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1 **High-*P* metamorphism in the Mesoproterozoic: petrochronological insights**
2 **from the Grenville Province**

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23 **Abstract:**

24 In the Grenville Province, high-P rocks that are discontinuously exposed along the margin of
25 the allochthonous belt preserve the record of deep crustal processes and are an essential
26 puzzle piece to understanding Mesoproterozoic geodynamics. The Manicouagan Imbricate
27 zone (MIZ) is one of the three high-P domains from the Grenville Province. It is located in the
28 Central Grenville between the Parautochthonous Belt to the North and the orogenic hinterland
29 to the South, that were metamorphosed during the 1005–980 Ma Rigolet and 1080–1020 Ma
30 Ottawa orogenic phases, respectively. In the western MIZ, the Lelukuau Terrane (LT)
31 mostly consists of Labradorian-age (~1650 Ma) mafic suites with a fringe of aluminous rocks
32 at its southern edge. Metamafic samples from the Western and Eastern parts of the MIZ
33 display a peak assemblage of garnet, clinopyroxene, plagioclase, rare pargasite or edenite, and
34 quartz ± kyanite. Pseudosection modelling suggests high-P granulite peak conditions at ca. 14
35 to 16 kbar and 800–900°C, with the scarcity of hydrous phases and quartz explaining the lack
36 of evidence for partial melting. Zircon cores from the Western LT sample show a maximum
37 magmatic age of ca 1.6 Ga. Lu–Hf and Sm–Nd dating on garnet from this sample yield ages
38 of 1020 ± 7 Ma and 1005 ± 13 Ma, respectively, overlapping within error and inferred to
39 represent peak metamorphic conditions followed by fast cooling. In the Eastern LT sample,
40 garnet Lu–Hf dating yields two ages that are consistent with a petrographically preserved two
41 stage growth, at 1033 ± 6 Ma and 1013 ± 6 Ma, while the Sm–Nd age indicates cooling at
42 1003 ± 8 Ma. The recorded high-P granulite facies conditions highlight a late Ottawa to
43 Rigolet-age localized crustal thickening at the margin of the hinterland during the propagation
44 of the orogen to the NW, with a possible younging of the high-P granulite-facies
45 metamorphism from the Eastern to Western LT. These new results indicate that the high-P
46 belt in the Central Grenville does not represent the exhumed base of an Ottawa age orogenic
47 plateau, as previously proposed, and that no tectonic hiatus exists between the two orogenic

48 phases, as generally thought. Finally, this publication highlights the diversity and
49 diachronicity of the high-P domains in the Grenville Province.

50

51 **Keywords:** Garnet geochronology, Zircon geochronology, high-P granulite, Grenville
52 Orogeny, Mesoproterozoic

53 **1. Introduction**

54 High-pressure (high-P) rocks, namely eclogite, high-P granulite, and kyanite-bearing
55 migmatite provide important evidence for active plate tectonics, recording the burial of the
56 crust and crustal thickening in convergence zones. In those settings, timescales and conditions
57 of metamorphism are crucial in deciphering the evolution of the lithosphere, as the tectonic
58 scenarios invoked largely rely on the rates of burial and exhumation of metamorphic terranes
59 (e.g., Warren, 2013), their corresponding size, and their temporal and spatial distribution
60 within an orogen (e.g., Kylander-Clark et al., 2012). In this regard, the advent of
61 petrochronology (see RIMG 2017 special volume, Kohn et al., 2017) has provided valuable
62 insights on the petrological evolution of chronometers by integrating their textural, isotopic,
63 and elemental context. Zircon and monazite are often targeted to access time information
64 during metamorphism (e.g., Baldwin and Brown, 2008; Gasser et al., 2012; Štípská et al.,
65 2016; Wang et al., 2017), as their potential equilibrium with garnet can be assessed by their
66 trace element record (e.g., Rubatto, 2002, 2017; Whitehouse and Platt, 2003). In recent years,
67 an increasing number of publications have highlighted the need to combine multiple
68 petrochronological tools in high-grade terranes (e.g., Manzotti et al., 2018; Lotout et al., 2018,
69 2020; Wang et al., 2019; Du et al., 2021; Li et al., 2022). This is supported by the fact that
70 prograde and/or retrograde metamorphic overprints can result in a complex record of
71 accessory minerals reflecting lack of equilibrium at the rock scale, and incomplete U–Pb
72 resetting or trace element inheritance (e.g., Harley et al., 2007; Yakymchuk and Brown, 2014;
73 Whitehouse et al., 2014; Kohn et al., 2015; Taylor et al., 2016; Lotout, et al., 2018; Pitra et al.,
74 2022), thus making it difficult to link ages to specific P–T stages. Petrochronological
75 investigation of both rock-forming minerals (like garnet) and accessory minerals (like zircon)
76 provides a strategy to obtain significant timing information. Combined with P–T

77 thermodynamic modelling, this has proven to be one of the most reliable approaches to
78 decipher the style of tectonic processes.

79 Exhumed cores of ancient orogens give direct access to formerly deep and hot levels of the
80 crust offering opportunities to both assess the condition and duration of high-T and high-P
81 processes and investigate the tectonic evolution of orogenic roots. The Grenville Province,
82 exposed in eastern North America from Canada to the Adirondack Mountains of the United
83 States (Fig. 1a), is recognized as the first Large Hot Orogen (LHO) on Earth (Rivers, 2009),
84 and is attributed to the collision between Laurentia and Amazonia in the late
85 Mesoproterozoic. Its orogenic core (Allochthonous belt, or hinterland) is an assembly of
86 crustal segments that were metamorphosed, mostly at granulite-facies conditions, at different
87 depths during the 1090–1020 Ma Ottawan phase of the Grenvillian orogeny (Fig. 1b) and is
88 inferred to represent remnants of a collapsed orogenic plateau (Rivers, 2008; 2012). In
89 contrast, the Parautochthonous belt of the Grenville Province (Fig. 1b) was deformed and
90 metamorphosed later, during the final propagation of the orogen to the NNW (Rigolet Phase;
91 1005–980 Ma), and after a presumed tectonometamorphic hiatus of about 15 Myr (e.g.,
92 Rivers, 2009, 2012).

93 Although geodynamic modelling has addressed key tectonic features of the Grenville orogen
94 (e.g., Jamieson et al., 2007, 2010), metamorphic data, crucial for tectonic interpretations, are
95 patchy and incomplete (see Indares and Dunning, 2018, and Indares, 2020 for a review), and
96 petrochronological studies remain scarce. For instance, garnet ages are only reported from
97 mid-P and high-T rocks from the Virginia Blue Ridge area (Johnson et al., 2018, 2020), a
98 tectonic window within the Appalachian Orogen.

99 In addition, recent debate on Mesoproterozoic global tectonic regimes, and changes of
100 orogenic style with time, has been spirited (e.g., Cawood and Hawkesworth, 2014; Tang et al.,
101 2021; Roberts et al., 2022), and some aspects of the orogen are questioned by recent studies.

102 For instance, Spencer et al. (2021), made the case that the orogenic crust was thin in the
103 Mesoproterozoic and Brudner et al., (2022) disputed the existence of a long-lived highly
104 elevated orogenic plateau in the Grenville. Considering this, high-P rocks exposed in the
105 Grenville Province are essential pieces to the Mesoproterozoic geodynamic puzzle as they
106 record orogenic processes operating at depth. These rocks are documented on either side of
107 the Allochthon Boundary Thrust (Fig. 1b). In the hinterland, they are grouped within the
108 “high-P belt” (Rivers et al., 2002) and occur (i) as mafic pods of eclogite retrogressed to
109 granulite, with early Ottawaan metamorphic ages, dispersed in orthogneiss (e.g.,
110 Davidson 1990; Marsh & Culshaw, 2014; western Grenville), and (ii) in coherent lithotectonic
111 packages dominated by mafic rocks with well-preserved high-P granulite to eclogite facies
112 assemblages (Indares 1997, Indares et al., 1998, 2000; central Grenville). In addition,
113 eclogitized metagabbros are reported in the Parautochthonous Molson Lake terrane (Indares
114 1993; Indares and Rivers 1995).

115 This contribution focuses on high-P mafic rocks from the Manicouagan Imbricate zone (MIZ)
116 of the Central Grenville. The MIZ is located structurally below the mid-P belt of the
117 hinterland, (Fig. 1b, c) and based on this configuration is well suited for comparing processes
118 operating in deep to intermediate levels of the Ottawaan orogenic crust. Based on poorly
119 constrained Ottawaan ages reported in the early literature (Indares et al., 2000), the MIZ was
120 inferred to represent the extruded base of the thickened Ottawaan crust (Rivers 2008), and
121 therefore it is a key area to bring new fundamental constraints on the timing and duration of
122 high-P metamorphism and subsequent tectonic evolution.

123 The samples were collected in the early 90s in the context of the Lithoprobe project (see
124 Clowes et al., 1999; Rivers et al., 2012). In the context of the present study, they were
125 investigated using textural observation, P–T thermodynamic modelling, garnet Lu–Hf and
126 Sm–Nd dating, zircon U–Pb dating, and trace element analysis in garnet and zircon. This

127 study shows that the high-P rocks of the Central Grenville experienced peak high-P
128 metamorphism straddling the interval between the Ottawa and Rigolet phases and reveals a
129 continuum where a tectonometamorphic hiatus was previously inferred. It also highlights that
130 this high-P granulite metamorphism reflects localized crustal thickening at the margin of the
131 hinterland, as the orogen was progressing towards the Grenville front. By bringing new P–T–t
132 information on this high-P metamorphic event of the Grenville Orogen, this study also
133 highlights the tectonically active character of the lithosphere during Mesoproterozoic times.

134

135 2. Geological background

136 The MIZ is a 2000 km² area of stacked high-P crustal slices (e.g., Indares, 1997), located in
137 the central Grenville between the structurally lower Parautochthonous Gagnon terrane to the
138 north, and structurally higher lithotectonic units of the hinterland, to the south (Fig. 1b, c).

139 The Gagnon terrane consists of Archean basement and Paleoproterozoic cover
140 metamorphosed, in the vicinity of the MIZ, at amphibolite to high-P granulite facies
141 conditions at ~990 to 980 Ma (Jordan et al. 2006; Jannin et al., 2018a). South of the MIZ, the
142 mid-P belt of the hinterland consists of ~1.5–1.4 and 1.2 Ga plutonic and supracrustal rocks
143 metamorphosed under mid-P granulite-facies conditions between 1.08 and 1.04 Ga (Dunning
144 and Indares 2010; Lasalle et al. 2014). However, its contact with the MIZ is obscured by the
145 Triassic Manicouagan impact crater. In contrast, to the SE, the MIZ is in direct contact with
146 the Hart Jaune terrane, which represents the highest crustal levels of the hinterland in this area
147 that largely escaped Grenvillian-age metamorphism and deformation (part of the Orogenic
148 Lid; Rivers 2008).

149 The MIZ is subdivided into two terranes, Lelukuau (LT, lower unit) and Tshenukutish (TT,
150 upper unit; Fig. 1c). Both terranes are dominated by plutonic units, with a discontinuous

151 fringe of supracrustal rocks, including anatectic aluminous gneisses, exposed in the southern
152 MIZ along the shores of the Manicouagan reservoir (Indares and Dunning 2001, Dunning and
153 Indares, 2010).

154 The LT is the largest component of MIZ and is mostly composed of Labradorian-age
155 anorthosite–mangerite–charnockite–granite (AMCG) bodies emplaced at 1650–1630 Ma
156 (Indares et al., 1998). In the eastern MIZ, the structurally higher TT is an assembly of highly
157 deformed tectonic slices, composed of Labradorian-age AMCG, Pinwarian-age granites
158 emplaced at ca. 1450 Ma, and ca. 1190 Ma mafic sills (Cox and Indares, 1999; Indares et al.,
159 2000). Mafic rocks in the two terranes show different metamorphic textures. Coronitic or
160 granoblastic textures, based on the protolith type (sill vs other types of magmatic bodies), are
161 observed in the TT (Indares, 2003; Cox and Indares, 1999), while mafic rocks from the LT are
162 pervasively recrystallized in a granoblastic assemblage of garnet–clinopyroxene–
163 plagioclase ± amphibole ± quartz, up to the point that the magmatic archive is only deduced
164 from the presence of microdomains mimicking igneous textures (Indares, 2003). P–T
165 estimates are mostly restricted to traditional thermobarometry results, with P–T conditions in
166 the range of 14–18 kbar and 800–900°C in the LT (Indares, 1997, 2003; Indares and Dunning,
167 2004), and 780–930°C and 16–19 kbar in the TT (Cox and Indares, 1999). The P–T
168 conditions of the LT are consistent with results of subsequent pseudosection modelling (Yang
169 and Indares, 2005). This was, however, limited by the lack of thermodynamic melt data suited
170 for mafic compositions, only recently provided by Green et al. (2016), to appropriately
171 bracket the temperature range. Metamorphic ages on mafic rocks, that represent the main rock
172 types of the MIZ, are scarce and mostly restricted to lower intercepts obtained by single
173 zircon grain dissolution using ID-TIMS, at 1052 ± 19 Ma (Indares et al., 1998), and
174 1030 ± 12 Ma (Cox et al., 1998; Fig. 2). The best approximation for the age of high-P
175 metamorphism is provided by a set of syn-orogenic dykes (“Themines dykes”; Indares and

176 Dunning 2004) cropping out in southern MIZ, which display high-P granuloblastic assemblages
177 (garnet–clinopyroxene–plagioclase–quartz) and are interpreted to have been emplaced at
178 high-P conditions. One of these dykes, in the TT, was dated at 1039 ± 2 Ma (Indares et al.,
179 1998).

180 The high-P anatectic aluminous rocks exposed in the southern MIZ have kyanite–garnet–K-
181 feldspar–plagioclase–quartz \pm biotite assemblages, with textures consistent with peak and
182 melt crystallization P–T conditions in the kyanite stability field. Pseudosection modelling has
183 constrained the peak P–T conditions at 15–16 kbar and 875°C (Indares et al., 2008; Lasalle
184 and Indares, 2014; Kendrick and Indares, 2018). In the southern LT, monazite from one
185 sample was analyzed by both ID-TIMS on single grains (Dunning and Indares, 2010) and
186 later by *in situ* Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS)
187 (Lasalle et al., 2014). Both methods yielded complex age data and the age of Grenvillian
188 metamorphism remains difficult to interpret owing to strong inheritance. LA-ICPMS ages
189 spread from 1362 ± 26 Ma to 1025 ± 22 Ma, with a cluster at 1070–1050 Ma, and a poorly
190 supported weighted average age of 1061 ± 9.6 Ma while ID-TIMS data yielded an average
191 age for Grenvillian metamorphism at 1044 ± 1.5 Ma. These data are interpreted to reflect
192 protracted growth of monazite during anatexis, and, in the case of ID-TIMS, varied mixing of
193 distinct monazite age domains (Lasalle et al., 2014). In contrast, monazite ages obtained in 5
194 samples from the southern boundary of the TT (single-grain dissolution, ID-TIMS, Indares
195 and Dunning, 2001) are better constrained as they are tightly clustered at the sample scale,
196 ranging from 1040 ± 2 Ma to 1017 ± 2 Ma from West to East (Fig. 2). These late Ottawa
197 ages likely indicate diachronism of the metamorphism, however they only represent the
198 southern fringe of the MIZ, while the timing of the high-P metamorphism in the interior of the
199 MIZ, that is dominated by mafic rocks, remains poorly constrained.

200

201 **3. Analytical Methods**

202 The analytical techniques were carried out at the Core Research Equipment and Instrument
203 Training (CREAIT) Network at Memorial University of Newfoundland (MUN, St John's,
204 Canada), Centre de Recherches Petrographiques et Géochimiques (CRPG, Nancy, France),
205 and Radiogenic and Isotopic Geochronology Lab (RIGL, Washington State University,
206 Pullman, USA). All operating conditions, standards, chemical procedures, and solid solution
207 models used and carried out are described in detail in the Appendix.

208 Bulk rock powders were produced at MUN and major and trace elements analyses were
209 performed by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) and
210 Inductively Coupled Plasma Mass Spectrometry (ICPMS), respectively, at the SARM
211 laboratory of CRPG, following the procedure described in Carignan et al. (2001;
212 Supplementary Table 1). Thin sections were imaged by Scanning Electron Microscope (SEM)
213 equipped with Mineral Liberation Analysis (MLA) software to provide false color mineral
214 maps illustrating textures, X-Ray maps of garnet were obtained using an Electron Probe
215 Microanalyzer (EPMA), and zircon were imaged using a SEM equipped with a Deben
216 Centaurus CathodoLuminescence (CL) detector at CREAIT (MUN). Quantitative mineral
217 analyses for major elements were carried out using a EPMA (Supplementary Table 2) and
218 trace elements in garnet were measured by LA-ICPMS (Supplementary Table 3) at CREAIT
219 (MUN). P–T pseudosections have been calculated in the $\text{Na}_2\text{O}-\text{CaO}-\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3-$
220 $\text{SiO}_2-\text{H}_2\text{O}-\text{Fe}_2\text{O}_3$ (NCFMASHO) system using the software Theriak/Domino (de Capitani
221 and Petrakakis, 2010), and the internally consistent thermodynamic data set 6.2 (Holland and
222 Powell, 2011, update ds62, 6th February 2012). Garnet and zircon mineral separation was
223 performed at MUN following standard procedure to concentrate heavy minerals and picking.
224 Lu-Hf and Sm-Nd garnet dating was performed at RIGL, following procedures described in
225 Cheng et al., (2008) and Johnson et al., (2018). Isotope data and corresponding calculated

226 dates were produced using isoplot (Ludwig, 2003) and ages are reported at 95% confidence
 227 level (Table 2, Fig. 9.). U-Pb and REE analyzes in zircon were performed at the National Ion
 228 Probe facility hosted by the CRPG, following Deloule et al. (2002) and Jeon & Whitehouse
 229 (2014). Isotope data are reported in Supplementary Table 3 and corresponding calculated
 230 dates, produced using isoplot (Ludwig, 2003), are shown in Fig.10 and reported at 95%
 231 confidence level. Abbreviations used in this manuscript are: apfu = atom per formula unit; g =
 232 garnet; cpx = clinopyroxene; di = diopside; amp = amphibole; prg = pargasite; edn = edenite;
 233 mu = muscovite; pl = plagioclase; scp = scapolite; q = quartz; ru = rutile; bi = biotite; ky =
 234 kyanite; zrn = zircon; ap = apatite; liq = liquid. Other symbols used (mole/atomic proportion)
 235 are: $X_{alm} = Fe / (Ca + Fe + Mg + Mn)$; $X_{py} = Mg / (Ca + Fe + Mg + Mn)$; $X_{grs} = Ca / (Ca + Fe +$
 236 $Mg + Mn)$; $X_{sps} = Mn / (Ca + Fe + Mg + Mn)$ (garnet); $X_{Jd} = Na / (Na + Ca)$; $CaT = Al^{IV} - X_{Jd}$
 237 (cpx); $X_{Mg} = Mg / (Fe + Mg)$ (garnet, clinopyroxene, amphibole); $X_{An} = Ca / (Ca + Na + K)$;
 238 $X_{Ab} = Na / (Ca + Na + K)$ (plagioclase); $X_{CO3} = CO3 / (CO3 + SO4 + Cl)$; $X_{eqAn} = 100 (Al -$
 239 $3) / 3$; $X_{Me} = Ca / (Ca + Na)$ (scapolite); $Mg\# = 100 * Mg / (Mg + Fe)$ (bulk rock).

240

241 **4. Results**

242 **4.1. Sample description**

243 Three mafic rocks were selected for this study. They belong to distinct levels of the LT
 244 following Indares (1997) and all have a gabbroic composition with high Al_2O_3 content (17 to
 245 20 wt%) and Mg# ranging from 41.7 to 61.7% (Supplementary Table 1). All samples are
 246 pervasively recrystallized showing a medium to fine grained granoblastic texture and
 247 containing the mineral assemblage garnet–clinopyroxene–plagioclase–amphibole–scapolite
 248 with varied mineral proportions (Fig.3 and 4, Table 1).

249 **4.1.1. Western Lelukuau: sample 135A**

250 Sample 135A is a homogeneous granoblastic rock which, in addition to the main mineral
251 assemblage, also contains rare biotite, quartz, zircon, and apatite (Figs. 3a and 4a, Table 1).
252 Garnet is subhedral, ranging in size from 2 to 4 mm and containing rare inclusions of kyanite,
253 zircon, or apatite. It is chemically characterized by $X_{Mg} = 0.54\text{--}0.57$ and $X_{Grs} = 0.21\text{--}0.29$, both
254 parameters decreasing towards the rims (Figs 4a, 5a, 6a, b, c). Clinopyroxene is light green
255 subhedral and up to 1 mm in size (Fig.5c). It has a diopside composition, with up to 10 % Ca-
256 Tschermak component, regardless the textural position, and 7–13% jadeite, uniform at the
257 grain scale. Clinopyroxene in contact with garnet systematically shows a higher Si content
258 (1.90–1.92 apfu), and all grains display Al enrichment in the core and Mg enrichment in the
259 rims. Plagioclase is subhedral with a grain size ranging from 0.2 to 0.5 mm. Its anorthite
260 component ($X_{An} = 0.35\text{--}0.50$) is varied at the thin-section scale, but single grains are
261 homogeneous (e.g., $X_{Anpl1} = 0.43\text{--}0.44$; $X_{Anpl6} = 0.35\text{--}0.36$; $X_{Anpl3} = 0.45\text{--}0.47$; Fig. 5d).
262 Amphibole, 0.2 to 0.4 mm in size, is exclusively associated with clinopyroxene. It is calcic
263 ($Ca^B = 1.84\text{--}1.93$, $Na+K = 0.77\text{--}0.92$, $Ti = 0.09\text{--}0.22$ apfu), Al rich ($Al M1 = 0.76\text{--}1.27$), and
264 magnesian ($X_{Mg} = 0.73\text{--}0.78$; Fig. 5b). Scapolite is disseminated across the thin section and
265 has a sylvialitic composition, with $X_{SO4} = 0.48\text{--}0.66$ (Fig.5e and Supplementary Table 2).
266 When the chemical formulae of the analyzed grains are recalculated following Ellis (1978) to
267 be compared to plagioclase, they show a significantly distinct composition of X_{eqAn} of 0.59–
268 0.70 (Fig.5d), homogeneous at the grain scale. Rare biotite (1.5%) is observed without
269 specific textural position. Quartz, zircon, and apatite are dispersed at the thin section scale.

270 **4.1.2. Eastern Lelukuau: samples KW4A and KW4C**

271 Samples KW4C and KW4A are metagabbros collected a few meters away from each other on
272 the same outcrop and have broadly similar chemical compositions (Supplementary Table 1).
273 Texturally, both are granoblastic but KW4A is homogeneous and fine-grained (<0.5 mm)

274 while KW4C is medium-grained (0.5–3 mm) and has polycrystalline plagioclase domains and
275 garnet porphyroblasts, as illustrated by the SEM–MLA maps (Fig.3b and c).

276 Sample KW4C – Subhedral plagioclase (0.15– 0.5 mm) forms polycrystalline domains (up to
277 1 cm) that are zoned with $X_{An} = 0.52 - 0.80$, decreasing from the cores toward the rims
278 (Fig.5d, Supplementary Table 2), but have a homogeneous grain size. The inner zones of the
279 domains contain rare kyanite inclusions and are locally altered to sericite. Garnet forms
280 subhedral grains of 0.5–2 mm, clustered into up to 4 mm composite grains (Fig.3b; Fig.6e, f,
281 h, i). Garnet cores have abundant inclusions of kyanite needles (up to 250 μm) and rare quartz
282 inclusions while the rims are inclusion-free (Fig.4b; Fig.6d to i). Garnet cores are Ca-rich with
283 $X_{Grs} = 0.26-0.29$, $X_{Prp} = 0.46-0.48$, and $X_{Alm} = 0.22-0.24$ while the borders (including those
284 of the subgrains) are enriched in Fe–Mg and show Ca depletion ($X_{Grs} = 0.19-0.21$,
285 $X_{Prp} = 0.52-0.57$, $X_{Alm} = 0.25-0.29$) with this trend being more pronounced at the outer rims
286 of the composite grains (Figs. 5a, 6e, f, h, i). Clinopyroxene forms anhedral grains of 0.5 to 1
287 mm, that are locally associated with quartz and plagioclase and/or amphibole in large
288 aggregates of 1 to 2 mm. It has a diopside composition, with 5 to 8% jadeite and 2 to 10% Ca-
289 Tschermak (Fig.4b, 5c). They all display Al enrichment in cores and Mg enrichment in rims.

290 Amphibole forms subhedral grains with embayed borders, closely associated to clinopyroxene
291 and, rarely, in the middle of plagioclase domains. Single grains are ca. 0.15–0.40 mm in size,
292 but locally form 2 mm elongated aggregates. Amphibole has edenitic composition with
293 $Ca^B = 1.88-1.93$, $Na+K = 0.53-0.64$, $Ti = 0.09-0.2$ apfu, $Al M1 = 0.97-1.32$ and $X_{Mg} = 0.85-$
294 0.87 (Fig.5b). The Si content varies from 6.50 to 6.89 apfu in all the analyzed grains but
295 doesn't reflect any general trend or textural position specificity. Quartz is only found in three
296 textural positions, either as rare inclusions in garnet, entrapped in the inner zones of garnet
297 composite grains, or associated to clinopyroxene (Fig. 6d, g). Scapolite grains are dispersed in
298 the thin section and commonly associated with garnet or plagioclase. They have a meionite

299 composition with $X_{SO_4} = 0.28\text{--}0.37$ (Fig. 5e and Supplementary Table 2). When recalculated
300 following Ellis (1978) to be compared to plagioclase (Fig., 5d), scapolite shows an
301 intermediate composition of X_{eqAn} of 0.65–0.69 and are homogeneous at the scale of the grain.
302 Kyanite is found in two textural positions: i) as needle inclusions in garnet and ii) locally in
303 the center of high-Ca plagioclase domains.

304 Sample KW4A – Plagioclase forms euhedral grains, 0.2–0.4 mm in size, that are
305 homogeneous throughout the thin section, with $X_{An} = 0.35\text{--}0.24$ (Fig. 3c, 5d, 6j to l) and
306 Supplementary Table 2). Locally, K-feldspar exsolutions are observed in the plagioclase
307 domains (<1%). Garnet forms grains mostly 0.5 mm in size that are commonly clustered into
308 3 mm-wide composite grains, homogeneously distributed across the thin section. Grains show
309 complex zoning (Fig. 5a, 6j to l), some subgrains being Ca-rich ($X_{Grs} = 0.23\text{--}0.25$, $X_{Prp} = 0.35\text{--}$
310 0.36 , $X_{Alm} = 0.39\text{--}0.41$) while others are Fe–Mg-rich ($X_{Grs} = 0.19\text{--}0.22$, $X_{Prp} = 0.38\text{--}0.41$,
311 $X_{Alm} = 0.37\text{--}0.41$). Clinopyroxene forms subhedral grains, 0.2–0.5 mm in size. It has diopside
312 composition, 7 to 11% jadeite and up to 10% Ca-Tschermak component, while total Al is low
313 ($0.18\text{--}0.41$ apfu). Scapolite is euhedral, 0.2 to 0.5 mm in size, and is homogeneously
314 distributed at the thin section scale. It has a sylvialitic composition ($X_{SO_4} = 0.50\text{--}0.70$, Fig. 5e)
315 and commonly clusters in larger domains up to 3 mm. Rare amphibole or quartz are dispersed
316 at the thin section scale.

317 **4.1.3. Mineral assemblages and background to the phase equilibria modelling**

318 The three samples are composed of varied amounts of garnet, clinopyroxene, and plagioclase
319 that are characteristic of high-P granulite facies conditions. Samples 135A and KW4C, that
320 are medium grained, also show a X_{Alm} increase in the garnet rim that is consistent with
321 diffusional re-equilibration of the rims during cooling. Because of high peak temperatures
322 attained and/or maintained in granulite facies rocks, the prograde history can be deciphered
323 mostly by mineral inclusions. To this end, KW4C provides a snapshot in the crystallization of

324 kyanite and quartz during an early part of the P–T path associated with plagioclase
325 destabilization and garnet crystallization following the reaction anorthite = grossular +
326 kyanite + quartz, at high-P conditions. Moreover, in this sample, the large, recrystallized
327 plagioclase domains are interpreted to pseudomorph former igneous plagioclase, preserving
328 original Ca-rich core and Na-rich rims. Rare kyanite included in garnet of sample 135A,
329 suggests a similar reaction history.

330 According to the literature, scapolite, and specifically S-scapolite, can either be (i) an igneous
331 phase (e.g., Boivin & Camus, 1981), (ii) result from plagioclase alteration (e.g. Touret &
332 Nijland, 2013), or (iii) be a metamorphic mineral (e.g., by replacement of igneous plagioclase:
333 Austheim, 2013). Given the textural evidence of pervasive granoblastic recrystallisation, the
334 magmatic phase option can be ruled out. If the scapolite were an alteration phase of
335 metamorphic plagioclase, then the X_{eqAn} would be spread along the same range given that
336 scapolite grains are not observed in one specific textural position. In all samples, scapolite
337 X_{eqAn} is different from X_{An} of plagioclase, and they are consequently interpreted as part of the
338 main metamorphic assemblage. This would require either a S-bearing mineral breakdown
339 during prograde metamorphism, or a S-bearing fluid phase at high-pressure.

340

341 **4.2. P-T estimates**

342 Samples 135A and KW4A were used to calculate P–T pseudosections. MnO, K₂O and TiO₂
343 were removed from the bulk-rock composition since their amounts are low in the bulk rock
344 (less than 0.65 wt.%; see Supplementary Table 1), and they consequently will not impact the
345 modelled stability of the main mineral assemblage present. For both calculations, $\text{Fe}^{3+}/\text{Fe}^{\text{tot}}$
346 was set at 0.1 while H₂O was calculated based on the proportion of amphibole in the rock.
347 Scapolite is part of the mineral assemblage and represents ca. 5 %. As no solid-solution model
348 was available, two approaches were considered: (i) scapolite was treated as plagioclase; and

349 (ii) scapolite was removed from the bulk-rock composition by subtracting the equivalent
350 amount of CaO, Na₂O, Al₂O₃ and SiO₂. Considering all scapolite as plagioclase results in
351 excess Al and Si, that impacts the Al–Si-bearing-mineral stability, either over-estimating
352 quartz or kyanite, but also over or under-estimating garnet, plagioclase, and clinopyroxene
353 modal proportions. Subtracting a mineral from a bulk rock composition is a common practice
354 to account for the lack of a solution model for some phases and is often used to correct for the
355 Ca content of apatite (see LaSalle and Indares, 2014, Lotout et al., 2018, 2020). Subtracting a
356 minor phase from the bulk is unlikely to influence rock-forming reactions, but it is an
357 oversimplification for major phase that *de facto* modifies the thermodynamic equilibrium state
358 of each assemblage. Both solutions have been tested, and we present results calculated from
359 an unmodified bulk, i.e., not removing scapolite from the bulk-rock composition, as it
360 provides the best fit.

361 Western-Lelukau – For sample 135A, the stability field of the peak assemblage garnet–
362 diopside–plagioclase–amphibole is limited by the appearance of liquid at higher T and kyanite
363 at higher P–T conditions (Fig. 7a). Quartz is stable at P–T conditions between 700°C/12 kbar
364 and 900°C/14 kbar, with modal proportion < 2 %, in good agreement with the observed
365 mineral proportion (Table 1). In the P–T pseudosection, amphibole has a pargasitic
366 composition, with modal proportions (12 to 8 %) decreasing gradually towards the melt-in
367 line. The plagioclase-out line at ca. 700°C/16 kbar and 850°C/19 kbar marks the limit
368 between the high-P granulite and the eclogite facies. The calculated modal proportions of
369 garnet and clinopyroxene (Fig. 7a, Table 1), the X_{Mg} of garnet and the grossular isopleth (Fig.
370 7b), together with the kyanite and melt boundary lines, restrict the stability field of the
371 assemblage between ca. 770°/14 kbar and 870°C/16 kbar, with garnet rims crystallizing in the
372 lower P and T part of this stability field. The calculated modal proportion of plagioclase is

373 however higher than the measured proportions, which is attributed to the exclusion of
374 scapolite from the modelling.

375 Eastern-Lelukauu – Sample KW4C could not be successfully modelled because it is too
376 dominated by local equilibria texture. In contrast, sample KW4A is well equilibrated at the
377 thin section scale and the garnet–clinopyroxene–plagioclase–quartz assemblage is stable in a
378 large P–T field from 700 to 900°C and up to 17 kbar, delimited by the kyanite-in and liquid-in
379 lines at lower and higher temperatures, respectively (Fig.7c). Calculated modal proportions of
380 clinopyroxene, garnet and plagioclase don't match the observed mineral proportion in thin
381 section. This could be the result of re-equilibration during cooling.

382

383 **4.3. Garnet petrochronology**

384 Samples 135A and KW4C were analyzed using the Lu–Hf and Sm–Nd garnet dating method.
385 A summary of the results is presented in Table 2 and plotted in Figure 9. Garnet fractions 1 to
386 4 were spiked for both Lu–Hf and Sm–Nd, while garnet fractions 5 and 6 were only spiked
387 for Lu–Hf analysis. For each sample, two representative whole rocks were also spiked for Lu–
388 Hf and Sm–Nd, and followed partial (WRS – Whole Rock Savillex; tabletop) and complete
389 (WRB – Whole Rock Bombed; Parr-bomb vessel) digestion procedures. One clinopyroxene
390 fraction was also analyzed for sample 135A. Single Lu–Hf or Sm–Nd dates were calculated
391 for each mineral fraction by pairing them to the WRB (2-pt ages). For each sample, a
392 representative trace element (TE) profile normalized to chondrite is presented in Fig.8.

393 **4.3.1. Western Lelukauu: sample 135A**

394 The Lu, Sm and Nd contents from sample 135A are mostly below 1 ppm across garnet grains,
395 and increase from core to rim, from 0.2 to 1 ppm, 0.4 to 1.6 ppm and 0.4 to 1.1 ppm,
396 respectively (Fig. 8a and Supplementary Table 3). Hf contents range from below the detection

397 limit to 0.3 ppm through garnet grains, at the limit of detection and with no specific pattern.
398 Gd/Yb ratios are systematically highest at the rims, at 0.9 to 2.2, while internal zones vary
399 from 0.2 to 0.8. The atypical Lu-depleted core and Lu-enriched rim could be the result of a
400 Lu-rich phase (such as zircon) reacting out during garnet growth. Garnet residues from the
401 dissolution procedure were mostly composed of rare quartz or clinopyroxene inclusions,
402 except of fraction 4 where a single zircon grain was found (z-Rg4, later subjected to U–Pb *in*
403 *situ* dating).

404 The six garnet aliquots represent a well averaged population, with Lu and Hf contents (0.58–
405 0.60 ppm and 0.13–0.14 ppm respectively; Table 2) similar to those obtained by *in situ*
406 measurements. The WRS and WRB show a significant difference in both Lu and Hf content
407 highlighting the contribution of zircon (e.g., Scherer et al., 2000). Two-point isochrons, using
408 the WRB fraction and garnet fractions 2, 3, 5 and 6, range from 1022.2 ± 6.1 to
409 1018.4 ± 6.3 Ma, and generate a mean date of 1020.3 ± 3.0 (MSWD = 0.34, Table 2).
410 Fractions 1 and 4 show slightly younger dates of 1009.3 ± 6 Ma and 997.1 ± 6 Ma,
411 respectively. With respect to fraction 4, all the two point garnet-whole rock isochron dates
412 yielded similar results within error when paired with the clinopyroxene, the WRS, or the
413 WRB fractions, at ca. 1018 ± 6.8 Ma (MSWD = 3.6; Fig. 9a). Garnet fractions 1, 2, 3, 5 and
414 6, the clinopyroxene fraction, and both whole rocks define an eight-point isochron date of
415 1019.9 ± 6.8 Ma (MSWD = 2.7; Fig 9a). Including fraction 4 in the calculation results in a
416 date of 1016 ± 14 Ma with higher MSWD of 8.7 reflecting excess scatter. Excluding fraction
417 1 and 4 results in a 7-point isochron age of 1022 ± 3.2 Ma with a slightly lower MSWD of
418 0.94.

419 Sm and Nd contents from the four garnet aliquots range from 1.54 to 1.60 ppm and from 2.19
420 to 2.74 ppm respectively (Table 2). The WRS and WRB fractions have significantly distinct
421 Sm and Nd concentrations, but almost identical $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$. This highlights

422 that, despite a contribution from a Sm- and Nd-rich refractory phase during the dissolution
423 procedure in bomb, the sample was well equilibrated and wasn't later disturbed by alteration
424 or Sm- or Nd-rich fluid. Altogether, the data align on an isochron that corresponds to a date of
425 1005 ± 13 Ma (MSWD = 0.25; Fig 9b), overlapping within error with the Lu–Hf results.

426 **4.3.2. Eastern Lelukuau: sample KW4C**

427 Chondrite-normalized REE patterns for sample KW4C show HREE-enriched cores and
428 MREE-enriched rims across garnet grains (Fig. 8b), typical of preferential incorporation of
429 HREEs during garnet early-growth (e.g., Otamendi et al., 2002). Garnet cores also show
430 higher LREE concentrations compared to the mantle and rim zones. The Lu contents decrease
431 from core to rim, from 0.4 to 0.1 ppm, and Hf content was systematically below 0.1 ppm to
432 below the detection limit. Sm systematically shows two pulses of concentration increases,
433 separated by a lower concentration, from ca. 0.4 to 1 ppm, followed by a 0.2 to 1.2 ppm zone,
434 and 0.1 to 1 ppm (Supplementary Table 3). The positive Eu anomaly in the whole rock (1.86)
435 is not observed consistently in the garnet, with maximum values in the garnet cores (1.1 to
436 2.0) and lowest values in garnet rims (0.9 to 1.4). Finally, the rim shows distinct REE pattern
437 differences from the core of garnet, and lack continuous depletion; instead, two population are
438 observed (Fig. 8b).

439 All residues from garnet dissolution procedures included variable amount of kyanite and
440 quartz needles, fractions 5 and 6 being 10 times richer than fractions 1, 4 and 5, while fraction
441 2 has an intermediate amount. Lu and Hf contents for the six garnet fractions are similar, at
442 0.21–0.22 ppm and 0.07–0.08 ppm respectively, and corresponding $^{176}\text{Lu}/^{177}\text{Hf}$ and
443 $^{176}\text{Hf}/^{177}\text{Hf}$ show little variation (Table 2). WRS and WRB fractions yield equivalent Lu and
444 Hf contents of 0.06 ppm and 0.32–0.34 ppm, showing that no Hf or Lu-rich phase
445 contributed. However, isotopic ratios are not identical, possibly resulting from an incomplete
446 spike-sample equilibration in the savillex tabletop fraction (WRS). The garnet Lu–Hf 2-point

447 isochron dates for fractions 2, 5 and 6 are 1023.9 ± 7.8 Ma, 1029.1 ± 7.9 Ma and
448 1036.8 ± 7.9 Ma, resulting in an average date of 1029.9 ± 4.6 Ma (MSWD = 2.7). Garnet
449 fractions 1, 3 and 4 resulted in 2-point isochron dates of 1014.6 ± 7.8 Ma, 1011.9 ± 6.6 Ma
450 and 1013.0 ± 7.8 Ma, respectively, and corresponding average date of 1013.0 ± 4.2 Ma
451 (MSWD = 0.87). Including all 6 of these dates result in a mean date of 1021 ± 11 Ma, with an
452 expectedly high MSWD of 7. The 2-point date of garnet fraction 2 is intermediate at
453 1023.9 ± 7.9 Ma, overlapping within error with all garnet fractions, corresponding to an
454 averaged population of two garnet endmembers. Altogether, the 9 fractions define an isochron
455 age of 1018 ± 18 Ma (MSWD = 8.1), reflecting scatter along the isochron due to the
456 variability observed in the garnet isotopic compositions. If we consider only the fractions with
457 similar 2-point dates to calculate two separate isochrons, garnet fractions 1, 3, and 4
458 correspond to an isochron date of 1013.2 ± 5.6 Ma (MSWD = 0.14) and garnet fractions 5 and
459 6 correspond to an isochron date of 1033 ± 6.3 Ma (MSWD = 2.4; Fig. 9c).

460 Sm and Nd contents of the four garnet aliquots are low, 0.70–0.75 ppm and 0.77–0.86 ppm
461 respectively (Table 2). WRS and WRB aliquots yielded almost identical Sm and Nd
462 concentrations of 1.08 and 1.09 ppm and 4.88 and 4.93 ppm, respectively, and corresponding
463 isotopic ratios are also identical within error. This indicates there was no contribution from a
464 Sm or Nd rich phase during the dissolution procedure in bomb, and Sm-Nd homogeneity
465 within the sample. Moreover, this is also independent evidence for reproducibility of the
466 results, emphasizing the absence of contamination in the overall dissolution and column
467 procedure. All fractions correspond to an isochron date of 1003.0 ± 8.3 Ma (MSWD = 0.07;
468 Fig. 9d), with a good alignment of the 8 points; the limited spread in the data is responsible
469 for the elevated error and very low MSWD.

470

471 **4.4. Zircon petrochronology**

472 Zircon was only found in sample 135A from western-Lelukuau. Six zircon grains were
473 analyzed directly in thick section and 14 zircon grains were handpicked from whole rock
474 mineral separate. Colorless zircon crystals are 60 to 200 μm in size, with variable shapes from
475 subhedral and elongated to anhedral grains. They all have a CL-bright rim of 1 to 60 μm , and
476 1 to 2 inner darker CL zones, some with a well-defined core. Some zircon grains show
477 complex textures, including fluid pathways across CL-zones (Fig.10, 135A-2-Z2; Z4), and
478 cracks in the external rim (Fig.10, 135A-1z3, 135A-5-z2b). Few cores present an oscillatory
479 zonation (Fig.10, Z1, Z6, Z8 and Z10). Forty-seven U–Pb analyses and 34 REE analyses were
480 acquired on distinct CL zones from these 20 zircon grains. Amongst the U–Pb data, 3
481 analyses were excluded due to high common lead contents ($Pb_c > 3\%$), the remaining 44
482 analyses showing a Pb_c content $< 0.7\%$ in most cases, with one outlier at 2.2 %. Uranium
483 contents are variable, spreading from 12 to 2623 ppm and Th/U ratios range from 0.02 to
484 1.83, this ratio showing the maximum spread for cores (ca. 0.4 to 1.7, Fig.11c). Analyzed
485 zircon zones are discordant to sub-concordant (92 to 99 % concordance, Fig 11a), and the
486 $^{207}\text{Pb}/^{206}\text{Pb}$ ages spread from ca 1.00 to 1.65 Ga (Fig. 11b, d). In cores and rims, the Lu
487 concentrations vary from 0.5 to 96 ppm independently from the corresponding Eu* anomaly
488 (Fig.11f), which spreads from 0.7 to 1.1. Chondrite-normalized REE patterns are similar with
489 enriched HREE and no to small Eu*, in both cores and rims ($Eu = 0.78\text{-}1.08$, Fig.11e). Three
490 spectra obtained in ca. 1.2 Ga rims show flat HREE pattern (Fig. 11e and Fig 10).

491 Zircon cores are composed of two $^{207}\text{Pb}/^{206}\text{Pb}$ population, at ca. 1.6 and 1.4 Ga, without any
492 specific distinction in U, Th, or REE contents (Fig. 11c, d, e, f). Average $^{207}\text{Pb}/^{206}\text{Pb}$ dates
493 calculated on ca. 1.6 Ga cores yields a mean date of 1630 ± 12 Ma ($N = 13$, $MSWD = 53$) and
494 an upper intercept date of 1653 ± 33 Ma ($N = 13$, $MSWD = 32$). Two cores and 4 rims
495 (Fig.10, core: z2 and z12, rims z3, z8, z9, z2b) yield an average $^{207}\text{Pb}/^{206}\text{Pb}$ date of
496 1415 ± 9 Ma ($N=6$; $MSWD = 3.3$) and an upper intercept of 1429 ± 9 Ma ($MSWD = 0.69$).

497 Six rims provided an average $^{207}\text{Pb}/^{206}\text{Pb}$ date of 1184 ± 9.1 Ma (MSWD = 0.72, N = 6) and
498 corresponding upper intercept of 1239 ± 76 Ma (MSWD = 0.13). However, the corresponding
499 trace element patterns are variable, with either enriched HREE or flat HREE patterns (Fig.
500 11e), and their Th/U ratio is also varied (Th/U = 0.11 to 0.47, U = 17-264 ppm). No
501 consistency could be observed between the remaining zircon analysis.

502

503 **5. General discussion and geodynamic implications**

504 **5.1. P-T conditions and equilibrium in HP mafic granulite**

505 The studied samples KW4A, KW4C, and 135A are textbook high-P granulites. However,
506 assessing their peak P–T conditions is limited by: (a) the preservation of microdomains with
507 restricted scale of equilibration likely due to a low amount of H₂O, which is a catalyst in
508 mineral reactions; and (b) the scarcity of quartz, which promotes mineral reactions in mafic
509 rocks, leading to wide P–T stability fields of the peak assemblage.

510 Among the two modelled rocks, sample 135A, from the western Lelukau, provided the
511 tightest P–T constrains. Modal proportions of phases calculated using P–T pseudosections of
512 the bulk rock composition including scapolite (which is inferred to be part of the main
513 assemblage) are consistent with the mineral proportions observed in the sample. Only slight
514 discrepancies in plagioclase (25–30 % instead 22 %), and quartz (up to 1.5 % instead of
515 < 0.5 %) are noted while the calculated clinopyroxene and garnet modal proportions are
516 within <10% compared to the proportions derived from SEM–MLA. Isopleths of X_{Mg} and
517 X_{Grs} in garnet are compatible with EMPA measurements and support the calculated P–T
518 estimates in the range between 770°/14 kbar and 870°C/16 kbar. These P–T estimates are in
519 line with available data on kyanite bearing anatectic rocks from the southern LT (e.g.,
520 14.5 kbar and 870–900°C, Lasalle and Indares, 2014), and with petrographic observations that

521 place the assemblages of both aluminous and mafic rocks in the high-P granulite field. In the
522 calculated pseudosections, the liquid-in line at $P < 18$ kbar, is between 900 and 950°C, close to
523 the minimum peak T of 875°C for aluminous anatectic rocks from southern LT (Lasalle and
524 Indares, 2014). The lack of partial melting in the samples is attributed to the scarcity of H₂O-
525 bearing phases. The slight discrepancy between the calculated temperature in metamafic and
526 aluminous migmatite is within the range of uncertainty of P–T modelling.

527 The sample from eastern Lelukuau (KW4C), that preserves inherited zonation of the original
528 igneous plagioclase, is dominated by local equilibria that makes it unsuitable for modelling,
529 but it provides clues on the prograde history. Quartz and kyanite inclusions in garnet cores,
530 together with garnet major element zoning, are consistent with a prograde portion of the P–T
531 path, through the kyanite stability field. In addition, the sharp boundaries of the inclusion-
532 bearing cores, in conjunction with the REE zoning, are consistent with two-stage garnet
533 growth (Fig. 6e, f, h, i; Fig 8b).

534 Textural equilibrium in the absence of chemical equilibrium suggests short-term residency
535 under high-grade conditions. Preservation of garnet prograde zoning, absence of retrograde
536 textures, preservation of S-scapolite and preservation of igneous zoning in recrystallized
537 plagioclase domains is consistent with fast cooling following the thermal peak. In addition,
538 the absence of retrograde textures testifies to a fluid-poor environment during cooling and
539 decompression.

540

541 **5.2. From ages to stages**

542 **5.2.1. Garnet petrochronology**

543 Western Lelukuau: sample 135A

544 In this sample, WR, clinopyroxene, and garnet fractions (excluding g4 for Lu–Hf) align and
545 yield a low MSWD isochron age for the two isotopic systems, which indicates closed system
546 evolution following equilibration. Together with petrographic and P–T evidence for high- P-
547 granulite-facies conditions, and with the Lu–Hf and Sm–Nd ages overlapping within error at
548 1019.9 ± 6.8 Ma (MSWD = 0.94) and 1005 ± 13 Ma (MSWD = 0.25), respectively, this
549 provides an age for the peak metamorphism of the Western Lelukuau Terrane. The Lu–Hf
550 ages are systematically skewed toward garnet early growth (e.g., see Anczkiewicz et al, 2007;
551 Lotout et al., 2018, Tual et al., 2022) and the Lu–Hf isotopic system has a higher closure
552 temperature than Sm–Nd (see Smit et al., 2013), which is particularly important in high-T
553 terranes. Given the ca. ± 7 Ma uncertainty on the isochron and the ~ 800 - 900°C peak
554 metamorphic temperatures, and despite that Lu–Hf and Sm–Nd ages slightly overlap, we
555 interpret the garnet Lu–Hf age to approximate garnet growth and crystallization at ca.
556 1020 Ma, and the garnet Sm–Nd age to approximate subsequent, fast cooling at ca. 1005 Ma
557 at lower P. The preserved zoning pattern in garnet with increasing Lu towards the rims, is
558 atypical, compared to the classic Lu-rich core to Lu-poor-rim resulting from Rayleigh
559 fractionation. Breakdown of a HREE-rich phase during garnet growth is most likely
560 responsible for this pattern. Given the low Lu concentration in garnet, and the fact that zircon
561 cores are rich in Lu (up to 1000 times more), zircon breakdown during garnet growth could be
562 sufficient to release enough Lu inducing such garnet zoning.

563 Eastern Lelukuau : sample KW4C

564 The Eastern Lelukuau sample preserves petrographic evidence of two-stage garnet growth,
565 that is corroborated by trace element zoning. The variable amount of kyanite needles and
566 quartz crystals in the residues from the different garnet fractions, together with the two mean
567 Lu-Hf age clusters, allow the interpretation of the older age of 1033 ± 6.3 Ma as
568 approximating first garnet growth, within the kyanite stability field. The younger Lu–Hf date

569 of 1013 ± 5.6 Ma is interpreted to estimate the age of the second garnet growth. The latter
570 also overlaps within error with the Sm–Nd date of 1003 ± 8.3 Ma. Given the petrographic
571 record, this date is interpreted to reflect cooling of the terrane at lower pressure.

572

573 **5.3. Zircon ages**

574 Zircon was only retrieved in sample 135A, and shows a complex history. The U–Pb dataset is
575 consistent with continuous or multiple lead loss event, and, potentially, several ages of zircon
576 growth. The oldest age of 1.6 Ga from 16 zircon cores is in good agreement with the ca.
577 1631 Ma age of a gabbro-troctolite from the AMCG suite in the same area (Indares et al.,
578 1998). Additional zircon growth episodes at ca. 1.4 Ga and 1.2 Ga are deduced from the
579 textures and the $^{207}\text{Pb}/^{206}\text{Pb}$ ages. The similarities between the REE patterns in the different
580 CL zones with different $^{207}\text{Pb}/^{206}\text{Pb}$ dates, and the large variability in the elemental record of
581 CL zones recording similar dates, could be attributed to partial dissolution-reprecipitation of
582 igneous zircon below the solidus. This would reset the age but preserve the initial REE
583 signature and new growth, both variably affected by lead loss during metamorphism.
584 Moreover, the Eu* and Lu content are not linked to a specific CL texture.

585 Only a few zircon rims are of Grenvillian age, and they are mostly discordant. The Eu*
586 anomaly is consistently low to absent, from 0.8 to 1.2. This could suggest absence of
587 plagioclase (e.g., Rubatto 2002, 2017; Whitehouse and Platt, 2003) and/or growth of garnet
588 that fractionate Fe^{2+} over Fe^{3+} , changing the overall oxidation state and converting Eu^{2+} to
589 Eu^{3+} (e.g., Tang et al., 2018). In both cases, it would imply crystallization of zircon under
590 high-pressure, at 1.6, 1.4 and 1.2 Ga. However, zircon show classic HREE-enrichment,
591 typical of crystallization in a garnet-absent assemblage, which contradicts this interpretation.
592 Another way to interpret this dataset would either be for zircon to 1) crystallize before or
593 during early plagioclase crystallization, 2) crystallize in an oxidized magma, or 3) crystallize

594 from kinetic disequilibrium, as has been invoked for Eu* anomalies in clinopyroxene (see
595 Tilhac et al., 2023). Option 1 can easily be ruled out, as late-stage crystallization of zircon
596 from a local high differentiated pocket of magma are needed to crystallize zircon in Zr under-
597 saturated mafic magmas. Given the homogeneous REE patterns, kinetic disequilibrium seems
598 unlikely, and an oxidized magma appears to be a preferable option.

599 Ages at 1.4 and 1.2 Ga are well known in Tshenukutish Terrane and in the Mid-P belt to the
600 south. 1.4 Ga corresponds to a major crust forming event (Pinwarian), whereas 1.2 Ga is the
601 time of localized extensional episodes (see review in Indares, 2020). However, it seems
602 unlikely that these events would have promoted metamorphic zircon growth in the dry MIZ
603 protoliths. Considering that sample 135A has no record of inherited gabbroic textures, an
604 alternate explanation for the variability in the zircon dataset would be that the protolith of this
605 sample is a mafic supracrustal rock with a sedimentary component rather than a plutonic rock,
606 and that the zircons are detrital. This is also supported by the large range of Th/U ratio at
607 distinct dates, that could suggest variable zircon sources.

608 Finally, regardless of the protolith nature of the sample and only looking at recorded dates,
609 zircon did not successfully recrystallize during the high P–T event. The absence of partial
610 melting and the dryness inherent to mafic high-P granulite is a plausible explanation for
611 zircon’s rare reactions despite the high P–T metamorphism that occurred at 1020 Ma.

612

613 **5.4. Overall metamorphic patterns in the MIZ and tectonic implications**

614 The new garnet ages reported in this study provide important constraints on the
615 metamorphism of the MIZ since they are derived from mafic rocks from the LT, that make up
616 its largest lithotectonic component. The Lu– Hf ages, at ca. 1033 Ma, with a second garnet
617 growth at ca 1013 Ma in the eastern LT sample and at ca. 1020 Ma in the western LT sample,

618 suggest that the high-P granulite assemblage formed during the late Ottawaan straddling the
619 Ottawaan-Rigolet hiatus. They also suggest that there may be diachronism in garnet growth
620 from East to West. In addition, the Sm-Nd isotope data are consistent with rapid cooling at ca.
621 1005 – 1003 Ma.

622 These ages are younger than the monazite dates from an aluminous anatectic rock in southern
623 LT (ca. 1060 – 1044 Ma, Dunning and Indares 2010; Lassalle et al., 2014), however, the
624 previously published ages are difficult to interpret because of strong inheritance.

625 Nevertheless, taken together, these data suggest a potential younging of the age of
626 metamorphism from the southern boundary of LT to the north, towards the Parautochthonous
627 Belt.

628 Anatectic aluminous rocks from the Tshenukutish Terrane, at the SSE margin of the MIZ,
629 were subjected to similar high-P metamorphic conditions (Indares et al., 2008; Lasalle and
630 Indares, 2014; Kendrick and Indares, 2018) and show well constrained monazite ages from
631 ca. 1040 to 1017 Ma, interpreted to approximate the age of high-P metamorphism. These ages
632 are younging to the east, towards the boundary of the Tshenukutish Terrane against the Hart
633 Jaune terrane (Fig. 1c), and were interpreted to represent progressively later incorporation of
634 tectonic slivers in the slice stack (Indares 2020). In contrast, ages of mid-P granulite facies
635 metamorphism, in the structurally overlying mid-P belt in the Manicouagan area, range
636 between ca. 1080 and 1040 Ma, i.e. they are early to mid-Ottawan (Dunning and Indares,
637 2010; Lassalle et al., 2014).

638 The high-P belt of the Grenville Province has been traditionally attributed to the extrusion of
639 lower crust from beneath an orogenic plateau that developed during the early stages of the
640 Ottawaan phase, prior to ca. 1050 Ma (e.g., Rivers, 2008, and reference therein). In this
641 scenario, the MIZ would show similar or older metamorphic ages than the overlying mid-P
642 belt. However, the diachronism observed in the metamorphic age pattern of the hinterland in

643 the central Grenville contradicts this interpretation, as younger, late Ottawaan transitional to
644 Rigolet ages are recorded in the MIZ relative to the early to mid-Ottawan ages in the
645 structurally overlying Mid-P belt. This highlights a general younging of the metamorphic ages
646 towards the NW that is best explained by local crustal thickening in the margin of the
647 orogenic front at the time the orogen was progressing (e.g., see Fig. 16b and c of Indares,
648 2020). This local thickening would have been facilitated by the presence of the rigid Archean
649 lithosphere of the Parautochthonous belt, as proposed by Indares (2020). Although the
650 presence of a thick orogenic plateau in the central Grenville cannot be excluded, the new data
651 show that the MIZ does not provide tangible evidence, and are in line with recent proposals
652 for overall thin orogenic crust in the Mesoproterozoic (e.g., Spencer et al., 2021).

653 These new metamorphic ages still predate the incorporation of the Parautochthonous Gagnon
654 terrane in the Grenville orogen during the Rigolet phase, as suggested by the ~1000–980 Ma
655 zircon and monazite metamorphic ages from the footwall of the MIZ (Jordan et al. 2006;
656 Jannin et al. 2018a, b). However, these ages indicate a continuum in the tectonic activity of
657 the orogen, and discount the tectonic hiatus hypothesis traditionally inferred between the
658 Ottawaan and Rigolet orogenic phases.

659 **5.5. High-P domains in the Grenville Province**

660 The characteristics of the MIZ are markedly distinct from the other two high-P segments
661 documented in the Grenville Province (Fig.1b). In the western high-P segment, eclogite pods
662 in orthogneisses (Davidson, 1990) have metamorphic ages as old as 1090 Ma, broadly
663 coincident with early stages of the continental collision (Hynes and Rivers, 2010), followed
664 by a 1080 Ma granulite-facies overprint (zircon; Marsh & Culshaw, 2014). Both the western
665 high-P segment and MIZ belong to the Allochthonous belt and are located structurally above
666 the Parautochthonous belt. They have been referred in the literature as the ‘high-P belt’,
667 however, it now appears that the ages in the western segment are much older than in the MIZ.

668 They consequently correspond to different orogenic episodes and, because of this, the term
669 “high-P belt” is not appropriate. Finally, east of the MIZ, the high-P Molson Lake terrane is
670 part of the Parautochthonous belt, structurally below the Orogenic Lid in that area (St Joseph
671 terrane, Connelly et al., 1995), with preliminary metamorphic ages at 1.00 Ga (see Rivers et
672 al. 2012).

673 Collectively, the three high-P segments provide evidence of significant crustal thickening in a
674 Mesoproterozoic orogenic setting. Although the tectonic significance of the other two
675 segments is poorly understood, they are all exposed at the frontal parts of the orogen, and
676 formed diachronously, defining a pattern of younging towards the Eastern part of the
677 Grenville Province, while also getting closer to the Grenville Front.

678

679 **6. Conclusions**

680 High-P domains exposed in the Grenville Province provide unequivocal evidence of crustal
681 thickening in a Mesoproterozoic orogenic setting; their characteristics, however, are far from
682 uniform. The metamorphic patterns and tectonic significance of the Manicouagan Imbricate
683 Zone (MIZ) explored in this study provide new insights on high-P processes in the
684 Mesoproterozoic. The key outcomes are summarized below:

- 685 1. Mafic rocks from the Manicouagan Imbricate Zone underwent high-P granulite
686 metamorphism of 14–16kbar and 800–900°C.
- 687 2. This study in the MIZ provides the first garnet Lu–Hf and Sm–Nd dating of high-P
688 granulite facies of the Grenville Province. Peak of metamorphism is dated ca. 1030
689 to 1020 Ma and followed by subsequent fast cooling, with an apparent younging of
690 the ages towards the Grenville Front.

- 691 3. Zircon, in dry high-P mafic granulites appears to not successfully recrystallize due
692 to lack of partial melt and hydrous phases.
- 693 4. The high-P granulite rocks in the Manicouagan Imbricate Zone are not related to
694 the extrusion of metamorphosed lower crust during collision and building of a
695 high-plateau during the early stage of the Ottawa phase as previously thought.
696 Instead, it is related to local crustal thickening as the orogen propagates towards
697 the Grenville front. Therefore, the existence of a thick orogenic plateau in the
698 Grenville is questioned.
- 699 5. The results from this study support a tectonic continuum in between the Ottawa
700 and Rigolet phases, and highlight the long-lived active tectonic character of the
701 Grenville Orogeny.
- 702 6. Finally, this study highlights the diachronicity of the high-P domains of the
703 Grenville Province, and calls for a better understanding of the overall pattern of
704 crustal thickening at the broad regional scale of the Province.

705 Debate on the Mesoproterozoic geodynamic styles continues and spans from single lid to
706 active tectonics. The multiplicity of tectonic scenarios for the Grenville Orogeny, and for
707 Mesoproterozoic orogenies in general, highlights that the scarcity of P-T-t data is a barrier to
708 comprehensive large-scale reconstructions and geodynamic interpretations.

709

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724

725 **CAPTIONS**

726 Figure 1 - A. Schematic map of the Grenville Orogen in North America, B. Schematic map
727 highlighting the tectono-metamorphic divisions of the Grenville Province, modified after
728 Rivers et al. (2008) and Indares (2020). ABT – Allochthon Boundary Thrust. C. Schematic
729 map highlighting the tectono-metamorphic divisions of the Manicouagan Imbricate Zone
730 (MIZ, Central Grenville Province), modified after Indares (2020), sample location indicated.
731 Light pink in the LT shows locations of the anatectic aluminous outcrops.

732 Figure 2 - Available ages compiled from Cox et al. (1998), Indares et al. (1998), Indares and
733 Dunning (2001, 2004), Dunning and Indares (2010), Lasalle et al. (2014), modified from
734 Indares and Dunning (2017). Error bars less than 5 my are not shown.

735 Figure 3 - False color mineral maps generated by Scanning Electron Microscopy and Mineral
736 Liberation Analysis of polished thin sections, and corresponding mineral abundances. A.
737 sample 135a, western Lelukuau terrane. B. sample KW4C, eastern Lelukuau terrane.
738 Plagioclase: light grey (low Ca) to dark grey (high Ca). Garnet: pink (low Ca) to burgundy
739 (high Ca). C. sample KW4A, eastern Lelukuau terrane. Corresponding proportions are shown
740 in Table 1.

741 Figure 4 – Photomicrographs of samples A. 135a, B. KW4C, C. KW4A

742 Figure 5- Compositional profiles (A) and diagrams (B to E) for the minerals from samples
743 135A (pink), KW4C (green) and KW4A (orange). A. Garnet. B. Amphibole ($CaB \geq 1.5$ and
744 $(Na+K)^A \geq 0.5$) following the Leake et al. (1997) classification. C. Clinopyroxene. D.
745 Plagioclase. The lighter colored symbols represent the scapolite composition recalculated as
746 plagioclase, following Ellis (1978). E. Scapolite.

747 Figure 6 - SEM pictures (A, D, G and J) and X-ray maps for Ca (B, E, H, K), Fe (C, F, L) and
748 Mg (I) of garnet grains for samples 135A, KW4C, KW4A. Abbreviations are listed in the
749 methodology section.

750 Figure 7 : P–T pseudosection calculated in the CNFMASHO system for samples 135A (A, B)
751 and KW4A (C).

752 Figure 8 - Rare Earth Element patterns normalized to chondrite (after Sun and Mcdonough
753 1989) acquired in garnet (yellow, magenta and blue) and for the bulk rock (black). Limit of
754 detection in grey for the corresponding set of analysis.

755 Figure 9– (A, C) Lu–Hf and (B, D) Sm–Nd isochron diagrams for samples 135A and KW4C.
756 WRB, whole rock bomb dissolution; WRS whole rock tabletop dissolution; g garnet; 1–6,
757 garnet fractions; cpx, clinopyroxene. Inserts show the mean age of garnet-WRB 2-point
758 isochrons. Zooms on the isochrons (B and D) show the reproducibility of the whole-rocks
759 Sm–Nd analysis and (C) the scatter amongst the Lu–Hf garnet fractions and the whole rocks.
760 “Zrn” in (A) indicate the sample in which a single grain of zircon was recovered after partial
761 dissolution.

762 Figure 10 - Cathodoluminescence images of the analyzed zircon crystals from sample 135a
763 (western Lelukuau), in thick section and epoxy mounts. Color-coded circles show the location
764 of the U–Pb and REE analyses, carried out on top of each other at the SIMS. $^{207}\text{Pb}/^{206}\text{Pb}$ dates
765 are quoted with 2σ uncertainty in Ma, with concordance > 90%. Th/U ratio and common lead
766 (*italic*) are shown.

767 Figure 11 – Zircon U–Pb, Th/U, and Rare Earth Element data for the Western-Lelukuau
768 sample (135A). A. Concordia diagram with theoretical recent lead loss and 1.0 Ga–1.6 Ga
769 discordia line. B. Kernel density plot of $^{207}\text{Pb}/^{206}\text{Pb}$ ages. C. $^{207}\text{Pb}/^{206}\text{Pb}$ dates as a function of
770 Th/U. D $^{207}\text{Pb}/^{206}\text{Pb}$ dates, selected data used for average date calculation are highlighted. E.

771 Rare Earth Element patterns normalized to chondrite (after Sun and McDonough 1989), with
772 color code for cores, rims and rims with an atypical pattern. F. Lu concentration as a function
773 of the Eu*.

774

775 Table 1 – Summary of the mineral proportion obtained by SEM–MLA on thin section of the
776 samples 135A, KW4C and KW4A, and corresponding to Fig.3. Kyanite, rutile, zircon and
777 apatite are below 0.5 % in all samples.

778

779 Table 2 – Summary of Lu-Hf and Sm-Nd isotopic data. Dates are produced using isoplot
780 (Ludwig, 2003) and are reported at 95% confidence level.

781 ^a g – garnet fraction, cpx – clinopyroxene fraction, wrs – whole-rock savillex tabletop
782 dissolution, wrb – whole-rock bomb dissolution.

783 ^b Lu, Hf, Sm, Nd concentration (ppm) obtained via isotope dilution (ca. 0.5% se).

784 ^c Uncertainty on the ¹⁴⁷Sm/¹⁴⁴Nd and ¹⁷⁶Lu/¹⁷⁷Hf ratios is estimated to be 0.5%.

785 ^d Within-run 2σ standard error (6th decimal), combined in quadrature with external
786 reproducibility of spiked whole-rock samples for age regression.

787 ^e ¹⁷⁶Lu decay constant used for age calculation is $1.867 \times 10^{-11} \text{ a}^{-1}$ (Söderlund et al., 2004).

788 ¹⁴⁷Sm decay constant used for age calculation is $6.54 \times 10^{-12} \text{ a}^{-1}$ (Lugmair & Marti, 1978). 2-

789 point dates are the date obtained from a two-point isochron pairing of a single garnet fraction

790 with wrb

791 Supplementary 1 – Whole rock major (in mol.% oxide) and REE (in ppm) composition.

792 Supplementary 2 – Representative microprobe analyses of minerals.

793 Supplementary 3 – Summary of the U-Pb SIMS and REE analysis for zircon (sheet1 and 2,
794 respectively), and REE analysis in garnet (sheet 3).

795 Appendix – Details on operating conditions, standards, chemical procedures, and solid
796 solution models used or carried out.

797

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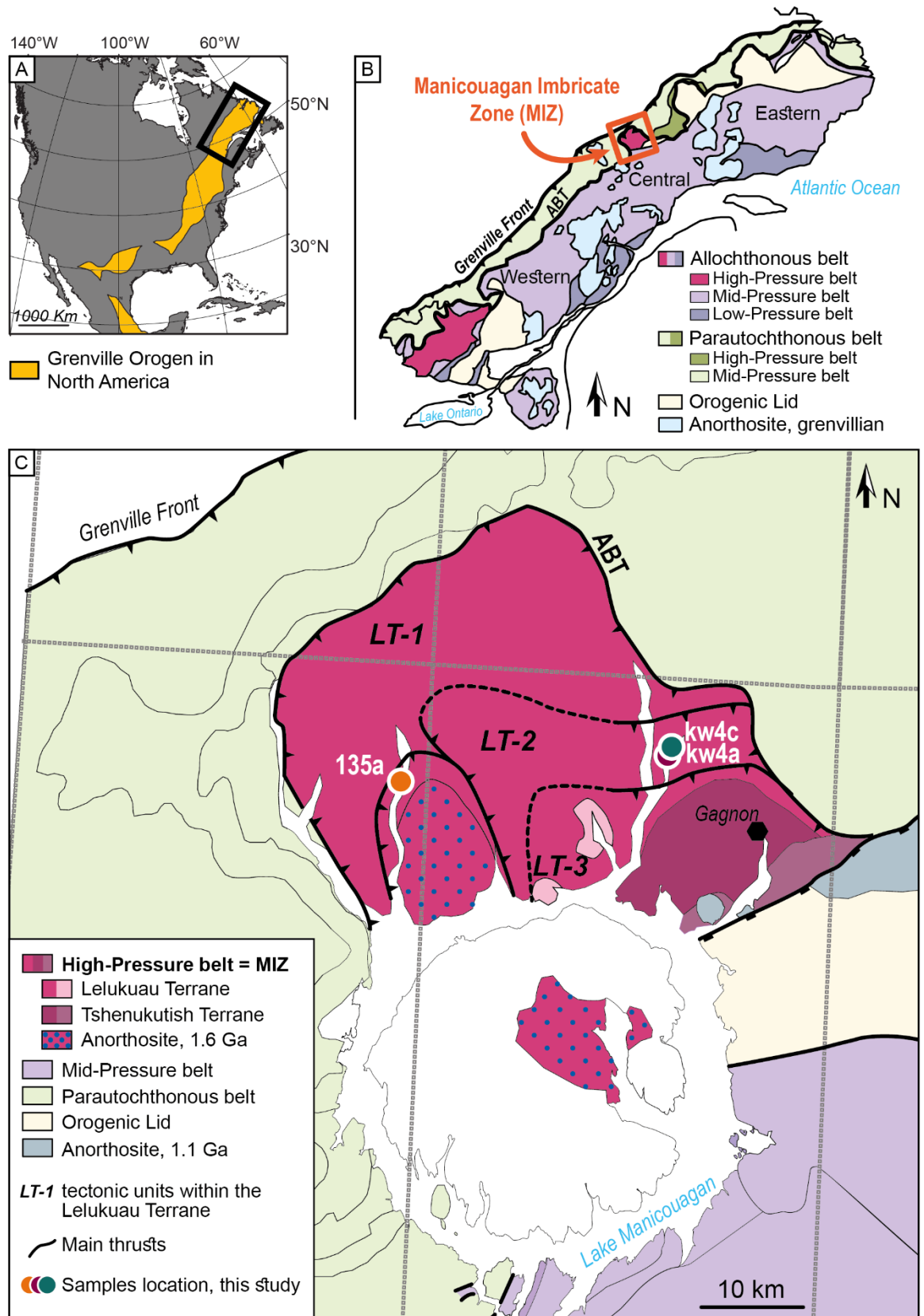


Figure 1

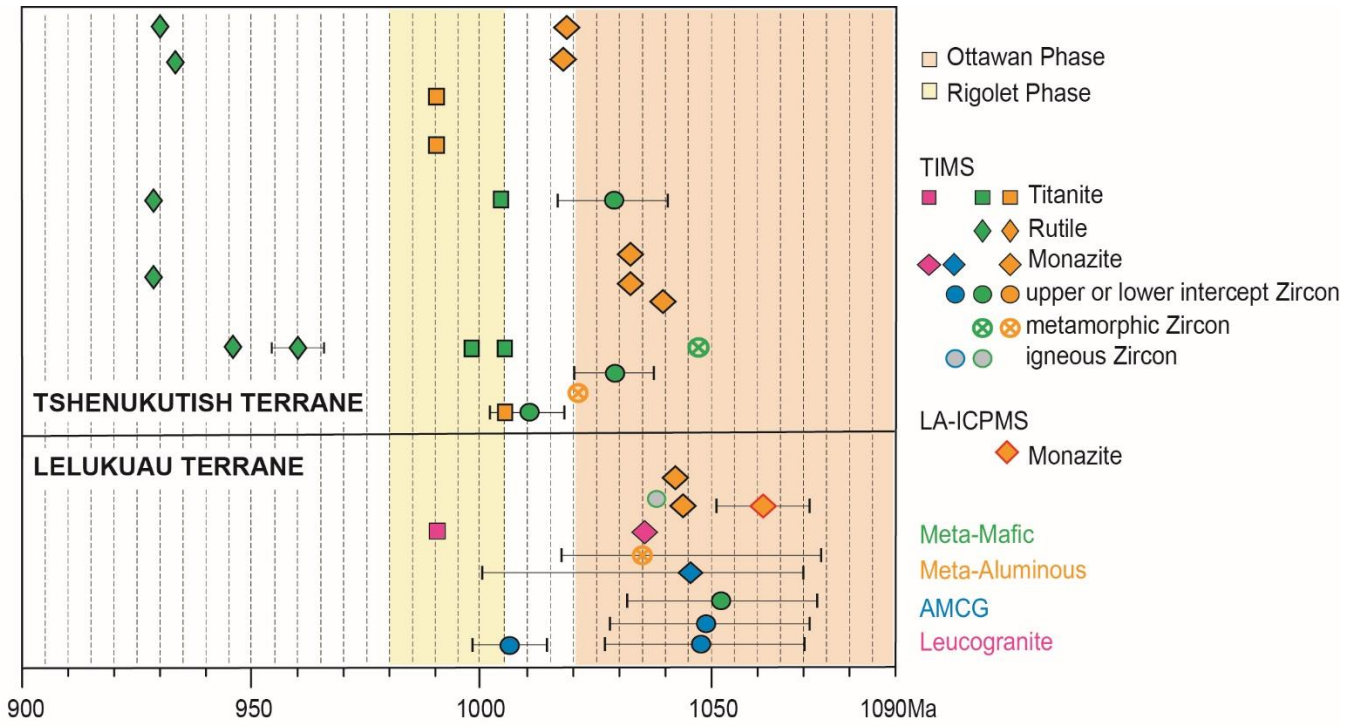


Figure 2

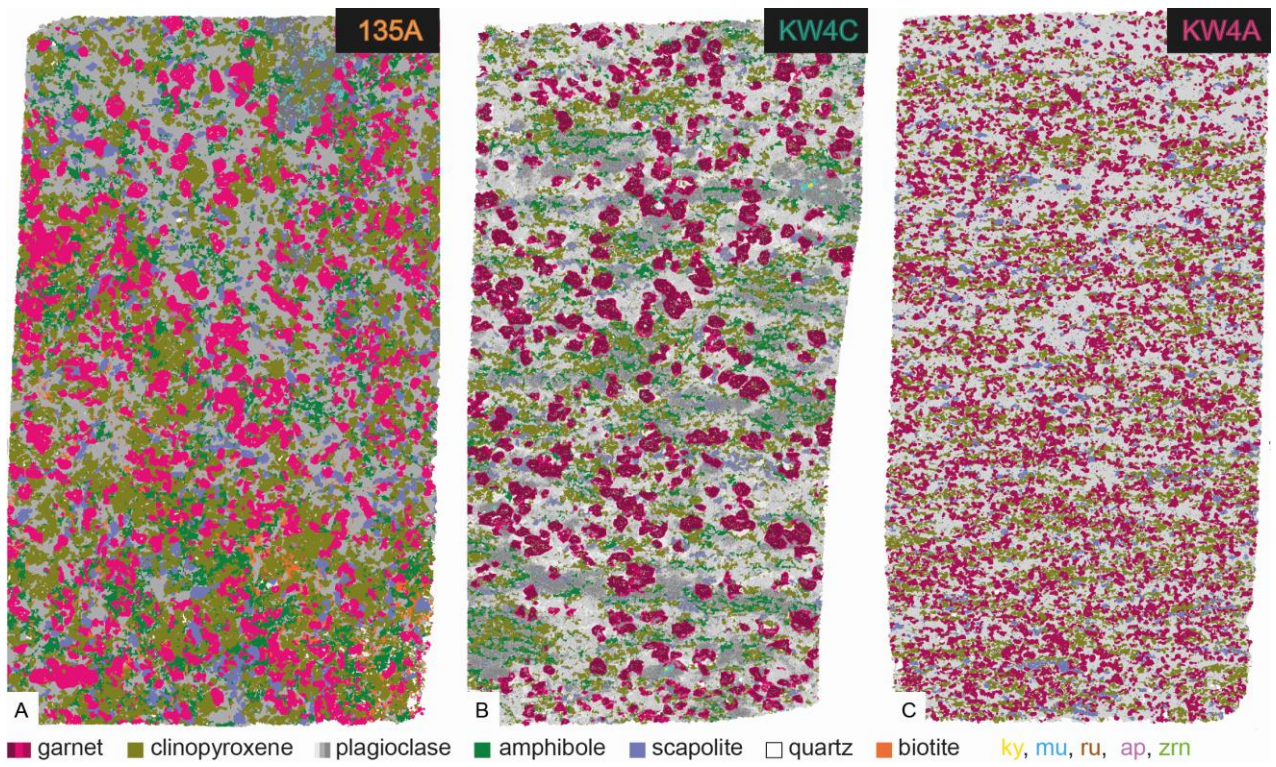


Figure 3

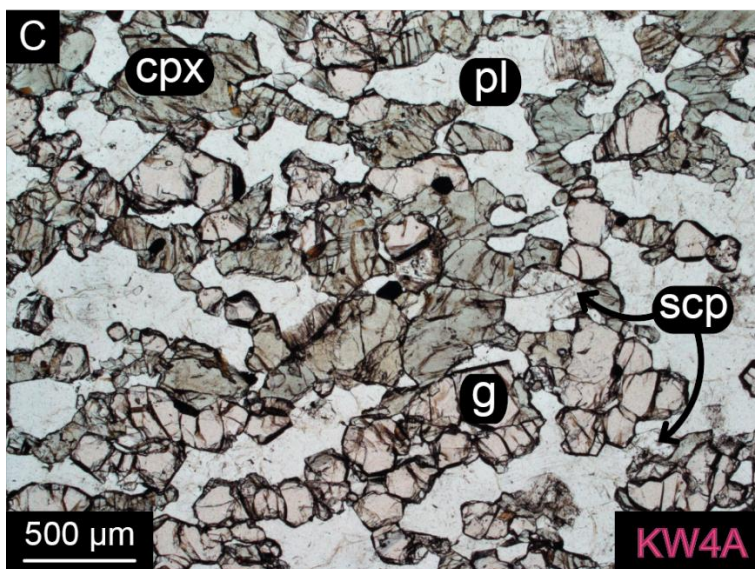
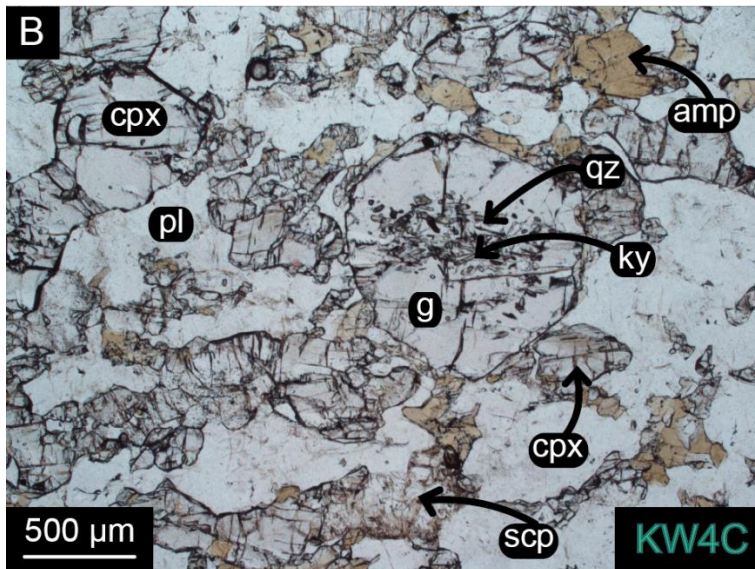
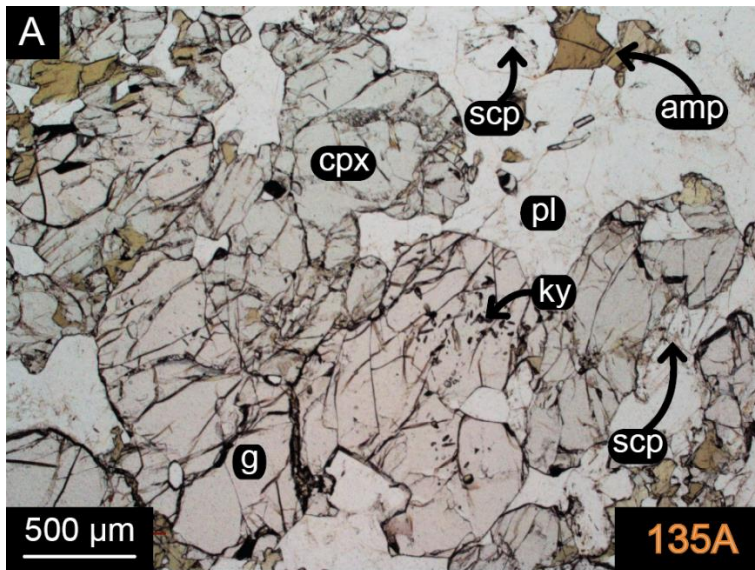


Figure 4

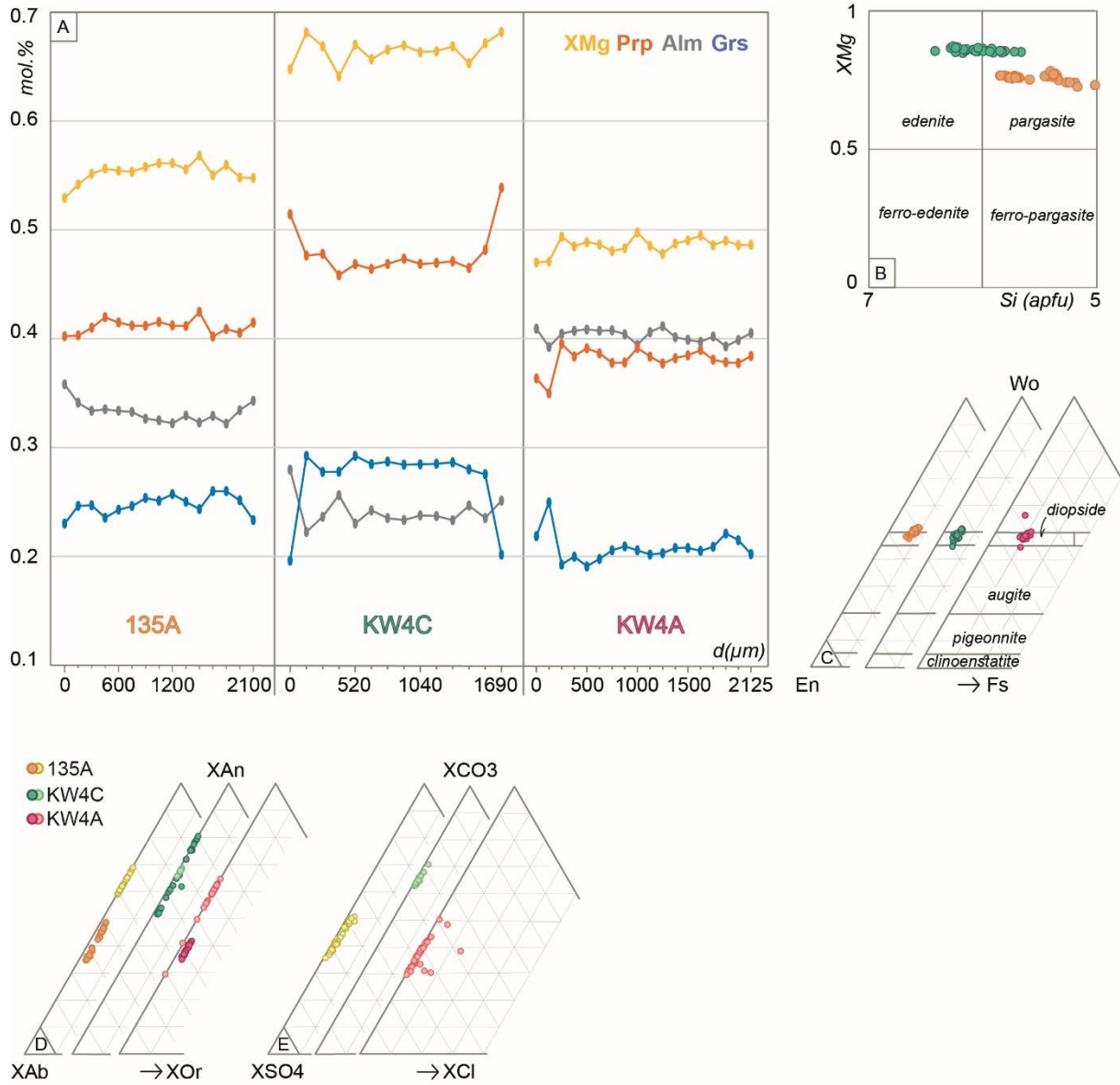
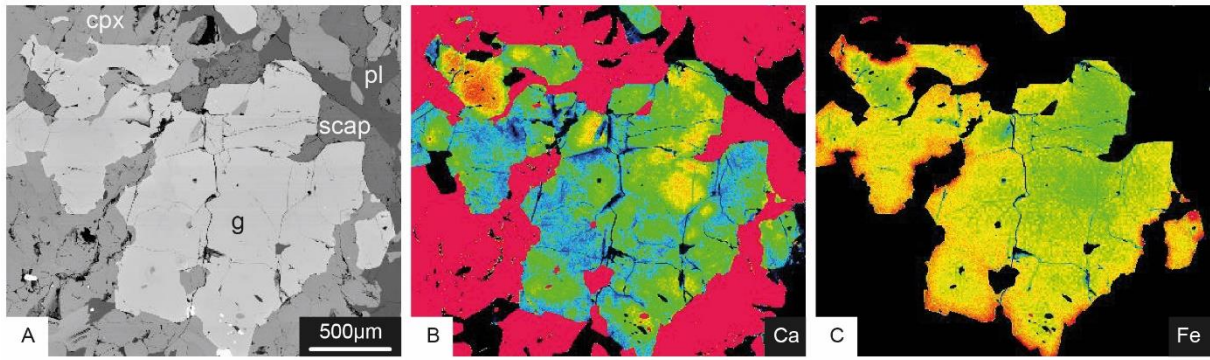
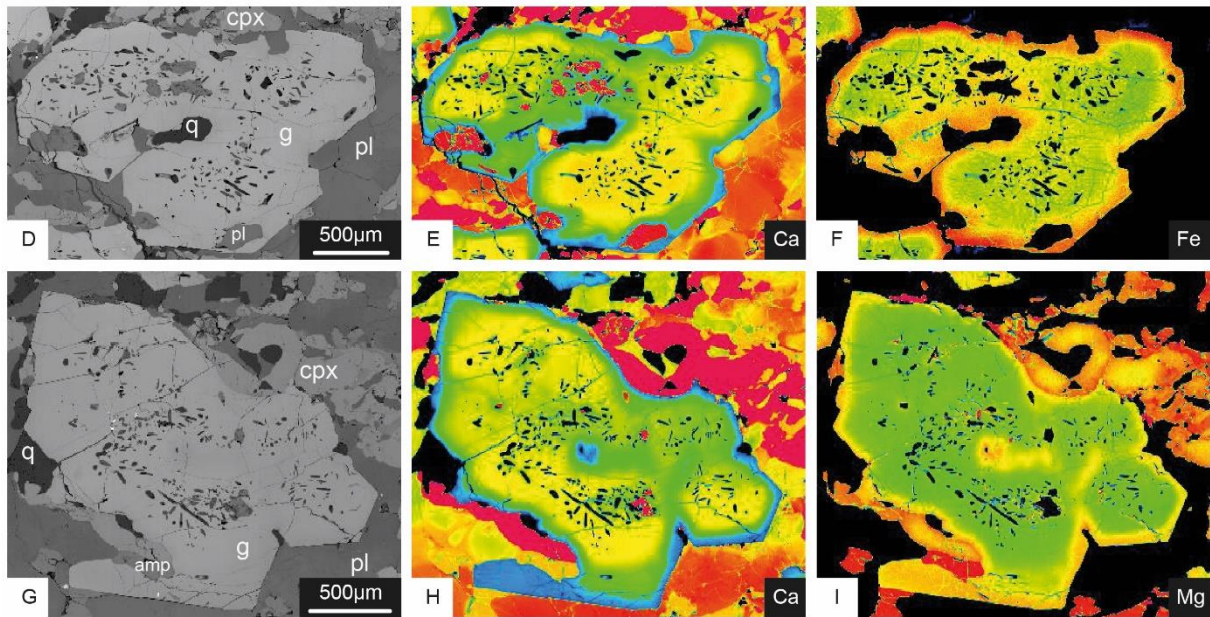


Figure 5

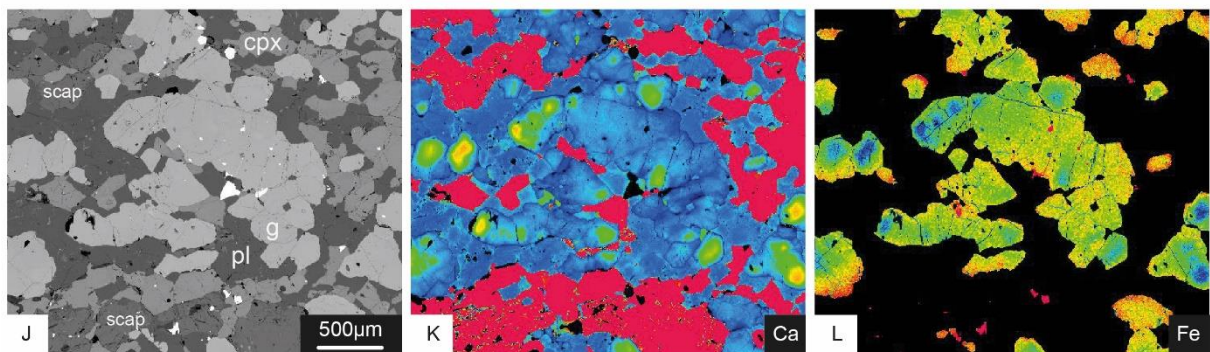
135A



KW4C



KW4A



*Figure 6

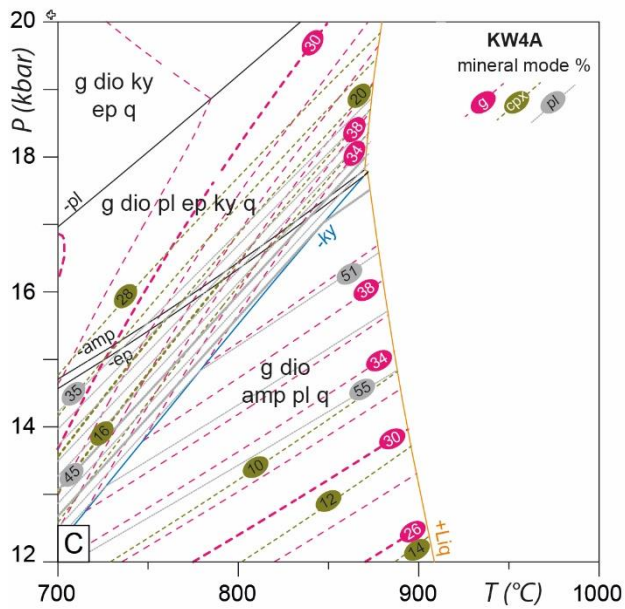
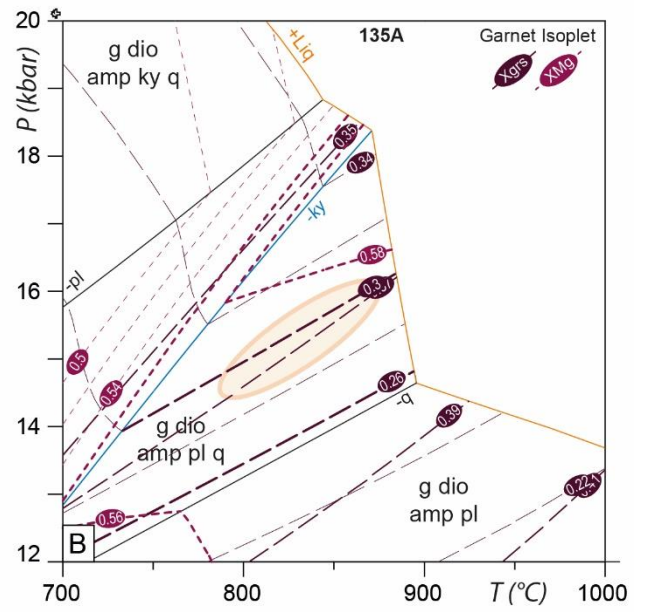
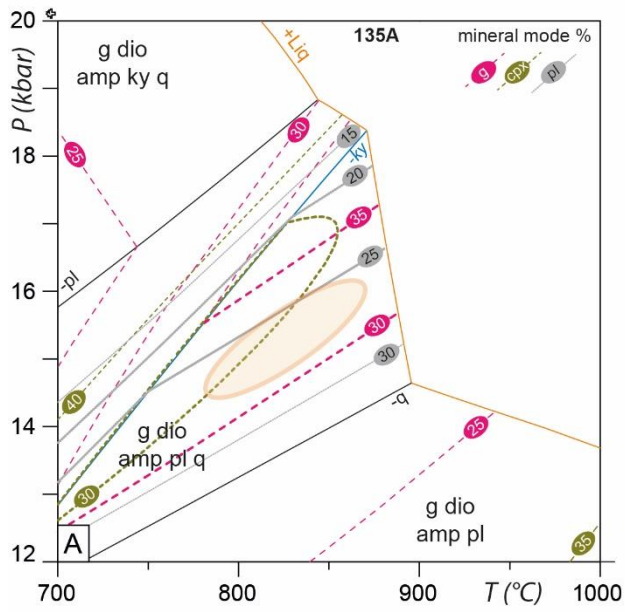


Figure 7

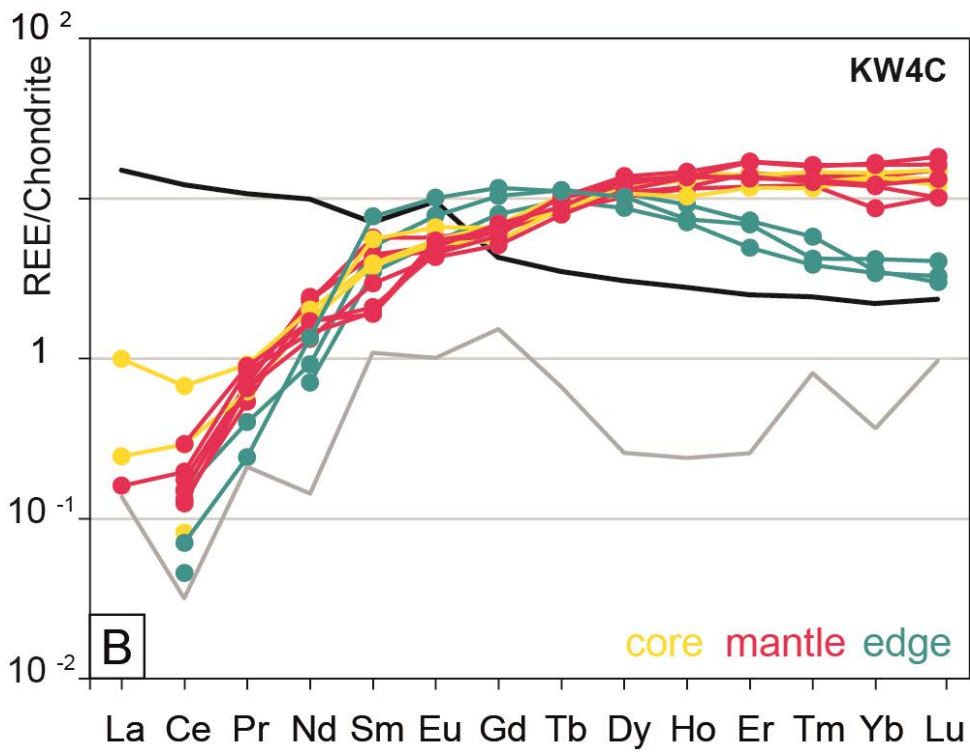
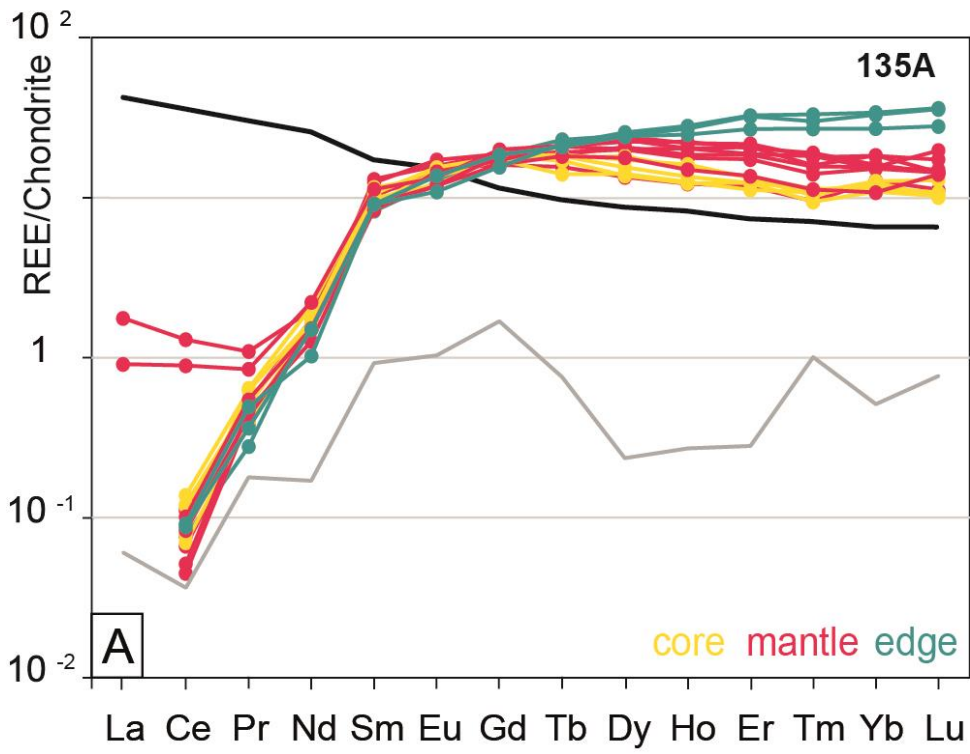


Figure 8

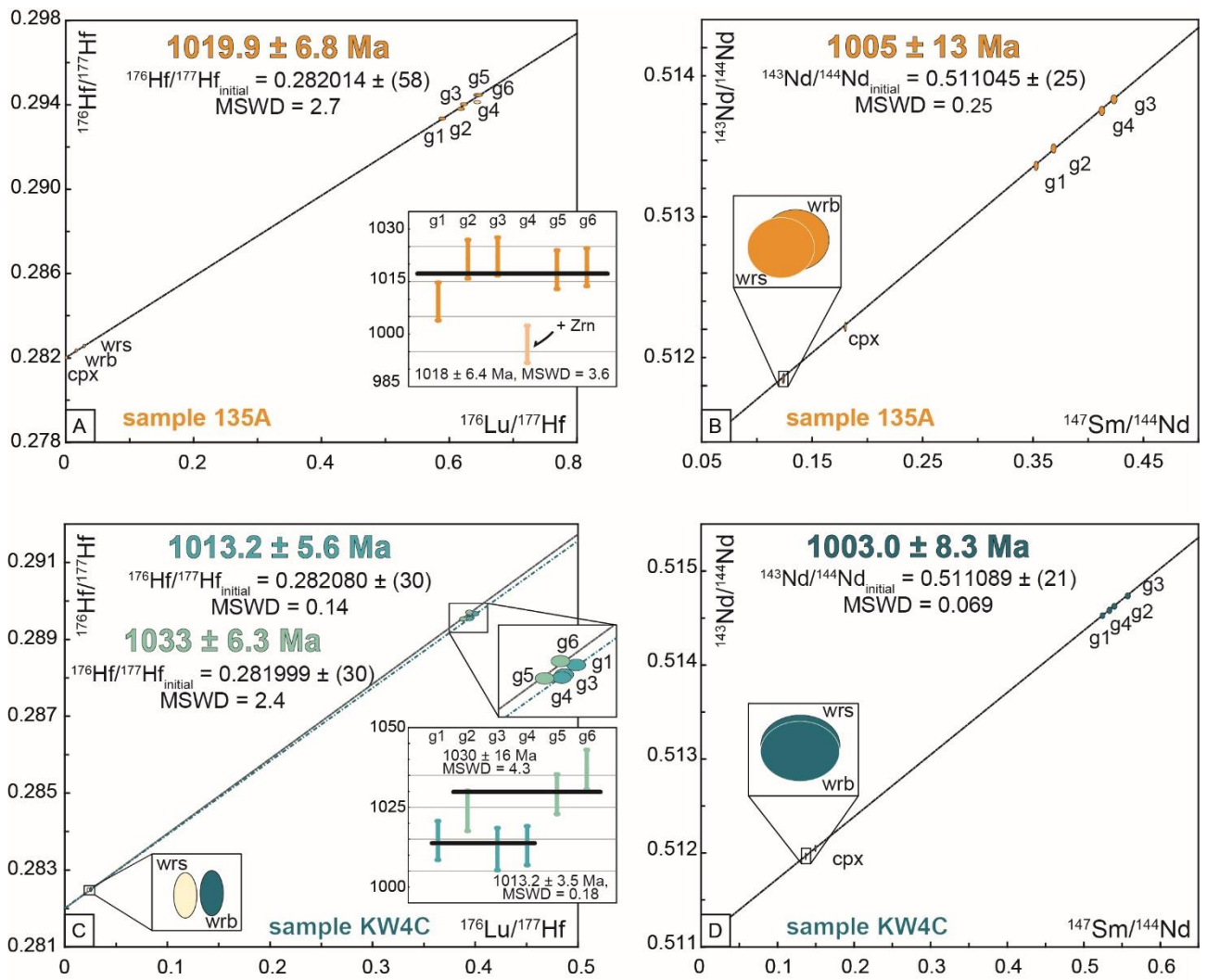


Figure 9

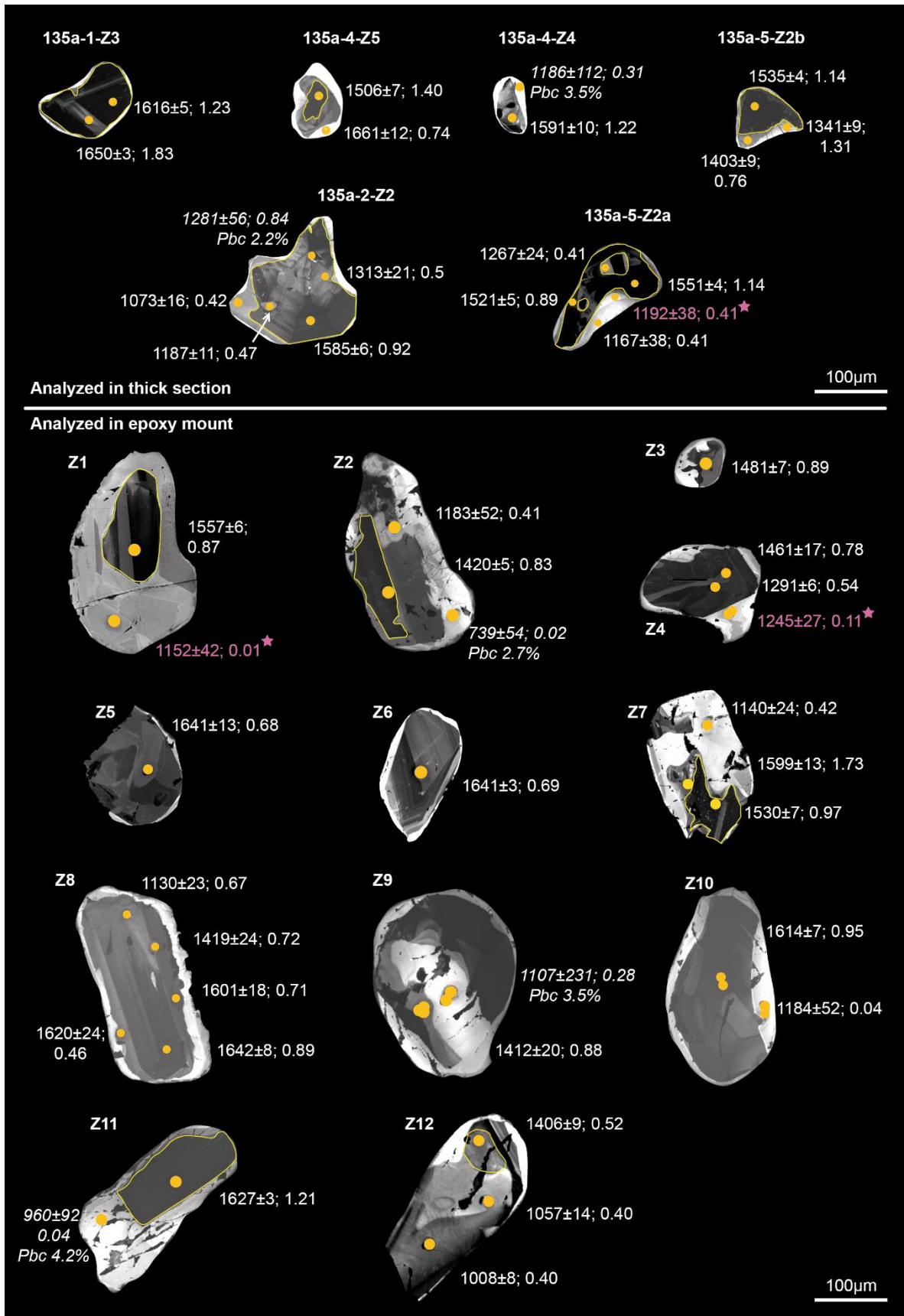


Figure 10

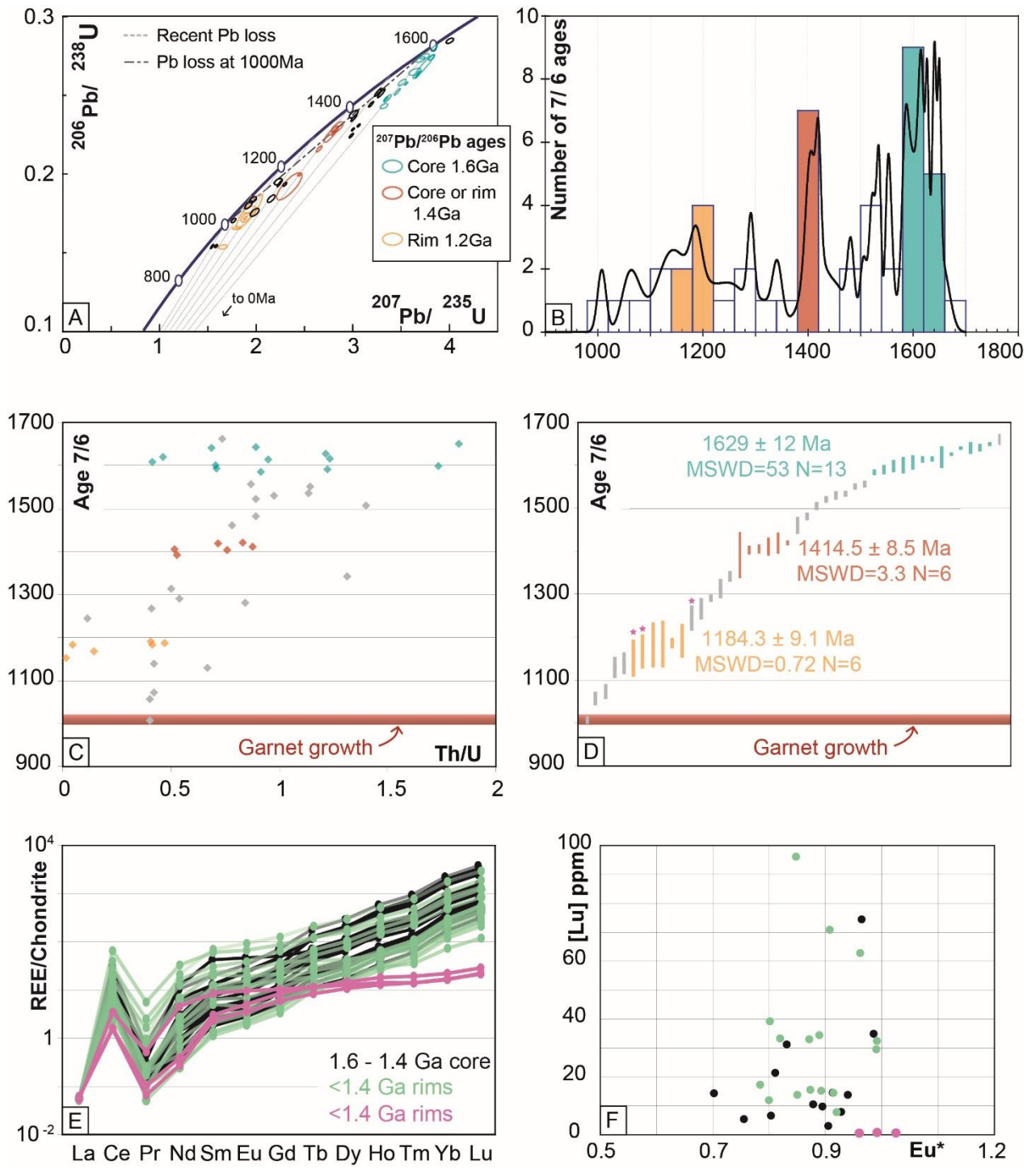


Figure 11

Table 1

	garnet	clinopyroxene	plagioclase	amphibole	scapolite	quartz	biotite
135A	30	30	22	10	5	<0.5	1.5
KW4C	21	14	50	8	2.5	4.5	<0.5
KW4A	47	28	17	<0.5	5	<0.5	<0.5

Sample ^a	Lu ^b (ppm)	Hf ^b (ppm)	¹⁷⁶ Lu/ ¹⁷⁷ Hf ^c	¹⁷⁶ Hf/ ¹⁷⁷ Hf	± ^d	2-point date (Ma) ^e	Sm ^b (ppm)	Nd ^b (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd ^c	¹⁴³ Nd/ ¹⁴⁴ Nd	± ^d	2-point date (Ma) ^e
135A												
g1	0.582	0.134	0.6187	0.293805	31	1009.3 ± 6.2	1.60	2.74	0.3526	0.513367	27	999 ± 26
g2	0.594	0.136	0.6234	0.294034	31	1021.4 ± 6.2	1.59	2.61	0.3692	0.513492	27	1010 ± 24
g3	0.600	0.132	0.6448	0.294456	31	1022.2 ± 6.1	1.54	2.19	0.4237	0.513839	27	1003 ± 20
g4	0.601	0.133	0.6433	0.294129	31	997.1 ± 6.0	1.56	2.29	0.4124	0.513757	27	998 ± 21
g5	0.583	0.140	0.5895	0.293350	31	1018.4 ± 6.3	*	*	*	*	*	*
g6	0.589	0.130	0.6466	0.294454	29	1019.1 ± 6.1	*	*	*	*	*	*
cpx	0.014	1.96	0.0010	0.282014	28		2.54	8.57	0.1791	0.512222	27	
wrs	0.160	0.783	0.0290	0.282572	28		1.11	5.45	0.1229	0.511853	27	
wrb	0.419	3.59	0.0166	0.282351	28		2.74	13.5	0.1232	0.511862	26	
KW4C												
g1	0.219	0.078	0.4002	0.289660	31	1014.6 ± 7.8	0.733	0.847	0.5232	0.514536	27	1006 ± 16
g2	0.217	0.077	0.4012	0.289747	32	1023.9 ± 7.9	0.702	0.789	0.5385	0.514635	27	1006 ± 15
g3	0.216	0.078	0.3956	0.289554	35	1011.9 ± 6.6	0.711	0.774	0.5563	0.514744	27	1002 ± 15
g4	0.221	0.079	0.3948	0.289546	30	1013 ± 7.8	0.754	0.856	0.5325	0.514593	27	1004 ± 16
g5	0.214	0.078	0.3879	0.289527	30	1029.1 ± 7.9	*	*	*	*	*	*
g6	0.205	0.074	0.3940	0.289699	30	1036.8 ± 7.9	*	*	*	*	*	*
cpx	0.006	1.15	0.0008	0.281973	28		5.44	22.4	0.1466	0.512056	27	
wrs	0.055	0.342	0.0228	0.282495	29		1.08	4.88	0.1343	0.511975	27	
wrb	0.057	0.321	0.0251	0.282488	28		1.09	4.93	0.1343	0.511968	26	

Table 2