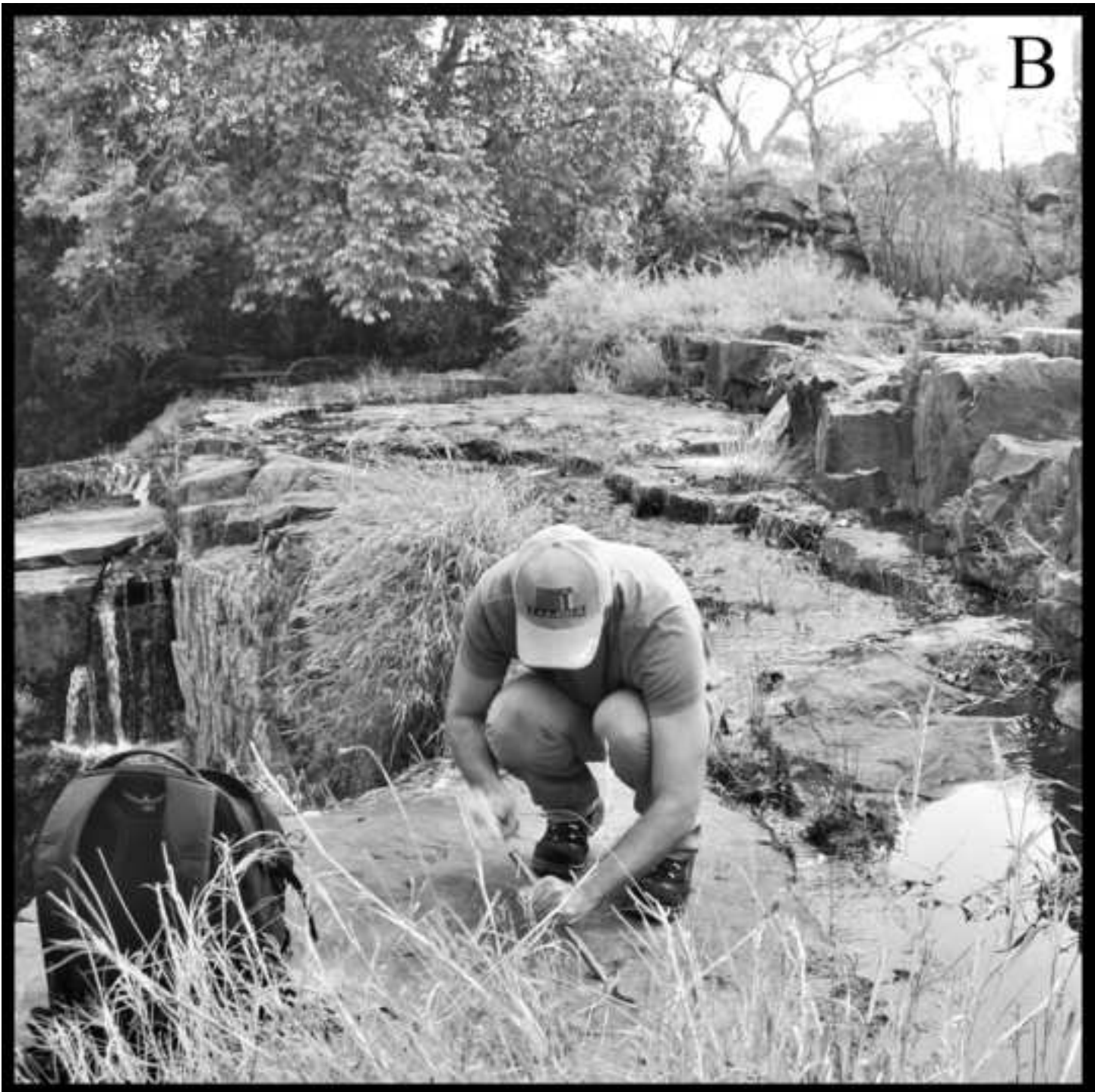


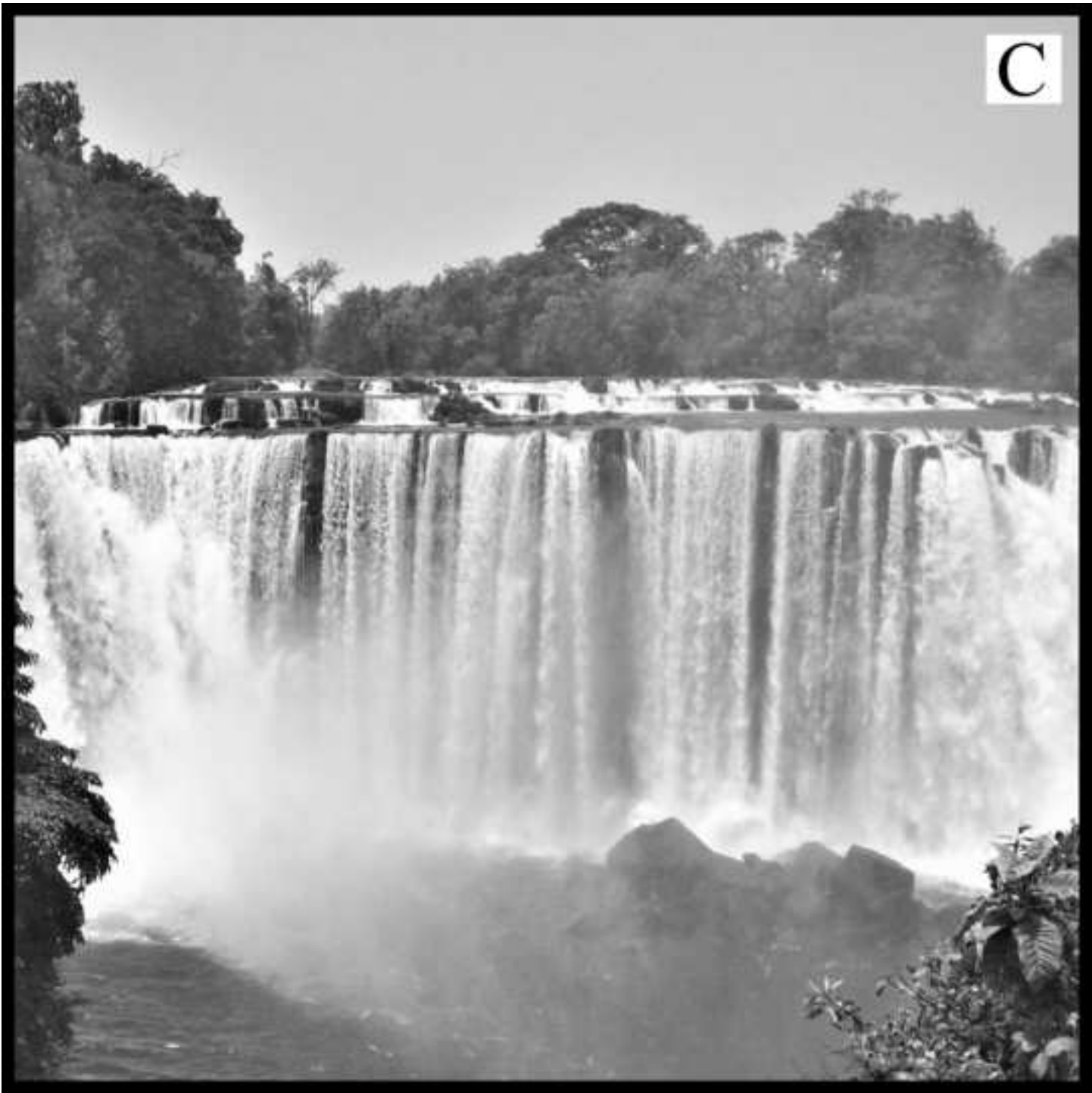
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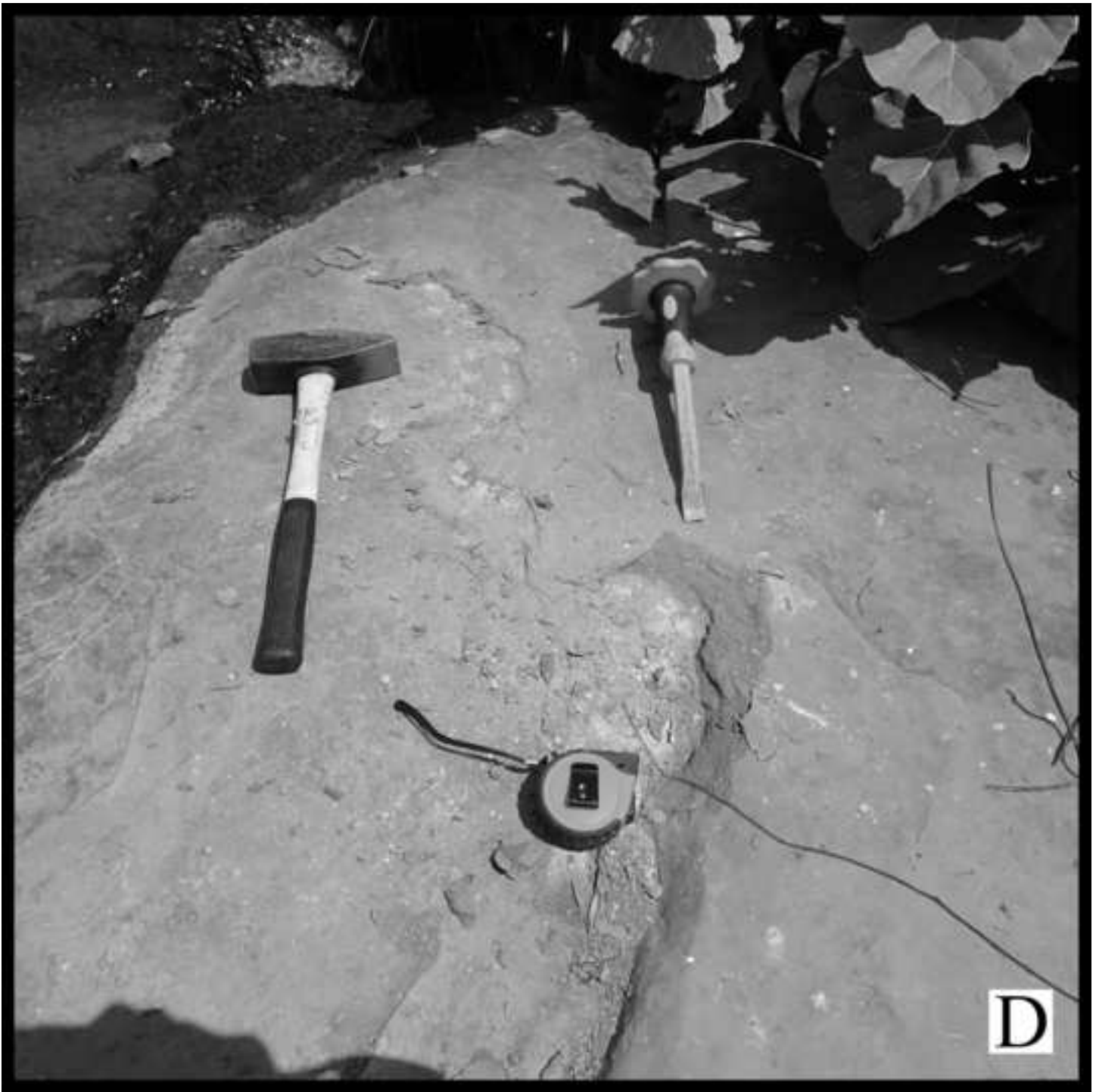
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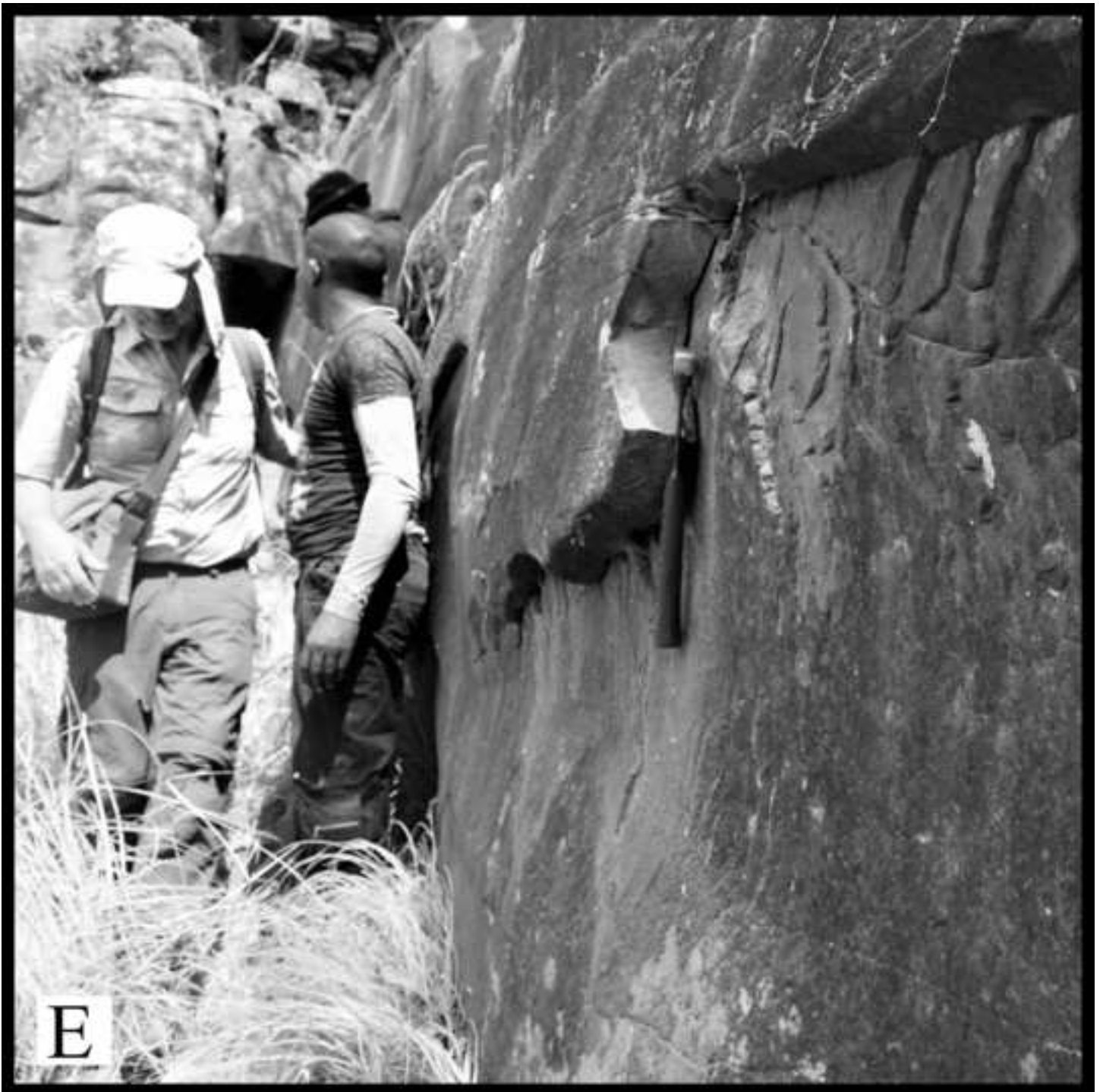


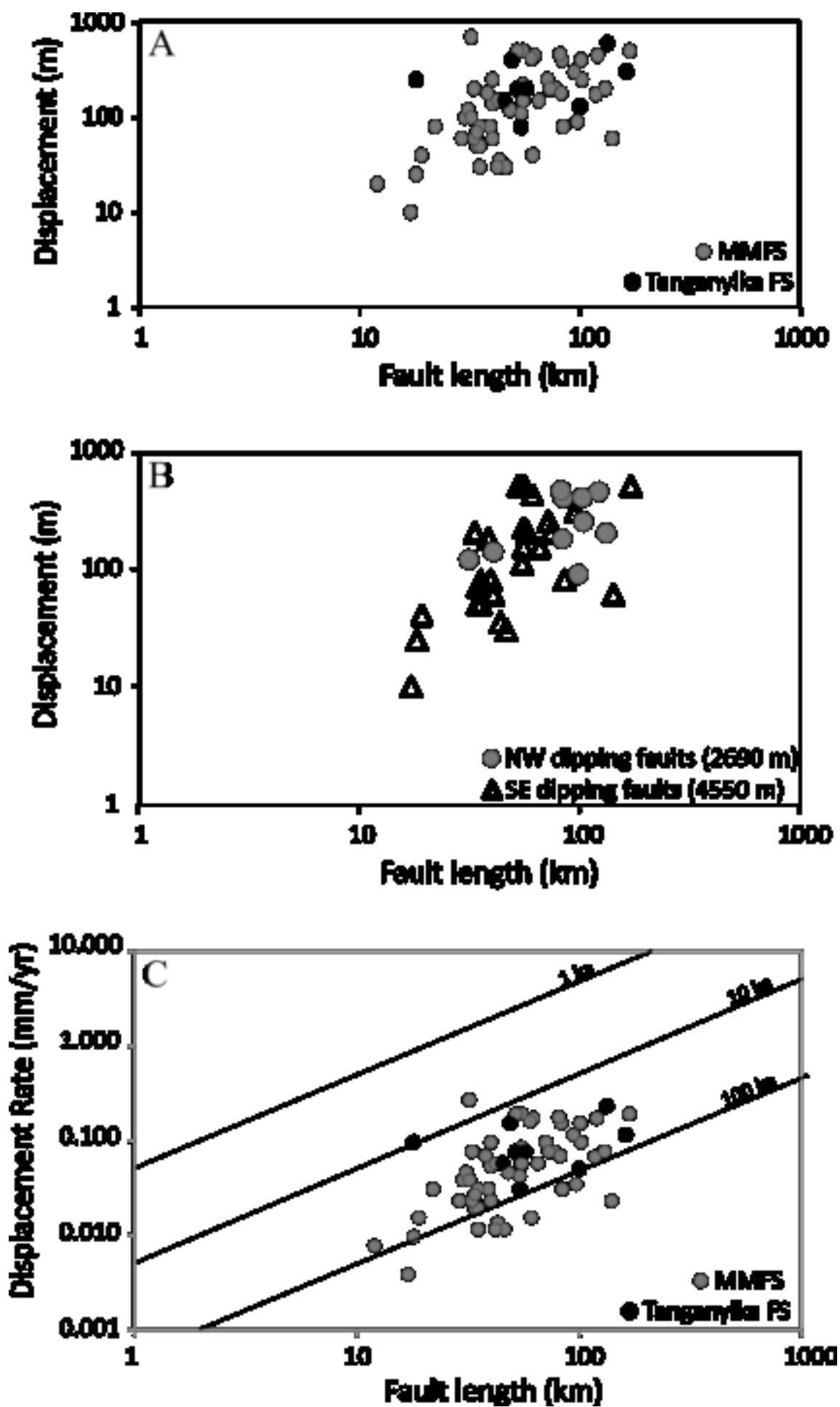


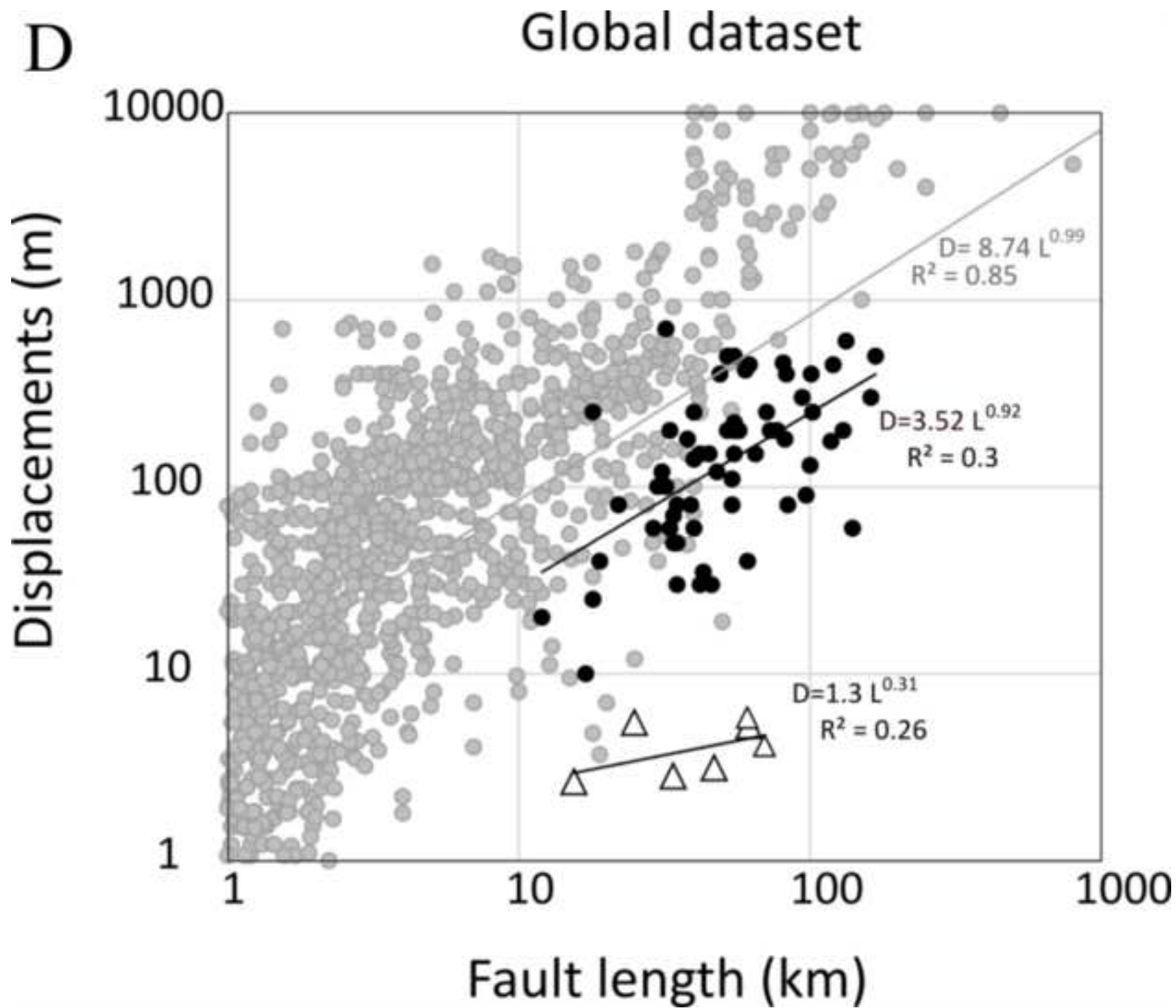


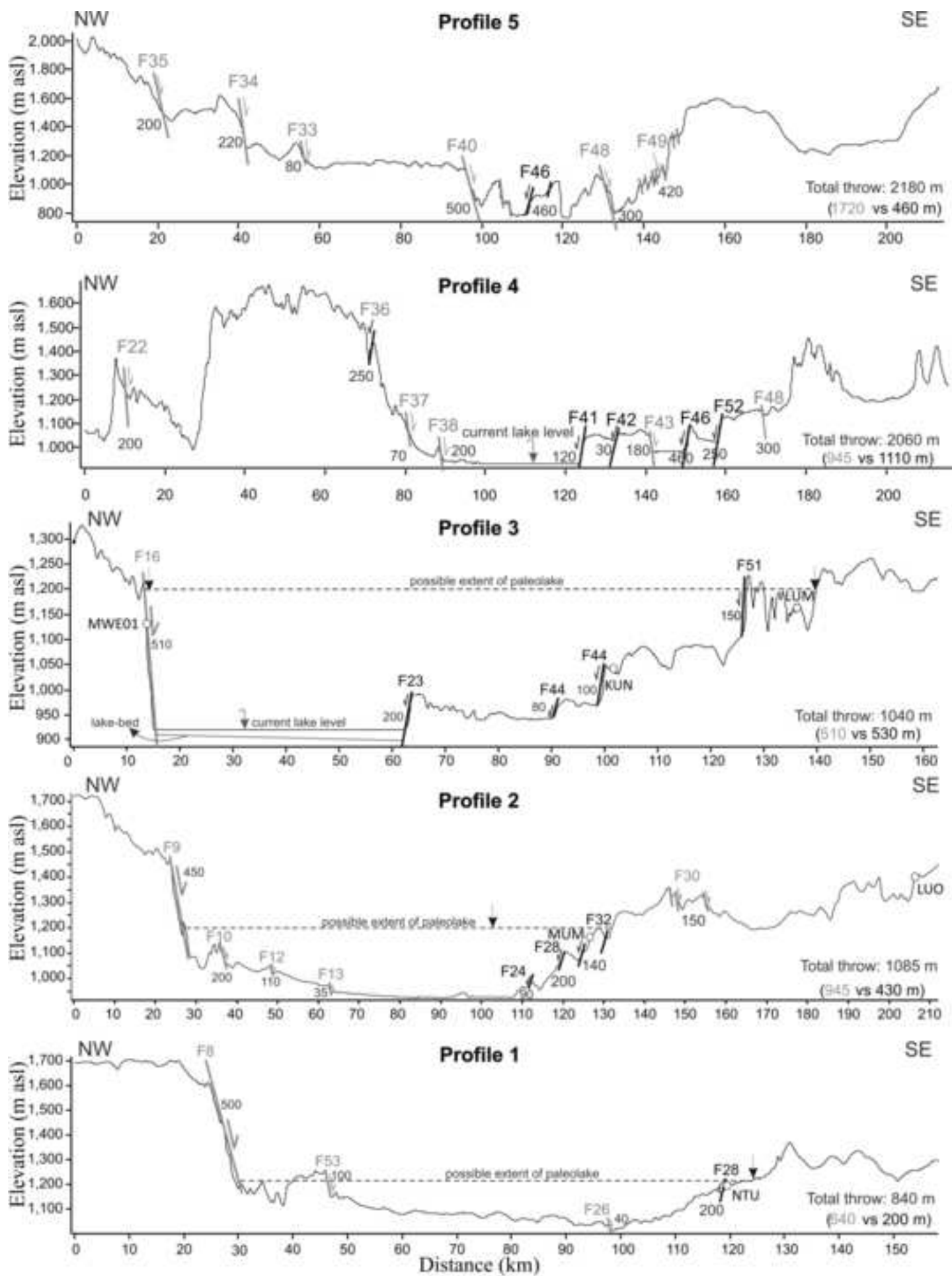


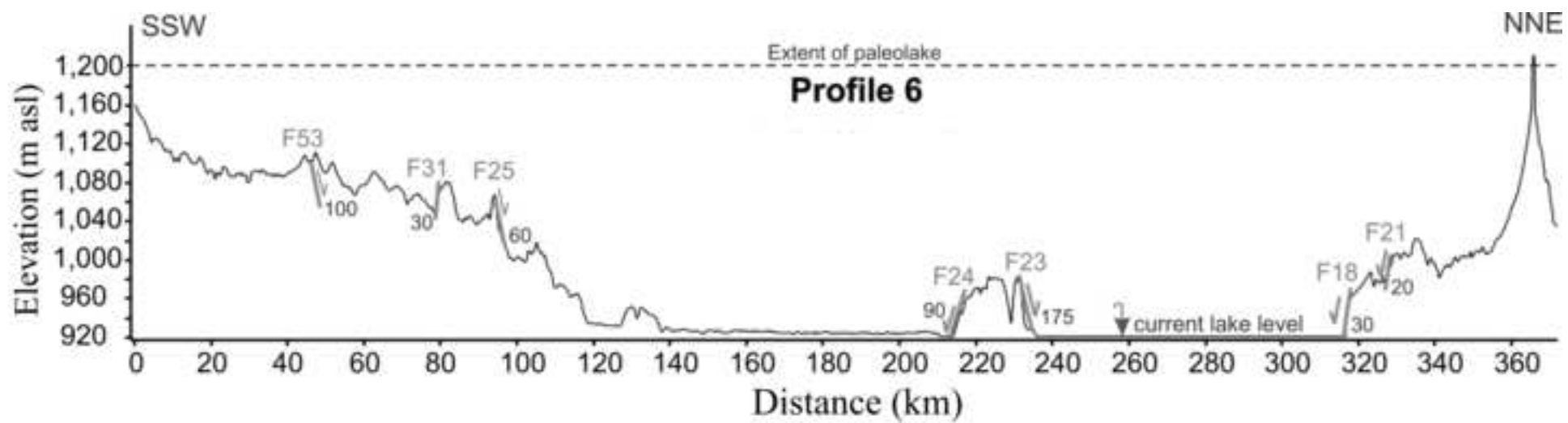


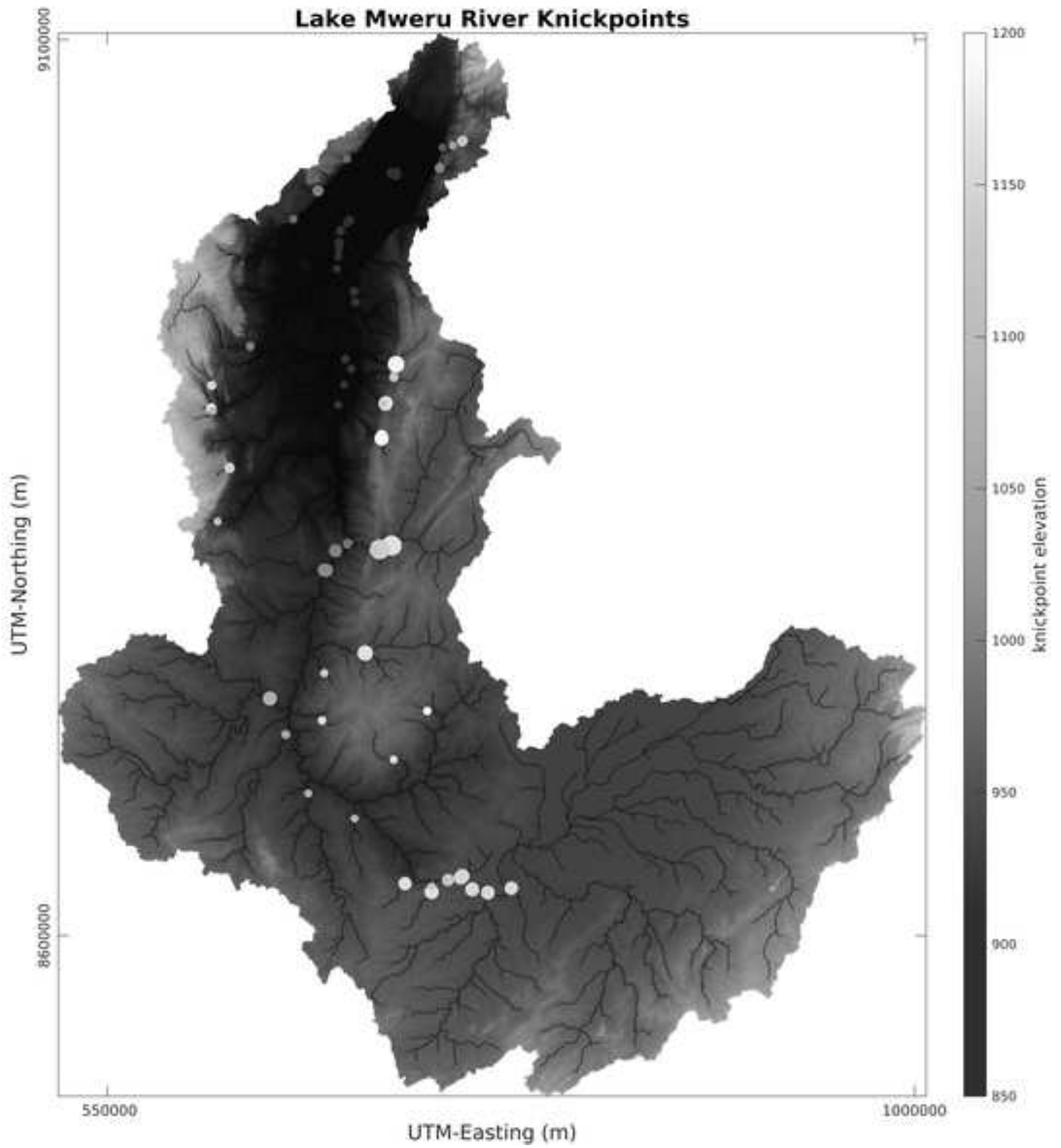


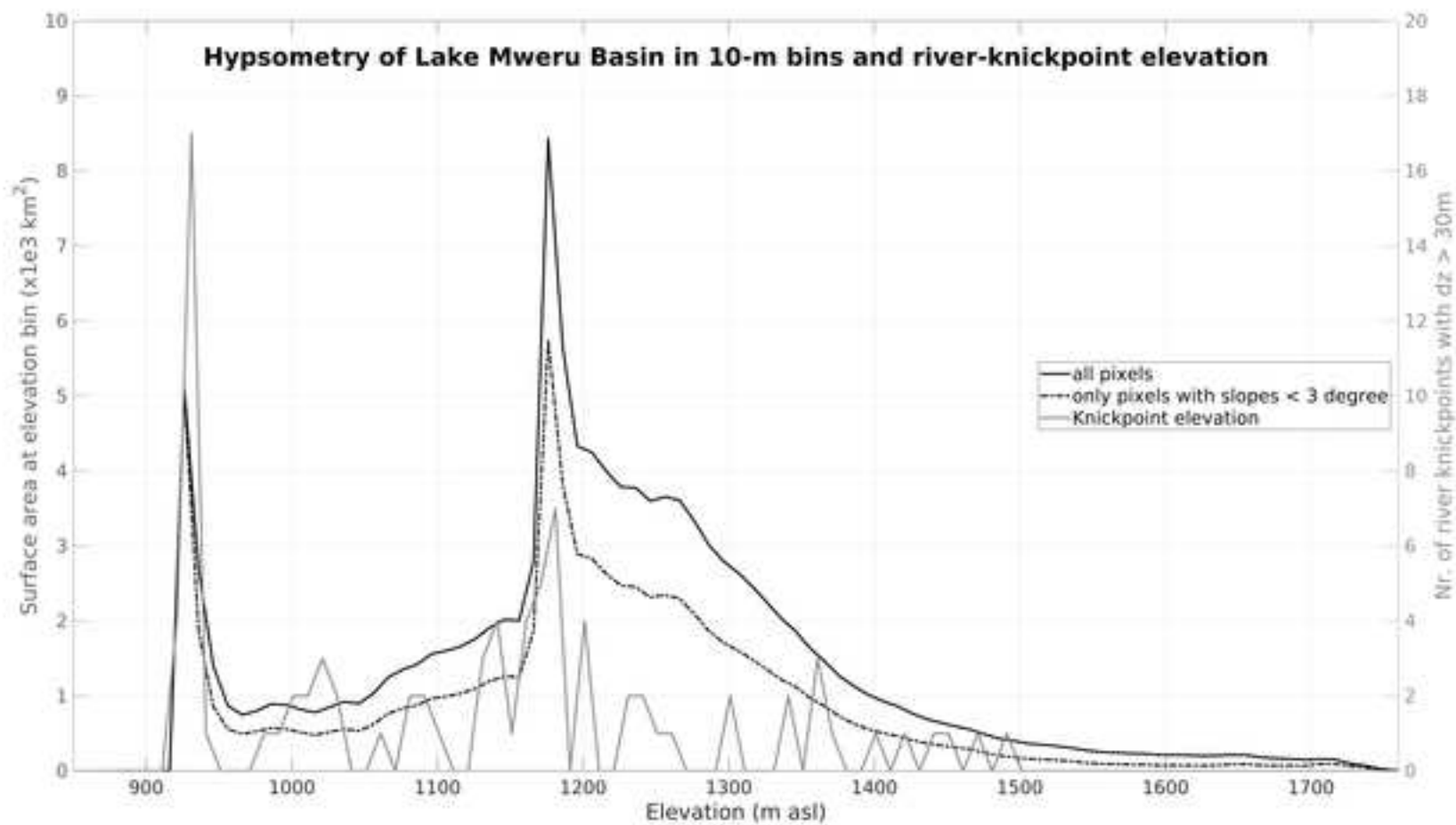


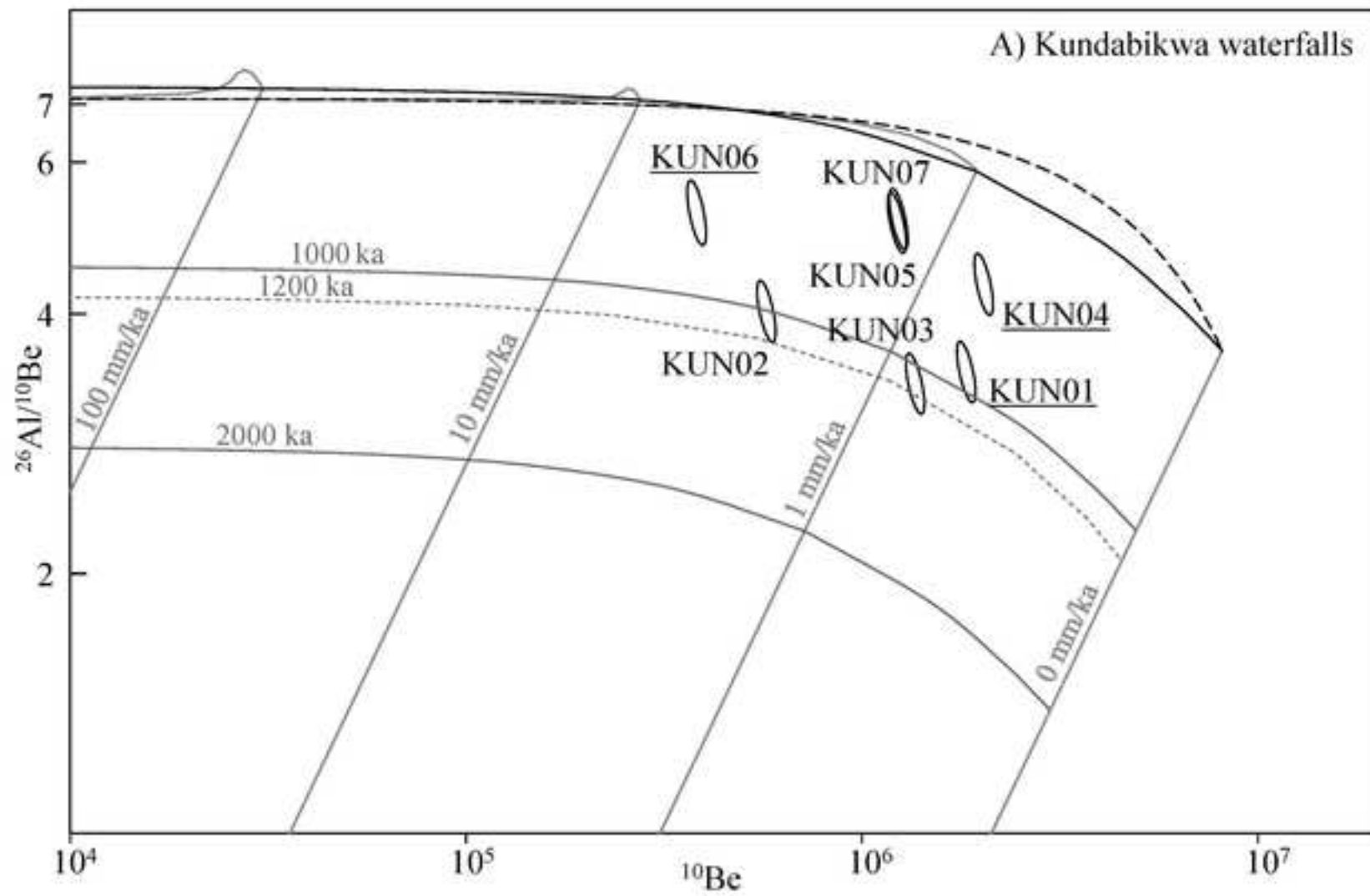


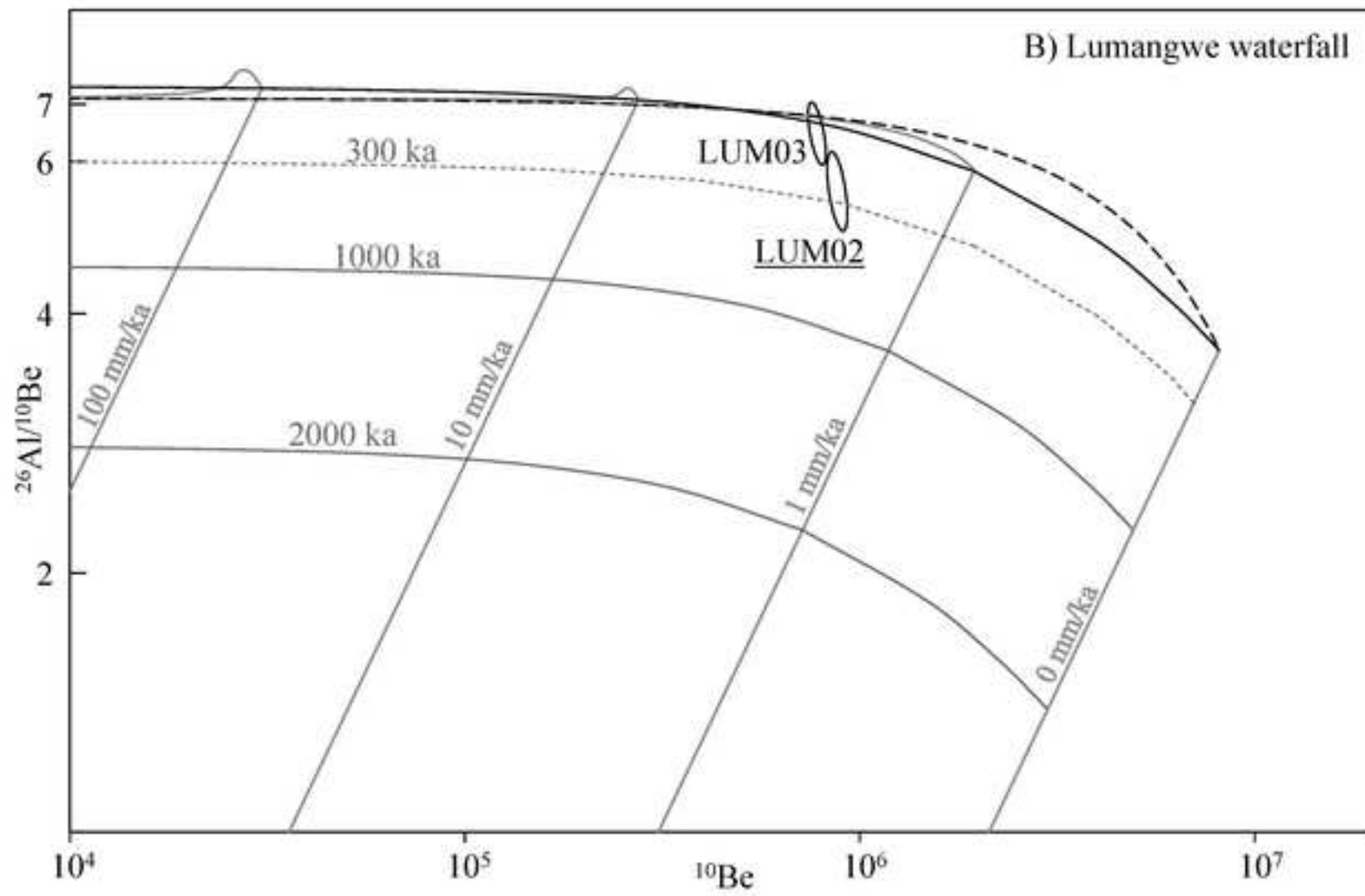


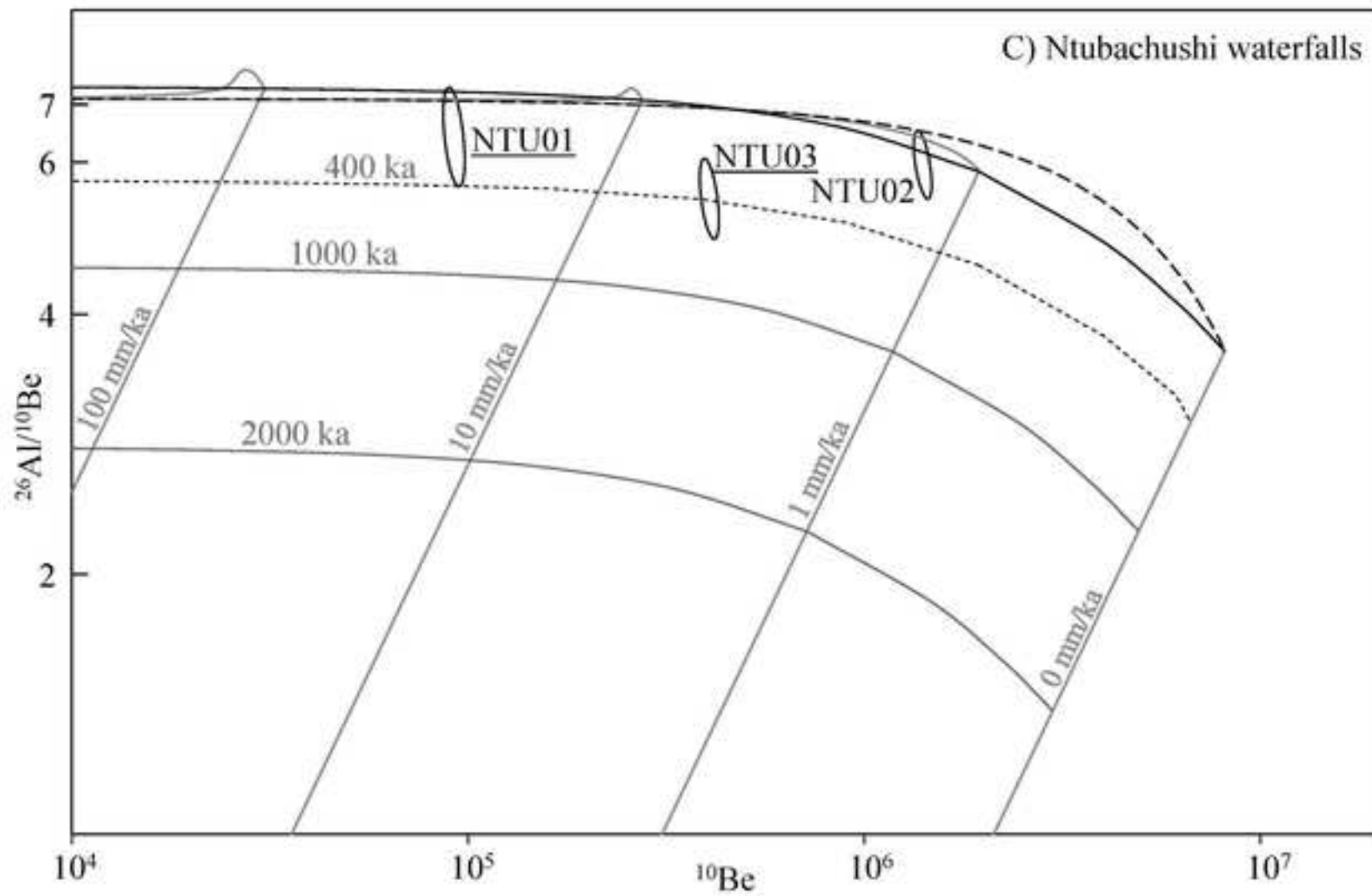


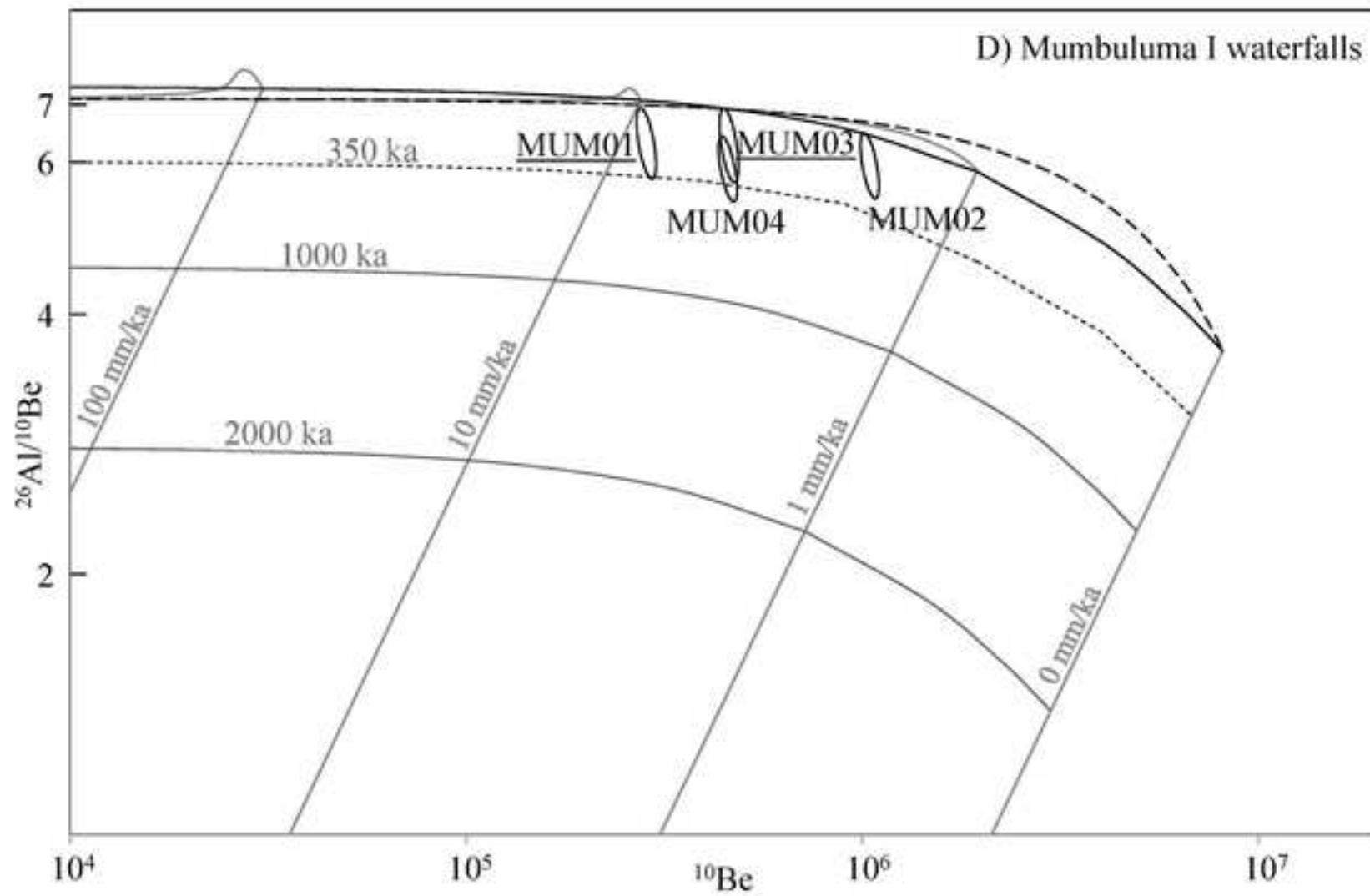


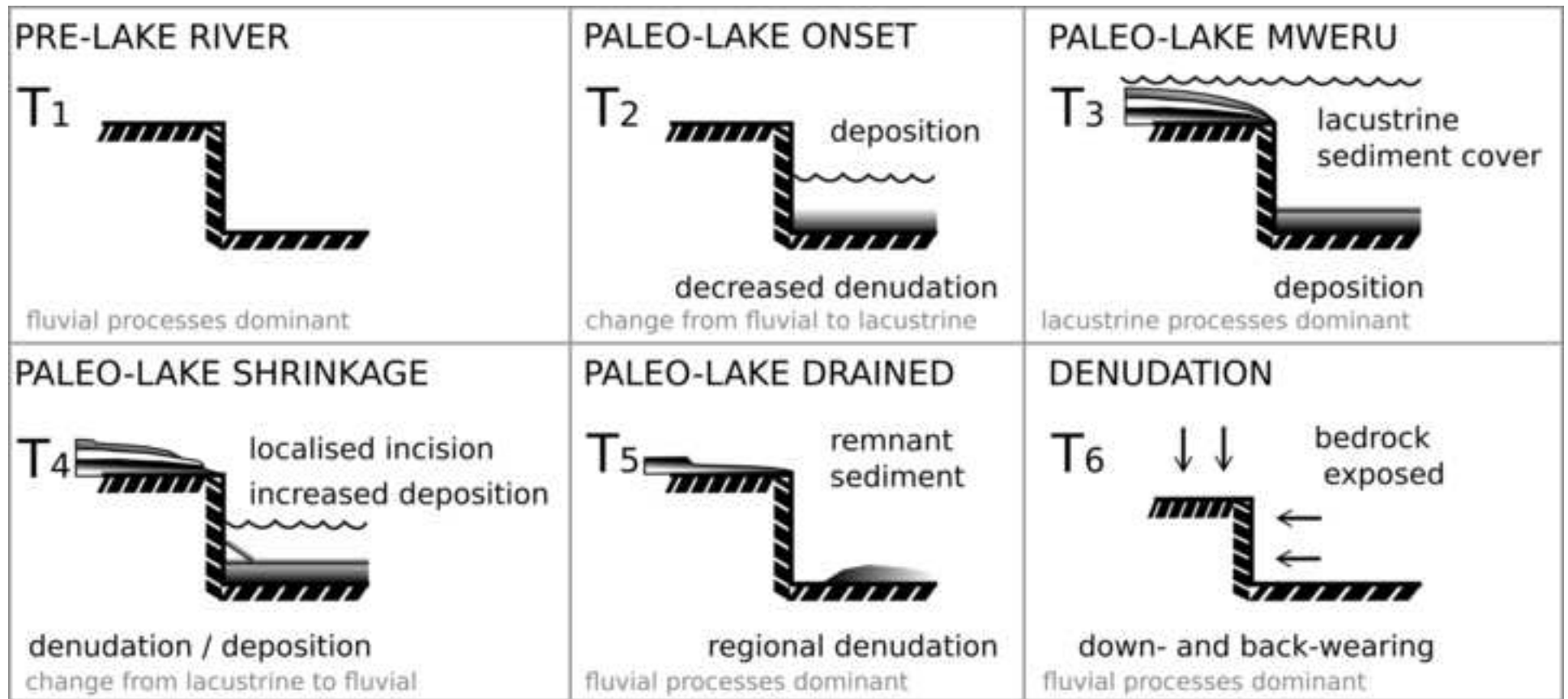


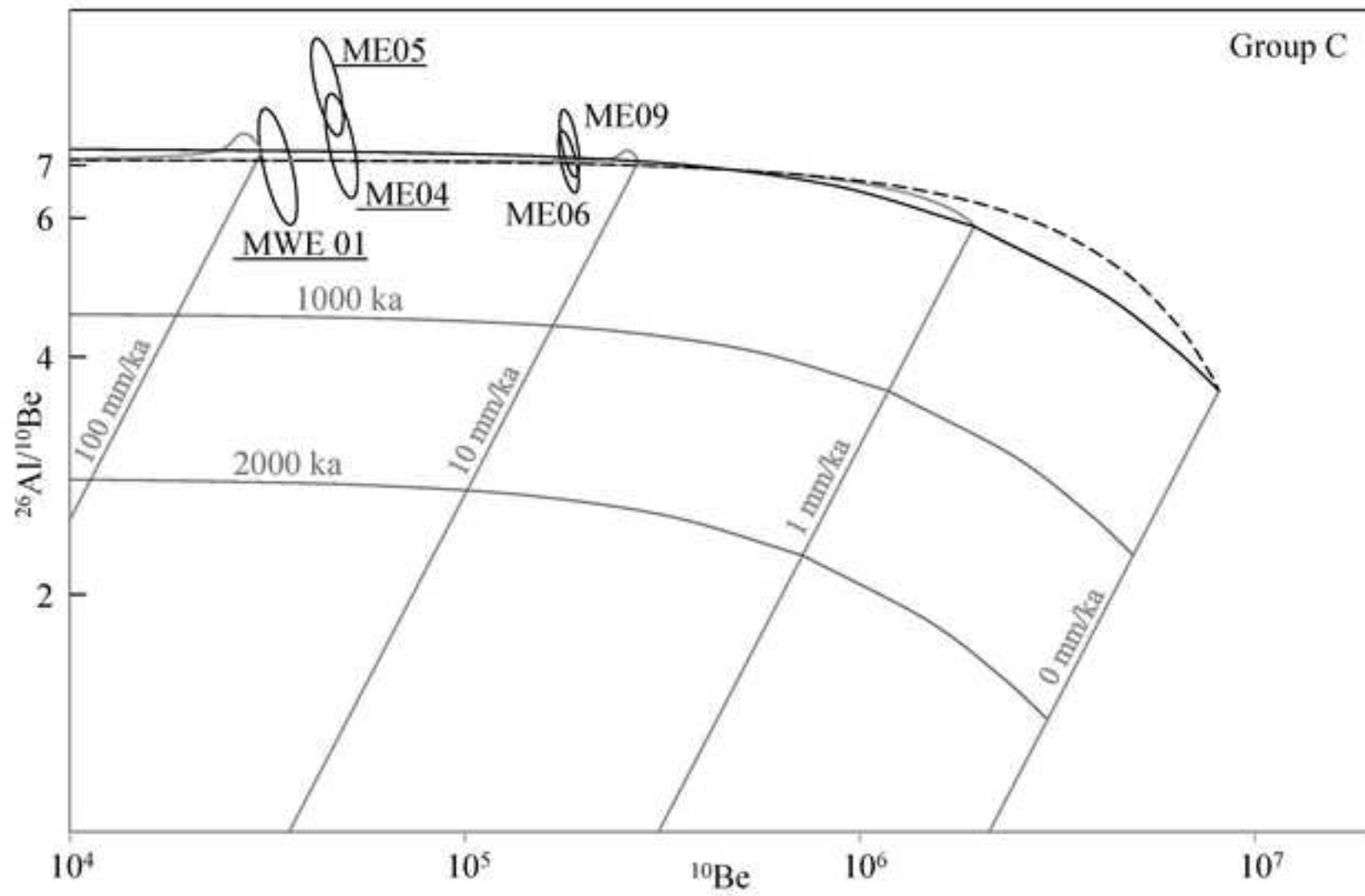


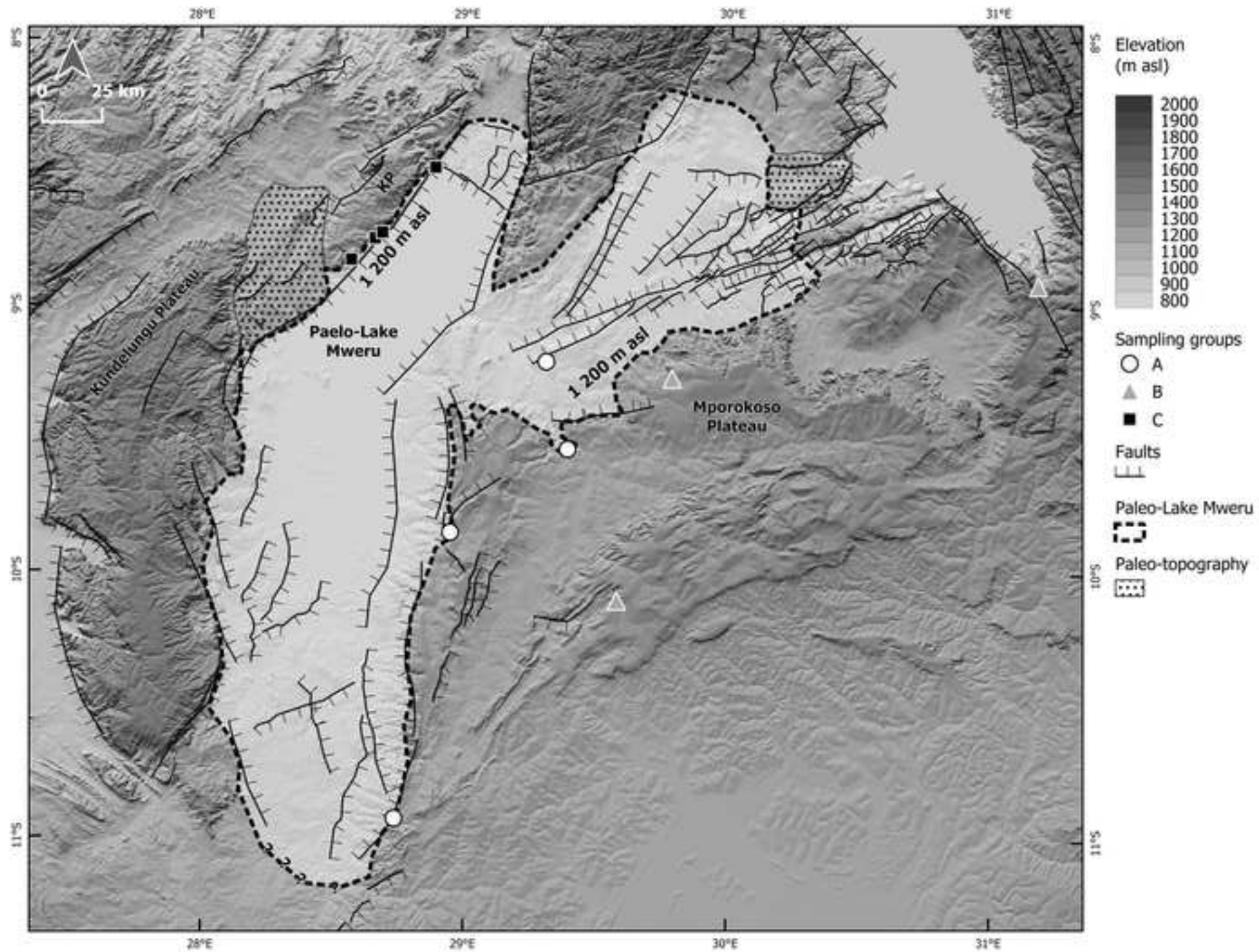


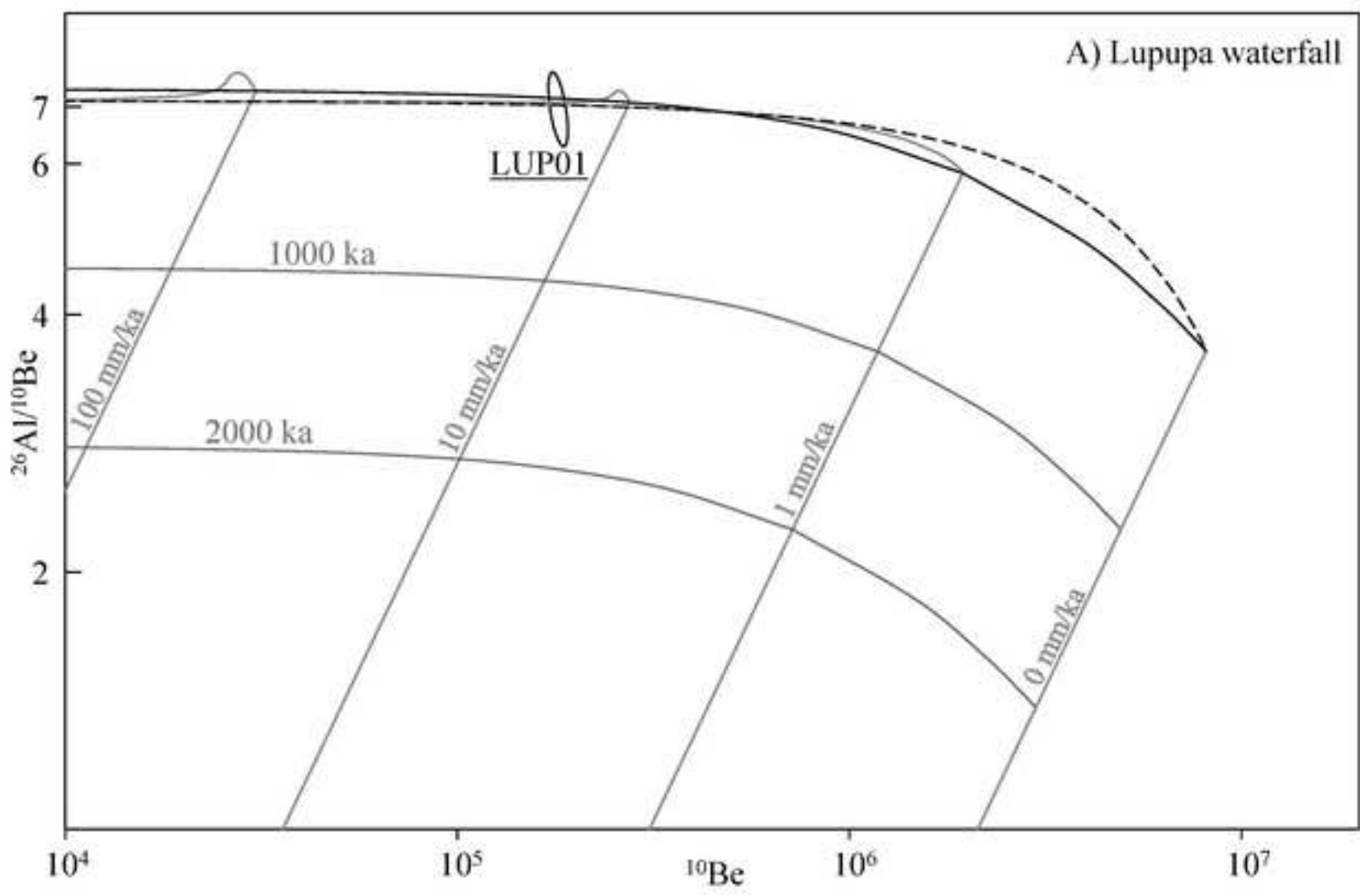


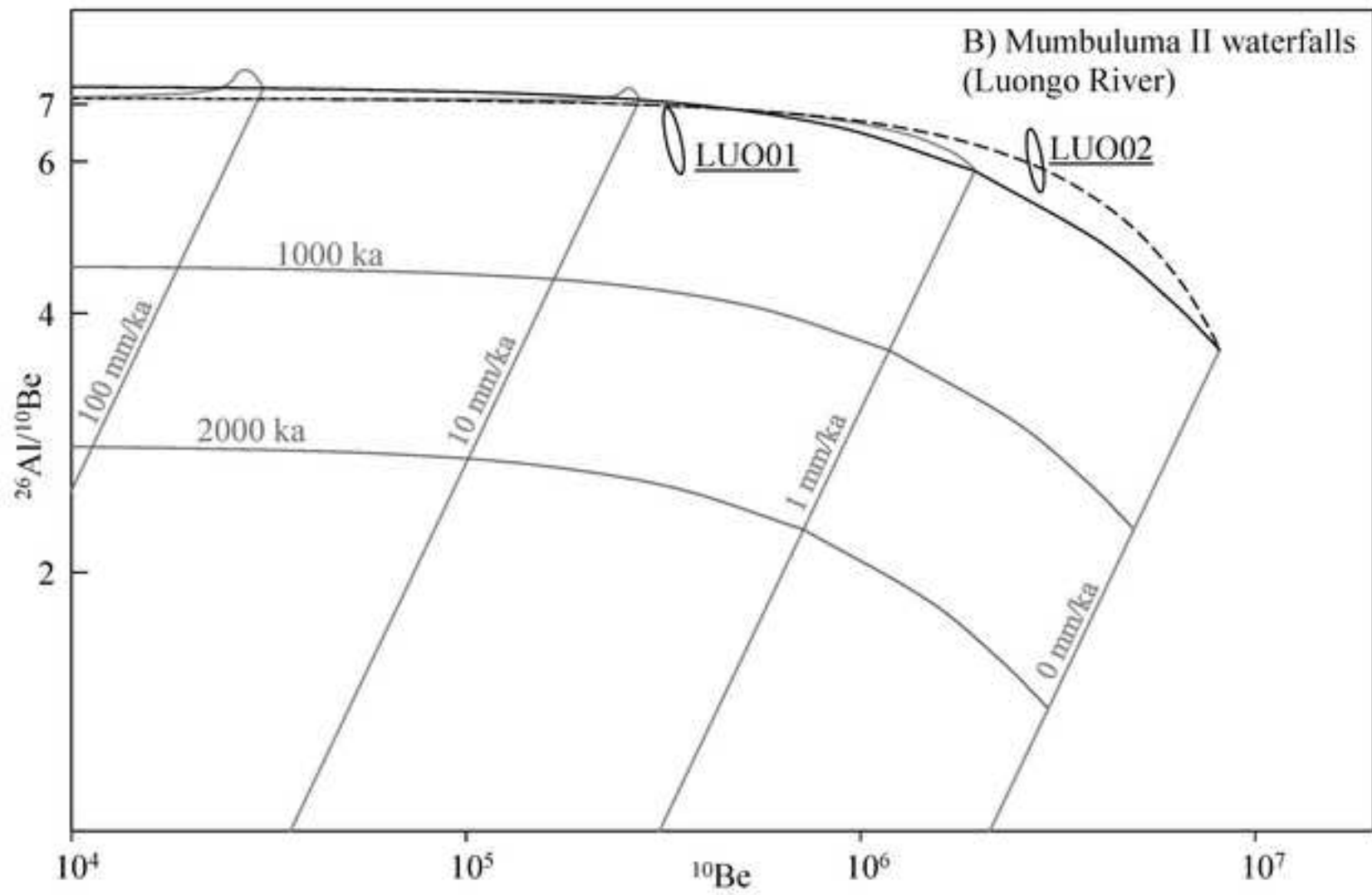


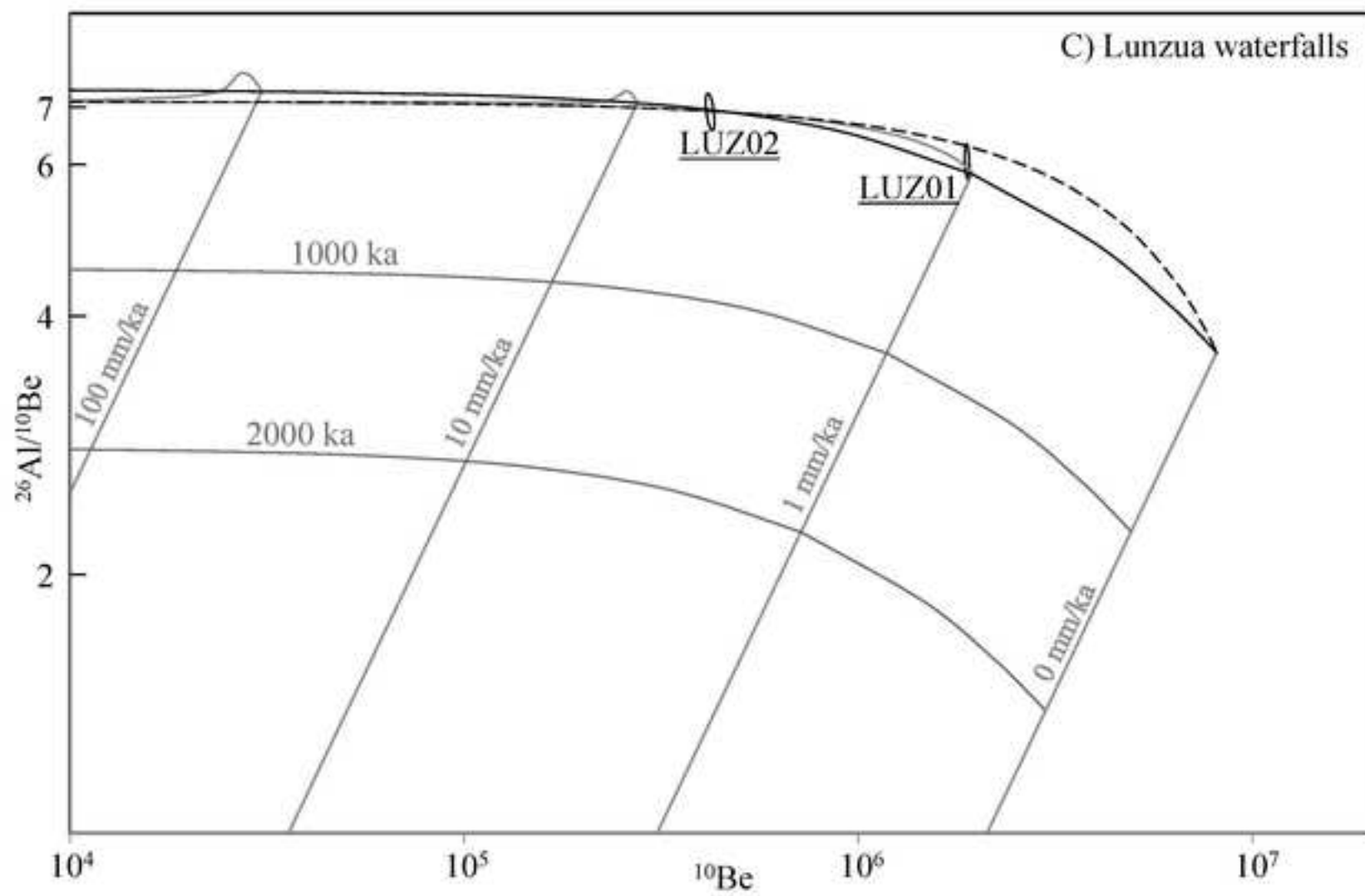


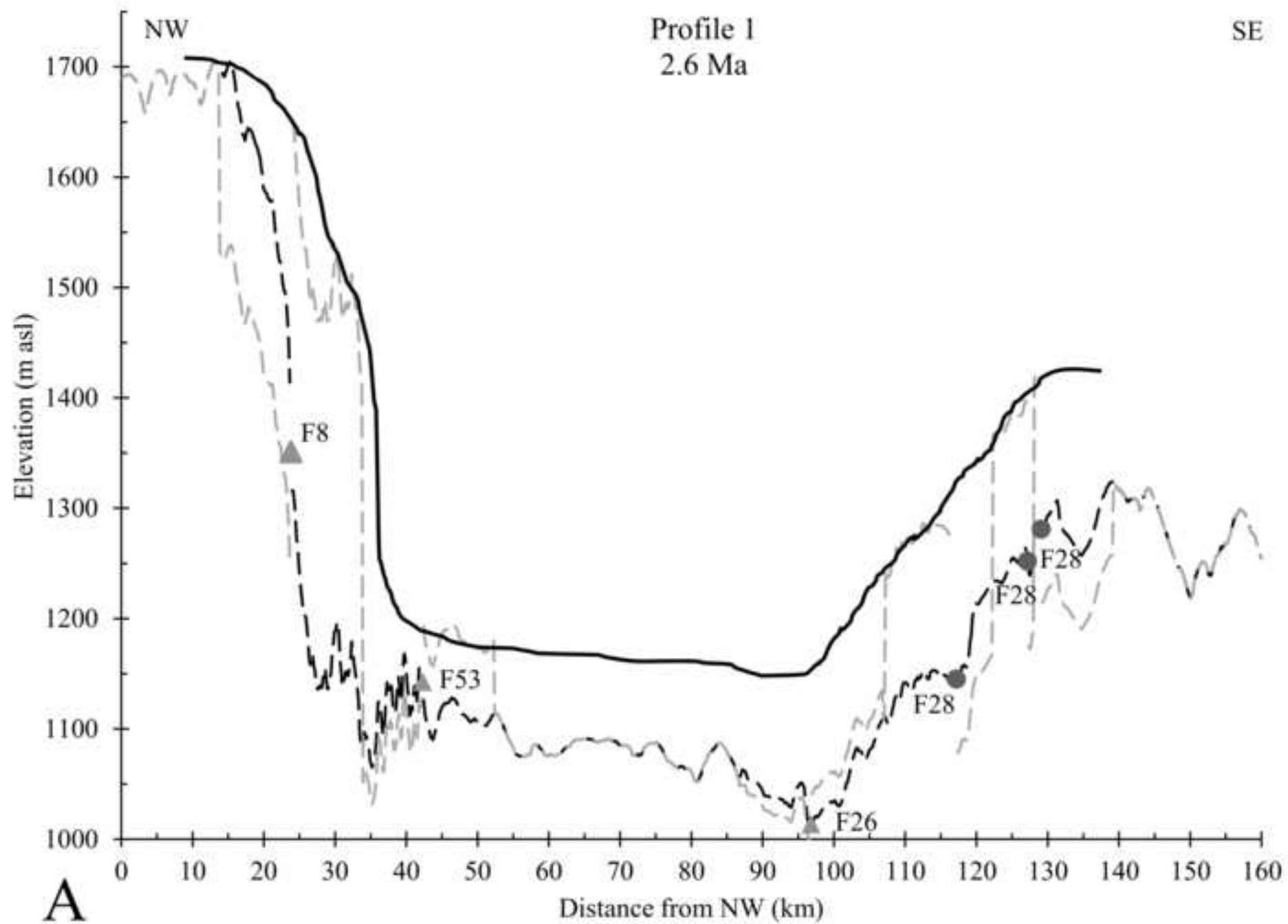


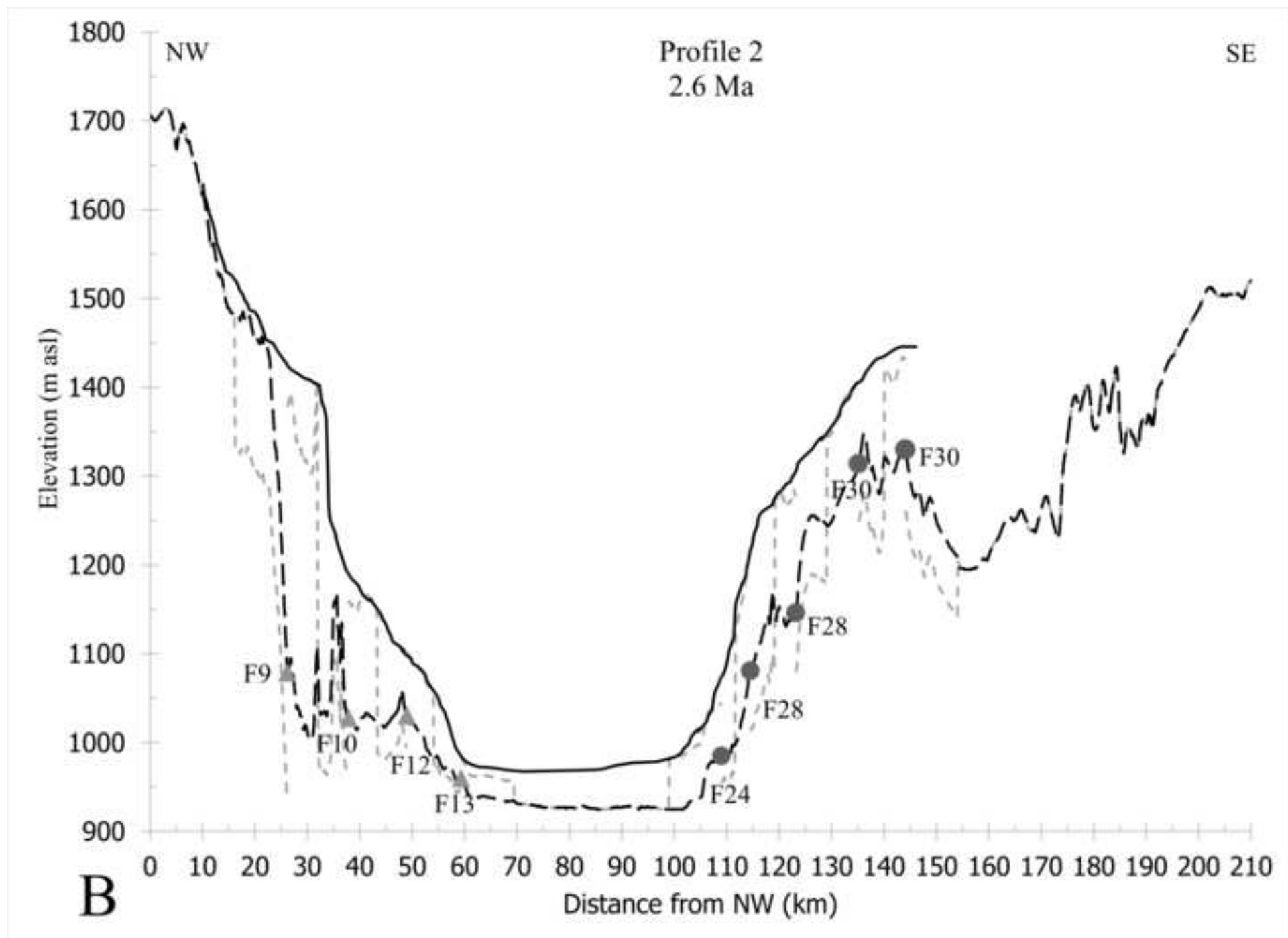


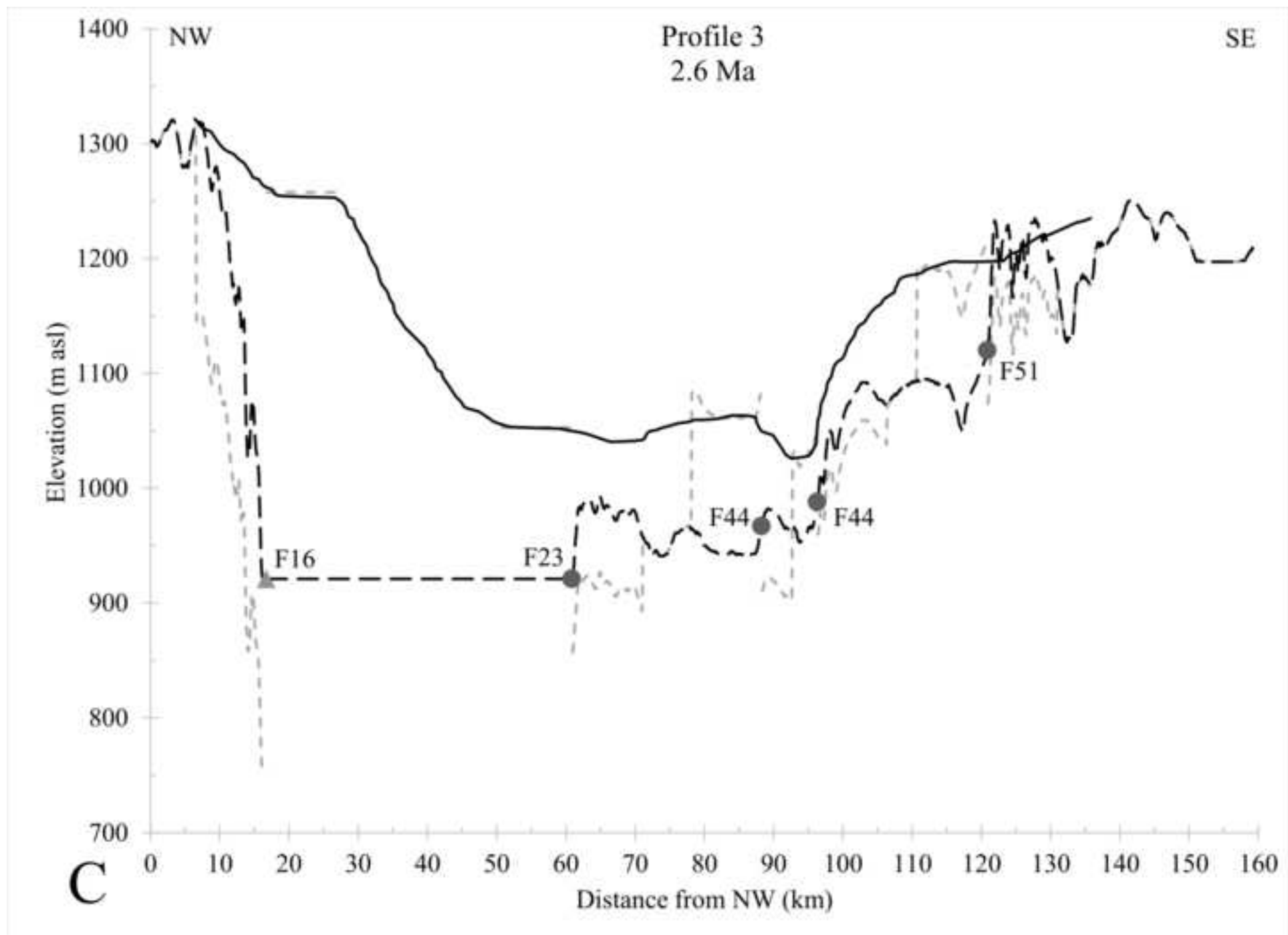


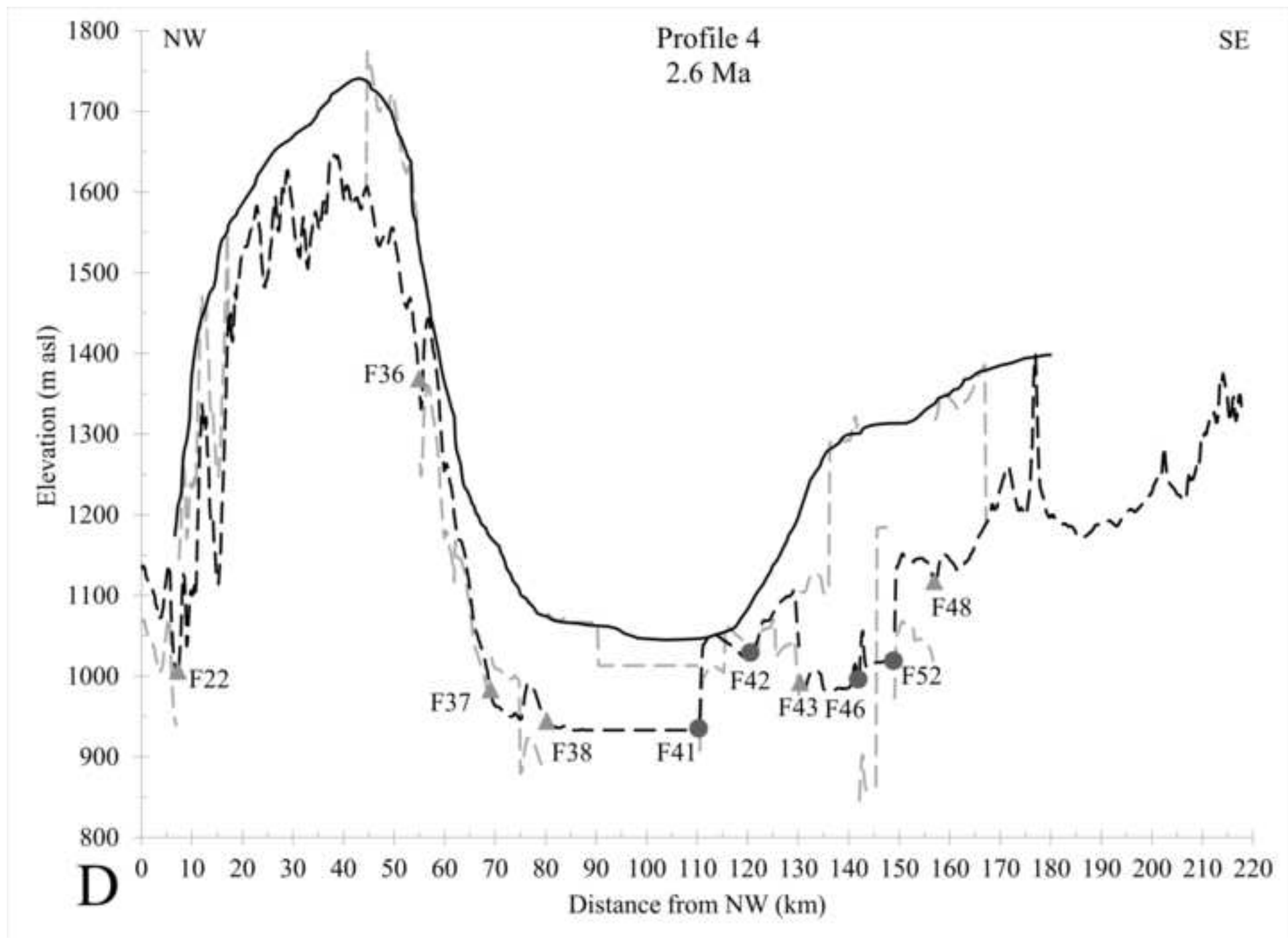


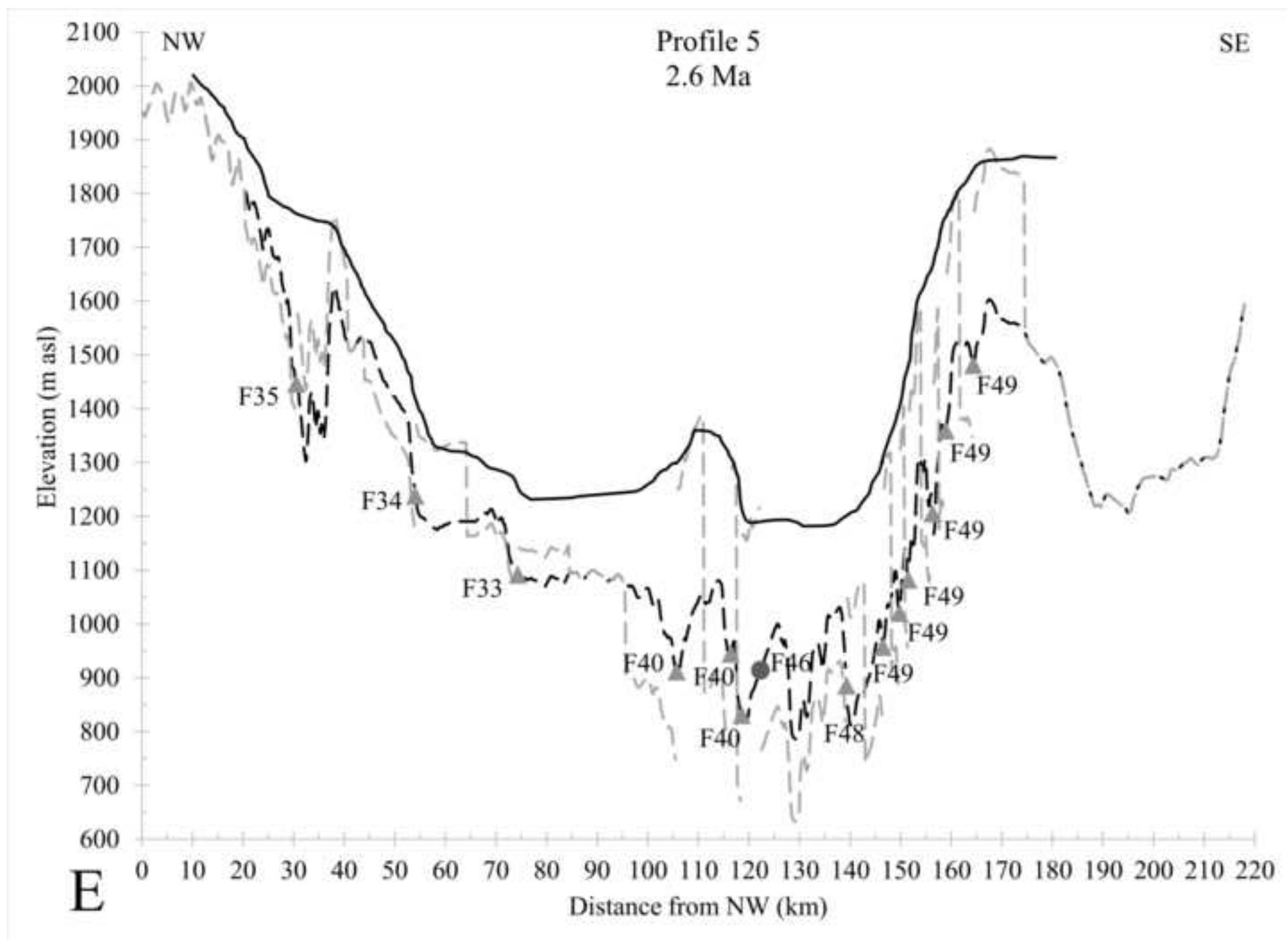


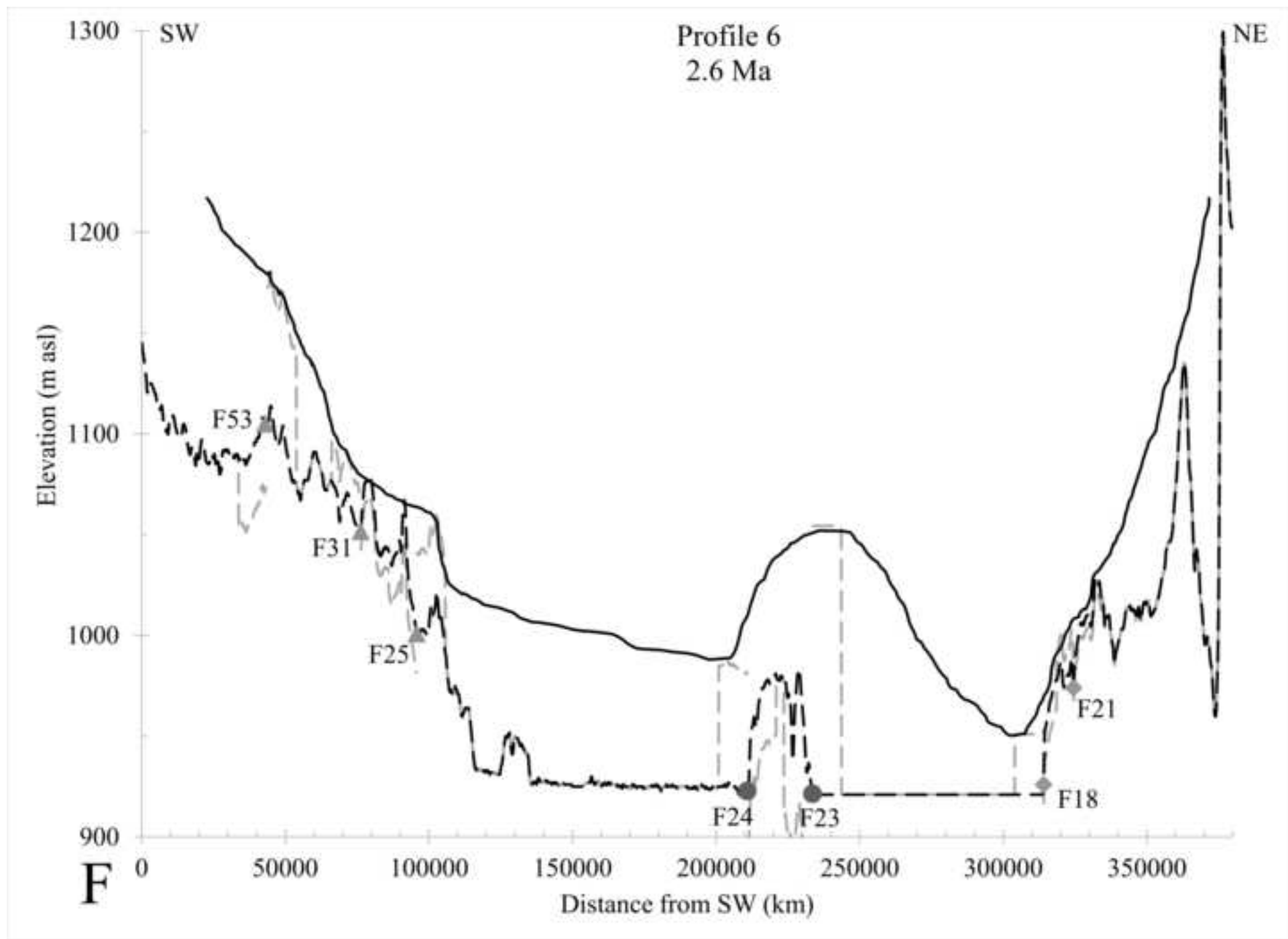


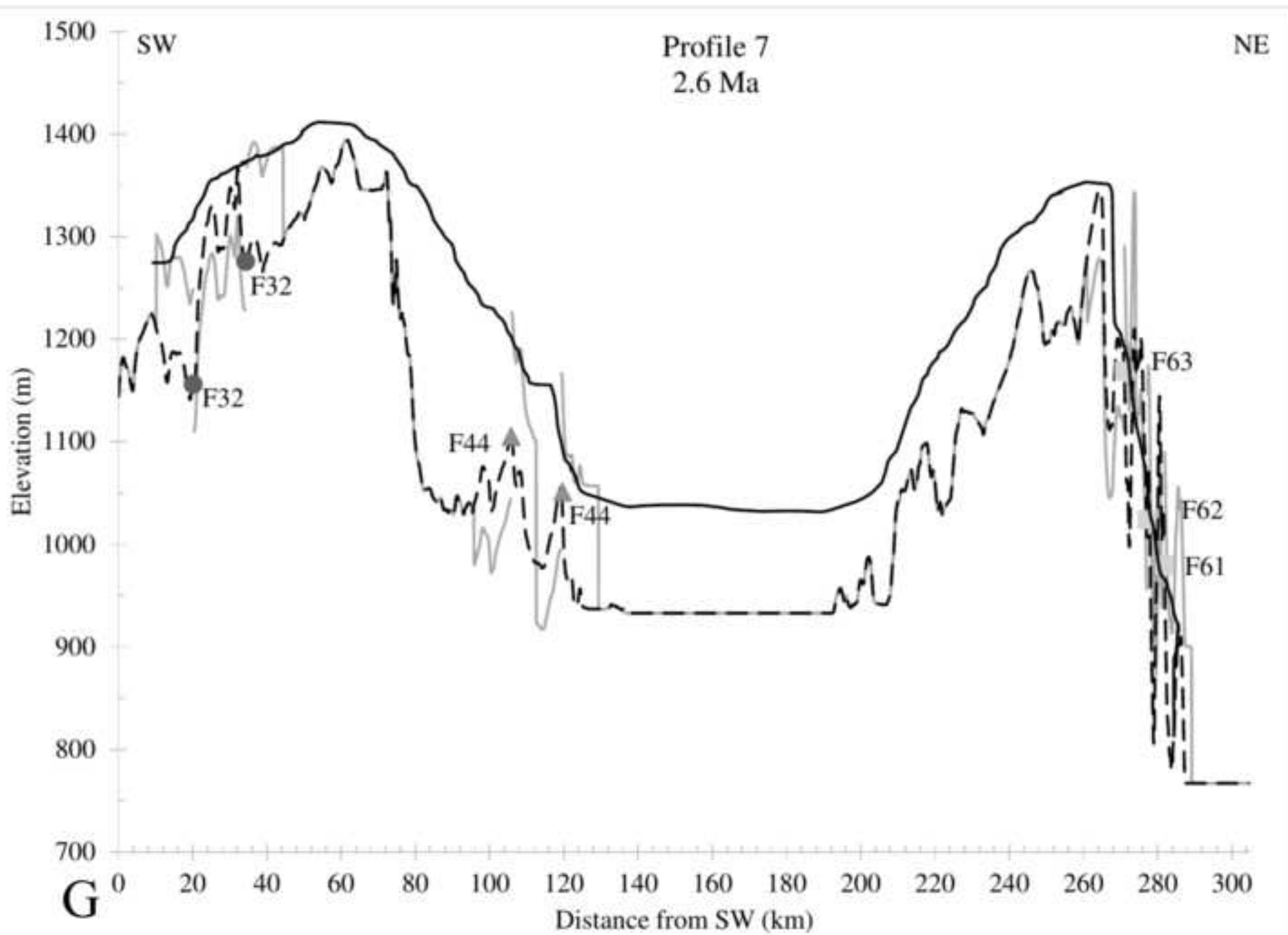


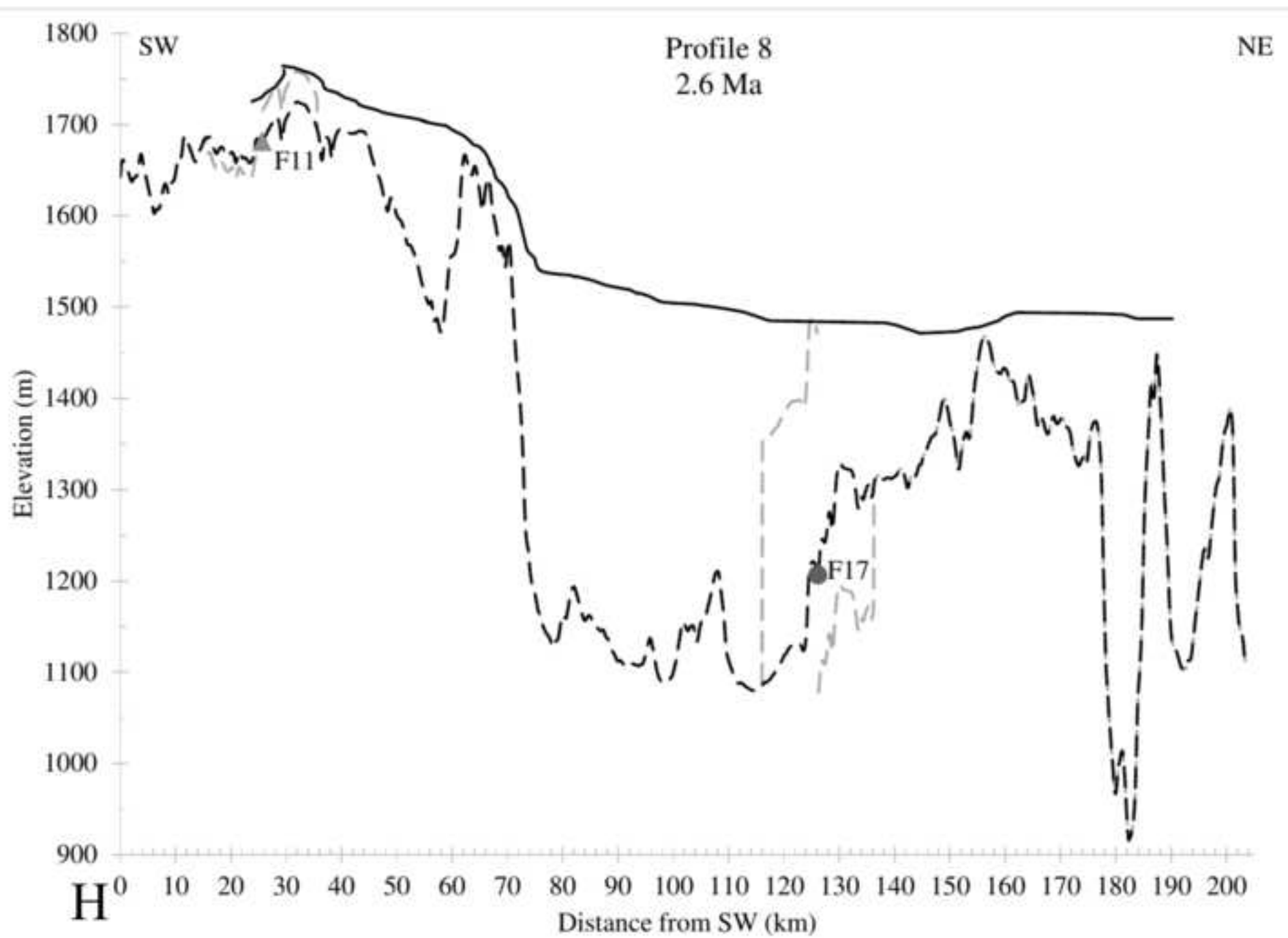








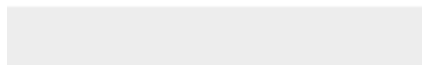
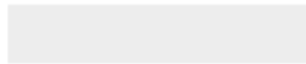






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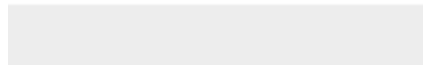
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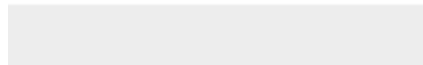




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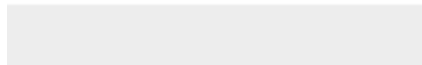
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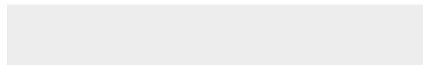
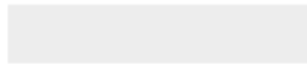
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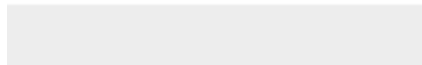
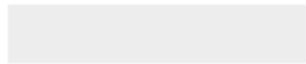
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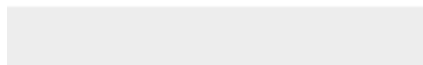
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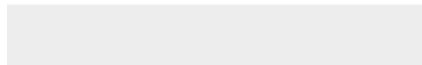
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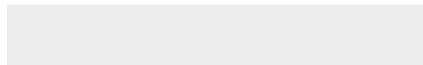
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