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# Monazite U–Th–Pb EPMA and zircon U–Pb SIMS chronological constraints on the tectonic, metamorphic, and thermal events in the inner part of the Variscan orogen, example from the Sioule series, French Massif Central

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## ► To cite this version:

Damien Do Couto, Michel Faure, Romain Augier, Alain Cocherie, Philippe Rossi, et al.. Monazite U–Th–Pb EPMA and zircon U–Pb SIMS chronological constraints on the tectonic, metamorphic, and thermal events in the inner part of the Variscan orogen, example from the Sioule series, French Massif Central. *International Journal of Earth Sciences*, 2016, 105, pp.557-579. 10.1007/s00531-015-1184-0 . insu-01167544

**HAL Id: insu-01167544**

**<https://insu.hal.science/insu-01167544>**

Submitted on 25 Jun 2015

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1 Monazite **U-Th-Pb** EPMA and zircon U-Pb SIMS chronological constraints on  
2 the tectonic, metamorphic and thermal events in the inner part of the Variscan  
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4

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## 15 **Abstract**

16 In the northern Variscan French Massif Central, the Sioule metamorphic series exposes from  
17 top to bottom the tectonic superposition of the Upper Gneiss Unit (UGU), Lower Gneiss Unit  
18 (LGU), and Para-autochthonous Unit (PAU). The nappe stacking developed throughout two  
19 **prograde** syn-metamorphic events: D<sub>1</sub> is a top-to-the SW shearing coeval with a **probable**  
20 Devonian migmatization, and D<sub>2</sub> is a top-to-the NW shearing **event**. Both events were  
21 completed before the unconformable deposition of the undeformed and unmetamorphosed  
22 “Tufs anthracifères” formation, dated at ca 330 Ma (Late Viséan). Furthermore, the UGU  
23 experienced a high pressure metamorphism ascribed to a D<sub>0</sub> event during which eclogite or  
24 granulite crystallized in several parts of the UGU. Monazite U-Th-Pb, and zircon U-Pb SIMS

25 datings were carried out in order to constrain the ages of these D<sub>0</sub>, D<sub>1</sub>, and D<sub>2</sub> tectonic-  
26 metamorphic events. These new geochronological results are placed in a P-T-t diagram  
27 constructed for the UGU, LGU, and PAU. Monazite sampled in UGU, LGU, PAU rocks  
28 yields similar 365-350 Ma ages consistent with the D<sub>2</sub> event dated in other places of the  
29 French Massif Central. A zoned monazite grain from a granulitic paragneiss yields 416±15  
30 Ma and 362±14 Ma ages interpreted as those of the D<sub>0</sub> and D<sub>2</sub> events, respectively. Zircon  
31 from the same granulitic paragneiss yields SIMS ages at 343±2 Ma, and 328±2 Ma that are  
32 interpreted as recrystallization processes associated with post-thickening thermal events,  
33 possibly recording the onset of orogenic collapse of the Northern Massif Central. It is worth  
34 to note that neither monazite nor zircon recorded the D<sub>1</sub> event.

35

36 **Key words** Variscan orogeny, monazite chemistry, monazite U-Th-Pb chemical dating,  
37 zircon SIMS geochronology, granulite facies, monazite chemistry, French Massif Central

38

39

40

## 41 **Introduction**

42 Dating **the syn-**metamorphic rocks and their related ductile fabrics remains a challenge.

43 **Indeed, many** of the common metamorphic phases such as biotite, muscovite, feldspar, and

44 amphibole can be dated by the  $^{40}\text{Ar}/^{39}\text{Ar}$  method, however it is well acknowledged that this

45 chronometer is highly sensitive **to any late thermal perturbation**, thus the radiometric ages

46 obtained by this method **may represent cooling ages or "re-opening" ages rather than genuine**

47 crystallization age of the dated minerals (**see Jourdan et al 2014 for a recent review**). Zircon is

48 also a common **accessory** phase used for U-Pb geochronology. Due to analytical

49 improvements, **punctual** measurements using SIMS, SHRIMP or LA-ICP-MS technique,

50 zircon yields precise age, however as for the  $^{40}\text{Ar}/^{39}\text{Ar}$  method, the significance of zircon U-

51 Pb geochronology must be carefully considered for dating metamorphic rocks since zircon

52 may crystallize or recrystallize at various stages of the rock history, including initial

53 magmatism formation stage for igneous protoliths. Monazite that may crystallize either from

54 magma or during metamorphic reactions appears as one of the **most useful** phase to assess the

55 timing of **tectono-**metamorphic events. **Although separated monazite grains can be dated by**

56 **SIMS or LA-ICP-MS**, the *in-situ* approach that preserves the textural relationships **between**

57 **minerals** allows the deciphering of superimposed magmatic and/or metamorphic high-

58 temperature stages. **Furthermore**, the size of the analytical spot (*ca* 20  $\mu\text{m}$ ) for LA-ICP MS

59 measurements generally prevents this detailed investigation **as metamorphic monazite is often**

60 **small-sized, chemically zoned or partly dissolved**. Nevertheless, though involving a non-

61 isotopic technique, **with a *ca* 5 to 15 Ma uncertainty, larger than the isotopic methods**, the

62 monazite U-Th-Pb EPMA method can provide one of the best estimate of the metamorphic

63 mineral crystallization ages in polymetamorphic terranes.

64 **Due** to the abundance of metapelitic and felsic magmatic protoliths, the Variscan belt

65 appears as a good example to determine the ages of successive tectono-metamorphic events,

66 in polymetamorphosed and polydeformed domains, particularly when thermo-barometric  
67 conditions preclude the use of temperature-sensitive geochronological methods such as  
68  $^{40}\text{Ar}/^{39}\text{Ar}$ . This paper aims to apply the monazite U-Th-Pb EPMA chemical, and zircon U-Pb  
69 SIMS dating methods to the Sioule metamorphic series, in the Northern part of the Variscan  
70 French Massif Central since **in this area**, the tectonic-metamorphic succession is **already** well  
71 established, but radiometric constraints still rare, **as presented in the following sections (e.g.**  
72 **Faure et al. 1993, 2002; Schulz et al. 2001; Schulz 2009).**

73

74

## 75 **Geological outline of the Variscan French Massif Central**

76 The stack of nappes

77 The French Massif Central (FMC thereafter) is an important segment of the Variscan Belt that  
78 results of a complex interplay between two main continents, namely Gondwana, and  
79 Laurussia, and several intervening microcontinents such as Avalonia, Mid-German  
80 Crystalline Rise, and Armorica (e.g. Matte 2001; Cocks 2000; Faure et al. 2005; Murphy et al.  
81 2011). It is now well acknowledged that the bulk architecture of the French Massif Central,  
82 alike the southern part of the Massif Armoricain or the Vosges-Black Forest massif, is a stack  
83 of metamorphic nappes developed diachronously from Late Silurian to Early Carboniferous at  
84 the expense of the north Gondwana margin (Matte 1986; Ledru et al. 1989; Faure et al. 2005,  
85 2009; Lardeaux et al. 2014; Fig . 1).

86 From bottom to top, and South to North, the following units are recognized (Figs. 1, 2). *1)*

87 *The foreland basin* develops in the southernmost part of the Massif Central. It is an **Early**  
88 Carboniferous (Visean-Serpukhovian) turbiditic basin that extends southward below the  
89 coastal plain of the Mediterranean Sea. *2) The Paleozoic Fold-and-Thrust Belt* consists of  
90 Early Cambrian to Visean unmetamorphosed sedimentary rocks displaced to the South as

91 thrust sheets or kilometre-scale recumbent folds well. There, the Early Devonian (i. e.  
92 Lochkovian, 416-411 Ma) unconformity argues for an Early Paleozoic tectonic event (at ca  
93 420-400 Ma), which is also recorded to the North of the Massif Central in the Lower and  
94 Upper Gneiss metamorphic units (cf. below). 3) *The Para-autochthonous Unit* that  
95 overthrusts the Paleozoic Fold-and-Thrust Belt is formed by greenschist to epidote-  
96 amphibolite facies metapelites, metagreywackes, quartzites, and a small amount of marbles  
97 and metabasites. In the northern Massif Central, the Para-autochthonous Unit crops out in  
98 tectonic windows surrounded by the Lower Gneiss Unit. In the Cévennes area, some granitic  
99 plutons, now transformed into orthogneiss, intruding the series, yield Cambrian to Early  
100 Ordovician zircons (Bé Mézème et al. 2006). 4) *The Lower Gneiss Unit (LGU)* is composed  
101 of metagreywackes, metapelites, and metarhyolites intruded by Cambrian to Early Ordovician  
102 porphyritic alkaline granitoids transformed into augen orthogneiss during the tectonic-  
103 metamorphic events. The LGU underwent a Middle Devonian metamorphism leading to  
104 crustal melting coeval with a ductile shearing dated in the Limousin at 375-370 Ma (Faure et  
105 al. 2008) and attributed to the D<sub>1</sub> event (cf below). Moreover, the LGU also experienced a  
106 medium pressure/medium temperature metamorphism characterized by a biotite-garnet-  
107 staurolite assemblage, dated at ca. 360-350 Ma (Costa 1989; Melleton et al. 2009), and  
108 attributed to the D<sub>2</sub> event. 5) *The Upper Gneiss Unit (UGU)* forms the overlying nappe whose  
109 the main protoliths are metapelites and metagrauwackes. This unit contains high-pressure  
110 rocks, such as eclogites or high pressure (HP) granulitic orthogneiss that may locally reach the  
111 coesite-eclogite facies (Santallier 1981; Pin and Vielzeuf 1988; Lardeaux et al. 2001; Berger  
112 et al., 2010). The upper part of the UGU consists of Devonian migmatites, yielding zircon U-  
113 Pb ages at ca 385-380 Ma, attributed to the D<sub>1</sub> event, and formed by the partial melting of  
114 pelitic and quartzo-feldspathic rocks (Duthou et al. 1994; Faure et al. 2008). These rocks  
115 contain amphibolite blocks derived from retrogressed eclogites that did not experience partial

116 melting. The HP metamorphism is dated at ca 420-400 Ma by U-Pb and Sm-Nd methods in  
117 several locations (Pin and Peucat 1986; Paquette et al. 1995; Faure et al. 2005).

118 The five units described above represent the classical nappe pile of the FMC in which the  
119 metamorphism increases from bottom to top. Furthermore, in the northern part of the French  
120 Massif Central, the undeformed and unmetamorphosed “Tuffs anthracifères” series, which  
121 consists of terrigenous rocks (sandstone, shales, conglomerates), coal measures, and felsic  
122 magmatic rocks (dacites and rhyolites), is dated as Late Viséan (*ca* 330 Ma, Bruguier et al.  
123 1998). These rocks unconformably cover Late Devonian-Early Carboniferous plutonic or  
124 metamorphic rocks of the UGU and LGU. The “Tuffs anthracifères” series provides a major  
125 time constraint for the evolution of the French Massif Central. As the “Tuffs anthracifères”  
126 series is coeval with the development of the Fold-and-Thrust Belt, it supports the north-south  
127 diachronism in the deformation at the scale of the entire massif.

128

129 The polyphase tectono-metamorphic evolution

130 The Variscan geodynamic evolution of the French Massif Central remains disputed. Some  
131 authors (e.g. Matte 1986; Ledru et al. 1989) consider that the formation of the FMC results of  
132 a continuous north-directed **oceanic then continental** subduction from early Silurian to early  
133 Carboniferous. **In contrast**, other authors (e.g. Pin 1990; Faure et al. 1997, 2008, 2009) argue  
134 for a polycyclic evolution. The Early Silurian to Early Devonian events correspond to the Eo-  
135 Variscan cycle due the collision of the Armorica microcontinent with the north Gondwana  
136 margin. From Middle Devonian to Early Carboniferous, the Variscan belt develops due to the  
137 southward subduction of the Rheic Ocean below Gondwana followed by the collision of  
138 Gondwana with Laurussia. In spite of differences between the two geodynamic scenarii, most  
139 of authors agree on the main tectonic, metamorphic, and magmatic events. Six tectono-  
140 metamorphic events are recognized (Faure et al. 2009).

141 The earliest event, D<sub>0</sub>, corresponds to the high to ultra high-pressure metamorphism  
142 recorded in the eclogite facies rocks of the UGU. Most of the HP rocks derive from mafic  
143 protoliths, but also HP relics are also found in orthogneiss are locally found. In the Lyonnais  
144 area, the UGU eclogites record pressure and temperature conditions of 1.8-2 GPa and 650-  
145 750°C, respectively (Lardeaux et al. 2001). On the basis of the HP metamorphism, the D<sub>0</sub>  
146 event took place around 415 Ma (Pin and Peucat 1986).

147 The Early to Middle Devonian, tectonic-metamorphic event D<sub>1</sub>, is coeval with the  
148 crustal melting of the metapelites and orthogneiss of the UGU and LGU, whereas mafic rocks  
149 are preserved as amphibolite restitic blocks in migmatites. The migmatisation is dated as  
150 Middle Devonian (385-375 Ma) in the Limousin or Lyonnais areas (Duthou et al. 1994, Faure  
151 et al. 2008 and enclosed references). P-T estimates from garnet-plagioclase and garnet-biotite  
152 pairs in migmatites, indicate metamorphic conditions of 0.7±0.05 GPa and 700±50°C  
153 respectively (Mercier et al. 1991; Roig and Faure 2000). The flat-lying foliation exhibits a  
154 NE-SW striking (N30 to N60E) stretching lineation marked by fibrolitic sillimanite or biotite  
155 in migmatites, and biotite or amphibole in amphibolites. Shear criteria indicate a top-to-the-  
156 SW displacement (Ledru et al. 1989; Faure et al. 1997; Roig and Faure 2000). Amphibolite in  
157 the northern Massif Central yields biotite and hornblende <sup>40</sup>Ar/<sup>39</sup>Ar cooling ages ranging from  
158 390 Ma to 381Ma (Costa and Maluski 1988; Boutin and Montigny 1993). In northeastern  
159 Massif Central, or Morvan area, Middle Devonian unmetamorphosed and undeformed  
160 sedimentary rocks unconformably overlying migmatites with eclogite relics suggest that, at  
161 least in the northern part of the Massif Central, the HP rocks were already exhumed before the  
162 Middle Devonian (Faure et al. 1997).

163 In the LGU, UGU, the dominant fabric is a NW-SE trending stretching lineation  
164 developed either on flat-lying or steeply dipping foliations, which is attributed to the D<sub>2</sub> event  
165 (Faure et al. 2005, 2008). Thermo-barometric constraints are well established in the Limousin



166 and Rouergue areas (Duguet et al. 2006; Bellot and Roig 2007). In the UGU, the syn-D<sub>2</sub>  
167 minerals, crystallized along the NW-SE lineation, indicate 0.7-1 GPa and 600-700°C  
168 metamorphic conditions. Paragneiss belonging to the LGU yield nearly similar conditions of  
169 0.8-1 GPa and 550-600°C. In the LGU, amphibolites that never experienced the high-pressure  
170 event indicate 0.8-1 GPa and 700-800°C metamorphic conditions (Santallier 1981). The D<sub>2</sub>,  
171 event, characterised by a top-to-the-NW ductile shearing, is widely documented from the  
172 southeast Massif Central up to the Southern part of the Massif Armoricain. This deformation  
173 is stratigraphically dated as pre-Early Viséan (i.e. older than 345 Ma) by the unconformity  
174 recognized in the Brévenne area (e.g. Leloix et al., 1999 and enclosed references, Fig. 1). The  
175 age of the syn-D<sub>2</sub> MP/MT metamorphism is constrained by <sup>40</sup>Ar/<sup>39</sup>Ar method on biotite,  
176 muscovite and amphibole, and by EPMA on monazite between 360 and 350 Ma (Costa 1989;  
177 Leloix et al. 1999; Melleton et al. 2009).

178 The syn-metamorphic D<sub>3</sub> deformation is recognized only in the Para-autochthonous  
179 Unit of the southern part of the Massif Central that experienced a first deformation at *ca* 340-  
180 335 Ma (Caron 1994; Faure et al. 2005). Further south, south-verging recumbent folds and  
181 thrusts of the Paleozoic series dated of Late Viséan-Early Namurian (*ca* 325 Ma) by the syn-  
182 orogenic sediments of the foreland basin, are also related to the D<sub>3</sub> event. This progressive  
183 southward younging of the nappe tectonics is coeval with the development of a flat-lying  
184 foliation and a N-S to NE-SW striking stretching lineation. In contrast to the southern part of  
185 the Massif Central, in its northern part, the Late Viséan deformation develops under brittle  
186 conditions. It is represented by a NW-SE stretching, related to the emplacement of NE-SW  
187 striking dykes of basalt, dacite, and microgranite in the Tuff Anthracifères series. This  
188 deformation is interpreted as the onset of the syn-orogenic extension (Faure 1995).

189 Ductile normal faults, such as Argentat or Nantiat faults, coeval with Serpukhovian-  
190 Bashkirian (or Namurian-Westphalian in W. European stratigraphy, *i.e.* 325-315 Ma)

191 synkinematic granite emplacement, argue for an extensional tectonic phase named the D<sub>4</sub>  
192 event (Faure 1995). As shown by petrofabric and AMS studies, most of the Late  
193 Carboniferous leucogranite and porphyritic monzogranite plutons and their metamorphic  
194 aureoles exhibit a well-defined NW-SE trending mineral or stretching lineation (Talbot et al.  
195 2005; Joly et al. 2007). The tectonic-plutonic D<sub>4</sub> event, widespread in the entire Massif  
196 Central, is interpreted as a syn-orogenic extensional process since at this time, compression  
197 was still active in the northern and southern outer zones of the Variscan belt, such as Ardenne  
198 and Montagne Noire-Pyrénées, respectively.

199         The last phase in the structural evolution of the French Massif Central is a Late  
200 Carboniferous (Kasimovian-Ghzelian, or Stephanian) D<sub>5</sub> late-orogenic extensional event that  
201 is distinguished from the previous one by the NNE-SSW strike of the maximum stretching  
202 direction. Intramontane coal basins develop either as half-grabens or left-lateral pull-aparts  
203 depending on the strike and kinematics of the bounding fault that controls the basin opening  
204 and sedimentary infill.

205

### 206 **The Sioule metamorphic series**

207 The bulk architecture

208 Located in the northern part of the French Massif Central, the Sioule metamorphic series is  
209 bound to the west by the Late Carboniferous Sillon Houiller sinistral wrench fault, and to the  
210 east by the Oligocene Ebreuil and Limagne grabens (Figs. 1, 2). The Tréban Massif and the  
211 S<sup>te</sup>-Christine wrench fault are the northern and southern limits of the Sioule metamorphic  
212 series, respectively (Fig. 2). The metamorphic series is intruded by two granitic plutons. The  
213 Pouzol-Servant porphyritic microgranite is a biotite granite dated at *ca* 330 Ma (Pin, 1991).  
214 The Echassières leucogranite is a small, differentiated, peraluminous pluton dated *at ca* 310  
215 Ma (Duthou and Pin 1987; Cheilletz et al. 1992). The Sioule series is a classic example of an  
216 inverted metamorphic sequence in the Massif Central (Grolier 1971). Three lithological and

217 structural units have been described (Richard 1938; Grolier 1971; Faure et al. 1993). From top  
218 to bottom, they are: a) an upper unit composed of biotite-sillimanite gneiss, and biotite-  
219 sillimanite± cordierite migmatite developed at the expense of the underlying gneiss that  
220 enclose a few meter-sized boudins of kyanite-garnet-plagioclase high-pressure granulitic  
221 paragneiss partly retrogressed under amphibolite facies conditions (Ravier and Chenevoy  
222 1979). This unit is correlated with the Upper Gneiss Unit (UGU) of the French Massif Central  
223 (cf section 2); b) an intermediate unit formed by biotite-muscovite-sillimanite-K feldspar-  
224 garnet paragneiss corresponding to the Lower Gneiss Unit (LGU), and c) a biotite-staurolite-  
225 garnet micaschist that crops out around the Echassières pluton. This unit, which is structurally  
226 below the two micas paragneiss of the LGU, **lacks of orthogneiss and anatectic melts, it is**  
227 **therefore** correlated with the Para-autochthonous Unit (PAU).

228

229 Structural outline of the Sioule metamorphic series

230 In the study area, the observed structures, and the related kinematics account well for a  
231 multistage tectonic evolution. In agreement with previous works (Grolier 1971; Feybesse and  
232 Teygey 1987; Faure et al. 1993; Schulz et al. 2001; Schulz 2009), the foliation is folded by  
233 NNW-SSE trending km-scale upright synform and antiform (Fig.2). A WNW-ESE striking  
234 stretching and mineral lineation is well developed in the foliation plane of the PAU, LGU, and  
235 UGU. Microscope-scale shear criteria, such as sigmoidal micas, asymmetric pressure shadows  
236 around feldspar or garnet, and S-shaped inclusion trails in garnet consistently indicate a top-  
237 to-the WNW shearing (Faure et al. 1993; Schulz 2009). These microstructural features are  
238 relevant to the D<sub>2</sub> event of the Massif Central.

239 In the UGU, in addition to the main NW-SE D<sub>2</sub> deformation, a NNE-SSW striking  
240 mineral and stretching lineation is also recognized (Grolier 1971; Feybesse and Teygey 1987;  
241 Faure et al. 1993). This deformation, characterized by elongated biotite-sillimanite

242 aggregates, stretched K-feldspar, and axes of intrafolial folds parallel to the stretching  
243 lineation, is associated with top-to-the SSW kinematic indicators. A Barrovian-type  
244 metamorphism with biotite-sillimanite-K-feldspar assemblage is coeval with this deformation  
245 event that appears less developed, and older, than the NW-SE D<sub>2</sub> one. In the upper part of the  
246 UGU, the biotite-sillimanite±cordierite migmatite exhibits also the NNE-SSW mineral and  
247 stretching lineation, with similar top-to-the-SW kinematics as those observed in the  
248 underlying biotite-sillimanite gneiss. By correlation with the general tectonic-metamorphic  
249 pattern of the FMC, this early phase is correlated with the D<sub>1</sub> event, thus a Middle Devonian  
250 age, dated from 385 to 375 Ma is suggested (Faure et al. 2009) but not documented yet.

251 Furthermore, top-to-the-WNW and top-to-the-ESE shearing, characterized by shear  
252 bands cutting through the regional foliation, sericite pressure shadows upon cataclazed  
253 staurolite or garnet porphyroclasts, develop around the Echassières pluton. These kinematic  
254 indicators, coeval with greenschist facies metamorphic conditions, are related to the  
255 emplacement of the Echassière leucogranite pluton in an extensional setting. Thus this  
256 deformation phase corresponds to the D<sub>4</sub> event (Faure et al. 2009).

257 In contrast with other areas of the French Massif Central, mafic eclogites formed  
258 during the earliest D<sub>0</sub> event are not recognized in the Sioule area. Nevertheless, kyanite-  
259 garnet-plagioclase-rutile high-pressure granulitic gneiss, garnet-pyroxenite, and rare  
260 serpentinite boudins are mapped in the UGU (Grolier 1971; Ravier and Chenevoy 1979).  
261 These rocks argue for an early HP event probably equivalent to the D<sub>0</sub> one. Moreover, in  
262 paragneiss, as shown by the symplectitic texture, these HP garnet and kyanite grains are  
263 surrounded by a biotite-sillimanite or muscovite assemblage representative of an amphibolite  
264 facies retrogression developed during the D<sub>1</sub> or D<sub>2</sub> events (Fig. 3). As in most areas of the  
265 Massif Central, the planar and linear fabrics related to the D<sub>0</sub> event have been erased by  
266 subsequent metamorphic recrystallization or deformation events. But since syn-D<sub>0</sub> minerals,

267 such as kyanite, core of garnet, and possibly monazite are preserved, the rocks may still be  
268 suitable to yield the age of the HP event.

269 Available time constraints in the Sioule metamorphic series are currently limited  
270 (Faure et al., 2002; Schulz, 2009). The Late Visean Pouzol-Servant microgranite and the  
271 Bashkirian-Moscovian Echassières leucogranite intrude the already metamorphosed and  
272 ductilely deformed series, and thus provide the upper time limit for the D<sub>0</sub>, D<sub>1</sub>, and D<sub>2</sub>  
273 tectono-metamorphic events. An <sup>40</sup>Ar/<sup>39</sup>Ar survey has been carried out in the metamorphic  
274 units of the Sioule series (Faure et al. 2002). All the minerals, whatever the rock type or the  
275 tectonic unit, yielded similar ca 335-330 Ma ages that were interpreted as the Late Visean  
276 thermal overprint since these ages are similar, within the errors, to the age of the “Tuffs  
277 Anthracifères” event. Thus, the ages of the different pre-Late Visean tectono-metamorphic  
278 events in the Sioule series remain presently unknown.

279

### 280 **Sampling and petrological description**

281 Twenty-four samples representative of the different metamorphic assemblages cropping out in  
282 the Sioule series have been petrologically studied in order to bring the time constraints on the  
283 metamorphic evolution of this series. After detailed microscopic observations, five samples  
284 were selected due to their suitable parageneses and textures to ensure the presence of  
285 accessory minerals such as monazite and zircon developed during the D<sub>1</sub> and D<sub>2</sub> tectono-  
286 metamorphic events. The sample location in the Sioule nappe pile, and the GPS position, are  
287 provided in Figure 2 and Table 1, respectively. The PAU is represented by a staurolite-garnet  
288 micaschist (SO3) located to the East of the Echassières pluton. The LGU is represented by a  
289 two-mica paragneiss (SO17) to the SE of the same pluton. The UGU is represented by a  
290 biotite-sillimanite gneiss (SO7), a migmatitic gneiss (SO11), and a biotite-kyanite-garnet  
291 paragneiss (SO15), located on both limbs of the antiform. The microstructural descriptions

292 herein refer to thin sections cut parallel to the stretching lineation (X) and perpendicular to the  
293 foliation plane (Z), i.e. in the XZ plane of the finite strain ellipsoid.

294 *Sample SO3*, belonging to the Para-autochthonous unit, consists of quartz, feldspar,  
295 biotite, muscovite, garnet, staurolite, sericite, and chlorite. In the field, structural observations  
296 show a low-angle ESE plunging foliation, and a N105E to N115E striking mineral lineation  
297 (Fig. 3a2). The foliation cut by shear bands, and sigmoidal quartz veins indicate a top-to-the-  
298 SE sense of shear (Fig. 3a1). Under the microscope, cataclazed garnet and staurolite  
299 surrounded by an asymmetric mantle of sericite developed during retrogression of the main  
300 assemblage indicate the same sense of shear (Fig 4a). Furthermore, garnet exhibits sigmoidal  
301 inclusions of quartz and opaque minerals indicating an earlier foliation. The asymmetry of  
302 these inclusions indicates a synkinematic crystallisation of these porphyroblasts during a  
303 noncoaxial deformation that is not in agreement with the top-to-the-SE sense of shear, but  
304 instead argues for a top-to-WNW sense of shear developed during the D<sub>2</sub> event. **According to**  
305 **Schulz et al (2001)**, the thermobarometry from the PAU micaschist indicates a prograde P-T  
306 evolution with increasing temperatures from 450°C to 600°C under slightly increasing  
307 pressure from 0.7 to 0.8 GPa, followed by a P and T decrease indicated by the formation of  
308 retrogressive sericite during the decompression. Scan Electron Microscope (SEM)  
309 backscattered electron (**BSE**) observation of sample SO3 reveals the presence of 50 to 100 µm  
310 sized, homogeneous, monazite grains included into biotite or crystallized along grain  
311 boundaries.

312 *Sample SO17* is a two-mica paragneiss presenting traces of incipient migmatization  
313 belonging to the LGU with a segregation of thick quartz-feldspar and thin biotite and  
314 sillimanite layers. The flat lying foliation contains a NW-SE striking mineral and stretching  
315 lineation related to the D<sub>2</sub> event. The mineral assemblage consists of quartz, feldspar, biotite,  
316 muscovite, chlorite, and accessory minerals including sillimanite, Fe-Ti-oxides, and monazite.

317 Muscovite often presents a clear secondary character, growing without preferred orientation  
318 while biotite is partially altered into chlorite in line with a late thermal overprint (Faure et al.  
319 2002). Biotite contains large subeuhedral monazite grains of *ca* 80-120  $\mu\text{m}$  size. Monazite  
320 also occurs as *ca* 80-100 $\mu\text{m}$  euhedral inclusions in biotite or quartz. Despite the existence of  
321 these two occurrences, in SEM BSE imaging, the monazite grains exhibit homogeneous  
322 internal textures without zoning.

323 *Sample SO7* is a biotite-sillimanite migmatitic paragneiss belonging to the UGU  
324 collected near Moulin du Bouchet (Fig. 2). This rock is composed of quartz, feldspar, garnet,  
325 biotite, muscovite, rare staurolite and fibrolitic sillimanite. Field observations of coarse-  
326 grained quartz-feldspar leucosome parallel to the foliation indicate that this rock underwent a  
327 limited partial melting. The biotite-sillimanite assemblage defines a pervasive foliation and a  
328 N50E striking mineral and stretching lineation that can be assigned to the regional  $D_1$   
329 deformation. However, as already pointed out by Schulz (2009), the subeuhedral shape of the  
330 garnet argues for a static growth after the development of the  $D_1$  structures. According to  
331 Schulz et al. (2001), the biotite-sillimanite gneiss of Moulin de Bouchet, which is located  
332 close to our sample SO7, underwent a prograde metamorphic evolution at low pressure (0.4-  
333 0.6 GPa) and high temperature (650°C-700°C). Thus, this biotite-sillimanite paragneiss might  
334 have also experienced the  $D_2$  event, although typical  $D_2$  NW-SE stretching lineation is not  
335 observed. In this rock, all the analyzed monazite grains, observed in SEM BSE mode, are  
336 homogeneous inclusions in biotite (Fig. 4b).

337 *Sample SO11*, collected at Pont de Menat (Fig. 2) is a migmatitic paragneiss belonging  
338 to the upper part of the UGU. This rock is composed of alternations of coarse-grained quartz-  
339 feldspar leucosome and fine-grained biotite-fibrolitic sillimanite-garnet melanosome. Field  
340 observation shows the occurrence of a pervasive deformation characterized by a flat-lying  
341 foliation and a N120E trending mineral and stretching lineation assigned to the  $D_2$  event (Fig.

342 3 c). All the analyzed monazite grains observed in SEM BSE mode are homogeneous  
343 inclusions in biotite (Fig. 4c).

344 *Sample SO15* is a kyanite-garnet ± rutile paragneiss coming from Saugères (Fig. 2).  
345 This rock is composed of biotite, feldspar, quartz, garnet, and kyanite. Garnet and kyanite are  
346 1-5 mm sized clasts included in a well-foliated granoblastic matrix composed of quartz,  
347 feldspar, and small biotite flakes (Fig. 3d). The kyanite-garnet assemblage that formed in  
348 high-pressure granulite facies underwent an amphibolite facies retrogression as shown by  
349 biotite overgrowths around garnet porphyroclasts (Ravier and Chenevoy 1979; Fig. 4d).  
350 Monazite inclusions in garnet and in biotite exhibit a core-rim chemical zoning.

351

## 352 **Monazite EPMA chemical dating**

353 Analytical method and strategy

354 Due to its high U and Th contents, and negligible initial Pb content (Parrish 1990), it is  
355 now well acknowledged that a crystallization (or recrystallization) age can be determined  
356 from monazite on the basis of its chemical composition in U, Th, and Pb determined by  
357 electron probe microanalysis (EPMA). Such a simple and fast technique has been successfully  
358 applied to several plutonic or metamorphic rocks (e.g. Suzuki and Adachi, 1991; Montel et  
359 al., 1996; Cocherie et al., 1998, 2005; Cocherie and Albarède, 2001; Schulz et al., 2009; Faure  
360 et al., 2010, and enclosed references). Monazite is a common accessory mineral in  
361 metamorphic rocks, especially in metapelites. It crystallizes in a wide range of P-T conditions,  
362 from greenschist facies (Cabella et al. 2001; Rasmussen et al. 2001) to amphibolite (Smith  
363 and Barreiro 1990; Kohn and Malloy 2004) and granulite facies (Bé Mézème et al. 2006; Mc  
364 Farlane and Frost 2009) in rocks metamorphosed under Barrovian P-T gradient during  
365 prograde or retrograde paths. Previous studies have shown also that monazite can crystallize  
366 in blueschist (Janots et al. 2006) or even eclogite facies (Nagy et al. 2002). Consequently,



367 analyzed monazite grains must be linked with petrological studies to delimit their P-T  
368 crystallization domain. The chemical composition of monazite is an important parameter in  
369 order to discuss the radiometric ages.

370 *In situ* chemical U-Th-Pb dating of monazite has been developed over the past fifteen  
371 years allowed by technological progress performed on electron microprobe analyses (EPMA;  
372 Suzuki and Adachi 1991; Montel et al. 1996; Cocherie et al. 1998, 2005). The method uses  
373 the radiochronometer between U and Th parent and Pb radiogenic elements, considering the  
374 restricted lead diffusion in monazite lattice below 900°C (Cocherie et al. 1998). The  
375 determination of U, Th and Pb contents can be performed directly by EPMA *in situ* analyses  
376 on polished thin section after textural optical microscope observation of crystallisation-  
377 deformation relationships between the constitutive minerals, and monazite internal structure  
378 determination using a SEM in BSE mode. This approach provides petrological constraints on  
379 the analyzed grains and thus allows us to discuss the significance of the calculated ages in the  
380 crystallisation-deformation history of the rock.

381 SEM BSE was used to define heterogeneous chemical compositional domains of  
382 monazite. In metamorphic rocks, contrasted chemical domains can be explained by the  
383 superimposition of metamorphic events that record a polyphase evolution during orogenic  
384 processes. Theoretical procedure to reduce the data and to calculate the average age from  
385 individual spot analyses is given by Cocherie and Albarède (2001), Cocherie et al. (2005), and  
386 Cocherie and Legendre (2007). The analysis of monazite grains directly from polished thin  
387 sections was performed by a Cameca SX 50 EPMA co-operated by BRGM-CNRS-Orléans  
388 University. An accelerating voltage of 20 kV, and a beam current of 100 nA were chosen as  
389 operating conditions. Synthetic phosphates, glasses and natural minerals were used as  
390 standards. The counting times (2/3 on peak and 1/3 on background) varies from 20s for Si, P,  
391 Ca, Nd, Gd, Y, Th, Ce and La, to 100s for U and 120s for Pb. Considering such parameters,

392 the detection limit for Th, U and Pb is 150 ppm (Cocherie and Albarede, 2001). X-ray  
393 element maps were also recorded with an accelerating voltage of 20 kV and beam current of  
394 100 nA, using the wavelength-dispersive spectrometers. Details on the analytical procedure  
395 are the same as those used in Cocherie et al. (2005) and Faure et al. (2008, 2010). Age  
396 calculations were done using the Isoplot/Ex (2.49) program of Ludwig (2001) and a Microsoft  
397 Excel add-in program for determining U-Th-Pb ages from EPMA measurements (Pommier et  
398 al. 2002). The  $2\sigma$  errors given on individual ages depend on U, Th, and Pb contents, and are  
399 calculated by propagating the uncertainties of these elements (at 95% confidence level).  
400 Because the mean age of an homogeneous age population is directly derived from the isochron  
401 plot Th/Pb vs U/Pb, only the uncertainty on these two parameters (Th/Pb and U/Pb) are  
402 required to calculate the uncertainty on the mean age.

403 The strategy followed for this study was to derive time constraints for the monazite  
404 included into the foliation forming biotite or in contact with it, in order to settle the  
405 crystallisation time of the main foliation. Consequently, we concentrated on subeuhedral to  
406 euhedral monazite grains. We focused on the dating of well-defined chemical domains so as  
407 not to shuffle different heterogeneous domains that would yield different crystallization  
408 periods.

409

## 410 Results

411 *Chemical composition of monazite grains.* SEM BSE images reveal chemically  
412 homogeneous monazite grains for the four samples SO3, SO7, SO11, and SO17. Conversely,  
413 the SO15 kyanite-garnet granulitic paragneiss sample presents zoned monazite grains. This  
414 zonation corresponds to a core/rim zonation as described by Bé Mézème et al. (2006), mostly  
415 due to the spatial distribution of U, Th and Pb. The EPMA analysis allows us to quantitatively  
416 characterize the chemical composition of the dated grains. The average U/Pb and Th/Pb ratio

417 values, details concerning the number of spot analyses, and analyzed grains are provided in  
418 Table 1. **Representative monazite chemical compositions with uncertainties for samples SO3,**  
419 **SO7, SO11, SO15, and SO17 are given in Table 2.** For the granulitic gneiss (sample SO15),  
420 core and rim chemical data have been separated. Monazite chemical data for each samples are  
421 plotted in the Monazite ( $2\text{REEPO}_4$ ) - Cheralite ( $\text{CaTh}(\text{PO}_4)_2$ ) - Huttonite ( $2\text{ThSiO}_4$ ) diagram  
422 (Linthout 2007; Fig. 5a), in order to show the relative substitution between **end-member**  
423 monazite phase and the cheralite or huttonite components (Fig. 5a). The cheralite substitution  
424 is always low, as already observed for various metamorphic environments (e.g. Franz et al.  
425 1996; Cabella et al. 2001), and huttonite substitution is absent or negligible. In samples SO3,  
426 SO7, SO11 and SO17, monazite grains appear as homogeneous domains in BSE images, and  
427 the analytical data scatter along the cheralite-monazite axis showing clearly a common  
428 substitution. In sample SO15, the analyzed monazite grain is composed of two domains in the  
429 BSE images, with a light (i.e. dense) core and a dark (i.e. light) rim. Data plotted in the  
430 Monazite ( $2\text{REEPO}_4$ ) - Cheralite ( $\text{CaTh}(\text{PO}_4)_2$ ) - Huttonite ( $2\text{ThSiO}_4$ ) diagram (Fig. 5a) show  
431 a relatively high Ce-monazite component into the core of the grain (**white** diamond) and a  
432 cheralite enriched rim (**black** diamond), corresponding to two different chemical domains.  
433 The  $(\text{Th}+\text{U}+\text{Si}+\text{Pb}) = f(\text{REE}+\text{P})$  plot, modified from Franz et al. (1996), confirms the spread  
434 of the analytical data for samples SO3, SO7, and SO11 along the  $\text{CaThREE}_2$  axis  
435 corresponding to the cheralite substitution (Fig. 5b). Monazite chemical data from the  
436 staurolite micaschist SO3 (Fig. 5b) indicate a limited huttonite substitution pointed out by  
437 small vertical variation in  $\text{Th}+\text{U}+\text{Si}+\text{Pb}$ . Chemical data of monazite from biotite-sillimanite  
438 gneiss SO7 and SO11 show a more significant huttonite substitution than for SO3. The core  
439 and the rim of dated monazite grain from sample SO15 are characterized by two distinct sets  
440 of chemical compositions. The rim is richer in cheralite component than the core, even if  
441 huttonite substitution in each domain seems to be similar (Fig. 5b). X-ray maps depicting the

442 semiquantitative distribution of Th, Ca, and U confirm the chemical differences between the  
443 core and the rim of SO15 grain (Fig. 5d). These maps show that the monazite rim of monazite  
444 is enriched in Th and Ca compared to the core. The U content is relatively equivalent in the  
445 core and rim, except for an enriched fringe in the rim. This domain was not analyzed because  
446 of holes on the polished surface. Despite the presence of several small-sized domains  
447 indicated by the Ca and Th contents, the entire core is homogeneous in Th and U  
448 composition.

449  
450 *U-Th-Pb chemical dating.* In this section, the ages of the analyzed monazite grains  
451 from samples SO3, SO 17, SO7, SO11, SO15 are presented following the tectonic order from  
452 bottom to top (Fig. 2).

453 Staurolite micaschist SO3. Data points are highly scattered on the Th/Pb vs. U/Pb  
454 diagram, leading to a small error envelope. The intercept ages are similar within errors, since  
455 the U-Pb age (intercept with U/Pb axis), and the Th-Pb age (intercept with Th/Pb axis) are at  
456  $379 +54/-62$  Ma, and  $357+26/-23$  Ma, respectively. The calculated MSWD of 1.3 indicates  
457 that the population of 73 analyses is statistically homogeneous within the analytical errors  
458 (Wendt and Carl 1991). As a consequence, it is possible to calculate the mean age at the  
459 centroid where the precision is the best within the error envelope. Thus, the monazite grains  
460 yield a mean age of  $363 \pm 8$  Ma (at  $2\sigma$  confidence level; Fig. 6a).

461 Two-mica gneiss (SO17). Data points are weakly scattered on the Th/Pb vs. U/Pb  
462 diagram, leading to a large error envelope. The intercept ages are similar within errors, since  
463 the **intercept** U-Pb age and the **intercept** Th-Pb age are at  $399 +44/-53$  Ma, and  $328+31/-26$   
464 Ma, respectively. The calculated MSWD of 0.63 indicates that the population of 38 analyses  
465 is statistically homogeneous within the analytical errors (Wendt and Carl 1991). As a  
466 consequence, it is possible to calculate the mean age at the centroid where the precision is the

467 best within the error envelope. Thus, the monazite grains yield a mean age of  $351 \pm 5$  Ma (at  
468  $2\sigma$  confidence level; Fig. 6b).

469 Biotite-sillimanite gneiss (SO7). Data points are relatively scattered on the Th/Pb vs.  
470 U/Pb diagram, leading to a small error envelope. The intercept ages are similar within errors,  
471 since the intercept U-Pb age and the intercept Th-Pb age are at  $331+39/-46$  Ma, and  $371+33/-$   
472  $28$  Ma, respectively. The calculated MSWD of 1.19 indicates that the population of 73  
473 analyses is statistically homogeneous within the analytical errors (Wendt and Carl 1991) and  
474 as a consequence, it is possible to calculate the mean age at the centroid. Thus, the monazite  
475 grains yield a mean age of  $355 \pm 7$  Ma (at  $2\sigma$  confidence level; Fig. 6c).

476 Migmatitic gneiss (SO11) of Pont de Menat. Data points on the Th/Pb vs. U/Pb  
477 diagram are less scattered than for previous sample, which may lead to a larger error envelop.  
478 However, the large number of analyses ( $n= 174$ ) decreases the envelop size. The intercept  
479 ages are similar within errors, since the intercept U-Pb age and the intercept Th-Pb age are at  
480  $342+45/-51$  Ma, and  $373+24/-21$  Ma, respectively. The calculated MSWD of 0.98 indicates  
481 that the population of 174 analyses is statistically homogeneous within the analytical errors  
482 (Wendt and Carl 1991). As a consequence, it is possible to calculate the mean age at the  
483 centroid. Thus, the monazite grains yield a mean age of  $363 \pm 4$  Ma (at  $2\sigma$  confidence level;  
484 Fig. 6d).

485 Kyanite-garnet granulitic paragneiss (SO15) of Saugères. Monazite in sample SO15  
486 exhibits a core-rim zonation of the grain, and in consequence, EPMA data were processed  
487 separately for the different domains in order to calculate two isochron ages. 47 and 21  
488 analyses were performed in the core and rim of a single grain, respectively. The 47 analyses  
489 from the core on the Th/Pb vs. U/Pb diagram are clustered, leading to a large error envelope.  
490 The intercept ages are similar within errors, since the intercept U-Pb age and the intercept Th-  
491 Pb age are at  $517+281/-322$  Ma, and  $390+81/-57$  Ma, respectively. The calculated MSWD of

492 1.15 indicates that the population of the 47 analyses is statistically homogeneous within the  
493 analytical errors (Wendt and Carl 1991). As a consequence, it is possible to calculate a mean  
494 age at the centroid. Thus, the core of this monazite grain yields a mean age of  $416 \pm 15$  Ma (at  
495  $2\sigma$  confidence level; Fig. 6e).

496 Moreover, the 21 analyses performed from the monazite rim are well-scattered,  
497 leading to a small error envelope. The intercept ages are similar within errors, since the  
498 intercept U-Pb age and the intercept Th-Pb age are at  $423^{+74}_{-88}$  Ma, and  $338^{+36}_{-30}$  Ma,  
499 respectively. The calculated MSWD of 0.93 indicates that the population of 21 analyses is  
500 statistically homogeneous within the analytical errors (Wendt and Carl 1991). As a  
501 consequence, it is possible to calculate the mean age at the centroid where the precision is the  
502 best within the error envelope. Thus, the monazite grains yield a mean age of  $362 \pm 14$  Ma (at  
503  $2\sigma$  confidence level; Fig. 6f).

504

## 505 **Zircon U-Pb SIMS dating**

### 506 Analytical procedure

507 Zircon concentrates were separated from a *ca* 5 kg of the granulitic paragneiss sample SO15  
508 using standard density and magnetic separation techniques. Zircon grains, together with  
509 standard zircons TEMORA 2, 91500, and an in-house standard zircon Qinghu, were mounted  
510 in an epoxy mount that was then ground and polished to section the crystals in half for  
511 analysis. Zircons were imaged with transmitted and reflected light photomicrographs as well  
512 as cathodoluminescence (CL) to reveal their internal structures, and the mount was vacuum-  
513 coated with high-purity gold prior to SIMS analyses. Measurements of U, Th and Pb isotopes  
514 were conducted using a Cameca IMS 1280 SIMS at the Institute of Geology and Geophysics,  
515 Chinese Academy of Sciences in Beijing. Analytical procedures are similar to those reported  
516 by Li et al. (2009). The primary  $O_2^-$  ion beam spot is about  $20 \times 30 \mu\text{m}$  in size. Positive

517 secondary ions were extracted with a 10 kV potential. In the secondary ion beam optics, a 60  
518 eV energy window was used, together with a mass resolution of *ca* 5400 (at 10% peak  
519 height), to separate Pb<sup>+</sup> peaks from isobaric interferences. A single electron multiplier was  
520 used in ion-counting mode to measure secondary ion beam intensities by peak jumping mode.  
521 Analyses of the standard zircon TEMORA 2 were interspersed with unknown grains. Each  
522 measurement consists of 7 cycles. Pb/U calibration was performed relative to zircon standard  
523 TEMORA 2 (<sup>206</sup>Pb/<sup>238</sup>U age = 417 Ma, Black et al. 2004); U and Th concentrations were  
524 calibrated against zircon standard 91500 (Th = 29 ppm, and U = 81 ppm, Wiedenbeck and  
525 Allen 1995). Measured compositions were corrected for common Pb using non-radiogenic  
526 <sup>204</sup>Pb, and an average of crustal composition (Stacey and Kramers 1975) **was** used for the  
527 common Pb. Data reduction was carried out using the Isoplot/Ex v. 2.49 program (Ludwig  
528 2001). In order to monitor the external uncertainties of SIMS U-Pb zircon measurements, an  
529 in-house standard zircon Qinghu was alternately analyzed as an unknown together with other  
530 unknowns. Twenty measurements on Qinghu zircon (Table 3) yield a Concordia age of 160 ±  
531 1 Ma (2SE, MSWD of concordance = 0.92), which is in good agreement within errors with  
532 the recommended U-Pb age of 159.5 ± 0.2 Ma (Li et al. 2009). Zircon U-Pb age data are  
533 presented in Table 3.

534

## 535 Results

536 **Fifty-five** zircon grains from the SO 15 granulitic paragneiss have been analyzed (Table 3).  
537 **All but four zircons are concordant within analytical uncertainties (discordance degree <4%).**  
538 **The dated zircons can be divided into two groups in terms of their morphological feature, ages**  
539 **and Th/U ratio. In group 1, zircons are mostly sub-rounded to multifaceted grains and yield**  
540 **ages between 324 and 349 Ma. They are characterized by low Th/U ratio (<0.1) and faint CL**  
541 **luminescence (Table 3, Fig. 7), similar to metamorphic zircons (Corfu et al. 2003). Contrarily,**

542 Group 2 zircons are dated between 368 Ma and 1.99 Ga (Table 3). They are mostly oval  
543 shaped grains showing concentric zoning under CL (Fig. 7), and relatively high Th/U ratio  
544 (mostly >0.1), similar to the magmatic zircons (Corfu et al. 2003). Among them, four zircons  
545 (spots @06, 26, 27 and 37) are highly discordant, with  $^{207}\text{Pb}/^{206}\text{Pb}$  ages between 1629 and  
546 1994 Ma. On the probabilistic histogram of U-Pb ages for 51 concordant analyses (Fig 8),  
547 Group 1 zircons form one major peak at 342 Ma (n = 24) and a subordinate peak at 327 Ma (n  
548 = 6), corresponding to Concordia age of  $343\pm 2$  Ma and  $328\pm 4$  Ma, respectively, on a U-Pb  
549 Concordia plot (Fig. 9). Thus, Group 1 zircons are most likely metamorphic in origin. The  
550 remaining 21 Group 2 zircons display a scattered age pattern ranging from 370 to 800 Ma,  
551 which might be detritus zircons of magmatic origin with or without later metamorphic and  
552 hydrothermal overprinting.

553

## 554 **Discussion**

555 Many studies have pointed out the relationships between the age and the chemical  
556 composition of monazite grains in polymetamorphic terranes (e. g. Martins et al., 2009; Kelly  
557 et al., 2012). In samples SO3, SO7, SO11 and SO17, SEM BSE images of monazite grains  
558 revealed homogeneous grains. The chemical compositions of the analysed monazite grains  
559 cluster near the Monazite-(Ce) pole and scatter along the cheralite axis (Fig. 5a and b). The  
560 weak data dispersal along the cheralite substitution line indicates that the analysed grains  
561 represent a rather homogeneous population. Monazite grains from sample SO15 that exhibit a  
562 light (i.e. dense) core and a dark (i.e. light) rim in BSE images, are scattered between the  
563 cheralite ( $\text{CaTh}(\text{PO}_4)_2$ ) and huttonite ( $2\text{ThSiO}_4$ ) substitutions (Fig. 5b). Compared with the  
564 other analysed samples, such a difference is explained by a high REE (La, Ce, Pr, Nd) content  
565 and absence of Y in the core of monazite grains from sample SO15 (Table 2). The analysed  
566 spots in both the core and rim parts delimit two clusters with different chemical composition.



567 It is noteworthy that i) the chemistry of the SO15 monazite rim is close to the chemistry of the  
568 other analysed monazite grains, and ii) the reaction leading to the rim crystallisation occurred  
569 contemporaneously to the crystallisation of the other monazite grains in samples SO3, SO7,  
570 SO11 and SO17. Datings carried out in this study have been made on grain populations with  
571 homogeneous chemical composition that make us confident about the age interpretation.

572 The kyanite-garnet granulitic gneiss SO15 preserves a core domain within monazite  
573 yielding a *ca* 415 Ma age. This Early Devonian age can be assigned to the D<sub>0</sub> event  
574 recognized in the UGU in several places in the Massif Central (Pin and Peucat 1986; Pin and  
575 Vielzeuf 1988; Paquette et al. 1995). All the dated samples, whatever the tectonic unit to  
576 which they belong, yielded similar within the error, monazite U-Th-Pb ages at *ca* 365-350 Ma  
577 (Fig. 10). Since they share common structural features, including a similar NW-SE striking,  
578 D<sub>2</sub>, stretching lineation, which is well developed in samples SO3, SO11, SO17, and SO15, the  
579 363-351 Ma ages yielded by the monazite in these rocks can be attributed to the D<sub>2</sub> tectono-  
580 metamorphic event. Similar ages were already reported for the D<sub>2</sub> tectono-metamorphic event  
581 in other areas of the French Massif Central, such as the Lot series (Costa 1989) or Limousin  
582 (Melleton et al. 2009). Moreover, these ages are consistent, **within the errors**, with the  
583 emplacement age of the Guéret and S<sup>t</sup>-Gervais d'Auvergne plutons (Figs 1, 2) that **exhibit a**  
584 **NW-SE striking magmatic lineation** (Faure et al. 2005; Cartannaz et al. 2007). These plutons,  
585 dated at 360-350 Ma, **emplaced** at the end of the D<sub>2</sub> event (Berthier et al. 1979; Cartannaz et  
586 al. 2007; Faure et al., 2009). The SO11 D<sub>1</sub> migmatite sample, deformed during the D<sub>2</sub> event,  
587 yields also a monazite U-Th-Pb age at *ca* 363 Ma, which is consistent with the Late  
588 Devonian-Early Carboniferous age of the D<sub>2</sub> event.

589 It is worth to note that although the D<sub>1</sub> migmatization is preserved in samples SO11,  
590 and SO7, **the P-T conditions of 0.4-0.6 GPa and 550-600°C, calculated in the UGU from a**  
591 **sample close to our sample SO7 (Schulz et al. 2001, Schulz 2009) are not in agreement with**

592 the D<sub>1</sub> event, as defined in other areas of the French Massif Central (e.g. Santallier 1981;  
593 Mercier et al. 1991; Lardeaux et al. 2001; Bellot and Roig 2007), but instead represent a low  
594 pressure-medium temperature event similar to the D<sub>2</sub> one as observed in the Limousin, Lot or  
595 Rouergue areas (Duguet et al. 2006; Bellot and Roig 2007; Melleton et al 2009). Thus this  
596 biotite-sillimanite paragneiss might have also experienced the D<sub>2</sub> event, even if the typical  
597 NW-SE D<sub>2</sub> stretching lineation is not observed in this rock. Furthermore, the NE-SW striking  
598 D<sub>1</sub> mineral lineation is clearly observed in sample SO17. In these three rocks, the analyzed  
599 monazites do not record the Devonian migmatization dated between 385 Ma and 375 Ma in  
600 Lyonnais (Duthou et al. 1994), Limousin (Faure et al. 2008) and S. Brittany (Cocherie et al.  
601 2005). This result can be variously interpreted. Firstly, monazite was unable to crystallize  
602 under the D<sub>1</sub> metamorphic conditions; **secondly, monazite effectively crystallized, but it may**  
603 **have been dissolved during the HT event, and then neocrystallized in biotite during the**  
604 **prograde D<sub>2</sub> event;** thirdly, due to the limited number of analyzed grains, our sampling missed  
605 any monazite grain formed during the D<sub>1</sub> event. Though the first hypothesis appears unlikely,  
606 since aluminous composition protoliths are suitable for monazite crystallization, the other two  
607 explanations cannot be discarded. Thus, the 365-350 Ma monazite ages obtained from  
608 samples SO3, SO17, SO7, SO11, and the monazite rim from sample SO15 are attributed to  
609 the neocrystallization or the complete recrystallization of monazite during the D<sub>2</sub> event,  
610 leading to the total loss of any early monazite. **In order to get a better understanding of the**  
611 **thermo-barometric and chemical conditions that allow monazite crystallization or dissolution**  
612 **with respect to other phases such as garnet and biotite, a detailed analysis of the chemical**  
613 **elements exchanges during the succession of the crystallization-deformation events would be**  
614 **necessary. On the contrary to Limousin or Maures areas (e. g. Duguet et al. 2006; Bellot and**  
615 **Roig 2007; Oliot et al. 2015), such a study is not available yet for the Sioule metamorphic**  
616 **series.**

617 Besides, zircon from the granulitic paragneiss yields U-Pb SIMS ages younger than  
618 the monazite ones at  $343\pm 2$  Ma, and  $328\pm 2$  Ma. The latest is close to the whole-rock Rb/Sr  
619 age of the Pouzol-Servant microgranite at 330 Ma (Duthou and Pin 1987; Pin 1991), and also  
620 to the cooling ages yielded by the  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses on biotite, muscovite and amphibole for  
621 the entire nappe-stack of the Sioule metamorphic series, either in the Upper Gneiss, Lower  
622 Gneiss, and Para-autochthonous Units (Faure et al. 2002; Fig. 11). As pointed out in the  
623 “Geological Setting” section, the *ca* 330 Ma age is that of the “Tufs anthracifères”  
624 magmatism widespread in the northern part of the French Massif Central (Fig. 11). The  
625  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of the Sioule metamorphic rocks, younger than the Late Visean unconformity,  
626 have been interpreted as a thermal reset provided by the high heat flux during the onset on the  
627 extensional tectonics in the northern part of the French Massif Central. Thus we suggest here  
628 that the zircon age at  $328\pm 4$  Ma might be due to recrystallizations processes, possibly  
629 assisted by hydrothermal fluids, also as a consequence of the Late Visean thermal reset.

630 **Indeed, the LGU and PAU rocks exhibit several evidence of retrogression such as chlorite**  
631 **developed at the expense of biotite, sericite surrounding staurolite, (Fig 4a) and albite**  
632 **overprinting the foliation. These minerals argue for a late metamorphic stage associated with**  
633 **fluid circulation. In the present state of knowledge, detailed petrological investigations to**  
634 **characterize this hydrothermal event are not available.** The  $343\pm 2$  Ma age yielded by 24  
635 zircon grains is more difficult to interpret in the geological framework. This age  
636 corresponding to the majority of analyzed concordant grains is different, **within the error,**  
637 from the  $328\pm 4$  Ma age. Furthermore, such a Middle Visean age is **rarely** reported in the  
638 northern part of the Massif Central. **However, to the East of the study area, in the Lyonnais,**  
639 **syn-kinematic granites emplaced along a NE-SW striking dextral strike-slip fault yield biotite**  
640 **and muscovite  $^{40}\text{Ar}/^{39}\text{Ar}$  ages at *ca*  $346\pm 3$  Ma and  $349\pm 3$  Ma, respectively (Costa et al. 1993).**  
641 **Such a NE-SW strike-slip shearing is not identified in the Sioule area, but the NW-SE striking**

642 **S<sup>te</sup>-Christine dextral strike slip fault develops in the southern boundary of the Sioule series**  
643 **(Fig. 2). One possible interpretation would be to relate this *ca* 343 Ma (i. e. Middle Viséan)**  
644 **age to fluid circulations coeval with a transcurrent shearing event too. Importantly, the zircon**  
645 **SIMS measurement did not recorded the 365-350 Ma D<sub>2</sub> ages.**

646 Previous monazite U-Th/Pb ages (Schulz 2009) range between 343 Ma and 327 Ma,  
647 i.e. much younger than those reported in this study. These dates were attributed to two distinct  
648 events, in agreement with the <sup>40</sup>Ar/<sup>39</sup>Ar ages (Faure et al. 2002), the monazite chemical ages  
649 younger than 340 Ma were considered as due to the Late Viséan **hydrothermal** event related to  
650 the “Tufs anthracifères” magmatism. Conversely, ages older than 340 Ma were considered as  
651 minimum ones associated to a top-to-the-SE tectonic event. However, structural  
652 investigations demonstrated that the top-to-the-SE shearing was coeval with the emplacement  
653 of the Echassières pluton at *ca* 310 Ma (Feybesse and Teygey 1987; Faure et al. 1993). The  
654 discrepancy between our results and the previous ages by Schulz (2009) can also be explained  
655 considering the data reduction method. The previous study uses frequency histograms to  
656 process the analytical data associated with very large, routinely *ca* 15 Ma, errors. Moreover,  
657 the frequency diagram method provides a mean age systematically younger than the one given  
658 by the Th/Pb= f(U/Pb) isochron method (Cocherie and Albarède 2001). For example, the  
659 **weighted average age** computed here for the monazite core and rim of sample SO15 (Fig. 5c)  
660 also yields ages at 392±16 Ma, and 359±18 Ma younger than 416±8 Ma, and 362±14 Ma  
661 yielded by the isochron method. In addition, the results provided by the isochron method are  
662 generally closer to the ICP-MS isotopic measurements than those provided by the histogram  
663 method (Cocherie et al. 1998; Cocherie and Albarède 2001), and thus are preferred here. As  
664 mentioned in the “Sioule metamorphic series” section, in the study area, two pre-Late Viséan  
665 events, namely D<sub>1</sub> and D<sub>2</sub>, are recognized. However, the age of the D<sub>1</sub> and D<sub>2</sub> range between

666 385-375 Ma and 360-350 Ma, respectively. Therefore, the *ca* 340 Ma monazite ages cannot  
667 be ascribed to a single tectono-metamorphic event.

668 Our new monazite chemical ages can be used to place time constraints in the pressure  
669 (P)-temperature (T) plot in order to settle the P-T-t paths experienced by each unit. P-T  
670 estimates from the Sioule area (Schulz et al. 2001) are consistent with P-T conditions from  
671 other areas of the Massif Central (e.g. Santallier 1981; Mercier et al. 1991; Lardeaux et al.  
672 2001; Bellot and Roig 2007; Faure et al. 2008). The UGU, LGU, and PAU underwent  
673 different P-T paths depending on their location in the French Massif Central. In the Lyonnais  
674 area, the coesite bearing eclogite argue for P conditions about 2.7-2.8 GPa (Lardeaux et al.  
675 2001) whereas such ultra-high pressure conditions are not recorded (or not preserved) in the  
676 Sioule area. On the basis of petrological studies in the Limousin and Artense areas (Santallier  
677 1981, Mercier et al. 1991), peak-conditions of *ca* 2 GPa for *ca* 800°C are inferred for the  
678 Sioule granulite (Fig. 12). Sample SO15 places a time constraint at *ca* 415 Ma on this HP  
679 event. On the contrary, in the Limousin area, the LGU reached a maximum P value of 1.1-1.2  
680 GPa for 500 °C (Bellot and Roig 2007; Faure et al. 2008). During their exhumation, the UGU  
681 and LGU followed nearly isothermal decompression paths coeval with migmatization, and  
682 subsequent cooling during the D<sub>1</sub> event at 385-375 Ma. The minimum P-T conditions  
683 experienced by the UGU and LGU during this eo-Variscan cycle are not precisely settled.  
684 Since andalusite replacing sillimanite or kyanite is never observed in the UGU or LGU, we  
685 assume that the two units were not exhumed close to the surface but remained buried in the  
686 upper crust, **even if aluminosilicates might have remained stable during exhumation.**  
687 Conversely, the PAU never experienced the D<sub>1</sub> metamorphism nor migmatization. This unit  
688 records maximum P and T values of 0.7-0.8 GPa, and 500-600°C, respectively. Our monazite  
689 age of sample SO3 at 363±8 Ma constrains the age of the MP/MT metamorphism coeval with  
690 the top-to-the-NW D<sub>2</sub> event. During the same late Devonian-Early Carboniferous period, the

691 UGU and LGU experienced a second metamorphic cycle leading to maximum P-T conditions  
692 of 0.7-0.8 GPa, and 500-600°C similar to those of the PAU. Our monazite U-Th-Pb ages at  
693 362Ma, 363 Ma, 355 Ma, and 351 Ma, for samples SO10, SO11, SO7, and SO17,  
694 respectively represent the age of the D<sub>2</sub> event recorded in the UGU and LGU (Fig. 12).

695 After the completion of the two Variscan metamorphic cycles, the Sioule metamorphic  
696 series, like most of the areas in the northern part of the FMC, experienced a huge late  
697 **orogenic** magmatic episode, **at ca** 335-330 Ma, represented both by deep seated plutonism,  
698 dyke emplacement, and aerial volcanism. As already proposed to account for the <sup>40</sup>Ar/<sup>39</sup>Ar  
699 ages, the hydrothermalism was responsible for the complete resetting of the zircon U-Pb  
700 isotopic systems during the Tufts Anthracifères event **but the U-Th-Pb chronometer was not**  
701 **affected by this late thermal event.**

702

### 703 **Conclusion**

704 This geochronological study in a key area of the Variscan French Massif Central, casts light  
705 on the importance of structural and petrological constraints when dealing with age  
706 determination of thermal, tectonic and metamorphic events in orogens. **These new radiometric**  
707 **ages** yielded by monazite and zircon included in the macroscopic foliation **allow us to place**  
708 **time constraints on the succession of superimposed deformation and related metamorphic**  
709 **events in the Sioule area. The early Variscan HP/HT D<sub>0</sub> event occurred at 416±15 Ma and the**  
710 **MP/MT D<sub>2</sub> event, coeval with the top-to-the NW shearing took place between 365 Ma and**  
711 **350 Ma. On the contrary, the ca 380 Ma D<sub>1</sub> event has not been recorded by monazite. Our**  
712 **study emphasizes that** radiometric ages must be carefully discussed in the light of the regional  
713 geological setting. Particularly, the knowledge of the thermo-barometric and hydrothermal  
714 processes must be a pre-requisite for the understanding of the geochronological data.

715

### 716 **Acknowledgements**

717 Field, and analytical expenses for this study have been supported by the French national  
718 program “Carte géologique de la France au 1/50 000” led in BRGM, and by a National  
719 Natural Science Foundation of China (NNSFC) grant 41273070. Ida di Carlo and Olivier  
720 Rouer are acknowledged for their help for the acquisition of SEM and EPMA analyses. Jean-  
721 Marc Lardeaux and Emilien Olliot are thanked for their constructive reviews.

722

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1024 Figure Captions

1025 Fig. 1. A: Location of the French Massif Central in the European Variscan framework. B:

1026 Structural map of the Massif Central (modified from Ledru et al., 1989, and Faure et al.,

1027 2009). D<sub>1</sub>, D<sub>2</sub>, D<sub>3</sub> refer to the stretching lineation and kinematics referred to the Early

1028 Devonian, Early Carboniferous, and Middle Carboniferous tectono-metamorphic events,

1029 respectively. SGA: S<sup>t</sup>-Gervais d’Auvergne pluton

1030

1031 Fig. 2. Structural map, and NW-SE cross-section of the Sioule series with sampling sites and

1032 microstructural data, after Grolier (1971), Feybesse and Teygey (1987), and Faure et al.

1033 (1993).

1034

1035 Fig. 3. Examples of representative macroscopic field structures of the Para-autochthonous (a),

1036 Lower Gneiss (b) and Upper Gneiss (c, d) Units. a1: outcrop of biotite-staurolite micaschist

1037 of sample SO3, with top-to-the-SE sigmoidal quart veins, a2: close-up of the mineral lineation

1038 marked by elongated biotite and staurolite porphyroblasts. This NW-SE lineation results of

1039 the superposition of D<sub>2</sub> and D<sub>4</sub> events. b) D<sub>1</sub> NE-SW striking isoclinal folds at Chouvigny. c)

1040 Biotite-sillimanite paragneiss with S1 flat-lying foliation and L1 mineral lineation, close to  
 1041 sample SO7. d) hand sample of garnet-kyanite granulitic paragneiss at Saugères (sample SO  
 1042 15). Note the biotite rim around garnet developed during the retrogression of the granulite  
 1043 facies metamorphic assemblage into amphibolite facies ones.

1044

1045 Fig. 4. Polarized light micrographs of analyzed samples showing the textural relationships of  
 1046 the dated monazite grains with other minerals (see location in Fig. 2). a: PAU micaschist  
 1047 sample SO3 from the Para-autochthonous Unit showing D<sub>2</sub> staurolite mantled by a sericite  
 1048 rim and deformed during the D<sub>4</sub> event. b: biotite-garnet-sillimanite gneiss (sample SO7) from  
 1049 the Upper Gneiss Unit with monazite included in biotite. c: biotite-sillimanite migmatite  
 1050 (sample SO11) foliated and lineated during the D<sub>2</sub> event, the dated monazite is included in  
 1051 biotite. d: kyanite-garnet granulitic paragneiss (sample SO15) with garnet surrounded by a  
 1052 biotite rim developed during the D<sub>2</sub> event.

1053

1054 Fig. 5. a: plot of the analyzed monazites in the  $2\text{REEPO}_4\text{-CaTh(PO}_4)_2\text{-2ThSiO}_4$  system  
 1055 (Linthout, 2007) showing that the grains are close to the Ce-monazite pole. b: plot of the  
 1056 analyzed monazite in the Th+U+Si+Pb vs REE+P diagram (Franz et al., 1996). c: **weighted**  
 1057 **average age** of the core and rim of monazite contained in kyanite-garnet paragneiss of  
 1058 Saugères (sample SO15). d: X-ray compositional map for Th, Ca, U of the analyzed monazite  
 1059 grain in the granulitic paragneiss sample SO15, showing the chemical zoning with a Th, Ca,  
 1060 and U enriched rim. White and black squares represent EPMA analyse points for core and  
 1061 rim, respectively.

1062

1063 Fig. 6. Th/Pb vs U/Pb plots with SEM BSE pictures of dated monazites, sample location  
 1064 shown on Fig. 2, and GPS in Table 1. a, b, c, b: Upper Gneiss Unit. a) core of monazite grain

1065 from SO 15 granulite (Saugères); b) rim of monazite grain from SO15 granulite (Saugères); c)  
1066 biotite-sillimanite migmatitic gneiss SO11 from Pont de Menat; d) biotite-sillimanite  
1067 migmatitic paragneiss SO7 from Moulin de Bouchet; e) biotite-staurolite micaschist SO3  
1068 from the Para-autochthonous Unit; f) two-mica paragneiss SO17 from the Lower Gneiss Unit.

1069

1070 Fig. 7. Cathodoluminescence (CL) images for representative zircons sample SO 15. The white  
1071 ellipses in the CL images represent the spots of SIMS U-Pb analysis. SIMS spots are 30  $\mu\text{m}$  in  
1072 length for scale.

1073

1074 Fig. 8. Probability histogram of U-Pb age for 51 concordant analyses showing the two groups  
1075 of zircon ages. Group 1 zircons have a main peak at 342 Ma and a secondary one at 327 Ma.

1076

1077 Fig. 9. Zircon U-Pb Concordia age of granulitic paragneiss sample S015.

1078

1079 Fig. 10. Synthetic map summarizing the available radiometric ages obtained through different  
1080 methods, whole rock Rb/Sr, biotite and muscovite  $^{40}\text{Ar}/^{39}\text{Ar}$ , monazite U-Th-Pb, and zircon  
1081 U-Pb SIMS for the Sioule series.

1082

1083 Fig. 11. Synoptic chart of the radiometric ages from the Sioule series presented in this paper,  
1084 compared with the ages of the D<sub>1</sub>, D<sub>2</sub>, D<sub>3</sub> tectono-thermal events for the French Massif  
1085 central, and the Guéret and S<sup>t</sup>-Gervais biotite granites, and Pouzol-Servant microgranite.

1086 (1): Average biotite, muscovite, and hornblende  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from Faure et al. (2002); (2):  
1087 zircon U-Pb age of the Pouzol-Servant microgranite (Pin 1991); (3): zircon U-Pb SHRIMP and  
1088 monazite U-Th-Pb chemical ages of the Guéret-St-Gervais plutons (Cartannaz et al. 2007).

1089

1090 Fig. 12. P-T-t paths for the Upper Gneiss Unit (UGU), Lower Gneiss Unit (LGU), and Para-  
1091 Autochthonous Unit (PAU) modified from Mercier et al. 1991, Lardeaux et al., 2001; Schulz  
1092 et al., 2001; Bellot and Roig 2007; Faure et al. 2007; Schulz 2009) emphasizing the  
1093 polycyclic evolution. During the eo-Variscan cycle, the UGU experienced the D<sub>0</sub> high to  
1094 ultra-high pressure metamorphism, and Devonian migmatization during its D<sub>1</sub> exhumation.  
1095 The LGU underwent burial under lower pressure conditions than the UGU, then Devonian  
1096 exhumation and migmatization during D<sub>1</sub>. During the Late Devonian-Early Carboniferous D<sub>2</sub>  
1097 event, the PAU followed its first burial and exhumation cycle, whereas the LGU and UGU  
1098 experienced a second metamorphic cycle before its Late Visean exhumation.

1099

1100 Table 1. Dated sample locations and analytical data

1101

1102 Table 2. Electron microprobe analyses of dated monazites

1103

1104 Table 3. Zircon U-Pb zircon analyses of granulitic paragneiss sample SO15

Figure 1  
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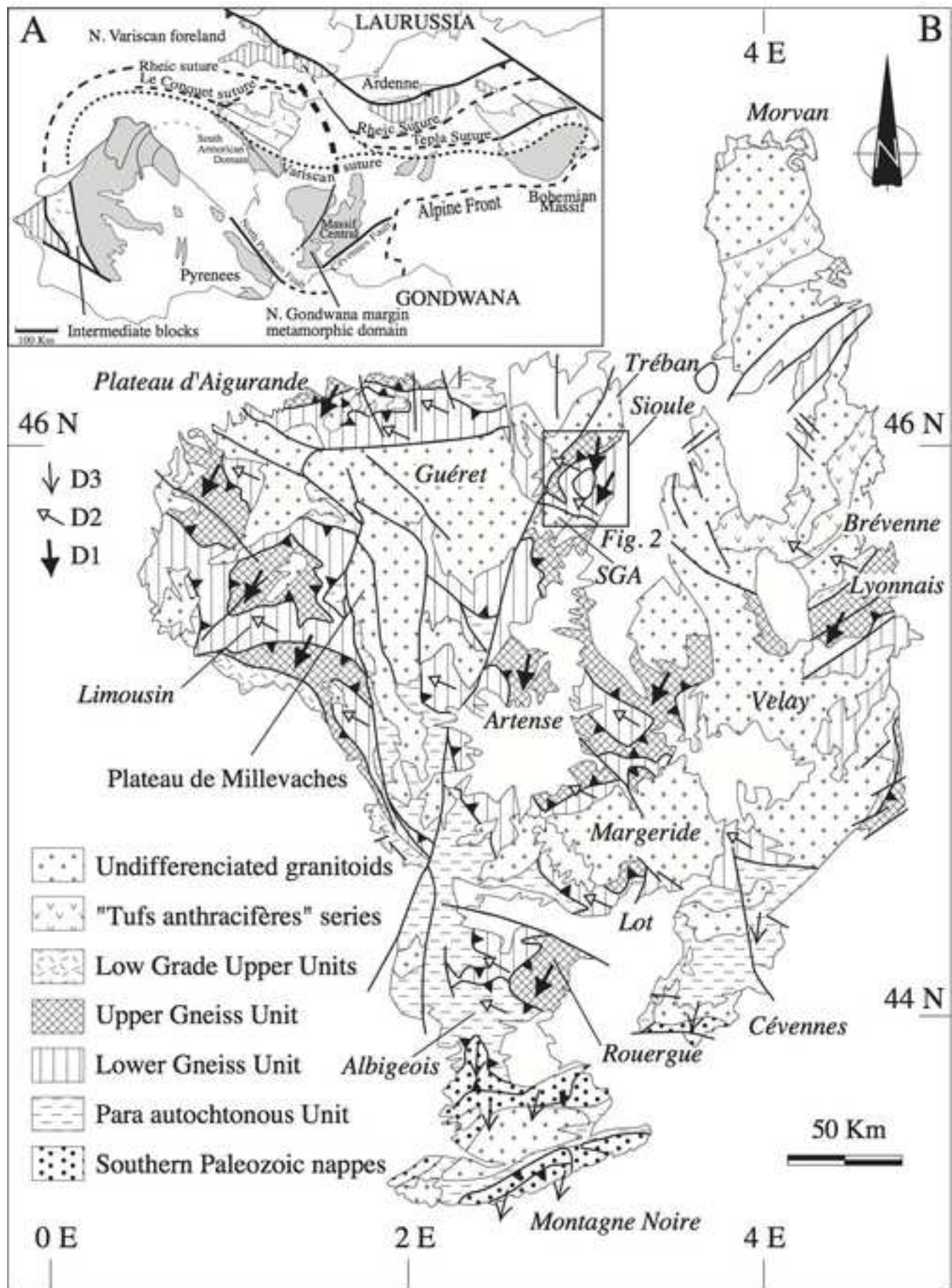


Fig. 1



Figure 2  
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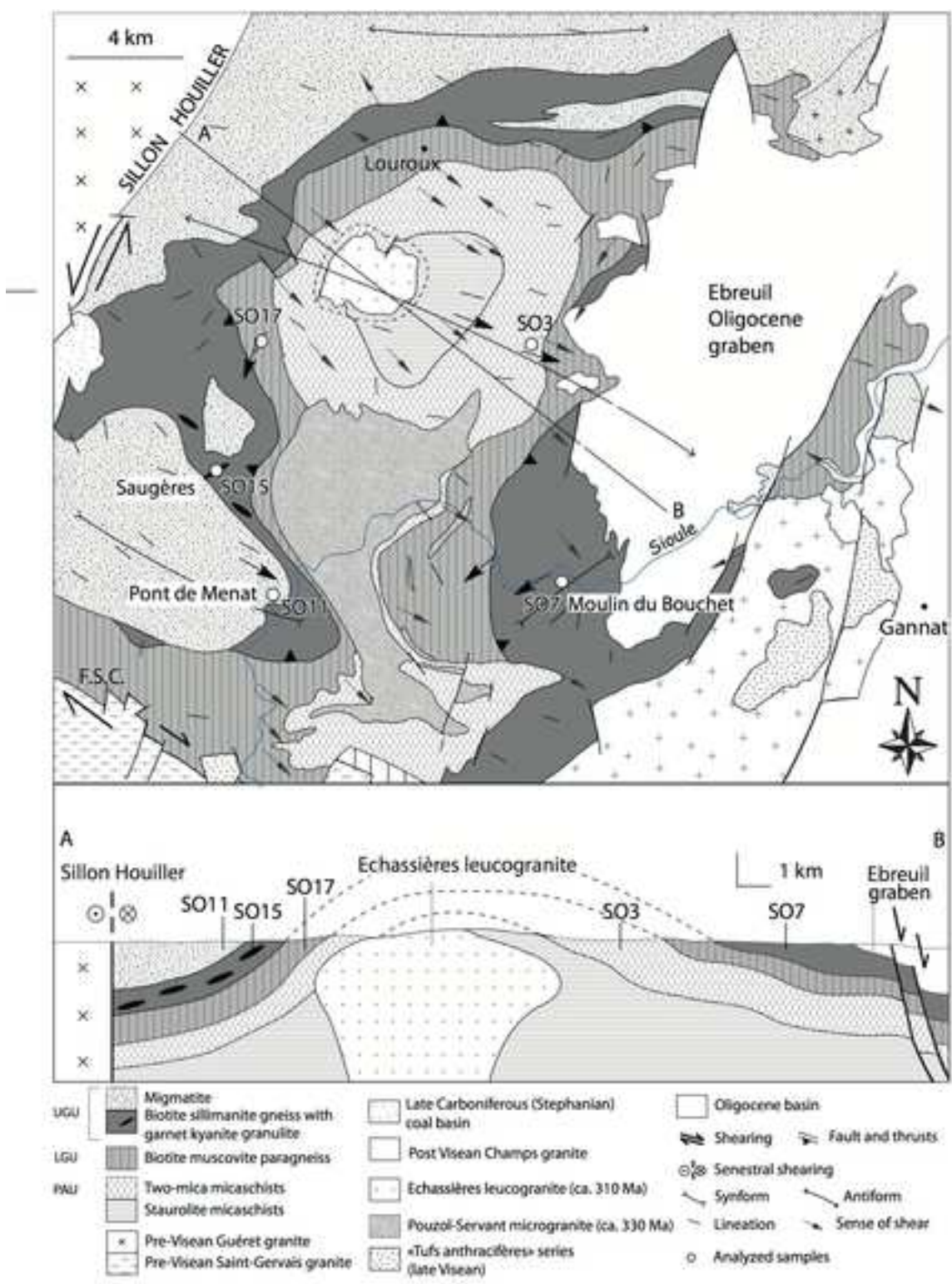


Fig. 2



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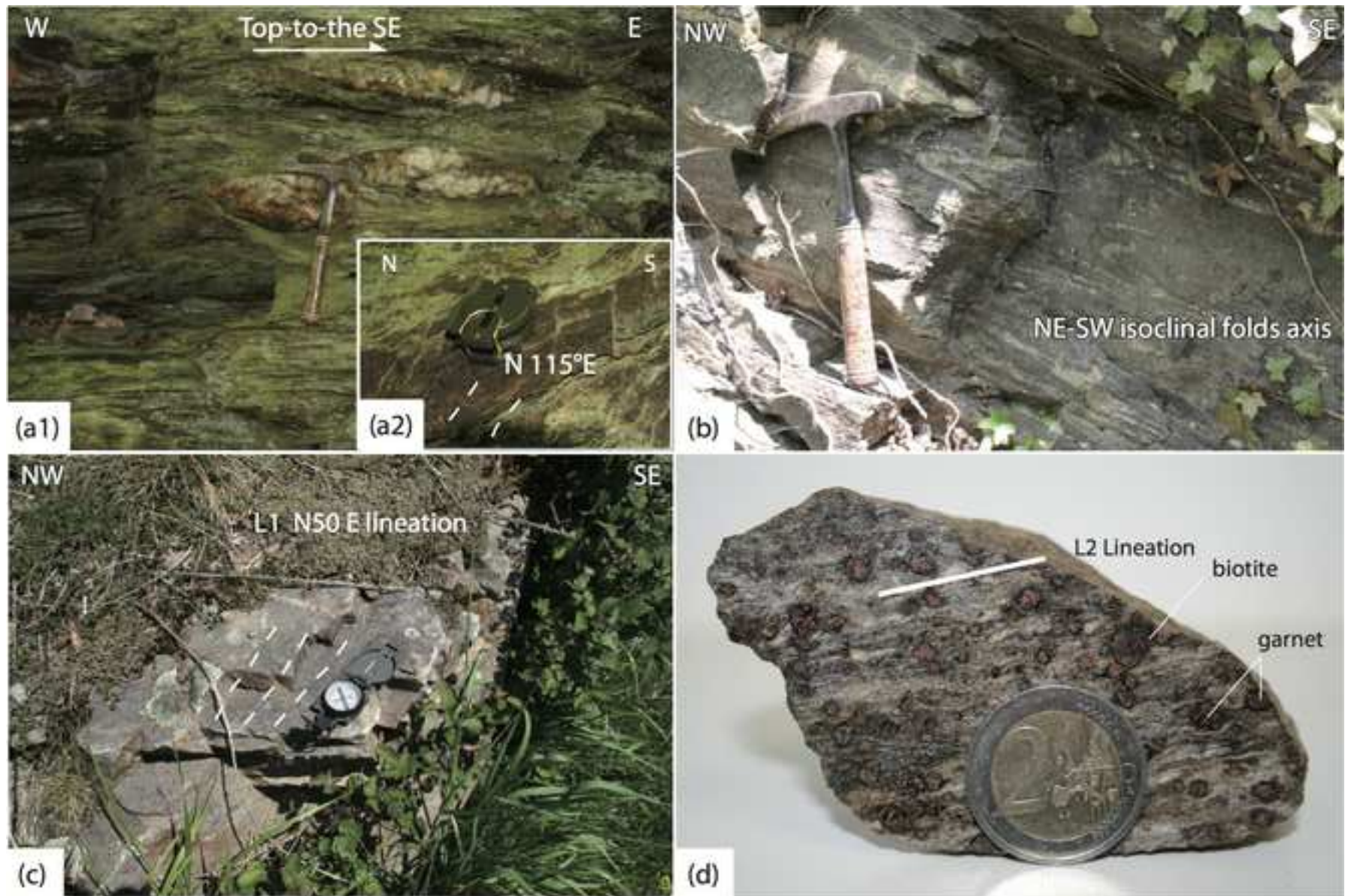


Fig. 3



Figure 4  
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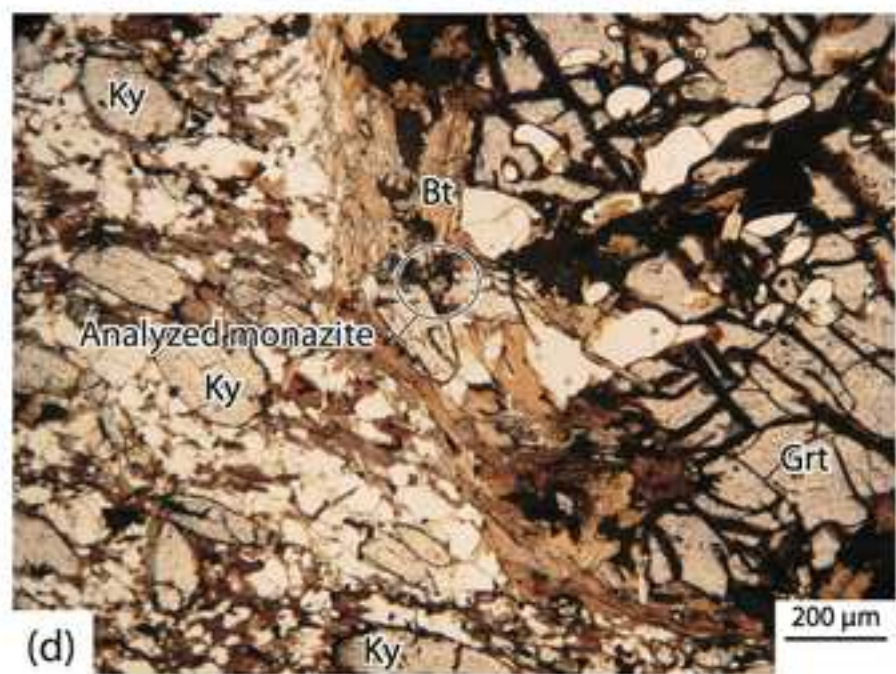
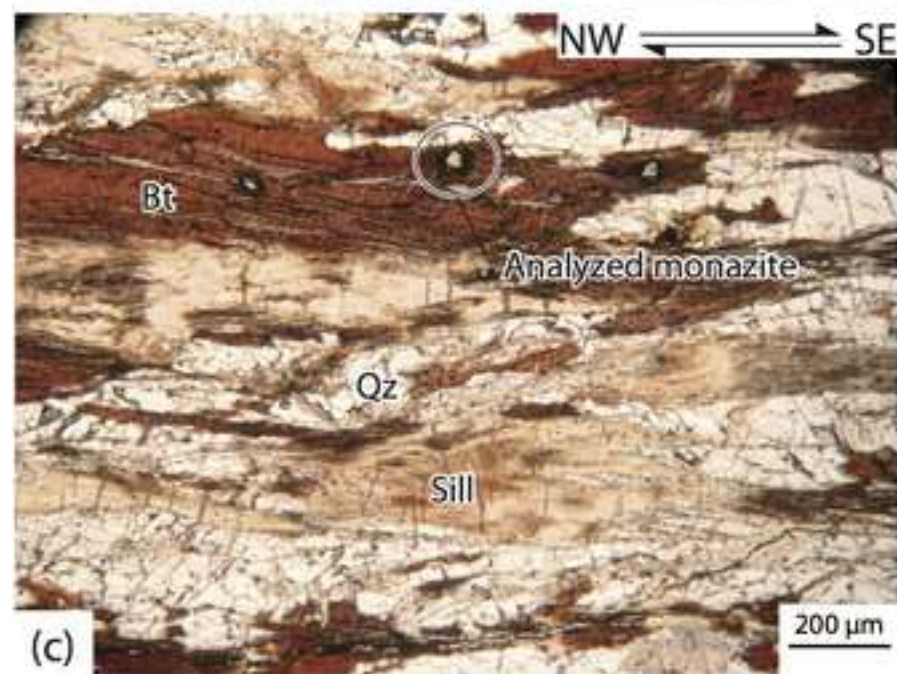
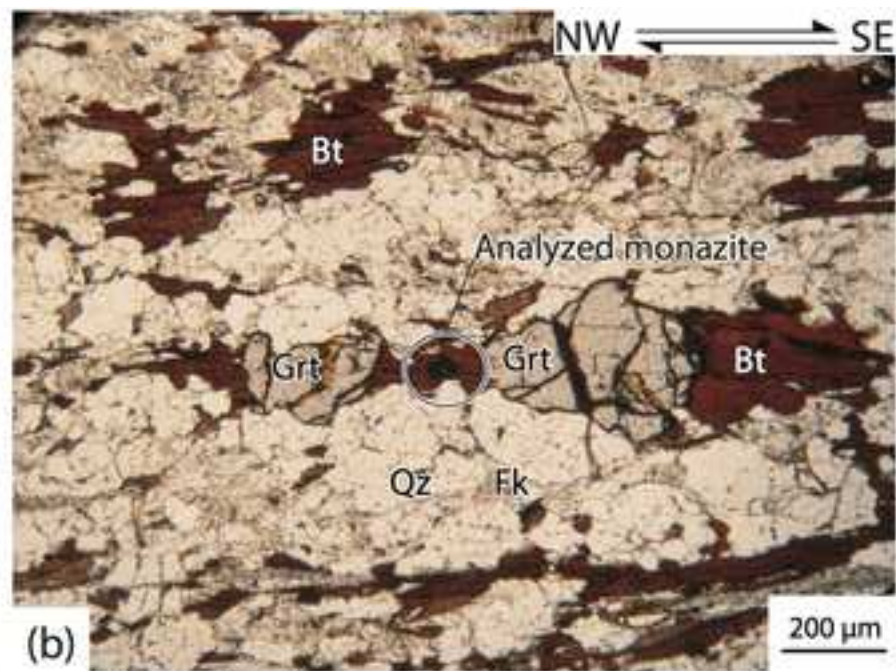
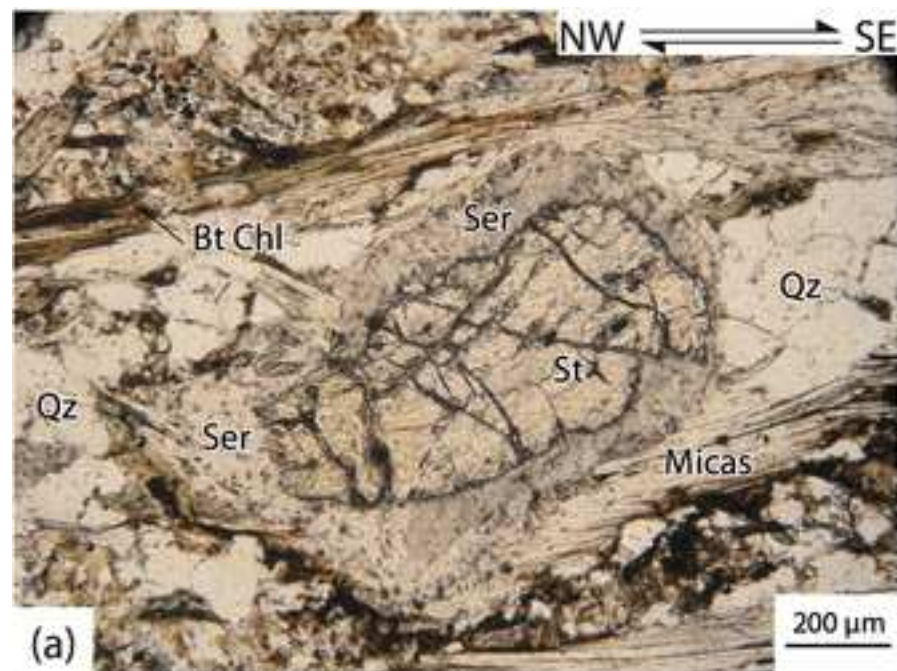


Fig 4



Figure 5  
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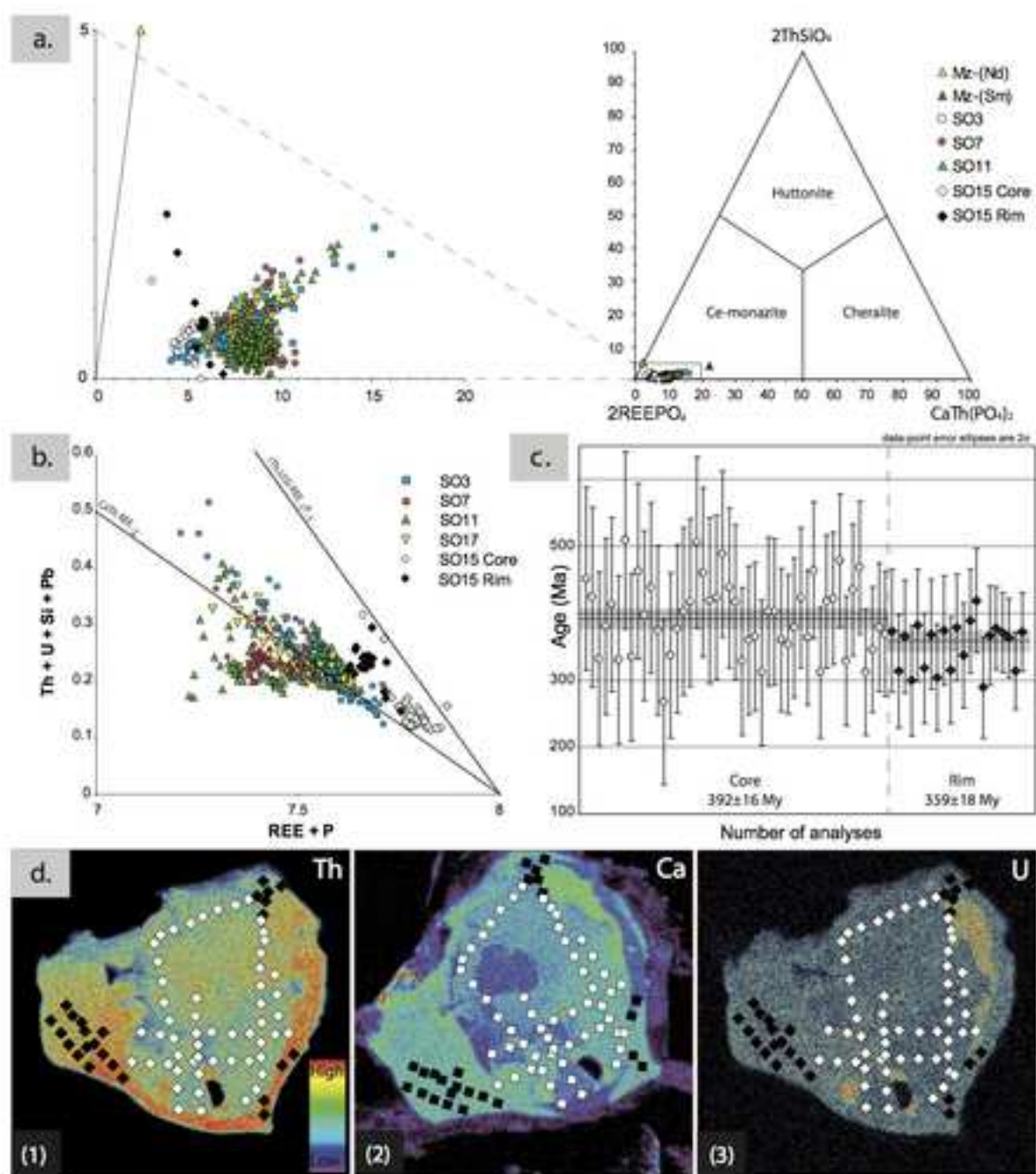


Fig. 5

Figure 6

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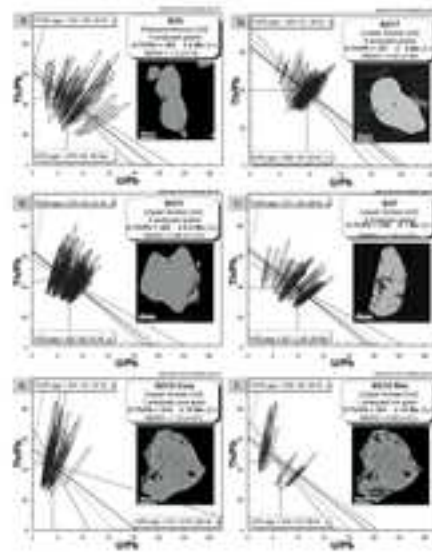


Fig 6

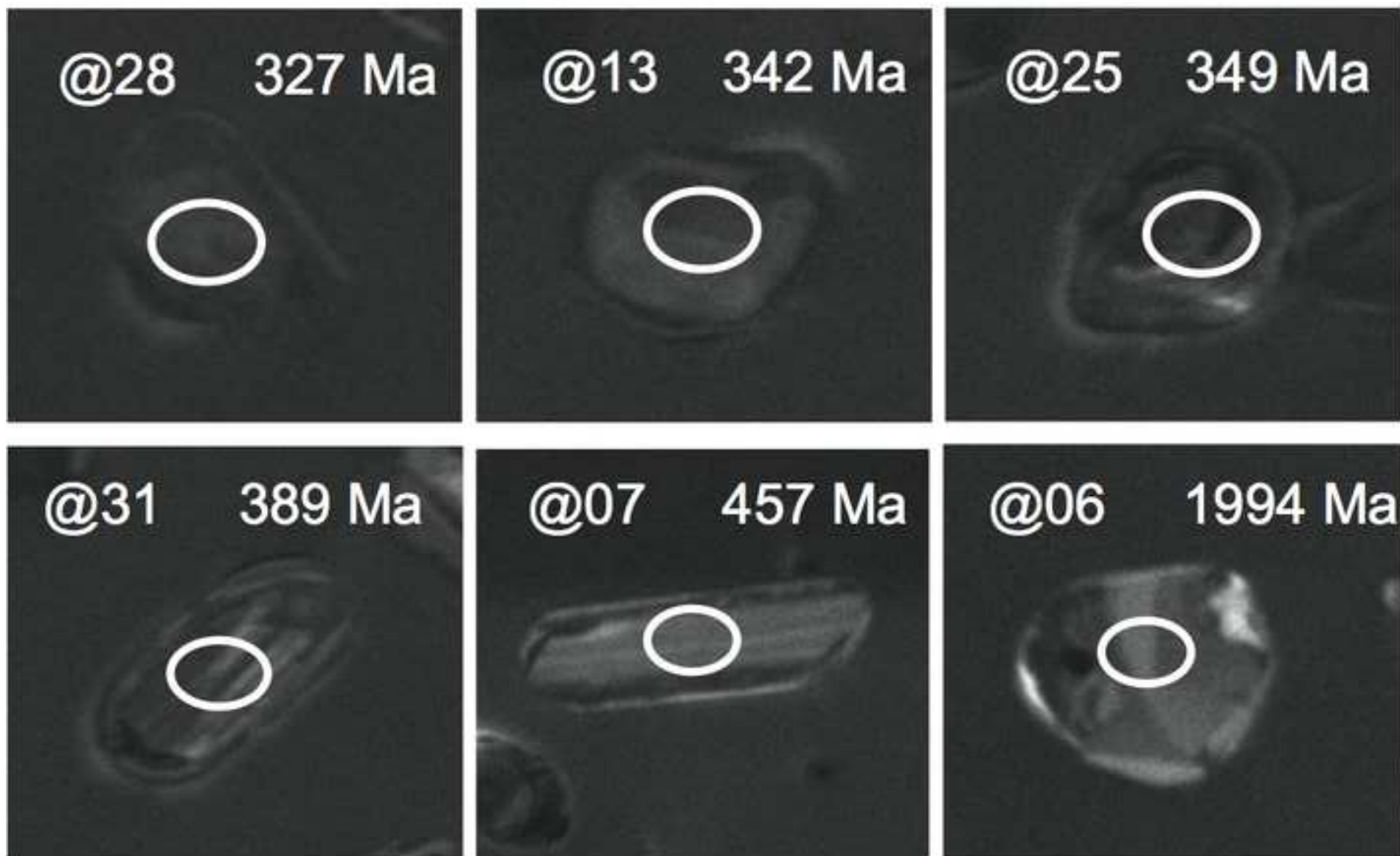


Fig. 2

Figure 8  
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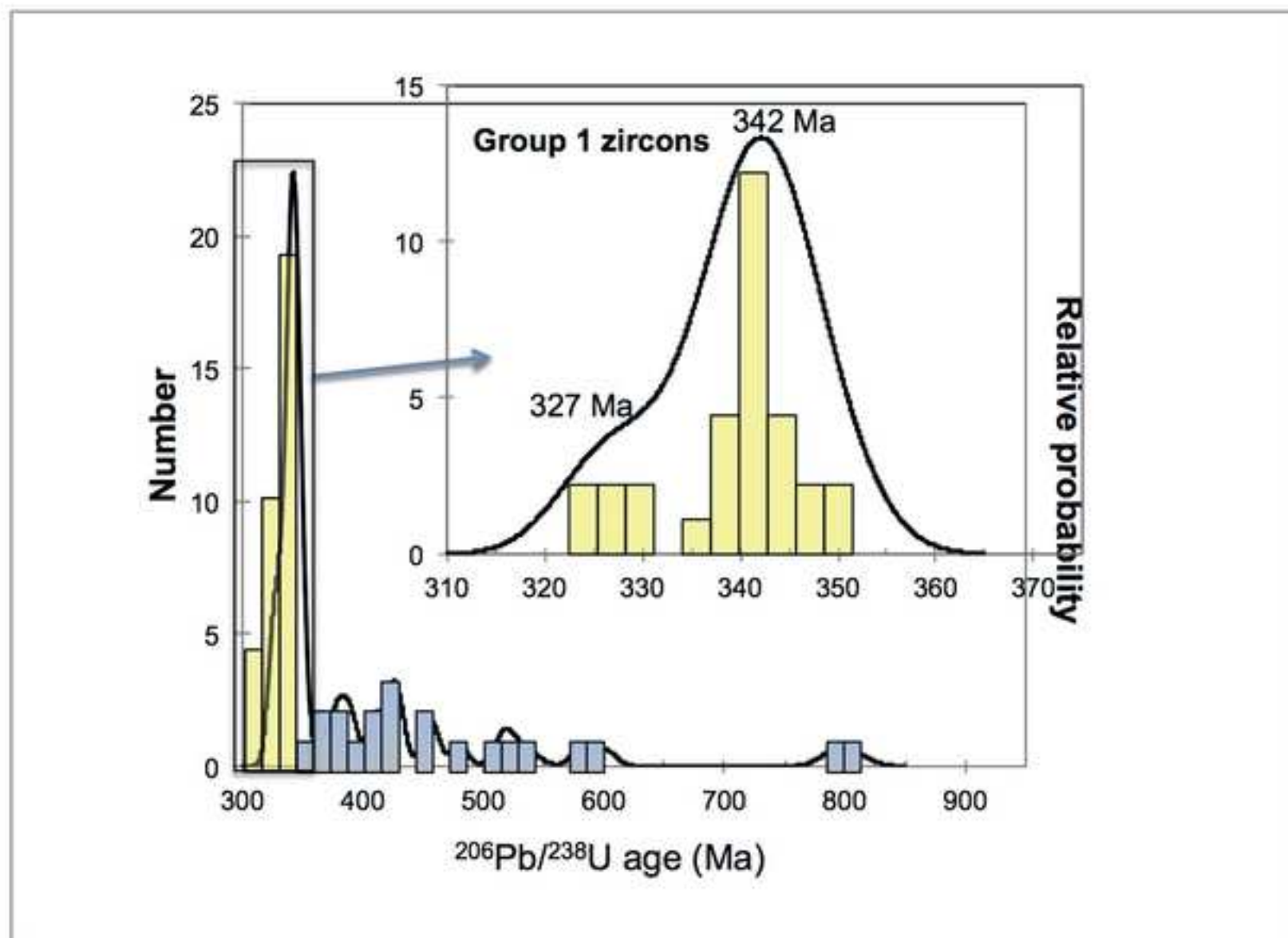


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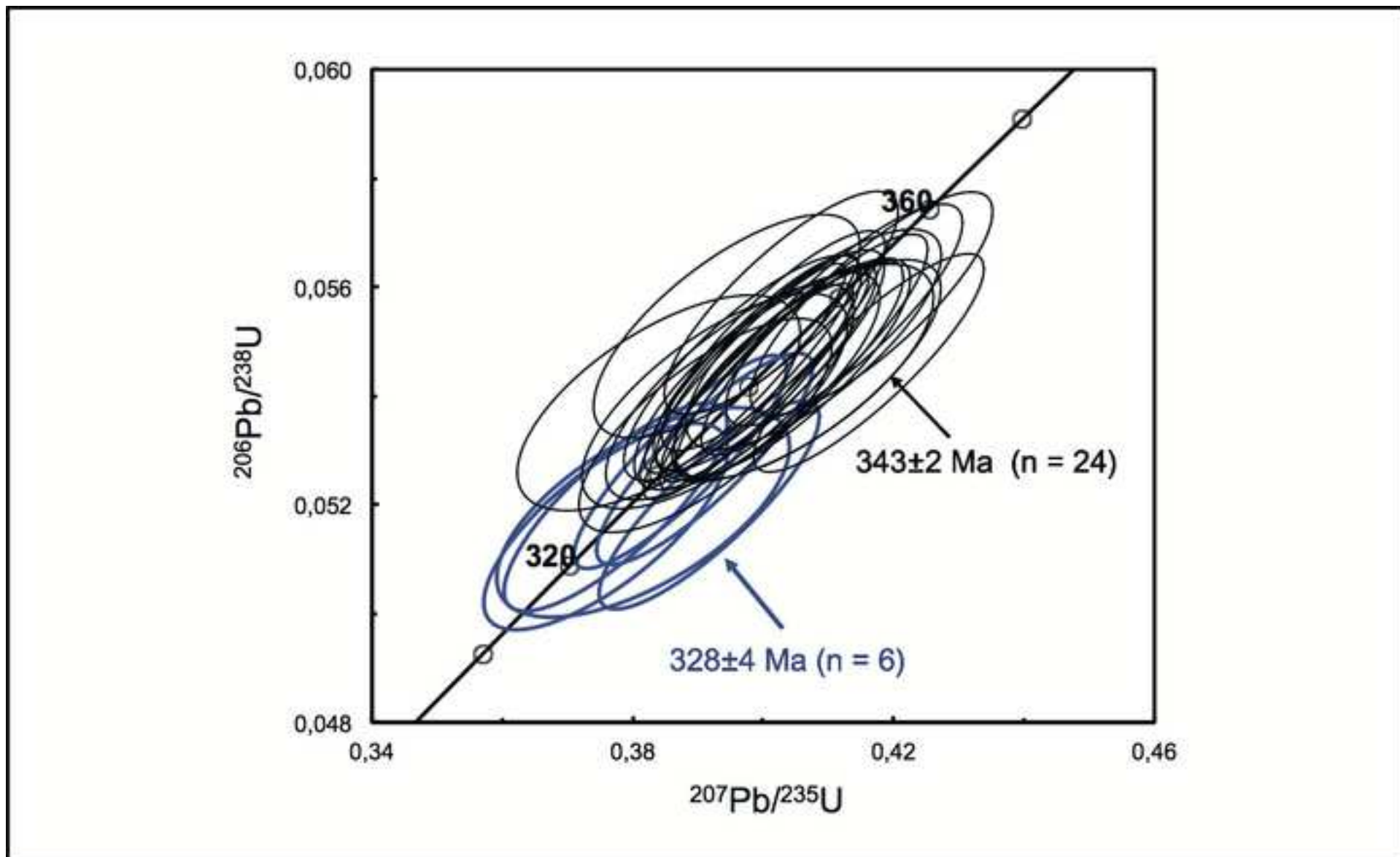




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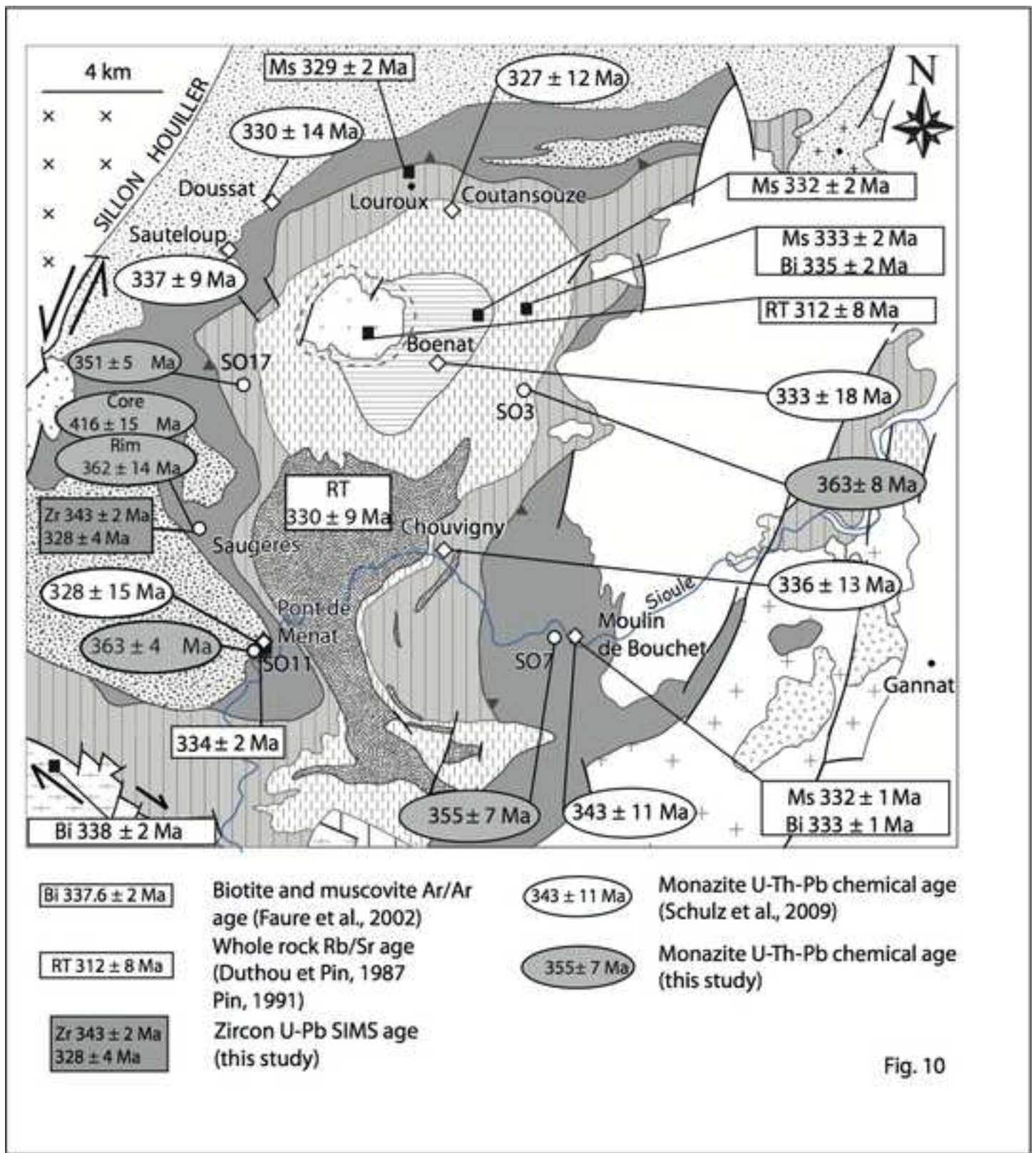


Fig. 10



Figure 11  
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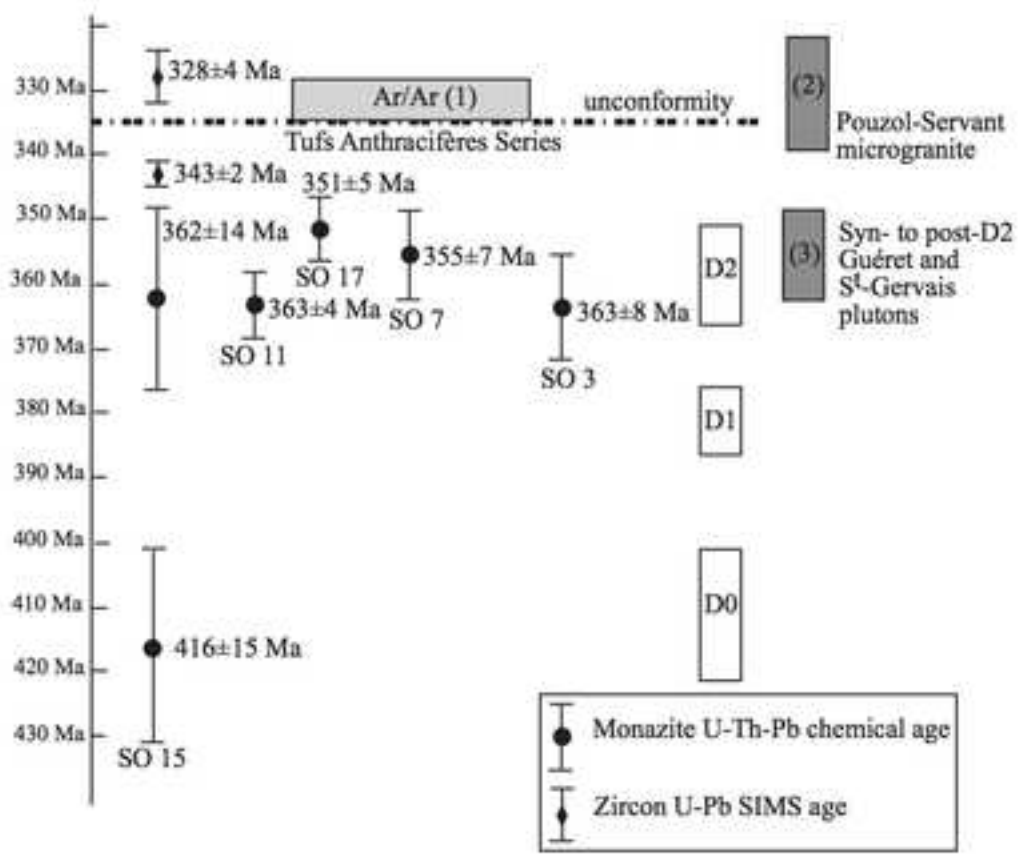


Fig. 11

Figure 12  
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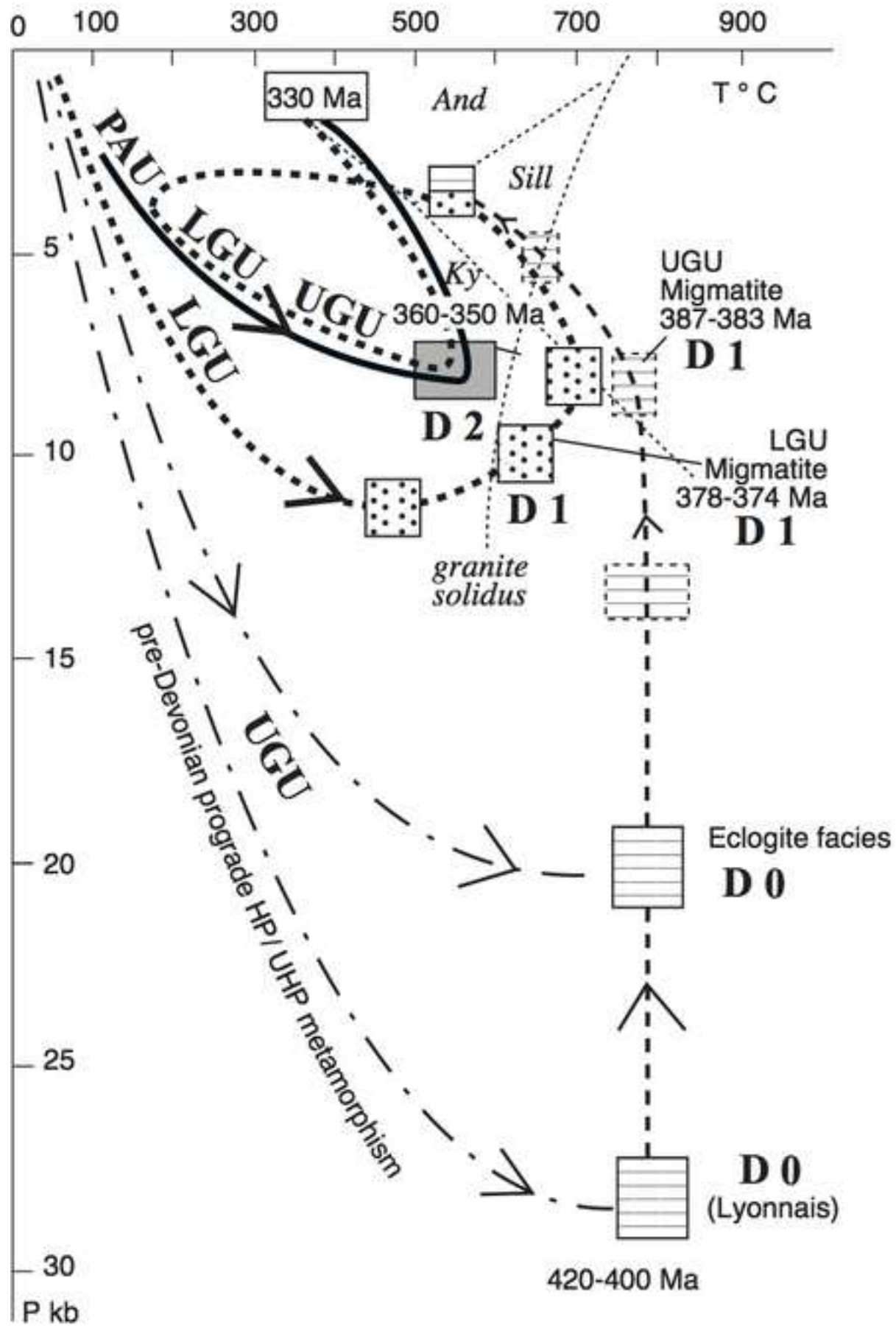


Fig. 12



Table 2. Electron microprobe analyses of dated monazites

Sample	UO <sub>2</sub>	PbO	Nd <sub>2</sub> O <sub>3</sub>	CaO	P <sub>2</sub> O <sub>5</sub>	ThO <sub>2</sub>	Gd <sub>2</sub> O <sub>3</sub>	Ce <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Sm <sub>2</sub> O <sub>3</sub>	La <sub>2</sub> O <sub>3</sub>	Y <sub>2</sub> O <sub>3</sub>	Pr <sub>2</sub> O <sub>3</sub>
SO3	0.55	0.10	12.27	0.88	29.27	4.25	1.34	29.27	0.67	2.21	14.08	0.99	3.51
	±	±	±	±	±	±	±	±	±	±	±	±	±
SO7	0.18	0.03	0.54	0.27	0.5	1.63	0.28	0.94	0.99	0.16	0.78	0.26	0.15
	±	±	±	±	±	±	±	±	±	±	±	±	±
SO11	0.91	0.13	11.16	1.04	28.82	4.45	1.57	28.33	0.28	1.98	13.9	2.11	3.29
	±	±	±	±	±	±	±	±	±	±	±	±	±
SO15	0.29	0.02	0.45	0.11	0.58	0.59	0.15	0.51	0.13	0.16	0.31	0.64	0.1
	±	±	±	±	±	±	±	±	±	±	±	±	±
SO15 Rim	0.61	0.1	11.9	0.99	29.39	4.48	1.32	28.85	0.25	2.03	14.92	0.74	3.44
	±	±	±	±	±	±	±	±	±	±	±	±	±
SO15 Core	0.15	0.01	0.32	0.11	0.92	0.68	0.29	0.94	0.11	0.14	0.6	0.86	0.11
	±	±	±	±	±	±	±	±	±	±	±	±	±
SO17	0.22	0.06	12.34	0.65	29.33	3.05	0.51	32.19	0.15	1.62	16.55		3.65
	±	±	±	±	±	±	±	±	±	±	±	0	±
SO17	0.07	0.01	0.34	0.49	0.49	0.39	0.08	0.37	0.17	0.12	0.52		0.09
	±	±	±	±	±	±	±	±	±	±	±		±
SO17	0.44	0.09	12.44	0.81	29.1	4.39	0.76	30.78	0.32	1.93	15.86		3.57
	±	±	±	±	±	±	±	±	±	±	±	0	±
SO17	0.3	0.02	0.23	0.14	0.48	0.44	0.14	0.59	0.15	0.15	0.32		0.08
	±	±	±	±	±	±	±	±	±	±	±		±
SO17	0.95	0.15	10.98	1.35	28.04	5.67	1.55	27.26	1.11	1.88	13.36	2.56	3.23
	±	±	±	±	±	±	±	±	±	±	±	±	±
SO17	0.13	0.03	0.55	0.24	1.03	1.72	0.13	0.74	2.79	0.17	0.39	0.28	0.13
	±	±	±	±	±	±	±	±	±	±	±	±	±

Table 2

Table 3 SIMS U-Pb zircon data

Sample/ spot #	Radiogenic isotopic ratios			Age (Ma)												
	[U]	[Th]	Th/U	$f_{206}$	$^{207}\text{Pb}$	$\pm\sigma$	$^{207}\text{Pb}$	$\pm\sigma$	$^{206}\text{Pb}$	$\pm\sigma$	$^{207}\text{Pb}$	$\pm\sigma$	$^{206}\text{Pb}$	$\pm\sigma$		
	ppm	ppm		%	$^{206}\text{Pb}$	%	$^{235}\text{U}$	%	$^{238}\text{U}$	%	$^{206}\text{Pb}$	$^{235}\text{U}$	$^{206}\text{Pb}$	$^{238}\text{U}$		
SO-15A@01	904	28	0,03	0,00	0,0534	0,77	0,401	1,69	0,0544	1,50	346,5	17,3	342,2	4,9	341,6	5,0
SO-15A@02	231	94	0,41	0,01	0,0580	1,33	0,675	2,05	0,0844	1,56	530,5	28,9	523,8	8,4	522,3	7,8
SO-15A@03	743	34	0,05	0,00	0,0538	0,87	0,408	1,74	0,0549	1,51	364,6	19,4	347,3	5,1	344,8	5,1
SO-15A@04	673	21	0,03	0,00	0,0528	1,06	0,397	1,88	0,0545	1,55	320,0	23,8	339,4	5,4	342,2	5,2
SO-15A@05	819	25	0,03	0,01	0,0529	0,89	0,402	1,74	0,0550	1,50	326,6	20,0	342,8	5,1	345,2	5,0
SO-15A@06	289	83	0,29	0,03	0,1226	1,44	3,497	3,62	0,2069	3,32	1994,2	25,4	1526,5	29,0	1212,2	36,8
SO-15A@07	250	106	0,43	0,39	0,0534	1,75	0,541	2,31	0,0734	1,51	346,5	39,1	438,8	8,3	456,6	6,6
SO-15A@08	632	85	0,13	0,02	0,0703	1,81	1,295	2,48	0,1335	1,70	937,8	36,6	843,5	14,3	808,1	12,9
SO-15A@09	377	159	0,42	0,10	0,0565	1,07	0,527	2,19	0,0677	1,91	470,5	23,6	430,0	7,7	422,4	7,8
SO-15A@10	953	22	0,02	0,07	0,0532	0,82	0,387	1,72	0,0528	1,51	338,0	18,5	332,4	4,9	331,6	4,9
SO-15A@11	843	107	0,13	0,02	0,0545	0,92	0,517	1,77	0,0687	1,50	393,2	20,6	423,0	6,1	428,5	6,2
SO-15A@12	661	37	0,06	0,02	0,0553	0,87	0,416	1,74	0,0546	1,50	423,5	19,3	353,3	5,2	342,7	5,0
SO-15A@13	444	15	0,03	0,00	0,0538	1,08	0,404	1,85	0,0545	1,50	361,7	24,2	344,7	5,4	342,2	5,0
SO-15A@14	817	115	0,14	0,00	0,0569	0,69	0,534	1,72	0,0681	1,57	487,0	15,2	434,7	6,1	424,9	6,5
SO-15A@15	389	324	0,83	0,01	0,0583	0,91	0,668	1,75	0,0831	1,50	542,5	19,7	519,7	7,2	514,5	7,4
SO-15A@16	1693	280	0,17	0,09	0,0561	0,55	0,531	1,64	0,0687	1,54	454,6	12,1	432,4	5,8	428,3	6,4
SO-15A@17	582	213	0,37	0,00	0,0591	1,05	0,707	2,33	0,0868	2,08	569,0	22,7	542,9	9,8	536,7	10,7
SO-15A@18	585	31	0,05	0,02	0,0532	0,94	0,401	1,78	0,0547	1,52	338,4	21,1	342,4	5,2	343,0	5,1
SO-15A@19	757	28	0,04	0,02	0,0539	0,99	0,412	1,80	0,0555	1,50	367,2	22,2	350,6	5,3	348,1	5,1
SO-15A@20	396	141	0,36	0,00	0,0570	0,93	0,607	1,78	0,0773	1,52	490,3	20,3	481,7	6,8	479,9	7,0
SO-15A@21	616	27	0,04	0,01	0,0546	0,92	0,392	1,76	0,0520	1,50	397,7	20,6	335,6	5,0	326,7	4,8
SO-15A@22	1050	42	0,04	0,02	0,0537	1,26	0,408	1,96	0,0550	1,50	359,8	28,2	347,3	5,8	345,4	5,1
SO-15A@23	758	36	0,05	0,03	0,0537	0,86	0,391	1,73	0,0528	1,50	357,3	19,4	335,1	5,0	331,9	4,9
SO-15A@24	536	837	1,56	0,05	0,0547	0,98	0,458	1,80	0,0607	1,51	400,2	21,8	382,9	5,7	380,1	5,6
SO-15A@25	954	203	0,21	0,18	0,0543	1,03	0,417	1,82	0,0557	1,50	381,5	23,0	353,6	5,5	349,4	5,1
SO-15A@26	734	325	0,44	0,23	0,1111	0,63	3,048	2,00	0,1989	1,89	1818,0	11,5	1419,8	15,4	1169,6	20,3
SO-15A@27	735	413	0,56	0,02	0,1087	0,71	3,219	1,69	0,2147	1,54	1778,2	12,8	1461,7	13,2	1253,9	17,5
SO-15A@28	845	27	0,03	0,09	0,0527	1,09	0,377	1,85	0,0520	1,50	315,0	24,5	325,1	5,2	326,5	4,8
SO-15A@29	586	447	0,76	0,05	0,0696	0,75	1,251	1,77	0,1304	1,60	916,0	15,3	823,9	10,0	790,2	11,9
SO-15A@30	910	365	0,40	0,09	0,0568	0,78	0,575	1,69	0,0733	1,50	485,2	17,1	461,0	6,3	456,2	6,6
SO-15A@31	693	187	0,27	0,56	0,0555	1,57	0,476	2,18	0,0622	1,50	430,5	34,7	395,2	7,2	389,2	5,7
SO-15A@32	434	162	0,37	0,24	0,0557	1,21	0,479	1,98	0,0623	1,56	441,3	26,7	397,2	6,5	389,7	5,9
SO-15A@33	388	67	0,17	0,00	0,0541	1,09	0,451	1,86	0,0605	1,51	374,0	24,4	378,1	5,9	378,8	5,5
SO-15A@34	396	73	0,18	0,04	0,0550	1,10	0,495	1,89	0,0653	1,54	410,6	24,3	408,3	6,4	407,9	6,1
SO-15A@35	958	29	0,03	0,02	0,0529	0,77	0,398	1,69	0,0546	1,50	324,9	17,4	340,4	4,9	342,6	5,0
SO-15A@36	579	129	0,22	0,03	0,0540	0,93	0,437	1,78	0,0587	1,52	370,1	20,7	368,1	5,5	367,8	5,5
SO-15A@37	244	60	0,25	0,11	0,1003	2,17	1,531	2,84	0,1107	1,83	1629,2	39,8	942,8	17,6	676,9	11,8
SO-15A@39	1787	32	0,02	0,00	0,0529	0,61	0,397	1,63	0,0544	1,51	324,0	13,9	339,4	4,7	341,6	5,0
SO-15A@40	1767	22	0,01	0,05	0,0534	0,62	0,400	1,64	0,0543	1,52	347,3	14,0	341,8	4,8	340,9	5,0
SO-15A@41	1067	79	0,07	0,01	0,0533	0,70	0,398	1,66	0,0541	1,50	343,2	15,8	340,0	4,8	339,5	5,0
SO-15A@42	648	161	0,25	0,04	0,0541	1,14	0,491	1,97	0,0659	1,61	373,2	25,4	405,5	6,6	411,2	6,4
SO-15A@43	604	28	0,05	0,01	0,0538	0,92	0,404	1,77	0,0545	1,51	362,3	20,7	344,6	5,2	342,0	5,0
SO-15A@55	606	22	0,04	0,05	0,0541	1,39	0,407	2,05	0,0545	1,51	377,3	30,9	346,6	6,0	342,0	5,0
SO-15A@57	636	35	0,06	0,03	0,0531	1,36	0,391	2,03	0,0535	1,50	331,7	30,5	335,2	5,8	335,7	4,9
SO-15A@58	649	52	0,08	0,00	0,0608	0,94	0,818	1,84	0,0976	1,58	631,1	20,2	606,9	8,5	600,4	9,1
SO-15A@59	1977	1432	0,72	0,06	0,0593	0,64	0,772	1,63	0,0944	1,50	576,8	13,9	580,7	7,2	581,7	8,3
SO-15A@60	781	22	0,03	0,07	0,0528	1,37	0,376	2,04	0,0516	1,50	321,6	30,9	324,0	5,7	324,3	4,8
SO-15A@61	477	31	0,07	0,00	0,0539	1,57	0,405	2,17	0,0544	1,50	368,0	34,9	345,0	6,4	341,6	5,0
SO-15A@62	725	25	0,03	0,00	0,0530	1,28	0,395	1,97	0,0541	1,50	327,4	28,8	338,0	5,7	339,5	5,0
SO-15A@63	810	31	0,04	0,02	0,0533	1,21	0,399	1,93	0,0543	1,50	343,0	27,2	341,0	5,6	340,7	5,0
SO-15A@64	696	28	0,04	0,09	0,0534	1,87	0,382	2,41	0,0519	1,52	344,5	41,7	328,2	6,8	325,9	4,8
SO-15A@65	573	26	0,05	0,00	0,0528	1,50	0,393	2,12	0,0539	1,50	320,8	33,7	336,2	6,1	338,5	4,9
SO-15A@66	2192	98	0,04	0,11	0,0524	1,03	0,403	1,82	0,0557	1,50	304,3	23,3	343,7	5,3	349,5	5,1
SO-15A@67	577	227	0,39	0,15	0,0517	1,76	0,384	2,31	0,0539	1,50	272,0	39,8	330,0	6,5	338,3	4,9
SO-15A@68	609	16	0,03	0,00	0,0517	1,48	0,394	2,12	0,0553	1,52	274,2	33,5	337,6	6,1	346,9	5,1
Qinghu@1	1552	930	0,60	0,04	0,0496	0,92	0,173	1,80	0,0253	1,55	176,0	21,2	162,3	2,7	161,3	2,5
Qinghu@2	1209	554	0,46	0,00	0,0491	1,00	0,170	1,80	0,0252	1,50	150,4	23,3	159,6	2,7	160,2	2,4
Qinghu@3	2014	557	0,28	0,01	0,0502	0,95	0,174	1,78	0,0251	1,50	204,0	22,0	162,8	2,7	159,9	2,4
Qinghu@4	945	409	0,43	0,00	0,0500	1,94	0,172	2,45	0,0249	1,50	195,2	44,5	160,9	3,7	158,6	2,4
Qinghu@5	633	227	0,36	0,00	0,0490	1,40	0,170	2,06	0,0251	1,51	146,2	32,5	159,0	3,0	159,9	2,4
Qinghu@6	1362	797	0,59	0,11	0,0499	1,21	0,174	1,93	0,0253	1,51	188,3	27,9	162,6	2,9	160,8	2,4
Qinghu@7	2559	1041	0,41	0,01	0,0491	0,70	0,174	1,66	0,0256	1,50	153,9	16,4	162,6	2,5	163,2	2,4
Qinghu@8	1301	551	0,42	0,00	0,0496	0,96	0,171	1,78	0,0250	1,50	175,2	22,4	160,5	2,7	159,5	2,4
Qinghu@9	703	300	0,43	0,07	0,0482	1,46	0,165	2,09	0,0249	1,50	107,3	34,1	155,4	3,0	158,6	2,4
Qinghu@10	980	440	0,45	0,10	0,0498	1,23	0,174	1,94	0,0253	1,50	184,4	28,3	162,7	2,9	161,2	2,4
Qinghu@11	980	440	0,45	0,10	0,0498	1,23	0,174	1,94	0,0253	1,50	184,4	28,3	162,7	2,9	161,2	2,4
Qinghu@12	1144	478	0,42	0,08	0,0480	1,30	0,169	1,99	0,0256	1,50	98,0	30,5	158,7	2,9	162,8	2,4