



HAL
open science

Relationships between magmatism and extension along the Autun-La Serre fault system in the Variscan Belt of the eastern French Massif Central

Flavien Choulet, Michel Faure, Olivier Fabbri, Patrick Monié

► **To cite this version:**

Flavien Choulet, Michel Faure, Olivier Fabbri, Patrick Monié. Relationships between magmatism and extension along the Autun-La Serre fault system in the Variscan Belt of the eastern French Massif Central. *International Journal of Earth Sciences*, 2012, 101 (2), pp.393-413. 10.1007/s00531-011-0673-z . insu-00596918

HAL Id: insu-00596918

<https://insu.hal.science/insu-00596918v1>

Submitted on 10 Jun 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Relationships between magmatism and extension along the Autun - La Serre fault system in
2 the Variscan Belt of the eastern French Massif Central

3

4

5 Flavien Choulet ^{1,*}, Michel Faure ¹, Olivier Fabbri ², Patrick Monié ³

6 ¹ ISTO, UMR 6113 - CNRS/Université d'Orléans, 1A, rue de la Férollerie, 45071 Orléans
7 Cedex 2, France

8 ² Chrono-environnement, UMR 6249 – Université de Franche-Comté, 16, route de Gray
9 25030 Besançon Cedex, France

10 ³ Géosciences Montpellier, UMR CNRS 5243, Université Montpellier II, Place Bataillon,
11 34095 Montpellier Cedex 5, France

12 Corresponding author

13 flavien.choulet@univ-orleans.fr, +33238492573

14

15 Abstract

16 The ENE-WSW Autun Shear Zone, in the northeastern part of the French Massif
17 Central has been interpreted previously as a dextral wrench fault. New field observations and
18 microstructural analyses document a NE-SW stretching lineation that indicates normal dextral
19 motions along this shear zone. Further east, similar structures are observed along the La Serre
20 Shear Zone. In both areas, a strain gradient from leucogranites with a weak preferred
21 orientation to highly sheared mylonites supports a continuous Autun-La Serre fault system.
22 Microstructural observations and shape and lattice preferred orientation document high-
23 temperature deformation and magmatic fabrics in the Autun and La Serre granites, whereas
24 low- to intermediate-temperature fabrics characterize the mylonitic granite. Electron
25 microprobe monazite geochronology of the Autun and La Serre granites yields a ca. 320 Ma

26 age for pluton emplacement, while mica ^{40}Ar - ^{39}Ar datings of the Autun granite yield plateau
27 ages from 305 to 300 Ma. The ca. 300 Ma ^{40}Ar - ^{39}Ar ages, obtained on micas from Autun and
28 La Serre mylonites, indicate the time of the mylonitization. The ca. 15 Ma time gap between
29 pluton emplacement and deformation along the Autun-La Serre fault system argue against a
30 synkinematic pluton emplacement during late-orogenic to post-orogenic extension of the
31 Variscan Belt. A ductile to brittle continuum of deformation is observed along the shear zone,
32 with Lower Permian brittle faults controlling the development of sedimentary basins. These
33 results suggest a two-stage Late Carboniferous extension in the northeastern French Massif
34 Central, with regional crustal melting and emplacement of the Autun and La Serre
35 leucogranites around 320 Ma, followed, at 305-295 Ma, by ductile shearing, normal brittle
36 faulting, and subsequent exhumation along the Autun –La Serre transtensional fault system.

37

38 Keywords: Variscan Belt, Late Carboniferous shear zones, synkinematic granite, ^{40}Ar - ^{39}Ar
39 dating, electron microprobe monazite dating, quartz c-axis, French Massif Central.

40

41 1. Introduction

42 Continental collision leads to the thrusting of two lithospheric plates and a subsequent
43 crustal thickening during orogen formation. Once the lithostatic and compressional strengths
44 are no longer balanced, the orogen becomes unstable and collapses (e.g. Malavieille 1987;
45 Dewey 1988). The gravitational collapse of the thickened crust is accommodated by extension
46 and is characterized by thermal relaxation inducing partial melting of the continental crust
47 (England and Thompson 1986). S-type magmatism, granite-gneiss domes and normal shear
48 zones document syn to post-orogenic extension (Reynolds and Spencer 1985; McClay et al.
49 1986; Norton 1986).

50 Extensional structures have also been described in the European Variscan Belt, a large
51 Paleozoic orogen interpreted as the result of the collision between Laurussia, Gondwana, and
52 several intermediate microcontinents such as Armorica or Avalonia (Matte 1986; 2001;
53 Franke 1989). In the French Massif central, one of the main pieces of the Variscan orogen,
54 successive phases of nappe stacking in Devonian and Early Carboniferous times (Burg and
55 Matte 1978; Ledru et al. 1989) led to an important thickening of the crust, and were followed
56 by an important episode of crustal melting (Duthou et al. 1984). During the Late
57 Carboniferous, the collapse of the Variscan Belt (Ménard and Molnar 1988; Burg et al. 1994;
58 Faure 1995) generated normal brittle faults (Echtler and Malavieille 1990; Faure and Becq-
59 Giraudon 1993), normal ductile shear zones (Mattauer et al. 1988; Malavieille et al. 1990),
60 synkinematic granitoids (Faure and Pons 1991; Talbot et al. 2004; Joly et al. 2009), and
61 granite-gneiss domes (Ledru et al. 2001). Although the timing of these events is relatively
62 well established (Faure 1995), the connection between magmatism and extensional tectonics
63 is not always clear. A common idea is that most of the plutons are synkinematic bodies
64 emplaced along normal or strike-slip faults (Faure and Pons 1991; Faure 1995).

65 This study deals with extensional structures documented by field observations,
66 microstructural analysis, and geochronology of granitoids and mylonites. We focus on the
67 Morvan and La Serre horsts in the northeastern part of the French Massif Central, where S-
68 type granites, ductile shear zones, and syn-sedimentary faults are exposed. We propose an
69 interpretation of the late orogenic to post-orogenic evolution of this segment of the Variscan
70 Belt. We shall use the classical chronostratigraphic stages of Western Europe for the Late
71 Paleozoic period, with Namurian corresponding to Late Mississippian - Early Pennsylvanian
72 (326-313 Ma), Westphalian to Middle Pennsylvanian (313-307 Ma), Stephanian to Late
73 Pennsylvanian (307-303 Ma), Autunian to Late Pennsylvanian - Middle Cisuralian (303-276
74 Ma), and Saxonian to Late Cisuralian - Middle Guadalupian (276-263 Ma) (Ogg et al. 2008).

75

76 2. Geological outline

77 2.1. The French Massif Central in the Variscan Belt

78 Two types of scenario have been proposed to account for the geodynamical evolution
79 of the Variscan Belt of Western Europe. The first type is monocyclic and is based on a
80 continuous Paleozoic convergence between Gondwana and Laurussia (Matte 1991; Lardeaux
81 et al. 2001). Alternatively, a polycyclic evolution with two successive orogenic episodes was
82 proposed (Pin 1990; Faure et al. 1997). The reliability of the two scenarios is extensively
83 discussed in several papers (e.g. Faure et al. 2005) and will not be addressed here. In this
84 contribution, the polycyclic scenario is retained. In this model, the first cycle resulted from
85 the Silurian north-directed subduction of the ocean that separated Gondwana and Armorica.
86 After an earlier high-pressure event dated at ca. 415 Ma (Pin and Peucat 1986; Lardeaux et
87 al., 2001), crustal nappes were stacked towards the SW, then partly migmatized, and finally
88 exhumed during the Devonian around 390-380 Ma (Floc'h 1983; Quenardel and Rolin 1984;
89 Roig and Faure 2000; Faure et al. 2008). The second cycle was related to the closure of the
90 Rheic Ocean that initially separated Laurussia and the Armorica microplate (Faure et al.
91 1997). A Devonian to Early Carboniferous calc-alkaline magmatic suite (Pin et al. 1982) and
92 the Devonian Brévenne ophiolite (Leloix et al. 1999) are interpreted as remnants of a
93 magmatic arc and a back-arc basin related to the southward subduction of the Rheic Ocean
94 (Faure et al. 1997).

95 During mid-Carboniferous times (Visean), the southern part of the Massif Central
96 experienced top-to-the south nappe stacking, while synorogenic extension prevailed in the
97 north. Late Visean magmatic series, locally called “Tufs Anthracifères”, postdate the mid-
98 Carboniferous events (Faure et al. 2002). The Late orogenic stage is characterized by two
99 successive events (Faure and Becq-Giraudon 1993; Burg et al. 1994; Faure 1995): a

100 Namurian to Westphalian NW-SE extension characterized by leucogranite emplacement
101 (Faure and Pons 1991), followed by a Stephanian to Permian NE-SW extension characterized
102 by brittle normal faulting and formation of coal-bearing half-grabens (Arthaud and Matte
103 1977; Echtler and Malavieille 1990; Malavieille et al. 1990). Whatever the geodynamic
104 scenario (monocyclic or polycyclic), the Late Carboniferous syn-orogenic to post-orogenic
105 extension is widely accepted.

106

107 2.2. The northeastern French Massif Central

108 The study area is located in the northeastern French Massif Central, also called
109 Morvan area, which forms a horst between the Cenozoic Limagne and Bresse grabens (Fig.
110 1). Paleozoic metamorphic units are unconformably overlain by Devonian to Early
111 Carboniferous sedimentary and magmatic rocks (Delfour 1989; Faure et al. 1997) and are
112 crosscut by Carboniferous magmatic intrusions with varied geochemical characteristics (Rolin
113 and Stussi 1991). The last manifestation of this magmatic event is the emplacement of
114 peraluminous plutons such as the Autun granite (Chévremont et al. 1999; Fig. 2a), located
115 close to ductile shear zones in the Autun and Avallon areas (Rolin and Stussi, 1991). Late
116 orogenic brittle wrench or normal faults controlled the development of the Stephanian to
117 Permian coal-bearing half-grabens or pull-apart basins such as the Autun, Epinac or Le
118 Creusot basins (Marteau 1983; Vallé et al. 1988; Fig. 1). These intramontane basins are
119 characterized by a terrigenous sedimentation, which started during the Late Stephanian and
120 remained active during the Permian (Courel 2001). Stephanian to Permian high-K acidic
121 volcanism is also reported (Carpena et al. 1987; Chévremont et al. 1999).

122 East of the Oligocene Bresse graben, and close to the northern end of the Jura fold-
123 and-thrust belt, the La Serre horst displays structures similar to those of the Autun area (Fig.

124 3), with a leucogranitic pluton separated from a Permian sedimentary basin by a ductile shear
125 zone and a brittle fault system (Coromina and Fabbri 2004).

126

127 3. Petrography and structure of the studied rocks

128 3.1. Field data

129 In the Autun area (Fig. 2a), a N70°E-trending, 500 m wide, mylonitic belt separates
130 Variscan migmatites and granites to the south from a Stephanian to Autunian coal basin to the
131 north (Delfour et al. 1991; Rolin and Stussi 1991). The Autun leucogranite (Fig. 4a) intruded
132 pre-Carboniferous gneisses and migmatites. A porphyritic facies of this leucogranite can be
133 observed in some places. At the hand sample scale, this granite locally shows a planar
134 preferred orientation of biotite and muscovite, and a linear preferred orientation, indicated by
135 K-feldspar and biotite aggregates. However, given the scarcity of outcrops, it is difficult to
136 draw a structural map of the whole pluton (Fig. 2a). To the north, the granitic rocks are more
137 deformed, and the magmatic foliation is reoriented and changed to a tectonic foliation (Fig 2a;
138 b). This change suggests that either the deformation might have occurred during the last
139 stages of pluton emplacement, or that the granitic pluton experienced a post-solidus ductile
140 deformation along the Autun fault. The mylonitization affects all the Variscan rocks, which
141 then display a N60°E to N80°E striking foliation that dips 45° to 80° to the north; a stretching
142 lineation trends N45°E and plunges to the NE (Fig. 2c). Macroscopic shear criteria indicate a
143 top-to-the-NE motion. Shearing was oblique combining strike-slip and dip-slip components
144 (Fig. 4b), not in agreement with previous results on the Autun Shear Zone for which a pure
145 dextral strike-slip faulting was postulated (Rolin and Stussi 1991). North of the shear zone,
146 the mylonites are unconformably overlain by Permian deposits. However, north of Morlet
147 (Fig. 2a), the contact between mylonites to the south and gneiss to the north is a brittle fault
148 hidden westward beneath onlapping Permian deposits (Fig. 2b). Cataclastic mylonitic granites

149 and silicified tectonic breccia, exposed at the southern border of the sedimentary basin,
150 indicate brittle deformation. In the northern part of the Autun basin, the Permian strata overlie
151 Stephanian strata (Marteau 1983; Chévremont et al. 1999) The Autun basin has been
152 described as either a half-graben bounded by normal faults, or a pull-apart basin associated
153 with left-lateral faults (Marteau 1983). The continental deposits composed of conglomerates
154 and sandstones interlayered with volcanic deposits (Carpena et al. 1987; Chévremont et al.
155 1999) yielded an Autunian to Saxonian flora described by Bergeron (1889) who defined the
156 Autunian stratotype. Sedimentary filling of this intramontane basin (Courel 2001) is coeval
157 with the activity along the normal boundary fault.

158 Similar structures are observed in the La Serre area (Fig 3a). A two-mica granite
159 (Morre-Biot 1969) with a weak mica preferred orientation is progressively deformed along
160 the N50°E-trending La Serre Shear Zone, characterized by a N50°E-striking and 60°- to 80°-
161 northwest-dipping mylonitic foliation and a N30°E-trending stretching lineation (Coromina
162 and Fabbri 2004; Fig. 3b). In thin sections, perpendicular to the foliation and parallel to the
163 lineation (XZ sections), sigmoidal muscovites, shear bands and asymmetric porphyroclasts
164 indicate a top-to-the-NE shear sense. To the northwest, the mylonitic belt is limited by the
165 N70°E- to N80°E striking, low angle La Serre Median Brittle Fault, marked by a silicified
166 volcanic breccia (Coromina and Fabbri 2004; Fig 3c). This breccia is similar to the silicified
167 breccia exposed along the Autun shear zone. North of the La Serre Median Brittle Fault,
168 Permian conglomerates and sandstones, with an Upper Autunian to Saxonian continental flora
169 are about 500 m thick (Campy et al. 1983). The La Serre Median Brittle Fault is postdated by
170 flat lying deposits, but it was probably moderately reactivated as a normal fault during the
171 Oligocene extensional tectonics of the Bresse graben and as a reverse fault during Alpine
172 shortening (Coromina and Fabbri 2004; Madritsch et al. 2008).

173

174 3.2. Microstructures, shape and lattice preferred orientation analyses

175 In order to understand the mechanisms of deformation of the Autun and La Serre
176 leucogranites, the rock fabric was studied by several methods. The evolution from a magmatic
177 planar fabric to a tectonic foliation was investigated by relying on mica preferred orientation.
178 Since rock fabric is not well defined, especially in apparently undeformed granites, systematic
179 manual measurements of the orientation of longitudinal sections of muscovite and biotite
180 platelets were carried out in the three principal planes of the strain ellipsoid (XY, XZ and
181 YZ). These planes were estimated from field observations. Manual measurements were also
182 supported by an automatic method using the “SPO” software (Launeau and Robin 2005). On
183 thin section images, each mica was handled as an isolated grain (Fig. 5). The orientation of
184 each grain was computed by using the intercept method, with measurements shown in rose
185 diagrams (Fig. 5). There are no significant differences between manual and automatic
186 procedures. Quartz lattice-preferred orientation (LPO) analysis provides information about
187 deformation mechanisms, glide systems, and activation temperature. Quartz c-axis orientation
188 (Fig. 6) was studied with an U-stage.

189 3.2.1. Magmatic microstructures

190 In the two samples of undeformed granite (AU16 and AU19, Fig. 5), a planar fabric
191 can be inferred from the orientation of mica flakes along the XZ and YZ sections. A linear
192 fabric visible along XY sections is better developed in sample AU16 than in sample AU19.
193 Coarse angular quartz grains show seriate to polygonal textures (Moore 1970). Quartz grains
194 display a chessboard pattern of subgrain boundaries (Fig. 4c). Myrmekite is also observed
195 (Fig. 4d) and could indicate a syn-magmatic deformation (Hibbard 1987), although
196 myrmekitic textures can also develop under solid-state conditions (Simpson et Wintsch 1989).

197 In samples from the undeformed Autun and La Serre granites (AU16, AU19, AU28,
198 AU29 and SE03, Fig. 6), c-axis maxima in the XZ plane are observed at 0 to 45° from the X

199 axis of the finite strain. Such a c-axis distribution is typical of prism <c> slip and is
200 representative of high-temperature deformation mechanisms (Mainprice et al. 1986).
201 Nevertheless, the chessboard textures observed in the two plutons indicate either a combined
202 basal <a> and prism <c> slip (Mainprice et al. 1986; Stipp et al. 2002), or the transition from
203 low-temperature to high-temperature quartz (Kruhl 1996). Whatever the mechanism is, and
204 considering that no fluids have caused a late recrystallization, microstructures in undeformed
205 granite reveal high temperature of deformation of ca. 700°C, close to the magma
206 crystallization (Kruhl 1996).

207 3.2.2. Low-temperature mylonite deformation

208 In the two samples of mylonitic granite (AU02 and AU20, Fig. 5), well-defined
209 maxima in the rose diagram correspond to the rock planar fabric. The bimodal orientation of
210 micas probably correlates with distinct shear bands and recrystallization of mica. In the
211 mylonitic granite, microstructures are characteristic of ductile deformation with shear bands
212 crosscutting a preexisting foliation (Fig. 4b). This geometry must be distinguished from the S-
213 C structures, which have been originally defined for a synkinematic pluton where S and C
214 surfaces are formed synchronously (Berthé et al. 1979). During mylonitization, the granite
215 experienced grain size reduction; undulatory quartz grains with lobate boundaries indicate
216 dynamic recrystallization during low-temperature deformation (Fig. 4e). Recrystallization of
217 such fine quartz grains may be due to combined subgrain rotation and bulging
218 recrystallizations (Stipp et al., 2002). The asymmetry of feldspar porphyroclasts with sigma-
219 type recrystallization tails (Fig. 4f), sigmoidal micafish (Fig. 4g), quartz ribbons, and shear
220 band geometry suggest a non-coaxial strain regime with a top-to-the-NE sense of shear (Fig.
221 4h, Passchier and Trouw 2005), in agreement with a normal-dextral sense of the shear.

222 In deformed granite samples (AU02, AU03, AU04, AU20, SE01 and SE02, Fig. 6),
223 quartz c-axis measurements reveal an incomplete type I crossed griddle pattern (Lister and

224 Hobbs 1980). Maxima around the main shortening direction axis (Z) indicate activity of basal
225 <a> slip systems, and the dominant recrystallization mechanism is bulging recrystallization
226 (Stipp et al. 2002). Submaxima distributed either close to the Y axis, or in between the Y and
227 Z axes stem from prism <a> and rhomb <a> slips (Bouchez 1977), with dominant subgrain
228 rotation recrystallization (Stipp et al. 2002). The coexistence of these slip systems may be due
229 to different activation temperature; at ca. 300°C, basal <a> slip is dominant, whereas, at
230 500°C, prism <a> is more important (Bouchez 1977; Stipp et al. 2002; Passchier and Trouw
231 2005) However, at low temperature, with an increasing strain, the slip sequence is basal <a>,
232 followed by prism <a>, and finally rhomb <a> (Passchier and Trouw 2005). Since basal <a>
233 slips are mainly observed in protomylonites, and both prism <a> and rhomb >a> slips are
234 dominant in the most deformed mylonites (Fig. 6), the second alternative seems more likely.
235 The asymmetry of the c-axis maxima suggests a non-coaxial progressive deformation, under
236 low to intermediate temperature, with a top-to-NE sense of shear in agreement with other
237 kinematic indicators.

238

239 4. New geochronological data

240 To constrain the age of the granitoid emplacement and the time of the ductile
241 deformation, monazite U-Th-Pb geochronology and micas $^{40}\text{Ar}/^{39}\text{Ar}$ dating have been carried
242 out.

243

244 4.1. Electron microprobe (EPMA) monazite geochronology

245 The EPMA U-Th-Pb dating on monazite is a chemical method based on two main
246 assumptions related to the mineral structure. (1) The common lead incorporated in monazite
247 during crystallization is negligible compared to the amount of radiogenic lead (Parrish 1990;
248 Cocherie et al. 1998), and (2) no radiogenic lead loss occurred since the system closure

249 (considered as the crystallization time in magmatic rocks). These assumptions have been
250 confirmed both by experimental studies, and by comparison of EPMA dating and
251 conventional U/Pb isotopic methods (Cocherie et al. 1998; 2005; Montel et al. 2002).
252 Moreover, altered domains with potential lead loss can be avoided with the EPMA resolution
253 (2 μm) associated with Backscattered Electron (BSE) microscopy. This monazite EPMA
254 method is well suited for the dating of leucogranite, as monazite is common in peraluminous
255 granite (e.g. Bé Mézème et al. 2006).

256 In-situ monazite grains were analyzed with a Cameca SX 50 electron microprobe, co-
257 operated by ITSO and BRGM, following the analytical procedure described in Cocherie et al.
258 (1998). Acceleration voltage is 20 kV, beam current is 200 nA, and U, Th, Pb absolute errors
259 are 105 ppm, 130 ppm and 110 ppm, respectively. The U-Th-Pb age calculations were done
260 by using the “EPMA dating” program written by Pommier et al. (2002). The age calculated
261 for each microprobe point analysis is rejected if out of the confidence range. The sorted
262 results are computed and plotted with the ISOPLOT program (Ludwig 1999; 2003). Due to a
263 relatively large range in Th/U ratios, the isochron method of Cocherie and Albarede (2001)
264 was used to produce the U/Pb vs Th/Pb diagrams reported in Figure 6. The following
265 parameters were extracted from the diagram and used to compute the best fit line age
266 calculation for each sample: (1) Th-Pb age (intercept with Th/Pb axis) and U-Pb age
267 (intercept with U/Pb axis) and their respective errors (2σ); (2) slope and error of the best fit
268 line, X-Y coordinates of the centroid of the best fit line. The results are statistically acceptable
269 if the following three conditions are fulfilled. : (1) The theoretical Mean Square Weight
270 Deviation (MSWD) is above the calculated MSWD, (2) the theoretical isochron crosscuts the
271 envelope error of each analysis and (3) the intercept ages are similar within the error margin.

272 In the studied samples, monazite grains are included in biotite and predate the
273 crystallization of the mica (Fig 7a). BSE images (Fig. 7b) of monazite in the Autun

274 undeformed leucogranite (AU16, N46°55'55''; E4°19'22'') show medium-sized euhedral to
275 sub-euhedral grains (50 to 100 μm) with no significant chemical zoning. The data scatter is
276 relatively good and an isochron age of 318 ± 7 Ma has been calculated on 8 grains (Fig. 7b).
277 The MSWD is slightly higher than the theoretical value (1.5 vs. 1.4).

278 BSE images of monazite in mylonitic Autun leucogranites sample (AU26,
279 N46°57'00"; 4°21'35") show euhedral grains not deformed during the ductile event and still
280 exhibiting typical growth zoning (Fig. 7c). Most of the analyses are clustered but, since some
281 analyses show a high U/Pb ratio, a best fit line can be drawn, and an isochron age of 321 ± 3
282 Ma has been calculated on 5 grains (Fig. 7c). The intercept ages (U-Pb age 323 ± 6 Ma and Th-
283 Pb age: 306 ± 36 Ma) are similar within errors. The MSWD is largely below the theoretical value
284 (0.23 vs. 1.30), a statistically meaningful result.

285 BSE images of monazite in the La Serre granite (SE03, N47°10'20"; E5°33'24") show
286 medium-sized sub-euhedral to anhedral grains (Fig. 7d). The data are widely spread in the
287 isochron diagram and a best fit line can be drawn. The calculation on 6 grains provides an
288 isochron age of 317 ± 5 Ma (Fig. 7d). Although the theoretical isochron is at the limit of the
289 error envelope of the best fit line, the results are acceptable as the intercept ages (U-Pb age
290 290 ± 30 Ma and Th-Pb age: 338 ± 25 Ma) are similar within error margin, and the calculated
291 MSWD is slightly lower than its theoretical value (1.3 vs. 1.38).

292

293 4.2. Deformation and cooling age of the Autun and the La Serre granites

294 In order to date the ductile faulting and to constrain the relationships between magmatism
295 and deformation, we performed $^{40}\text{Ar}/^{39}\text{Ar}$ dating on mylonites from the two shear zones and
296 on the Autun granite, and assumed that muscovite and biotite ages from these samples would
297 provide constraints on their cooling history in the 300°C-450°C range (Harrison et al. 1985,
298 2009; Hames and Bowring 1994). As these cooling temperatures are similar to those deduced

299 from LPO measurements in mylonitic rocks, the $^{40}\text{Ar}/^{39}\text{Ar}$ method should give a reliable
300 estimate of the age of deformation and an estimate of the cooling rate of the granite.

301 Details about the analytical procedure for laser probe $^{40}\text{Ar}/^{39}\text{Ar}$ dating can be found in
302 York et al. (1981), Dalrymple (1989), McDougall and Harrison (1999), Monié et al. (1994)
303 and Monié and Agard (2009). Each sample was first crushed and micas were separated under
304 a binocular from the 0.5-07 mm size fraction. After ultrasonic cleaning, micas were enveloped
305 in aluminium foils and irradiated at McMaster (Canada) together with several aliquots of the
306 MMhb1 monitor amphibole (520.4 ± 1.7 Ma; Samson and Alexander 1987). After irradiation,
307 the micas and standards were placed on a copper holder inside the sample chamber and heated
308 at 150°C under ultrahigh vacuum. Step-heating degassing of individual grains was performed
309 using a continuous CO_2 laser until complete fusion of the mineral. For each step, the released
310 gas was cleaned on getters and then introduced in a MAP 215-250 mass spectrometer for
311 analysis of the isotopic composition, estimated by regression on 15 runs. Extraction, cleaning,
312 and analysing processes involve 1, 2 and 8 minutes respectively. System blanks were realized
313 every three experiments. Depending on the samples, 9 to 17 steps were performed. Individual
314 age (Tab. 1) was calculated after usual isotope corrections including blanks, mass
315 discrimination, radioactive decay of ^{37}Ar and ^{39}Ar , and irradiation-induced mass interference.
316 For the MAP 215-250 mass spectrometer, a $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 285.0 ± 2.0 was used for mass
317 discrimination of all analyses. The uncertainty on the J-factor was propagated in the
318 calculation of the error on the total age of each sample, equivalent to a K–Ar age. Results are
319 reported as classical $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra (Fig. 8).

320 The term “plateau age” is defined as the segment of a spectrum, made of three consecutive
321 steps, containing more than 70% of the total ^{39}Ar released, and whose ages overlap within two
322 sigma errors (McDougall and Harrison, 1999). Ages are reported with a 1σ uncertainty. It is
323 worth to mention that the Autun shear zone experienced an important fluid circulation that

324 caused silicification, galena mineralization and secondary large muscovite flake
325 crystallization, probably during late brittle faulting (Delfour et al., 1991). Since this alteration
326 event possibly influenced the argon isotopic system, only unaltered samples were chosen.

327 Biotite from the inner part of the Autun granitic massif shows a discordant spectrum with
328 ages varying from 297 Ma to 308 Ma and a plateau age of 306.4 ± 4 Ma calculated on the last
329 70 % of ^{39}Ar released (sample AU29, N46°54'30"; E4°16'20", Fig. 8a). Muscovite from the
330 Autun protomylonite (sample AU17, N46°56'9"; E4°19'10", Fig. 8b) displays a slightly
331 discordant spectrum with ages ranging from 261 to 355 Ma. More than 80 % of the total ^{39}Ar
332 released gives a plateau age of 303.9 ± 3 Ma in the intermediate portion of the spectrum.

333 Biotite from the Autun granite (AU16, N46°55'55"; E4°19'22", Fig. 8c) has a discordant
334 spectrum with evidence of argon loss at the beginning of degassing and excess argon at the
335 end, resulting in ages varying from 133 Ma to 310 Ma. A plateau age of 299.6 ± 3 Ma has
336 been calculated on more than 75 % of ^{39}Ar released in the intermediate portion of the
337 spectrum. Muscovite from sample AU16 (Fig. 8d) shows a relatively flat spectrum with
338 values ranging mainly between 291 Ma and 301 Ma, with the exception of the first step
339 related to argon bound to the mica surface. A plateau age of 299.8 ± 3 Ma is calculated for
340 more than 80 % of the total ^{39}Ar released.

341 Biotite from the Autun mylonite (AU15, N46°56'24"; E4°18'53", Fig. 8e) displays a
342 highly discordant spectrum with ages varying from 220 Ma to 303 Ma and no plateau age. It
343 is likely that incipient chloritization is responsible for such a pattern, with combined effects of
344 argon loss and neutron-induced ^{39}Ar recoil (Turner and Cadogan, 1974; Ruffet et al., 1991).
345 Muscovite from sample AU15 gives a much less discordant spectrum with young ages for
346 low experimental temperatures (Fig. 8e). With the exception of the three first steps, the ages
347 are bracketed between 295 and 304 Ma, and a plateau age of 299.8 ± 3.0 can be calculated on
348 95% of the total ^{39}Ar released.

349 Muscovite from the La Serre mylonite (sample SE01Ms, 47°11'19"; 5°31'27", Fig. 8f)
350 displays a discordant spectrum ranging from 289 to 321 Ma, with argon excess released at
351 low experimental temperature. However for 75 % of the total ³⁹Ar released, ages are
352 bracketed between 296 Ma and 299 Ma and correspond to a plateau age of 298.2 ± 3 Ma. In
353 this sample, the deformation is very strong, and biotite is often replaced by chlorite.

354

355 5. Discussion

356

357 5.1. Regional correlations of the Autun and La Serre Faults

358 The western and eastern continuations of Variscan shear zones in the northern French
359 Massif Central remained speculative for a long time (Arthaud and Matte 1977). Rolin and
360 Stussi (1991) considered the Autun Shear Zone as an Upper Devonian to Middle
361 Carboniferous dextral wrench fault and, after restoring the sinistral offset of the Sillon
362 Houiller Fault, correlated it with the Marche-Combrailles Fault (see also Lerouge and
363 Quenardel 1985; Rolin & Colchen 2001). However, our new data and other recent ⁴⁰Ar-³⁹Ar
364 dating in the La Marche area (Gebelin et al. 2007) indicate that the Marche-Combrailles and
365 the Autun shear zones are two different shear zones. Recent geophysical studies also suggest
366 that the eastern continuation of the Marche-Combrailles Fault is the Avallon Fault (Edel
367 2008; Fig. 9). The eastern continuation of the Autun Shear zone is less hypothetical, as shown
368 by the similar structures observed along the La Serre Fault Zone. After restoring the E-W
369 offset related to the Cenozoic opening of the Bresse graben, the two areas belong to the same
370 fault system. However, vertical derivation of the Bouguer gravity anomaly map does not
371 support a direct continuity between the two shear zones (Edel, unpublished data), but rather
372 suggest that the Autun Shear Zone joins a fault zone parallel to the La Serre Shear Zone,
373 located about 10 km to the north of the La Serre Shear Zone. The southwestern extension of

374 the N65°E trending La Serre brittle Fault might be the fault that rims the Creusot Basin (Fig.
375 1). Presently, there is no evidence of the western continuation of the La Serre ductile shear
376 zone to the Morvan area. The La Serre ductile shear zone may extend westward below the
377 Creusot sedimentary basin. All these E-W to N65°E trending faults are crosscut by the La
378 Serre Southern brittle Fault (Fig. 3), a segment of the NE-SW striking Sainte-Marie-Aux-
379 Mines Fault. This sinistral fault hides the eastern extension of the Autun-La Serre fault system
380 (Fig. 9). However, recent work on the Upper Rhine graben (Edel et al. 2007; Ustaszewski and
381 Schmid 2007) and along the Rhine-Bresse Transfer Zone (Madritsch et al. 2008) indicate the
382 presence beneath the Mesozoic sedimentary cover of a large set of NE-SW to E-W pre-
383 Mesozoic steeply dipping faults that might represent the eastern continuations of the Autun-
384 La Serre fault system (Fig. 9). These Variscan faults were locally reactivated by the Late
385 Eocene-Oligocene extension in the Upper Rhine graben (Edel et al. 2007) or by the Pliocene
386 shortening during formation of the Jura fold-and-thrust belt (Giamboni et al. 2004). The
387 gentle curvature of the Autun La Serre Fault System, from an E-W trend, to the west, to an
388 ENE-WSW trend, to the east, could be related to local block rotations either due to Late
389 Variscan adjustments as suggested by Edel and Schulmann (2007) or by Oligocene extension
390 in the Bresse graben, or due to Pliocene tectonics of the Jura Mountains.

391

392 5.2. Timing of the extensional processes

393 Microstructural observations, and shape and lattice preferred orientation analyses
394 indicate several types of deformation. As deduced from quartz $\langle c \rangle$ axis measurements and
395 chessboard pattern, the Autun and La Serre plutons underwent a high-temperature
396 deformation, the mechanisms of which remains controversial; it could be either be due to
397 prism $\langle c \rangle$ slip (Mainprice et al. 1986) or grain growth and boundary migration (Gapais and
398 Barbarin 1986) or α to β quartz transition (Kruhl 1996). Whatever the mechanism is,

399 deformation likely occurred during granite emplacement. Furthermore, low- to intermediate
400 temperature shearing in protomylonites, mylonites and ultramylonites indicates a strain
401 gradient from the pluton margin, where a tectonic fabric dominates, to the pluton core, where
402 sub-solidus preferred orientation is prominent. Such a strain gradient could be due to
403 localized deformation either during magma crystallization or under solid-state conditions after
404 granite emplacement.

405 Monazite U-Th/Pb dating yields consistent ages at ca. 320-318 Ma (Namurian) for the
406 Autun and La Serre granites and the Autun mylonitic granite, indicating that the U-Th-Pb
407 system was not reset during deformation (Figs. 7 and 10). A modification of the chemistry of
408 the monazite can occur in amphibolite facies shear zones (Berger et al. 2006) but, in the
409 present case, the lack of core-and-mantle zoned grains and the preservation of growth zoning
410 suggest that monazite grains did not recrystallize during mylonitization. Moreover, since the
411 dated monazites are included in biotite, they predate the crystallization of the micas.
412 Crystallization of magmatic monazite in peraluminous systems occurs during granite
413 emplacement (Braun et al. 1998; Förster 1998), at temperatures of about 900°C (Cherniak et
414 al. 2004). Thus, the monazite U-Th/Pb ages mirror the crystallization age of the magma. The
415 Namurian age assignment is significantly different from the Stephanian age previously
416 proposed for the Autun granite (Rolin and Stussi 1991) and from the Devonian U-Pb (TIMS)
417 age proposed for the La Serre granite (Morre-Biot and Storet 1967). The consistency between
418 our new monazite U-Th/Pb ages and the petrographic and microstructural observations
419 reveals that mylonite formed at the expense of the Autun granite. During the pluton
420 emplacement, a poorly defined subsolidus fabric was acquired. However, the significance of
421 this magmatic preferred orientation is not clear and might be due to magmatic processes in the
422 magma chamber or to a combination of magma dynamics and regional tectonics (Brun and
423 Pons 1981).

424 Whatever the deformation gradient obtained in the Autun and La Serre areas might be,
425 the Late Carboniferous $^{40}\text{Ar}/^{39}\text{Ar}$ ages around 300 Ma show a regional consistency (Figs. 8
426 and 10a). One interpretation could be that a Late Carboniferous thermal event reset the argon
427 isotopic system, a phenomenon recognized for the Late Visean evolution in the central part of
428 the French Massif Central (Faure et al. 2002). Although a Stephanian to Permian volcanism is
429 recorded in the northeastern part of the French Massif Central (Carpena et al. 1987;
430 Chévremont et al. 1999), it seems to be too scattered and too small in volume to have caused
431 such a large thermal overprint.

432 Protomylonites and undeformed granite exhibit $^{40}\text{Ar}/^{39}\text{Ar}$ spectra with plateau ages
433 ranging from 305 to 300 Ma (Fig. 8), representing the time when the cooling path of the
434 granite intersected the mica closure temperature. Due to their different closure temperatures,
435 the concordance between muscovite and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages indicates a fast cooling
436 between 400°C and 300°C. The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of undeformed rocks is statistically
437 undistinguishable from those of mylonites (Figs. 8 and 10a). The range of closure temperature
438 of the two micas is similar to the temperature interval in which quartz lattice slip was
439 activated. The Stephanian age thus likely corresponds to the time of the low-temperature non-
440 coaxial ductile deformation experienced by the Autun and La Serre plutons. The age of this
441 ductile deformation is furthermore constrained by the Lower Autunian (303 Ma to 290 Ma)
442 sedimentary deposits of the Autun basin (Fig. 10). The earliest activity along the Autun-La
443 Serre shear zone remains unknown, as $^{40}\text{Ar}-^{39}\text{Ar}$ dating only provides the age of the youngest
444 ductile motion. Deformation the Autun-La Serre Fault System might have started before 305
445 Ma. However, several lines of evidence suggest that these granites are not syntectonic
446 plutons. High-temperature post-solidus shearing could not be demonstrated in the analyzed
447 rocks and only magmatic sub-solidus textures are observed in undeformed granites.
448 Moreover, the time gap of at least 15 myrs between granite emplacement and the last shear

449 motion would imply a long-lived localized tectonic zone. As described in the geological
450 outline section, such a time gap is not documented in the French Massif Central, where the
451 Namurian - Westphalian NW-SE extension was followed by the Stephanian - Permian NE-
452 SW extension (Faure and Becq-Giraudon 1993; Faure 1995). If a syntectonic granite had been
453 emplaced in Namurian times, it would probably have recorded the NW-SE stretching
454 associated with the widespread first extensional stage, (Faure 1995; Talbot et al. 2005; Joly et
455 al. 2009).

456 Our results demonstrate the existence of a Stephanian - Autunian NE-SW Autun-La Serre
457 transtensional shear zone system. Its age is slightly younger than the Westphalian to
458 Stephanian Pilat detachment fault that shows similar mechanisms and structures (Malavielle
459 et al. 1990). Although well documented (Burg et al. 1994; Faure 1995), the Stephanian -
460 Permian NE-SW stretching must be distinguished from the NW-SE Namurian - Westphalian
461 extension reported from the western part of the Massif Central (Faure, 1995). Extensional
462 structures are also documented beyond the Rhine Bresse transfer zone in the Vosges
463 Mountains and Black Forest. Similar to the French Massif Central, the convergence of
464 Gondwana and Laurussia has resulted in thrust tectonics and metamorphism in the Vosges
465 Mountains (Fluck et al., 1987; Rey et al. 1989; Schulmann et al. 2002), and in the Black
466 Forest (Wickert and Eisbacher, 1988; Eisbacher et al., 1989; Echtler and Chauvet 1992;). The
467 thickened crust experienced syn-orogenic to post-orogenic extension represented by
468 detachment faults and syntectonic plutons, documented in the Vosges Mountains (Rey et al.
469 1992; Kratinova et al. 2007), and in the Black Forest (Krohe and Eisbacher 1988; Eisbacher et
470 al. 1989; Echtler and Chauvet, 1992).

471

472 5.3. Implications for the thermal conditions during post-orogenic extension

473 As ^{40}Ar - ^{39}Ar ages of undeformed and deformed granites exhibit similar plateau ages
474 around 300 Ma and are ca. 15 myrs younger than the monazite U-Th-Pb ages of pluton
475 emplacement, the contemporaneity between the emplacement of plutons and the oblique-slip
476 displacement along the Autun-La Serre Shear Zone is ruled out. However, additional
477 geochronological studies are required to solve the question of « the synkinematic granites ».

478 Furthermore, the time gap of 15 myrs between U-Th/Pb ages and ^{40}Ar - ^{39}Ar ages of the
479 granite is larger than ca. 5 myrs cooling times from 750°C (emplacement temperature) to
480 300°C, experimentally established for similarly-sized leucogranites (Annen et al. 2006;
481 Annen and Scaillet 2006). We propose two different cooling paths (Fig. 10b). One two-stage
482 cooling path is characterized by a “normal cooling” during the first 5 myrs, with a 100°C/Myr
483 cooling rate, followed by a 10 myrs steady-state step around 300°C; in this case, ^{40}Ar - ^{39}Ar
484 ages of micas in undeformed granites should be close to U-Th/Pb ages and significantly older
485 than age of mylonitization. An alternative cooling model could be a single step path, with
486 continuous cooling from 800°C at 320 Ma to 300°C at 305 Ma. Such a 500°C temperature
487 drop in 15 myrs represents a 33°C/myr cooling rate. Such a slow rate would require a constant
488 heat flow during the Late Carboniferous in order to maintain a high mean crustal temperature.
489 The formation of the Velay migmatitic dome (Ledru et al. 2001) is characterized by a Late
490 Carboniferous continuous melting of the metasediments of the lower crust. Crustal melting,
491 assisted by underplating of mantle-derived magma (Williamson et al. 1996) from
492 asthenospheric upwelling (Ledru et al. 2001), supports the existence of a regional high heat
493 flow hypothesis in the Eastern Massif Central. However, this thermal anomaly remains
494 limited to the Velay area, and indications of an important Westphalian and Stephanian
495 magmatism are lacking in the Morvan, Vosges and Black Forest areas. The rare Stephanian
496 shoshonites in the Epinac basin (Chévremont et al., 1999) cannot account for a continuous
497 heat flow during the 315-300 Ma period. The most significant magmatic event recorded in

498 Morvan, Vosges and Black Forest areas dates back to Early Permian times (Lippolt and Hess,
499 1983; Carpena et al., 1987). The current available data do not allow to determine which
500 cooling path did the Autun and La Serre plutons follow.

501 Whatever its path is, cooling was followed by ductile and brittle faulting along the
502 Autun-La Serre transtensional fault system. The normal component deduced from field
503 observations and microstructural analysis could have accommodated the rapid exhumation
504 indicated by the cooling between 400°C and 300°C and by the rapid transition from ductile
505 conditions along the shear zone at 300 Ma to brittle, normal, syn-sedimentary faulting at
506 around 297 Ma (Figs. 8 and 10a). Such a ductile-brittle continuum is known in the Aegean
507 extensional realm (Mehl et al. 2005) and also in the Massif Armoricain (Turrillot et al.
508 submitted). In the Autun region, the ductile-brittle transition is also marked by a rotation of
509 the stretching direction from NE-SW in Stephanian - Early Autunian times to N-S in Late
510 Autunian times (Marteau 1983; Faure 1995). Under brittle conditions, exhumation continued
511 during Autunian times, accomodated by normal faulting. Evidence for Autunian normal
512 faulting can be observed in the sedimentary basin of Autun, where at least 1200 m of detrital
513 lacustrine and fluviatile sediments accumulated (Chévremont et al. 1999). Moreover, in the
514 sedimentary filling of the Autun basin, plant fragments were buried and transformed into coal.
515 Coalification requires rapid burial to ensure the preservation of the organic matter. The huge
516 abundance of coal in the Autun basin suggests that the subsidence of the basin was
517 tectonically controlled and was probably coeval with a rapid exhumation of the Variscan
518 basement.

519 In the northeastern French Massif Central, the post-orogenic evolution is characterized
520 by Namurian - Westphalian granite emplacement followed by Stephanian - Autunian NE-SW
521 extension. This last stage contributed to the exhumation of the Variscan rocks, although it
522 remains difficult to propose an exhumation rate for the Stephanian - Permian period since the

523 geothermal gradient at that time is unknown and since the estimation of the P-T conditions of
524 the granite before the initiation of the deformation is not available. The two-stages extension
525 interpretation agrees with Faure (1995) who pointed out that the Namurian - Westphalian
526 extension is more pronounced in the western part of the French Massif Central than in the
527 eastern part, where Stephanian to Permian extension is well recorded. The extensional
528 processes thus appear to be subdivided into small intervals of regionally localized shearina
529 and related to a large period of crustal melting.

530

531 6. Conclusion

532 New structural and geochronological data on the Autun and La Serre areas constrain
533 the Late Variscan evolution of the northeastern part of the French Massif Central. The
534 similarity between the Autun and La Serre shear zones suggests the existence of an ENE-
535 WSW trending fault system, which was probably reactivated under brittle conditions during
536 the Cenozoic. The major results include: 1) the recognition of normal-dextral ductile shear
537 zones and 2) documentation of a diachronism of ca. 15 myrs between the Namurian -
538 Westphalian pluton emplacement and the Stephanian - Permian extensional tectonics and
539 basin subsidence. The Stephanian - Autunian Autun and La Serre shear zones affected the
540 Namurian plutons during their post-emplacement cooling, but these plutons are not
541 synkinematic. This shows that the widespread idea of synkinematic plutonism as as a
542 characteristic of late-orogenic to post-orogenic extension suffers exceptions. Several points
543 remain unclear, such as the tectonic setting during the emplacement of the Autun pluton.
544 More detailed studies, such as a study of the anisotropy of the magnetic susceptibility of the
545 pluton, could improve our understanding of the Namurian - Westphalian extensional stage
546 and its relationships with plutonism.

547

548 Acknowledgements

549 This work is a part of F. Choulet's master thesis dissertation. Field and analytical expenses
550 have been funded by ISTO and Chrono-environnement. Alain Cocherie is acknowledged for
551 his help during monazite U-Th-Pb calculations. The authors thank G. Eisbaier and J-B Edel,
552 for constructive review.

553

554 References

555 Annen C, Scaillet B (2006) Thermal evolution of leucogranites in extensional faults:
556 implications for Miocene denudation rates in the Himalaya. Special Publication 268,
557 Geological Society, London pp 309-326

558 Annen C, Scaillet B., Sparks RSJ (2006) Thermal Constraints on the Emplacement
559 Rate of a Large Intrusive Complex: The Manaslu Leucogranite, Nepal Himalaya. *J Petrol*
560 47:71-95

561 Arthaud F, Matte P (1977) Late Paleozoic strike-slip faulting in southern Europe and
562 northern Africa: Result of a right-lateral shear zone between the Appalachians and the Urals.
563 *GSA Bull* 88:1305-1320, doi: 10.1130/0016-7606.

564 Bé Mézème E, Cocherie A, Faure M, Legendre O, Rossi P (2006) Electron
565 microprobe monazite geochronology of magmatic events: Examples from Variscan
566 migmatites and granitoids, Massif Central, France. *Lithos* 87:276-288

567 Berger A, Herwegh M, Gnos E (2006) Deformation of monazite in an amphibolite-
568 facies shear zone. *Geochem Cosmochim Acta* 70:18 Supp. 1 A47

569 Bergeron J (1889) *Etude géologique du Massif ancien situé au Sud du Plateau Central.*
570 Thèse Fac. Sci. Paris Ann Sci Géol, Masson, Paris

571 Berthé D, Choukroune P, Jegouzo P (1979) Orthogneiss, mylonite and non coaxial
572 déformation of granites: the example of the South Armorican Shear Zone. *J Struct Geol* 1:31-
573 34

574 Bouchez J-L (1977) Plastic deformation of quartzites at low temperature in an area of
575 natural strain gradient. *Tectonophysics* 39:25-50

576 Braun I, Montel J-M, Nicollet C (1998) Electron microprobe dating of monazite from
577 high-grade gneisses and pegmatites of the Kerala Khondalite Belt, southern India. *Chem Geol*
578 146:65–85

579 Brun J-P, Pons J (1981) Strain patterns of pluton emplacement en a crust undergoing
580 non-coaxial deformation, Sierra Morena, Southern Spain. *J Struct Geol* 3:219-229

581 Burg J-P, Matte P (1978) A cross-section through the French Massif Central and the
582 scope of its Variscan geodynamic evolution. *Ztg Dtsch Geol Ges* 109:429-460

583 Burg J-P, Van den Driessche J, Brun J-P (1994) Syn-to post-thickening extension in
584 the Variscan Belt of Western Europe: Modes and structural consequences. *Géologie de la*
585 *France* 3:33-51.

586 Campy M, Chauve P, Pernin C (1983) Notice explicative de la carte géologique de
587 Pesmes au 1:50000, Bureau de recherches géologiques et minières, Orléans

588 Carpena J, Doubinger J, Guérin R, Juteau J, Monnier M (1987) Le volcanisme acide
589 de l'Ouest Morvan dans son cadre géologique: caractérisation géochimique, structurale et
590 chronologique de mise en place. *Bull Soc Géol Fr* 7:839-859

591 Cherniak DJ, Watson EB, Grove M, Harrison TM (2004) Pb diffusion in monazite: a
592 combine RBS/SIMS study. *Geochem Cosmochim Acta* 68:829-840

593 Chévremont P, Rémond C, Marteau P et al (1999) Notice explicative de la carte
594 géologique d' Epinac-Les-Mines au 1:50000, Bureau de recherches géologiques et minières,
595 Orléans

596 Cocherie A, Albarède F (2001) An improved U-Th-Pb age calculation for electron
597 microprobe dating of monazite. *Geochem Cosmochim Acta* 65:4509-4522

598 Cocherie A, Legendre O, Peucat J-J, Kouamelan AN (1998) Geochronology of
599 polygenetic monazites constrained by in situ electron microprobe Th-U-total Pb
600 determination: implications for lead behaviour in monazite. *Geochem Cosmochim Acta*
601 62:2475-2497

602 Cocherie A, Bé Mézème E, Legendre O, Fanning CM, Faure M, Rossi P (2005)
603 Electron-microprobe dating as a tool for determining the closure of Th-U-Pb systems in
604 migmatitic monazites. *Am Mineral* 90:607-618

605 Coromina G, Fabbri O (2004) Late Palaeozoic NE-SW ductile-brittle extension in the
606 La Serre horst, eastern France. *C R Geoscience* 336:75-84

607 Courel L (2001) Histoire tardi-hercynienne et couverture méso-cénozoïque. *Géologues*
608 130-131:47-49

609 Dalrymple GB (1989) The GLM continuous laser system for. $^{40}\text{Ar}/^{39}\text{Ar}$ dating:
610 description and performance characteristics. *US Geol Surv Bull* 1890:89-96

611 Delfour J, Arène J, Clozier L, Carroue J-P, Cornet J, Delance J-H, Feys R, Lemièrre B
612 (1991) Notice explicative de la carte géologique d'Autun au 1:50000, Bureau de recherches
613 géologiques et minières, Orléans

614 Delfour J (1989) Données lithostratigraphiques et géochimiques sur le Dévono-
615 Dinantien de la partie sud du faisceau du Morvan (nord-est du Massif Central français).
616 *Géologie de la France* 4:49-77

617 Dewey J (1988) Extensional collapse of orogens. *Tectonics* 7:1123-1139

618 Duthou J-L, Cantagrel J-M, Didier J, Vialette Y (1984) Palaeozoic granitoids from the
619 French Massif Central: age and origin studied by ^{87}Rb - ^{87}Sr system. *Phys Earth Planet Inter*
620 35:131-144

621 Echtler H, Chauvet A (1992) Carboniferous convergence and subsequent crustal
622 extension in the southern Schwarzwald (SW Germany). *Geodin Acta* 5:37-49

623 Echtler H, Malavieille J (1990) Extensional tectonics, basement uplift and Stephano-
624 Permian collapse basin in a late Variscan metamorphic core complex (Montagne Noire,
625 Southern Massif Central). *Tectonophysics* 177:125-138

626 Edel J-B, Schulmann K, Rotstein Y (2007) The Variscan tectonic inheritance of the
627 Upper Rhine Graben: evidence of reactivations in the Lias, Late Eocene-Oligocene up to the
628 recent. *Int J Earth Sci* 96:305-325

629 Edel J-B, Schulmann K (2007) Paleomagnetic constraints on the evolution of the
630 Variscan belt in Carboniferous times. In: Schulmann K, Ledru P, Faure M, Lardeaux J-M
631 (eds.) *Mechanics of Variscan Orogeny: a modern view on orogenic research*. Sept 2007,
632 Orléans, Abstr Vol.

633 Edel J-B (2008) Structure et nature du socle anté-permien du Bassin de Paris d'après
634 les données gravimétriques et magnétiques - Le problème de l'Anomalie Magnétique du
635 Bassin de Paris (AMBP). *Géochronique* 105:31-37

636 Eisbacher GH, Lüschen E, Wickert F (1988) Crustal-scale thrusting and extension in
637 the Hercynian Schwarzwald and Vosges, Central Europe. *Tectonics* 8:1-21

638 England PC, Thompson AB (1986) Some thermal and tectonic models for crustal
639 melting in continental collision zones. In Coward MP, Ries AC (eds.) *Collision tectonics*.
640 Geological society of London, Special Publication, 19:83-94

641 Faure M, Becq-Giraudon J-F (1993) Sur la succession des épisodes extensifs au cours
642 du dés-épaississement carbonifère du Massif Central français. *C R Acad Sci, Paris* 316:967-
643 973

644 Faure M, Pons J (1991) Crustal thinning recorded by the shape of the Namurian-
645 Westphalian leucogranite in the Variscan Belt of the Northwest Massif Central, France.
646 *Geology* 19:730-733

647 Faure M, Leloix C, Roig J-Y (1997) L'évolution polycyclique de la chaîne
648 hercynienne. *Bull Soc Géol Fr* 168:839-859

649 Faure M, Bé Mézème E, Duguet M, Cartier C, Talbot J (2005) Paleozoic tectonic
650 evolution of medio-europa from the example of the French massif central and massif
651 armoricain. In: (eds.) Carosi R. Dias R. Iacopini D. and Rosenbaum G. The southern Variscan
652 belt, *Journal of the Virtual Explorer* 19 (5)

653 Faure M, Bé Mézème E, Cocherie A, Rossi P, Chemenda A, Boutelier D (2008)
654 Devonian geodynamic evolution of the Variscan Belt, insights from the French Massif
655 Central and Massif Armoricain. *Tectonics*. doi:10.1029/2007TC002115.

656 Faure M, Monié M, Pin C., Malusky H, Leloix C (2002) Late Visean thermal event in
657 the northern part of the French Massif central: new $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb-Sr isotopic constraints
658 on the Hercynian syn-orogenic extension. *Int J Earth Sci (Geol Rundsch)* 91:53-75

659 Faure M. (1995) Late orogenic carboniferous extensions in the Variscan French
660 Massif Central. *Tectonics* 14:132-153.

661 Floc'h J-P (1983) La série métamorphique du Limousin central, Thèse, Univ. Limoges.

662 Fluck P, Edel J-B, Gagny C, Montigny R, Piqué A, Schneider J-L, Whitechurch H
663 (1987) Le socle vosgien, segment de la chaîne varisque d'Europe : projet Vosges : état des
664 connaissances, propositions d'axes de recherches. *Géologie Profonde de la France*,
665 Document BRGM 146

666 Förster HJ (1998) The chemical composition of REE-Y-Th-U-rich accessory minerals
667 in peraluminous granites of the Erzgebirge-Fichtelgebirge region, Germany, Part I: The
668 monazite (Ce)-brabantite solid solution series. *Am Min* 83:259-272

669 Franke W (1989) Variscan plate tectonics in Central Europe. Current ideas and open
670 questions. *Tectonophysics* 169:221-228

671 Gapais D, Barbarin B (1986) Quartz fabric transition in a cooling syntectonic granite
672 (Hermitage massif, France). *Tectonophysics* 125:357-370

673 G ebelin A, Brunel M, Moni e P, Faure M, Arnaud N (2007) Transpressional tectonics
674 and Carboniferous magmatism in the Limousin, Massif Central, France: Structural and
675 $^{40}\text{Ar}/^{39}\text{Ar}$ investigations. *Tectonics* doi:10.1029/2005TC001822.

676 Giamboni M, Ustaszewski K, Schmid SM, Schumacher ME, Wetzel A (2004) Plio-
677 Pleistocene Transpressional Reactivation of Paleozoic and Paleogene Structures in the Rhine-
678 Bresse transform Zone (northern Switzerland and eastern France). *Int J Earth Sci* 93:207–223,
679 doi. 10.1007/s00531-003-0375-2

680 Hames WE, Bowring SA (1994) An empirical evaluation of the argon diffusion in
681 muscovite. *Earth Planet Sci Lett* 124:161-169.

682 Harrison TM, Duncan I, McDougall I (1985) Diffusion of ^{40}Ar in biotite : temperature,
683 pressure and compositional effects. *Geochim Cosmochim Acta* 49:2461-2468

684 Harrison TM, Celerier J, Aikman AB, Hermann J, Heizler MT (2009) Diffusion of
685 ^{40}Ar in muscovite, *Geochim Cosmochim Acta* 73:1039-1051.

686 Hibbard M.J. (1987) Deformation of incompletely crystallized magma systems:
687 granitic gneisses and their tectonic implications. *J Geol* 95:543-561

688 Joly A, Faure M, Martelet G, Chen Y, (2009) Gravity inversion, AMS and
689 geochronological investigations of syntectonic granitic plutons in the southern part of the
690 Variscan French Massif Central. *J Struct Geol* 31:421-443

691 Kratinova Z, Schulmann K, Edel J-B, Je ek J, Schaltegger U (2007) Model of
692 successive granite sheet emplacement in transensional setting: Integrated microstructural and
693 anisotropy of magnetic susceptibility study. *Tectonics* doi:10.1029/2006TC002035

694 Krohe A, Eisbacher GH (1988) Oblique crustal detachment in the Variscan
695 Schwarzwald, southwestern Germany. *Geol Rdsch* 77:25-43

696 Kruhl JH (1996) Prism- and basal-plane parallel subgrain boundaries in quartz: a
697 microstructural geothermobarometer. *J Metam Geol* 14:581-589

698 Lardeaux JM, Ledru P, Daniel I, Duchêne S (2001) The Variscan Drench Massif
699 Central – a new addition to the ultra-high pressure metamorphic “club”: exhumation
700 processes and geodynamic consequences. *Tectonophysics* 323:143-167

701 Launeau P, Robin P-YF (2005) Determination of fabric and strain ellipsoids from
702 measured sectional ellipses – Implementation and applications. *J Struct Geol* 27:2223-2233

703 Ledru P, Lardeaux J-M, Santallier D, Autran A, Quenardel J-M, Floch J-P, Lerouge G,
704 Maillet N, Marchand J, Ploquin A (1989) Où sont les nappes dans le Massif Central français?
705 *Bull Soc Géol Fr* 8:605-618

706 Ledru P, Courrioux G, Dallain C, Lardeaux J-M, Montel J-M, Vanderhaeghe O, Vitel
707 G (2001) The Velay dome (French Massif Central): melt generation and granite emplacement
708 during orogenic evolution. *Tectonophysics* 342:207-237

709 Leloix C, Faure M, Feybesse J-L (1999) Hercynian polyphase tectonics in north-east
710 French Massif Central: the closure of the Brévenne Devonian-Dinantian rift. *Int J Earth Sci*
711 88:409-421

712 Lerouge G, Quenardel J-M (1985) Chronologie des événements tectoniques dans le
713 Nord-Ouest du Massif Central français et le Sud du bassin de Paris du Carbonifère inférieur
714 au Plio-quadernaire. *C R Acad Sci, Paris* 301:621-626.

715 Lippolt HJ, Hess JC (1983) Isotopic evidence for the stratigraphic position of the Saar-
716 Nahe Rotliegend volcanism, I $^{40}\text{Ar}/^{40}\text{K}$ and $^{40}\text{Ar}/^{39}\text{Ar}$ investigations. *N Jb Geol Paläont*
717 713-730.

718 Lister GS, Hobbs BE (1980) The simulation of fabric development during plastic
719 deformation and its application to quartzite: the influence of deformation history. *J Struct*
720 *Geol* 2:355-371

721 Ludwig KR (1999) Users manual for ISOPLOT/EX, version 2. A geochronological
722 toolkit for Microsoft Excel – Berkeley Geochronology Center, Special Publication 1a

723 Ludwig KR (2003) User's manual for Isoplot 3.00. A geochronological toolkit for
724 Microsoft Excel. Berkeley Geochronology Center, 70 p.

725 Madritsch H, Schmid SM, Fabbri O (2008) Interactions between thin- and thick-
726 skinned tectonics at the northwestern front of the Jura fold-and-thrust belt (eastern France).
727 *Tectonics*. doi:10.1029/2008TC002282.

728 Mainprice D, Bouchez J-L, Blumenfeld P, Tubia J-M (1986) Dominant c-slip in
729 naturally deformed quartz: implications for dramatic plastic softening at high temperature.
730 *Geology* 14:819-822

731 Malavielle J, Guilhot P, Costa S, Lardeaux J-M, Gardien V (1990) Collapse of the
732 thickened Variscan crust in the French Massif Central: Mount Pilat extensional shear zone
733 and St-Etienne upper Carboniferous basin. *Tectonophysics* 177:139-149

734 Malavielle J (1987) Kinematics of compressional and extensional ductile shearing
735 deformation in a metamorphic core complex of the northeastern Basin and Range. *J Struct*
736 *Geol* 9:541-554

737 Marteau P (1983) Le bassin permo-carbonifère d'Autun. Stratigraphie, sédimentologie
738 et aspects structuraux. Document BRGM, 64

739 Mattauer M, Brunel M, Matte P (1988) Failles normales ductiles et grands
740 chevauchements. Une nouvelle analogie entre l'Himalaya et la chaîne hercynienne du Massif
741 central français. *C R Acad Sci, Paris* 306:671–676

742 Matte P (1986) Tectonics and plate tectonics model for the Variscan Belt of Europe.
743 Tectonophysics 126:329-374

744 Matte P (2001) The Variscan collage and orogeny (480-290 Ma) and the tectonic
745 definition of the Armorica microplate: a review. Terra Nova 13:117-121

746 Matte P (1991) Accretionary history and crustal evolution of the Variscan Belt in
747 western Europe. Tectonophysics 196:309-337

748 McClay KR, Norton MG, Coney P, Davis GH (1986) Collapse of the Caledonian
749 orogen and the Old Red Sandstones. Nature 323:147-149

750 McDougall I, Harrison TM (1999) Geochronology and Thermochronology by the
751 $^{40}\text{Ar}/^{39}\text{Ar}$ method. Oxford University Press, New York, USA

752 Mehl C, Jolivet L, Lacombe O (2005) From ductile to brittle: evolution and
753 localization of deformation below a crustal detachment (Tinos, Cyclades, Greece) Tectonics
754 doi:4010.1029/2004TC001767

755 Ménard G, Molnar P (1989) Collapse of a Hercynian Tibetan Plateau into a late
756 Palaeozoic European Basin and Range province. Nature 334:235-237

757 Monié P, Torres-Roldan RL, Garcia-Casco A (1994) Cooling and exhumation of the
758 western Betic Cordilleras, $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronological constraints on a collapsed terrane.
759 Tectonophysics 238:353-379

760 Monié P, Agard P (2009) Coeval blueschist exhumation along thousands of km :
761 implications for subduction channel processes, Geochem Geophys Geosyst 10, Q07002,
762 doi:10.1029/2009GC002428.

763 Montel J-M, Devidal JL, Avignand D (2002) X-ray diffraction study of brabantite-
764 monazite solid solutions. Chem Geol 191:89-104

765 Moore AC (1970) Descriptive terminology for the textures of rocks in granulite facies
766 terrains. Lithos 3:123-127

767 Morre-Biot N, Storet J (1967) Sur l'âge absolu du granite de la Serre. C R Acad Sci,
768 Paris 265:1869-1870

769 Morre-Biot N (1969) Étude pétrologique du socle cristallin du massif de la Serre, Bull
770 BRGM (2e série) I 3, 1-16.

771 Norton MG (1986) Late Caledonide extension in western Norway: a response to
772 extreme crustal thickening. *Tectonics* 5:195-204

773 Ogg JG, Ogg G, Gradstein FM (2008) *The Concise Geologic Time Scale*. Cambridge
774 University Press.

775 Parrish RR (1990) U-Pb dating of monazite and its application to geological problems.
776 *Can J Earth Sci* 27:1431-1450

777 Passchier CW, Trouw RAJ (2005). *Microtectonics*. Springer

778 Pin C, Dupuy C, Peterlongo J-M (1982) Répartition des terres rares dans les roches
779 volcaniques basiques dévono-dinantiennes du nord-est du Massif central. *Bull Soc Géol Fr*
780 7:669-676

781 Pin C, Peucat JJ (1986) Ages des épisodes de métamorphisme paléozoïques dans le
782 Massif central et le Massif armoricain. *Bull Soc Géol Fr* 8:461-469

783 Pin C (1990) Variscan oceans: ages, origins and geodynamic implications inferred
784 from geochemical and radiometric data. *Tectonophysics* 177:215-227

785 Pommier A, Cocherie A, Legendre O (2002) *EPMA Dating User's Manual: Age*
786 *Calculation from Electron Probe Microanalyser Measurements of U–Th–Pb*. BRGM
787 Documents, 9 p.

788 Quenardel J-M, Rolin P (1984) Palaeozoic evolution of the Plateau d'Aigurande (NW
789 Massif Central, France). *Special Publications* 14, Geological Society, London, pp 63-70

790 Rey P, Burg J-P, Lardeaux J-M, Fluck P (1989) Evolutions contrastées dans les
791 Vosges orientales: témoins d'un charriage dans la chaîne varisque. C R Acad Sci, Paris
792 309:815-821

793 Rey P, Burg J-P, Caron J-M (1992) Middle and Late Carboniferous extension in the
794 Variscan belt: structural and petrological evidence from the Vosges massif (eastern France).
795 Geodin Acta 5:17-36

796 Reynolds SJ, Spencer JE (1985) Evidence for large-scale transport on the Bullard
797 detachment fault, west-central Arizona. Geology 13:353-356

798 Roig J-Y, Faure M (2000) La tectonique cisailante polyphasée du S. Limousin
799 (Massif central français) et son interprétation dans un modèle d'évolution polycyclique de la
800 chaîne hercynienne. Bull Soc Géol Fr 171:295-307

801 Rolin P, Colchen M (2001) Carte structurale du socle Varisque Vendée-Seuil du
802 Poitou-Limousin. Géologie de la France, 1-2:3-6

803 Rolin P, Stussi J-M (1991) Décrochements intracrustaux et intrusions granitiques
804 carbonifères dans le Morvan (Massif central français). Bull Soc Géol Fr 162:839-859

805 Ruffet G, Féraud G, Amouric M (1991) Comparison of ^{40}Ar - ^{39}Ar conventional and
806 laser dating of biotites from the North Trégor Batholith. Geochim Cosmochim Acta 55:1675-
807 1688.

808 Samson SD, Alexander ECJ (1987) Calibration of the interlaboratory ^{40}Ar - ^{39}Ar dating
809 standard, MMhb-1. Chem Geol 66:27-34

810 Schulmann K, Schaltegger U, Jezek J, Thompson A, Edel J-B (2002) Rapid burial and
811 exhumation during orogeny: thickening and synconvergent exhumation of thermally
812 weakened and thinned crust (Variscan orogen in western Europe). Am J Sci 302:856-879

813 Simpson C, Wintsch RP (1989) Evidence for deformation-induced K-feldspar
814 replacement by myrmekite. J Metamorph Geol 7:261-275

815 Stipp M, Stünitz H, Heilbronner R, Schmid SM (2002) The eastern Tonale fault zone:
816 a “natural laboratory” for crystal plastic deformation of quartz over a temperature range from
817 250 to 750 °C. *J Struct Geol* 24:1861-1884

818 Talbot J-Y, Martelet G, Courrioux G, Chen Y, Faure M (2004) Emplacement in an
819 extensional setting of the Mont Lozère-Borne granitic complex (SE France) inferred from
820 comprehensive AMS, structural and gravity studies. *J Struct Geol* 26:11-28

821 Talbot J-Y, Faure M, Chen Y, Martelet G (2005) Pull-Apart emplacement of the
822 Margeride granitic complex (French Massif Central). Implications for the late evolution of the
823 Variscan orogen. *J Struct Geol* 27:1610-1629

824 Turner G, Cadogan PH (1974) Possible effects of ^{39}Ar recoil in ^{40}Ar - ^{39}Ar dating.
825 *Proceedings of the Fifth Lunar Science Conference* 2:1601-1615

826 Ustaszewski K, Schmid SM (2007) Latest Pliocene to recent thick-skinned tectonics at
827 the Upper Rhine Graben - Jura Mountains junction. *Swiss Journal of Geosciences* 100:293-
828 312

829 Vallé B, Courel L, Gélard J-P (1988) Les marqueurs de la tectonique synsédimentaire
830 et syndiagénétique dans le bassin stéphanien à régime cisailant de Blanzky-Montceau (Massif
831 Central, France). *Bull Soc Géol Fr* 8, IV 4:529-540

832 Wickert F, Eisbacher GH (1988) Two-sided Variscan thrust tectonics in the Vosges
833 Mountains, northeastern France. *Geodin Acta* 2:101–120

834 Williamson BJ, Shaw A, Downes H, Thirlwall MF (1996) Geochemical constraints on
835 the genesis of Hercynian two-mica leucogranites from the Massif Central, France. *Chem Geol*
836 127:25-42

837 York D, Hall CM, Yanase Y, Hanes JA, Kenyon WJ, (1981) $^{40}\text{Ar}/^{39}\text{Ar}$ dating of
838 terrestrial minerals with a continuous laser. *Geophys Res Lett* 8:1136-1138.

839

840 Figure captions

841 Figure 1: Geological map of the NW French Massif Central and the Vosges (modified
842 after Fluck et al., 1987; Coromina and Fabbri, 2004; Faure et al. 2008). Location of the Autun
843 and La Serre areas are also represented. AU: Autun Basin; EP: Epinac Basin; LC: Le Creusot
844 Basin; SH: Sillon Houiller; MCSZ: La Marche-Combrailles Shear Zone; ASZ: Autun Shear
845 Zone; SMF: La Serre Median Fault ; SMMF: Sainte-Marie-aux-Mines Fault.

846 Figure 2: a): Simplified geological map of the Autun area; b) cross section of the Autun
847 area c) stereoplots of foliations and lineations observed in the granite and along the mylonitic
848 zone.

849 Figure 3: a): Simplified geological map of the la Serre area (modified after Coromina
850 and Fabbri, 2004); b) cross section of the La Serre area c) stereoplots of foliations and
851 lineations observed in the granite and in the mylonite.

852 Figure 4: Microstructure of the granite and the mylonite of the Autun and La Serre
853 shear zones. Bt: biotite; Ms: muscovite; Ort: orthoclase; Plg: plagioclase; Qz: quartz. a:
854 undeformed, with weak preferred orientation Autun leucogranite, b: Shear bands (yellow)
855 cutting primary magmatic foliation (red) in Autun mylonite, c: chessboard texture in quartz
856 showing prismatic subgrains in the La Serre granite, d: myrmekite indicating syn-magmatic
857 deformation of the Autun granite, e: dynamically recrystallized quartz ribbons in the La Serre
858 mylonite, f: mantle porphyroclasts of a K-feldspar in Autun mylonite, with a σ -type shear
859 criterion, g: muscovite micafish in shear bands in Autun mylonite, h: detail of elongated
860 newly formed quartz grains developed by dynamic recrystallization in Autun mylonite.

861 Figure 5: 3D fabric of Autun granites and mylonites deduced from preferred
862 orientation of mica in three perpendicular planes. AU19 and AU16 are granites, AU20 and
863 AU02 are mylonites. Manual (Man.) and automatic (Auto.) measurements of the orientation

864 of elongated micas are given in rose diagrams with 10° equal intervals (see text for more
865 explanation).

866 Figure 6: Universal Stage measurements of the lattice preferred orientation of the
867 quartz c-axes of Autun granite (a) and La Serre granite (b). Schmidt stereographic net (lower
868 hemisphere) was used for projecting quartz c-axes. Contours are 1, 2, 3, 4, 5, 6, 7, 8% for 1%
869 area. For each area, the mylonite shows a well-developed quartz c-axis maximum
870 representative of crystal plasticity. The magmatic fabric in granite presents a high-temperature
871 preferred orientation.

872 Figure 7: a: Photomicrograph of a monazite grain enclosed in biotite in the La Serre
873 granite. Ap: Apatite; Bt: biotite; Mzt: monazite; Ort: orthoclase; Plg: plagioclase; Qz: quartz.
874 b, c and d) : Isochron Th/Pb vs. U/Pb diagrams of samples AU16, AU26 SE03. For each rock,
875 examples of Back-Scattered Electron Scan Electron Microscope images of analyzed monazite
876 grains are shown. See sample locations in Fig. 2 and Fig. 3.

877 Figure 8: $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of Autun granite and mylonite (a to e)) and La Serre
878 mylonites (f). See location in Fig. 2 and Fig. 3.

879 Figure 9: Simplified basement map of northeastern France. Deep Carboniferous basins
880 and faults are modified after Ustaszewski et al. (2007) and hidden leucogranites are inferred
881 from the gravimetric map of Edel (2008).

882 Figure 10: Synoptic chart of new geochronological data, showing that a ca. 15 myrs
883 time gap separates the pluton emplacement and the ductile deformation. Two possible cooling
884 paths of Autun and La Serre plutons are depicted.

885 Table 1 $^{40}\text{Ar}/^{39}\text{Ar}$ analytic data.

886

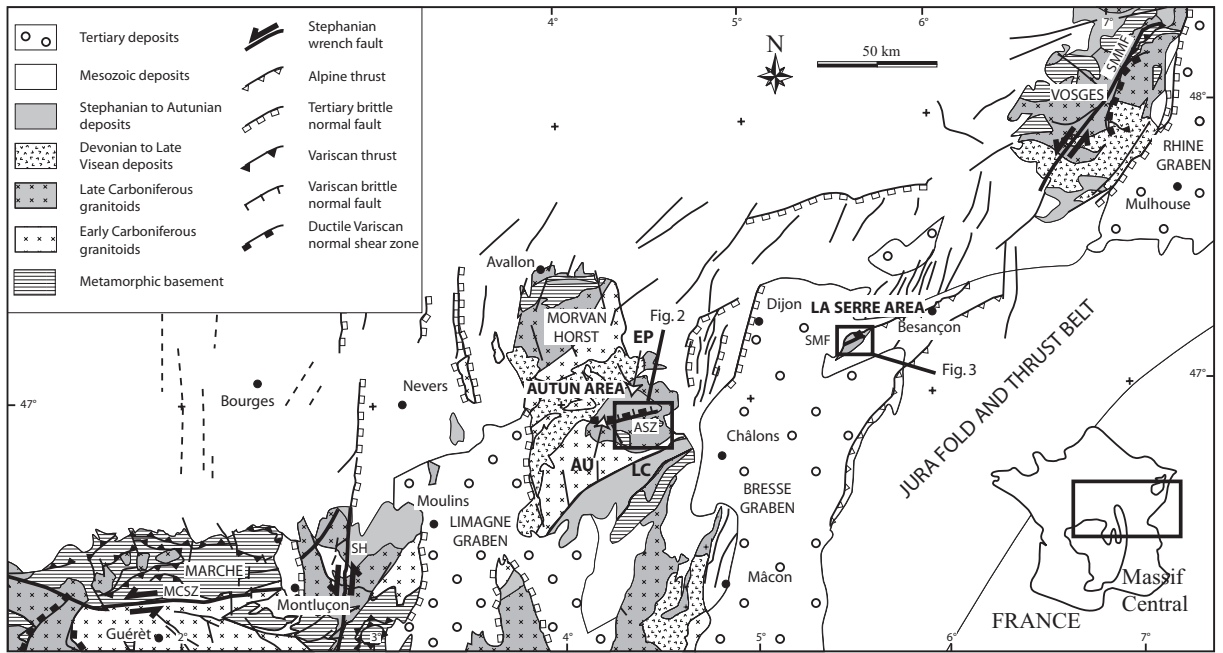
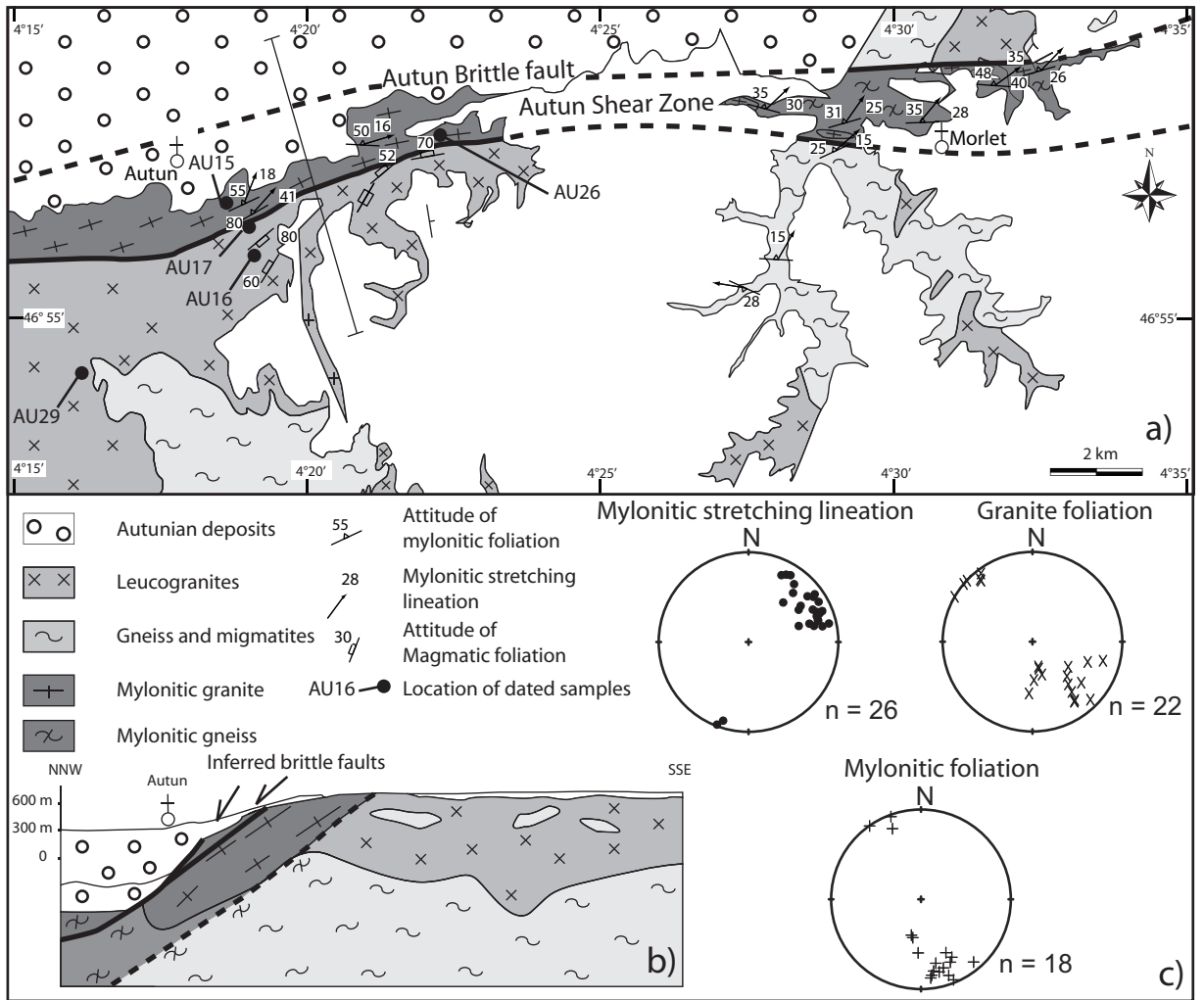


Figure 1

887

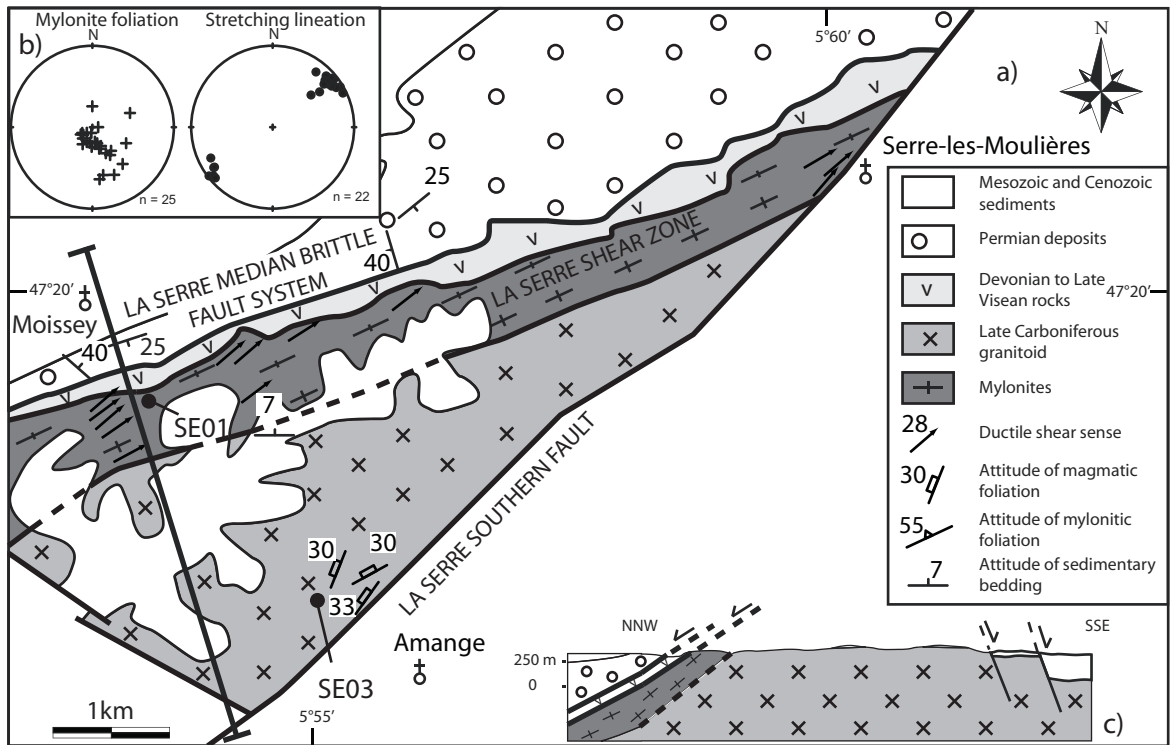
888



889

890

Figure 2



891

892

Figure 3

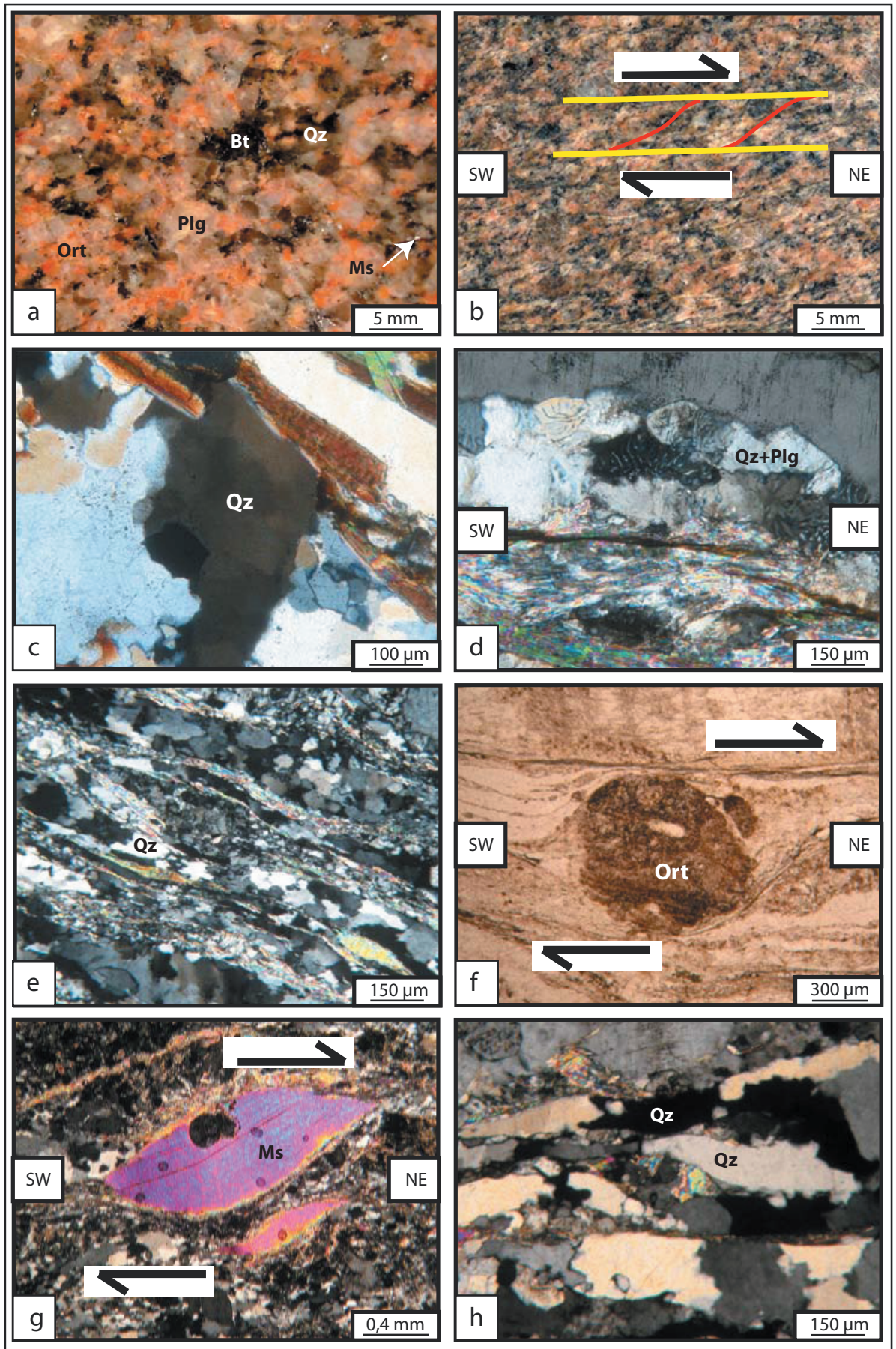


Figure 4

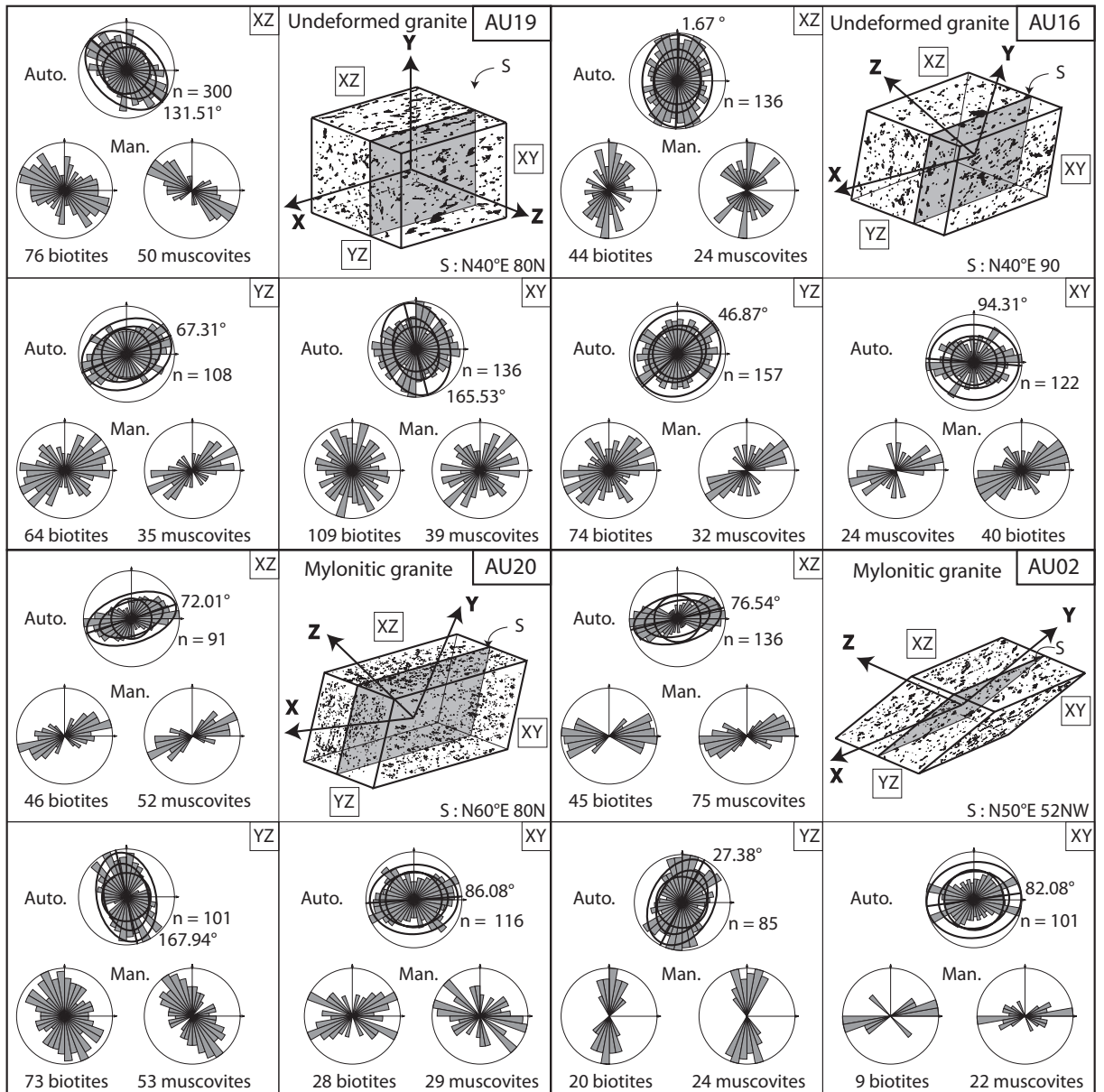


Figure 5

895

896

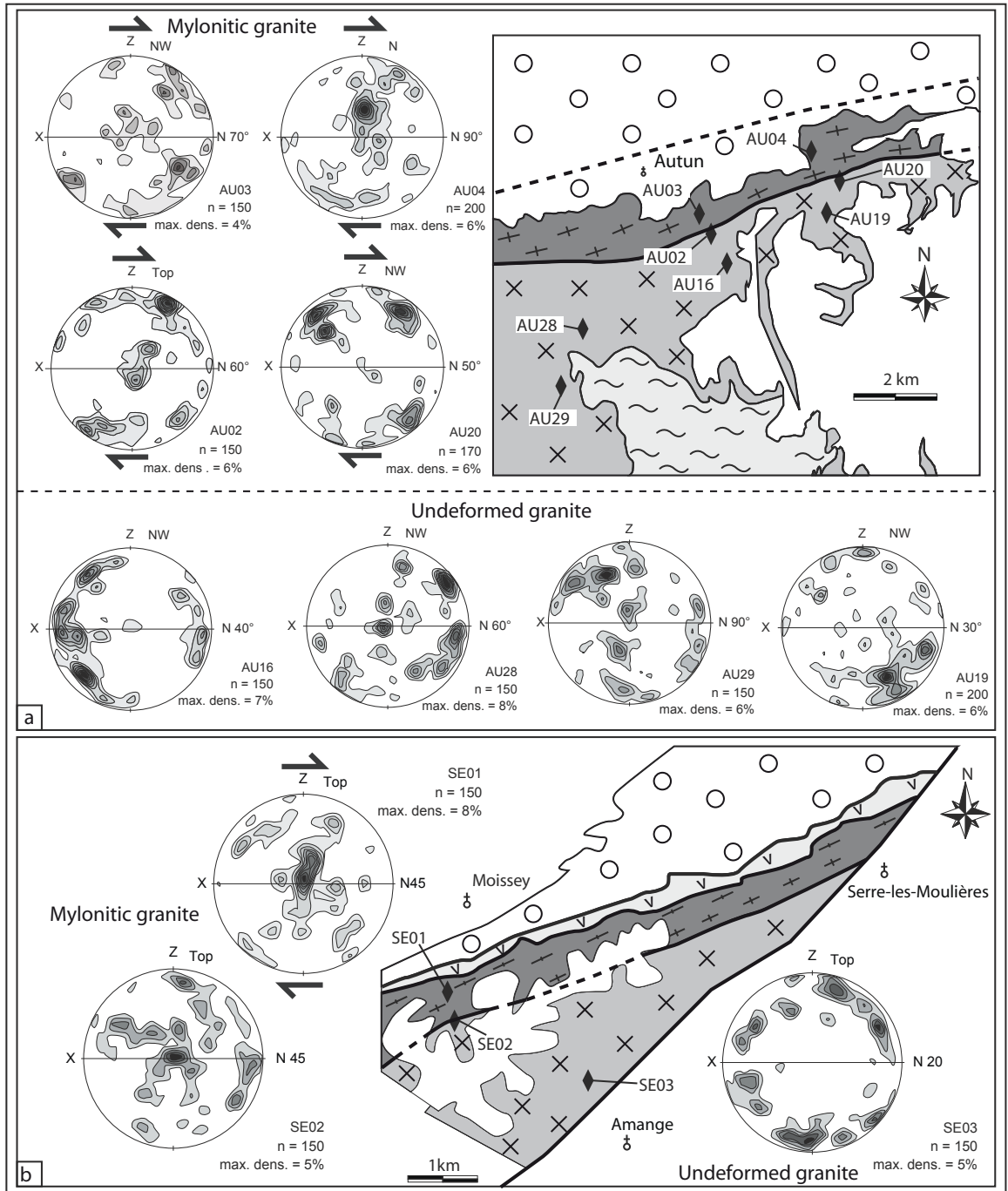


Figure 6

897

898

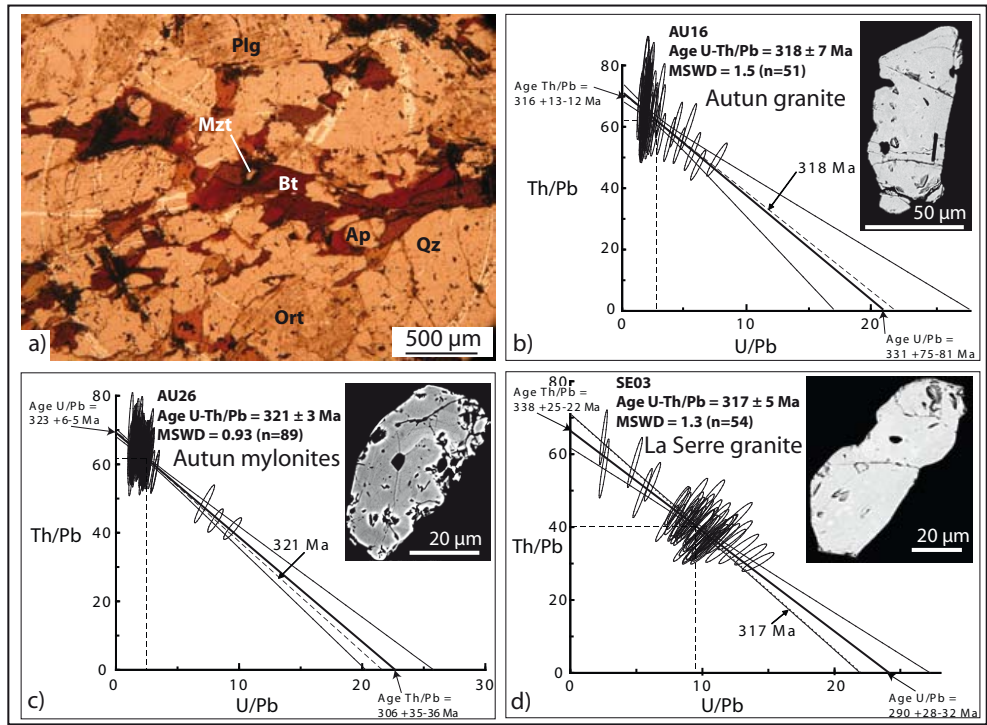


Figure 7

899

900

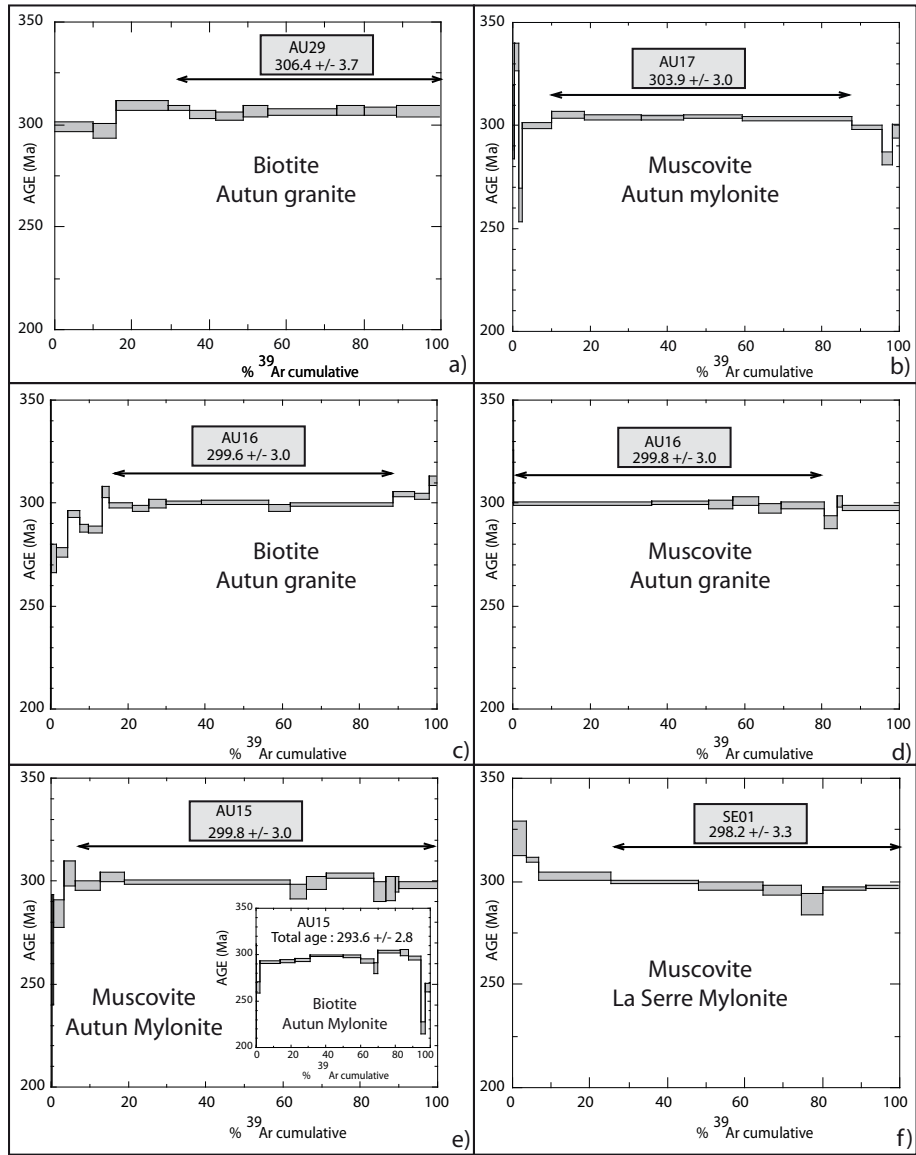


Figure 8

901

902

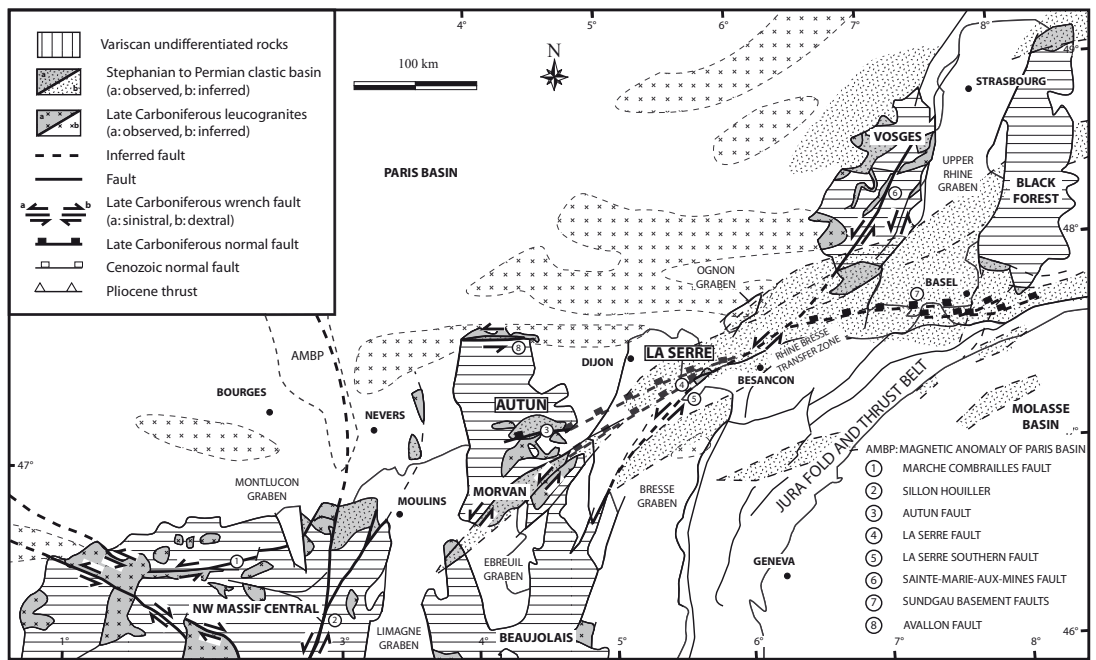


Figure 9

903

904

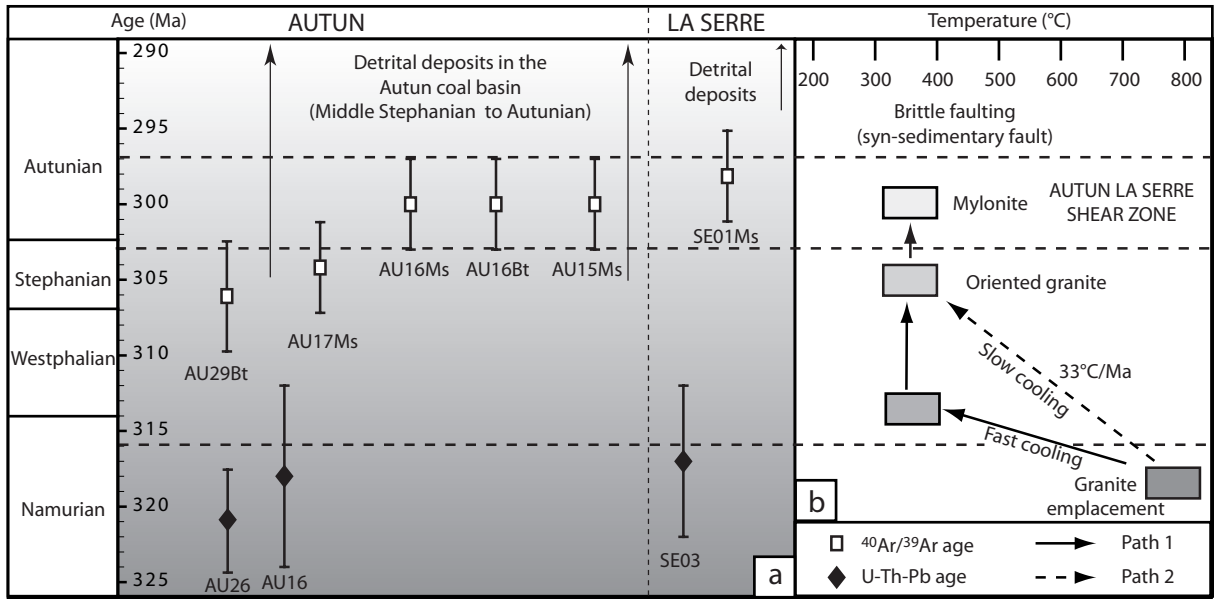


Figure 10

905

906

Step	⁴⁰ Ar/ ³⁹ Ar	³⁶ Ar/ ³⁹ Ar	³⁷ Ar/ ³⁹ Ar	³⁶ Ar/ ³⁹ Ar (.10.3)	% ³⁹ Ar (released)	% ⁴⁰ Ar*	⁴⁰ Ar*/ ³⁹ Ar _c	Age (Ma)	± 1s.Ma
AU16 Bt J= 0.00972									
1	399.480	0.445	0.17507	1325.176	0.14	1.97	7.89	133.3	245.8
2	41.632	0.066	0.00000	83.906	1.55	40.41	16.82	273.2	6.8
3	21.224	0.049	0.00000	14.202	4.40	80.15	17.01	276.1	2.2
4	19.546	0.047	0.00534	4.308	7.48	93.41	18.26	294.7	1.9
5	19.494	0.046	0.00863	5.695	9.78	91.29	17.80	287.8	2.0
6	19.191	0.048	0.02039	4.814	13.30	92.51	17.75	287.2	1.5
7	19.293	0.048	0.00389	1.020	15.21	98.36	18.98	305.4	2.9
8	18.948	0.043	0.01477	1.327	21.21	97.85	18.54	298.9	1.3
9	18.950	0.046	0.01560	1.710	25.47	97.26	18.43	297.3	1.5
10	18.805	0.046	0.00000	0.673	29.81	98.86	18.59	299.7	2.1
11	18.752	0.045	0.00638	0.390	39.11	99.31	18.62	300.1	1.0
12	18.791	0.047	0.00277	0.474	56.57	99.17	18.64	300.3	0.9
13	18.850	0.047	0.01177	1.291	61.99	97.90	18.45	297.6	1.8
14	19.055	0.046	0.00475	1.585	88.51	97.46	18.57	299.4	0.8
15	18.975	0.046	0.00000	0.194	94.26	99.62	18.90	304.3	1.4
16	19.063	0.046	0.00000	0.700	97.91	98.83	18.84	303.4	1.6
17	19.574	0.047	0.00000	0.720	100.00	98.83	19.35	310.9	2.3
								Total age : 298.3 +/- 2.8	
AU16 Ms J= 0.00972									
1	23.566	0.069	0.00000	0.075	0.25	99.84	23.53	371.6	45.7
2	18.772	0.014	0.00250	0.546	35.86	99.06	18.60	299.7	0.7
3	18.684	0.012	0.01567	0.163	50.60	99.66	18.62	300.1	0.9
4	18.843	0.013	0.01452	0.889	56.81	98.53	18.57	299.3	2.0
5	18.863	0.014	0.02630	0.578	63.66	99.02	18.68	301.0	2.0
6	19.147	0.014	0.00431	2.317	69.31	96.34	18.45	297.5	2.3
7	18.625	0.013	0.00419	0.259	80.61	99.51	18.53	298.8	1.7
8	18.504	0.013	0.00000	1.681	83.95	97.23	17.99	290.7	3.3
9	18.678	0.003	0.01472	0.000	85.22	99.92	18.66	300.8	2.8
10	18.634	0.012	0.00000	0.584	100.00	98.99	18.45	297.5	1.3
								Total age : 299.4 +/- 2.8	
AU17 Ms J= 0.00972									
1	63.087	0.132	0.00000	137.842	0.10	35.41	22.34	354.5	66.6
2	29.948	0.066	0.01518	37.907	0.45	62.55	18.73	301.8	17.8
3	22.628	0.019	0.00000	5.901	1.49	92.22	20.87	333.2	6.7
4	20.199	0.017	0.02163	14.006	2.35	79.44	16.05	261.5	8.1
5	19.184	0.013	0.01127	1.886	10.05	97.02	18.61	300.0	1.4
6	19.012	0.013	0.00000	0.118	18.61	99.73	18.96	305.2	1.8
7	18.909	0.012	0.00281	0.067	33.30	99.81	18.87	303.9	1.2
8	18.870	0.012	0.01473	0.000	44.22	99.92	18.86	303.6	1.0
9	18.957	0.012	0.00613	0.109	59.29	99.75	18.91	304.4	0.8
10	18.870	0.013	0.00052	0.066	87.68	99.81	18.83	303.3	1.1
11	18.562	0.012	0.01037	0.000	95.50	99.92	18.55	299.0	1.1
12	18.479	0.014	0.03320	3.118	98.19	94.94	17.54	284.1	3.0
13	18.932	0.010	0.05406	1.659	100.00	97.35	18.43	297.3	3.5
								Total age : 302.7 +/- 2.8	
AU15 Bt J= 0.00972									
1	21.501	0.015	1.18856	27.782	0.13	62.16	13.38	220.5	90.9
2	19.145	0.041	0.05400	9.726	2.15	84.93	16.26	264.7	6.0
3	19.269	0.037	0.00664	3.948	13.87	93.87	18.09	292.2	1.5
4	18.885	0.035	0.00736	2.429	22.29	96.12	18.15	293.2	1.7
5	18.748	0.036	0.01071	1.690	31.10	97.26	18.23	294.4	1.7
6	18.852	0.036	0.00534	0.996	50.01	98.36	18.54	299.0	1.0
7	19.063	0.038	0.00109	1.879	59.99	97.01	18.49	298.2	1.5
8	18.920	0.036	0.01655	2.516	67.57	95.99	18.16	293.3	2.5
9	18.689	0.038	0.07582	3.505	69.79	94.41	17.64	285.6	5.9
10	19.079	0.037	0.00000	0.792	82.82	98.69	18.83	303.2	1.4
11	19.578	0.039	0.00000	2.653	87.58	95.92	18.78	302.5	3.3
12	18.997	0.035	0.02738	2.098	94.66	96.66	18.36	296.3	2.1
13	19.586	0.044	0.00000	20.704	97.05	68.56	13.43	221.3	6.5
14	19.553	0.039	0.00000	11.124	100.00	83.11	16.25	264.6	4.6
								Total age : 293.6 +/- 2.8	
AU15 Ms J= 0.00972									
1	36.742	0.213	1.22569	113.397	0.16	9.01	3.31	57.2	95.9
2	21.106	0.021	0.40918	15.991	0.66	77.68	16.40	266.8	26.7
3	23.784	0.017	0.07458	21.037	3.42	73.82	17.56	284.3	6.7
4	20.026	0.015	0.01079	3.908	6.21	94.16	18.86	303.6	6.0
5	19.572	0.015	0.02945	3.655	12.78	94.41	18.48	298.0	2.3
6	19.078	0.013	0.00000	1.033	19.06	98.32	18.76	302.1	2.3
7	18.650	0.013	0.00062	0.200	61.87	99.60	18.58	299.4	1.0
8	19.113	0.012	0.00000	2.759	66.01	95.65	18.28	295.1	3.6
9	19.001	0.013	0.00000	1.427	71.11	97.70	18.56	299.3	3.1
10	18.814	0.013	0.00000	0.055	83.55	99.83	18.78	302.5	1.3
11	18.971	0.011	0.00994	2.316	86.61	96.31	18.27	294.9	4.8
12	19.166	0.014	0.00750	2.619	89.00	95.88	18.38	296.5	5.8
13	18.540	0.006	0.00000	0.000	89.99	99.92	18.52	298.7	3.8
14	18.835	0.011	0.00000	1.111	100.00	98.17	18.49	298.2	1.7
								Total age : 298.7 +/- 2.9	
SE01 Ms J= 0.009621									
1	20.815	0.020	0.00000	1.879	3.57	97.26	20.24	321.0	8.5
2	19.549	0.014	0.00000	0.000	6.77	99.92	19.53	310.7	1.4
3	19.007	0.010	0.00000	0.033	25.36	99.87	18.98	302.6	2.2
4	18.779	0.009	0.00000	0.000	48.12	99.92	18.76	299.4	0.8
5	18.673	0.009	0.00000	0.000	64.81	99.92	18.66	297.8	1.9
6	18.557	0.012	0.00000	0.002	74.58	99.91	18.54	296.1	2.3
7	18.449	0.006	0.02845	1.287	80.28	97.87	18.06	289.0	5.5
8	18.585	0.006	0.02262	0.000	91.42	99.92	18.57	296.6	0.9
9	18.643	0.005	0.01161	0.000	100	99.92	18.63	297.4	1.0
								Total age : 299.6 +/- 2.9	
AU29 Bt J= 0.009621									
1.00000	21.229	0.03600	0.00000	8.368	9.95000	88.28000	18.74000	299.06900	2.43500
2.00000	20.064	0.03300	0.00000	4.940	16.00000	92.65000	18.59000	296.82900	3.69700
3.00000	19.688	0.03300	0.00273	0.725	29.28000	98.83000	19.46000	309.58100	2.26800
4.00000	19.364	0.03100	0.03638	0.000	34.93000	99.92000	19.35000	308.02000	1.33700
5.00000	19.627	0.03200	0.00596	1.585	41.60000	97.54000	19.14000	304.98300	2.29300
6.00000	19.629	0.03300	0.00000	1.820	48.66000	97.18000	19.08000	303.98800	2.04600
7.00000	19.410	0.03200	0.00708	0.459	55.11000	99.22000	19.26000	306.67000	2.76900
8.00000	19.450	0.03300	0.00363	0.672	73.11000	98.90000	19.24000	306.33800	1.78700
9.00000	19.626	0.03200	0.00000	1.158	80.33000	98.18000	19.27000	306.80400	2.25700
10.00000	19.718	0.03300	0.01081	1.587	88.44000	97.55000	19.23000	306.31700	2.13500
11.00000	19.306	0.03200	0.00269	0.088	100.00000	99.79000	19.26000	306.74900	2.82400
								Total age : 305.6 +/- 2.9	