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Linking thermochronological data to transient geodynamic regimes; new insights from kinematic modeling and Monte Carlo sampling of thermal boundary conditions

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1 **Linking thermochronological data to transient geodynamic regimes; new insights**
2 **from kinematic modeling and Monte Carlo sampling of thermal boundary conditions**

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10 **Abstract**

11 It is common practice to assume values for basal heat flow or basal temperatures as a
12 lower boundary condition for thermo-kinematic models of crustal tectonics. Here, we infer
13 spatial and temporal variations of the paleo-basal temperature from integrated modelling of
14 thermochronological ages, to relate the inferred variations to the geodynamic setting. To
15 this end, we consider the Argentine Precordillera as a natural laboratory, given that its
16 kinematic evolution is relatively well constrained and therefore, the focus can be placed on
17 the variations of its basal thermal state. By means of a simple Monte Carlo sampling
18 approach with thermochronological data as constraints, we infer the paleo-basal
19 temperature history. This is compared to estimates posed by models existing in the
20 literature concerning flat-slab subduction. Our results imply that, given the kinematic
21 models used to date in the area, extremely low temperature gradients ($< 15^{\circ}\text{C}/\text{km}$) are
22 required to adequately predict the observed thermochronological ages. Substantial cooling
23 of the lithosphere around 10 Ma is also required in order to fit measured values. This
24 agrees with previous thermal simulations carried out in the region. Furthermore, major
25 controls of the thermal architecture on the Argentine Precordillera are implied, thus
26 reigniting the debate on thermal driving mechanisms in the evolution of mountainous
27 settings and their relationship with deeper processes within the Earth, such as on the
28 effects of the flat-slab subduction.

29

30

31 Introduction

32 Thermochronological data have been extensively used as constraints for models of the
33 thermal evolution of the lithosphere (see Reiners and Ehlers, 2005; Guillaume et al.,
34 2013., Dávila and Carter, 2013; Fosdick et al., 2015; and also England and Molnar, 1990;
35 Ring et al., 1999; for a review of cooling processes). In that sense, the growing use of
36 thermochronological data has propelled major advances in kinematic thermochronological
37 modeling in the last two decades (Braun et al., 2012; Almendral et al., 2015, among
38 others). Moreover, inverse thermochronologic modeling carried out under the assumption
39 of constant lower boundary conditions (such as basal temperature or heat flow) has
40 rendered valuable information on heat transfer in settings where the geodynamic evolution
41 is relatively well understood (Braun, 2003; Fillon and van der Beek, 2012; Coutand et al,
42 2014; Olivetti et al., 2017). In general, the lower boundary conditions are rarely treated as
43 variable (spatially and/or temporally) parameters (although see Schildgen et al., 2009 for
44 an example of transient lower thermal boundary conditions). Furthermore, no studies have
45 focused on inferring transient boundary conditions from thermochronological
46 measurements. Not taking geodynamic variability into account in regions where major
47 changes have clearly occurred (e.g. modification of the subduction angle; see for example
48 Dávila et al., 2018), can lead to equivocal results and conflicting interpretations. These
49 concerns are corroborated by studies demonstrating the thermal evolution of the
50 continental lithosphere is dependent on the evolving geodynamic scenario (Vitorello and
51 Pollack, 1980; Sachse et al., 2016; Ávila and Dávila, 2020). Thus, the relationship between
52 transient geodynamics and thermochronological modeling of the upper crust calls for
53 special attention.

54 To understand the implications of unsteady subduction and, as would be likely, an
55 unsteady or transient lower boundary condition for the overlying lithosphere, we consider
56 the well-known Argentine Precordillera (AP) as a preliminary case study. Structural
57 reconstructions in the Jachal area (near Jachal city, see Fig. 1; Jordan et al., 1993;
58 Allmendinger and Judge, 2014; Nassif et al., 2019) have been complemented with
59 thermochronological data (Levina et al., 2014; Fosdick et al., 2015; Val et al., 2016; and
60 new data from this work) and estimations of erosion rates (Fosdick et al; 2015; Val et al.,
61 2016; Nassif et al., 2019). These multiple constraints make the Argentine Precordillera of
62 Jachal an ideal test case to assess the potential of extracting novel geodynamic
63 information from measured thermochronological ages. Furthermore, the present work

64 seeks to build on previous findings exploring the influence of basal temperatures on
65 thermochronological data (see for instance Shildgen et al., 2009), and also to cast new
66 light on heating mechanisms. As has been previously suggested (Ehlers, 2005; Dávila and
67 Carter, 2013; Nassif et al., 2020, in press), physical phenomena other than burial and
68 denudation processes may play a significant role regarding rates and durations of heating
69 and cooling. Hence, we take advantage of the state-of-the-art knowledge of the Argentine
70 Precordillera to pose questions not directly concerning exhumation and/or erosion. In
71 particular, can we constrain variations of paleo-basal temperatures with kinematic and
72 thermochronological data? What implications may such estimates have on our
73 interpretations and thermochronologically driven conclusions? The present effort
74 addresses those questions by means of Monte Carlo sampling to infer basal temperature
75 values over time. We apply an easy-to-implement statistical framework to compare model
76 predictions with existing and new thermochronological data. These data are
77 complemented with diagenetic indicators (% Illite to Smectite; see Środoń et al., 1986),
78 the combination of which lets us set bounds on the lower thermal boundary condition, i.e.
79 basal temperature over time. The model results are compared to proposed thermal states
80 in the study region (Gutscher et al., 2000) which are of particular importance given the
81 uncommon nearly-flat subduction angle in the region. We propose that the stochastic
82 sampling approach described here may be suitable for other geological scenarios where
83 inversion of thermochronological data can aid reducing uncertainties of first-order variables
84 present in thermal simulations.

85

86 **Geological setting**

87 The Argentine Precordillera (AP) is an intraplate fold-and-thrust belt located at the
88 southern end of the Central Andes foreland. It is composed of N-S trending mountains that
89 record a prolonged Paleozoic to Cenozoic tectonic history, suggested being controlled by
90 subduction processes and the accretion of exotic terranes (Ramos et al, 1986; 2004).
91 Major Andean deformation and uplift in this region have been related to the ongoing flat
92 subduction of the Nazca plate beneath the South American lithosphere (Isacks et al.,
93 1982; Jordan et al., 1983a-b; Kay and Abbruzzi, 1996; Dávila et al., 2018).

94 The present-day landscape in the AP shows meridional and sub-parallel thrust sheets
95 separated by seven major thrust faults, named from west to east: Tranca, Caracol W,
96 Caracol E, Blanco, Blanquitos, San Roque, and Niquivil (Fig. 1; Allmendinger and Judge,
97 2014). Such structures, suggested to be associated with a deep decollement (~ 16 km),
98 are responsible for the complex scenario outcropping in Jachal section (see Fig 1). Studies
99 of the chronology of motion of the thrustbelt have elucidated its kinematics (Allmendinger
100 and Judge, 2014; Jordan et al., 1993), and have been complemented by recent efforts to
101 estimate Tertiary erosion and deposition (Fosdick et al., 2015; Val et al., 2019; Nassif et
102 al., 2019). Taken together, the structural and thermochronological endeavours in the area
103 have successfully constrained the spatial evolution of the region, but kinematic models
104 relating such deformation to the thermal evolution of the belt remain to be developed.
105 Given that the AP constitutes an exploratory frontier (Pérez et al., 2011), insights into the
106 thermal history experienced by potential source-rocks within the Cambro-Ordovician
107 limestone sequence. (Pérez et al., 2011; see Fig. 1 for reference), are of importance to
108 both researchers and industry.

109 Regarding its thermal state, the AP has been linked to refrigerated thermal regimes, as it
110 sits over the Chilean-Pampean flat slab segment (see Collo et al., 2018). Shifting of the
111 asthenospheric wedge caused by slab flattening is suggested to produce thermal cooling
112 of the upper crust (Gutscher et al., 2000; English et al. 2003; Álvarez et al. 2014), with
113 evidence of the 'cold state' provided in the Vinchina Basin. Here extremely low heat flow
114 values ($< 30 \text{ mW/m}^2$) were proposed to explain thermal calibration data (Collo et al., 2011;
115 2015). Such low heat flow values may have varied with the slab geometry, which has also
116 been constrained in the study region. Several authors (Gutscher et al. 2000; Jordan et al.,
117 2001; Ramos and Folguera, 2009; among others) have postulated the beginning of the
118 flattening episode at ~15-18 Ma, with the slab becoming sub-horizontal at ~7-6 Ma
119 (Gutscher et al. 2000; Kay and Mpodozis, 2002). Taking into account the already
120 understood spatial deformation at Jachal (see Fig. 1, above), the available data and
121 interpretations make this region of the Pampean flat slab an ideal scenario to explore the
122 relationship between a) the record of crustal cooling and exhumation, and b) the combined
123 effects of thin-skinned deformation and changes in subduction geometry at the lithospheric
124 scale.

125

126

127

128 **Methodology**129 **a) Inversion of time-dependent boundary conditions from thermochronological and**
130 **kinematics data**

131 Using the documented deformational sequence for the AP (see Jordan et al., 1993;
132 Allmendinger and Judge, 2014; Nassif et al.; 2019, and references therein) as a geological
133 reference framework, we used Fetkin (Finite element kinematics; see Almendral et al.,
134 2015) to predict thermochronological ages along the thrustbelt. Fetkin is a 2D thermo-
135 kinematic code which takes as input a series of structural sections to forward-model low-
136 temperature thermochronological ages at user-specified locations by solving the heat
137 equation, given as

$$138 \quad \frac{\partial T}{\partial t} \rho C = \nabla \cdot (\lambda \nabla T) - (q \rho C \cdot \nabla T) + H$$

139 where T is temperature, t is time, λ is the thermal conductivity, ρ and C are the density
140 and specific heat capacity, respectively; and q is the rock velocity, determined by the
141 tectonic history of the setting. Rock velocities are obtained directly in Fetkin by tracking the
142 position of material particles throughout the simulation of the structural evolution. H
143 represents heat sources and sinks, which for simplicity, were not included in the models
144 considered here. Moreover, to solve the 2D form of the heat transfer equation, four
145 boundary conditions; namely B_1 (lower), B_2 (upper), B_3 (right boundary) and B_4 (left
146 boundary) are required. In this work, the lower boundary condition, B_4 , was allowed to vary
147 over time to better represent the geodynamic evolution of the system. The numerical
148 model starts from an equilibrated thermal steady-state, thereafter solving the heat equation
149 considering thrusting kinematics and boundary enforcements.

150 Our thermo-kinematic model for the Jachal AP (see Fig. 1 for location) started at 16 Myrs,
151 when movement along the westernmost thrust, Tranca (see Fig. 1), was triggered (Jordan
152 et al., 1993; Allmendinger and Judge, 2014). Thermo-kinematic calculations were carried
153 out to the present day, with the final model form being equivalent to the outcropping
154 structural configuration today (see Allmendinger and Judge, 2014; Nassif et al., 2019). For

155 the thermal model calibration, we incorporated 2 sets of unpublished fission track data
 156 (processed by Late Andes laboratory, Argentina, see Table 1). Sample J272, belonging to
 157 Permian strata within the San Roque nappe (see Fig. 1 for location in the thrustbelt),
 158 yielded a central AFT age of 152.3 ± 12.9 Ma. Track lengths measurements were also
 159 carried out in this sample, resulting in a unimodal distribution with a mean track length
 160 (MTL) of 10.17 ± 1.68 μm (see Table 1 and also Supplementary Material, S1). In the
 161 easternmost nappe, Niquivil, analysis in a Silurian sandstone yielded a central AFT age of
 162 10.9 ± 2.1 Ma, but no track lengths were observed in this sample. It is highlighted that the
 163 two central ages obtained (ages for samples J259 and J272) were concordant (passed the
 164 chi-squared test, see Supplementary Material 2) and are also considerably younger than
 165 their stratigraphic ages. Moreover, no appreciable relationship between the single grain
 166 ages and the kinetic parameter considered, Dpar (measured on each grain) was seen in
 167 any sample (see Supplementary Material). These ages are therefore considered to reflect
 168 primarily the post-depositional thermal history and are interpreted in terms of the samples'
 169 cooling to the surface.

170

| Sample | X | Y | Z (m) | Geologic unit | Ns | Ni | Nd | Rho-d ($1/\text{cm}^2$) | grains | Dpar (μm) | MTL(μm) | U (ppm) | Central ages (Ma) | Disp. | P(χ^2) |
|--------|----------|----------|-------|----------------|-----|-----|-------|---------------------------|--------|------------------------|----------------------|---------|-------------------|-------|---------------|
| J272 | 68.64° W | 30.30° S | 1125 | Fm Panacan | 777 | 519 | 10000 | 6.48E+05 | 15 | 1.46 | 10.16 | 37.52 | 152.3+ -12.9 | 0.06 | 34.98 |
| J259 | 68.62° W | 30.31° S | 1195 | Fm Los Espejos | 33 | 314 | 10000 | 6.48E+05 | 21 | 1.36 | no lengths | 17.21 | 10.9+2.1 | 0.13 | 46.51 |

171

Table 1. AFT data from this work

172

173 In addition to the new AFT measurements, data from 3 U-Th/He samples are available
 174 from the literature (Fosdick et al., 2015; see Fig. 4, results) and these were also
 175 incorporated as constraints. Finally, in order to complement the inferences based on the
 176 thermochronological data, diagenetic indicators in clays (Smectite to Illite, I/S%) were also
 177 measured along the easternmost nappe, Niquivil; following standard procedures for clay
 178 treatment at the clay laboratory at Universidad Nacional de Córdoba (see Środoń et al.,
 179 1986; an references therein).

180 Regarding the 2D heat transfer and thermochronological age simulations, the model
 181 considers: a) a mesh resolution of 2500 nodes covering the modeled thrust belt ; b) a

182 timestep of 1 Myr; c) kinetics for AFT and U-Th-Sm/He from Ketcham et al. (2007) and
183 Wolf et al. (1998), respectively; d) an inherited age of 152 Myrs for the apatites in the study
184 region before Andean deformation took place. The last assumption is based on AFT
185 detrital results that registered such age (152.3 ± 16 Ma; see sample HC07 from Fosdick et
186 al., 2015) in grains from the foreland basin, Huaco (see Fig. 1 for location). Likewise,
187 results (this work) from AFT measurements in an eastern nappe of the thrust belt (San
188 Roque nappe; 152.3 ± 12.9 Ma; see also Supplementary Material); point also to a
189 Mesozoic inherited age of apatite grains before Andean deformation started in the AP (16
190 Ma). The program assumes the same inherited age for all thermochronological systems,
191 which poses no major problems in modeling exercises as long as thermal resetting in U-
192 Th-Sm/He samples is guaranteed (as occurs in this work; see results). Radiation damage
193 effects on He retentivity were not incorporated into the modelling (see also *Limitations and*
194 *further insights*)

195 The depth scale of the model, i.e. the depth to the lower thermal boundary condition, was
196 defined to be 20 km. In accordance with lithological characterizations in the area stating
197 that the thrustbelt is mostly composed by siliciclastic sediments (see Allmendinger and
198 Judge, 2014), we assigned a thermal conductivity of $2.5 \text{ W/m}^2\text{K}$, a density of 2500 Kg/m^3
199 and specific heat of $1000 \text{ J/kg}^{\circ}\text{K}$ (see Hantschel and Kauereauf, 2009; for value
200 references) across the whole model. Given the limited amount of calibration data, a more
201 complex set of thermophysical parameters or the inclusion of heat production, was not
202 justified for this preliminary study. The top boundary condition at mean sea level was set to
203 $23 \text{ }^{\circ}\text{C}$, after climate characterizations in the region (arid to semi-arid for the studied time
204 interval; see Walcek and Hoke, 2012).

205 As the aim of this work is to infer the lower thermal boundary condition
206 (temperature at 20 km), values for this parameter were allowed to vary in the range 100-
207 800°C , corresponding to very low ($5 \text{ }^{\circ}\text{C/km}$) to high (40°C/km) thermal gradients (see
208 Hantschel and Kauereauf, 2009). These are broadly equivalent to a range in heat flow of
209 10 to 100 mWm^{-2} . To allow for some time dependence, and following thermal numerical
210 models involving slab-flattening processes (Gutscher et al., 2000), we parameterized the
211 basal temperature history in 3 stages, in a step-function manner, with a constant but
212 unknown value in each stage. The time intervals considered for each stage were 1) 16-8
213 Ma, 2) 8-4 Ma and 3) 4 Ma to present (see Fig. 2). The time interval of the first stage was
214 selected to be relatively wide as that the slab-flattening process started around 20 Ma (Kay

215 and Mpdozis, 2002), and that its associated thermal effects would not have been
216 perceived before 10 Ma in the upper crust, equivalent to the depth scale of our model (see
217 Gutscher et al., 2000; Jaupart and Mareschal, 2010). Using simple Monte Carlo (MC)
218 sampling we select candidates for the basal temperatures in each time interval from the
219 temperature range defined earlier. To avoid drawing non-physical candidates (for example,
220 “scissor-like” ones implying rapid and large oscillations in the basal temperature), our
221 Monte Carlo sampling proceeded as follows: First, we drew a value from a uniform
222 distribution between 100°C (T_{\min}) and 800 °C (T_{\max}), corresponding to the first time
223 interval (16 to 8 Ma). Then, we drew a second value (part 2) from a uniform distribution
224 centered on the candidate value in the first time interval and extending 200°C on either
225 side. This large range (400°C) was set to ensure that a wide set of physically plausible
226 possibilities could be tested. The same prior lower and upper limits set ($T_{\min} = 100^{\circ}\text{C}$, T_{\max}
227 = 800°C) as for the first part were also enforced in this instance, so samples were modified
228 accordingly when necessary (for example when values from the first draw corresponded to
229 temperatures near a limit). The basal temperatures for the first and second stages (see
230 Fig. 2) were constant in space, consistent with subduction numerical models that suggest
231 no major lateral variation in the relatively short spatial scale defined by the AP, at the
232 depth scale concerned by this work (see 2D predictions in Gutscher et al., 2000; Gutscher
233 and Peacock, 2003; Manea and Manea, 2011; and also 3D models in Ji et al, 2017; see
234 also Fig. 2). Finally, a candidate model was drawn for the final stage (part 3; 4 Ma to
235 present; Fig 2), using constrained sampling conditional on the value for the second stage,
236 as described previously. For this final stage, we also allowed for spatial variation for the
237 basal temperature (see Fig. 2) as flat-slab Andean thermal models predict an appreciable
238 gradient in the lateral direction (west-east) for this time interval (4 Ma to present; see
239 Gutscher et al., 2000). Hence, a candidate model for this part (3) consisted of two values,
240 both drawn from the same distribution (a uniform centered on the value for previous stage;
241 2). 10000 iterations of the process above described were performed, and the proposed
242 lower boundary condition temperature history were then entered into Fetkin to run a
243 thermal simulation for each iteration. As the final stage of a candidate model consisted of
244 two values (at the lateral boundaries), the values were interpolated linearly in space in the
245 Fetkin environment. A Python program to parallelize thermal modeling calculations carried
246 out by the Fetkin algorithm was deployed. To measure the agreement of predictions from
247 the thermal model with the observed data, we adopted the following misfit expression (φ)

248

$$\phi = \sqrt{\sum_{i=1}^N \sum_{j=1}^M \frac{(\alpha_{j,\text{mod}}^i - \alpha_{j,\text{sam}}^i)^2}{\sigma_j^i}}$$

249 where N the number of data sets and M the samples in each data set, $\alpha_{j,\text{mod}}$ the modeled
 250 age for a particular set of parameters and $\alpha_{j,\text{sam}}$ the sampled value (measured age). σ_j
 251 refers to the data uncertainty. Following Valla et al. (2010), we adopted an uncertainty of
 252 0.5 Myrs to equally weight all data in terms of the difference between the observed and
 253 predicted ages.

254

255 **b) Additional views from classical inverse thermal history modelling**

256 To complement insights derived from the 2D thermochronological simulations, we used
 257 inverse thermal history modeling for samples J259 and J272, using the software HeFTy
 258 (see Ketcham, 2005). To account for the depositional history of each sample, as well as
 259 episodes of heating (potential resetting) before the period concerned by this work (16 Ma
 260 to present), the inverse modeling exercises were set considering the following constraints:

| Sample | Time (Ma) | Temp. range (°C) | Rationale |
|--------|-----------|------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| J272 | 400-280 | >170 | simulate provenance |
| | 300-280 | 0-30 | sediment accumulation |
| | 260-80 | 60-140 | burial heating |
| | 60-23 | 20-45 | Paleozoic rocks should have been close to the surface anytime in the Cenozoic, as implied by the Neogene/Permian unconformity in the maps |
| | 23-0 | 60-100 | burial and heating of Paleozoic rocks as Andean-related subsidence took place |
| J259 | 500-440 | >170 | simulate provenance |
| | 440-420 | 0-30 | sediment accumulation |
| | 300-90 | 60-140 | burial heating |
| | 60-23 | 20-45 | Paleozoic rocks should have been close to the surface (but deeper than sample J259, and therefore hotter) anytime in the Cenozoic, as implied by the Neogene/Permian unconformity in the maps |
| | 23-0 | 60-100 | burial and heating of Paleozoic rocks as Andean-related subsidence took place |

261

262 Table 2. Constraints considered in classical inverse thermal modeling.

263

264 Results and discussion

265 a) Misfit distribution

266 Results from the MC inversion are shown in Fig. 2. Fig. 2A shows the AP kinematics used
267 after Nassif et al (2019), which considered an in-sequence thrustbelt deformation starting
268 at 16 Ma. Fig. 2B displays a “noodle plot” of thermal candidates for each of the 3 periods
269 considered (16 Myrs to 8 Myrs, 8 Myrs to 4 Myrs, 4 Myrs to 0 Myrs), and their respective
270 misfit values. Misfits were normalized for this figure to a 0-1 scale, with 0 representing the
271 lowest misfit observed (best agreement between model predictions and data) and 1 the
272 highest (worst agreement between model predictions and data). We note that a
273 normalized misfit value of 0 does not represent a perfect agreement between data and
274 predictions. The distance along the AP axis is also shown rescaled (-1 to 1 representing
275 west to east; see Fig. 2). Finally, Fig. 2C shows 1D marginal distributions obtained via
276 Neighborhood Algorithm Bayes (see Sambridge, 1999), along with deterministic
277 temperature estimates at the base of the model (20 km) after the flat slab subduction
278 model of Gutscher et al (2000). Best-fit temperature candidates are also shown in Fig. 2C
279 for clarity (see red lines).

280 We remark that the conditional dependence (or correlation) between parameters from
281 each of the 3 periods plays a major role regarding the misfit values. For example,
282 normalized misfit values for $T = 200^{\circ}\text{C}$ in the first stage (16 Myrs to 8 Myrs; see Fig. 2B),
283 vary between 0.7 and 0.1, depending on the values of the other 3 parameters. Some
284 combinations of this candidate ($T=200^{\circ}\text{C}$) with candidates from the other two stages
285 yielded better misfits than others, demonstrating a conditional dependence or trade-off
286 among values drawn for each of the 3 periods. Overall, however, basal temperatures in
287 the range between 400°C to 800°C represent poor models (high normalized misfit, 0.6 or
288 higher; see Fig. 2) for all of the 3 stages considered, regardless of how they were
289 combined.

290 Lower values of misfit for the first stage (16 Myrs to 8 Myrs) are obtained when candidates
291 are in the 300°C - 100°C range (with some conditional dependence on the other two

292 periods, as discussed above). Misfit values are lower when candidates are around 200°C
293 to 100°C in the second stage (8 Myrs to 4 Myrs), implying that basal temperatures (at 20
294 km depth) in the AP for this time interval may have decreased. This statement also holds
295 true for the third stage (4 Myrs to present). However, since a lateral variation of
296 temperature was allowed for this time interval of the simulations, the results appear more
297 dispersed across the temperature axis relative to the second phase. Furthermore, our MC
298 inversion results suggest that heat coming into the base of the AP (20 km) during the
299 Miocene may have never led to temperatures in excess of 300°C, implying low thermal
300 gradients ($\sim 15^\circ\text{C}/\text{km}$, or heat flow about 30mWm^{-2}).

301 Marginal distributions obtained for each variable considered (Fig. 2C) using the NA
302 resampling method (see Sambridge, 1999) corroborate previous comments in regards to
303 temperature reduction after 8 Ma (see Fig. 2C), as the range of temperatures in the
304 marginal pdf is strongly peaked at lower values (2 modes seen in the distribution) for the
305 interval 8-4 Ma. It can also be noted that marginal distributions from T1 and T2 barely
306 overlap, disclosing the diminution in basal temperatures after 8 Ma (see Fig. 2C). The 2
307 distributions for the last stage (in the period 4 to 0 Myrs, W and E) span a similar range to
308 the 2nd stage, and both are peaked at low values (100-120°C).

309 To complement the previous assertions on conditional dependence, we used the same
310 resampling approach to construct the 2D marginal distributions for each combination of
311 variables analyzed (T1, T2, T3, T4; see Fig. 3) and we also calculated the correlation
312 matrix for the 4 parameters (Fig. 3; bottom). These results show that there are indeed
313 correlations between parameters, the strongest being between the parameters for stages
314 1 (T1) and 2 (T2) (correlation coefficient of -0.67), implying a trade-off such that as T1
315 increases T2 decreases. This is also manifested in the orientation of the contours in the
316 2D marginal distribution for these two parameters. There are less strong correlations of
317 stage 1 and stage 2 with the parameter in the west (T3) from stage 3 (correlation
318 coefficients of -0.25, and 0.26 respectively, implying slightly negative and positive
319 correlations). The temperature parameter in east (T4) has correlation coefficients of $< 10^{-2}$
320 with the other 3 parameters, so effectively no correlation. Both the 1D and 2D marginal
321 distributions also demonstrate that the more probable values for all 4 temperature
322 parameters are below 300°C, highlighting the dominantly cold thermal regime since 16 Ma.

323 **b) Comparison with the Andean flat-slab subduction model of Gutscher et al. (2000)**

324 The results presented in this work are consistent with previous subduction models
325 (Gutscher et al., 2000; Gutscher and Peacock, 2003; Manea and Manea, 2011), that
326 propose refrigerated thermal architectures after slab flattening (see estimates from
327 Gutscher et al., 2000; Fig. 2C). Moreover, the trends from our best-fit models agree well
328 with the pronounced cooling after c.a. 10 Myrs proposed by Gutscher et al. (2000; see Fig.
329 2C). The main difference between our best-fit result and Gutscher et al. (2000) occurs for
330 the period from 8 to 4 Myrs (Fig. 2C), where our inferred best temperature values (around
331 100°C for T2) are lower than those after Gutscher et al. (2000; around 200°C). However,
332 the marginal distributions suggest that there is a local maximum (equivalent to a local
333 minimum for the misfit) around 200°C, so the results overall are consistent with Gutscher
334 et al. (2000). More data are required to resolve more definitively whether the thermal effect
335 of the flat slab had already perturbed the upper crust by 8 Myrs (for our best model) or if
336 this effect arrived at a later stage (as implied by Gutscher et al., 2000). Regarding the last
337 4 Myrs, our best-fit candidate implies the same eastward increase in temperature as in the
338 Gutscher et al. (2000) model, but again more data are needed to better constrain the basal
339 temperature values for that period. A lack of resolution is implied by the variable
340 orientations among basal temperature candidates and associated lack of correlation for
341 that interval (see Fig 2B, 2C and Fig. 3). We note that the implied present day gradients
342 resulting from all the lower misfit candidates ($\sim 13^\circ\text{C}/\text{km}$ to $5^\circ\text{C}/\text{km}$) are consistent with low
343 thermal gradients derived from borehole measurements (Collo et al, 2018; $18^\circ\text{C}/\text{Km}$).
344 Collo et al. (2018) highlighted a westward reduction of thermal gradients between 64°W
345 and 68°W attributable to a flat-slab.

346 **c) Discussion on modeled thermochronological ages**

347 Results obtained for modeled thermochronological data are shown in Fig. 4, along with the
348 interpreted structural state of the Jachal AP for the present day (after Nassif et al., 2019;
349 Allmendinger and Judge, 2014). Table 3 summarizes the measured (from this and other
350 works) and modeled values. We note that although the thermochronological ages exhibit
351 significant variation along the transect (see AFT ages of Permian and Silurian rocks in the
352 easternmost nappe; 152.3 ± 12.9 Myrs and 10.9 ± 2.1 Myrs, respectively; Fig. 4); predicted
353 ages (obtained with the best-fit model) and measured ages follow the same trend. In
354 particular, the thermal resetting of U-Th/He samples from Blanco (JT07), Blanquitos (JT12)
355 and Niquivil (JT01) is well replicated, with all ages implying Andean cooling (see Fig. 4 and
356 Fig. 1 for reference). We remark that modeled U-Th/He age of sample J701 (8.4 Myrs)

357 implies, like the measured age (12.3 ± 1.4 Myrs; Fosdick et al., 2015), cooling that
 358 predates deformation along Niquivil thrust (see Fig. 4). This inference is significant given
 359 that kinematic reconstructions point to a major burial episode at that time (~ 4 Km at 5
 360 Myrs, see Nassif et al., 2019), which might be hard to reconcile with the observed U-Th/He
 361 ages, which are older than Niquivil faulting (see Fig. 4, samples JT01 and JT259).
 362 Modeling incorporating a normal gradient (20 °C/km to 30 °C/km) would fail to reproduce
 363 such a situation, producing totally reset ages that reflected later cooling around the time of
 364 Niquivil thrust activation (5 Myrs or less; see also Nassif et al., 2020; in press).

365

| | Sample | Depositional age | Measured age (Ma) | Measured MTL (μm , c-axis corrected) | Modeled age (Ma) | Modeled MTL (μm) |
|------------|-----------------------------|------------------|-------------------|--------------------------------------------------|------------------|-------------------------------|
| AFT | J259 (this work) | Silurian | 10.9 ± 2.1 | | 23.14 | 12.3 |
| AFT | J272 (this work) | Permian | 152.30 ± 12.9 | 12.57 ± 1.18 | 114.321 | 12.63 |
| U-Th-Sm/He | JT07 (Fosdick et al., 2015) | Silurian | 14.1 ± 1.0 | | 7.85 | |
| U-Th-Sm/He | JT01 (Fosdick et al., 2015) | Silurian | 12.3 ± 1.4 | | 8.42 | |
| U-Th-Sm/He | JT012(Fosdick et al., 2015) | Permian | 11.7 ± 4.1 | | 6.8 | |

366

Table 3. Modeled and measured ages and track lengths

367 The AFT modeled ages agree with observations (see also supplementary material), both
 368 implying partial annealing of fission tracks during Andean structuration (see Fig. 4). The
 369 high content of Illite in I/S mixed layers (around 80%; R3; see Fig.4 and supplementary
 370 material) in AFT Permian and Silurian samples (J272 and J259, respectively) tentatively
 371 imply that Paleozoic rocks were heated above temperatures over 100 °C (see Velde and

372 Vasseur, 1992; Huang et al, 1993; among others). Given that maximum temperatures
373 rendered by the best-fit model for partially-reset AFT Silurian sample J259 do not exceed
374 the 90-100°C range (see Fig. 4, inset), and that AFT age of Permian sample J272 points to
375 a very minor degree of thermal resetting (152.3 ± 12.9 Myrs, Fig. 4), our results suggest
376 that temperatures in excess of 120°C might have been reached prior to Tertiary
377 deformation. Such a proposal is consistent with 1D modeling exercises previously
378 performed for the AP (Fosdick et al., 2015), which suggested temperatures always below
379 80°C for the period modeled in this work (16 Myrs to present). We note that the proposed
380 pre-Andean heating might imply that Cambro-Ordovician marine sedimentary rocks (see
381 Fig.1), suggested to be potential oil source rocks (see Pérez et al., 2011; Fig. 1), would
382 have reached temperatures in the oil window before the Miocene orogenesis, therefore
383 ruling out Tertiary-trap hydrocarbon accumulation.

384 **d) Complementary views from 1D thermal models**

385 As discussed previously in the methodology, inverse thermal models using HeFTy for the
386 two AFT samples (J272 and J259) were performed. The inverse thermal model for sample
387 J272 considered age and length measurements, since both were available. In contrast, the
388 inverse thermal model for sample J259 only had age measurements as constraints, as no
389 confined lengths were observed (see SM1) for that sample. Fig. 5 shows the results for
390 both samples, outlining major observations that can be obtained from the time-temperature
391 paths inverted, which can be summarized as follows:

392 i) Sample J272 (San Roque nappe, see Fig. 5A): the thermal history of this Permian
393 sample exhibits two episodes of thermal resetting; at Mesozoic and at Miocene. Full
394 thermal resetting of sample J272 at ~220 Ma points to an old (> 150 Ma) remnant age of
395 the sample by the time it underwent Andean-related burial and consequent heating. Such
396 Andean heating only promoted maximum temperatures around 80°C, producing only
397 partial annealing in fission tracks. This partial annealing was followed by rapid Neogene
398 cooling, which might be interpreted in terms of thrusting and kinematics of the AP (see
399 Fosdick et al., 2015; Val et al., 2016, Nassif et al., 2019). Moreover, according to the
400 HeFTy inverse model (and also 2D kinematic simulations), the sample J272 was never
401 heated by temperatures above 90°C during the Tertiary, so the remnant age was not
402 altered substantially during Andean deformation. Such partial thermal-resetting during
403 Andean tectonics remarks the strong influence of the basal boundary conditions on the

404 thermal history of the thrust belt: the sample underwent cooling since 10 Ma despite the
405 fact that, indeed, the sample was being substantially buried (see sedimentation estimation
406 in Nassif et al., 2019) as a consequence of thrusting-related syn-sedimentation.

407 ii) Sample J259 (Niquivil nappe, see Fig. 5B): the degree of Miocene thermal resetting in
408 this sample remains unconstrained by thermochronological data alone, as the lack of
409 length data means that many possible models can explain the age measurements.
410 However, considering similar constraints as those imposed for sample J272, the inverse
411 model rendered corroborates previous assertions regarding a Miocene cooling episode not
412 linked to rock exhumation but to transient boundary conditions instead. Alike sample J272,
413 the thermal history of sample J259 also points to a cooling event after 10 Myrs, which
414 seems counterintuitive as by this time most volume of the Argentine Precordillera was
415 being translated from western nappes to eastern ones (see Fosdick et al., 2015; Val et al.,
416 2016, Levina et al., 2014; and kinematics in Nassif et al., 2019), therefore implying
417 substantial burial and deepening of sediments within the Niquivil block; i.e. what might be
418 considered the opposite of cooling. Hence, the inverted Andean thermal evolution of
419 sample J259, to some extent unpaired with the kinematics and sedimentation of the thrust
420 belt, discloses the major effects of the flat-slab subduction (and its associated changes in
421 basal heat flow) on time-temperature paths and thermochronological ages.

422 **e) Regional geodynamic context**

423 Although a complex thermal structure is inferred for this region (Sánchez et al. 2019) and
424 some discrepancies exist regarding the associated thermal regime during the transition
425 from normal to flat subduction (see Collo et al., 2011 and Goddard and Carrapa, 2018),
426 the cooling of the thermal regime by 8 Myrs implied by our models is consistent with the
427 inferred low heat flow in the region based on borehole, seismic, thermochronological and
428 magnetic data (Marot et al., 2014; Collo et al., 2018; Sánchez et al. 2019) and with the
429 extremely low gradients in the Huaco foreland basin proposed by authors such as Dávila
430 and Carter (2013), Richardson et al. (2013), Hoke et al. (2014), Bense et al. (2014), and
431 Collo et al. (2018); as well as with those recorded for other flat slab regions (eg. Dumitru
432 et al., 1991, Gutscher 2002, Manea and Manea 2011).

433 Moreover, our results support the proposals of Dávila & Carter (2013), who suggested that
434 thermochronological ages in this region not only record erosion/exhumation, but also
435 changing subduction geometry and dynamics. Building on these previous qualitative

436 propositions, the present effort represents the first attempt to quantify the influence of the
437 Pampean flat slab subduction in the thermal regime of the AP. Our findings are similar to
438 those seen in deep Vinchina Basin (around 10 km depth), where sediments belonging to
439 the depocenter were not thermally reset during Miocene deformation (Collo et al., 2011,
440 2015, 2018). Such unreset AFT ages (and also U-Th/He ages, see sample JT01) within
441 the AP, a fold-and-thrust belt where the magnitude of erosion is probably >5 km (see
442 Zapata and Allmendinger, 1996; Jordan et al., 2001; Fosdick et al., 2015, Val et al., 2016;
443 Nassif et al., 2019), suggest that other heating/cooling mechanisms apart from burial and
444 exhumation may need to be invoked. The reduction of heat transfer from below by fluid
445 flow (Nassif et al., 2020, in press) would also allow higher basal temperatures to fit the
446 measured thermochronological data. However, the extent of fluid flow through the AP is
447 yet to be precisely quantified (Lynch and van der Pluijm, 2017) and only then can such
448 effects be better understood.

449 **f) Limitations and further insights**

450 Although the numerical model performed in this study satisfactorily explains the
451 thermochronological data set, we highlight that model results could be enhanced by
452 considering the following: a) incorporation of radiation damage effects in the AHe analysis;
453 which, as discussed by Zapata et al. (2020), might be a first-order factor conditioning U-
454 Th-Sm/He thermochronological measurements (and interpretations) near the study region.
455 Moreover, overlapping of AHe and AFT ages in sample J259; might point in that direction,
456 or could also just reflect rapid cooling across the partial retention/annealing zones. b)
457 Consideration of isostatic effects in the kinematic and erosional model of Nassif et al.
458 (2019), which could reduce the amount of eroded material and thus, the thickness of the
459 Neogene sedimentary column considered in the simulations (see also McQuarrie and
460 Ehlers, 2015); c) refinement of the numerical model by incorporating physical phenomena
461 not considered in this work (for instance radiogenic heat production, variable
462 thermophysical parameters or fluid flow), which could lead to different basal temperatures
463 that also fit the thermochronological constraints. However, as the main aim of this work
464 was to explore a new way of exploiting thermochronological data; i.e. inversion of time-
465 dependent basal temperatures, the methods considered and the simplifications implicit in
466 them is sufficient to demonstrate the potential of this approach.

467

468 Conclusion

469 The basal temperature inversion exercise presented here, based on classic Monte Carlo
470 sampling, shows an alternative use of thermochronological data, that is, to try and
471 constrain time and spatial variations in the lower thermal boundary condition (at 20 km) for
472 thermo-kinematic models. The motivation is to link geodynamically induced thermal signals
473 from the deeper Earth with those related to upper-crust structural kinematics and to shed
474 more light on the nature of heat transfer in subduction settings. However, this may seem
475 counter-intuitive as the thermochronological data are sensitive to temperatures < 150°C,
476 and also the inversion approach and model parameterizations we used were simple; the
477 preliminary results are promising. This is in part due to the very low basal temperatures
478 associated with the refrigerated thermal regime associated with flat subduction, suggesting
479 similar (or more sophisticated) approaches and other types of higher temperature
480 thermochronological data (e.g. He dating of zircon, $^{40}\text{Ar}/^{39}\text{Ar}$ on feldspar, U-Pb on apatite)
481 may be usefully applied in other areas where the structural evolution and the geodynamic
482 regime can be constrained.

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485

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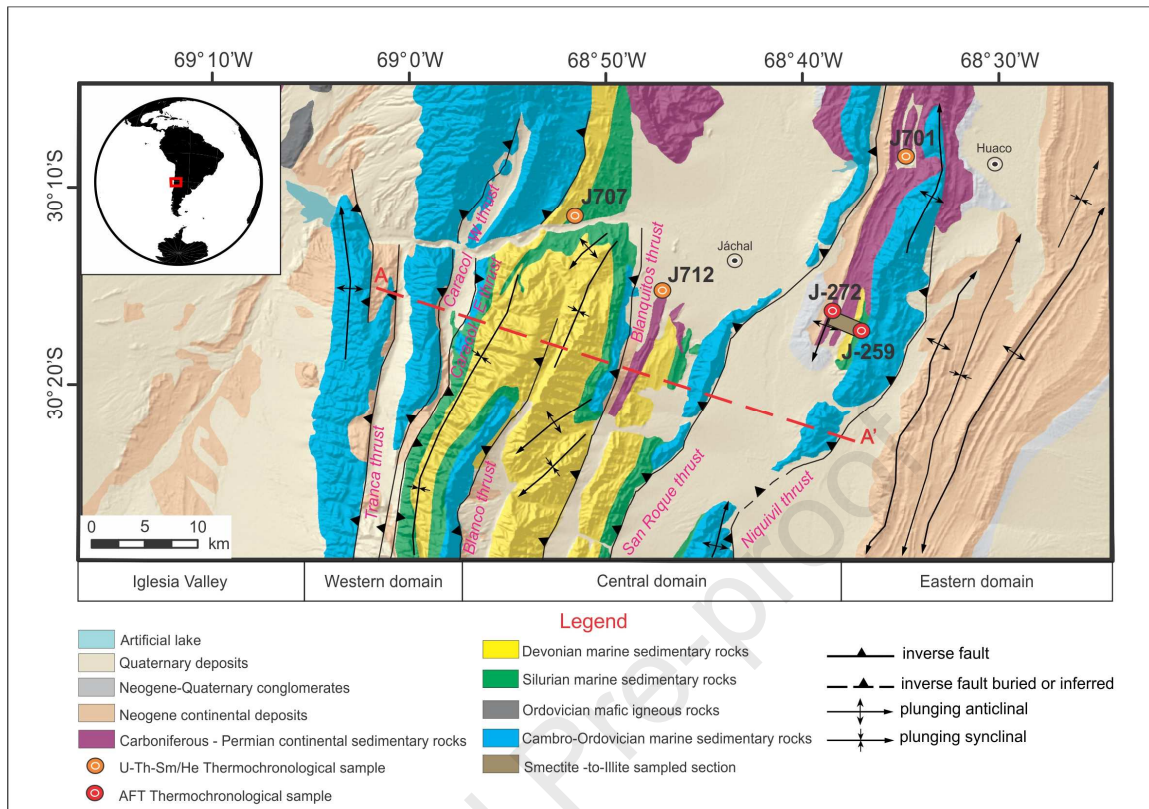
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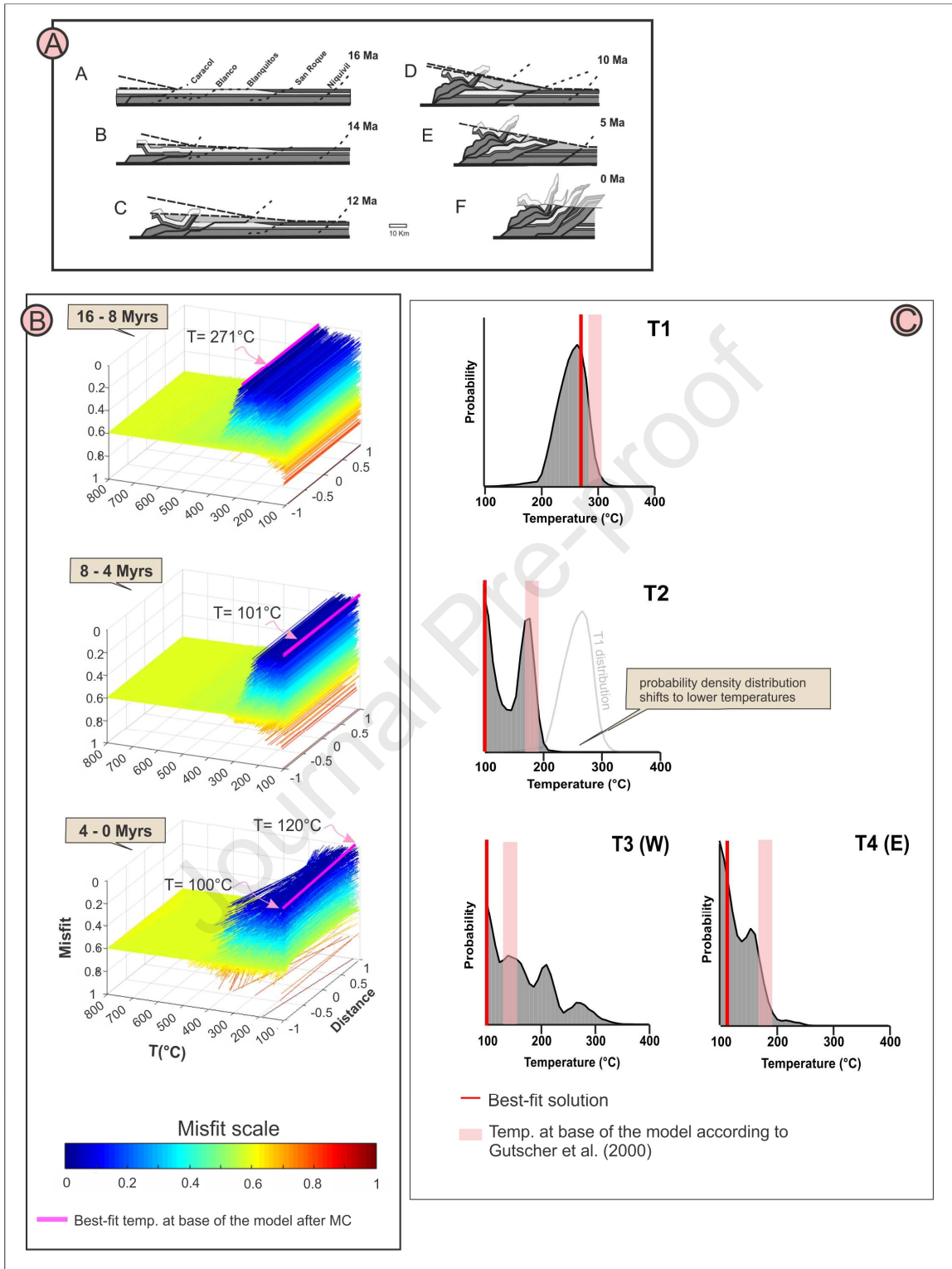
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669 Fig 1. Geological-structural map of the study area (Jachal-Rodeo section after Nassif et al., 2019.
 670 Geological characterization after Allmendinger and Judge, 2014). U-Th/He thermochronological
 671 samples J701, J707 and J712 after Fosdick et al. (2015) and J272 and J259 are our own AFT
 672 samples.

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675 Fig 2. Monte Carlo sampling results. A) Kinematics considered after Nassif et al. (2019); B) Thermal
676 candidates for each of the three periods considered displayed with their respective normalized

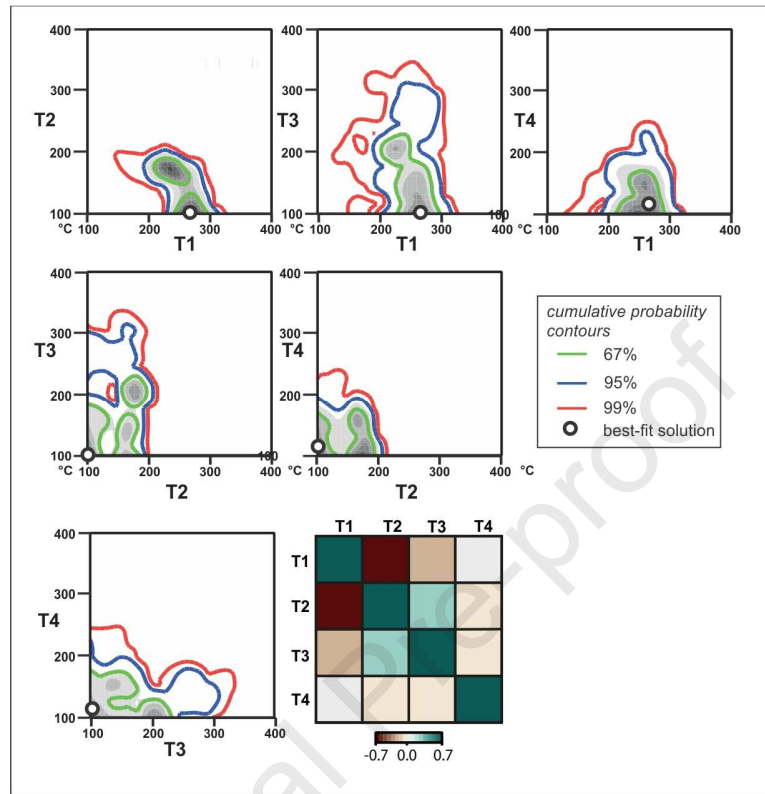
677 misfit value (see color scale); C) 1D marginal probability distributions for the four parameters
678 calculated with the approach of Sambridge (1999). The red lines mark values for the best model
679 obtained from the MC sampling (the model with the minimum misfit over all 4 parameters).
680 Estimates of temperatures at the base of the model (20 Km), after numerical subduction models of
681 Gutscher et al (2000), are also shown (see pink rectangles)

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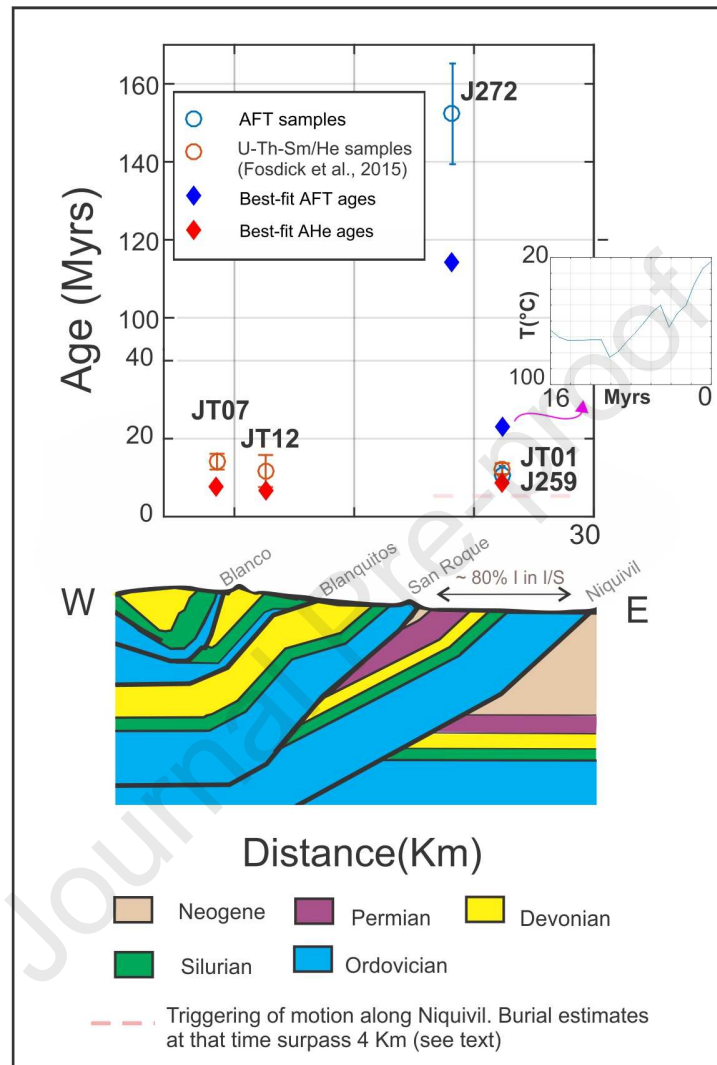
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686 Fig. 3. 2D marginal probability distributions for the 6 combinations of the 4 temperature
 687 parameters. The green, blue and red contours indicate 67, 95 and 99% probability and the white
 688 circles indicate the values for the best model obtained from the MC sampling (the model with the
 689 minimum misfit over all 4 parameters). The lower right panel illustrates the correlation matrix for
 690 the 4 parameters, with each square indexed by the parameter values on the top and the left of the
 691 image. The green colours indicate a positive correlation, brown colours a negative correlation and
 692 the lighter the colour, the closer to zero the correlation coefficient (i.e. low correlation). All
 693 parameters are perfectly correlated with themselves, so the diagonal (dark green) = 1.

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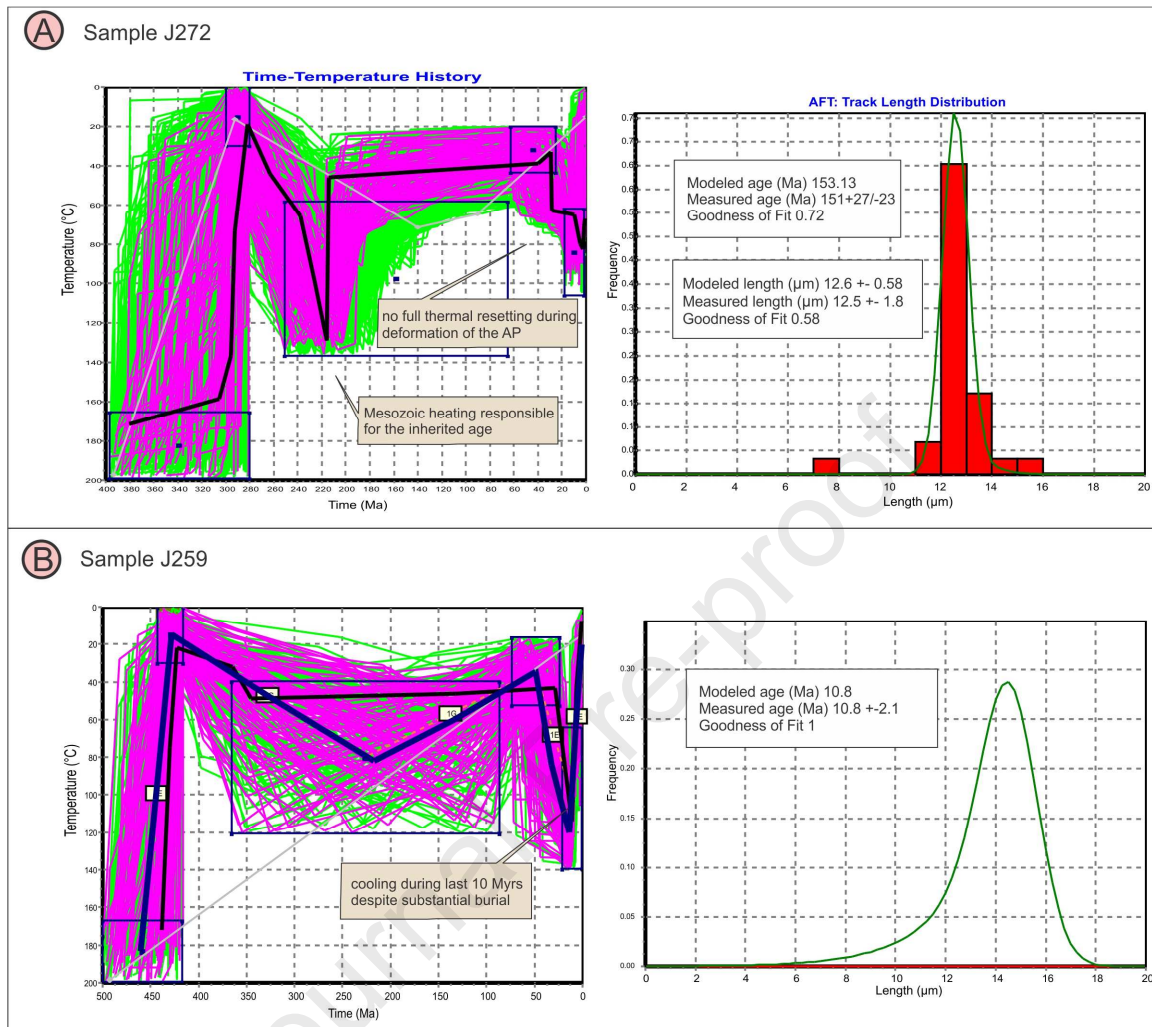
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698 Fig 4. Forward modeled thermochronological ages. Interpreted present-day structural section of
 699 Jachal AP (Nassif et al., 2019) and measured %I in mixed I/S (this work), are also shown. U-Th-
 700 Sm/He ages after Fosdick et al. (2015)

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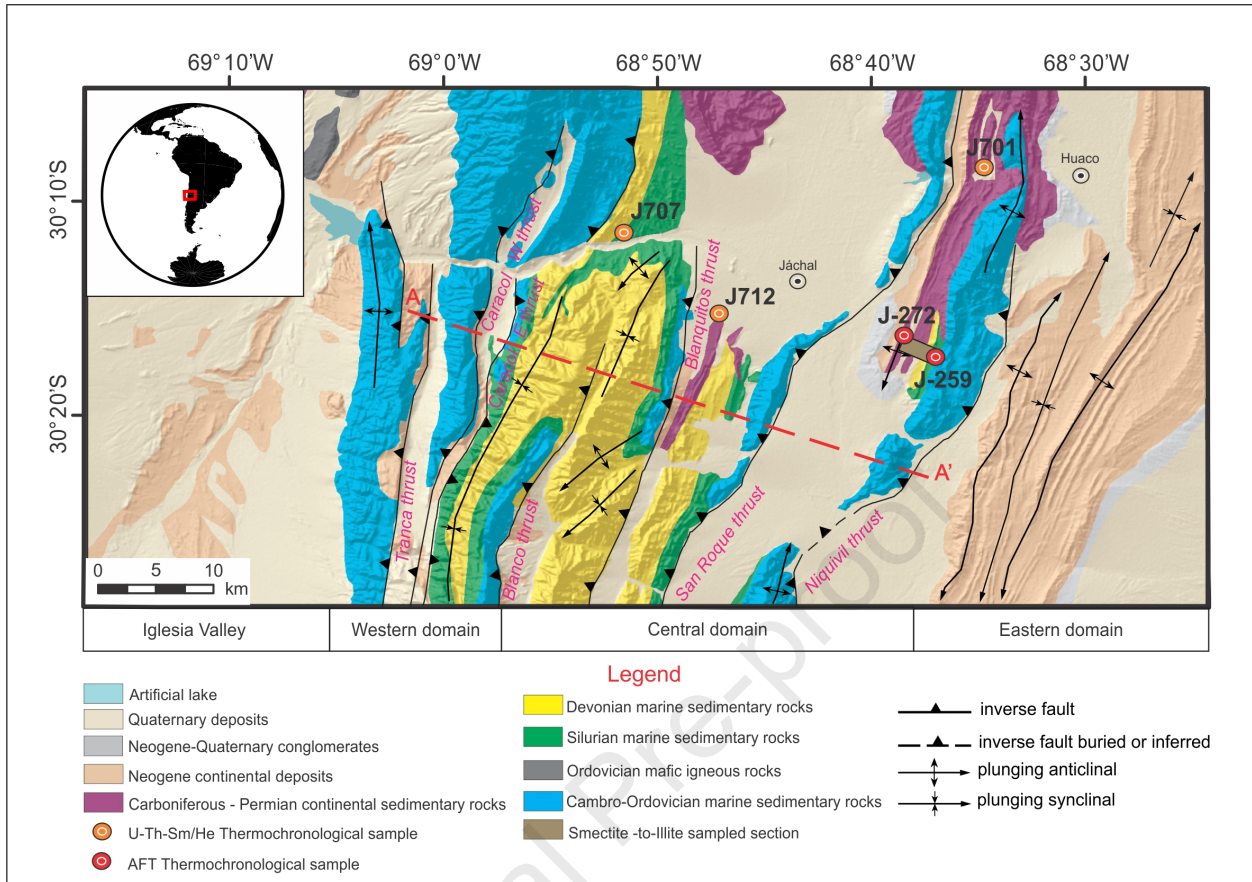
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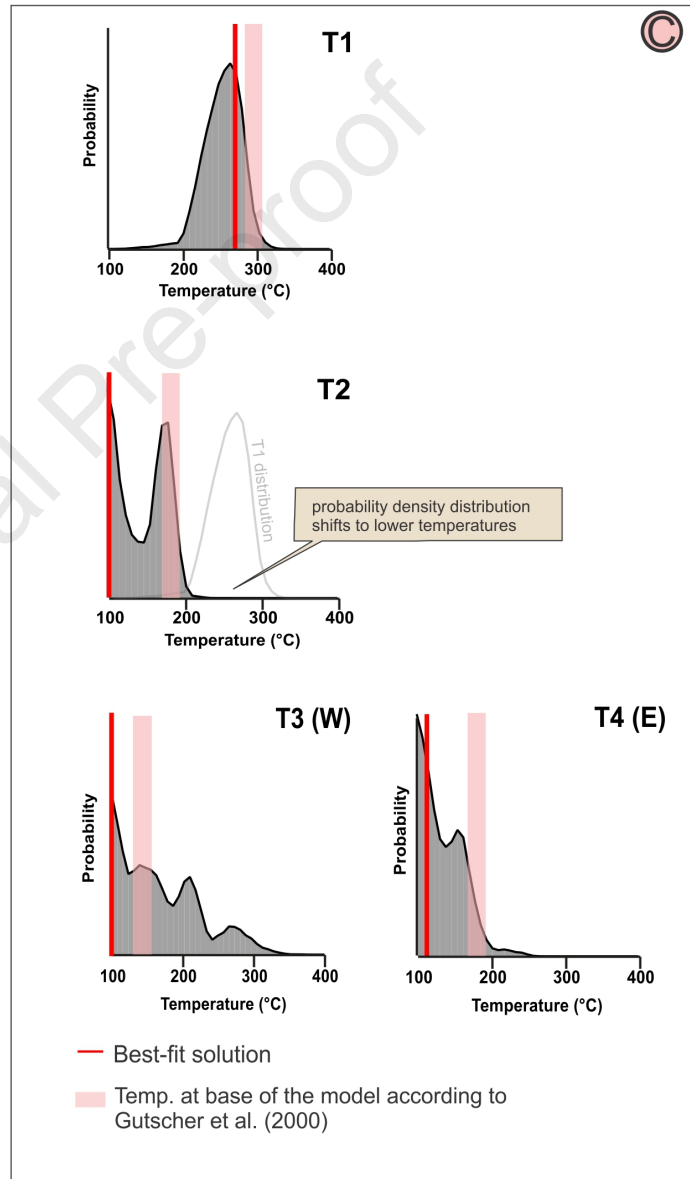
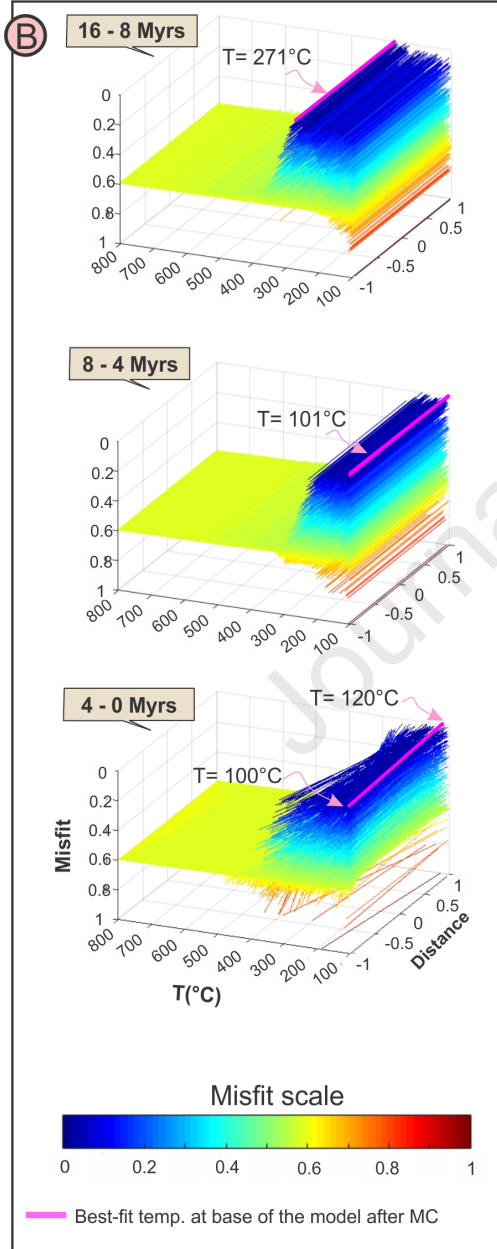
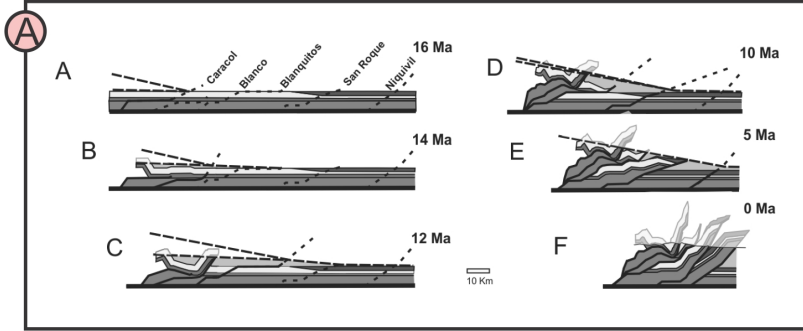
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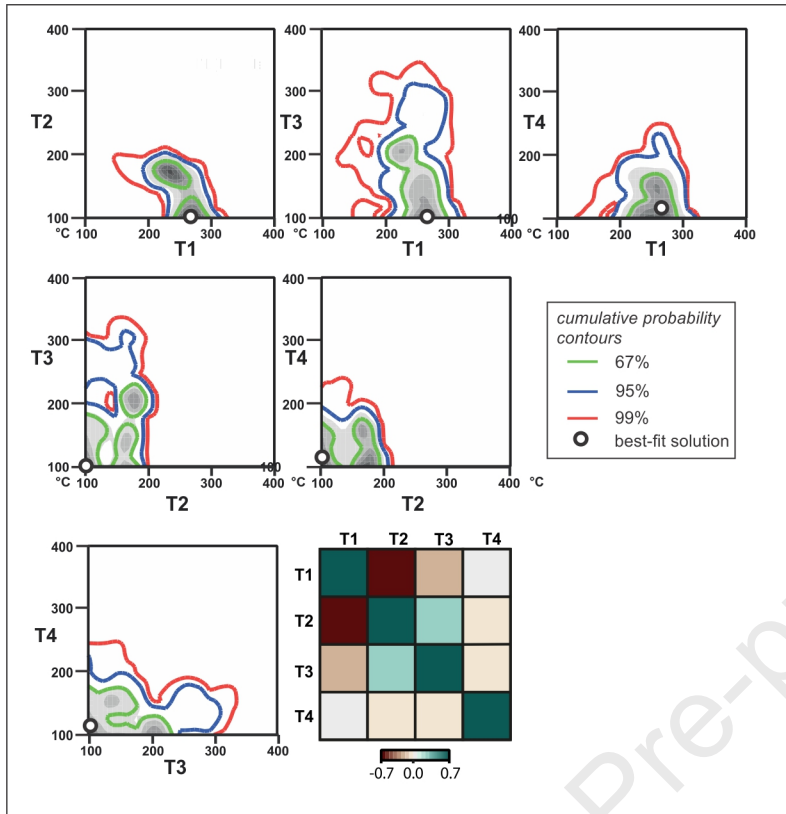
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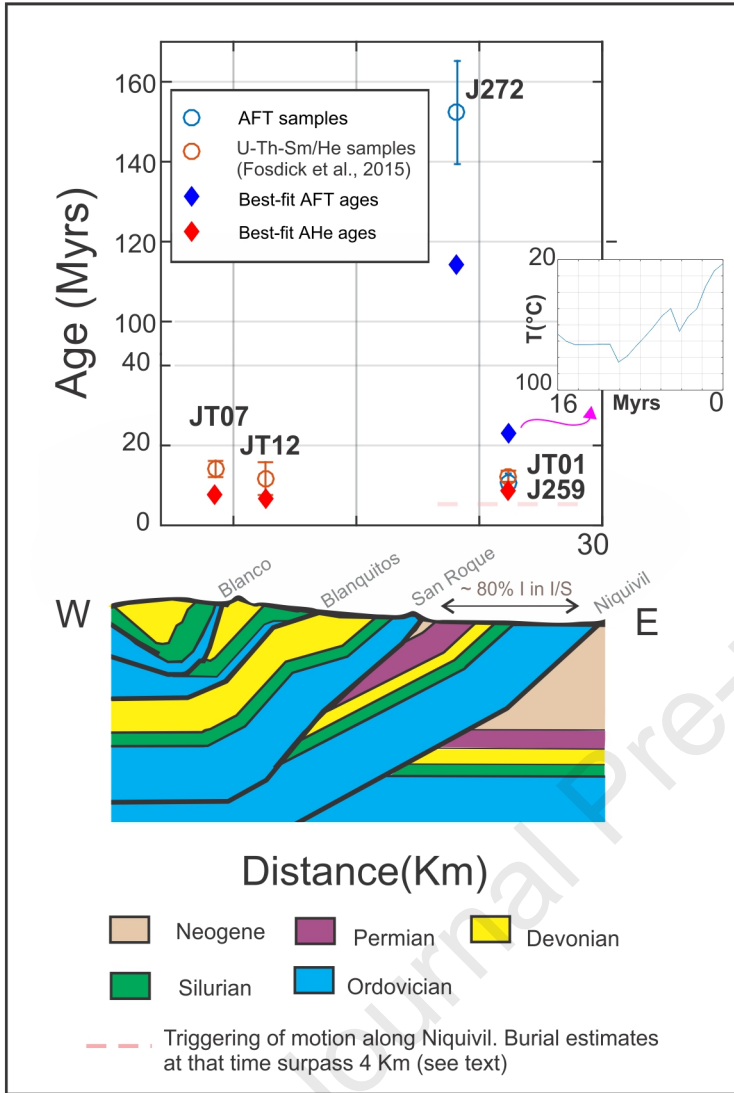
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Fig. 5. Inverted time-temperature histories and track length distributions of samples J272 and J259, considering length and age FT data.

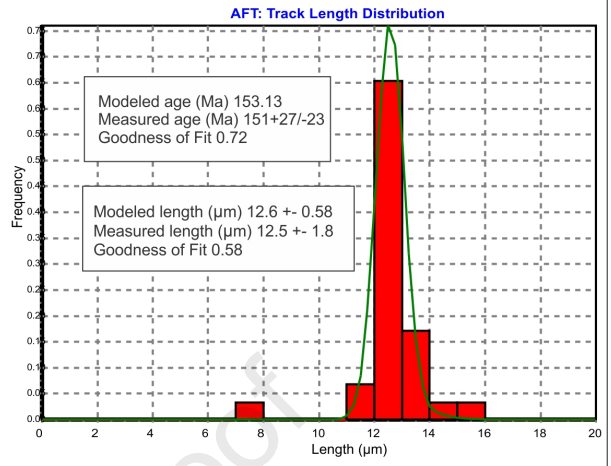
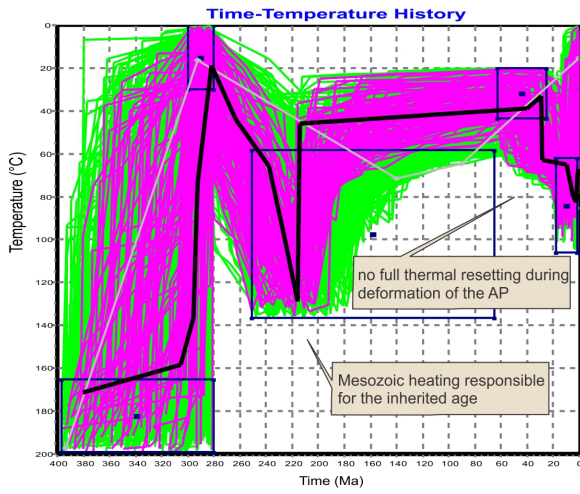




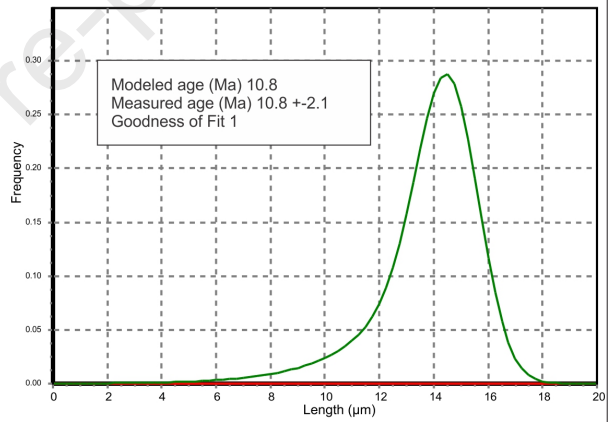
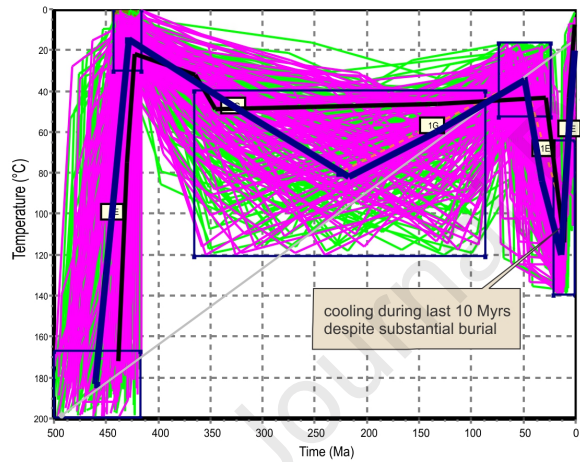




(A) Sample J272



(B) Sample J259



- Low-temperature thermochronological data are used to estimate unsteady basal boundary conditions in 2D thermokinematic simulations
- Geodynamic signals from deep Earth processes are linked to shallow-crust thermochronological signals by means of Monte Carlo sampling
- Inversion of transient boundary conditions discloses effects of flat slab subduction in the Argentine Precordillera

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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