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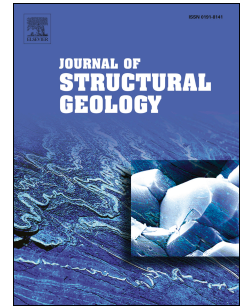


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Multi-scale strainfield analysis using geostatistics: Investigating the rheological behavior of the hot Variscan crust of the Pyrenees (Axial Zone)

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1 Multi-scale strainfield analysis using geostatistics: Investigating  
2 the rheological behavior of the hot Variscan crust of the  
3 Pyrenees (Axial Zone)

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**20 Abstract**

21 The present study provides a quantitative way to analyze and interpolate strainfields from ductile  
22 fabric field measurements using geostatistics. Based on variogram analysis and kriging  
23 interpolations, the developed methodology allows computing automatic cleavage and lineation  
24 trajectory maps at different scales from a same field structural dataset. For the example provided  
25 by the hot Variscan crust of the Pyrenees, the analysis of cleavage/stretching lineations  
26 orientation and kinematic data document pure shear conditions recorded during convergence.  
27 Strain was vertically partitioned between an upper crust submitted to homogeneous thickening  
28 responding to N-S (orogen-normal) shortening and a hot and partially molten mid-lower crust  
29 affected by horizontal longitudinal (orogen-parallel) flow. The emplacement of plutons and  
30 gneiss domes generated heterogeneities in the upper crust and induced strain localization into  
31 steep anastomosed transpressional shear zones flanking those structures. The results show that  
32 geostatistics applied to structural geology are powerful tools for retrieving tectonic regimes of  
33 large orogenic segments by identifying and quantifying perturbations in the strainfields induced  
34 by protracted and potentially complex tectonic histories. The variogram analysis also gives first  
35 order clues to evaluate whether the considered structural domains underwent single continuous  
36 ductile or polyphased brittle-ductile deformation.

**37 Keywords**

38 Strain partitioning, variogram analysis, kriging interpolation, transpression, hot orogen

39

40

41

## 42 1. Introduction

43 Determination of principal strain and stress directions in the lithosphere has always been a key  
44 task for understanding and constraining plate tectonics. Mapping and analysis of strain/stress  
45 field patterns bring constraints on the mechanical behavior of crust/lithosphere. Such an approach  
46 allows evaluating (i) the meaning of spatial shear gradients and finite strain values in terms of  
47 displacement(s), (ii) the way deformation localizes, (iii) the role of rheological contrasts between  
48 adjacent lithologies during deformation and (iv) the rheological contrasts between structural  
49 levels and their degree of coupling. In active tectonic domains, approximate stress fields can be  
50 obtained using measured GPS velocity fields (e.g. Welsch, 1983; Kahle et al., 1999; Grenerczy et  
51 al., 2000, Zang et al., 2004; Titus et al., 2011) or focal mechanisms from earthquakes (e.g.  
52 McKenzie, 1972; Calais et al., 2002; Engdahl and Villasenor, 2002). Structural analyses of  
53 fractures and faults further allow retrieving paleo-stress fields (e.g. Angelier, 1984; Blès et al.,  
54 1989). For ductile deformation, foliation and stretching lineations can be considered as good  
55 proxies of principal strain axes orientations (Ramsay, 1967; Siddans, 1972; Wood, 1974).  
56 Foliation and lineation trajectories allow (i) investigating how the direction of principal strain  
57 axes change through space and (ii) deciphering homogeneous from heterogeneous strains by  
58 considering gradients and trajectory curvatures (i.e., convergence of trajectories) (see Cobbold  
59 and Barbotin, 1988). Following Cobbold and Barbotin (1988), the amount of strain is mostly  
60 difficult to quantify for natural case, therefore foliation and lineations trajectories – once coupled  
61 to a kinematic analysis of fabrics – are used to build paleo strainfields (or strain patterns). These  
62 trajectory maps are mostly extrapolated manually on the basis of structural measurements data  
63 (e.g. Brun and Pons, 1981; Brun, 1983; Chown et al., 1992; Gautier and Brun 1994; Bouchez and  
64 Gleizes, 1995). Moreover, extracting regional trends from individual local structural

65 measurements may not be straightforward and would hardly be reproducible in case of low data  
66 density at a considered scale. The resulting trajectory maps may thus be intrinsically qualitative.

67 Considering the limitations of manual strainfields' interpolation, geostatistics can be used to  
68 quantitatively analyze spatial variations in the orientation of structural measurements and to  
69 obtain the best fitted interpolated maps, whatever the scale considered. The general approach has  
70 first been introduced by Matheron (1962). Such geostatistical analysis has already been used for  
71 brittle deformation to retrieve stress fields using fracture or fault data set (Escuder Viruete et al.,  
72 2003; Rafiee and Vinches, 2008; Koike et al., 2015; Hanke et al., 2017; Riller et al., 2017) and  
73 3D modeling of geological objects at local scale (e.g. folds, see Hillier et al., 2013; Grose et al.,  
74 2017). It has been also developed and successfully applied to the analysis of ductile fabrics  
75 directional data (Gumiaux et al., 2003). Based on a preliminary statistical analysis (the variogram  
76 analysis or variography), spatial interpolations can be computed, leading to automatic cleavage or  
77 foliation trajectory maps (Gumiaux et al., 2003, 2004).

78 In this study, we apply such geostatistical approach in order to obtain quantitative insights on the  
79 way strain has been spatially (i.e. horizontally and vertically) partitioned during convergence.  
80 Indeed, in orogenic contexts, geotherms control – at first order – vertical rheological layering and  
81 mechanical coupling in the lithosphere (Davy, 1986). Contrary to cold collisional belts such as  
82 the Alps and Taiwan (Brun, 2002; Lacombe and Mouthereau, 2002), old accretionary or mature  
83 orogens have undergone critical weakening on a lithospheric scale, inducing specific vertical  
84 strain partitioning pattern and mass redistribution between the upper crust and a particularly weak  
85 lower crust (Chardon et al., 2009). In order to investigate such space-time strain partitioning  
86 patterns, the present study focuses on a segment of the Variscides exposed in the Pyrenees, which  
87 underwent both thickening upper crust and the laterally flow of its mid-lower crust (Cochelin et

88 al., 2017). In a first step, processing of the overall structural dataset allows producing a strain  
89 trajectory map corresponding to the total finite strainfield of this crustal segment. Strainfield is  
90 then successively deconvoluted to constrain strain interference effects induced by crustal domains  
91 or units of contrasted mechanical behaviors (i.e. the upper crustal metasediments, the mid-lower  
92 crust and plutons). The analysis of strainfields based on strain trajectory modeling is performed  
93 from regional to local scale, with some focuses made on the Canigou gneiss dome and the Mt-  
94 Louis pluton.

## 95 **2. Geological setting**

96 The Pyrenees form an east-west trending intra-continental mountain range resulting from the  
97 collision between the Iberian and the European plates (Choukroune, 1992). During upper  
98 Cretaceous to Early Tertiary convergence, shortening was responsible for the exhumation and  
99 erosion of the Mesozoic cover, allowing exposure of the Paleozoic basement, which preserves  
100 Variscan (i.e., Late Paleozoic) orogenic deformation patterns. This portion of the Variscan  
101 orogen corresponds to the foreland of the belt and occupied the core of the Iberian-Armorican  
102 syntax during the latest stages of the orogeny (310-290 Ma) (Cochelin et al., 2017). The largest  
103 uplifted unit of pre-Mesozoic rocks outcropping in the Pyrenees is called Axial Zone and forms  
104 the core and highest part of the Cenozoic belt (Fig. 1a). Differential denudation of the Axial Zone  
105 provides an access to a continuous vertical section of the Variscan crust from the shallowest parts  
106 in the west (i.e. Carboniferous sedimentary basins) to mid-crustal levels in the east. Despite the  
107 “recent” (i.e., Alpine) Pyrenean orogeny, the structural continuity of the Variscan crust is  
108 maintained in the Axial Zone; which forms a consistent tectonic domain affected by only local  
109 and moderate perturbations due to post-Paleozoic deformation (Zwart, 1986; Carreras and Debat,

110 1996, Carreras and Druguet, 2014, Cochelin et al., 2017, 2018). The present study focuses on the  
111 pre-Mesozoic Axial Zone.

112 Figure 1 here

113 The Axial Zone is mainly made of Ediacaran to Upper Carboniferous sedimentary rocks having  
114 undergone High Temperature-Low Pressure (HT/LP) metamorphism that induced regional partial  
115 melting (Guitard et al., 1996 and references therein). These metasedimentary rocks were intruded  
116 from ca. 310 to 290 Ma by large calc-alkaline plutons (Denèle et al., 2014 and reference therein).  
117 Two contrasted structural levels are distinguished (de Sitter and Zwart, 1962; Zwart, 1979;  
118 Carreras and Capella, 1994). The low-grade metasedimentary rocks belonging to the upper crust  
119 are characterized by open to tight EW trending folds and steep N95-110°E striking axial plane  
120 cleavage (Figs. 1b & c) bearing steeply plunging stretching lineations (Cochelin et al., 2017,  
121 2018). The average strike of cleavage around N100°E associated to an average pitch of lineations  
122 around 83°W is compatible with transpression due to ~NS shortening (Cochelin et al., 2017). The  
123 lower structural level comprises the partially molten mid-lower crust that appears in gneiss domes  
124 elongate parallel to the regional structural trend (Figs. 1a & c) and mostly bearing longitudinal  
125 stretching lineations (Carreras and Debat, 1996; Mezger and Passchier, 2003; Denèle et al., 2007;  
126 2009; Cochelin et al., 2017). The chronological and structural relationship between steep and  
127 shallowly dipping structures has been subjected to debates since the 60's (e.g. de Sitter and  
128 Zwart, 1960; Zwart, 1979; Soula et al., 1986; Carreras and Capella, 1994; Carreras and Debat,  
129 1996) but recent structural studies, especially within calc-alkaline plutons and gneiss domes,  
130 showed that they were formed during a single, protracted period of deformation, under dextral  
131 transpressional regime (Bouchez and Gleizes, 1995; Gleizes et al., 1998; Mezger and Passchier,  
132 2003; Aurejac et al., 2004; Vilà et al., 2007; Denèle et al., 2007; 2008; 2009; Mezger, 2009;

133 Cochelin et al., 2017 among others). In spite of the N-S convergent context, HT-rock of the mid-  
134 lower crust were exhumed in gneiss domes (Mezger and Passchier, 2003; Vilà et al., 2007;  
135 Aguilar et al., 2015). This has been favored by strain localization near the biotite-andalusite  
136 transition, forming retrogressive extensional shear zones (Van den Eeckout, 1986; Van den  
137 Eeckout and Zwart, 1988; Mezger and Paschier, 2003; Cochelin et al., 2017) while the core of the  
138 domes was affected by horizontal longitudinal flow (Denèle et al., 2007; 2009; Mezger, 2009;  
139 Cochelin et al., 2017).

140 Figure 2 here

141 The transition between the thickening upper crust and the laterally flowing lower crust is well  
142 exposed in the Central and Eastern Pyrenees by the succession of ~EW trending regional scale  
143 synforms and gneiss domes (e.g. the Villefranche syncline and the Canigou gneiss dome, see  
144 Figs. 1c & 2). The Canigou gneiss dome is characterized by a pervasive foliation reworking  
145 Ordovician plutons turned into orthogneisses and their country-rocks (Fig. 2, Casas et al., 2010;  
146 Martinez et al., 2011). Stretching lineations are mainly NE trending in the core of the dome and  
147 are associated with dominant top-to-the SW shearing (Guitard, 1960; Soliva et al., 1989; Carreras  
148 and Debat, 1996; Cochelin et al., 2017). This massif was lately cut by post-Paleozoic faults like  
149 the Alpine Canigou Thrust and the Neogene Têt-Cerdagne and Py-Fillols faults (Fig. 2).  
150 Immediately to the north west of the Canigou gneiss dome crops the Mt-Louis pluton, which was  
151 emplaced at ca. 301-303 Ma (Figs. 1a & 2) (Denèle et al., 2014). It shows a complex internal  
152 structure and can be divided into three subintrusions (Bouchez and Gleizes, 1995) and, like most  
153 plutons in the Axial Zone, this pluton was deformed under sub-magmatic to solid-state conditions  
154 (Bouchez and Gleizes, 1995; Debon et al., 1996, Denèle et al., 2014). The Canigou and Mt-Louis  
155 massifs can be regarded as demonstrative examples of gneiss dome and pluton of the Axial Zone,

156 respectively. Focus analyses of local scale strainfields are made on these massifs in the present  
157 study.

### 158 **3. Methodology and data set**

159 The computation of cleavage trajectory maps results from an interpolation process of the striking  
160 value between individual structural measurements. This technique allows imaging the continuous  
161 spatial variations of the finite strain field that can be deduced from discrete natural observations.  
162 Thereby, some difficulties may arise when measurements (i) are heterogeneously distributed  
163 through the area and/or (ii) display significant local-scale variations in orientation. In particular, it  
164 is often not straightforward when one has to *a priori* choose whether to highlight local tendencies  
165 or regional ones through a hand drawing process, using curvy or smooth trajectories shape,  
166 respectively. Here, we employ a geostatistical approach to automatically map both cleavage and  
167 lineation trajectories and cleavage dip angle variations from a given field structural dataset.  
168 Ideally, interpolations should be made from foliation-lineation pairs in order to integrate the full  
169 information of the finite strain ellipsoid's orientation (see the critical review of Davis and Titus,  
170 2017). However, such approach requires a very homogeneous dataset in which each lineation  
171 trend/plunge measurement can be associated to a foliation strike/dip one and vice versa. In the  
172 case of regional-scale studies (as the one exposed here), structural data are often compiled from  
173 various types and ages (e.g. digitized maps from PhD theses, articles), and such a prerequisite is  
174 unfortunately hardly tenable. Alternatively, structural data sets can be decomposed into four one-  
175 dimensional numbers (i.e. strike, dip, trend and plunge) and analyzed separately. While dip value  
176 is interpolated using simple kriging on a scalar variable (for a 0-90° range in that case), kriging  
177 interpolation of the strike value (which is of circular data type) is performed following the  
178 approach developed by Gumiaux et al. (2003). Based on a theoretical and unscaled case study

179 (see Figs 3 & 4), details of the different steps of our approach developed are given below (3.1)  
180 and, in particular, some keys for the pre-interpolation variogram analysis (3.2). This synthetic  
181 cleavage and stretching lineation dataset simulates interactions between a roughly E-W regional  
182 trending structure and termination of an elliptical body, to the west, which may correspond to an  
183 intrusion. It results in a triple point as visible in the center of the map (Fig. 3.1).

### 184 *3.1. Computation of automatic trajectory maps*

185 The computation process has been developed in a GIS environment and all the structural  
186 measurements are firstly compiled into a spatial database (37 cleavage orientation measurements  
187 in the synthetic case study, with 20 stretching lineations; Fig. 3.1). Secondly, spatial variations of  
188 the dataset values can be quantified by the computation of experimental variograms (Figs 3.2 &  
189 4.2) (Matheron, 1962). Initially developed for mining purposes and applied to scalar values  
190 (Matheron, 1962), this method has been adapted by Gumiaux et al. (2003) for the analysis of  
191 circular angular variables such as structural striking data. The goal is to assess the degree of  
192 correlation between values of the studied variable (e.g. azimuth or dip of cleavage data) measured  
193 at different locations and according to the interdistance separating them. If this correlation degree  
194 changes with increasing interdistance, the variable is thus categorized as regionalized. The  
195 variogram analysis allows (i) quantifying the maximum distance to which distant data values  
196 show significant mutual dependence, (ii) constraining their dependence function to the distance,  
197 (iii) deciphering any potential anisotropy in the spatial variations of the regionalized variable and  
198 (iv) given the scale of the study area, filtering “regional” and “local” variation trends from the  
199 dataset (see details in the next section). In a third stage, kriging interpolation can be achieved on  
200 both the dip values and azimuth directions following the method developed by Gumiaux et al.  
201 (2003) for circular data. Kriging weights are computed based on a given theoretical variogram

202 model whose equation has been adjusted – for each data set – to the parameters deduced from the  
203 detailed variogram analysis (parameters include the function type, the *range* value, the  
204 proportional *nugget effect* and *sill* values; see part 3.2 below). In the example, interpolations  
205 allow obtaining cleavage direction map, cleavage dip map (Fig. 3.3) or lineation trend maps (Fig.  
206 4.3), as continuous grids covering the overall study area, and where corresponding data is  
207 available. During the two-fold computation/interpolation of the directional map, the local  
208 direction variance can be estimated using the parameter R, which reflects the degree of dispersion  
209 of data (Upton and Fingleton, 1989). In [0,1], low R values reflect high variation in measured  
210 direction values for short distances, whereas a R of a theoretical maximum value of 1 reflects  
211 strictly parallel cleavage directions in the neighborhood (see Gumiaux et al., 2003 and Figs 3.3c  
212 & 4.3b). In the example, low R values computed from the cleavage data point to significant  
213 directional variations induced by the eastern termination of the elliptical body and its associated  
214 cleavage triple point (forming a singular point; see Fig. 3.3c). In contrast, the trend of stretching  
215 lineations shows only minor variations for short distances with R values above 0.5 for most of the  
216 study area (Fig. 4.3b). Trajectories are then computed, giving a good picture of variation of  
217 cleavage directions at the scale of the studied area and reproducing at high resolution cleavage  
218 singular points (including neutral or triple points), both within and outside the simulated  
219 intrusion, and small scale variations within the elliptical geological body (Fig. 3.4). Besides, the  
220 continuous and radial distribution of stretching lineations, as implied by dataset in Figure 3.1, is  
221 also well-modeled and imaged following this fully automatic process (Fig. 4.4). In order to better  
222 constrain the strain field geometry, trajectory maps can be superposed over the interpolated dip  
223 angle map. In the example case study, shallow dipping cleavage areas correspond to the elliptical  
224 shape structure to the west and to more scattered cleavage direction zones, as highlighted by  
225 rather high R values (compare maps in Figs. 3.4 & 4.4). Note that the low R values obtained in

226 low dip domains may be overlooked compared to those from steep cleavage domains as this  
227 analysis of cleavage direction was performed in 2D (i.e. map view). Indeed, strike value of sub-  
228 horizontal fabrics (i.e.  $< 20^\circ$ ) may significantly vary in response to local orientation  
229 perturbations.

230 Figure 3 here

231 Figure 4 here

### 232 3.2. Variogram analysis

233 As a general principle, two close data measurements may have more similar values than two  
234 distant ones. Yet, superimposed phenomenon at different scales can control variations in the  
235 regionalized variable. For instance, cleavage orientation can result from the combination of (i) a  
236 tectonic regional-scale maximum shortening direction, (ii) influence of the expansion of a  
237 neighboring synkinematic intrusion (medium-scale) and (iii) very local cleavage refraction due to  
238 lithological contrast in the rock unit considered. Thus, in order to determine and evaluate the  
239 mutual dependence between data values, experimental variograms are calculated as a squared  
240 root difference between individual angle values as a function of their separating distance (Figs.  
241 3.2 & 4.2); increasing values with distance show decreasing correlation between data values with  
242 a rate depending on the steepness. Thus, the shape of the resulting experimental variogram plot  
243 gives key information on the spatial structure of the strain field. This is estimated by fitting a  
244 theoretical function to the experimental variogram (see continuous grey curves in Figs. 3.2 and  
245 4.2) and extracting several parameter values from the latter, as detailed below (see Matheron,  
246 1962 for details). Acceptable functions include spherical, exponential or Gaussian.

- 247 - An increasing variogram can reach a constant *sill* value for a maximum correlation *range*  
248 distance value (Fig. 3.2 left) and is then defined as *stationary*. This shows that the  
249 kinematical and/or rheological phenomena controlling the spatial strain variations have a  
250 distance of influence shorter than the maximum width of the study area. In the synthetic  
251 example, the *stationary* cleavage directions variogram highlights deformation process  
252 with effects over 9 to 10 distance units (Fig. 3.2 left). This feature is also consistent with  
253 the computed trajectory map which displays the overall structure of the junction area (Fig.  
254 3.4). On the contrary, the *non-stationary* variograms computed for the lineation directions  
255 or cleavage dip angle show that the phenomenon driving strain orientation's variations  
256 has some influence out of scale of the study area (i.e. *range* is not reached, Figs. 3.2 right  
257 & 4.2),
- 258 - Adjustment and analysis of the trend of the variogram for shorter distances is of primary  
259 importance and in particular its initial slope characterizing the type of influence linked to  
260 the phenomenon. Exponential function (Fig. 3.2 left), for instance, displays a notably  
261 quick increase from its original. This corresponds to continuous spatial variations in the  
262 strain direction but with a rather limited size (or rapid decrease) of influence. In the  
263 synthetic example, such feature is attested to by the narrowness of triple junction's zones  
264 and rather high curvature of the trajectories there (Fig. 3.4). In contrast, the Gaussian  
265 theoretical variogram function displays a nearly null slope from its origin (Fig. 4.2)  
266 showing a very slow decrease of influence of the phenomenon in space. This is expressed  
267 in the strain field by low curvature and very smooth variations in the trajectories pattern  
268 (Fig. 4.4).
- 269 - Finally, a non-null ordinate value at the origin of the variogram – the *nugget-effect* –  
270 reflects some variations in the strain field that cannot be considered regarding the given

271 density of the data points. This includes a proportion of either background noise in the  
272 dataset (i.e. different kinds of uncertainties or errors made during the acquisition process),  
273 very local rheological effects (such as cleavage refraction in layered rocks for instance)  
274 that can be regarded as insignificant at the scale of the strain field considered, or both. In  
275 the synthetic case study presented here, the variogram computed for stretching lineations  
276 direction measurements displays a null *nugget effect* (original variogram  $\Gamma$  is zero, Fig.  
277 4.2). This corresponds to an idealistic situation where neither measurement error nor very  
278 local deviation effects exist in the dataset and 100% of the cleavage direction variations  
279 can be modeled in the trajectories map computation. For natural case studies, a significant  
280 proportion of the variance may be included in the *nugget* and, thus, not modeled.

281 In order to detect potential anisotropy in strainfield variations, *directional* individual variograms  
282 can be calculated by selecting data pairs along predefined space direction classes. This technique  
283 is particularly efficient (i) to quantify the *range* of significant variations of values in the  
284 investigated directions and (ii) to highlight main structural anisotropies such as folds or sigmoidal  
285 trends induced by regional shearing (Gumiaux et al., 2003, 2004, Branquet et al., 2012).

### 286 3.3. Data set

287 All the structural data available to date in the Axial Zone of the Pyrenees (Cochelin et al., 2017)  
288 have been treated. This extensive structural compilation (see supplementary materials) comprises  
289 14 275 cleavage and foliation plane measurements, including 12 665 with dip information and  
290 only 1 623 mineral-stretching lineations. At first, analysis and interpolation of structures'  
291 orientation is performed for the entire dataset over the Axial Zone. Then, in order to deconvolute  
292 the finite strain field, three distinct structural sub-sets have been selected based on the type of  
293 geological units in which structural measurements have been made: (i) a first set for the upper

294 crustal metasedimentary rocks called hereafter ‘upper crust’ comprising 5 366 cleavage planes  
295 and 272 stretching lineation measurements, (ii) a second set for the plutons comprising 3610  
296 foliation planes (with a zoom on the Mt Louis pluton) and (iii) a third set for mid-lower crustal  
297 rocks called hereafter ‘mid-lower crust’ including 5 299 foliation planes and 1 351 mineral-  
298 stretching lineation measurements (with a zoom on the Canigou gneiss dome). Spatial selection  
299 have been made using digitalized outlines of the corresponding units in the maps.  
300 Cleavage/foliation data points are spatially duly distributed over the Axial Zone (see  
301 supplementary materials) and the strikes show a normal distribution centered on  $N96.5^{\circ}E$  and a  
302 skewness factor of about 0 (nonparametric skew used here; Fig. 5a). Cleavage strikes from the  
303 mid-lower crust follow a very similar normal distribution (Fig. 5b) with a mean value at  $N94.6^{\circ}E$ .  
304 In contrast, the directional data from the upper crust are skewed to the left and show a mean value  
305 of  $N102^{\circ}E$  (Fig. 5c). For the whole Axial Zone, the dip values of cleavage/foliation data show a  
306 mean value of  $51^{\circ}$  and a skewness around 0 (Fig. 5d). In the middle crust, dip values also show a  
307 skewness about 0 with a mean value of  $47^{\circ}$  (Fig. 5e) while data in the upper crust are skewed to  
308 the steep values and show a mean value of  $51^{\circ}$  (Fig. 5f). In the whole data set, flat-lying  
309 foliations (i.e.  $< 20^{\circ}$ ) represent less than 7% of the measurements. Therefore, their relative impact  
310 on interpolations of strike values can be considered as negligible in the present case study.  
311 Stretching lineations have principally been measured in gneiss domes. Considering their data  
312 points’ spatial distribution, geostatistics were applied to mid-lower crust and solely statistics for  
313 upper crust data.

314 Figure 5 here

## 315 4. Results

### 316 4.1. Axial Zone strain field

317 The omni-directional variogram for the Axial Zone dataset displays a sill reached for a 10km  
318 general range value (grey dots/black curve, Fig. 6a). An abrupt change in slope at 1.8km indicates  
319 a second, intermediate range, which indicates the change to a different structuration, from local to  
320 more regional scale phenomenon effects. As a whole, this variogram can be modeled with (i) a  
321 nested (or imbricated) structure of two spherical functions of distinct range values and (ii) a  
322 global sill of 1095 square degrees and a nugget-effect value of 503 square degrees (corresponding  
323 to 46% of the total variance for this dataset).

324 The omni-directional variogram obtained for dip measurements over the Axial Zone shows an  
325 exponential trend, reaching a sill of about 480 square degrees at a 21 km range and showing 60%  
326 of proportional nugget effect (grey dots/black curve, Fig. 6b). This later suggests, on average, a  
327 significant variability of the dip values measured over short distances (i.e. distances shorter than  
328 1 km).

329 Figure 6 here

330 Based on the variograms (Fig. 6a), interpolation of cleavage trajectories at the scale of the whole  
331 Axial Zone was performed using a 10km range. In this case, the interpolated trajectories display  
332 an average N100°E parallel trend over most of the Axial Zone and rotates to an average of  
333 N130°E in eastern part of the Axial Zone (Fig. 7a). Based on the R parameter map (Fig. 7b),  
334 domains belonging to the upper crust show limited cleavage strike dispersions (with R values  
335 above 0.5). This is also shown by the regular trend of the trajectory map in the upper-crust  
336 domains and especially in a ~30km wide N-S corridor displaying sub-parallel trajectories in  
337 Central Pyrenees (Fig. 7b). This corridor is devoid of plutons (see Figs. 1b & 7a), suggesting a  
338 role of such intrusions in local- to intermediate-scale variations of the upper crust strainfield.

339 Figure 7 here

340 Interpolation of cleavage dip values for the whole Axial Zone dataset (Fig. 8a) displays a clear N-  
341 S segmentation, with steep cleavage in a northern domain and shallowly dipping cleavage in a  
342 southern domain. This N-S fanning of cleavage dip is well expressed, especially in the ~N-S  
343 corridor of sub-parallel trajectories referred to above (Fig. 7b). This variation corresponds to the  
344 fan of cleavage that had been early noticed by Zwart (1979) in this region. Calculation of the  
345 gradients between interpolated dip values (Carrara et al., 1991) allows identifying zones or bands  
346 with rough variations of dip, and, in another hand, undisturbed domains such as in the upper crust  
347 level (Fig. 8b; note in particular the delineation of the ~NS corridor in the central part).

348 At second order, the strain field appears rather heterogeneous. Gneiss domes and plutons are very  
349 well individualized and evidenced by circular to concentric trajectories (Fig. 7a). Heterogeneity is  
350 also highlighted by converging and tightening of the trajectories underlining at least 5  
351 longitudinal 100 to 150 km long shear zones. They mostly trend ~N100°E and locally N130°E,  
352 where they wrap around gneiss domes and plutons. Trajectories that converge in N100°E  
353 trending bands show rather symmetrical pattern with both clockwise and counterclockwise  
354 rotations on both sides of these bands. In contrast, N130°E trending bands induce convergence  
355 and bending of trajectories as smooth sigmoids. Such sigmoidal patterns (i.e. asymmetrical) for  
356 trajectories are compatible with dextral shearing (Fig. 7a) (Ramsay and Graham, 1970). These  
357 sigmoidal patterns form locally asymmetrical singular points (neutral or triple points) at western  
358 and eastern tips of elliptical bodies (e.g. around the Néouvielle pluton), which is also compatible  
359 with dextral shearing. Otherwise, cleavage singular points at eastern and western terminations of  
360 the domes and plutons appear mainly symmetrical in respect of the elongation axe of these domes  
361 and plutons.

362 Figure 8 here

363 Thus, the upper-crustal cleavage appears disturbed only around granitic plutons with particularly  
364 low R values coinciding with (i) cleavage singular points and (ii) some known composite plutons  
365 showing internal imbricated magmatic structures (e.g. Causerets plutons, Fig. 7b). In the eastern  
366 part of the Axial Zone, high dispersion zones (i.e. with low R values) surround the gneiss domes.  
367 Some folded gneiss domes display internal dispersion too (e.g. the Aston gneiss dome, see  
368 Denèle et al. 2009). Discrete dispersion bands, sometimes oblique to the cleavage trajectories, are  
369 also mapped within gneiss domes, like in the Canigou (Fig. 7b). This kind of dispersion could be  
370 related to post-Variscan faulting (see section 4.4).

371 The impact of gneiss domes and plutons on the regional strainfield is also well shown by  
372 cleavage dip variations (Fig. 8b) outlining concentric shapes and reflecting short-length gradients  
373 between the cores and envelopes of these bodies (e.g. the Causerets plutons). Other short-  
374 wavelength variations that are not directly related to domes or plutons display highly to slightly  
375 oblique trends to trajectories. For instance, N60° to N80°E trending bands are detected south of  
376 the Canigou gneiss dome. This reflects late tilting of the cleavage along Neogene normal faults as  
377 well as Alpine thrusts (Fig. 8b). The relative scarcity of such perturbations shows that the  
378 Variscan structures are only weakly affected by post-Paleozoic deformation phases within the  
379 Axial Zone (see Cochelin et al. 2017, 2018).

380 As a whole, the overall strain field looks homogenous on a regional-scale and locally disturbed  
381 by the presence of gneiss domes and plutons, forming areas with curved cleavage trajectories and  
382 lower dip values (e.g. in eastern Axial Zone).

383 *4.2. Upper crust*

384 The omni-directional variogram computed for the upper crust dataset (blue dots/curve, Fig. 6a)  
385 shows an exponential trend with a significantly lower variance (849 square degrees) than that of  
386 the entire data set, but a similar nugget effect proportion (47%). The best-fitted theoretical  
387 variogram suggests an intermediate range at ca. 5 km. The four directional-variograms display a  
388 same trend than the omni-directional one (compare Figs. 6a & 9a, b) with similar range (5km),  
389 sill (810 square degrees) and proportional nugget effect (between 47 and 53%) values. The NE-  
390 SW (i.e. from  $N22.5^\circ$  to  $N67.5^\circ E$ ) trending directional-variogram differs from the others, with a  
391 sinusoidal trend of periodicity around 18 km. This illustrates systematic regional scale  
392 undulations of directional data, along the NE-SW direction (i.e. forming perpendicular ~NW-SE  
393 striking bands like).

394 Figure 9 here

395 Considering cleavage dip values in the upper crust, the omni-directional variogram is similar to  
396 that of the entire Axial Zone dataset but tends to show a greater instability (blue dots/curve, Fig.  
397 6b). Directional-variograms are calculated from dip measurements parallel and perpendicular to  
398 the average cleavage strike (i.e.  $\sim N100^\circ E$ , Fig. 9c). The “parallel”  $N100^\circ E$  directional-variogram  
399 has an exponential trend with a 5km range (much shorter than for the omni-directional  
400 variogram) and a proportional nugget effect around 52%. In contrast, the “perpendicular”  $N10^\circ E$   
401 oriented directional variogram (Fig. 9d) displays an exponential trend but is non-stationary (it  
402 does not reach a sill up to the maximum possible 40 km computational distance). The latter  
403 depends on the N-S width of the Axial Zone and on the critical number of data pairs available for  
404 calculation, which dramatically decreases beyond 40km and makes the variogram unstable (Fig.  
405 9d). These two directional-variogram show that cleavage dip value does not have regional-scale  
406 variations along strike in the upper crust, whereas such variations are evidenced in the N-S

407 direction, perpendicularly to the fabric. Following the exponential best fit function on the 40 first  
408 kilometers, the range of the N-S directed variogram and the characteristic distance of influence of  
409 the corresponding phenomenon could be reached around 80-100km. This variation can be related  
410 to the regional N-S fan of schistosity (section 4.1).

411 Interpolations of cleavage directions have been performed up to 20 km interdistance, which  
412 corresponds to the largest range revealed by the variogram analysis of the upper-crust (i.e. in  
413 directional variogram, Fig. 9a). Regional trajectories computed from the sole upper crust are  
414 roughly parallel. They display an overall arc shape (Fig. 10a) from N110°E trends in the western  
415 part of the Axial Zone, longitudinal trends in the central Axial Zone to N130-140°E trends in the  
416 easternmost Axial Zone, which is quite similar to trajectories obtained in Fig. 7a. At second  
417 order, E-W elongated lens patterns can be deciphered in the Eastern Axial Zone. In the western  
418 Axial Zone, trajectories are weakly disturbed and only display a few variations over short (<10  
419 km) wavelength undulations. The convergence of N110°E trending trajectories in the median part  
420 of the Axial Zone (e.g. between Ct and Nv) and disappearing to the east is the only apparent  
421 regional strain gradient revealed by the interpolation (Fig. 10a). Indeed, the rather consistent  
422 spacing of the trajectories indicates a more homogeneous strain pattern than obtained using the  
423 entire data set (Fig. 7a). Similarly as on the first trajectory map, singular points are symmetrically  
424 displayed at western and eastern tips of the 10 to 20 km elliptical bodies and aligned along the  
425 cleavage mean trend (Fig. 10a). The only asymmetrical converging pattern (i.e. sigmoidal) of  
426 trajectories are located, from west to east, around the Chiroulet-Lesponne domes (CL), the  
427 Néouvielle plutons (Nv) and the eastern part of the Canigou dome (Ca) (Fig. 10a). These  
428 sigmoidal trajectories again suggest dextral shearing within shear bands.

429 Figure 10 here

430 The interpolation of cleavage dip values for the upper crust data set upholds a NS segmentation  
431 over the Axial Zone (Fig. 10b) with a northern part showing steep to vertical cleavage and a  
432 southern one where the cleavage is progressively tilted southward to reach moderate to low  
433 northward dips. In the Eastern Axial Zone, this segmentation of cleavage dip is still visible but is  
434 disturbed by the influence of gneiss domes and plutons (compare Figs. 1a & 10b). In central and  
435 western Axial Zone, the influence of Bossost and Chiroulet-Lesponne domes is also documented  
436 by two “anomalies” of shallowly-dipping cleavage inside the northern steeply-dipping domain  
437 (Fig. 10b). Even though only the upper crust structural dataset is considered in the present  
438 interpolations, both cleavage trajectories (showing lens shapes map structures) and interpolated  
439 dip map display anomalies surrounding gneiss domes and plutons (compare Figs. 7 & 10).

440 Whatever the cleavage dip, stretching lineations measured in the upper crust are, in most cases,  
441 characterized by high pitch values ( $>60^\circ$  for 61 % of the set). As cleavage is mostly steeply  
442 dipping (Fig. 1b & 10b), lineations often have high plunges. In regional shear zones (Figs. 1 &  
443 7a), lineations are associated with either dip-slip or reverse sense of shear with minor dextral  
444 component (Cochelin et al., 2017, 2018). If plotted in a Dip-Pitch-Plunge ternary diagram (Fig.  
445 11-left; see Chardon et al., 2009), two distinct sub-populations are identified. Most of the dataset  
446 shows a trend from the vertical flow to the horizontal flow pole, which reflects a decrease of  
447 foliation dip with nearly constant high pitch values. The remaining part of the data is closer to the  
448 Orogen-parallel “strike-slip” flow pole, reflecting lower pitches on steep planar fabrics (Fig. 11-  
449 left). At very first order, the upper-crust is thus characterized by (orogen-normal) horizontal  
450 shortening and (sub-) vertical stretching. In more details, variations from the vertical to the  
451 horizontal flow poles can be related to (i) the regional-scale N-S segmentation of the upper-crust  
452 strain in two main cleavage dip domains (Fig. 10b) or (ii) the shallowing of upper crust cleavage

453 around the domes (e.g. the Bossost dome and the Canigou dome, Fig. 10b). Furthermore, at a  
454 third order, the dispersion of the data between the vertical flow pole and the orogen parallel  
455 “strike-slip” flow pole (left axis of the triangle plot) reflects strain partitioning within strike-slip  
456 dominated transcurrent shear zones. In the Axial Zone, these shear zones – mainly N120-130°E  
457 trending – show dextral-reverse kinematics and are flanking gneiss domes and plutons (Cochelin  
458 et al., 2017; e.g. the Mérens and Têt shear zones; Fig. 7a).

459 Figure 11 here

#### 460 *4.3. Upper crustal plutons: focus on the Mt Louis massif*

461 The omni-directional variogram computed from the fabric direction measurements in the Mt  
462 Louis pluton (extracted from Anisotropy of Magnetic Susceptibility - AMS - foliation orientation  
463 extracted for each station of Bouchez and Gleizes, 1995) is stationary (Fig. 12a): it reaches a  
464 1142 square degrees sill at 3.4 km range and includes 54% of proportional nugget effect. The  
465 global cleavage direction variance for this pluton (corresponding to the sill) and its variability at  
466 very short distances (the nugget) are similar to those obtained for the global omni-directional  
467 variogram computed for the entire Axial Zone (Fig. 6a). This suggests that this massif – and  
468 certainly plutons in general – are of prime importance in the structuration of the strainfield. Yet,  
469 the Mt Louis experimental variogram displays a distinct range value and follows a Gaussian trend  
470 (with flat behavior close to the original) corresponding to particularly smooth tendency variations  
471 of the cleavage directions at the scale of the pluton. The regional interpolation (Figs. 7a & 12b)  
472 over the Mt Louis pluton and its wall rocks is characterized by longitudinal trajectories on the  
473 central-western part of the pluton with large and smooth undulations, whereas the concentric  
474 trajectories inside the pluton is only and roughly evidenced in its eastern part. As expected, the  
475 resulting interpolated trajectories at local-scale are more sensitive to local variations than those

476 obtained with larger range parameters (compare Fig. 12b & c). The sub-massifs are well  
477 individualized by concentric trajectories patterns, as exemplified in its western and eastern parts.  
478 These concentric patterns are in agreement with the trajectories obtained manually by Bouchez  
479 and Gleizes (1995) (Fig. 12d). Furthermore, our interpolations looks delineating three NW-SE  
480 bands showing asymmetrical converging trajectories (s-shape sigmoidal structures) coinciding  
481 with dextral shear zones inferred by Bouchez and Gleizes (1995) (Fig. 12d). Even though  
482 interpolated sigmoids are compatible with apparent dextral shearing (Fig. 12c), trajectories  
483 display very smooth variations and non-localized/pervasive shearing.

484 Figure 12 here

#### 485 *4.4. The lower crust and focus on the Canigou dome*

486 The omni-directional variogram of the mid-lower crust exposed in the domes displays, as a  
487 whole, a slightly higher variance (i.e. average sill) and higher proportional nugget effect values  
488 (50%) than for the entire Axial Zone dataset (orange dots/red curve Fig. 6a). It shows a nested  
489 structure with (i) an exponential evolution up to 6-7 km and, beyond, (ii) a sinus trend of 15-20  
490 km periodicity around the average sill (Fig. 6a). Such a rhythmic variogram can be related to the  
491 peculiar spatial distribution of measurements, which form evenly spaced clusters centered on the  
492 gneiss domes. The periodicity may thus simply reflect the average size of these domes, which is  
493 known as a hole-effect.

494 Focusing on the Canigou dome, the local-scale omni-directional variogram computed for  
495 cleavage striking data is stationary. It displays a lower maximum range (5 km) and a lower  
496 proportional nugget value (~38%) than the regional-scale one (compare Figs. 6a & 13a). This  
497 indicates less variable cleavage orientations and thus a more consistent strain field when focusing

498 on the lower-crust. The variogram follows an exponential trend corresponding to a rapid  
499 decreasing effect of the phenomena with distance. The interpolated foliation trajectories reveal  
500 two half domes (Fig. 13b), with E-W hinges. Considering the R parameter (Fig. 13c), the contact  
501 zone between the two sub-domes coincides with a N50°E to N80°E trending band of highly  
502 dispersed cleavage directions. The high-R band actually coincides with the Neogene Py-Fillols  
503 normal faults, which cross-cuts the gneiss dome. Besides, the low-R domain at the south-eastern  
504 boundary of the dome also appears to be related to post-Variscan faults and reflects the local  
505 impact of the South Canigou Alpine thrust (Fig. 2) as suspected from the regional-scale map (Fig.  
506 7b).

507 Figure 13 here

508 The stretching lineations measured within (Fig. 14a) the Canigou dome display only limited  
509 variations in direction. The omni-directional variogram (Fig. 14b) is characterized by a high  
510 ~57% proportional nugget effect and is defined by a sinusoidal trend. The interpolated  
511 trajectories of stretching lineations exhibit an overall NE-SW trend (in red, Fig. 14c), with a very  
512 smooth pattern. In contrast to the cleavage measurements, lineations do not show disturbance that  
513 could be related to post-Variscan faulting. Indeed, the Py-Fillols faults are sub-parallel to the  
514 lineation trajectories and the latter thus look poorly affected by late brittle deformation. First  
515 order stretching trajectories are oblique on the hinge of the dome (compare Figs. 13b & 14c). In  
516 greater details, trajectories display a systematic and progressive curvature, stretching becoming  
517 progressively more transverse along the dome's limbs than in its core. This defines a map radial  
518 trend from NE-SW in the lowermost structural levels of the dome to a NNE-SSW direction in the  
519 southern limb and up to NW-SE trend in its north-western part. This latter trend is not well  
520 expressed because the northern flank of the dome is actually truncated by the Neogene Têt-

521 Cerdagne fault (Fig. 2). As a whole, interpolated cleavage and lineation trajectories within the  
522 Canigou massif thus look particularly smooth and continuous; cleavage is only disturbed by  
523 significant but quite local effect of recent faulting.

524 Figure 14 here

525 Considering the overall Axial Zone, the average stretching direction is c.a. N98°E in the mid-  
526 lower crust (Fig. 15a) and, in a Dip-Pitch-Plunge diagram, data are clustered close to the orogen-  
527 parallel horizontal flow pole (Fig. 11-right). Dispersion of lineations towards the orogen-parallel  
528 “strike-slip” flow pole (Fig. 11-right) must be due to the late amplification of gneiss dome by  
529 folding, producing steep to overturned southern limbs in some cases (see Denèle et al., 2007,  
530 2009, Vilà et al., 2007, Cochelin et al., 2017). In greater details, stretching lineations display two  
531 distinct direction families with regard to the gneiss domes’ cartographic long axes. Longitudinal  
532 to slightly oblique stretching/flow is dominant, representing ca. 90% of the measurements within  
533 the domes (see the above described focus on the Canigou). Transverse stretching directions (i.e.  
534 NS trends) are restricted to the domes’ envelope and represent only 10% of the exposed middle  
535 crust (Figs. 15a & 15b). In details, oblique WNW-ESE to NW-SE trends are documented in the  
536 core of all gneiss domes from the northern and western parts of the Axial Zone (i.e. Aston, Lys-  
537 Caillaouas, Bossost, Chiroulet and Lesponne domes) and from the Albères massif to the East  
538 (Fig. 15b). Purely longitudinal stretching is restricted to the Hospitalet dome while the Canigou  
539 shows a specific ENE-WSW trend (Figs 15b). Transverse stretching directions are observed in  
540 the envelope of the Chiroulet, Aston and Canigou domes and can be noticed in the Bossost dome  
541 (Fig. 15b). In the Chiroulet and Aston, the transition between longitudinal and transverse  
542 direction of stretching is abrupt, whereas it appears to be more gradual from the core to the limbs  
543 of the Canigou, Hospitalet and the Bossost domes (Fig. 15b). We consider the direction of

544 stretching in the core of gneiss domes as representative of the deep flow within the crust while  
545 direction of stretching in domes' envelope is related to their exhumation (Cochelin et al., 2017).

## 546 **5. Discussion**

### 547 *5.1. Strain partitioning and crustal flow in the Variscan crust of the Pyrenees*

548 The variogram calculated for the upper crust is stationary and shows the minimum of all the  
549 global variances (i.e. *sill* values) calculated in this study (compare variograms in Fig. 6). Such  
550 features reflect an overall steady strain direction throughout this domain, which bears the regional  
551 structural grain (Fig. 7a). Regional-scale interpolated cleavage trajectories for the upper crust are  
552 longitudinal and roughly collinear (Fig. 10a), which is typical of homogeneous deformation  
553 (Choukroune et al., 1995). Such cleavage trajectories pattern coupled with a dominant steep  
554 stretching (Fig. 11-left) is compatible with a bulk pure shear dominated deformation regime  
555 (Tikoff and Greene, 1997; Teyssier and Tikoff, 1999) with ~N-S horizontal shortening and  
556 subvertical principal stretch (Cochelin et al., 2017, 2018).

557 The partially molten mid-lower crust is observed in domes (Fig. 1a). The interpolated foliation  
558 trajectories, both at regional and local scales (see Figs. 7a & 13b), display circular to concentric  
559 trajectories within and around the domes. At regional scale, the ca. 15-20 km periodicity in the  
560 cleavage striking variations observed in the experimental variogram (Fig. 6a) shows that the  
561 domes display almost constant widths and could represent the periodical average map  
562 interdistance between them. We infer that this is related to a mechanical instability effect in the  
563 Variscan crust during original doming and exhumation of mid-lower crust. Smooth cleavage and  
564 lineation trajectories within gneiss domes (e.g. the Canigou massif) point to a rather  
565 homogeneous strainfield in the mid-lower crust with mainly longitudinal to slightly oblique  
566 stretching (Fig. 15) within domes' core.

567 Figure 15 here

568 In order to study the transitions from the upper crust to the mid-lower crust strains, one must  
569 consider the overall cleavage measurements dataset. At first glance, the nested structure of the  
570 regional-scale experimental variogram (Fig. 6a, grey dots/black curve) suggests that the Axial  
571 Zone includes distinct strainfields. Indeed, when considered separately, the cleavage  
572 measurements from the upper- and the mid-lower crust give two different variograms with  
573 distinct trends and parameters (Fig. 6a). Yet, if the two strain fields evidenced would display  
574 directions cross-cutting relationships (in particular within the contact/transition zones), the  
575 variogram computed for the overall data (in black, Fig. 6a) would display a significantly higher  
576 *nugget* value than the two others taken individually; which is not the case here. Besides, cleavage  
577 of the upper-crust has very steady orientations (i.e. both in strike and dip) and a dominant  
578 longitudinal collinear trend across the overall Axial Zone but some “disturbances” are linked to  
579 the gneiss domes. Thus, the finite strain orientation of upper-crust is dependent on the mid-lower  
580 crust fabric orientation when approaching domes’ envelops, suggesting coeval deformation.  
581 While shallow parts of the Variscan crust of the Pyrenees was affected by homogeneous  
582 thickening, the mid-lower crust was contemporarily affected by homogeneous longitudinal  
583 stretching (Figs 11 & 15) reflecting lateral horizontal flow, which is also compatible with NS  
584 horizontal shortening. This suggests vertical coupling during deformation (Tikoff et al., 2002).  
585 As proposed by Cochelin et al. (2017), such a vertical strain partitioning is typical of hot and  
586 ultra-hot orogens, where lithosphere has been significantly weakened (Cagnard et al., 2006a,b,  
587 Cruden et al., 2006, Chardon et al., 2009).

588 When considering the overall cleavage direction dataset – including upper-crust, plutons and  
589 gneiss domes – the interpolated trajectory map underline a quite heterogeneous pattern, with

590 strain localization into regional scale, anastomosed longitudinal bands (Fig. 7a). These bands  
591 correspond to dextral-reverse shear zones observed in the field and mapped (e.g. Carreras, 2001;  
592 Cochelin et al., 2017). The localization of these anastomosed shear zones seems to be intimately  
593 linked to the emplacement of gneiss domes and syn-kinematics plutons, as shear zones border  
594 these massifs (Fig. 7a). Domes and plutons must have acted as regional heterogeneities while the  
595 crust was affected by NS horizontal shortening. Therefore, we consider that these regional shear  
596 zones nucleated because of the emplacement of domes and plutons – themselves driven by  
597 mechanical instability during regional-scale shortening. Such an interpretation is further  
598 supported by geochronological and field structural studies arguing that steep shear zones were  
599 activated during and after the emplacement of gneiss domes and plutons (Vilà et al., 2007;  
600 Denèle et al., 2007; 2009; Druguet et al., 2014; Cochelin et al., 2017; Van Lichtenvelde et al.,  
601 2017).

602 At second order, directional-variograms computed for the upper-crust (Fig. 9a) document ~15-  
603 20km periodical undulations of the cleavage directions following a NE-SW spatial direction.  
604 Likewise, the corresponding interpolated trajectories display asymmetrical strain gradients  
605 (sigmoidal undulations) compatible with a dextral component of simple shear along few N120-  
606 140°E trending bands (Fig. 7a), which are characterized by domains of more shallowly plunging  
607 lineations (Fig. 11-left). Nevertheless, these bands appear poorly significant at regional scale as  
608 the trajectories are mostly collinear and symmetrical. Thus, these undulations reflect horizontal  
609 strain partitioning in response to the emplacement of local heterogeneities in a more  
610 homogeneous general strainfield. Therefore, our results show that the dextral shearing  
611 component of deformation has been over- stressed in previous studies because most of them were  
612 focused on syn-kinematic plutons, and had had a minor impact on the strainfield.

613 5.2. *The variogram analysis, a tool to investigate the rheological behavior of the crust*

614 As a preliminary step, the variogram calculation and analysis is critical to detect and quantify  
615 significant variations (including the maximum correlation distance, variance and behavior at  
616 short distances) of the studied *regionalized variable* as well as potential anisotropy. We propose  
617 hereafter that, whatever the scale considered, the best fitted trend of variograms can be used to  
618 characterize the rheological behavior or the tectonic history of the geological object/domain  
619 investigated.

620 Amplitude of the variations in the measured values is evaluated by the *sill* (general variations;  
621 variance) and the *nugget* values in an experimental variogram. On the other hand, whatever those  
622 variations, the behavior to the origin of the variograms allows quantifying the way the variable  
623 varies with distance. In this study, gaussian or sinusoidal variograms have been computed for  
624 structures such as syn-kinematic plutons and gneiss domes. The very low original slope of these  
625 variogram functions points to limited and very progressive variations between structural  
626 orientation measurements, as exemplified by the Mt-Louis pluton and the Canigou gneiss dome  
627 (Figs. 12a & 14b). Indeed, the Mt Louis pluton, displays highly continuous and progressive strain  
628 variations and non-localized simple shear corridors. As shearing of the pluton happened during  
629 its cooling (Bouchez & Gleizes, 1995), we argue that the trend of the corresponding variogram  
630 can be diagnostic of such homogeneous/continuous deformation through time in case of weak  
631 mechanical behavior such as cooling magmas (Fig. 16). Similarly, in the Canigou gneiss dome,  
632 stretching lineations formed during pervasive metamorphism and crustal flow show continuous  
633 and smooth variations in trends, as illustrated by a sinusoidal variogram (Fig. 14b). To us, this  
634 phenomenon may also reflect a continuous ductile deformation at high temperature, which  
635 remains undisturbed during late Variscan folding and post-Paleozoic faulting (Fig. 16).

636 Figure 16 here

637 Exponential or spherical variogram trends – with a significantly high original slope – correspond  
638 to a fast decorrelation between data point values with distance. We thus argue that geological  
639 objects or structural domains characterized by such variogram trends have experienced less  
640 homogeneous deformation or a polyphased tectonic history. Indeed, zooming on the Canigou  
641 dome shows that variations of cleavage directions are mainly disturbed by post-metamorphic  
642 structural discontinuities (i.e. faults). Such discontinuities may induce the modification of an  
643 initially sinusoidal or gaussian variogram trend – as witnessed by the lineations dataset – into a  
644 typically disturbed variogram (i.e. exponential trend), as illustrated in Figure 16. At regional  
645 scale, the cleavage orientations from the whole upper crust (metasediments) reflect interferences  
646 between a regional and consistent trend and the domes and plutons. For upper crust, the  
647 corresponding variogram clearly displays an exponential trend with a quite short *range* distance  
648 (Fig. 16). Domes and plutons can be regarded as geological discontinuities in the upper crust,  
649 explaining the exponential variogram trend for the upper crust dataset (Fig. 16) and the resulting  
650 interpolated trajectories showing local bending and reorientations around them (Fig. 10). Finally,  
651 the spherical trend of the omnidirectional-variogram that characterizes the whole Axial Zone  
652 reflects multi-scale interferences in a homogeneous strainfield recorded through time in the  
653 basement. This variogram corresponds to the imbrication, the convolution of all the variograms  
654 including local to regional variations induced by all the geological and structural objects/domains  
655 that compose the exposed crust (Fig. 16).

## 656 **6. Concluding points**

657 The present study shows that geostatistics is a powerful tool to model continuous strain  
658 trajectories from local ductile structure measurements. This inversion method can be considered

659 as alternative and complementary to forward analog or thermo-mechanical modelling to  
660 investigate strainfields and the interplay of different mechanical controls leading to the  
661 development of finite strain in the crust. In particular, this study shows that the approach  
662 developed allows:

- 663 - Separating (i) significant local to regional variations in strainfields from (ii) variations  
664 that cannot be considered and modeled from structural data. Variogram analysis allows  
665 determining the spatial scale (maximum distance) of influence of the tectonic and/or  
666 rheological controls on strain spatial variations. To the opposite, background noise or very  
667 local variations are integrated to the nugget effect and not modeled in computed  
668 trajectories for instance. At the scale of the Axial Zone of the Pyrenees, such non-  
669 significant variations make ~50% of the total variance of the dataset.
- 670 - Investigating strainfields at different scales, from a same structural dataset. By separating  
671 trends which are significant at a given scale from variations regarded as some noise or too  
672 “local”, different sub-scales can thus be explored within a study area. When zooming on  
673 very local sub-domains, variations initially considered as “noise” in the regional-scale  
674 nugget effect can become significant and be interpreted. In the case of the Pyrenean Axial  
675 Zone, local interpolated map of the Canigou gneiss dome or Mt-Louis pluton display  
676 more detailed trajectories than at regional-scale, where internal variations can be regarded  
677 as irrelevant.
- 678 - Deconvoluting juxtaposed strainfields. Nested structures of experimental variograms  
679 point out combined effects of different imbricated phenomena. The variogram analysis of  
680 data sub-sets, for distinct structural domains, allows quantifying their relative impact on

681 the strainfield, which can be regarded as composed of multiple-signals of specific spatial  
682 range and structural significance.

683 - Revealing contrasted mechanical behaviors of lithological/structural domains. Indeed,  
684 results show that spatial strain gradients of structural domains can be evaluated from the  
685 trend of the corresponding variogram functions. Geostatistical analysis thus allows  
686 distinguishing pervasive vs. localized deformation regimes at a given scale. Besides, the  
687 original variogram trend can also point-out a role of late structures (faults in particular)  
688 forming discontinuities and perturbations in the paleo-strainfield.

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901

902 **Figure captions**

903 Figure 1: a) Sketch map of the Paleozoic crust of the Pyrenees. The plutons and gneiss domes  
904 cited in the text are located. Location of the two cross-sections of Figs. 1b & 1c and Fig. 2 are  
905 also shown. Abbreviation for west to east: Ct: Cauterets pluton, CL: Chiroulet-Lesponne dome,  
906 Nv: Néouvielle pluton, LC: Lys-Caillaouas dome, Bo: Bossost dome, Ma: Maladeta pluton, Ba:  
907 Bassiès pluton, As: Aston gneiss dome, Ho: Hospitalet gneiss dome, ML: Mt Louis pluton, Qt:  
908 Quérigut pluton, Mi: Millas pluton, Ca: Canigou gneiss dome, Ab: Albères gneiss dome. In dark-  
909 grey: main Variscan shear zones; in blue: main Alpine faults; b) Simplified cross-section from  
910 the central Axial Zone, modified from Cochelin et al., 2018; c) simplified cross-section from the  
911 eastern Pyrenees, modified from Cochelin et al., 2017

912 Figure 2: Simplified geological map of the Canigou gneiss dome, modified from Guitard et al.,  
913 (1992) Carreras et al., (2004); Baudin et al., (2008); Donzeau et al., (2010).

914 Figure 3: Summary of the following steps to compute foliation trajectories. See in the text for  
915 further explanation.

916 Figure 4: Summary of the following steps to compute lineation trajectories, using lineation data  
917 set presented in Fig. 3.

918 Figure 5: a) Histogram of cleavage directional data, b) histogram of cleavage directional data in  
919 the upper crust; c) histogram of foliation directional data in the middle crust. The calculated  
920 skewness for each histogram corresponds to the nonparametric skew. Rose diagrams of dip  
921 values of cleavage/foliation planes in the Axial Zone (d), the middle crust (e) and the upper crust  
922 (f).

923 Figure 6: a) Omni-directional variograms computed for schistosity directional data, with the  
924 omni-directional variograms computed for the whole Axial Zone in black, the upper crust in blue

925 and the mid-lower crust in red. Dots represent the experimental variograms and full lines are the  
926 best-fit functions; b) Omni-directional variograms of dip values for the Axial Zone (black) and  
927 the upper crust (blue).

928 Figure 7: a) Cleavage trend trajectories computed from the interpolated cleavage direction in the  
929 whole Axial Zone, taking into account gneiss domes and plutons; b) R map computed from the  
930 interpolated cleavage direction. High dispersion is highlighted by low R values in orange and red.

931 Figure 8: a) Interpolated dip of cleavage in the Axial Zone. Gneiss domes are located in red and  
932 plutons in black. b) Computed slope of dip values in the Axial Zone. Sharp variations are  
933 highlighted by high slopes in red (0.83 to 2.26%) and beige (0.45-0.82%).

934 Figure 9: Directional variograms computed in the upper crust: a) for azimuth of cleavage along  
935 the  $N45^\circ$  direction in the upper crust; b) for azimuth of cleavage along EW, NW-SE and NS  
936 directions in the upper crust. c)  $N100^\circ$  directed variogram computed for dip values in the upper  
937 crust. d)  $N10^\circ$  directed variogram computed for dip values in the upper crust.

938 Figure 10: a) Cleavage trend trajectories computed from the interpolated cleavage direction in the  
939 upper crust; b) Interpolated dip of cleavage in the upper crust. These interpolations were obtained  
940 using nugget effect and ranges deduced from the variogram analysis of the upper crust (Fig.6a).

941 Figure 11: Ternary diagrams (Pitch-Plunge-Dip) illustrating the crustal flow mode in orogens,  
942 after Chardon et al., (2009) for mineral-stretching lineations in the upper crust (left) and the mid-  
943 lower crust (right) of the Variscan Pyrenees. Because the association of foliation and lineation in  
944 each station was not possible for digitalized data, those presented in this figure come from our  
945 own measurement (see Cochelin et al., 2017).

946 Figure 12: a) Omni-directional variogram computed for directional data in the Mt Louis pluton;  
947 b) Zoom on the regional trajectories obtained around the Mt Louis pluton (Fig. 7a); c) Foliation  
948 trajectories obtained using parameters deduced from the omni-directional variogram of the  
949 pluton; d) Foliation trajectories obtained manually by Bouchez and Gleizes (1995) on the basis of  
950 ASM measurement and field observations.

951 Figure 13: Zoom on the Canigou gneiss dome. a) Omni-directional variogram calculated for  
952 foliation planes within the gneiss dome; b) Local foliation trajectories in the Canigou gneiss  
953 dome (in red); Trajectories around the gneiss dome (in grey) are from the regional interpolation  
954 (Fig. 7a). c) Location of high dispersion of directional data in the Canigou gneiss dome  
955 combining of zoom of the R map (Fig. 7b), local trajectories (Fig. 13b) and location of the main  
956 fault zones (Fig. 2).

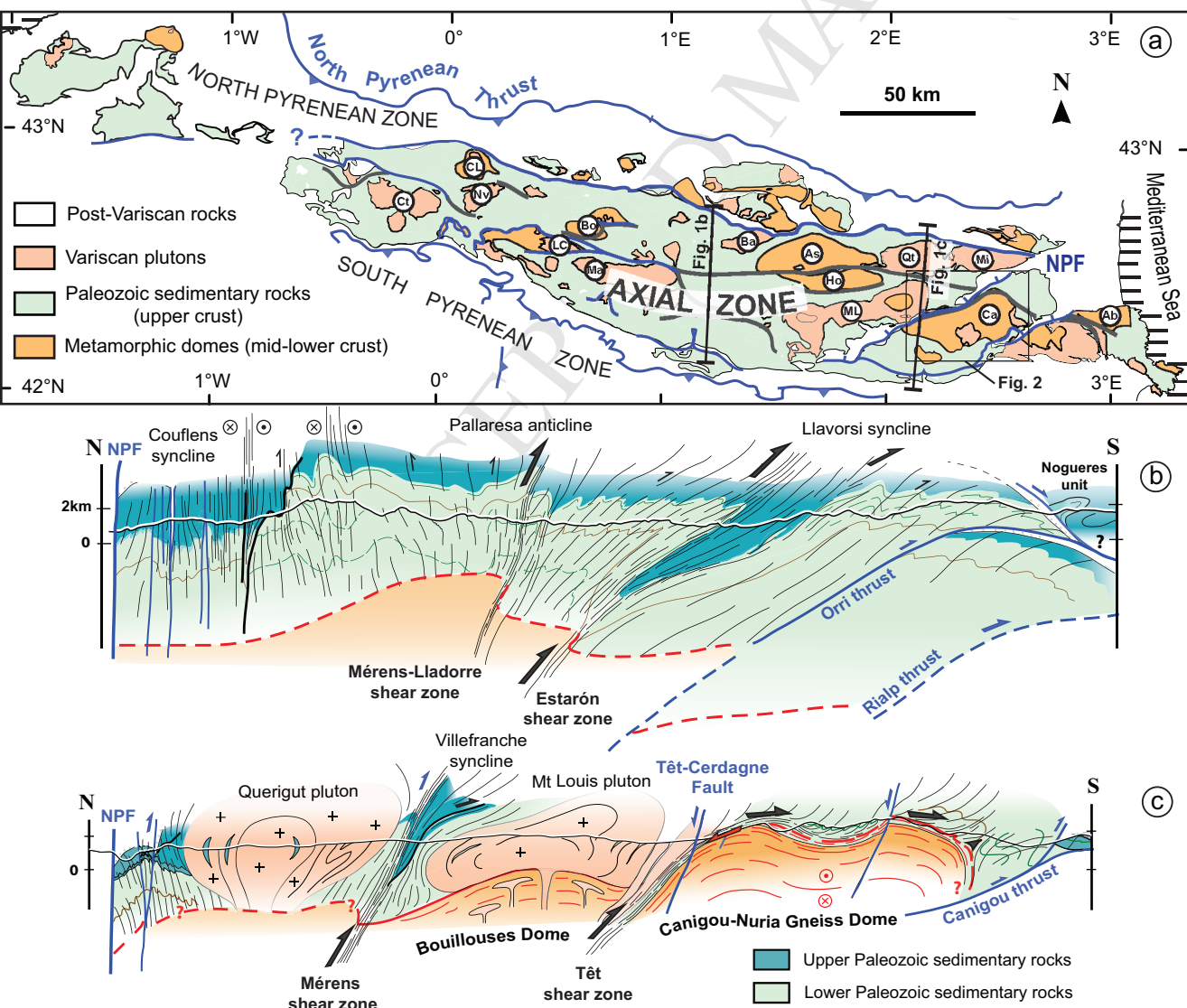
957 Figure 14: a) Stereogram of mineral-stretching lineations in the Canigou gneiss dome; b) Omni-  
958 directional variogram computed for stretching lineations; c) Computed lineation trajectories in  
959 the Canigou gneiss dome.

960 Figure 15: a) Synthesis of direction of stretching within gneiss domes in the Axial Zone,  
961 modified from Cochelin et al., 2017; b) Rose diagram of mineral-stretching lineations set  
962 available for gneiss domes

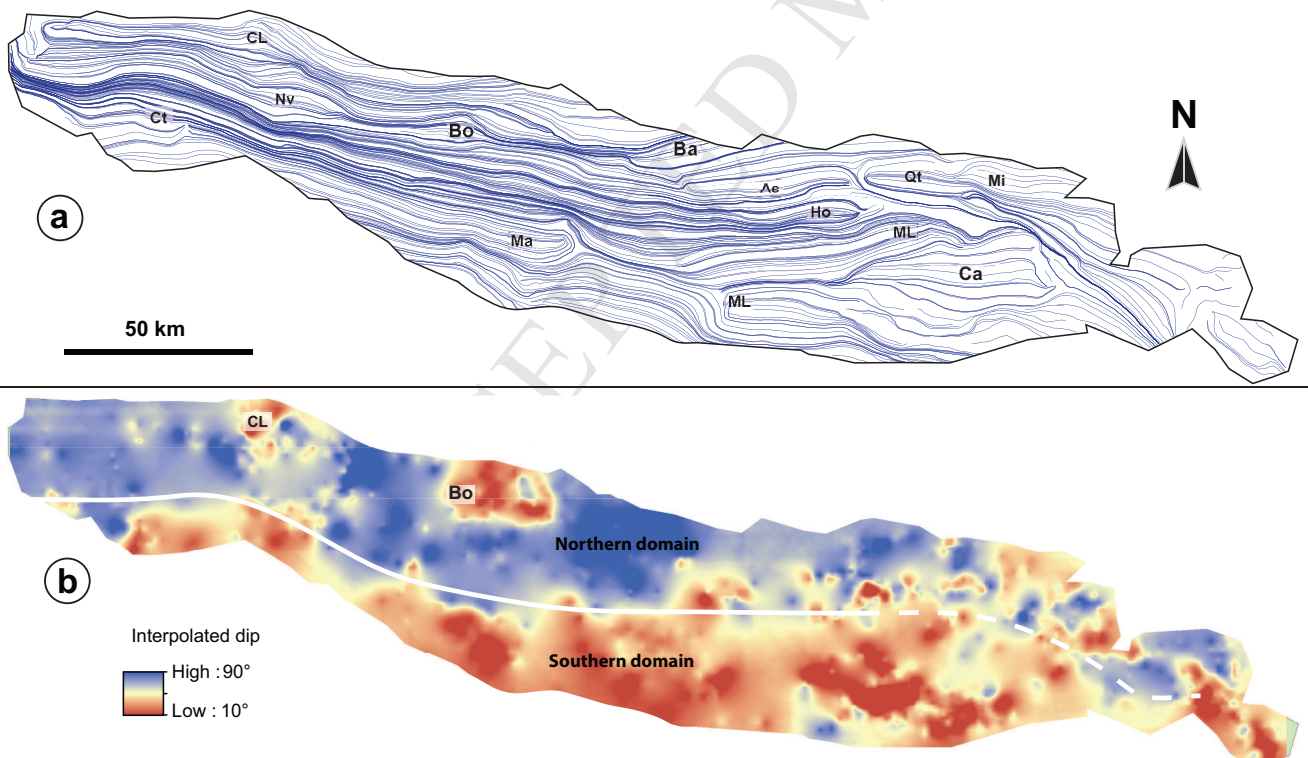
963 Figure 16: Bloc diagram summarizing how strain was spatially partitioned in the Axial Zone,  
964 showing: the steep longitudinal cleavage trajectories in the upper crust (1) and associated  
965 transpressional shear zones in blue surrounding syn-kinematic plutons (2) and gneiss domes (3)  
966 affected by longitudinal stretching. The simplified trend of variograms for each structural features  
967 is presented: the nested variogram of the Axial Zone, summing the individual variograms of (1)

968 the upper crust with its exponential trend; (2) syntectonic plutons showing sinusoidal trend; (3)  
969 gneiss domes which could have a sinusoidal trend (i.e. single phased or “undisturbed” domes) or  
970 an exponential trend (i.e. polyphased domes like the Canigou).

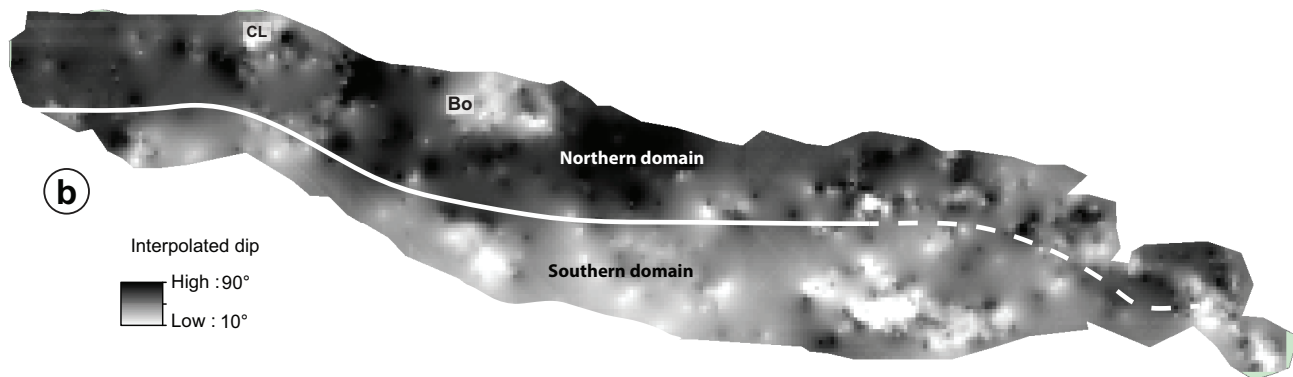
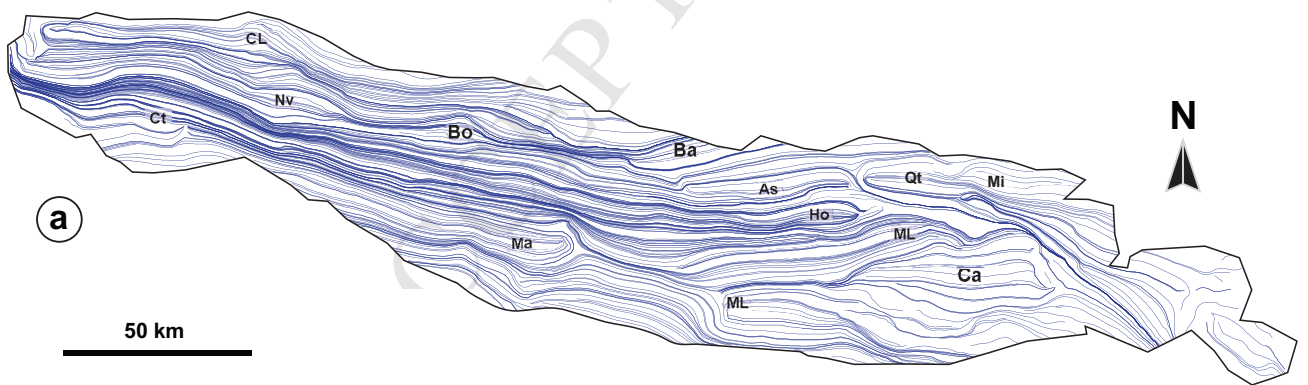
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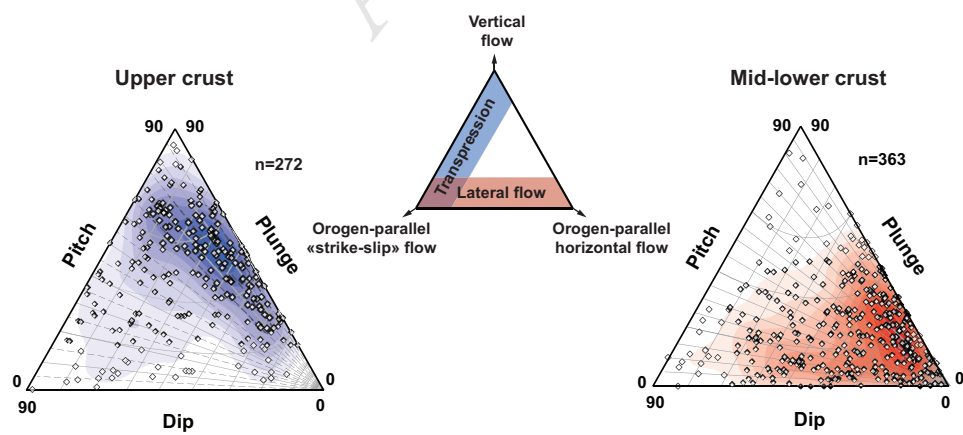


Cochelin et al. Figure 1

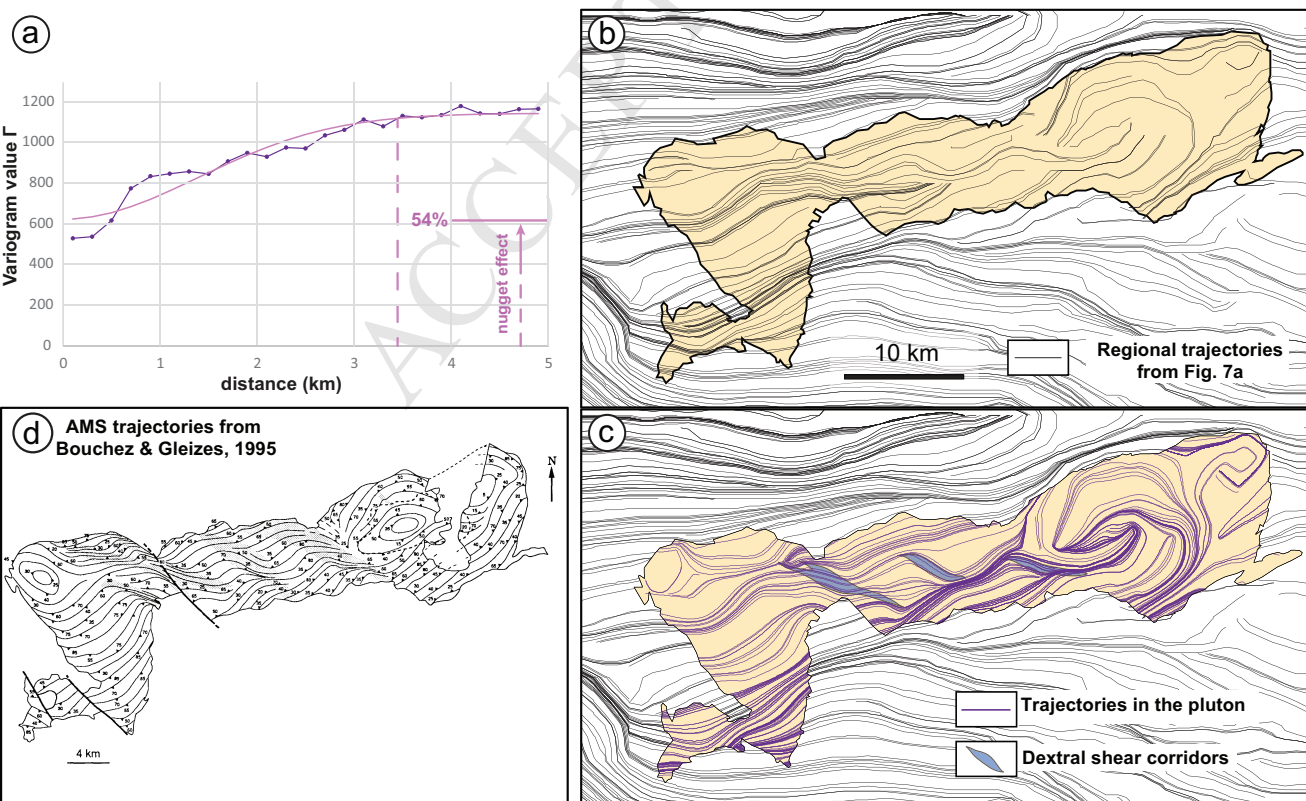


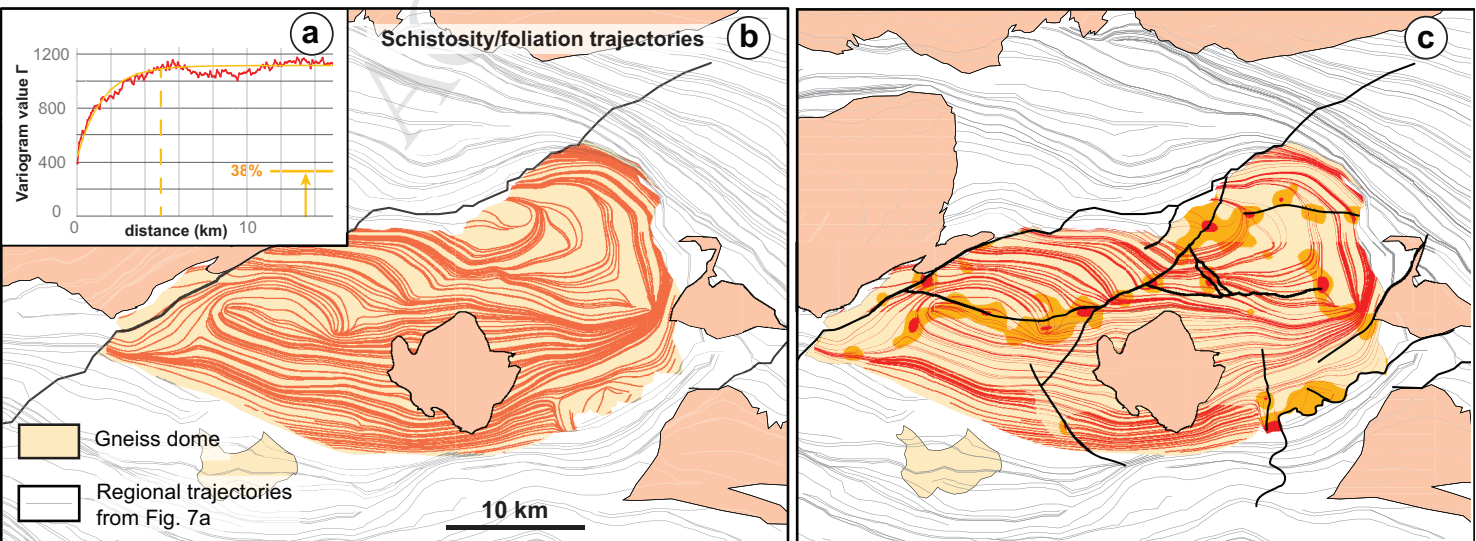
Cochelin et al., Figure 10

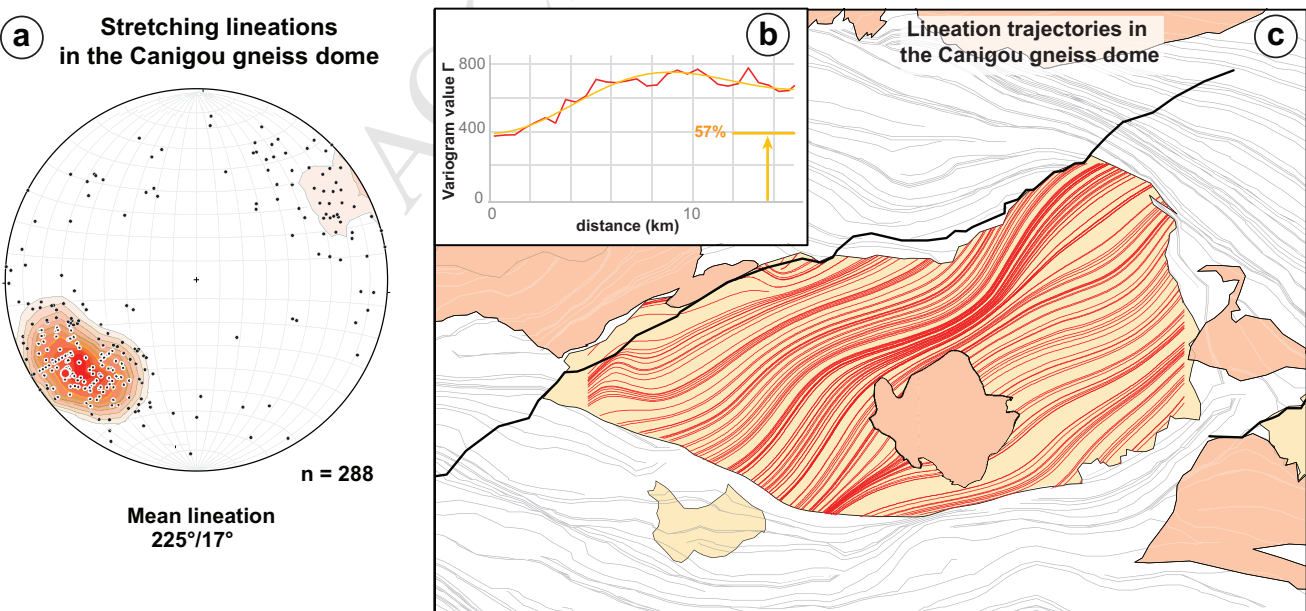


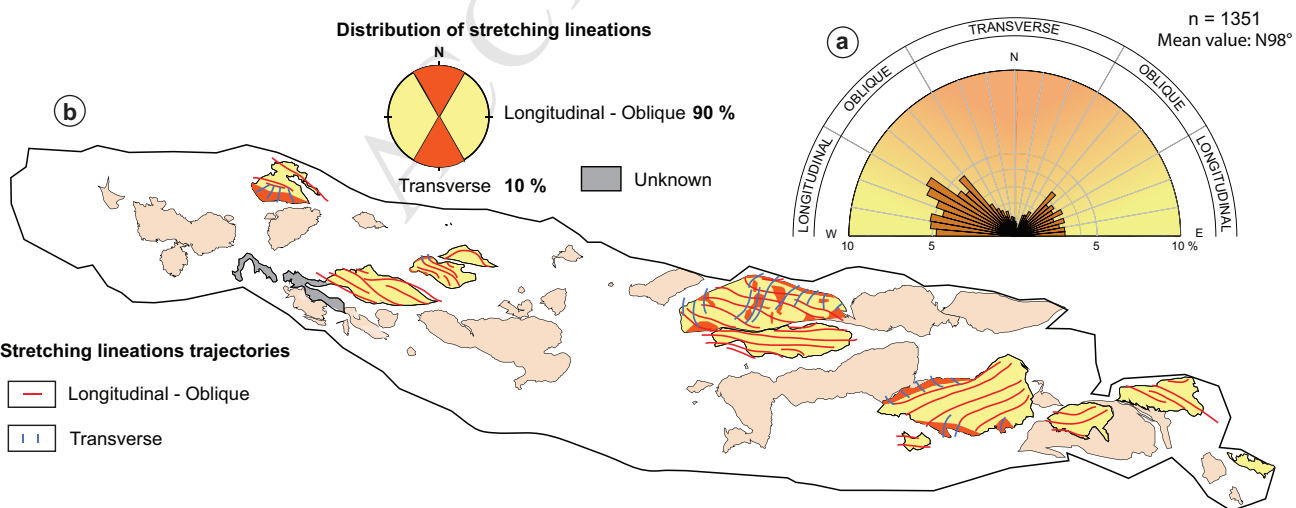


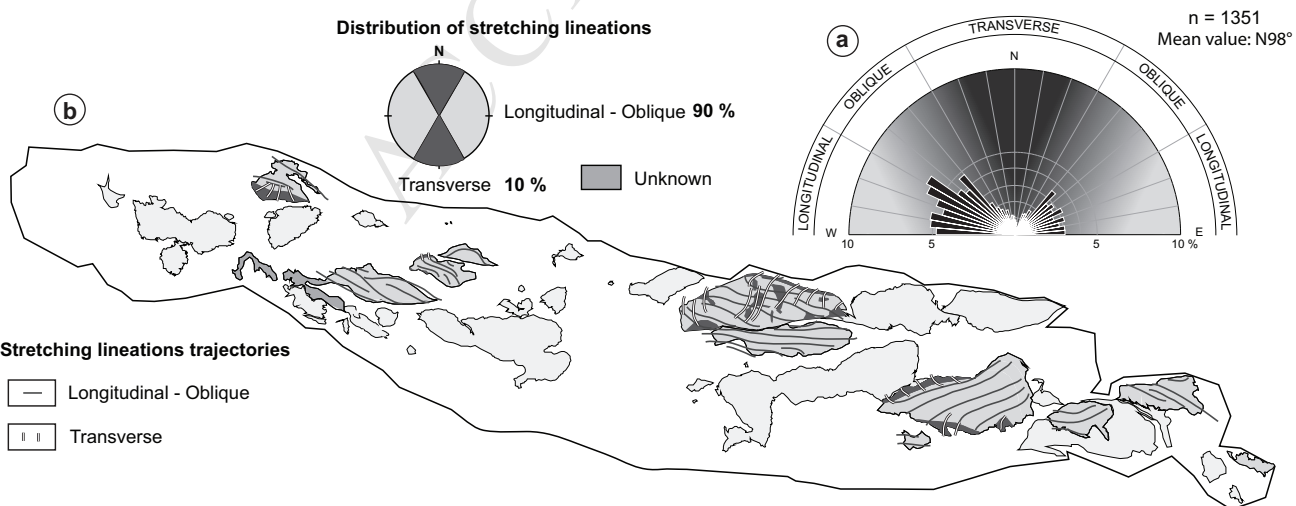
Cochelin et al., Figure 11



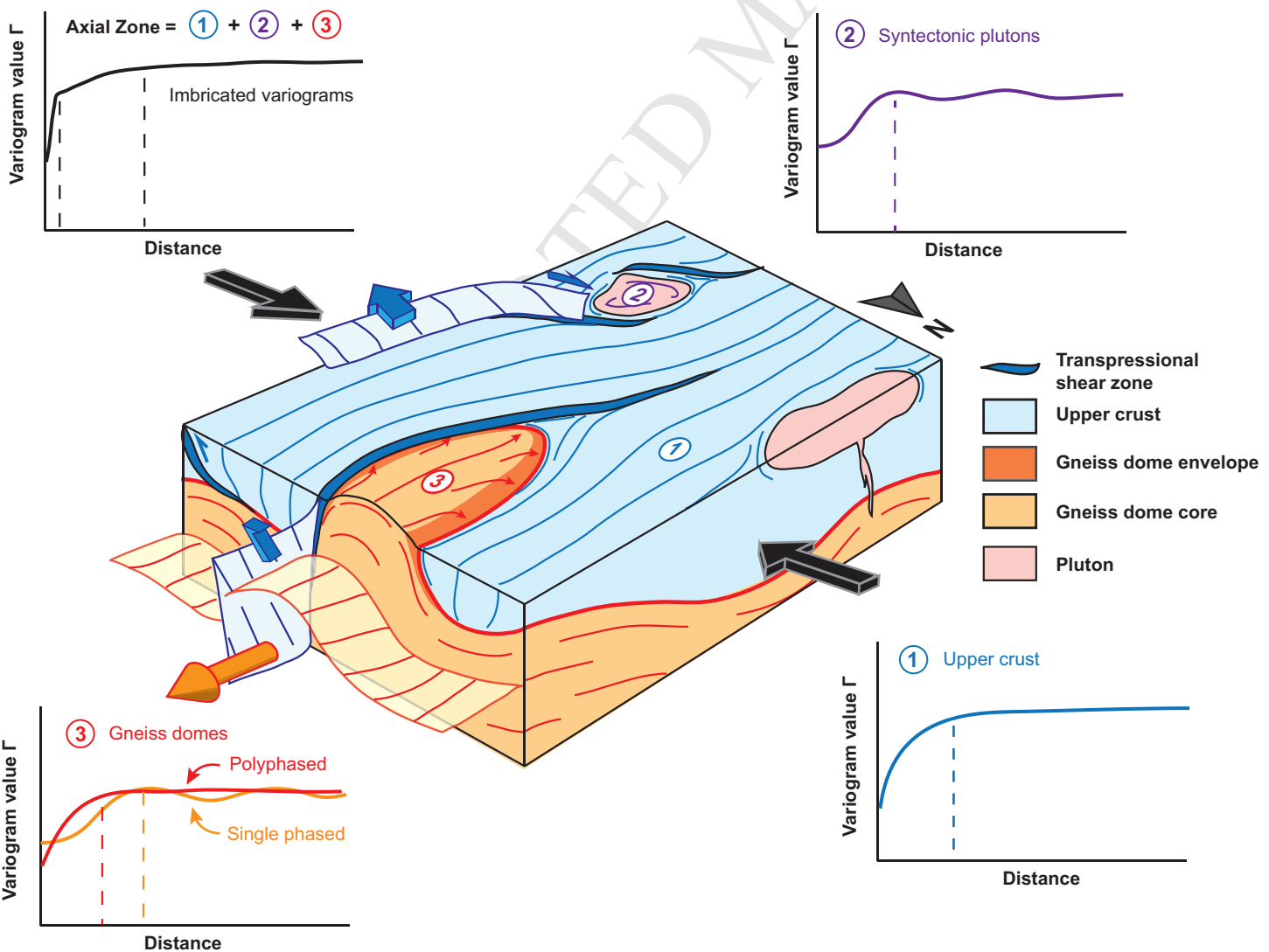




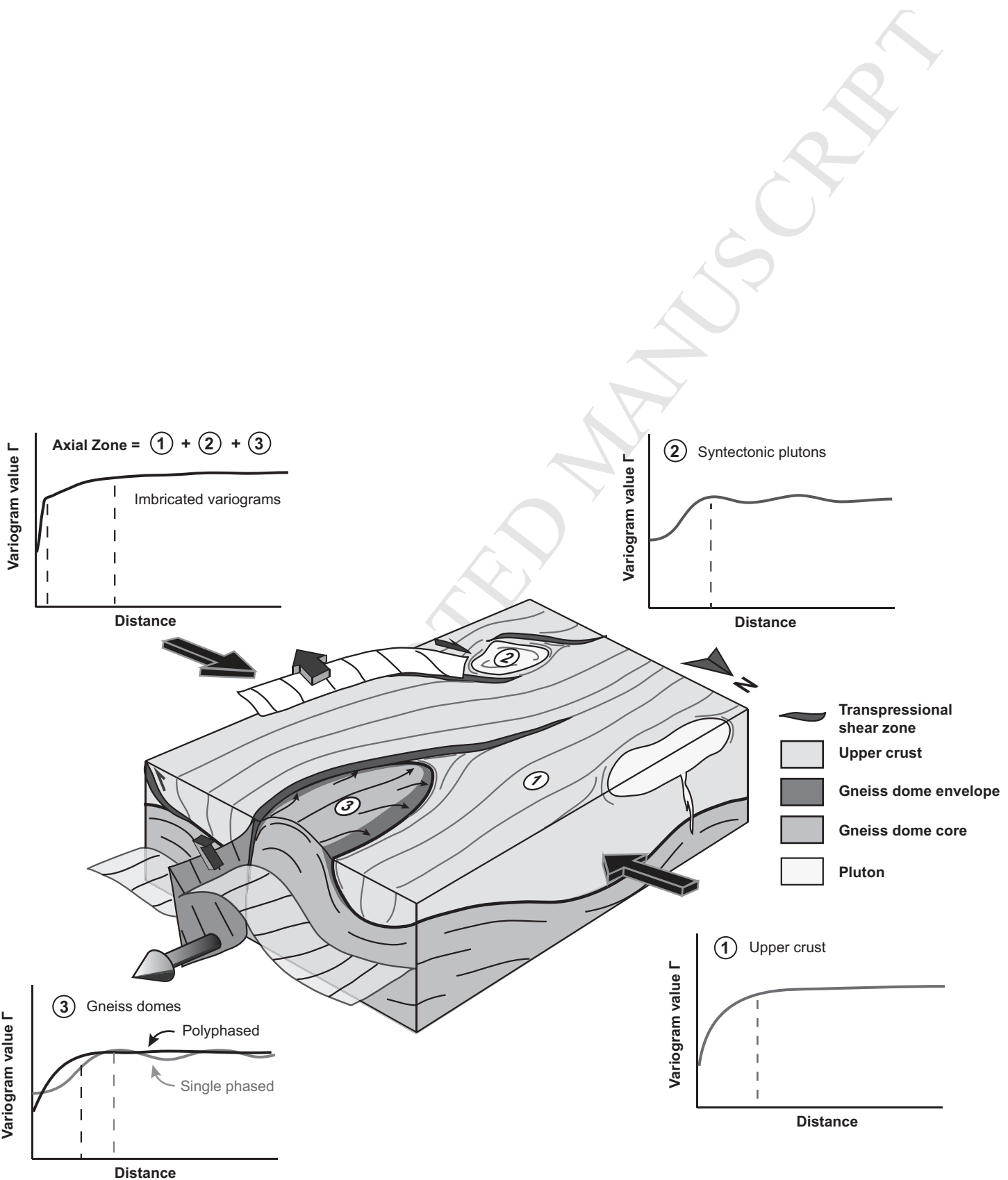


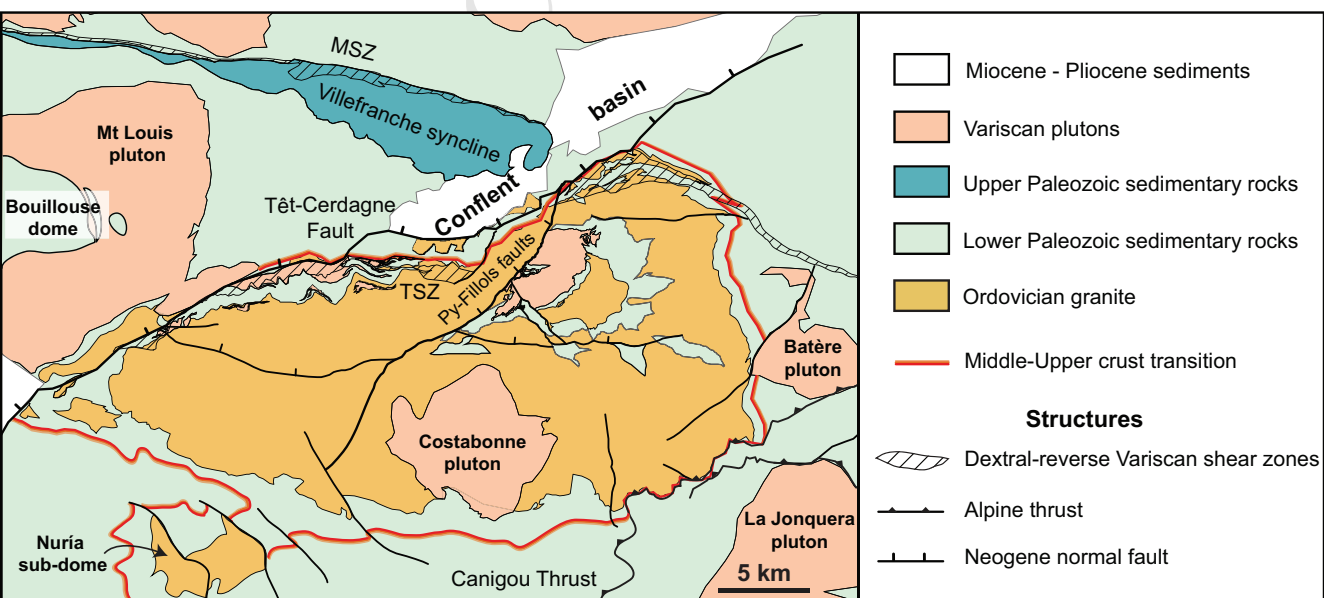


Cochelin et al. Figure 15



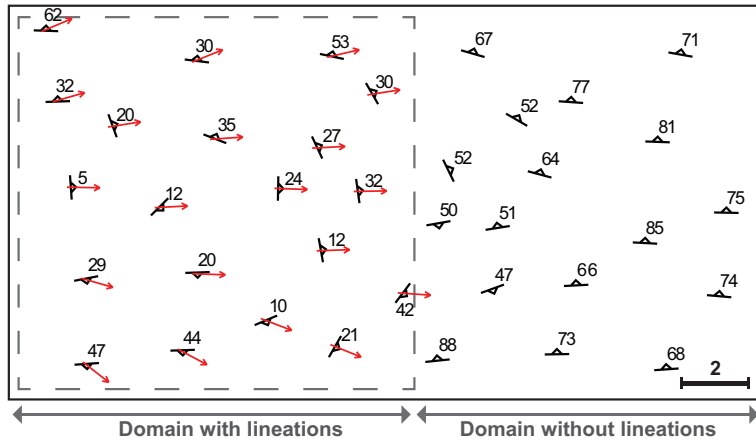
Cochelin et al. Figure 16



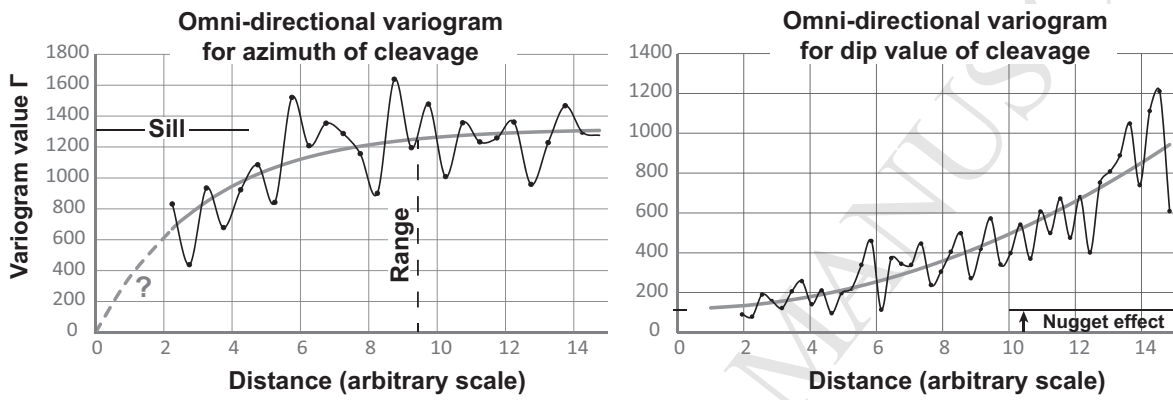


Cochelin et al. Figure 2

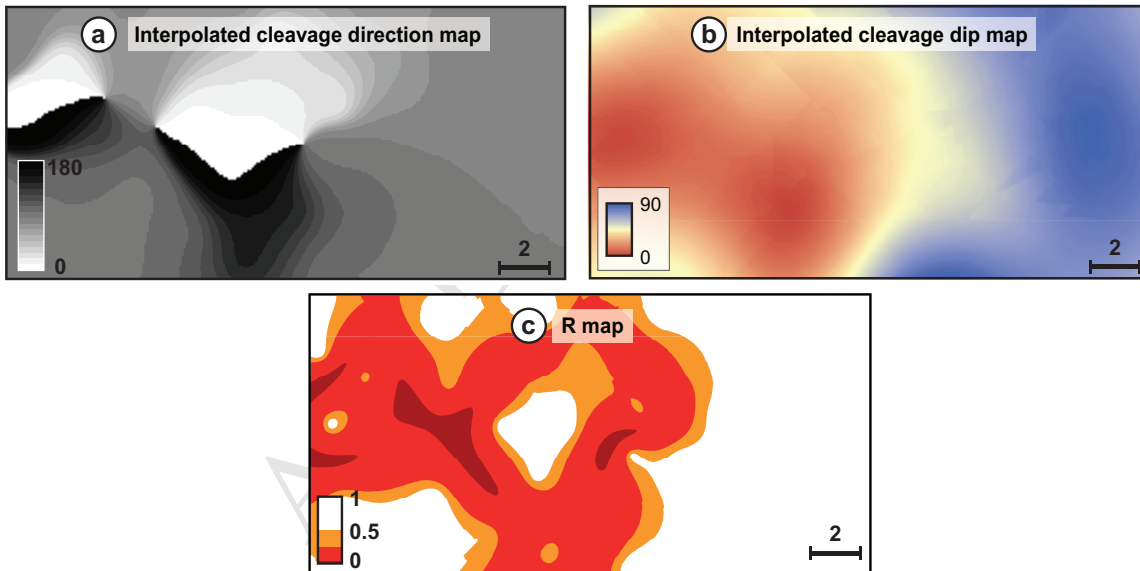
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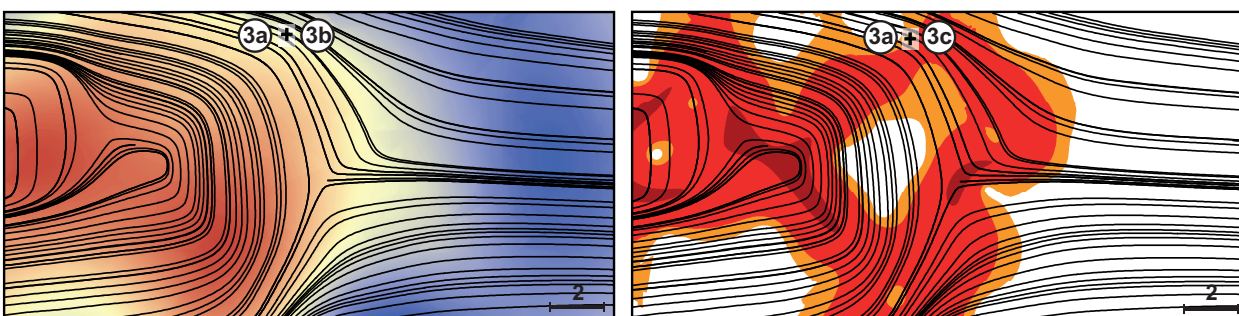
2 - Variogram calculation and analysis



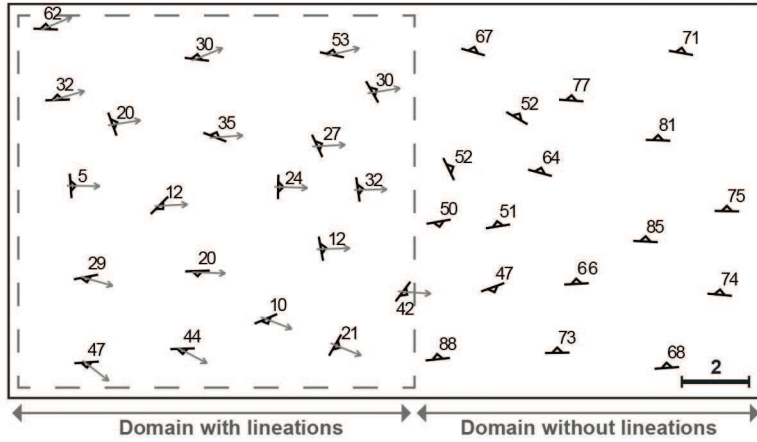
3 - Kriging interpolation



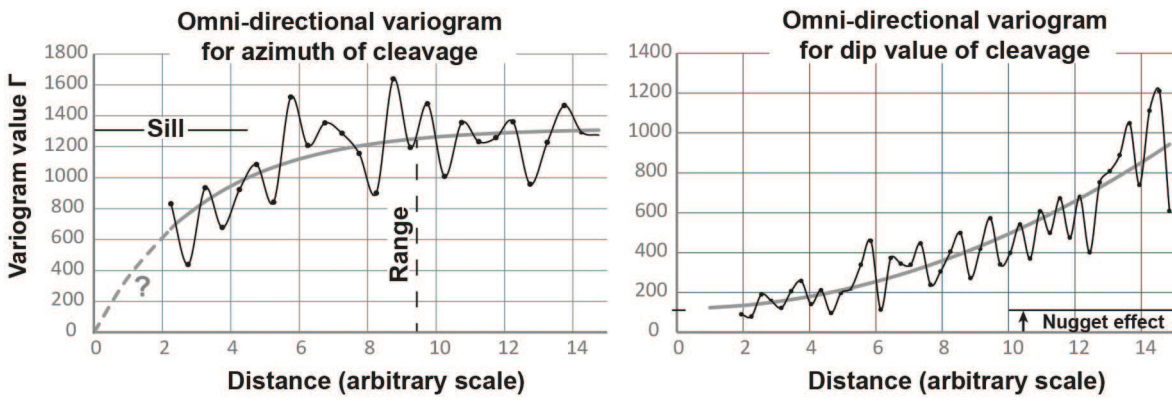
4 - Trajectories computation



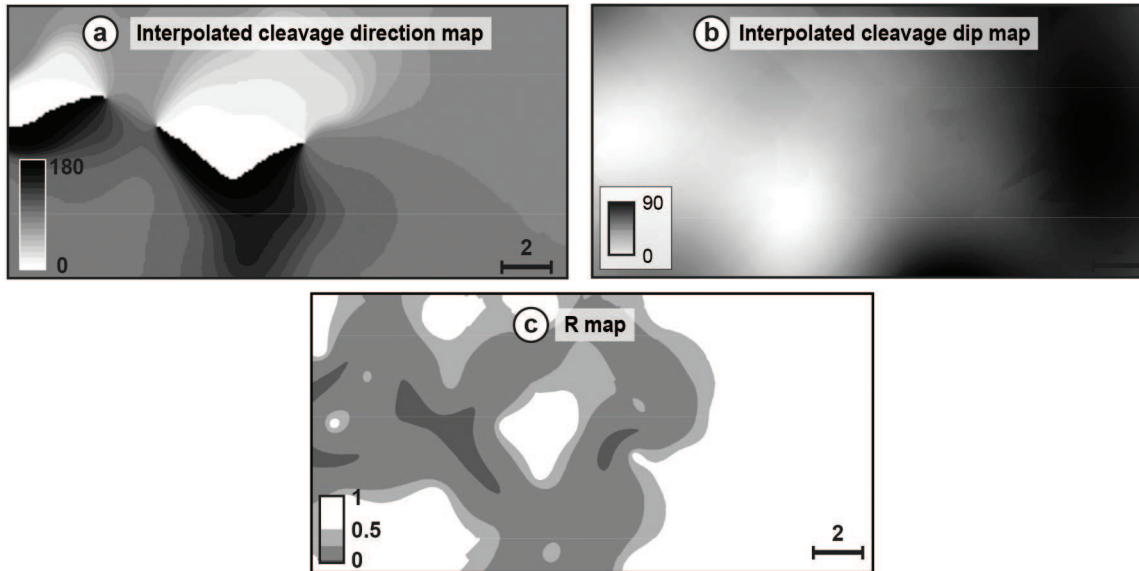
## 1 - Compilation of structural data



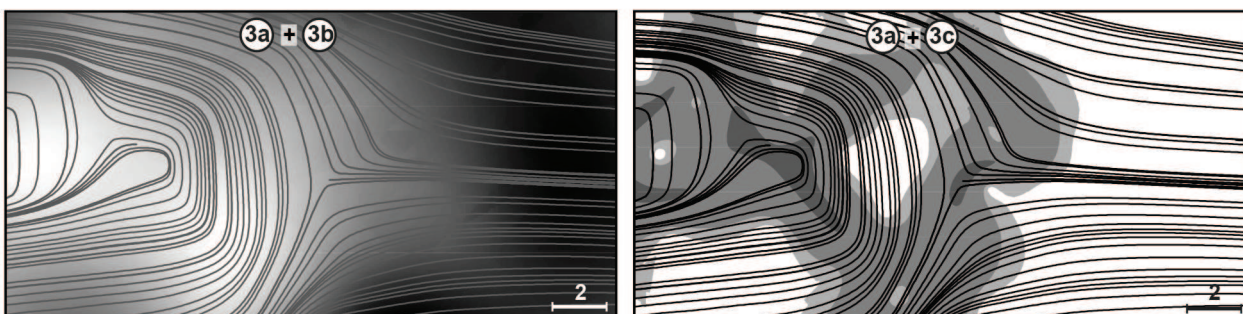
## 2 - Variogram calculation and analysis



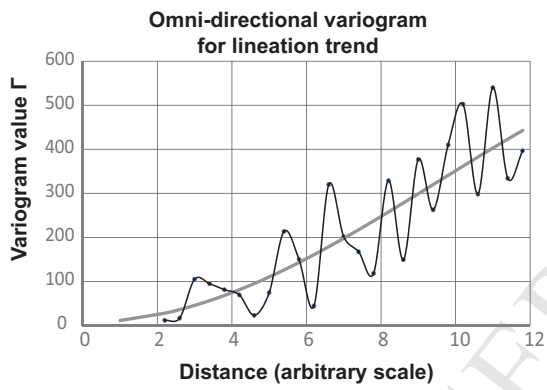
## 3 - Kriging interpolation



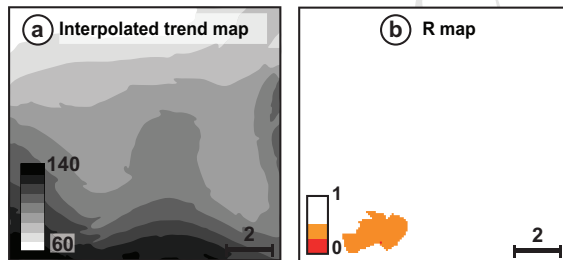
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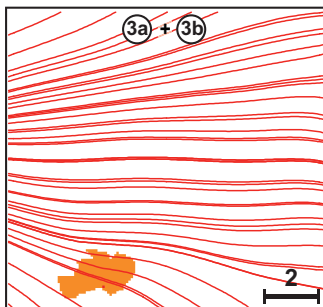
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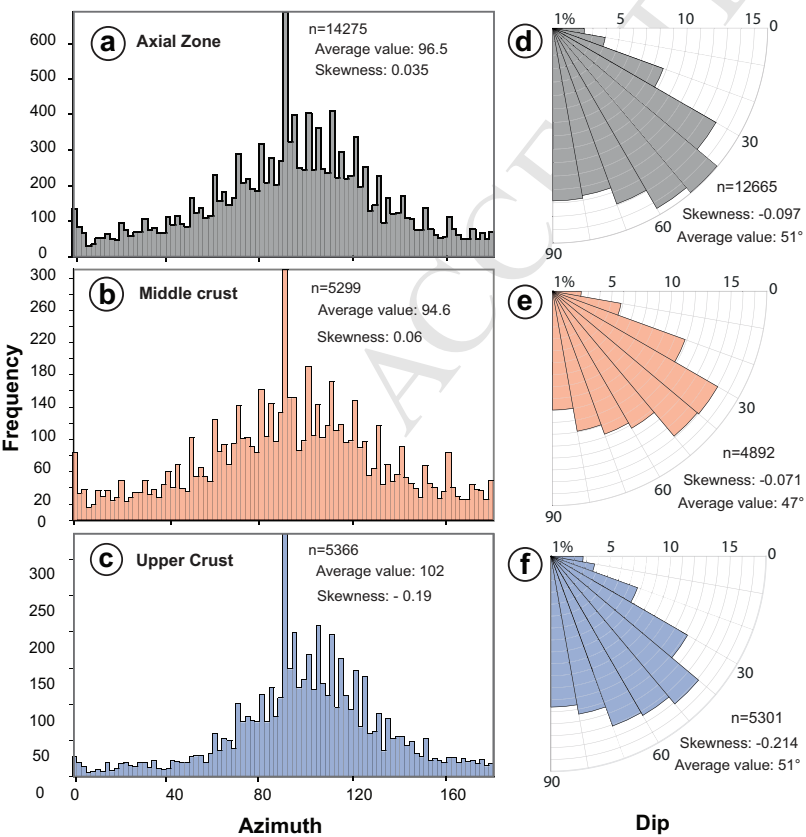


3 - Kriging interpolation

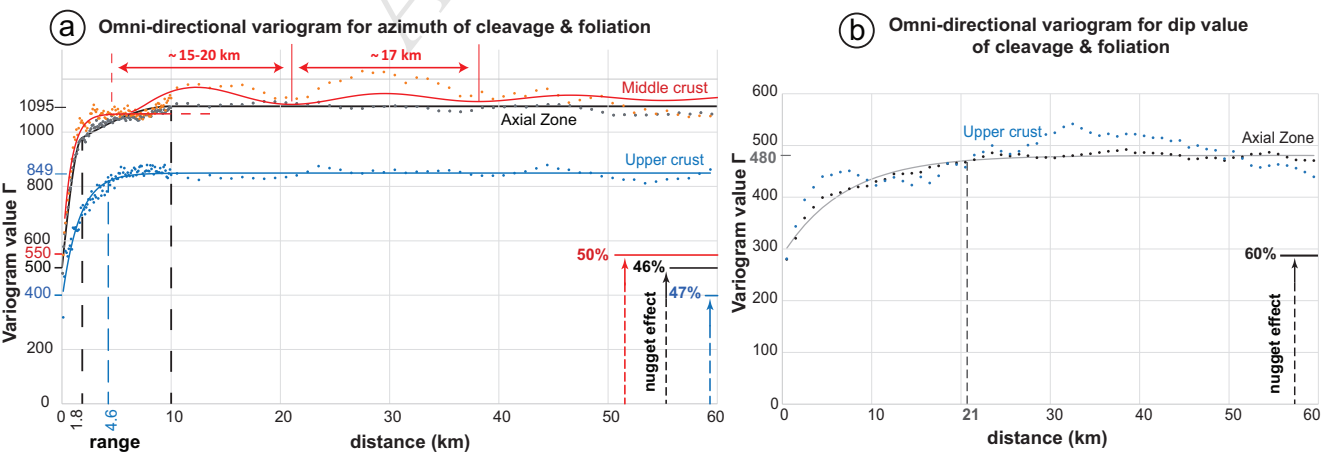


4 - Trajectories computation

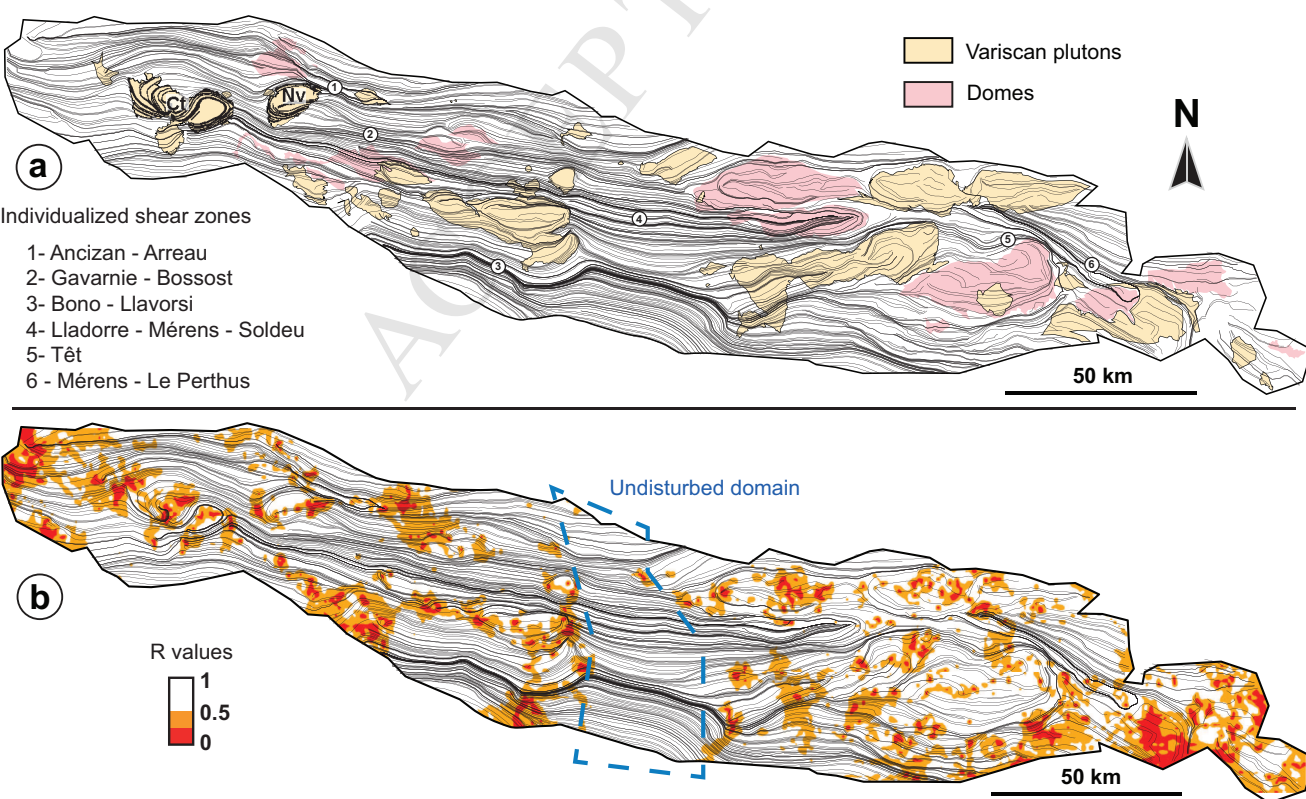


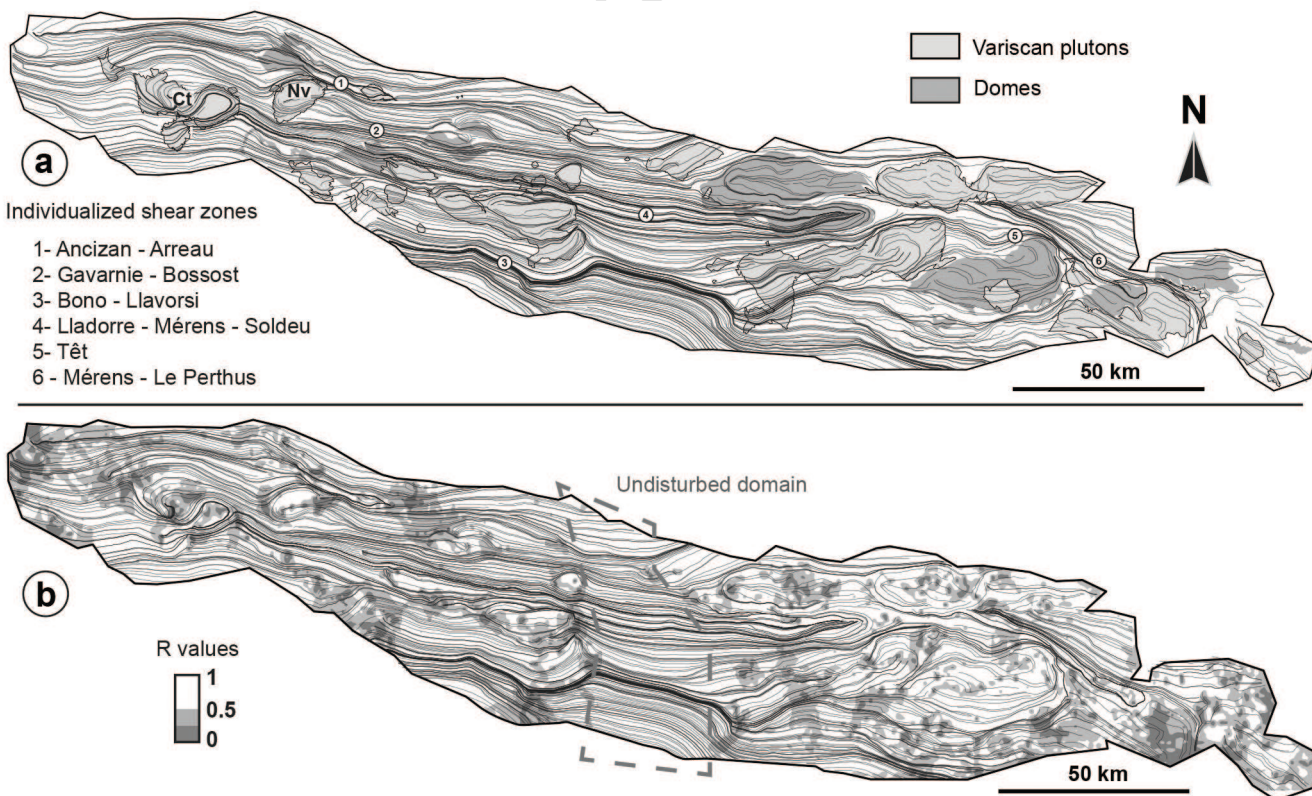


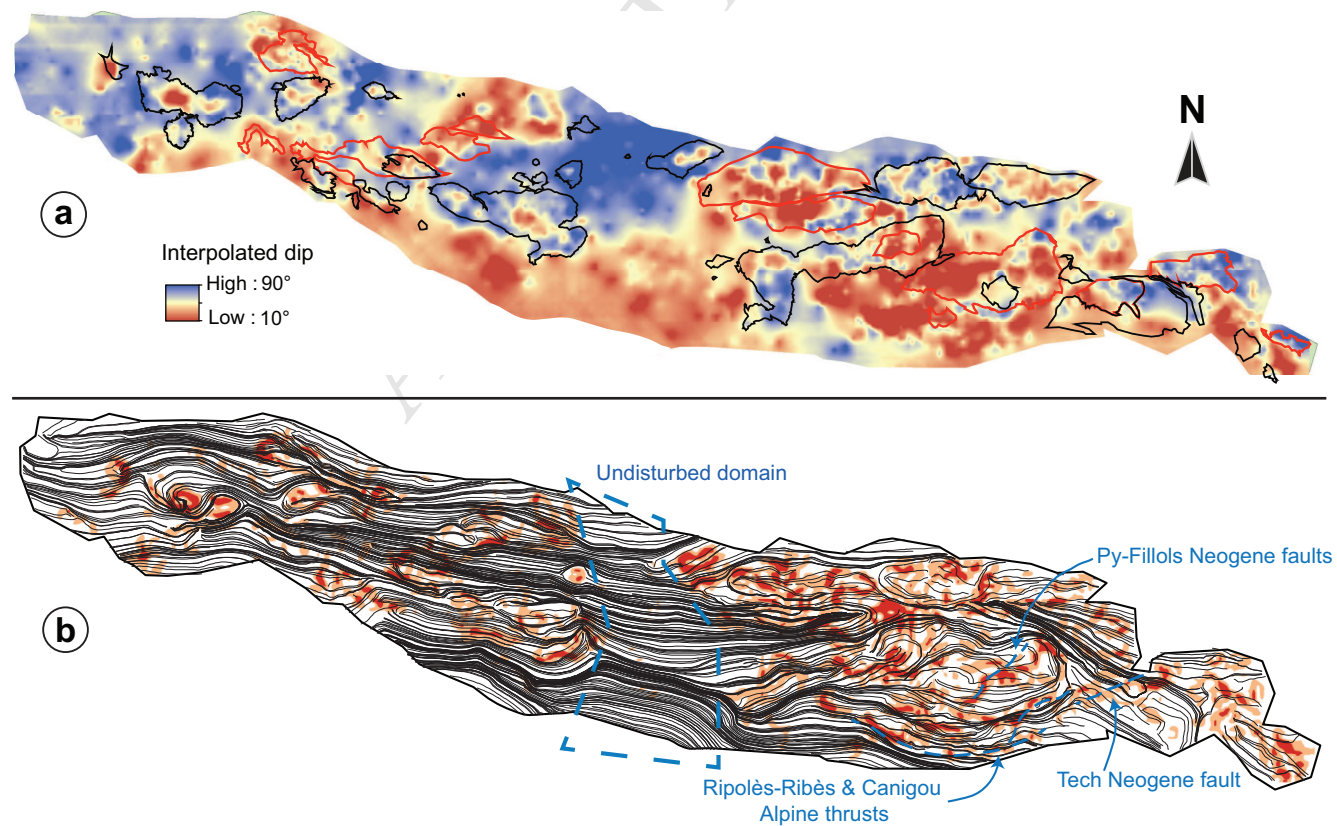
Cochelin et al., Figure 5



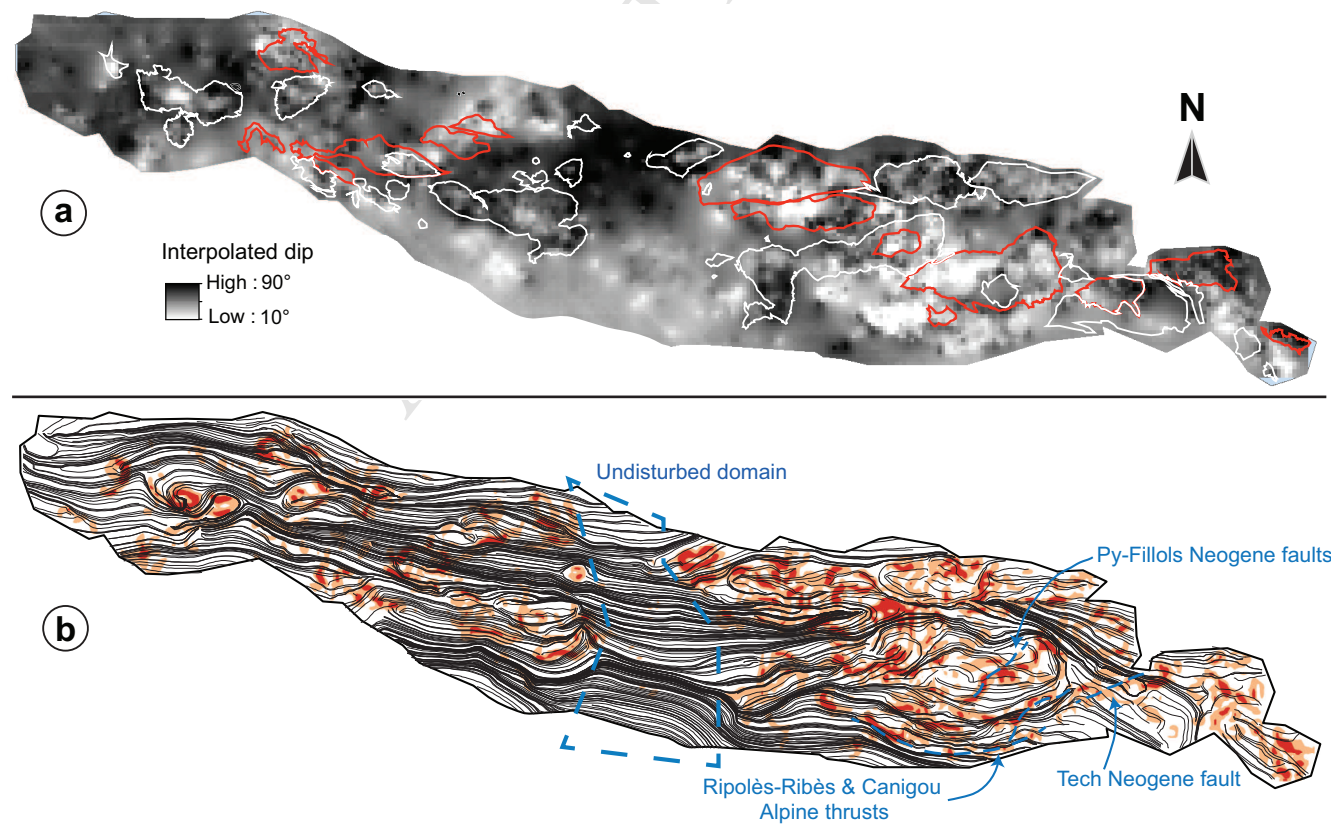
Cochelin et al. Figure 6

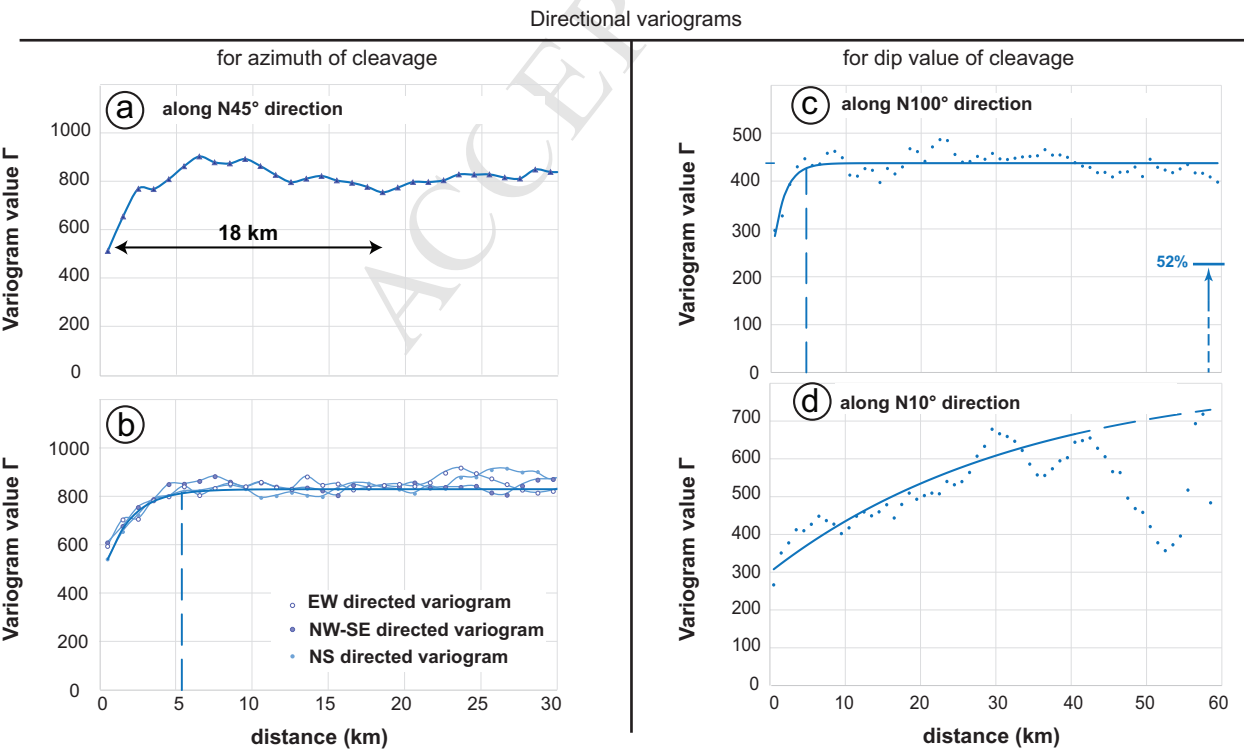






Cochelin et al., Figure 8





## Highlights

- Spatial orientation variability of schistosity planes is quantified by variograms
- Building of quantitative regional and local strainfields using kriging interpolations
- The analysis of fabrics and kinematic data documents strain partitioning patterns
- Variogram analysis allows deciphering continuous from polyphased deformation