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1 **Microstructurally controlled trace element (Zr, U–Pb)**
2 **concentrations in metamorphic rutile: An example from the**
3 **amphibolites of the Bergen Arcs**

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17

18 **Abstract**

19 As a common constituent of metamorphic assemblages, rutile provides constraints on the
20 timing and conditions of rock transformation at high resolution. However, very little is
21 known about the links between trace element mobility and rutile microstructures that result
22 from syn-metamorphic deformation. To address this issue, here we combine in situ LA-ICP-
23 MS and SHRIMP trace element data with EBSD microstructural analyses to investigate the
24 links between rutile lattice distortions and Zr and U–Pb systematics. Furthermore, we apply
25 this integrated approach to constrain further the temperature and timing of amphibolite-facies
26 metamorphism and deformation in the Bergen Arcs of southwestern Norway. In outcrop, the
27 formation of porphyroblastic rutile in dynamically hydrated leucocratic domains of otherwise
28 rutile-poor statically-hydrated amphibolite provides key contextual information on both the
29 ambient conditions of hydration and deformation and the composition of the reactive fluid.
30 Rutile in amphibolite recorded ambient metamorphic temperatures of ~590–730°C during
31 static hydration of the granulitic precursor. In contrast, rutile from leucocratic domains in the
32 directly adjacent shear zone indicates that deformation was accompanied by a localized
33 increase in temperature. These higher temperatures are recorded in strain-free rutile (~600–
34 860°C) and by Zr concentration measurements on low-angle boundaries and shear bands
35 (620–820°C). In addition, we also observe slight depletions of Zr and U along rutile low-
36 angle boundaries relative to strain-free areas in deformed grains from the shear zone. This
37 indicates that crystal-plastic deformation facilitated the compositional re-equilibration of
38 rutile upon cooling to slightly below the peak temperature of deformation. Cessation of
39 deformation at mid-crustal conditions near ~600°C is recorded by late stage growth of small
40 (< 150 µm) rutile in the high strain zones. U–Pb age data obtained from the strain-free and
41 distorted rutile grains cluster in distinct populations of 437.4 ± 2.7 Ma and *c.* 405–410 Ma,
42 respectively. These different ages are interpreted to reflect the difference in closure for

43 thermally-induced Pb diffusion between undeformed and deformed rutile during post-
44 deformation exhumation and cooling. Thus, our results provide a reconstruction of the
45 thermochronological history of the amphibolite-facies rocks of the Lindås Nappe and
46 highlight the importance of integration of microstructural data during application of
47 thermometers and geochronometers.

48 **KEYWORDS**

49 Zr-in-rutile thermometry, U–Pb geochronology, deformation microstructures, amphibolite,
50 high diffusivity pathways

51 **1. INTRODUCTION**

52 Accessory minerals are useful tracers of the timing and the conditions at which rocks
53 undergo physical and chemical changes. Recognition of the strong temperature dependence
54 of Zr-content in rutile (Tomkins, Powell, & Ellis, 2007; Watson, Wark, & Thomas, 2006;
55 Zack, Moraes, & Kronz, 2004) has caused a growing interest in rutile due to its applicability
56 as a metamorphic thermometer. Combined application of Zr-in-rutile thermometry with rutile
57 U–Pb geochronology (e.g. Kylander-Clark, Hacker, & Mattinson, 2008; Zack et al., 2011;
58 Zeh, Cabral, Koglin, & Decker, 2018) can therefore provide invaluable constraints on a
59 rock's metamorphic history. While providing an abundance of important geochemical data,
60 the incomplete understanding of the susceptibility of rutile composition to deformation and
61 fluid alteration during metamorphism complicates its application as a thermochronometer in
62 strained and hydrated rocks.

63 Most studies of rutile Zr-thermometry and U–Pb geochronology have either focused
64 on high-temperature granulites that have undergone slow cooling (e.g. Kooijman, Mezger, &
65 Berndt, 2010; Vry & Baker, 2006) or have been performed under anhydrous experimental

66 conditions (Cherniak, Manchester, & Watson, 2007). Thus, compositional re-equilibration of
67 rutile is commonly attributed to volume diffusion, whereas the effects of deformation and
68 fluid alteration have received relatively little attention. Accordingly, rutile ages are
69 interpreted as the time at which the grain cooled below the closure temperature for volume
70 diffusion (e.g. Dodson, 1973; Flowers, Bowring, Tulloch, & Klepeis, 2005; Ganguly &
71 Tirone, 1999; Hirdes & Davis, 2002; Mezger, Hanson, & Bohlen, 1989). For grains larger
72 than 200 μm in diameter the U–Pb system closure is estimated to be at 600°C (2–3°C/Ma
73 cooling rate; Cherniak, 2000; Vry & Baker, 2006), and that of Zr above \sim 640°C (2°C/Ma
74 cooling rate; Cherniak et al., 2007). This implies that rutile in retrogressed metamorphic
75 rocks should generally display correlating age and temperature data. However, analyses of
76 natural rutile suggest that the concept of closure temperature mostly applies to the U–Pb
77 system, whereas the frequently observed lack of correlation between grain size and calculated
78 temperatures implies that Zr concentrations in rutile are relatively insensitive to volume
79 diffusion (Ewing, Hermann, & Rubatto, 2013; Pape, Mezger, & Robyr, 2016).

80 Therefore, investigation into post-crystallisation modification of Zr contents in rutile
81 is of importance to applications of the thermometer. Recent studies have demonstrated that
82 high-pressure fluid alteration may not only mobilize Zr from the rutile but also provide the
83 required Si for zircon formation, thus controlling Zr partitioning with rutile (Harley, 2008;
84 Luvizotto & Zack, 2009; Meyer, John, Brandt, & Klemd, 2011; Mitchell & Harley, 2017;
85 Pape et al., 2016). In addition, the variability of Zr concentration within and among grains
86 has been attributed to the proximity of nearby Zr-bearing phases and rutile grain morphology,
87 further indicating a textural control on the Zr concentration in rutile (Ewing et al., 2013;
88 Kooijman, Smit, Mezger, & Berndt, 2012; Mitchell & Harley, 2017; Pape et al., 2016). Thus,
89 despite the apparent validity of closure temperatures for the U–Pb system, mechanisms other
90 than volume diffusion need to be considered when interpreting Zr concentrations in rutile. In

91 addition to the mechanisms outlined above, it is reasonable to assume that rutile Zr and U–Pb
92 contents may be further modified by deformation. Particularly, low-angle boundaries have
93 been shown to act as fast diffusion pathways for trace elements in both pyroxene and zircon
94 (Piazolo, Austrheim, & Whitehouse, 2012; Piazolo et al., 2016; Timms et al., 2011),
95 enhancing the resetting of both temperature and age data. If the effect of deformation on
96 composition is similarly significant in rutile, then previous observations of the inconsistent
97 nature of temperatures recorded by rutile within samples may be partially explained.

98 In the Lindås Nappe of the Bergen Arcs in southwestern Norway the complete
99 dehydration of rocks at granulite-facies conditions prior to the fluid-induced Caledonian
100 tectonometamorphic amphibolite-facies overprint provides an ideal geological setting for
101 investigating the effects of fluid-rock interaction and deformation on element mobility in
102 rutile. We observe a spatial association between strain, fluid infiltration and rutile distribution
103 in amphibolite-facies rocks. Through targeted sampling of rutile-rich high strain zones and
104 fractures, we show how combined microstructural and geochemical analyses of rutile can
105 constrain the hydration-deformation history of the Lindås Nappe amphibolite. Furthermore,
106 we explore the link between deformation and trace element distribution in rutile, which
107 highlights the benefit of incorporating microstructural analyses in future applications of the
108 Zr-in-rutile geothermometer.

109 **2. BACKGROUND AND OUTCROP DESCRIPTION**

110 **2.1. General background and previous geochronological work**

111 The Bergen Arcs lie within the hanging wall of the extensional Bergen Arc shear zone.
112 The arcs encompass the Øygards gneiss complex, structurally overlain by a set of nappes,
113 including the Lindås Nappe, which is the focus of this study (Figure 1a). The Lindås Nappe
114 mainly consists of an anorthosite-mangerite-charnockite-granite (AMCG) suite and banded
115 gneiss complexes. Pulse-like intrusion of the AMCG suite occurred between 1237 Ma and

116 951 Ma (Bingen, Davis, & Austrheim, 2001), followed by pervasive recrystallization at
117 granulite-facies conditions during the late Grenvillian-Sveconorwegian Orogeny at *c.* 930–
118 910 Ma (Bingen et al., 2001; Cohen, O'Nions, Siegenthaler, & Griffin, 1988). Partial
119 transformation of the granulite-facies rocks to eclogite and amphibolite-facies mineral
120 assemblages advanced via localized fluid infiltration along fractures (Austrheim, 1987;
121 Jamtveit, Bucher-Nurminen, & Austrheim, 1990) between *c.* 440 Ma and 420 Ma during the
122 Caledonian Orogeny (Bingen et al., 2001).

123 Previously acquired geochronological data for the amphibolite-facies rocks of the
124 Bergen Arcs define a broad time-span for amphibolite-facies metamorphism and deformation
125 (Figure 1b). Amphibole Ar-Ar data record the oldest ages at 455 ± 2 Ma and 439 ± 4 Ma
126 (Boundy, Essene, Hall, Austrheim, & Halliday, 1996). However, the validity of these early
127 ages has been questioned based on the interpretation that these Ar-Ar data might reflect the
128 presence of excess Ar in the amphiboles instead of constraining the cooling age below the
129 closure temperature for Ar diffusion (Kühn, Glodny, Austrheim, & Råheim, 2002; Roffeis,
130 Corfu, & Austrheim, 2012). Zircon generally records slightly younger U–Pb concordia ages
131 between 426 ± 4 Ma and 430 ± 3 Ma (Glodny, Kühn, & Austrheim, 2008; Roffeis et al.,
132 2012). One U–Pb age of 437 ± 11 was obtained from zircons that had been deformed by
133 amphibolite-facies shear (Piazolo et al., 2012). A zircon U–Pb age of 418 ± 9 Ma (Kühn et
134 al., 2002) and a 433 ± 3 Ma biotite Ar-Ar age (Fossen & Dunlap, 1998) from a sheared
135 trondhjemite dyke are interpreted as directly recording the timing of amphibolite-facies
136 deformation. These ages define a span of *c.* 20 Ma for the amphibolite-facies deformation.
137 Rb-Sr multi-mineral isochron data provide the youngest age estimates at 414 ± 5 Ma (apatite,
138 feldspar, white mica; Glodny et al., 2008) and 409 ± 8 Ma (apatite, amphibole, biotite;
139 Bingen et al., 2001), consistent with the reported low temperature resetting of the Rb-Sr

140 system in mica, giving an estimate for the timing of crystallization of these lower temperature
141 minerals.

142 Additional constraints on the timing of the amphibolite-facies metamorphism are
143 given by biotite muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages from the Ulriken Gneiss unit immediately
144 to the west of the Lindås Nappe (Fossen & Dunlap, 1998). Plateau ages of *c.* 410 Ma from
145 greenschist-facies shear zones constrain the time of nappe stacking in the Bergen Arcs,
146 marking the end of Caledonian contractional deformation. In addition to the amphibolite-
147 facies rocks, pre- to syn-tectonic pegmatites have been dated by Rb-Sr and Sm-Nd multi-
148 mineral isochron methods at *c.* 425 Ma (Kühn et al., 2002) and by U–Pb in zircons at 424 ± 1
149 Ma (Jamtveit et al., 2018). These dates, interpreted as crystallization ages, indicate that the
150 mobility of hot silicate rich fluid was synchronous with metamorphism. However, the exact
151 relationship between the emplacement of the pegmatites and the amphibolite-facies alteration
152 remains unknown.

153 If interpreted as an isolated event, the geochronology derived from the amphibolite-
154 facies mineral assemblages provides a sensible timeline. However, this apparent *c.* 430 Ma
155 amphibolite-facies episode overlaps with the 429 ± 3 Ma (Glodny et al., 2008) and 423 ± 4
156 Ma (Bingen, Austrheim, Whitehouse, & Davis, 2004) ages derived from eclogite-facies
157 assemblages that are intercalated with the amphibolites on Holsnøy (Figure 1b). This
158 overlapping of ages has been explained by a west-to-east pressure decrease during
159 simultaneous amphibolite- and eclogite-facies metamorphism (Roffeis et al., 2012).
160 However, the interpretation remains contentious, since the characteristics and timing of the
161 amphibolitization are somewhat ambiguous compared to the robustly constrained eclogite
162 facies metamorphism.

163 Here we focus on integrating rutile Zr-thermometry, U–Pb age determination, and
164 EBSD microstructural analyses to establish a rigorous temperature-deformation-time history

165 of the amphibolite-facies event. With an emphasis on distinguishing the deformational and
166 metamorphic controls on the amphibolite-facies rutile temperature and age data.

167 **2.2. Description of lithological relationships**

168 The sampled outcrop, situated on Radøy in the northeastern part of the Lindås Nappe
169 (Figure 1a) (UTM zone 31V, 620260E, 6718524N), includes three main lithologies;
170 granulite, amphibolite, and leucocratic domains within the shear zone (Figure 2a). The
171 amphibolite occurs between the other two lithologies. The granulite, characterized as a lilac
172 corona-bearing medium-grained rock, shares an irregular and transitional contact with the
173 amphibolite. Where the granulite grades into the amphibolite the foliation becomes defined
174 by elongate amphibole clusters (1-2 cm in length), directly replacing coronitic diopside and
175 garnet that define the foliation in the granulite. Strain increases markedly throughout the
176 amphibolite towards the shear zone that contains additional leucocratic domains (Figure 2a).
177 Within 50 cm from the first appearance of leucocratic domains, the foliation of the
178 amphibolite grades into a 5-40 cm wide zone, where the foliation is defined by mafic and
179 felsic bands with 5 mm spacing, marking the outer limit of the shear zone. In the following
180 we refer to this part of the amphibolite as strained amphibolite. Within the shear zone, the 2-3
181 cm spaced foliation is defined by dark, amphibole- and feldspar-bearing amphibolite bands
182 that alternate with creamy white leucocratic domains dominated by feldspar and strongly
183 aligned clinozoisite.

184 In addition, the granulite contains two types of fractures (Figure 2b). Fracture type-I
185 presents as a 1-2 cm wide plane hosting amphibole. Fracture type-II is apparent as 1-2 mm
186 wide greenish fractures surrounded by white alteration haloes with a width of 1-2 cm,
187 oriented subparallel to the high strain zone.

188 **3. METHODS**

189 **3.1. Sample preparation**

190 Polished thin sections were used for electron microprobe (EMP) analyses of rutile
191 grains from the amphibolite and fracture alteration haloes. Additional EMP analyses were
192 performed on plugs (3.8 mm diameter) drilled from lineation parallel (XZ) sections of
193 leucocratic domains. Plugs were mounted in epoxy resin, polished initially with 6 µm and 1
194 µm diamond suspension fluid and given a final chemomechanical polish with colloidal silica
195 for electron back-scatter diffraction (EBSD) analysis.

196 **3.2. Imaging and quantification of rutile microstructures**

197 Back-scatter electron (BSE) imaging and EBSD analyses were carried out on the
198 Tescan Mira3 Variable Pressure Field Emission Scanning Electron Microscope (VP-FESEM)
199 at the John de Laeter Centre (JDL), Curtin University, Australia. For both BSE and EBSD
200 acquisition, the VP-FESEM was run at a high vacuum with an accelerating voltage of 20 kV
201 and a beam current of 5.0 nA.

202 EBSD patterns were acquired with a HKL NordlysNano high sensitivity EBSD
203 detector and indexed with AzTec analysis software (Oxford Instruments). The samples were
204 tilted to 70° and analysed at a working distance of 20 mm to 24.5 mm. The step size ranged
205 between 1 µm and 10 µm depending on the grain size and required spatial resolution. EBSD
206 data was processed using HKL's Channel 5 software. Non-indexed solutions were replaced
207 by the most common neighbour orientation to reduce data noise following the procedure
208 outlined in Prior, Wheeler, Peruzzo, Spiess, and Storey (2002), Bestmann and Prior (2003)
209 and Piazzolo, Bestmann, Prior, and Spiers (2006).

210 Mineral abbreviations used in the figures follow Whitney and Evans (2010).

211 3.3. U–Pb geochronology

212 The sensitive high-resolution ion microprobe (SHRIMP) analytical procedure broadly
213 follows those described by Compston, Williams, and Meyer (1984) and Williams (1998).
214 SHRIMP rutile data were collected from one mount (N17-44) over one analytical session at
215 JDL. During this session, a 10-15 μm diameter spot for grains 30 and 32 and a 20-25 μm
216 diameter spot for grains 29, 31 and 33 were used (Table S4b), with a mass-filtered O^- -
217 primary beam of ~ 7.6 - 8.3 and 25.0 - 29.5 nA on rutile from a leucocratic domain sample,
218 respectively. Data for each spot was collected in sets of 6 scans on the rutile through the mass
219 range of $^{192}\text{Ti}_3\text{O}_3^+$, $^{200}\text{WO}^+$, $^{204}\text{Pb}^+$, Background, $^{206}\text{Pb}^+$, $^{207}\text{Pb}^+$, $^{208}\text{Pb}^+$, $^{248}\text{ThO}^+$, $^{254}\text{UO}^+$ and
220 $^{270}\text{UO}_2^+$. The rutile age standard used was WH (Windmill Hill), a multigrain standard from
221 an Archean quartzite, with a $^{206}\text{Pb}/^{238}\text{U}$ age of 2625 Ma (Clark, Hensen, & Kinny, 2000).
222 WH has been calibrated against the Wodgina single rutile crystal described by Ewing (2011)
223 and Ewing, Rubatto, Beltrando, and Hermann (2015) using the procedures described therein.
224 Although we note that a small proportion of rutile grains from WH have $^{207}\text{Pb}/^{206}\text{Pb}$ ages
225 slightly older than the dominant age population (manuscript in preparation), we only observe
226 this in the more precise $^{207}\text{Pb}/^{206}\text{Pb}$ ages, not in the $^{206}\text{Pb}/^{238}\text{U}$ data. These "older" grains
227 were avoided during analysis of the WH standard. No U standard was analysed during this
228 session although estimated U contents are shown in Table S4b and based on the average U
229 concentration in WH of 164 ppm. The common Pb correction was based on the measured
230 ^{208}Pb due to the negligible Th contents on rutile. The programs SQUID II and Isoplot
231 (Ludwig, 2003, 2009) were used for rutile data processing.

232 Uncertainties (2σ) cited for individual analyses include uncertainties from counting
233 statistics and the common-Pb correction. Analyses for which the proportion of common Pb
234 was $\geq 1.4\%$ were not considered in the age discussion or plotted on the Concordia diagram.

235 Weighted mean values for the mean age given on pooled analyses are at the 95% confidence
236 level.

237 Rutile grains from leucocratic domains were analysed for U–Pb ratios by LA-ICP-MS
238 at the Institut für Mineralogie, University of Münster, Germany. Ablation was done with an
239 excimer laser (Analyte G2, Photon Machines) connected to a Thermo Fisher Scientific
240 Element2 magnetic sector field single collector ICP-MS, at a repetition rate of 10 Hz and a
241 spot size of 50 μm , producing a pit depth of $\sim 30 \mu\text{m}$. Prior to sample analyses, the system
242 was tuned for high sensitivity, stability, and low oxide-interference rates ($^{232}\text{Th}^{16}\text{O}/^{232}\text{Th} <$
243 0.05%). For rutile U–Pb measurements five unknowns were bracketed with two analyses of
244 R10, which was used as external standard (Luvizotto et al. 2009). Along with the unknowns,
245 secondary reference rutiles SP1 (Mezger et al., 1989, $911 \pm 2 \text{ Ma}$), Sugluk-4 (Bracciali,
246 Parrish, Horstwood, Condon, & Najman, 2013, $1723.0 \pm 6.8 \text{ Ma}$), and R-632 (Axelsson et al.,
247 2018, $496 \pm 2 \text{ Ma}$) were analysed to check for precision and accuracy. Obtained results show
248 good agreement with the published values ($917.2 \pm 8.5 \text{ Ma}$ for SP1, $1729 \pm 14 \text{ Ma}$ for
249 Sugluk-4, $505.9 \pm 6.4 \text{ Ma}$ for R-632). U–Pb rutile data were corrected for common Pb and
250 processed following the procedures described in Kooijman, Berndt, and Mezger (2012) and
251 Zack et al. (2011). A common Pb correction was applied to analyses if the contribution of the
252 estimated common ^{206}Pb to the total measured ^{206}Pb exceeded 1%. The isotope ratios for the
253 common Pb were calculated using the evolution model for terrestrial Pb by Stacey and
254 Kramers (1975).

255 LA-ICP-MS and SHRIMP data are presented in Concordia, weighted mean, and
256 radial plots, produced in IsoplotR (Vermeesch, 2018). Ages in figures are $^{206}\text{Pb}/^{238}\text{U}$ dates.

257 **3.4. Trace elements and Zr-in-rutile thermometry**

258 Rutile trace element concentration measurements by EMP ($n = 72$) were carried out
259 on a field-emission JEOL 8530F Hyperprobe equipped with five Wavelength-Dispersive

260 Spectrometers at the Centre for Microscopy, Characterization and Analysis (CMCA), The
261 University of Western Australia. Operating conditions were a beam energy of 25 keV, the
262 beam current was 60 nA, and the beam was fully focused. Elements were acquired using the
263 following analysing crystals: LiF for Ti K α , V K α , Cr K α , Mn K α , Fe K α , and Ni K α ; TAP
264 for Si K α and Al K α ; and PETH for Ca K α , Zr L α and Nb L α . The standards employed were
265 commercially available silicates, oxides, and metals. Counting time was 20 s for Ti K α , 70 s
266 for Cr K α , Mn K α , Fe K α , Ni K α , Hf L α , Si K α , Al K α , Ca K α , Zr L α and Nb L α , and 100 s
267 for V K α . Mean atomic number background corrections were employed throughout
268 (Donovan and Tingle, 1996). Unknown and standard intensities were corrected for dead time
269 and the ZAF algorithm was used for matrix absorption (Armstrong, 1988). On-peak
270 interference corrections were applied as appropriate (Donovan et al., 1993). Detection limits
271 ranged from 10 ppm for Ca to 40 ppm for Hf.

272 Rutile grains were analysed for trace elements also by LA-ICP-MS at the Institut für
273 Mineralogie, University of Münster. For trace element analyses the NIST 610 glass was used
274 as external standard while synthetic TNT666 and TNT777 glasses (Klemme et al., 2008) as
275 well as natural rutile R10 (Luvizotto et al., 2009) were measured along with the unknowns to
276 monitor precision and accuracy. Obtained results generally match the published range of
277 concentrations given in the GeoReM database (version 23) (Jochum et al., 2005).
278 Approximately 25 sample measurements were bracketed by three analyses of the external
279 standard. ^{47}Ti was used as internal standard element. Trace element data reduction was
280 performed using Glitter 4.4.4 (Griffin, 2008). For LA-ICP-MS the elemental concentrations
281 were analysed by measuring the following isotopes: ^{238}U , ^{118}Sn , ^{121}Sb , ^{182}W , ^{95}Mo , ^{53}Cr , ^{66}Zn ,
282 ^{51}V , ^{181}Ta , ^{93}Nb , ^{90}Zr , and ^{178}Hf . The obtained trace element data were filtered to exclude all
283 measurements with > 800 ppm Si showing abnormally high Zr contents, a method adapted

284 from Zack et al. (2004) and Luvizotto and Zack (2009) in an effort to detect zircon-lamellae
285 rich rutile and zircon micro inclusions.

286 Zr-in-rutile thermometry calculations follow the method of Tomkins et al. (2007),
287 using pressure estimates obtained from associated amphibole through Al-in-hornblende
288 barometry (Johnson & Rutherford, 1989; Schmidt, 1991). For accurate estimates, the
289 thermometer requires the presence of zircon and quartz in equilibrium with rutile.
290 Representative amphibole compositions and pressure estimates are provided in Table S1.

291 **4. RESULTS**

292 **4.1. General microstructural description of the main lithologies**

293 The transition from granulite to amphibolite is marked by an overall grain size
294 reduction and replacement of diopside-garnet coronas by amphibole clusters (Figures 3a and
295 b). The amphibolite features 1 cm-scale interlayering of two characteristic domains; an
296 amphibole-rich and a plagioclase-rich domain. The amphibole-rich domain is composed of
297 amphibole with minor amounts of chlorite, biotite, quartz, and kyanite (Figure 3b). Within
298 the amphibole-rich domain, trace amounts of rutile and pyrite are observed associated with
299 replaced diopside. The plagioclase-rich domain is composed of plagioclase with minor
300 amounts of zoisite, kyanite, quartz and CO₃-rich scapolite (Figure 3b). The replacement of
301 diopside and garnet by amphibole is also observed in alteration haloes around fractures type-I
302 and II (Figure 4a).

303 In the strained amphibolite, interlayering of amphibole and plagioclase domains
304 occurs on a finer, 1 mm-scale (Figure 3c). Amphibole-rich and plagioclase-rich domains of
305 the strained amphibolite differ from those in the amphibolite in that they contain a higher
306 abundance of clinozoisite and zoisite.

307 In the shear zone the foliation is defined by mm-scale interlayering of dark
308 amphibole-rich with plagioclase-rich domains (Figure 3d), consistent with the lithological
309 variation in the strained amphibolite. On the cm-scale, these dark bands are interlayered with
310 porphyroblastic rutile-bearing leucocratic domains (Figures 3d and 5a). In areas of increased
311 leucocratic component, small (< 100 µm) plagioclase and zoisite grains dominate the rock
312 and define the foliation (Figures 3d and 5b, c). In these areas clinozoisite and biotite laths are
313 aligned with the foliation (S; Figure 3d) and form in shear bands at ~30° to S (C; Figure 5a).

314 **4.2. General occurrence of rutile and its mineral association**

315 Rutile occurs as an accessory phase (< 1 volume %) in all lithologies except for the
316 granulite. Rutile always occurs together with quartz and zircon, except in the fracture
317 alteration haloes where zircon is absent. In general, rutile overall abundance and grain size
318 positively correlate with clinozoisite, biotite, quartz, CO₃-rich scapolite and tschermakite
319 abundances.

320 **4.2.1. Amphibolite**

321 Hydration of granulite to amphibolite proceeded through the replacement of granulite-
322 facies diopside by secondary clusters of Mg-hornblende, tschermakite, quartz, carbonate and
323 rutile (Figures 3b and 4b). In the strained parts of the amphibolite rutile grains (<10 µm) are
324 associated with amphibole clusters, whereas larger rutile grains (< 150 µm) occur in
325 association with small (< 100 µm) clinozoisite grains, very small zircon grains (< 20 µm) and
326 large grains (< 1 mm) of biotite that are aligned with the foliation (Figure 4c).

327 **4.2.2. Fracture alteration haloes within granulite**

328 The fracture filling assemblage of type-I fractures comprises quartz and tschermakite
329 (Figure 4a). Alteration haloes around type-I fractures in the granulitic anorthosite, visible
330 only in thin section, contain abundant rutile in amphibole clusters (Figure 4d). Here, rutile
331 grains are equant and rounded with diameters of up to 30 µm. On the outer edge of the

332 fracture type-I alteration halo, diopside is replaced by symplectites of magnesio-hornblende,
333 clinozoisite, quartz, and rutile (Figure 4e).

334 Type-II fractures predominantly contain quartz, with minor amounts of fine-grained
335 (< 10 μm) biotite and amphibole. Type-II fracture alteration haloes are visible at both the
336 outcrop and thin section scale due to abundant zoisite inclusions in the host plagioclase,
337 producing a milky white appearance. In the alteration halo, rutile is present in clinozoisite-
338 and pargasite-filled fractures in diopside as clusters of rounded-cusped shaped grains ranging
339 in diameter between 10 μm and 30 μm (Figure 4f). Zircon is not observed in association with
340 either fracture types.

341 **4.2.3. Leucocratic domains**

342 The leucocratic domains of the shear zone are the primary rutile-bearing lithology. In
343 the shear zone the mineralogical variation typical of the strained amphibolite is evidenced by
344 amphibole-rich foliation-parallel bands primarily consisting of Mg-hornblende with
345 tschermakitic rims, quartz and minor amounts of clinozoisite and rutile (< 20 μm in diameter)
346 (Figure 5f). Where the strained amphibolite is interlayered at a higher frequency with the
347 leucocratic domains, there is an increase in tschermakitic amphibole, coarse grained rutile (<
348 200 μm diameter), biotite and clinozoisite, concomitant with a decrease in Mg-hornblende
349 (Figure 5d). In areas where the amphibole domains of the strained amphibolite are no longer
350 interlayered with the leucocratic domains, the mafic component primarily consists of (< 1
351 mm) foliation-parallel laths of clinozoisite and biotite and porphyroblastic rutile (< 1 mm),
352 aligned with their long axes parallel to the foliation (Figure 5b).

353 In plagioclase-dominated areas of the leucocratic domains, porphyroblastic rutile,
354 biotite, CO_3 -rich scapolite and clinozoisite occur in S and C foliation parallel bands (Figure
355 5a, e). Rutile also occurs as foliation-parallel grains in the felsic component of the leucocratic
356 rock together with plagioclase, kyanite, zoisite and quartz but only minor amounts of biotite

357 and clinozoisite (Figure 5c). Throughout the leucocratic domains zircon occurs as very small
358 grains ($< 10 \mu\text{m}$) on the rim of rutile (Figure 5b and c) and, uncommonly, as inclusions
359 within the rutile grain (Figure 5c).

360 **4.3. Details of rutile microstructures and quantitative orientation analysis**

361 Since the leucocratic domains are the main rutile-bearing lithology, most of this
362 section investigates rutile in the leucocratic domains unless stated otherwise. Rutile is
363 categorized based on grain size, morphology, structure and the mineral assemblage described
364 above. A first order division is made based on grain size into subsets of large ($> 150 \mu\text{m}$) and
365 small grains ($< 150 \mu\text{m}$).

366 Large porphyroblastic rutile is mostly present as substructure-free grains (Figure 6a,
367 b) that exhibit an internal grain orientation spread (GOS) of $< 1^\circ$. Porphyroblastic rutile has a
368 highly irregular grain shape, typically displaying cusped protrusions into the surrounding
369 matrix (e.g. Figure 6a). Most commonly, these grains are observed in the leucocratic domains
370 (Figures 6a and c) and only one occurrence was found in an amphibole cluster within the
371 amphibolite (Figure 6b).

372 However, there are substructured large porphyroblastic rutile grains showing a GOS
373 of $> 1^\circ$ (Figures 7a, e and h). For these grains, four types of substructures can be identified:
374 (1) shear bands; (2) continuous lattice bending and low-angle boundaries; (3) distinct, straight
375 growth twins and (4) deformation twins. To exclude the possibility that the observation of
376 substructured versus substructure-free grains is due to an orientation effect, the c-axis
377 orientations of all large grains have been plotted (Figure S1), demonstrating no preferred
378 orientations for grains of either structure.

379 Shear bands are observed in large rutile ($> 150 \mu\text{m}$) and are associated with a high
380 occurrence of recrystallized rutile and/or kyanite inclusions and are marked by a change in

381 trace element chemistry (Figure 8) and a $\sim 4^\circ$ grain orientation change across the plane
382 (Figure 7a). Misorientation data for large substructured rutile grains identify three types of
383 lattice distortions (Types-I to -III) associated with low-angle boundaries and/or shear bands.
384 The first type, Type-I, is observed at low-angle boundaries associated with shear bands with a
385 rotation axis near $\langle 112 \rangle$, lying on the low-angle boundary wall (Figure 7b and c). Shear
386 bands are distinguished from continual lattice bending by their sharp misorientation profile.
387 The misorientation profile across the boundary (A-A'; Figure 7d) shows a sharp change in
388 orientation at the low-angle boundaries on the order of $\sim 1^\circ/\mu\text{m}$, without significant
389 orientation variation outside of the bounding low-angle boundaries.

390 Low-angle boundaries appear as subparallel discontinuous bands, which are most
391 commonly parallel to the short axis of the grain (Figure 7e). They may be associated with
392 continuous lattice bending on either side of the low-angle boundary (Figure 7g). Continuous
393 lattice bending is associated with Type-II lattice distortions. Type-II lattice distortions are
394 characterized by their lamellar, subparallel appearance (Figure 7e) and a rotation axis lying
395 approximately on the pole to the (110)-plane (Figure 7f). The misorientation profile across
396 lamellar boundaries (B-B'; Figure 7g) indicates stepwise misorientation on the order of
397 $0.6^\circ/\mu\text{m}$ at each boundary wall, resulting in a progressively increasing misorientation relative
398 to the original grain orientation.

399 While both twin types are identified as a 65° misorientation around [010], deformation
400 twins are differentiated from growth twins based on their characteristic thin and tapered
401 appearance (e.g. Figures 6a and 7a, e). In contrast, growth twin boundaries appear lobate and
402 irregular (e.g. Figure 7h). Type III lattice distortions are commonly spatially related to growth
403 twinning (Figure 7h). Type-III lattice distortions are exclusively present within the outer 100
404 μm of the grain and are characterized by a rotation axis lying approximately on the pole to
405 the (100)-plane (Figure 7i). Overprinting relationships between the different lattice distortion

406 types indicate that deformation twinning preceded the formation of shear bands and growth
407 twins (Figure 7a), but occurred after at least some crystal lattice bending and is associated
408 with the formation of low-angle boundaries (Figure 7e).

409 Small rutile grains occur either associated with porphyroblastic biotite (Figures 4c and
410 5e) or around large porphyroblastic rutile grains (Figure 5b). These grains exhibit a GOS of <
411 1° and very rarely show any low-angle boundaries or crystal lattice bending.

412 **4.4. Trace element geochemistry**

413 Fifty-one LA-ICP-MS trace element spot analyses were obtained from 39 rutile grains
414 in the leucocratic gneiss. Trace element concentrations are summarised in Table S2 and
415 plotted against distance to the grain boundary (Figure 8).

416 Hafnium, Zr and U concentrations show systematic changes in large grains vs. small
417 grains, shear bands, low-angle boundaries and twins (Figure 8a, c and d). Due to the thin
418 width of deformation twins and the resolution of the instruments used, trace element analyses
419 of deformation twins could not be performed, hence chemical characteristics of only the
420 growth twins are provided. The concentration of U is generally between 0.1 ppm and 18 ppm
421 with an average concentration of 6 ppm. In substructure-free grains, the average U
422 concentration is 8 ppm. In contrast, small grains and grains with irregular twins and shear
423 bands have less than 5 ppm U. Grains with low-angle boundaries have on average 3 ppm U.
424 The average concentrations of Zr and Hf of all analysed grains are 1260 ppm and 35 ppm,
425 respectively. If only substructure-free grains are considered, the average concentrations of Zr
426 and Hf are 1500 and 40 ppm, in comparison to an average of 950 ppm Zr and 30 ppm Hf for
427 spot analyses on grains containing low-angle boundaries and 265 ppm Zr and 11 ppm Hf
428 average concentrations in small grains and growth twins. Concentrations of V, Nb and Ta
429 vary non-systematically (Figure 8b, e and f).

430 **4.5. Zr-in-rutile thermometry**

431 Rutile Zr concentrations and calculated temperature estimates for all rutile-bearing
432 lithologies are summarised in Table S3 (Figure 9). The Al-hornblende pressure estimates
433 used in the calculation are derived from tschermakite, ranging from 10 kbar to 14 kbar (Table
434 S1). In the amphibolite, rutile contains between 146 ppm (607 ± 27 °C) and 572 ppm Zr (727
435 ± 17 °C) (Figure 9a). Small rutile from the strained amphibolite contains between 74 ppm Zr
436 (557 ± 35 °C) and 247 ppm Zr (655 ± 22 °C) (Figure 9c). The Zr concentration in rutile from
437 type-I fracture alteration haloes varies between 125 ppm (588 ± 28 °C) and 462 ppm ($690 \pm$
438 18 °C), whereas rutile from type-II fracture haloes shows a narrower range between 238 ppm
439 (640 ± 23 °C) and 470 ppm (696 ± 18 °C) (Figure 9b).

440 Rutile from the leucocratic domains shows the largest variation in Zr concentrations,
441 ranging from 97 ppm (598 ± 32 °C) to 2331 ppm (861 ± 45 °C). Substructure-free areas in
442 large rutile grains show a slightly smaller spread in Zr concentrations between 230 ppm (637
443 ± 23 °C) and 2331 ppm (861 ± 45 °C) (Figure 9f). Shear bands have a Zr concentration of up
444 to 1330 ppm (797 ± 31 °C), while low-angle boundaries contain between 184 ppm ($620 \pm$
445 25 °C) and 1690 ppm Zr (823 ± 33 °C) (Figure 9e). Small grains and growth twins in the
446 leucocratic domains record lower values, ranging between of 97 ppm (598 ± 32 °C) to 262
447 ppm (669 ± 22 °C) (Figure 9d) and 231 ppm (638 ± 26 °C) to 596 ppm (718 ± 37 °C) (Figure
448 9e), respectively.

449 **4.6. Rutile U–Pb Geochronology**

450 Ninety-eight analyses were obtained from 33 large grains in the leucocratic domains
451 by LA-ICP-MS ($n = 68$; 28 grains) and SHRIMP ($n = 30$; 5 grains) (Table S4). The results
452 are shown in Concordia and radial plots (Figure 10). All rutile grains have less than 10%
453 common Pb, defined here as the percentage of common ^{206}Pb on total ^{206}Pb . Common Pb
454 ranges between 1.7 to 9.9% for LA-ICP-MS analyses and 0.4 to 1.4% for SHRIMP analyses.

455 **4.6.1. LA-ICP-MS analyses**

456 All analyses yield overlapping concordant ages, producing a LA-ICP-MS Concordia
457 age of 416.4 ± 1.7 Ma (Figure 10a). By excluding LA-ICP-MS data points with more than
458 5% discordance ($n = 4$), the mean LA-ICP-MS age is 415.7 ± 2.7 Ma with a mean square
459 weighted deviation (MSWD) of 2.0 (Figure 10c). Radial plots indicate that the LA-ICP-MS
460 data are consistent with multiple age groups. For ages obtained by LA-ICP-MS, 36% of the
461 analyses correspond to an age of 438.2 ± 5.9 Ma and 64% of the analyses correspond to an
462 age of 404.8 ± 4.2 Ma (Figure 10e).

463 **4.6.2. SHRIMP analyses**

464 SHRIMP analyses produce a Concordia age of 419.6 ± 1.4 Ma (Figure 10b). For the
465 calculated SHRIMP mean age of 419.2 ± 3.3 Ma all analyses were considered. However, the
466 elevated MWSO of 5.6 (Figure 10d) indicates over-dispersion of the data relative to the
467 estimated analytical uncertainty. Age data obtained by SHRIMP define two age populations
468 of 437.4 ± 2.7 Ma (39%), 409.1 ± 2.2 Ma (57%) and one analysis with a younger date at
469 379.9 ± 7.2 Ma (3.6%) (Figure 10f).

470 **5. DISCUSSION**

471 **5.1. Origin of rutile**

472 Rutile exhibits distinct textures and a heterogeneous distribution in the different
473 assemblages that result from localized deformation and/or hydration reactions. Large rutile is
474 particularly abundant in leucocratic domains, whereas only a small quantity of fine-grained
475 acicular to rounded rutile occurs in fracture alteration haloes and in the amphibolite (Figures
476 4, 5, and 11). The Ti required to form this fine-grained rutile in the amphibolite is most likely
477 derived from the breakdown of the diopside during hydration, as evidenced by the spatial
478 association between relict diopside and rutile (Figures 3b and 4b). Textural features, such as
479 the cusped grain boundary morphology and the clustering of the rutile grains in the

480 leucocratic domains (Figures 5b - d) and fracture alteration haloes (Figures 4d and f) indicate
481 that rutile in these areas precipitated from a grain boundary fluid. This is consistent with the
482 general requirement of fluid for driving the retrogression of the granulite to amphibolite
483 (Austrheim & Robins, 1981). Furthermore, the correlated abundance of rutile with
484 tschermakite, clinozoisite, CO₃-rich scapolite, quartz and biotite in both fracture alteration
485 haloes (Figures 4e, f) and leucocratic domains (Figure 5b) suggests a genetic link between
486 rutile precipitation and the composition of the alteration fluid resulting in the described
487 assemblage. In particular, the presence of quartz in fractures that are surrounded by rutile-rich
488 alteration haloes (Figure 4a) likely reflects cm-scale Ti mobilisation in a Si-bearing fluid.
489 Concomitant Si and Ti mobility is in agreement with experimental and natural observations
490 of enhanced rutile solubility in Na-Al-Si-bearing crustal fluids, indicating that complexing
491 with major rock-forming constituents is governing Ti mobility in fluids in addition to
492 pressure and temperature (Antignano & Manning, 2008; Gao, John, Klemm, & Xiong, 2007;
493 John, Klemm, Gao, & Garbe-Schönberg, 2008; Rapp, Klemm, Butler, & Harley, 2010).
494 Hence, the spatial affinity between rutile grains and their host lithology suggests that both
495 fractures and leucocratic domains acted as pathways channelizing Na-Al-Si-bearing fluid.
496 Without more data concerning the chemical properties of the Na-Al-Si-bearing fluid it is not
497 possible to make the distinction of whether it is in the form of a hydrous melt or an aqueous
498 solution, both of which may be stable at the determined PT conditions (see discussion below
499 for conditions) (Bureau & Keppler, 1999; Hermann, Spandler, Hack, & Korsakov, 2006;
500 Manning, 2004). Nevertheless, in remainder of the discussion the Na-Al-Si-bearing fluid is
501 distinguished from the fluid that forms the amphibolite due to a higher solute concentration.

502 **5.2. Deformation microstructures of rutile**

503 Low-angle boundaries are consistent with subgrain boundaries, some of which may
504 have formed via crystal-plastic mechanisms. To date, very few examples of natural

505 deformation microstructures in rutile have been reported in the literature (e.g. Plavsa et al.,
506 2018; Puelles et al., 2017). Nevertheless, experimental observations provide evidence for the
507 activation of two slip systems in rutile, the $\{101\}\langle-101\rangle$ system and the $\{110\}[001]$ system
508 (Ashbee & Smallman, 1963; Hirthe & Brittain, 1963). These earlier studies attribute the
509 activation of the different systems to the crystal orientation relative to the compressive axis
510 during deformation, independent of temperature. Following these initial investigations,
511 Blanchin, Bursill, and Lafage (1990) reported on the activation of the $\{101\}\langle-101\rangle$ and
512 $\{110\}[001]$ slip systems at temperatures above 600°C and 900°C, respectively. However, for
513 the investigated substructured rutile grains the rotation axis orientations of $[110]$ and $[100]$
514 (Figures 7f and i, respectively) combined with the subgrain boundary geometry indicate
515 activation of both the $\{101\}\langle-101\rangle$ and the $\{110\}[001]$ slip systems during deformation
516 (Figures 7f and i). The $[112]$ rotation axis observed on the shear band (Figures 7b and c) may
517 be a result of the activation of multiple slip systems, unresolvable with the current EBSD
518 data. It is unlikely that temperatures exceeded 900 °C during deformation, supporting the
519 observation of temperature independence of slip system activation, thus highlighting the need
520 for further research on rutile deformation-induced microstructures.

521 **5.3. Conditions of rutile precipitation, deformation and recrystallization**

522 The basic assumption made when applying the Zr-in-rutile thermometer is that
523 activities of Zr and Si are 1 during rutile crystallization and re-equilibration (Tomkins et al.,
524 2007; Watson et al., 2006; Zack et al., 2004). This condition is usually satisfied if it can be
525 demonstrated that rutile precipitated in the presence of zircon and quartz, in which case the
526 Zr-in-rutile temperature is representative of the rutile formation temperature. By contrast, the
527 lack of zircon and/or quartz during rutile formation is equivalent to reduced Zr- and Si-
528 activities, in which case the calculated temperature is either an overestimate ($a_{\text{Si}} < 1$) or
529 underestimate ($a_{\text{Zr}} < 1$). If the presence of zircon and quartz can be demonstrated, then the

530 variability of Zr concentration of rutile allows for evaluation of post-formation Zr
531 mobilization. In our samples rutile always occurs together with quartz and zircon is only
532 absent from the fracture halo assemblage (Figures 3, 4 and 5). Furthermore, rutile likely
533 crystallized in the presence of a Na-Al-Si-bearing fluid. Therefore, we infer that the high Zr-
534 in-rutile temperatures reflect the temperature conditions during rutile growth and that the
535 lower temperatures measured along deformation microstructures may be attributed to Zr
536 mobilization during subsequent cooling.

537 Zr-in-rutile temperature estimates obtained for the amphibolite and the fracture
538 alteration haloes are between $588 \pm 28^\circ\text{C}$ and $727 \pm 17^\circ\text{C}$ (Figures 9a and b) and the pressure
539 range of 10-14 kbar for the crystallization of tschermakite has been estimated by amphibole
540 barometry (Table S1). This PT range is consistent with estimates of $\sim 700^\circ\text{C}$ and 9-11 kbar
541 obtained through thermodynamic modelling of the amphibolite assemblages in this outcrop
542 (Moore, Beinlich, Austrheim, & Putnis, 2019). They are also consistent with estimates of
543 690°C and 10-12 kbar for petrographically similar amphibolites of the Bergen Arcs (see
544 Figure 1a for locality; Boundy et al., 1996) that are based on the garnet-amphibole
545 thermometer of Graham and Powell (1984), the hornblende-plagioclase thermometer of
546 Blundy and Holland (1990) and garnet-rutile-ilmenite-plagioclase-silica (GRIPS) barometry
547 (Bohlen & Liotta, 1986). The consistency with previously reported metamorphic conditions
548 corroborates our PT estimate for the granulite hydration and indicates that rutile from the
549 amphibolite is likely to be in equilibrium with its host assemblage.

550 In contrast, Zr-in-rutile temperature estimates for the leucocratic domains in the shear
551 zone are between $598 \pm 32^\circ\text{C}$ and $861 \pm 45^\circ\text{C}$ (Table S3; Figure 9f), which are higher than
552 most previously reported temperatures for the amphibolites of the Lindås Nappe. However,
553 similar values ($874 \pm 26^\circ\text{C}$) are reported by Piazzolo et al. (2012) using Ti-in-zircon
554 thermometry on undeformed inherited zircons hosted within veins cross-cutting an

555 anorthosite body in the Lindås Nappe. While the authors report the possibility of an
556 erroneously high temperature due to potential integration of undetected rutile micro-
557 inclusions during the zircon analysis, the similarity with our temperature estimate may also
558 represent evidence for a high temperature Si-rich fluid event in the Lindås Nappe.
559 Furthermore, temperature values obtained from deformed porphyroclastic zircon (~760 -
560 820°C; Piazzolo et al., 2012) are also similar to those obtained from low-angle boundaries of
561 large rutile (~620 – 820°C; Figure 9e), reflecting deformation near peak metasomatic
562 temperatures.

563 The closure temperature for volume diffusion of Zr-in-rutile with a grain radius of
564 200 μm is between 635 °C to 725 °C, for an initial temperature of 800°C and cooling rates of
565 1 and 10°C/Ma, respectively (Cherniak et al., 2007; Dodson, 1973; Ganguly & Tirone, 1999).
566 Hence, even at fast cooling rates, large rutiles should have been modified by volume
567 diffusion of Zr during cooling and temperatures up to ~860°C should not have been
568 preserved. The lack of Zr diffusion profiles in rutile, i.e. Zr-depleted rims in large rutile
569 (Figure 8c) thus indicates that volume diffusion does not mobilize Zr during cooling.
570 Therefore, we infer that the high temperature recorded reflects the thermal condition during
571 rutile crystallization. However, we observe systematically lower Zr concentrations at low-
572 angle boundaries compared to the undeformed parts of the same grains (Figure 8c). This
573 correlation may hint at enhanced geochemical exchange through fast-diffusion pathways in
574 areas of high dislocation density, as previously described for zircon (Timms, Reddy, Gerald,
575 Green, & Muhling, 2012), feldspar (Kramer & Seifert, 1991; Yund, Smith, & Tullis, 1981),
576 garnet (Büttner & Kasemann, 2007), and pyroxene (Chapman, Clarke, Piazzolo, Robbins, &
577 Trimby; Lund, Piazzolo, & Harley, 2006). Strain-enhanced diffusion occurs via
578 crystallographic ordering and disordering due to the increased atomic mobility around
579 dislocation cores (pipe diffusion). Both “static” and “dynamic” modals of strain-enhanced

580 diffusion have been proposed by previous workers. The dynamic model of strain-enhanced
581 diffusion may only occur during the creep of dislocations, elemental mobility being enabled
582 by dislocation climb or glide (Kramer & Seifert, 1991; Yund & Tullis, 1980). During creep,
583 dislocations organise into lower energy arrangements, i.e. low-angle boundaries, forming fast
584 diffusion pathways. This is the static model for strain-enhanced diffusion, where the grain
585 size is effectively decreased due to the introduction of fast diffusion pathways, lowering the
586 closure temperature and allowing increased interaction with infiltrating fluids (Büttner &
587 Kasemann, 2007; Plümper et al., 2012; Reddy, Timms, Pantleon, & Trimby, 2007; Timms et
588 al., 2011). While the models are not mutually exclusive, only the dynamic model of strain-
589 enhanced diffusion is in agreement with the sustained record of high temperatures (up to
590 $\sim 820^{\circ}\text{C}$) along low-angle boundaries, as these temperatures indicate that diffusion of Zr
591 along dislocation cores was not effective during post-deformational cooling but during active
592 deformation. These results indicate that while volume diffusion may not effectively
593 equilibrate Zr-in-rutile, the distortion of the crystal-lattice during deformation may enhance
594 the mobility of trace elements within the affected lattice.

595 Calculated temperatures from small rutile grains from the leucocratic domains ($\sim 610 -$
596 670°C) and rutile in the strained amphibolite ($\sim 560 - 660^{\circ}\text{C}$) are distinctly lower than those
597 of large rutile in the leucocratic domains (Figures 9c and d). These small grains, mostly
598 present within biotite porphyroblasts (Figures 4c and 5e) and around large porphyroblastic
599 rutile grains (Figure 5b), have a textural positioning that is consistent with late stage growth.
600 The low Zr-content and the textural positioning of small grains suggest that these are new
601 rutiles that precipitated at lower temperatures. Thus, the variability in Zr-in-rutile within the
602 amphibolite-facies shear zone is attributed to initial growth of rutile at high temperatures
603 followed by the remobilization of Zr along high diffusivity pathways during lattice distortion,
604 and finally, late stage growth of small rutiles at lower temperatures.

605 Growth twins exhibit trace element concentrations that are more similar to those
606 measured on low-angle boundaries (Figures 8 and 9e) than to substructure-free grains,
607 suggesting that twinning also enhances Zr mobility. Even though the idea of twin boundaries
608 acting as fast diffusion-pathways in rutile has been suggested previously (Zack & Kooijman,
609 2017), data with higher spatial resolution is still needed for further confirmation.

610 **5.4. Timing of rutile crystallization and deformation**

611 We consider the two age populations defined by SHRIMP U–Pb data (Figure 10f)
612 (437.4 ± 2.7 Ma, 409.1 ± 2.2 Ma) as statistically valid. While the statistical analysis of the U–
613 Pb data obtained from LA-ICP-MS and SHRIMP yielded consistent age populations, the
614 relationship between age and grain microstructure can only be resolved with confidence by
615 SHRIMP data due to its superior precision and spatial resolution (Figure 10). The
616 combination of EBSD and SHRIMP data shows an apparent positive correlation of age with
617 GOS, i.e. the apparently younger grains ($n = 2$) exhibit a larger orientation spread than the
618 “older” undeformed grain (Figure 10f). The relationship between grain microstructure and
619 LA-ICP-MS ages is consistent with the correlation found for the SHRIMP ages (Figure 10e;
620 Table S4).

621 The resetting of U–Pb ages due to diffusive transport of mainly Pb from the rutile into
622 the surrounding matrix is controlled by temperature and the diffusion length scale (Dodson,
623 1986). Consequently, closure temperatures are grain size dependent, while the cooling rate
624 determines the timescale for diffusion to occur above the closure temperature (Cherniak,
625 2000; Kooijman et al., 2010; Vry & Baker, 2006). In addition, enhanced diffusion of U and
626 Pb as has been demonstrated to occur at low-angle boundaries in zircon (Piazolo et al., 2016;
627 Timms et al., 2011) and enhanced elemental diffusion in other deformed silicates such as
628 pyroxene, feldspar and garnet (e.g. Chapman, Clarke, Piazolo, Robbins, & Trimby, 2019;
629 Lund et al., 2006; Yund et al., 1981). The continued post-deformational loss of Pb is in

630 agreement with a static strain-enhanced diffusion model rather than a dynamic one (as
631 described above for Zr). The presence of low-angle boundaries in rutile grains is expected to
632 reduce the diffusion length scale, thus enhancing U and Pb transport, equivalent to lowering
633 the closure temperatures for deformed grains versus undeformed grains of equal size. In such
634 a scenario low-angle boundaries enhance element mobility and enable continuous re-
635 equilibration during fluid-assisted deformation.

636 Indeed, U concentrations at low-angle boundaries and in growth twins (Figure 8a) are
637 too low for reliable age determination. This indicates a likely mobility of U associated with
638 the formation of low-angle boundaries subsequent to lattice distortion, suggesting that U
639 mobility was syn-deformational. Due to its smaller ionic radii, Pb should diffuse much faster
640 than U (Dowty, 1980; Fortier & Giletti, 1989), as a result Pb-loss should have continued after
641 crystal-plasticity of rutile became inactive, if the rocks remained at mid-crustal temperatures.
642 This does not however, reconcile the static diffusion of Pb versus the dynamic diffusion of U
643 and Zr, the contrasting modes of mobility insinuating that there must be a further
644 crystallographic influence on the diffusion of these elements, unresolvable with the data
645 presented here. Thus, deformation-induced open system behaviour of both U and Pb provides
646 an explanation for the bimodality of the measured rutile age data, the younger age reflecting
647 the eventual closure for Pb diffusion in substructured grains.

648 **5.5. Temperature-time-deformation path**

649 The field relationships, temperature conditions, fluid composition and the
650 geochronological data can be integrated to develop a comprehensive thermal and deformation
651 chronology for the amphibolites of the Lindås Nappe. The rutile microstructures and
652 corresponding U–Pb and Zr-in-rutile analyses are illustrated in Figure 11.

5.5.1. Stage 1 – Syn-tectonic fluid infiltration at lower to mid-crustal conditions

The location of type-I and –II fractures in the outcrop (Figure 2b) together with assemblages present within the fractures and the surrounding alteration haloes suggest that they either represent (1) a record of initial fluid infiltration along brittle fractures and were subsequently overprinted by hydration and deformation and/or (2) localized sites of brittle failure during hydration within the dry protolith. Both scenarios are consistent with syn-deformation fluid infiltration as has been suggested as the general mechanism for hydration of the Lindås Nappe (Austrheim, 1987; Jamtveit et al., 1990). Syn-tectonic fluid infiltration is further supported by the subparallel alignment of biotite, clinozoisite and rutile porphyroblasts in the leucocratic domains (Figures 5a, b, and e). Furthermore, the presence of similar mineral assemblages and the higher rutile abundance in the fracture haloes and the leucocratic domains suggest alteration of the granulite by a similar or even the same fluid. This relationship between the presence of the rutile-bearing assemblage and localization of fluid and deformation in the shear zone, producing the leucocratic domains, is summarised schematically in Figure 11a. Since the interlayering and consistent foliation of the amphibolite and the leucocratic domains (Figures 2a and 5a) indicate contemporaneous deformation of both lithologies, hydration is assumed to begin with the breakdown of the diopside in the granulite to form the amphibolite (Figure 11a). Where syn-deformational reaction continues at amphibolite-facies conditions, the rutile-bearing assemblage (tschermakite, clinozoisite, quartz and biotite) dominates.

Following rutile crystallization, large grains underwent crystal-plastic deformation in the presence of fluid (Figures 11a and b). Evidence of element transport associated with crystal-plastic deformation of rutile indicates that syn-tectonic fluid infiltration along fractures initiated the formation of the shear zone. Following initial fluid infiltration, the continuous syn-deformational re-equilibration of the rutile Zr concentrations is evidenced by

678 the spread of Zr-in-rutile temperatures between 620 to 820°C measured on rutile low-angle
679 boundaries in the leucocratic domains (Figures 9 and 11b).

680 Rutile lattice deformation concomitant with re-equilibration of U resulted in the
681 observed low concentrations at low angle boundaries (Figure 8a). Since the temperature
682 during deformation was significantly higher than the Pb diffusion closure temperature of
683 approximately 600°C (Cherniak, 2000; Vry & Baker, 2006), it is unlikely that U–Pb in both
684 substructured and substructure-free rutile reached closure until the end of deformation. The
685 437 ± 2.7 Ma age is therefore interpreted to reflect the minimum age of deformation,
686 recorded in large substructure-free rutile in the leucocratic domains (Figure 11b).

687 Ages of 455 ± 2 Ma and 439 ± 4 Ma recorded by Ar-Ar in amphibole (Boundy et al.,
688 1996) have previously been interpreted to be erroneous due to possible excess Ar in the
689 amphibole (Kühn et al., 2002; Roffeis et al., 2012). Alternatively, they may also reflect the
690 first stage of fluid infiltration as recorded by rutile in the leucocratic domains. A similar re-
691 interpretation of phengitic muscovite ages in Lindås Nappe eclogites (433 ± 1 to 429 ± 1 ;
692 Boundy et al., 1996) was suggested by Bingen et al. (2004), based on evidence for the
693 retention of radiogenic Ar in phengite in high-pressure environments at relatively high
694 temperatures ($> 500^\circ\text{C}$) (Di Vincenzo, Tonarini, Lombardo, Castelli, & Ottolini, 2006;
695 Giorgis, Cosca, & Li, 2000; Rodriguez, Cosca, Ibarguchi, & Dallmeyer, 2003).

696 However, the coeval formation of leucocratic domains and amphibolite does not
697 reconcile with the distinct temperature values recorded by rutile from the two lithologies. Zr-
698 in-rutile temperatures range from 640 to 860°C for large substructure-free grains in the
699 leucocratic domains and 610 to 730 °C for the amphibolite (Figures 9a, f). Since a 130 °C
700 temperature gradient over a distance of only 0.5 m appears inconsistent with a regional-scale
701 thermal state, further explanation is required to account for the high temperatures recorded in
702 the shear zone. Three explanations are considered: (1) Zr is undersaturated in the

703 amphibolite, resulting in an underestimation of the temperature by Zr-in-rutile thermometry
704 for the statically hydrated wall rock of the shear zone; (2) rutile temperatures from the shear
705 zone reflect infiltration of an externally derived high temperature fluid; (3) the high
706 temperatures recorded by rutile from the shear zone reflect rutile formation during shear
707 heating.

708 In the first explanation, temperature is controlled by the regional thermal state but
709 rutile in the static amphibolite formed in Zr-unsaturated conditions and was therefore unable
710 to reach the equilibrium concentration of Zr consistent with the temperature of formation
711 (Watson et al., 2006). In this scenario, localized flow of Si-Al-Na-bearing fluid within the
712 leucocratic domains facilitates transport of normally immobile elements through the
713 deforming rock volume, thus enhancing the availability of Zr within Si-Al-Na-bearing fluid
714 hosted zones. In contrast to option two, which requires an external fluid for heat input, in this
715 option a hydrous fluid with low thermal mass could infiltrate the rock and produce an
716 internally derived Si-Na-Al-bearing fluid along fractures pathways. The Si-Na-Al-bearing
717 fluid, being of higher viscosity than the hydrous fluid, would be restricted to these fracture
718 pathways, resulting in temperature and consequently textural and mineralogical differences
719 that are coupled to strain variations as observed between the amphibolite and leucocratic
720 domains and localized re-equilibration of trace element concentrations.

721 The second explanation is that the localized occurrence of high-temperature rutile is
722 due to the channelization of externally derived hot Na-Al-Si-bearing fluid along a
723 deformation-induced high permeability zone (e.g. Daczko, Piazzolo, Meek, Stuart, & Elliott,
724 2016). Modelling of heat transfer by fluids suggests that conduction or advection of heat
725 requires a large, channelized, continuous flux and/or repeated pulses of high temperature
726 fluid (Bickle & McKenzie, 1987; Brady, 1988; Hoisch, 1991; Thompson & Connolly, 1990).
727 Fluid channelization is consistent with the distribution of leucocratic domains, appearing as

728 highly localized zones of distinct composition in outcrop and thin section (Figures 2a and 4a).
729 Fluid channelization most effectively occurs under high strain, where the partitioning of
730 strain into discrete zones of deformation couples with fluid-flow (Mancktelow, 2006). To
731 account for the coupling between high strain and fluid flow the initial infiltration must have
732 been syn-tectonic, resulting in localized mechanical weakening and subsequent fluid
733 channelization along optimally orientated pathways. This link between deformation and syn-
734 tectonic fluid channelling has been recently shown to occur in the lower continental crust
735 (Daczko et al., 2016; Meek, Piazzolo, & Daczko, 2019; Stuart, Meek, Daczko, Piazzolo, &
736 Huang, 2018).

737 In the third option, increased temperature coupled with strain is accounted for by
738 shear heating. Shear heating occurs at relatively high shear stresses (>100 MPa) and strain
739 rates ($10^{-11} - 10^{-12} \text{ s}^{-1}$) (Molnar & England, 1990) and is the result of the conversion of
740 mechanical energy into heat during progressive deformation (Brun & Cobbold, 1980).
741 Temperature increases in shear zones as result of shear heating have been inferred to be in the
742 order of $100 - 200^\circ\text{C}$ above ambient conditions (Camacho, McDougall, Armstrong, & Braun,
743 2001; Whittington, Hofmeister, & Nabelek, 2009). The coincidence here between the
744 deformation zone and higher temperatures (up to $\sim 860^\circ\text{C}$; Figures 9 and 11b) is in agreement
745 with these previous estimates. At ambient crustal temperatures exceeding $\sim 600^\circ\text{C}$ heat
746 produced by shear heating may be retained due to thermal insulation (Whittington et al.,
747 2009). In fact, thermo-mechanical modelling indicates that during intermittent stress
748 relaxation the shear zone temperature remains elevated and progressively increases toward
749 the peak temperature with successive shear heating events (Kelemen & Hirth, 2007). This is
750 consistent with the range of Zr-in-rutile temperatures recorded in substructure-free areas of
751 deformed porphyroblastic rutile ($620-820^\circ\text{C}$; Figures 9e and 11b). In contrast to the second

752 explanation, Si-Al-Na-bearing fluid is produced internally by dissolution of the rock during
753 deformation.

754 Based on the data presented in this study none of the above explanations can be
755 excluded with certainty. However, the consistency of temperatures of 610 – 730°C recorded
756 by rutile in the statically hydrated amphibolite with previous estimates of regional peak-
757 metamorphic conditions (~690 °C) of the Bergen Arcs (Bhowany et al., 2018; Boundy et al.,
758 1996; Glodny et al., 2008) supports a scenario where rutile formed above ambient
759 temperature within the shear zone, requiring either shear heating or heat advection through an
760 externally derived fluid. Crystallization ages of 428±8 Ma and 422±17 Ma (Kühn et al.,
761 2002) and a U–Pb zircon age of 424±1 Ma (Jamtveit et al., 2018) for pegmatites within the
762 Lindås Nappe further support the transport of Na-Al-Si-bearing fluids at a time approximate
763 to the amphibolite-facies event. However, whether the emplaced pegmatites are derived
764 externally or from internal reactions remains ambiguous.

765 **5.5.2. Stage 2 – Exhumation to the upper-crust**

766 The 404.8 ± 4.5 Ma and 409.1±2.2 Ma LA-ICP-MS and SHRIMP rutile ages agree
767 with reported Rb-Sr ages of 413±4 Ma (Glodny et al., 2008) and 409±8 Ma (Bingen et al.,
768 2001). These ages are interpreted to record the cessation of diffusional re-equilibration of Pb
769 along low-angle boundaries during exhumation. According to estimated closure temperatures
770 for Pb-loss from rutile, the investigated rocks must have resided at temperatures in the range
771 of ~500-700°C (Cherniak, 2000; Kooijman et al., 2010; Vry & Baker, 2006). Any
772 temperature in excess of this range would have resulted in complete resetting of the
773 substructure-free grains, indicating Pb-loss at mid-crustal temperature conditions for a period
774 of *c.* 30 My following Stage 1 deformation. In addition, the *c.* 410-405 Ma age for
775 exhumation is additionally consistent with ⁴⁰Ar/³⁹Ar plateau ages of *c.* 410 Ma from Fossen
776 and Dunlap (1998), interpreted as the last stage of nappe stacking and cooling below ~500°C.

777 The eventual cessation of Pb-loss at *c.* 410-405 Ma therefore marks the exhumation to upper-
778 crustal conditions where thermally driven Pb loss is no longer operative.

779 **6. CONCLUSIONS/IMPLICATIONS**

780 Rutile from the Bergen Arcs amphibolite-facies shear zone records not only the cooling
781 history of the amphibolites but also the timing and temperature of deformation. Combined
782 microstructural and geochemical analyses of rutile allow a reconstruction of the multi-stage
783 history of the shear zone. While mid-crustal conditions ($\sim 610\text{--}730^\circ\text{C}$) are recorded in the
784 statically hydrated wall rock of the shear zone, syn-tectonically precipitated rutile in the
785 dynamically hydrated shear zone records a localized temperature increase to $\sim 860^\circ\text{C}$.
786 Whether this temperature increase was driven by externally derived high-temperature fluids
787 or by shear heating remains to be investigated. Progressive fluid-assisted deformation
788 resulted in the localized resetting of U–Pb ages and slightly lower Zr-in-rutile temperatures of
789 $\sim 820^\circ\text{C}$ along deformation structures in deformed grains from the shear zone. Finally,
790 crystal-plastic deformation subsides at conditions consistent with the statically hydrated rock
791 ($\sim 560\text{--}670^\circ\text{C}$) accompanied by the formation of small ($< 150\ \mu\text{m}$) rutile in the strained
792 lithologies. This is estimated to be concomitant with the cessation of U mobility along low-
793 angle boundaries at 437.4 ± 2.7 Ma. The final closure of Pb diffusion from rutile is recorded
794 at *c.* 410–405 Ma, indicating that the rocks remained at mid-crustal conditions ($\sim 500\text{--}700^\circ\text{C}$)
795 during the interim period.

796 Our findings indicate that U–Pb ages and trace element concentrations in rutile may
797 be strongly dependent on microstructure. In this particular instance both U–Pb and Zr-in-
798 rutile show systematic changes with crystal-lattice distortion. Young ages are consistently
799 correlated with significant crystal-plastic deformation and low-angle boundaries have lower
800 Zr concentrations than substructure-free domains in rutile. Low-angle boundaries are
801 therefore proposed to act as fast diffusion pathways in rutile, allowing for enhanced element

802 mobility. Therefore, in instances where the trace element distribution and U–Pb ratios are
803 controlled by fast diffusion due to deformation, rutile can be a useful tool for constraining a
804 near complete deformation and cooling history of the rock.

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816 **REFERENCES**

- 817 Antignano, A., & Manning, C. E. (2008). Rutile solubility in H₂O, H₂O–SiO₂, and H₂O–
818 NaAlSi₃O₈ fluids at 0.7–2.0 GPa and 700–1000 C: implications for mobility of
819 nominally insoluble elements. *Chemical Geology*, 255(1-2), 283-293.
- 820 Ashbee, K., & Smallman, R. E. (1963). The plastic deformation of titanium dioxide single
821 crystals. *Proc. R. Soc. Lond. A*, 274(1357), 195-205.
- 822 Austrheim, H. (1987). Eclogitization of lower crustal granulites by fluid migration through
823 shear zones. *Earth and Planetary Science Letters*, 81(2-3), 221-232.
- 824 Austrheim, H. (1990). *Fluid induced processes in the lower crust as evidenced by Caledonian*
825 *eclogitization of Precambrian granulites, Bergen Arcs, western-Norway*.
- 826 Austrheim, H., & Robins, B. (1981). Reactions involving hydration of orthopyroxene in
827 anorthosite-gabbro. *Lithos*, 14(4), 275-281.
- 828 [http://dx.doi.org/https://doi.org/10.1016/0024-4937\(81\)90055-4](http://dx.doi.org/https://doi.org/10.1016/0024-4937(81)90055-4)

- 829 Axelsson, E., Pape, J., Berndt, J., Corfu, F., Mezger, K., & Raith, M. M. (2018). Rutile
830 R632—A New Natural Reference Material for U-Pb and Zr Determination.
831 *Geostandards and Geoanalytical Research*, 42(3), 319-338.
- 832 Bestmann, M., & Prior, D. J. (2003). Intragranular dynamic recrystallization in naturally
833 deformed calcite marble: diffusion accommodated grain boundary sliding as a result
834 of subgrain rotation recrystallization. *Journal of Structural Geology*, 25(10), 1597-
835 1613.
- 836 Bhowany, K., Hand, M., Clark, C., Kelsey, D., Reddy, S., Pearce, M., . . . Morrissey, L.
837 (2018). Phase equilibria modelling constraints on P–T conditions during fluid
838 catalysed conversion of granulite to eclogite in the Bergen Arcs, Norway. *Journal of*
839 *Metamorphic Geology*, 36(3), 315-342.
- 840 Bickle, M., & McKenzie, D. (1987). The transport of heat and matter by fluids during
841 metamorphism. *Contributions to Mineralogy and Petrology*, 95(3), 384-392.
- 842 Bingen, B., Austrheim, H., Whitehouse, M. J., & Davis, W. J. (2004). Trace element
843 signature and U–Pb geochronology of eclogite-facies zircon, Bergen Arcs,
844 Caledonides of W Norway. *Contributions to Mineralogy and Petrology*, 147(6), 671-
845 683.
- 846 Bingen, B., Davis, W. J., & Austrheim, H. (2001). Zircon U-Pb geochronology in the Bergen
847 arc eclogites and their Proterozoic protoliths, and implications for the pre-Scandian
848 evolution of the Caledonides in western Norway. *Geological Society of America*
849 *Bulletin*, 113(5), 640-649.
- 850 Blanchin, M., Bursill, L., & Lafage, C. (1990). Deformation and microstructure of rutile.
851 *Proc. R. Soc. Lond. A*, 429(1876), 175-202.
- 852 Blundy, J. D., & Holland, T. J. (1990). Calcic amphibole equilibria and a new amphibole-
853 plagioclase geothermometer. *Contributions to mineralogy and petrology*, 104(2), 208-
854 224.
- 855 Bohlen, S. R., & Liotta, J. J. (1986). A barometer for garnet amphibolites and garnet
856 granulites. *Journal of Petrology*, 27(5), 1025-1034.
- 857 Boundy, T. M., Essene, E. J., Hall, C. M., Austrheim, H., & Halliday, A. (1996). Rapid
858 exhumation of lower crust during continent-continent collision and late extension:
859 Evidence from ⁴⁰Ar/³⁹Ar incremental heating of hornblendes and muscovites,

860 Caledonian orogen, western Norway. *Geological Society of America Bulletin*,
861 108(11), 1425-1437.

862 Boundy, T. M., Mezger, K., & Essene, E. J. (1997). Temporal and tectonic evolution of the
863 granulite-eclogite association from the Bergen Arcs, western Norway. *Lithos*, 39(3-4),
864 159-178.

865 Bracciali, L., Parrish, R. R., Horstwood, M. S., Condon, D. J., & Najman, Y. (2013). UPb
866 LA-(MC)-ICP-MS dating of rutile: New reference materials and applications to
867 sedimentary provenance. *Chemical Geology*, 347, 82-101.

868 Brady, J. B. (1988). The role of volatiles in the thermal history of metamorphic terranes.
869 *Journal of Petrology*, 29(6), 1187-1213.

870 Brun, J., & Cobbold, P. (1980). Strain heating and thermal softening in continental shear
871 zones: a review. *Journal of Structural Geology*, 2(1-2), 149-158.

872 Bureau, H., & Keppler, H. (1999). Complete miscibility between silicate melts and hydrous
873 fluids in the upper mantle: experimental evidence and geochemical implications.
874 *Earth and Planetary Science Letters*, 165(2), 187-196.

875 Büttner, S. H., & Kasemann, S. A. (2007). Deformation-controlled cation diffusion in
876 tourmaline: A microanalytical study on trace elements and boron isotopes. *American*
877 *Mineralogist*, 92(11-12), 1862-1874.

878 Camacho, A., McDougall, I., Armstrong, R., & Braun, J. (2001). Evidence for shear heating,
879 Musgrave Block, central Australia. *Journal of Structural Geology*, 23(6-7), 1007-
880 1013.

881 Centrella, S., Austrheim, H., & Putnis, A. (2015). Coupled mass transfer through a fluid
882 phase and volume preservation during the hydration of granulite: An example from
883 the Bergen Arcs, Norway. *Lithos*, 236, 245-255.

884 Chapman, T., Clarke, G. L., Piazzolo, S., Robbins, V. A., & Trimby, P. W. Grain-scale
885 dependency of metamorphic reaction on crystal plastic strain. *Journal of*
886 *Metamorphic Geology*, 0(ja) <http://dx.doi.org/doi:10.1111/jmg.12473>

887 Chapman, T., Clarke, G. L., Piazzolo, S., Robbins, V. A., & Trimby, P. W. (2019). Grain-scale
888 dependency of metamorphic reaction on crystal plastic strain. *Journal of*
889 *Metamorphic Geology*,

890 Cherniak, D. (2000). Pb diffusion in rutile. *Contributions to Mineralogy and Petrology*,
891 139(2), 198-207.

- 892 Cherniak, D., Manchester, J., & Watson, E. (2007). Zr and Hf diffusion in rutile. *Earth and*
893 *Planetary Science Letters*, 261(1-2), 267-279.
- 894 Clark, D., Hensen, B., & Kinny, P. (2000). Geochronological constraints for a two-stage
895 history of the Albany–Fraser Orogen, Western Australia. *Precambrian Research*,
896 102(3-4), 155-183.
- 897 Cohen, A., O'nions, R., Siegenthaler, R., & Griffin, W. (1988). Chronology of the pressure-
898 temperature history recorded by a granulite terrain. *Contributions to Mineralogy and*
899 *Petrology*, 98(3), 303-311.
- 900 Compston, W., Williams, I., & Meyer, C. (1984). U-Pb geochronology of zircons from lunar
901 breccia 73217 using a sensitive high mass-resolution ion microprobe. *Journal of*
902 *Geophysical Research: Solid Earth*, 89(S02), B525-B534.
- 903 Daczko, N. R., Piazzolo, S., Meek, U., Stuart, C. A., & Elliott, V. (2016). Hornblendite
904 delineates zones of mass transfer through the lower crust. *Scientific reports*, 6, 31369.
- 905 Di Vincenzo, G., Tonarini, S., Lombardo, B., Castelli, D., & Ottolini, L. (2006). Comparison
906 of ^{40}Ar – ^{39}Ar and Rb–Sr data on phengites from the UHP Brossasco–Isasca Unit
907 (Dora Maira Massif, Italy): implications for dating white mica. *Journal of Petrology*,
908 47(7), 1439-1465.
- 909 Dodson, M. (1986). *Closure profiles in cooling systems*. Paper presented at the Materials
910 Science Forum
- 911 Dodson, M. H. (1973). Closure temperature in cooling geochronological and petrological
912 systems. *Contributions to Mineralogy and Petrology*, 40(3), 259-274.
- 913 Dowty, E. (1980). Crystal-chemical factors affecting the mobility of ions in minerals.
914 *American Mineralogist*, 65(1-2), 174-182.
- 915 Ewing, T. A. (2011). Hf isotope analysis and U-Pb geochronology of rutile: technique
916 development and application to a lower crustal section (Ivrea-Verbano Zone, Italy).
- 917 Ewing, T. A., Hermann, J., & Rubatto, D. (2013). The robustness of the Zr-in-rutile and Ti-
918 in-zircon thermometers during high-temperature metamorphism (Ivrea-Verbano Zone,
919 northern Italy). *Contributions to Mineralogy and Petrology*, 165(4), 757-779.
920 <http://dx.doi.org/10.1007/s00410-012-0834-5>
- 921 Ewing, T. A., Rubatto, D., Beltrando, M., & Hermann, J. (2015). Constraints on the thermal
922 evolution of the Adriatic margin during Jurassic continental break-up: U–Pb dating of

- 923 rutile from the Ivrea–Verbano Zone, Italy. *Contributions to mineralogy and*
924 *petrology*, 169(4), 44.
- 925 Flowers, R., Bowring, S., Tulloch, A., & Klepeis, K. (2005). Tempo of burial and
926 exhumation within the deep roots of a magmatic arc, Fiordland, New Zealand.
927 *Geology*, 33(1), 17-20.
- 928 Fortier, S. M., & Giletti, B. J. (1989). An empirical model for predicting diffusion
929 coefficients in silicate minerals. *Science*, 245(4925), 1481-1484.
- 930 Fossen, H., & Dunlap, W. J. (1998). Timing and kinematics of Caledonian thrusting and
931 extensional collapse, southern Norway: evidence from $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology.
932 *Journal of Structural Geology*, 20(6), 765-781.
933 [http://dx.doi.org/https://doi.org/10.1016/S0191-8141\(98\)00007-8](http://dx.doi.org/https://doi.org/10.1016/S0191-8141(98)00007-8)
- 934 Galbraith, R. (1988). Graphical display of estimates having differing standard errors.
935 *Technometrics*, 30(3), 271-281.
- 936 Galbraith, R. F. (1990). The radial plot: graphical assessment of spread in ages. *International*
937 *Journal of Radiation Applications and Instrumentation. Part D. Nuclear Tracks and*
938 *Radiation Measurements*, 17(3), 207-214.
- 939 Ganguly, J., & Tirone, M. (1999). Diffusion closure temperature and age of a mineral with
940 arbitrary extent of diffusion: theoretical formulation and applications. *Earth and*
941 *Planetary Science Letters*, 170(1-2), 131-140.
- 942 Gao, J., John, T., Klemd, R., & Xiong, X. (2007). Mobilization of Ti–Nb–Ta during
943 subduction: evidence from rutile-bearing dehydration segregations and veins hosted in
944 eclogite, Tianshan, NW China. *Geochimica et Cosmochimica Acta*, 71(20), 4974-
945 4996.
- 946 Giorgis, D., Cosca, M., & Li, S. (2000). Distribution and significance of extraneous argon in
947 UHP eclogite (Sulu terrain, China): insight from in situ $^{40}\text{Ar}/^{39}\text{Ar}$ UV-laser ablation
948 analysis. *Earth and Planetary Science Letters*, 181(4), 605-615.
- 949 Glodny, J., Kühn, A., & Austrheim, H. (2002). Rb/Sr record of fluid-rock interaction in
950 eclogites, Bergen Arcs, Norway. *Geochimica et Cosmochimica Acta*, 66(15 A), A280-
951 A280.
- 952 Glodny, J., Kühn, A., & Austrheim, H. (2008). Geochronology of fluid-induced eclogite and
953 amphibolite facies metamorphic reactions in a subduction–collision system, Bergen
954 Arcs, Norway. *Contributions to Mineralogy and Petrology*, 156(1), 27-48.

- 955 Graham, C. M., & Powell, R. (1984). A garnet–hornblende geothermometer: calibration,
956 testing, and application to the Pelona Schist, Southern California. *Journal of*
957 *metamorphic Geology*, 2(1), 13-31.
- 958 Griffin, W. (2008). GLITTER: data reduction software for laser ablation ICP-MS. *Laser*
959 *Ablation ICP-MS in the Earth Sciences: Current practices and outstanding issues*,
960 308-311.
- 961 Harley, S. (2008). Refining the P–T records of UHT crustal metamorphism. *Journal of*
962 *metamorphic Geology*, 26(2), 125-154.
- 963 Hermann, J., Spandler, C., Hack, A., & Korsakov, A. V. (2006). Aqueous fluids and hydrous
964 melts in high-pressure and ultra-high pressure rocks: implications for element transfer
965 in subduction zones. *Lithos*, 92(3-4), 399-417.
- 966 Hirdes, W., & Davis, D. W. (2002). U–Pb zircon and rutile metamorphic ages of Dahomeyan
967 garnet-hornblende gneiss in southeastern Ghana, West Africa. *Journal of African*
968 *Earth Sciences*, 35(3), 445-449.
- 969 Hirthe, W. M., & Brittain, J. O. (1963). High-Temperature Steady-State Creep in Rutile.
970 *Journal Of The American Ceramic Society*, 46(9), 411-417.
- 971 Hoisch, T. D. (1991). The thermal effects of pervasive and channelized fluid flow in the deep
972 crust. *The Journal of Geology*, 99(1), 69-80.
- 973 Jamtveit, B., Bucher-Nurminen, K., & Austrheim, H. (1990). Fluid controlled eclogitization
974 of granulites in deep crustal shear zones, Bergen arcs, Western Norway. *Contributions*
975 *to Mineralogy and Petrology*, 104(2), 184-193.
- 976 Jamtveit, B., Moulas, E., Andersen, T. B., Austrheim, H., Corfu, F., Petley-Ragan, A., &
977 Schmalholz, S. M. (2018). High Pressure Metamorphism Caused by Fluid Induced
978 Weakening of Deep Continental Crust. *Scientific Reports*, 8(1), 17011.
979 <http://dx.doi.org/10.1038/s41598-018-35200-1>
- 980 Jochum, K. P., Nohl, U., Herwig, K., Lammel, E., Stoll, B., & Hofmann, A. W. (2005).
981 GeoReM: a new geochemical database for reference materials and isotopic standards.
982 *Geostandards and Geoanalytical Research*, 29(3), 333-338.
- 983 John, T., Klemd, R., Gao, J., & Garbe-Schönberg, C.-D. (2008). Trace-element mobilization
984 in slabs due to non steady-state fluid–rock interaction: constraints from an eclogite-
985 facies transport vein in blueschist (Tianshan, China). *Lithos*, 103(1-2), 1-24.

- 986 Johnson, M. C., & Rutherford, M. J. (1989). Experimental calibration of the aluminum-in-
987 hornblende geobarometer with application to Long Valley caldera (California)
988 volcanic rocks. *Geology*, 17(9), 837-841.
- 989 Kelemen, P. B., & Hirth, G. (2007). A periodic shear-heating mechanism for intermediate-
990 depth earthquakes in the mantle. *Nature*, 446(7137), 787.
- 991 Klemme, S., Prowatke, S., Münker, C., Magee, C. W., Lahaye, Y., Zack, T., . . . Kaeser, B.
992 (2008). Synthesis and preliminary characterisation of new silicate, phosphate and
993 titanite reference glasses. *Geostandards and Geoanalytical Research*, 32(1), 39-54.
- 994 Kooijman, E., Berndt, J., & Mezger, K. (2012). U-Pb dating of zircon by laser ablation ICP-
995 MS: recent improvements and new insights. *European Journal of Mineralogy*, 24(1),
996 5-21.
- 997 Kooijman, E., Mezger, K., & Berndt, J. (2010). Constraints on the U-Pb systematics of
998 metamorphic rutile from in situ LA-ICP-MS analysis. *Earth and Planetary Science
999 Letters*, 293(3-4), 321-330.
- 1000 Kooijman, E., Smit, M., Mezger, K., & Berndt, J. (2012). Trace element systematics in
1001 granulite facies rutile: implications for Zr geothermometry and provenance studies.
1002 *Journal of Metamorphic Geology*, 30(4), 397-412.
- 1003 Kramer, M. J., & Seifert, K. E. (1991). Strain enhanced diffusion in feldspars *Diffusion,
1004 atomic ordering, and mass transport* (pp. 286-303): Springer.
- 1005 Kühn, A., Glodny, J., Austrheim, H., & Råheim, A. (2002). The Caledonian tectono-
1006 metamorphic evolution of the Lindås Nappe: Constraints from U-Pb, Sm-Nd and Rb-
1007 Sr ages of granitoid dykes. *Norwegian Journal of Geology/Norsk Geologisk Forening*,
1008 82(1)
- 1009 Kylander-Clark, A., Hacker, B., & Mattinson, J. (2008). Slow exhumation of UHP terranes:
1010 titanite and rutile ages of the Western Gneiss Region, Norway. *Earth and Planetary
1011 Science Letters*, 272(3-4), 531-540.
- 1012 Lund, M. D., Piazzolo, S., & Harley, S. L. (2006). Ultrahigh temperature deformation
1013 microstructures in felsic granulites of the Napier Complex, Antarctica.
1014 *Tectonophysics*, 427(1-4), 133-151.
- 1015 Luvizotto, G., & Zack, T. (2009). Nb and Zr behavior in rutile during high-grade
1016 metamorphism and retrogression: an example from the Ivrea-Verbano Zone.
1017 *Chemical Geology*, 261(3-4), 303-317.

- 1018 Luvizotto, G., Zack, T., Meyer, H., Ludwig, T., Triebold, S., Kronz, A., . . . Klemme, S.
1019 (2009). Rutile crystals as potential trace element and isotope mineral standards for
1020 microanalysis. *Chemical Geology*, 261(3-4), 346-369.
- 1021 Mancktelow, N. S. (2006). How ductile are ductile shear zones? *Geology*, 34(5), 345-348.
- 1022 Manning, C. E. (2004). The chemistry of subduction-zone fluids. *Earth and Planetary
1023 Science Letters*, 223(1-2), 1-16.
- 1024 Meek, U., Piazzolo, S., & Daczko, N. R. (2019). The field and microstructural signatures of
1025 deformation-assisted melt transfer: Insights from magmatic arc lower crust, New
1026 Zealand. *Journal of Metamorphic Geology*,
- 1027 Meyer, M., John, T., Brandt, S., & Klemd, R. (2011). Trace element composition of rutile
1028 and the application of Zr-in-rutile thermometry to UHT metamorphism (Epupa
1029 Complex, NW Namibia). *Lithos*, 126(3-4), 388-401.
- 1030 Mezger, K., Hanson, G., & Bohlen, S. (1989). High-precision UPb ages of metamorphic
1031 rutile: application to the cooling history of high-grade terranes. *Earth and Planetary
1032 Science Letters*, 96(1-2), 106-118.
- 1033 Mitchell, R. J., & Harley, S. L. (2017). Zr-in-rutile resetting in aluminosilicate bearing ultra-
1034 high temperature granulites: Refining the record of cooling and hydration in the
1035 Napier Complex, Antarctica. *Lithos*, 272, 128-146.
- 1036 Molnar, P., & England, P. (1990). Temperatures, heat flux, and frictional stress near major
1037 thrust faults. *Journal of Geophysical Research: Solid Earth*, 95(B4), 4833-4856.
- 1038 Moore, J., Beinlich, A., Austrheim, H., & Putnis, A. (2019). Stress orientation-dependent
1039 reactions during metamorphism. *Geology*,
- 1040 Pape, J., Mezger, K., & Robyr, M. (2016). A systematic evaluation of the Zr-in-rutile
1041 thermometer in ultra-high temperature (UHT) rocks. *Contributions to mineralogy and
1042 petrology*, 171(5), 44.
- 1043 Piazzolo, S., Austrheim, H., & Whitehouse, M. (2012). Brittle-ductile microfabrics in naturally
1044 deformed zircon: Deformation mechanisms and consequences for U-Pb dating.
1045 *American Mineralogist*, 97(10), 1544-1563.
- 1046 Piazzolo, S., Bestmann, M., Prior, D., & Spiers, C. (2006). Temperature dependent grain
1047 boundary migration in deformed-then-annealed material: observations from
1048 experimentally deformed synthetic rocksalt. *Tectonophysics*, 427(1), 55-71.

- 1049 Piazzolo, S., La Fontaine, A., Trimby, P., Harley, S., Yang, L., Armstrong, R., & Cairney, J.
1050 M. (2016). Deformation-induced trace element redistribution in zircon revealed using
1051 atom probe tomography. *Nature communications*, 7, 10490.
- 1052 Plavsa, D., Reddy, S. M., Agangi, A., Clark, C., Kylander-Clark, A., & Tiddy, C. J. (2018).
1053 Microstructural, trace element and geochronological characterization of TiO₂
1054 polymorphs and implications for mineral exploration. *Chemical Geology*, 476, 130-
1055 149.
- 1056 Plümper, O., King, H. E., Vollmer, C., Ramasse, Q., Jung, H., & Austrheim, H. (2012). The
1057 legacy of crystal-plastic deformation in olivine: high-diffusivity pathways during
1058 serpentinization. *Contributions to Mineralogy and Petrology*, 163(4), 701-724.
- 1059 Prior, D. J., Wheeler, J., Peruzzo, L., Spiess, R., & Storey, C. (2002). Some garnet
1060 microstructures: an illustration of the potential of orientation maps and misorientation
1061 analysis in microstructural studies. *Journal of Structural Geology*, 24(6), 999-1011.
- 1062 Puelles, P., Beranoaguirre, A., Ábalos, B., Gil Ibarguchi, J., García de Madinabeitia, S.,
1063 Rodríguez, J., & Fernández-Armas, S. (2017). Eclogite inclusions from subducted
1064 metaigneous continental crust (Malpica-Tui Allochthonous Complex, NW Spain):
1065 Petrofabric, geochronology, and calculated seismic properties. *Tectonics*, 36(7), 1376-
1066 1406.
- 1067 Rapp, J., Klemme, S., Butler, I., & Harley, S. (2010). Extremely high solubility of rutile in
1068 chloride and fluoride-bearing metamorphic fluids: An experimental investigation.
1069 *Geology*, 38(4), 323-326.
- 1070 Reddy, S. M., Timms, N. E., Pantleon, W., & Trimby, P. (2007). Quantitative
1071 characterization of plastic deformation of zircon and geological implications.
1072 *Contributions to Mineralogy and Petrology*, 153(6), 625-645.
- 1073 Rodríguez, J., Cosca, M., Ibarguchi, J. G., & Dallmeyer, R. (2003). Strain partitioning and
1074 preservation of ⁴⁰Ar/³⁹Ar ages during Variscan exhumation of a subducted crust
1075 (Malpica–Tui complex, NW Spain). *Lithos*, 70(3-4), 111-139.
- 1076 Roffeis, C., Corfu, F., & Austrheim, H. (2012). Evidence for a Caledonian amphibolite to
1077 eclogite facies pressure gradient in the Middle Allochthon Lindås Nappe, SW-
1078 Norway. *Contributions to Mineralogy and Petrology*, 164(1), 81-99.
- 1079 Schmidt, M. (1991). *Experimental calibration of the Al-in-hornblende geobarometer at 650*
1080 *C, 3.5-13.0 kbar*. Paper presented at the Terra abstr

- 1081 Stacey, J. t., & Kramers, J. (1975). Approximation of terrestrial lead isotope evolution by a
1082 two-stage model. *Earth and planetary science letters*, 26(2), 207-221.
- 1083 Stuart, C., Meek, U., Daczko, N., Piazzolo, S., & Huang, J.-X. (2018). chemical signatures of
1084 melt–rock interaction in the root of a magmatic arc. *Journal of Petrology*, 59(2), 321-
1085 340.
- 1086 Thompson, A. B., & Connolly, J. (1990). Metamorphic fluids and anomalous porosities in the
1087 lower crust. *Tectonophysics*, 182(1-2), 47-55.
- 1088 Timms, N. E., Kinny, P. D., Reddy, S. M., Evans, K., Clark, C., & Healy, D. (2011).
1089 Relationship among titanium, rare earth elements, U–Pb ages and deformation
1090 microstructures in zircon: Implications for Ti-in-zircon thermometry. *Chemical
1091 Geology*, 280(1-2), 33-46.
- 1092 Timms, N. E., Reddy, S. M., Gerald, J. D. F., Green, L., & Muhling, J. R. (2012). Inclusion-
1093 localised crystal-plasticity, dynamic porosity, and fast-diffusion pathway generation
1094 in zircon. *Journal of Structural Geology*, 35, 78-89.
- 1095 Tomkins, H., Powell, R., & Ellis, D. (2007). The pressure dependence of the zirconium-in-
1096 rutile thermometer. *Journal of metamorphic Geology*, 25(6), 703-713.
- 1097 Vermeesch, P. (2018). IsoplotR: A free and open toolbox for geochronology. *Geoscience
1098 Frontiers*,
- 1099 Vry, J. K., & Baker, J. A. (2006). LA-MC-ICPMS Pb–Pb dating of rutile from slowly cooled
1100 granulites: confirmation of the high closure temperature for Pb diffusion in rutile.
1101 *Geochimica et Cosmochimica Acta*, 70(7), 1807-1820.
- 1102 Watson, E., Wark, D., & Thomas, J. (2006). Crystallization thermometers for zircon and
1103 rutile. *Contributions to Mineralogy and Petrology*, 151(4), 413.
- 1104 Whitney, D. L., & Evans, B. W. (2010). Abbreviations for names of rock-forming minerals.
1105 *American mineralogist*, 95(1), 185.
- 1106 Whittington, A. G., Hofmeister, A. M., & Nabelek, P. I. (2009). Temperature-dependent
1107 thermal diffusivity of the Earth’s crust and implications for magmatism. *Nature*, 458,
1108 319. <http://dx.doi.org/10.1038/nature07818>
- 1109 Williams, I. S. (1998). U-Th-Pb geochronology by ion microprobe. *Reviews in Economic
1110 Geology*, 7, 1-35.
- 1111 Yund, R., Smith, B., & Tullis, J. (1981). Dislocation-assisted diffusion of oxygen in albite.
1112 *Physics and Chemistry of Minerals*, 7(4), 185-189.

- 1113 Yund, R. A., & Tullis, J. (1980). The effect of water, pressure, and strain on Al/Si order-
1114 disorder kinetics in feldspar. *Contributions to Mineralogy and Petrology*, 72(3), 297-
1115 302.
- 1116 Zack, T., & Kooijman, E. (2017). Petrology and geochronology of rutile. *Reviews in*
1117 *Mineralogy and Geochemistry*, 83(1), 443-467.
- 1118 Zack, T., Moraes, R., & Kronz, A. (2004). Temperature dependence of Zr in rutile: empirical
1119 calibration of a rutile thermometer. *Contributions to Mineralogy and Petrology*,
1120 148(4), 471-488.
- 1121 Zack, T., Stockli, D. F., Luvizotto, G. L., Barth, M. G., Belousova, E., Wolfe, M. R., &
1122 Hinton, R. W. (2011). In situ U–Pb rutile dating by LA-ICP-MS: 208 Pb correction
1123 and prospects for geological applications. *Contributions to Mineralogy and Petrology*,
1124 162(3), 515-530.
- 1125 Zeh, A., Cabral, A. R., Koglin, N., & Decker, M. (2018). Rutile alteration and authigenic
1126 growth in metasandstones of the Moeda Formation, Minas Gerais, Brazil—A result of
1127 Transamazonian fluid–rock interaction. *Chemical Geology*, 483, 397-409.

1128 **LIST OF SUPPORTING INFORMATION**

1129 Supporting information is in the form of data tables and can be found in the document

1130 Supdataset.xlsx. The data tables provided are as follows:

- 1131 - Figure S1 – c-axis orientation of large rutile
- 1132 - Table S1 – Representative amphibole
- 1133 - Table S2 – LA-ICP-MS trace element
- 1134 - Table S3 – EMPA Major and trace element
- 1135 - Table S4a – LA-ICP-MS U-Pb
- 1136 - Table S4b – SHRIMP U-Pb

1137 **FIGURE CAPTIONS**

1138 **FIGURE 1** – (a) Regional setting of study area at Radøy in the Lindås Nappe of the Bergen

1139 Arcs, Western Norway. The outcrop locality is indicated by the white star. The locality of

1140 amphibolite-facies samples collected for age data and P-T estimates by previous workers are
1141 annotated on the map with symbols corresponding to those used in (b) and numbered
1142 according to the references listed below. MCTZ = Main Caledonian Thrust Zone. BASZ =
1143 Bergen Arcs Shear Zone. Modified from Boundy, Mezger, and Essene (1997), Glodny et al.
1144 (2008) and Centrella, Austrheim, and Putnis (2015). (b) Summary of previous
1145 geochronological work for Caledonian age events affecting the Lindås Nappe. Amphibolite
1146 zircon U–Pb data are from ¹Kühn et al. (2002), ²Roffeis et al. (2012), ³Piazolo et al. (2012),
1147 and ⁴Glodny et al. (2008). Multi-mineral Rb-Sr and Sm-Nd data for amphibolites are from
1148 ⁵Glodny, Kühn, and Austrheim (2002), ⁴Glodny et al. (2008) and ⁸Austrheim (1990).
1149 Amphibole and white mica Ar-Ar data are from ⁶Boundy et al. (1996), biotite Ar-Ar data are
1150 from ⁷Fossen and Dunlap (1998). Rb-Sr and Sm-Nd Pegmatite ages were determined by
1151 ¹Kühn et al. (2002) and the U–Pb zircon age is from ⁹Jamtveit et al. (2018). Eclogite U–Pb
1152 data are from the following sources: U–Pb zircon (Bingen et al., 2004; Bingen et al., 2001;
1153 Glodny et al., 2008), titanite-epidote-zircon U–Pb (Boundy et al., 1997). Error bars represent
1154 2σ uncertainty.

1155 **FIGURE 2** – Lithological relationships in outcrop. (a) The porphyroblastic rutile-bearing
1156 lithology, the leucocratic domains, are observed interlayered with the amphibolite in the shear
1157 zone. (b) Fracture type-I and type-II in the granulite in outcrop. Sample locations are
1158 indicated by red boxes, annotated with image figure numbers.

1159 **FIGURE 3** – Photomicrographs of the main lithologies (a) granulite (b) amphibolite, here
1160 incompletely reacted, (c) strained amphibolite and (d) the shear zone rock comprised of the
1161 amphibolite interlayered with leucocratic domains. Scale bar is 5 mm.

1162 **FIGURE 4** – Rutile occurrence in amphibolite and in association with fracture haloes in the
1163 granulite. (a) Fracture type-I, hosting quartz and tschermakite, crosscutting horizontal
1164 foliation in partially replaced granulite. BSE images (b-f) showing (b) rutile needles in

1165 amphibole clusters in the amphibolite (c) rutile associated with both amphibole clusters and
1166 biotite and clinozoisite in the strained amphibolite (d) rutile in amphibole clusters in
1167 alteration halo of fracture type-I, and, (e) rutile forming in a symplectitic assemblage of
1168 magnesio-hornblende quartz and zoisite replacing diopside on the edge of the fracture type-I
1169 alteration halo. (f) Rutile in a clinozoisite and pargasite filled fracture in diopside, occurring
1170 in the alteration halo of fracture type-II.

1171 **FIGURE 5** - Rutile distribution in leucocratic domains, interlayered with strained
1172 amphibolite in the shear zone. (a) Photograph of sample showing the location of
1173 microtextural analyses. Note the bottom to top increase in the proportion of the leucocratic
1174 component. BSE images (b-f) illustrate the mineralogical changes with increased leucocratic
1175 component. (f) Original amphibole clusters display a lower abundance of rutile and biotite
1176 then (d) amphibole clusters interlayered with the leucocratic component. Porphyroblastic
1177 rutiles are apparent in both (b) the mafic (c) and plagioclase dominated components of the
1178 leucocratic vein. Within leucocratic domains porphyroblastic clinozoisite and biotite form in
1179 (b) foliation parallel mafic clusters and in (e) foliation parallel bands. All images are aligned
1180 with the S foliation parallel to that shown in (a).

1181 **FIGURE 6** – Microstructures of substructure-free rutile associated with leucocratic domains;
1182 rutiles are characterized by low GOS ($< 1^\circ$) and lack of subgrain boundaries; (a-d) EBSD
1183 phase maps with grain, subgrain and twin boundaries in rutile show (a, c) grain morphology
1184 and phase associations of large substructure- free grains in both the plagioclase dominated
1185 leucocratic domain and, (b) in the preserved amphibole banding, as well as, (d) small
1186 substructure-free grains in the extensional veinlets. GOS: Grain orientation spread ($^\circ$). Grain
1187 numbering applies to grains with reported U–Pb data (see Table S4).

1188 **FIGURE 7** – Microstructures of large substructured rutile grains in the leucocratic domains.
1189 For visualisation of substructures, representative large substructured grains are presented as

1190 EBSD maps showing the deviation of each pixel from the mean orientation of the grain (a, e
1191 & h). Presented here are grains showing (a) shear bands, (e) lamellar subgrain boundaries and
1192 (h) low-angle boundaries related to twinning at grain edges. Lower hemisphere equal area
1193 plots (b, f, & i) exhibit disorientation axes relative to the crystallographic directions. (b)
1194 disorientation axes for the entire grain shown in (a); (f and i) disorientation axes for selected
1195 areas in (e) and (h) that are outlined by stippled boxes. For (a) the shear band the (b)
1196 disorientation axes cluster on the $\langle 112 \rangle$ axis but show no correlation with known slip
1197 systems while for (f) disorientation axes plot at $\langle 110 \rangle$, consistent with operation of the
1198 $\langle 001 \rangle \{110\}$ slip system and (i) and at $\langle 100 \rangle$ consistent with the $\{101\} \langle -101 \rangle$ slip system.
1199 Plotted grain orientation axes (c), coloured according to the misorientation in the EBSD map,
1200 further exhibit that the principal rotation axis for the sheared grain is $\sim \langle 112 \rangle$. Cumulative
1201 misorientation profile (d, g) showing the misorientation across the subgrain boundaries
1202 associated with the shear band (d) and the lamellar subgrain boundaries (g). GOS: Grain
1203 orientation spread ($^\circ$). Grain numbering applies to grains with reported U–Pb data (see Table
1204 S4).

1205 **FIGURE 8** – LA-ICP-MS trace element spot analyses plotted by distance from grain
1206 boundary. Individual analyses are coloured to represent the grain structure of the analysis
1207 spot. Shaded grey areas indicate the spread of the data from low-angle boundaries (LAB)
1208 (darker) and substructure free grains (lighter). The weighted average concentration for trace
1209 elements measured from substructure free spots within $80 \mu\text{m}$ of the grain boundary in large
1210 grains (grey stippled line) is compared to the weighted average value of spots containing low-
1211 angle boundaries (cyan stippled lines). Dotted lines represent the mean 2σ uncertainty.

1212 **FIGURE 9** - Frequency histograms displaying Zr-in-rutile temperature estimates for
1213 individual EMP and LA-ICP-MS analyses in all lithologies (a-f).

1214 **FIGURE 10** - U–Pb data for porphyroblastic rutile in leucocratic domains obtained via LA-
1215 ICP-MS (a, c, and e) and SHRIMP (b, d, and f) analysis. (a, b) U–Pb concordia diagrams,
1216 ellipses representing the 2-sigma uncertainty. (c, d) Weighted mean age of individual
1217 analyses. (e, f) Radial plot exhibiting dispersion of U–Pb ages, coloured according to GOS;
1218 for graphical method see Galbraith (1988); Galbraith (1990). The grey coloured analyses in
1219 (f) represent a grain with no corresponding EBSD data. In weighted mean and radial plots
1220 data are restricted to analyses within 5% discordance, eliminating 4 of the LA-ICP-MS
1221 analyses.

1222 **FIGURE 11** - Characteristic textural setting of rutile in each lithology, showing correlation
1223 between rutile growth, recorded temperature and strain. (a) Schematic illustration of (i) the
1224 microstructure of rutile in the amphibolite where it forms as part of a symplectitic assemblage
1225 replacing diopside, (ii) rutile in strained and shear zone amphibolite where it occurs with
1226 biotite and quartz in amphibole and (iii) large and small rutile replacing amphibole in the
1227 leucocratic domains of the shear zone due to increasing deformation and reaction. (b)
1228 Schematic of deformation microstructures in large rutile in the leucocratic domains and box
1229 plots showing the corresponding spread in Zr-in-rutile temperatures for microstructures and
1230 small grains.

1231

Figure 1

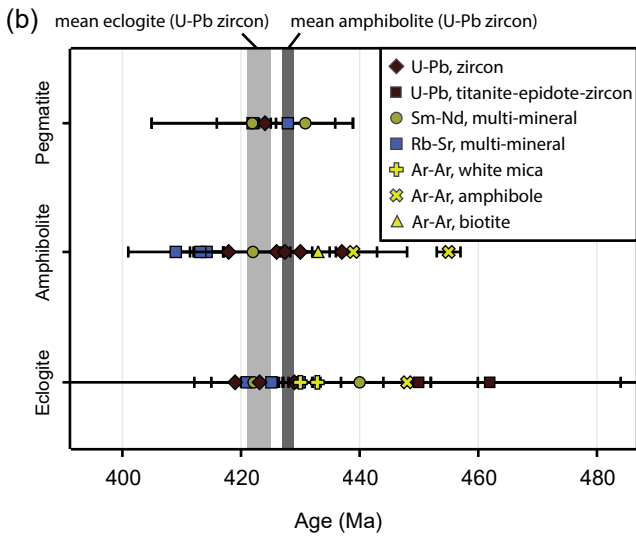
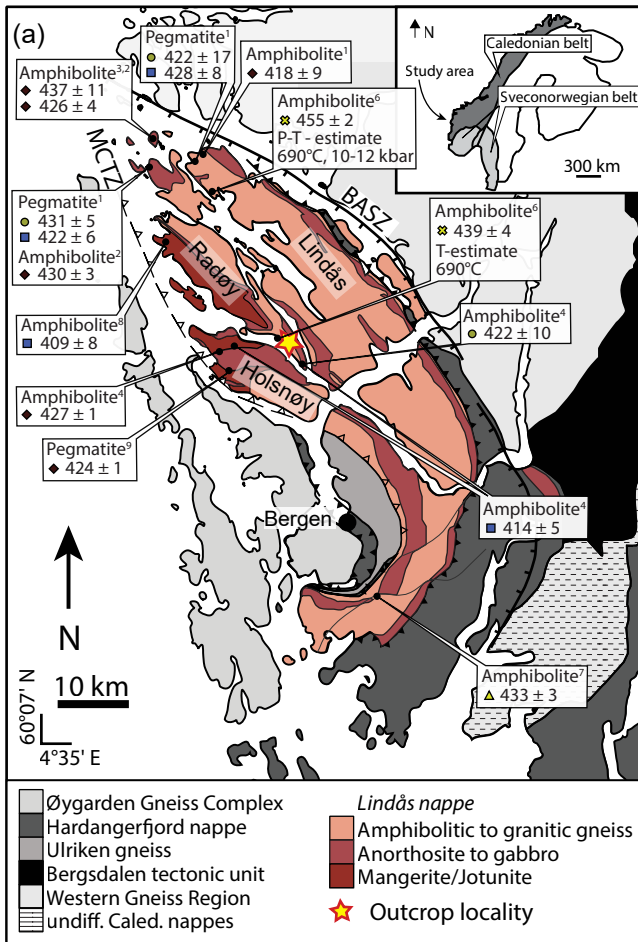


Figure 2

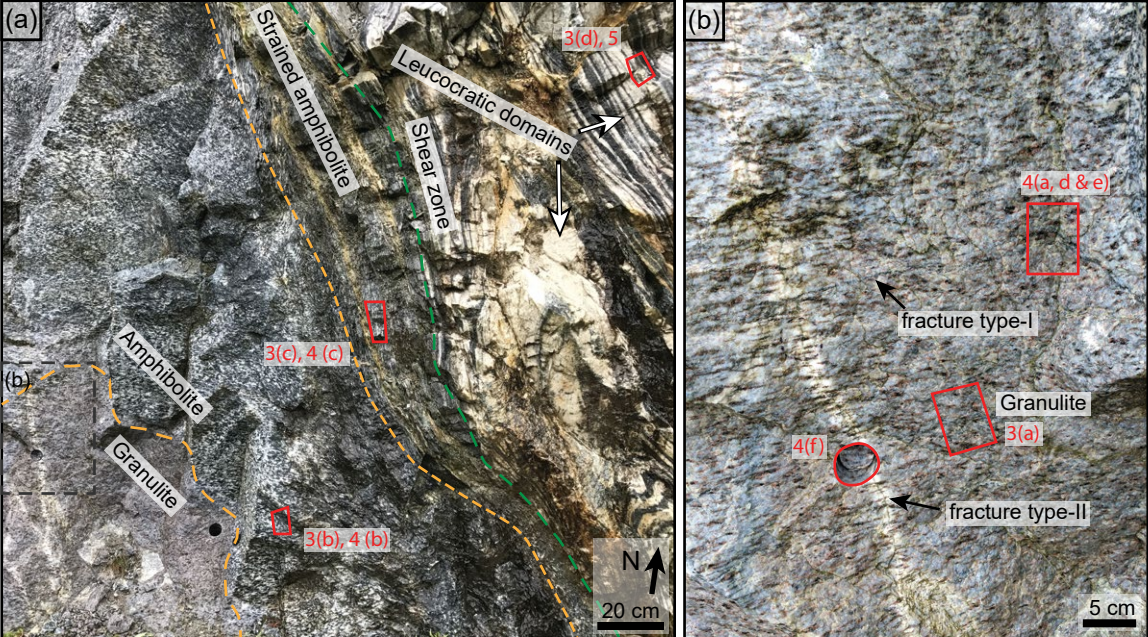


Figure 3

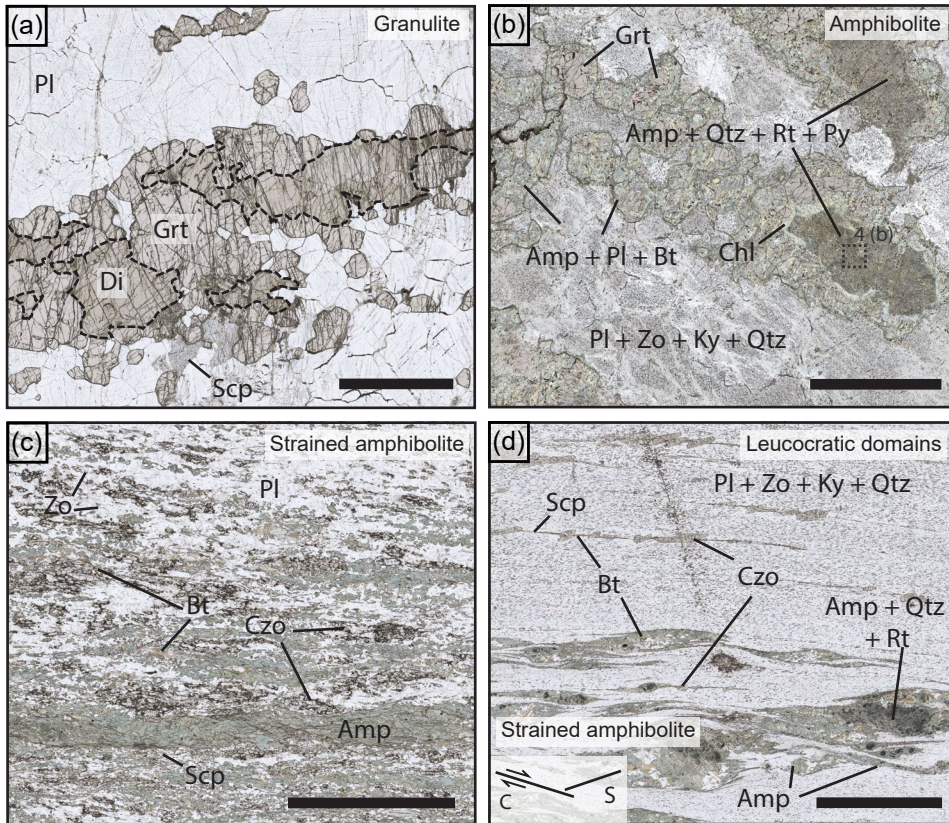


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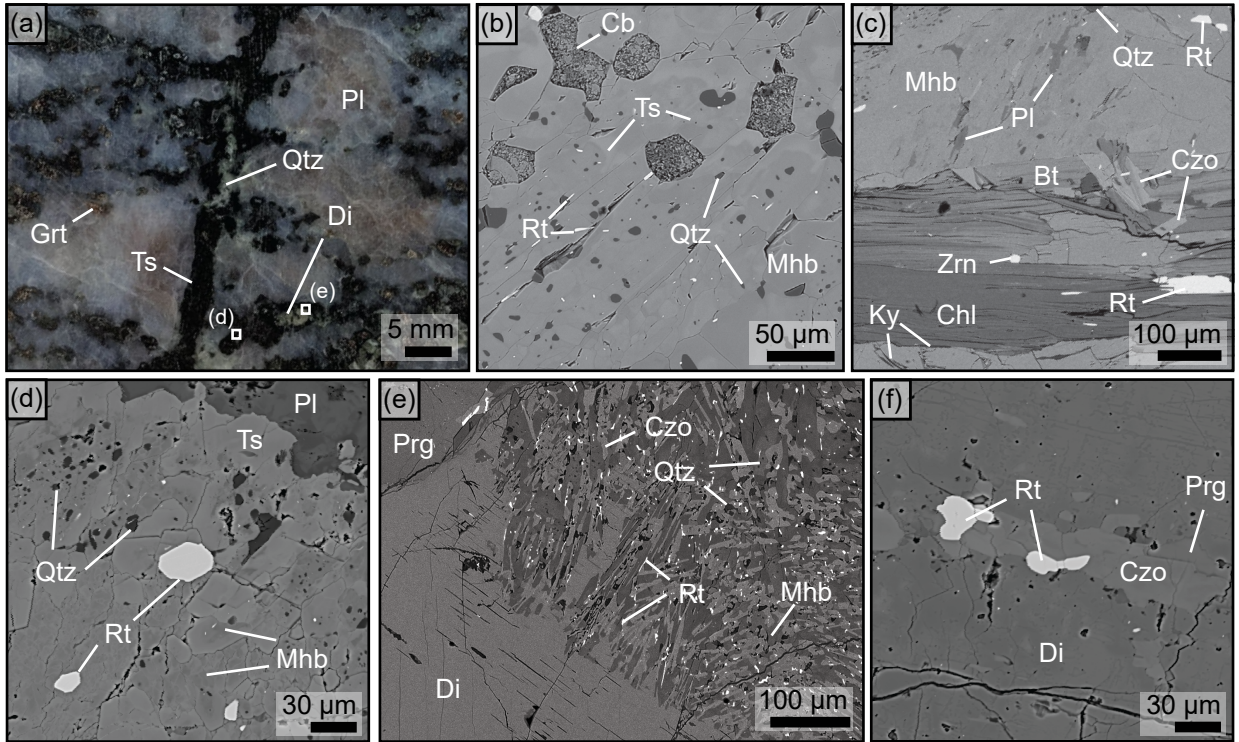


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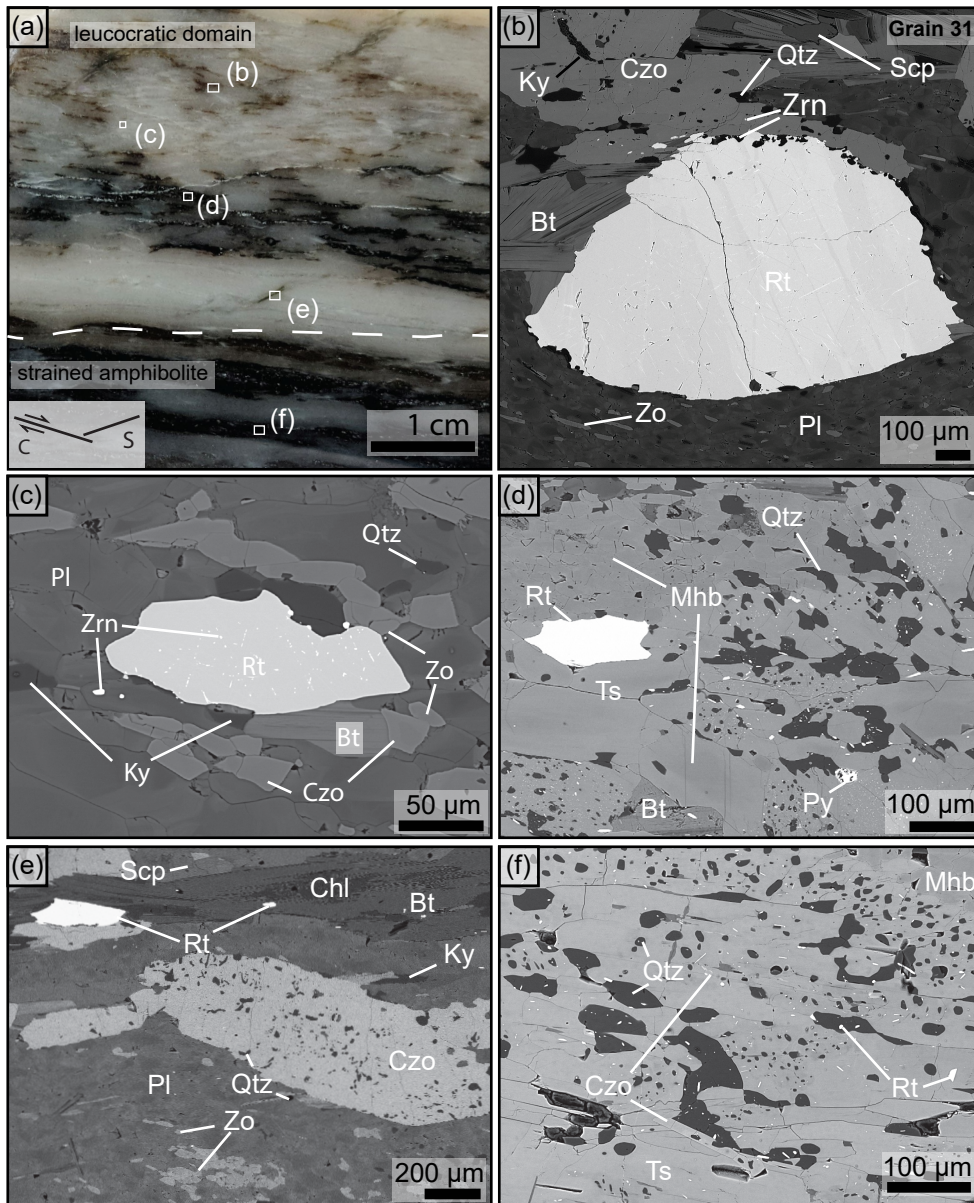


Figure 6

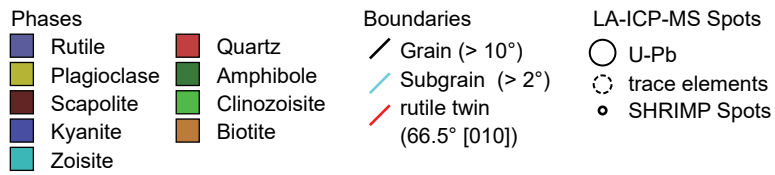
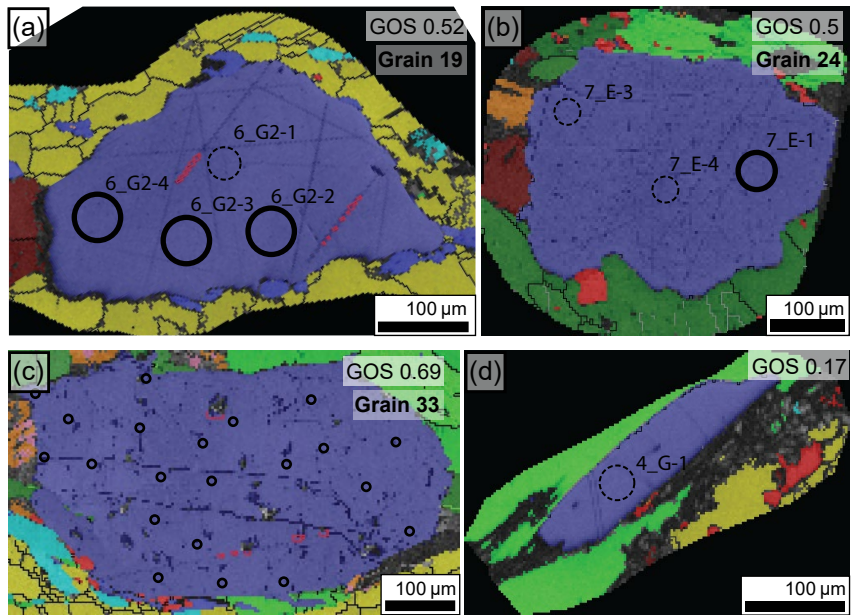


Figure 7

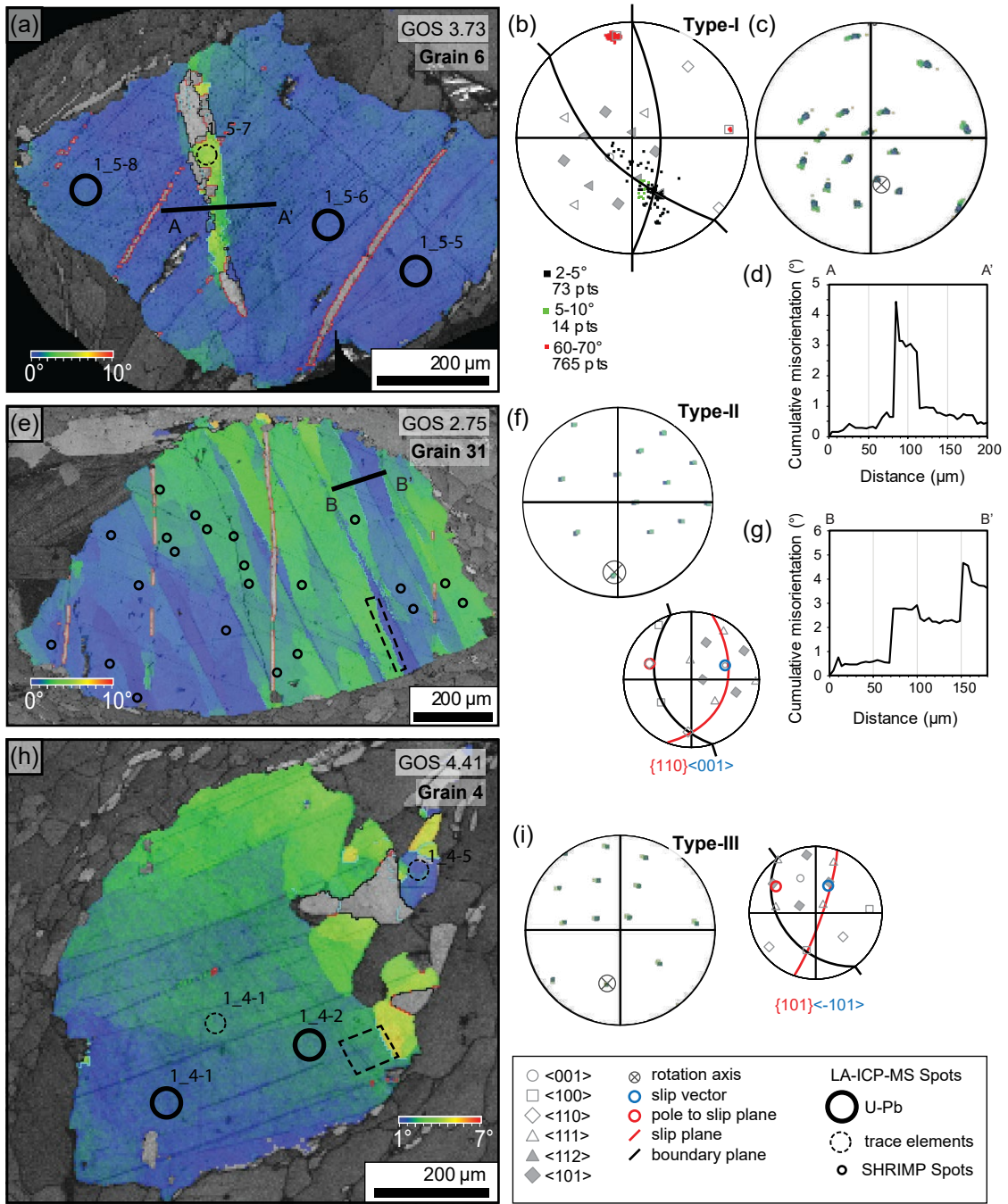
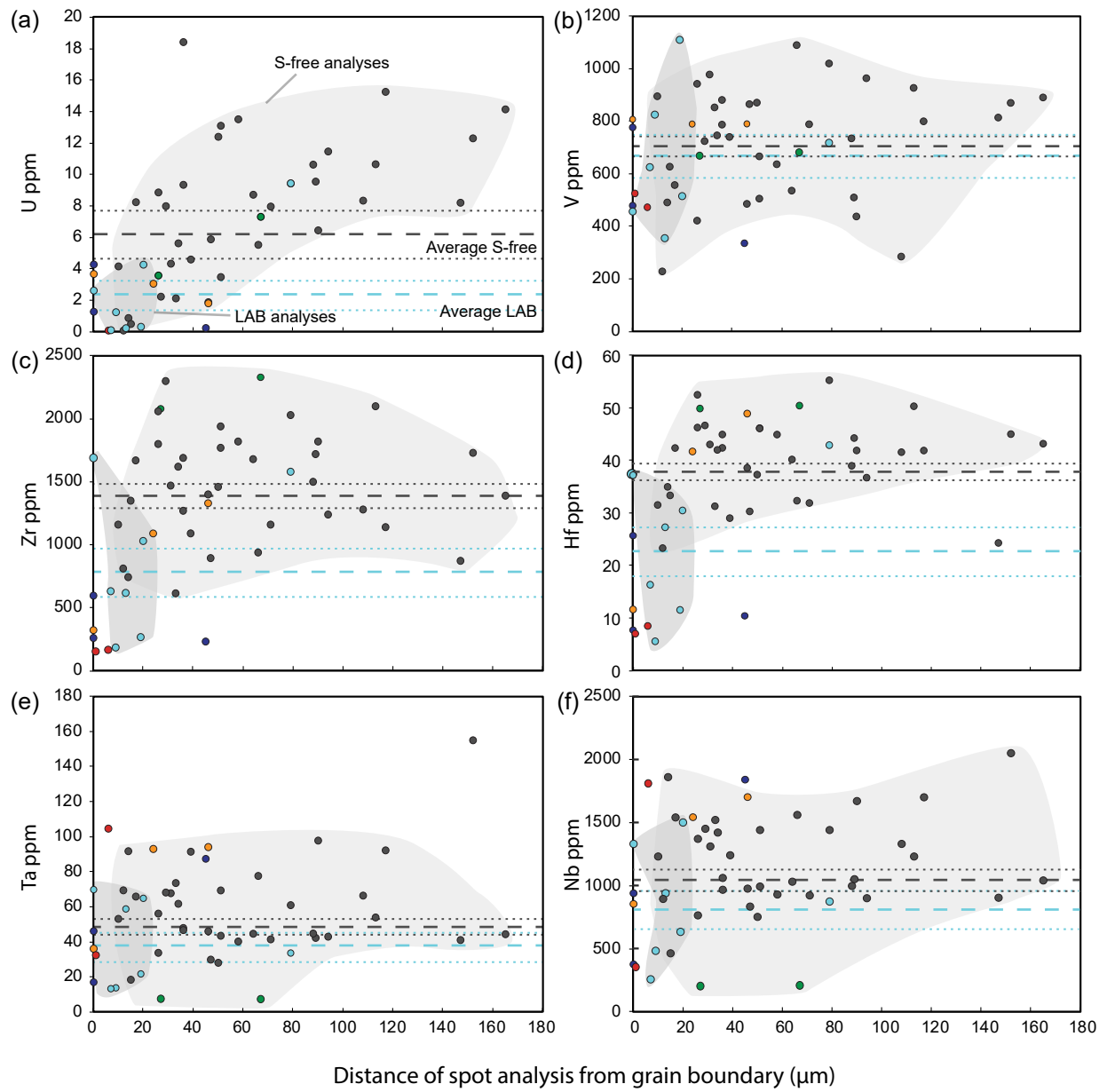


Figure 8



LEGEND

| | |
|--|--|
| ● small rutile (2) | |
| Large rutile | |
| Substructure free | Substructured |
| ● leucocratic domain (34) | ● shear band (3) |
| ● amphibole cluster (2) | ● low-angle boundary (7) |
| | ● growth twin (3) |

Figure 9

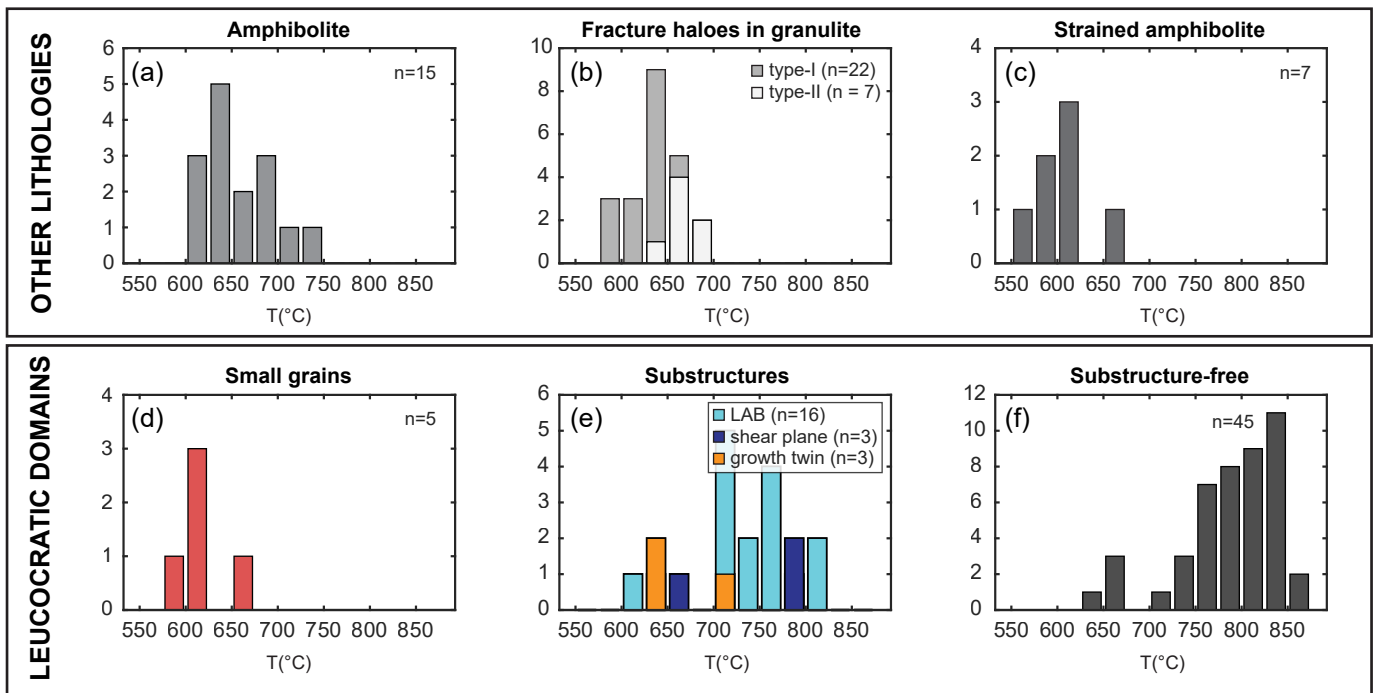


Figure 10

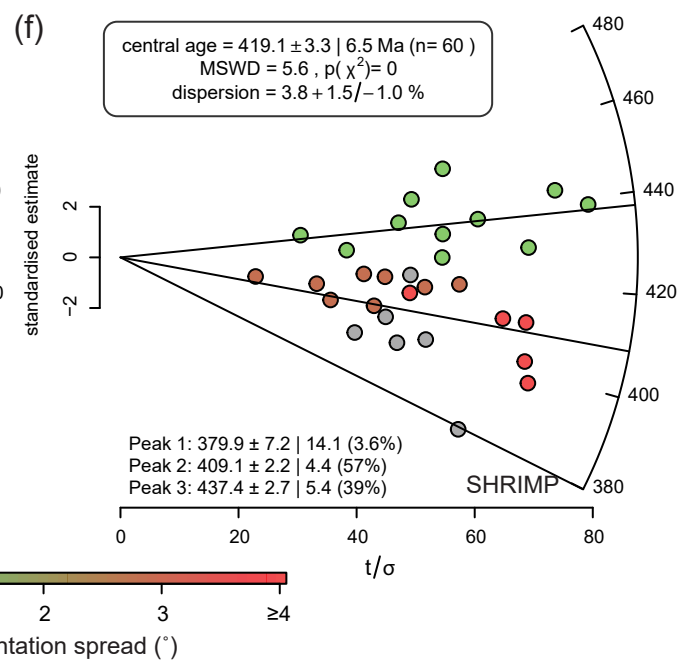
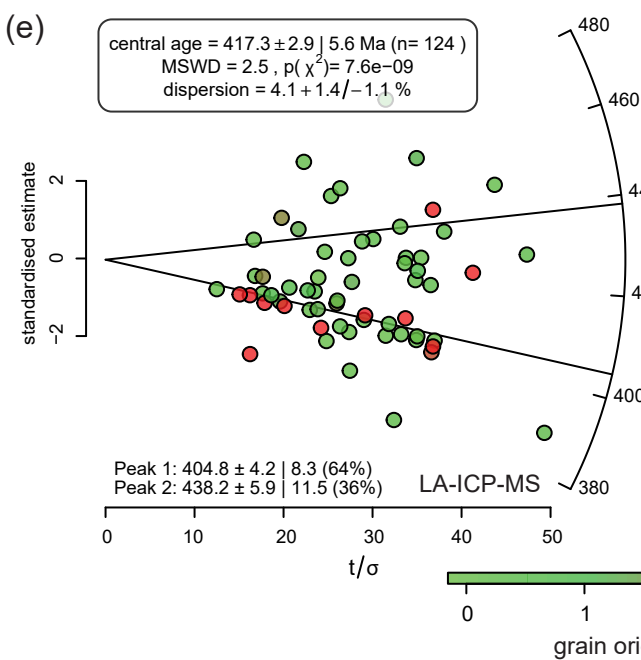
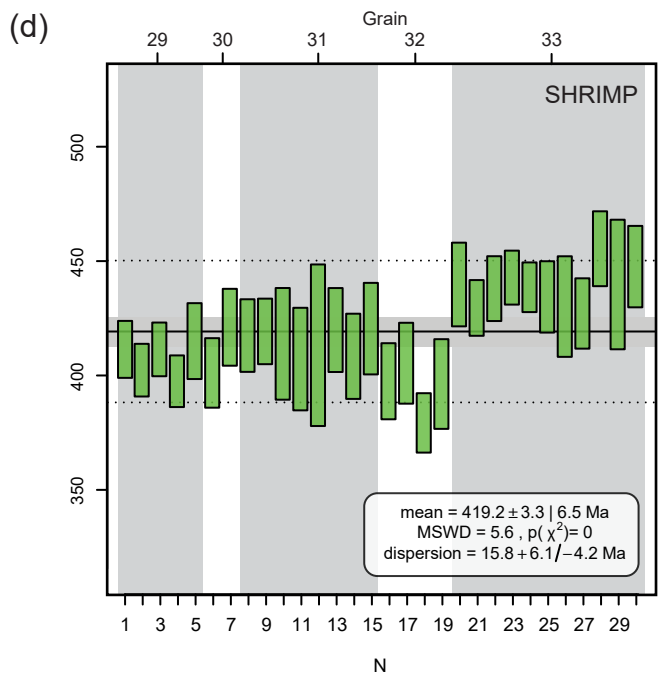
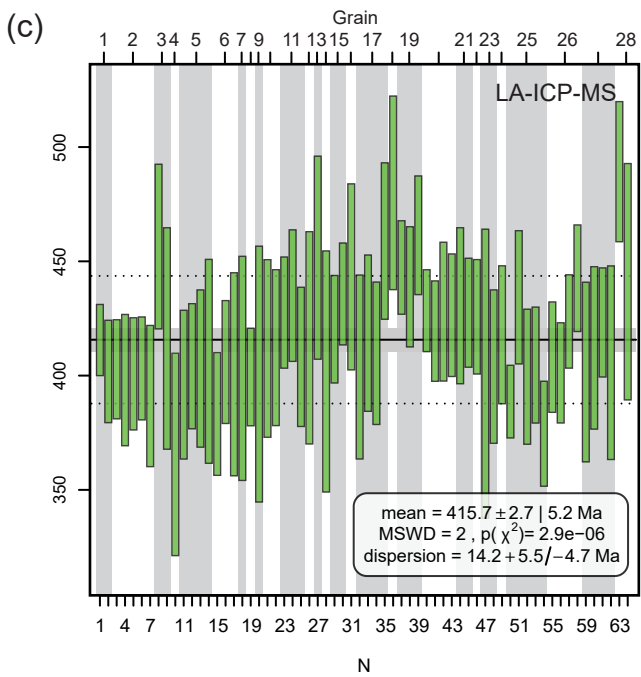
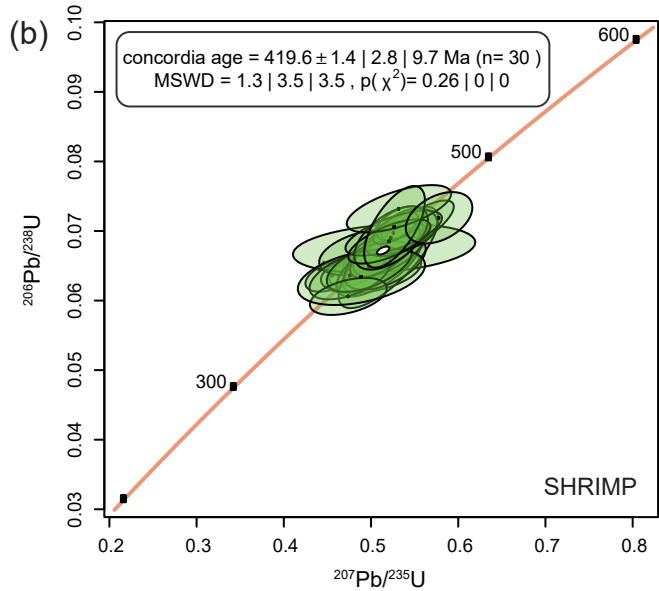
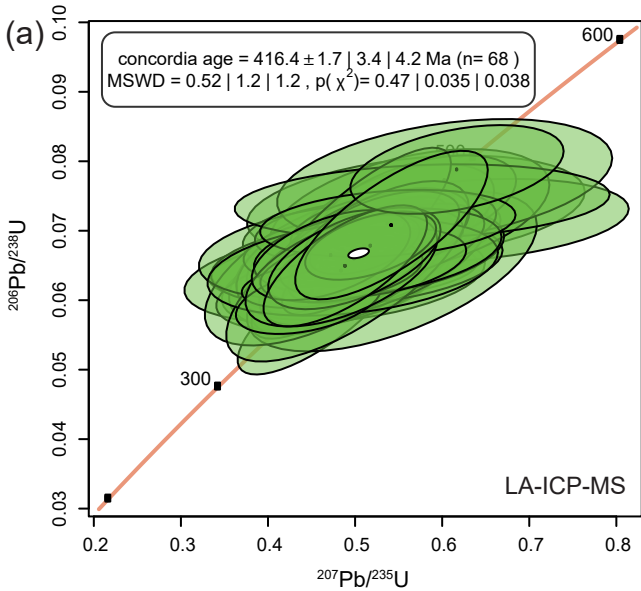
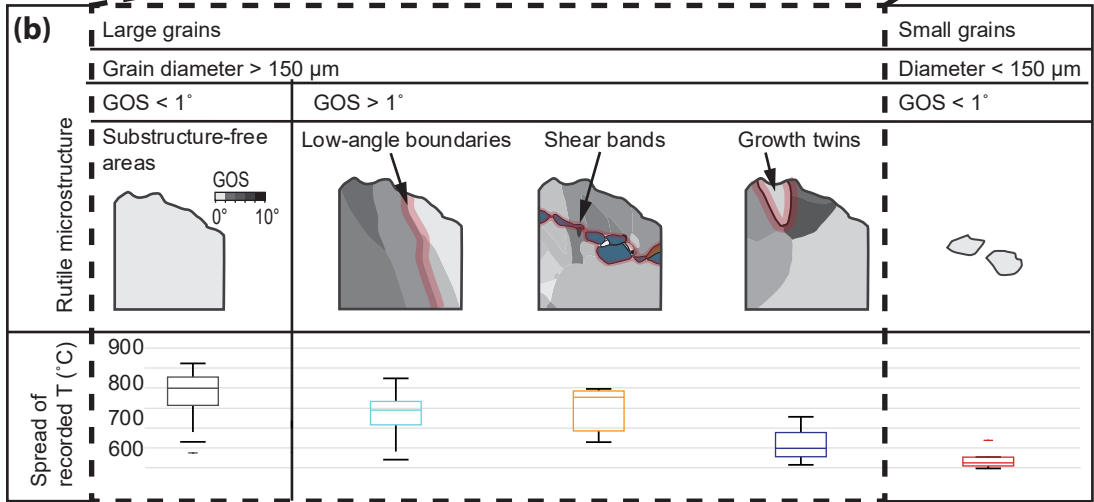
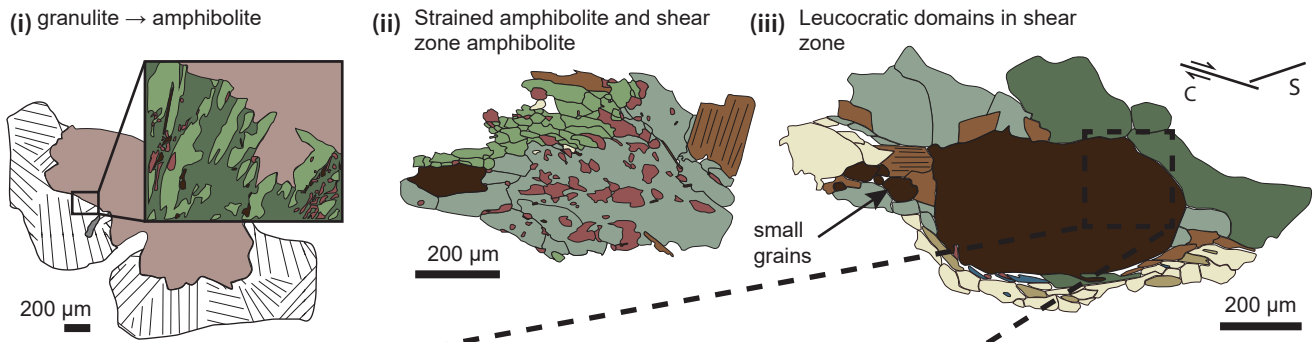


Figure 11

(a) Textural setting of rutile by lithology



- Diopside
- ▨ Symplectite
- Rutile
- Mg-hornblende
- Tschermakite
- Clinozoisite
- Biotite
- Plagioclase
- Zoisite
- Quartz
- Kyanite

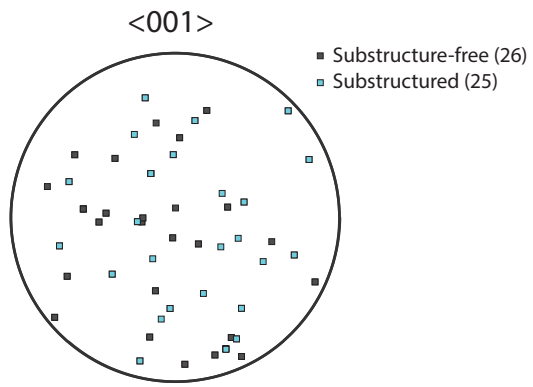


Figure S1 - C-axis orientation of all large rutile grains in respect to the cutting plane.

Table S1 - Representative amphibole analyses used for pressure calculations (b.d.l.; below detection limit, n.m.; not measured)

| Lithology Calcic amphibole classification Technique | Fracture type-I halo | | Fracture type-II halo Amphibolite | | Strained amphibolite | |
|---|----------------------------|-----------------------------|-----------------------------------|----------------------------|-----------------------------|-----------------------------|
| | tschermakite EDS | Mg-hornblende EDS | pargasite WDS | tschermakite WDS | Mg-hornblende WDS | Mg-hornblende WDS |
| P estimate (kbar) | | | | | | |
| Johnson and Rutherford, 1989 (± 0.5 kbar) | 11.6 | 6.0 | 12.4 | 13.6 | 7.8 | 12.7 |
| Schmidt 1991 (± 0.6 kbar) | 10.6 | 4.3 | 11.5 | 12.8 | 6.3 | 11.8 |
| Wt% oxide | | | | | | |
| SiO ₂ | 43.2 | 48.8 | 42.2 | 41.5 | 48.0 | 44.7 |
| TiO ₂ | 0.330 | 0.650 | 0.143 | 0.147 | 0.0836 | 0.144 |
| Al ₂ O ₃ | 17.0 | 9.20 | 17.6 | 19.4 | 11.6 | 16.8 |
| Cr ₂ O ₃ | b.d.l. | b.d.l. | b.d.l. | 0.0348 | b.d.l. | b.d.l. |
| Fe ₂ O ₃ | 4.55 | 3.45 | 0.594 | 0.939 | 1.73 | #REF! |
| FeO | 7.03 | 3.23 | 9.75 | 9.71 | 7.55 | 9.02 |
| MnO | b.d.l. | b.d.l. | 0.116 | 0.117 | 0.166 | 0.206 |
| MgO | 12.8 | 18.0 | 11.4 | 10.9 | 14.6 | 11.8 |
| CaO | 11.9 | 13.1 | 12.1 | 12.2 | 12.0 | 11.3 |
| Na ₂ O | 1.60 | 0.690 | 1.50 | 1.48 | 1.08 | 1.72 |
| K ₂ O | 0.270 | 0.250 | 0.720 | 0.503 | 0.217 | 0.745 |
| Cl | 0.260 | b.d.l. | 0.341 | 0.206 | 0.0714 | 0.324 |
| F | b.d.l. | b.d.l. | 0.01 | b.d.l. | b.d.l. | b.d.l. |
| O | n.m. | n.m. | 0.00 | n.m. | n.m. | n.m. |
| H ₂ O | 2.02 | 2.14 | 1.98 | 2.02 | 2.10 | 2.01 |
| Total | 101 | 99.5 | 98.5 | 99.1 | 99.3 | 100 |

Table S1 - Representative amphibole analyses used for pressure calculations (b.d.l.; below detection limit, n.m.; not measured)

| Lithology Calcic amphibole classification Technique | Leucocratic domain | |
|---|----------------------------|-----------------------------|
| | tschermakite WDS | Mg-hornblende WDS |
| P estimate (kbar) | | |
| Johnson and Rutherford, 1989 (± 0.5 kbar) | 12.7 | 11.1 |
| Schmidt 1991 (± 0.6 kbar) | 11.9 | 10.1 |
| Wt% oxide | | |
| SiO ₂ | 42.1 | 44.6 |
| TiO ₂ | 0.246 | 0.390 |
| Al ₂ O ₃ | 18.0 | 16.1 |
| Cr ₂ O ₃ | 0.0177 | b.d.l. |
| Fe ₂ O ₃ | 2.07 | #REF! |
| FeO | 11.2 | 11.2 |
| MnO | 0.180 | 0.206 |
| MgO | 9.90 | 10.8 |
| CaO | 11.7 | 11.7 |
| Na ₂ O | 1.50 | 1.44 |
| K ₂ O | 0.489 | 0.543 |
| Cl | 0.238 | 0.205 |
| F | b.d.l. | 0.06 |
| O | n.m. | 0.00 |
| H ₂ O | 2.00 | 2.00 |
| Total | 99.6 | 100 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | Elements (ppm) (MDL filtered) | Growth twin | | | | | | Shear plane | | |
|--|----------------------------------|-------------|---------------|---------|---------------|---------|---------------|-------------|---------------|-------|
| | | 25 | | No U-Pb | | No U-Pb | | 6 | | 11 |
| | | 7_G1-1 | $\pm 2\sigma$ | 7_B-3 | $\pm 2\sigma$ | 2_H-1 | $\pm 2\sigma$ | 1_5-7 | $\pm 2\sigma$ | 3_K-4 |
| Analyses | Si | 498 | 180 | 346 | 150 | 252 | 150 | 311 | 170 | 446 |
| | Fe | 4400 | 940 | 5010 | 1200 | 6860 | 990 | 7220 | 1000 | 6000 |
| | U | 4.26 | 1.10 | 1.26 | 0.34 | 0.22 | 0.040 | 3.65 | 0.56 | 3.04 |
| | V | 777 | 190 | 479 | 130 | 336 | 53 | 807 | 130 | 790 |
| | Zr | 260 | 61 | 596 | 150 | 231 | 35 | 322 | 48 | 1090 |
| | Hf | 7.59 | 1.8 | 25.6 | 6.6 | 10.3 | 1.5 | 11.5 | 1.7 | 41.7 |
| | Cr | 49.8 | 12 | 42.1 | 11 | 16.5 | 3.2 | 47.1 | 7.8 | 75.0 |
| | Nb | 374 | 88 | 938 | 240 | 1840 | 270 | 854 | 130 | 1542 |
| | Ta | 16.8 | 4.0 | 46.0 | 12 | 87.3 | 13 | 36.0 | 5.4 | 92.9 |
| | Zn | 136 | 36 | 4.78 | 4.5 | 8.72 | 4.1 | 12.6 | 4.7 | 6.00 |
| | Mo | 180 | 42 | 55.4 | 14 | 33.5 | 5.1 | 58.2 | 8.8 | 49.7 |
| | W | 58.3 | 14 | 47.1 | 12 | 76.8 | 12 | 31.4 | 4.9 | 44.7 |
| | Sb | 1.57 | 0.44 | 1.40 | 0.42 | 2.44 | 0.44 | 1.34 | 0.28 | 1.34 |
| | Sn | 8.72 | 2.2 | 11.0 | 3.0 | 10.2 | 1.7 | 10.5 | 1.7 | 13.5 |
| Ratios | Nb/Ta | 22.2 | | 20.4 | | 21.1 | | 23.7 | | 16.6 |
| | Zr/Hf | 34.2 | | 23.3 | | 22.5 | | 27.9 | | 26.1 |
| Thermometry | Ln (Zr) | 5.56 | | 6.39 | | 5.44 | | 5.77 | | 6.99 |
| | P (Kbars) | 12 | | 12 | | 12 | | 12 | | 12 |
| | Temperature (°C) | 647 | 33 | 718 | 37 | 638 | 26 | 664 | 26 | 776 |
| Distance from grain boundary (μm) | | 0.1 | | 0.1 | | 45 | | 0.1 | | 24 |
| | GROD | 56 | | 3.4 | | 1.9 | | 4.46 | | 1.5 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | Elements (ppm) (MDL filtered) | <i>Low angle boundaries</i> | | | | | | | | | |
|--|----------------------------------|-----------------------------|-------|---------------|-------|---------------|-------|---------------|---------|---------------|---------|
| | | 11 | | | 4 | | 7 | | No U-Pb | | No U-Pb |
| | | $\pm 2\sigma$ | 3_K-6 | $\pm 2\sigma$ | 1_4-5 | $\pm 2\sigma$ | 2_D-1 | $\pm 2\sigma$ | 4_BI-4 | $\pm 2\sigma$ | 7_K-1 |
| Analyses | Si | 170 | 364 | 150 | 642 | 200 | 1084 | 290 | 1703 | 450 | 329 |
| | Fe | 890 | 5480 | 820 | 3610 | 510 | 3440 | 500 | 3740 | 610 | 3730 |
| | U | 0.50 | 1.79 | 0.30 | 1.23 | 0.19 | 4.25 | 0.68 | 2.60 | 0.48 | 0.09 |
| | V | 130 | 790 | 130 | 825 | 130 | 515 | 83 | 456 | 83 | 625 |
| | Zr | 170 | 1330 | 210 | 184 | 27 | 1030 | 150 | 1690 | 290 | 631 |
| | Hf | 6.4 | 48.9 | 7.6 | 5.45 | 0.80 | 30.4 | 4.6 | 37.2 | 6.4 | 16.3 |
| | Cr | 12 | 61.0 | 10 | 13.0 | 2.6 | 30.6 | 5.3 | 43.1 | 8.1 | 13.1 |
| | Nb | 240 | 1702 | 260 | 481 | 69 | 1500 | 230 | 1330 | 230 | 255 |
| | Ta | 14 | 94.0 | 15 | 13.6 | 2.0 | 64.7 | 9.8 | 69.7 | 12 | 13.1 |
| | Zn | 4.1 | 3.68 | 3.8 | 1.28 | 3.0 | 11.9 | 4.5 | 4.07 | 4.1 | 9.53 |
| | Mo | 7.8 | 57.9 | 9.1 | 4.66 | 0.78 | 59.6 | 9.1 | 18.0 | 3.2 | 17.2 |
| | W | 7.2 | 42.4 | 6.8 | 77.1 | 12 | 49.6 | 7.8 | 99.4 | 18 | 57.2 |
| | Sb | 0.28 | 1.52 | 0.30 | 2.37 | 0.42 | 1.72 | 0.34 | 2.21 | 0.46 | 2.26 |
| | Sn | 2.3 | 15.3 | 2.5 | 6.34 | 1.0 | 13.8 | 2.2 | 5.82 | 1.1 | 7.55 |
| Ratios | Nb/Ta | | 18.1 | | 35.3 | | 23.2 | | 19.1 | | 19.4 |
| | Zr/Hf | | 27.2 | | 33.8 | | 33.8 | | 45.5 | | 38.8 |
| Thermometry | Ln (Zr) | | 7.19 | | 5.22 | | 6.94 | | 7.43 | | 6.45 |
| | P (Kbars) | | 12 | | 12 | | 12 | | 12 | | 12 |
| | Temperature (°C) | 29 | 797 | 31 | 620 | 25 | 770 | 28 | 823 | 33 | 723 |
| Distance from grain boundary (μm) | | | 46 | | 9 | | 20 | | 0.1 | | 7 |
| | GROD | | 2.47 | | 1.21 | | 6.99 | | 24.6 | | 6.33 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | Elements (ppm) (MDL filtered) | 22 | | | | | | | Small grains | | |
|--|----------------------------------|---------------|------------------|---------------|------------------|---------------|--------|---------------|-------------------|---------------|------------------|
| | | $\pm 2\sigma$ | No U-Pb 3_I-1 | $\pm 2\sigma$ | No U-Pb 5_B-1 | $\pm 2\sigma$ | 6_H3-3 | $\pm 2\sigma$ | No U-Pb 4_BI-1 | $\pm 2\sigma$ | No U-Pb 4_G-1 |
| Analyses | Si | 150 | 282 | 140 | 445 | 190 | 486 | 180 | 66.9 | 130 | 1366 |
| | Fe | 790 | 3330 | 500 | 3890 | 700 | 6920 | 1400 | 4130 | 660 | 2790 |
| | U | 0.024 | 0.301 | 0.054 | 0.21 | 0.050 | 9.41 | 2.20 | 0.06 | 0.016 | b.d.l |
| | V | 150 | 1110 | 180 | 355 | 71 | 718 | 160 | 473 | 84 | 525 |
| | Zr | 150 | 267 | 42 | 618 | 120 | 1580 | 350 | 166 | 28 | 153 |
| | Hf | 3.8 | 11.4 | 1.8 | 27.2 | 5.2 | 42.9 | 9.5 | 8.37 | 1.4 | 6.90 |
| | Cr | 3.6 | 32.3 | 5.7 | 86.2 | 18 | 66.6 | 16 | 42.4 | 7.9 | 16.5 |
| | Nb | 59 | 632 | 99 | 939 | 180 | 873 | 190 | 1810 | 310 | 353 |
| | Ta | 3.1 | 21.6 | 3.4 | 58.7 | 11 | 33.5 | 7.5 | 105 | 18 | 32.3 |
| | Zn | 4.9 | 6.38 | 4.0 | 8.41 | 5.4 | 7.07 | 4.4 | 3.33 | 3.7 | 2.31 |
| | Mo | 4.0 | 13.5 | 2.2 | 40.8 | 7.9 | 78.5 | 17 | 23.4 | 4.1 | 3.85 |
| | W | 14 | 101 | 16 | 37.3 | 7.4 | 43.5 | 9.9 | 78.0 | 14 | 103 |
| | Sb | 0.60 | 2.59 | 0.50 | 2.24 | 0.52 | 1.00 | 0.28 | 1.92 | 0.40 | 1.49 |
| | Sn | 1.9 | 8.2 | 1.4 | 11.4 | 2.4 | 13.2 | 3.1 | 8.23 | 1.5 | 3.73 |
| Ratios | Nb/Ta | | 29.3 | | 16.0 | | 26.0 | | 17.3 | | 10.9 |
| | Zr/Hf | | 23.3 | | 22.7 | | 36.8 | | 19.8 | | 22.2 |
| Thermometry | Ln (Zr) | | 5.59 | | 6.43 | | 7.37 | | 5.11 | | 5.03 |
| | P (Kbars) | | 12 | | 12 | | 12 | | 12 | | 12 |
| | Temperature (°C) | 35 | 649 | 26 | 721 | 31 | 816 | 39 | 613 | 26 | 607 |
| Distance from grain boundary (μm) | | | 19 | | 13 | | 79 | | 6 | | 1 |
| | GROD | | 1.07 | | 5.17 | | 0.225 | | 22.9 | | 0.265 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | Elements (ppm) (MDL filtered) | $\pm 2\sigma$ | <i>Amphibole cluster</i> | | | | <i>Large grains in leucocratic domain</i> | | | | |
|--|----------------------------------|---------------|--------------------------|---------------|-------|---------------|---|---------------|-------|---------------|-------|
| | | | 24 | | 24 | | 1 | | 2 | | 2 |
| | | | 7_E-3 | $\pm 2\sigma$ | 7_E-4 | $\pm 2\sigma$ | 1_1-1 | $\pm 2\sigma$ | 1_2-2 | $\pm 2\sigma$ | 1_2-4 |
| Analyses | Si | 380 | 516 | 190 | 276 | 140 | 307 | 160 | 718 | 250 | 435 |
| | Fe | 490 | 4310 | 980 | 3620 | 820 | 4950 | 700 | 6650 | 940 | 5740 |
| | U | | 7.28 | 1.9 | 2.21 | 0.58 | 18.4 | 2.8 | 14.1 | 2.1 | 9.32 |
| | V | 100 | 682 | 170 | 669 | 170 | 787 | 120 | 891 | 140 | 881 |
| | Zr | 28 | 2330 | 580 | 2080 | 520 | 1690 | 240 | 1390 | 200 | 1270 |
| | Hf | 1.3 | 50.5 | 13 | 49.9 | 13 | 44.9 | 6.5 | 43.2 | 6.3 | 42.4 |
| | Cr | 3.7 | 14.4 | 4.1 | 13.3 | 3.9 | 32.0 | 5.4 | 46.2 | 7.7 | 42.1 |
| | Nb | 65 | 207 | 51 | 202 | 50 | 966 | 140 | 1040 | 150 | 1060 |
| | Ta | 6.1 | 7.20 | 1.8 | 7.38 | 1.9 | 47.8 | 7.0 | 44.2 | 6.5 | 46.6 |
| | Zn | 4.1 | 1.79 | 4.7 | 16.7 | 6.6 | 4.40 | 3.5 | 6.64 | 4.7 | 5.43 |
| | Mo | 0.86 | 35.8 | 8.8 | 30.4 | 7.6 | 60.4 | 8.9 | 64.8 | 9.7 | 65.2 |
| | W | 20 | 11.7 | 3.0 | 13.0 | 3.4 | 25.9 | 3.9 | 32.5 | 4.9 | 32.7 |
| | Sb | 0.36 | 1.14 | 0.34 | 1.38 | 0.40 | 1.05 | 0.22 | 1.20 | 0.26 | 1.16 |
| | Sn | 0.80 | 15.8 | 4.1 | 14.6 | 3.9 | 15.5 | 2.4 | 15.5 | 2.5 | 14.2 |
| Ratios | Nb/Ta | | 28.8 | | 27.3 | | 20.2 | | 23.5 | | 22.7 |
| | Zr/Hf | | 46.2 | | 41.7 | | 37.6 | | 32.2 | | 30.0 |
| Thermometry | Ln (Zr) | | 7.75 | | 7.64 | | 7.43 | | 7.24 | | 7.15 |
| | P (Kbars) | | 12 | | 12 | | 12 | | 12 | | 12 |
| | Temperature (°C) | 27 | 861 | 45 | 847 | 43 | 823 | 30 | 802 | 30 | 792 |
| Distance from grain boundary (μm) | | | 67 | | 27 | | 36 | | 165 | | 36 |
| | GROD | | 0.125 | | 0.595 | | 0.585 | | 0.865 | | 0.255 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | Elements (ppm) (MDL filtered) | 3 | | 4 | | 5 | | 5 | | 7 | |
|--|----------------------------------|---------------|-------|---------------|--------|---------------|-------|---------------|-------|---------------|-------|
| | | $\pm 2\sigma$ | 1_3-1 | $\pm 2\sigma$ | 1_4-1 | $\pm 2\sigma$ | 1_5-2 | $\pm 2\sigma$ | 1_5-4 | $\pm 2\sigma$ | 2_D-3 |
| Analyses | Si | 210 | 354 | 170 | 705 | 210 | 1280 | 390 | 612 | 290 | 492 |
| | Fe | 810 | 8660 | 1200 | 7160 | 1000 | 7650 | 1100 | 5160 | 730 | 4900 |
| | U | 1.4 | 8.31 | 1.3 | 12.3 | 1.8 | 10.6 | 1.6 | 4.14 | 0.64 | 8.22 |
| | V | 140 | 285 | 45 | 870 | 130 | 927 | 140 | 895 | 140 | 557 |
| | Zr | 180 | 1280 | 190 | 1730 | 250 | 2100 | 310 | 1160 | 170 | 1670 |
| | Hf | 6.2 | 41.6 | 6.2 | 45.0 | 6.5 | 50.3 | 7.4 | 31.5 | 4.6 | 42.4 |
| | Cr | 7.1 | 31.0 | 5.4 | 18.4 | 3.3 | 45.3 | 7.8 | 46.1 | 8.0 | 32.3 |
| | Nb | 150 | 1330 | 200 | 2050 | 300 | 1230 | 180 | 1230 | 180 | 1540 |
| | Ta | 6.9 | 66.3 | 9.9 | 155 | 23 | 53.8 | 7.9 | 53.0 | 7.9 | 65.7 |
| | Zn | 4.7 | 5.92 | 4.2 | b.d.l. | 3.0 | 13.5 | 6.7 | 12.4 | 6.8 | 12.6 |
| | Mo | 9.7 | 66.3 | 10 | 68.3 | 10 | 92.0 | 14 | 77.0 | 12 | 73.6 |
| | W | 5.0 | 41.2 | 6.4 | 42.3 | 6.3 | 55.6 | 8.5 | 56.0 | 8.6 | 52.8 |
| | Sb | 0.24 | 1.03 | 0.22 | 1.11 | 0.22 | 1.11 | 0.26 | 1.73 | 0.36 | 1.16 |
| | Sn | 2.3 | 15.3 | 2.5 | 17.6 | 2.7 | 17.1 | 2.7 | 15.1 | 2.4 | 15.4 |
| Ratios | Nb/Ta | | 20.1 | | 13.2 | | 22.9 | | 23.2 | | 23.4 |
| | Zr/Hf | | 30.8 | | 38.4 | | 41.7 | | 36.8 | | 39.4 |
| Thermometry | Ln (Zr) | | 7.15 | | 7.46 | | 7.65 | | 7.06 | | 7.42 |
| | P (Kbars) | | 12 | | 12 | | 12 | | 12 | | 12 |
| | Temperature (°C) | 29 | 793 | 30 | 826 | 30 | 849 | 31 | 783 | 28 | 822 |
| Distance from grain boundary (μm) | | | 108 | | 152 | | 113 | | 10 | | 17 |
| | GROD | | 0.485 | | 2.04 | | 0.295 | | 0.415 | | 1.23 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | Elements (ppm) (MDL filtered) | 8 | | 9 | | 10 | | 11 | | No U-Pb | |
|--|----------------------------------|---------------|-------|---------------|-------|---------------|--------|---------------|-------|---------------|---------|
| | | $\pm 2\sigma$ | 2_G-1 | $\pm 2\sigma$ | 3_C-1 | $\pm 2\sigma$ | 3_G2-1 | $\pm 2\sigma$ | 3_K-1 | $\pm 2\sigma$ | 4_BII-1 |
| Analyses | Si | 180 | 277 | 150 | 536 | 180 | 988 | 280 | 331 | 160 | 462 |
| | Fe | 710 | 5480 | 800 | 3980 | 600 | 6970 | 1000 | 6700 | 990 | 4990 |
| | U | 1.3 | 11.4 | 1.8 | 4.31 | 0.72 | 6.43 | 1.1 | 15.2 | 2.4 | 0.86 |
| | V | 90 | 964 | 150 | 978 | 160 | 438 | 72 | 800 | 130 | 491 |
| | Zr | 250 | 1240 | 190 | 1470 | 230 | 1820 | 290 | 1140 | 170 | 743 |
| | Hf | 6.4 | 36.7 | 5.5 | 43.0 | 6.8 | 41.9 | 6.5 | 41.9 | 6.4 | 34.9 |
| | Cr | 5.5 | 60.3 | 9.9 | 48.9 | 8.4 | 34.3 | 6.1 | 69.7 | 12 | 38.1 |
| | Nb | 230 | 899 | 130 | 1310 | 210 | 1670 | 260 | 1700 | 260 | 1860 |
| | Ta | 10 | 42.8 | 6.5 | 67.7 | 11 | 97.7 | 15 | 92.1 | 14 | 91.7 |
| | Zn | 4.6 | 13.1 | 4.6 | 2.01 | 3.9 | 6.45 | 4.9 | 6.52 | 4.3 | 2.42 |
| | Mo | 11 | 69.0 | 11 | 50.4 | 8.1 | 70.0 | 11 | 76.9 | 12 | 40.3 |
| | W | 8.3 | 32.5 | 5.1 | 42.6 | 7.0 | 49.0 | 7.9 | 42.4 | 6.7 | 62.2 |
| | Sb | 0.24 | 1.17 | 0.24 | 1.39 | 0.28 | 1.16 | 0.26 | 1.20 | 0.24 | 1.60 |
| | Sn | 2.5 | 15.0 | 2.4 | 14.0 | 2.4 | 17.3 | 2.9 | 17.2 | 2.8 | 12.1 |
| Ratios | Nb/Ta | | 21.0 | | 19.4 | | 17.1 | | 18.5 | | 20.3 |
| | Zr/Hf | | 33.8 | | 34.2 | | 43.4 | | 27.2 | | 21.3 |
| Thermometry | Ln (Zr) | | 7.12 | | 7.29 | | 7.51 | | 7.04 | | 6.61 |
| | P (Kbars) | | 12 | | 12 | | 12 | | 12 | | 12 |
| | Temperature (°C) | 31 | 790 | 29 | 808 | 31 | 832 | 32 | 781 | 29 | 738 |
| Distance from grain boundary (μm) | | | 94 | | 31 | | 90 | | 117 | | 14 |
| | GROD | | 0.185 | | 0.35 | | 0.475 | | 1.99 | | 0.305 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | Elements (ppm) (MDL filtered) | 13 | | 14 | | 15 | | 16 | | No U-Pb | |
|--|----------------------------------|---------------|-------|---------------|--------|---------------|-------|---------------|---------|---------------|-------|
| | | $\pm 2\sigma$ | 4_I-1 | $\pm 2\sigma$ | 4_M-2 | $\pm 2\sigma$ | 4_N-5 | $\pm 2\sigma$ | 4_NII-2 | $\pm 2\sigma$ | 5_A-1 |
| Analyses | Si | 170 | 1050 | 300 | 377 | 190 | 514 | 180 | 1768 | 470 | 317 |
| | Fe | 820 | 6370 | 1100 | 6030 | 1000 | 4940 | 840 | 4480 | 770 | 5330 |
| | U | 0.16 | 5.51 | 1.1 | 2.11 | 0.40 | 9.40 | 1.8 | 8.83 | 1.7 | 3.46 |
| | V | 90 | 1090 | 210 | 853 | 160 | 1020 | 190 | 943 | 180 | 667 |
| | Zr | 130 | 939 | 170 | 614 | 110 | 2030 | 370 | 1800 | 330 | 1770 |
| | Hf | 6.1 | 32.3 | 6.0 | 31.2 | 5.5 | 55.3 | 10 | 52.5 | 9.6 | 46.1 |
| | Cr | 7.3 | 38.8 | 7.8 | 64.3 | 12 | 67.7 | 13 | 77.6 | 15 | 42.9 |
| | Nb | 320 | 1560 | 290 | 1520 | 270 | 1440 | 260 | 1370 | 250 | 1440 |
| | Ta | 16 | 77.5 | 14 | 73.5 | 13 | 60.8 | 11 | 56.0 | 10 | 69.2 |
| | Zn | 3.8 | 14.2 | 5.2 | b.d.l. | 5.1 | 6.24 | 4.0 | 10.8 | 4.5 | 5.05 |
| | Mo | 7.1 | 67.3 | 12 | 59.6 | 11 | 70.5 | 13 | 65.9 | 12 | 68.9 |
| | W | 11.2 | 49.8 | 9.5 | 39.4 | 7.3 | 41.2 | 7.7 | 44.7 | 8.5 | 44.7 |
| | Sb | 0.34 | 1.15 | 0.28 | 1.29 | 0.32 | 1.26 | 0.28 | 1.50 | 0.34 | 1.00 |
| | Sn | 2.3 | 15.0 | 3.0 | 14.1 | 2.7 | 14.2 | 2.8 | 16.8 | 3.3 | 14.9 |
| Ratios | Nb/Ta | | 20.1 | | 20.7 | | 23.7 | | 24.5 | | 20.8 |
| | Zr/Hf | | 29.1 | | 19.7 | | 36.7 | | 34.3 | | 38.4 |
| Thermometry | Ln (Zr) | | 6.84 | | 6.42 | | 7.62 | | 7.50 | | 7.48 |
| | P (Kbars) | | 12 | | 12 | | 12 | | 12 | | 12 |
| | Temperature (°C) | 30 | 761 | 31 | 720 | 29 | 845 | 35 | 831 | 35 | 829 |
| Distance from grain boundary (μm) | | | 66 | | 33 | | 79 | | 26 | | 51 |
| | GROD | | 0.615 | | 0.405 | | 1.02 | | 1.706 | | 0.295 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | Elements (ppm) (MDL filtered) | No U-Pb | | No U-Pb | | 19 | | 20 | | 20 | |
|--|----------------------------------|---------------|-------|---------------|-------|---------------|--------|---------------|--------|---------------|--------|
| | | $\pm 2\sigma$ | 6_A-1 | $\pm 2\sigma$ | 6_B-1 | $\pm 2\sigma$ | 6_G2-1 | $\pm 2\sigma$ | 6_H1-2 | $\pm 2\sigma$ | 6_H1-3 |
| Analyses | Si | 150 | 678 | 220 | 544 | 200 | 520 | 190 | 476 | 170 | 401 |
| | Fe | 950 | 4440 | 910 | 4600 | 940 | 7300 | 1300 | 5140 | 1000 | 4050 |
| | U | 0.70 | 3.56 | 0.84 | 4.57 | 1.1 | 13.5 | 2.8 | 12.4 | 2.8 | 5.86 |
| | V | 130 | 422 | 98 | 740 | 170 | 637 | 130 | 871 | 190 | 865 |
| | Zr | 340 | 2060 | 460 | 1090 | 240 | 1820 | 360 | 1460 | 310 | 894 |
| | Hf | 8.8 | 46.3 | 10 | 29.0 | 6.5 | 44.9 | 8.9 | 37.3 | 8.1 | 30.3 |
| | Cr | 8.9 | 26.0 | 6.3 | 46.7 | 11 | 63.0 | 13 | 78.1 | 18 | 69.9 |
| | Nb | 270 | 763 | 170 | 1240 | 280 | 928 | 180 | 751 | 160 | 833 |
| | Ta | 13 | 33.6 | 7.6 | 91.4 | 21 | 40.1 | 8.1 | 27.9 | 6.1 | 29.7 |
| | Zn | 4.6 | 8.29 | 4.5 | 5.94 | 4.6 | 6.75 | 4.8 | 2.53 | 3.6 | 4.44 |
| | Mo | 13 | 48.6 | 11 | 59.6 | 13 | 73.6 | 15 | 73.7 | 16 | 52.3 |
| | W | 8.8 | 28.9 | 6.7 | 50.7 | 12 | 44.3 | 9.1 | 46.2 | 10 | 47.9 |
| | Sb | 0.26 | 1.06 | 0.30 | 1.20 | 0.32 | 1.08 | 0.28 | 1.09 | 0.28 | 1.23 |
| | Sn | 3.0 | 15.5 | 3.7 | 12.9 | 3.1 | 13.3 | 2.8 | 14.2 | 3.3 | 12.2 |
| Ratios | Nb/Ta | | 22.7 | | 13.6 | | 23.1 | | 26.9 | | 28.0 |
| | Zr/Hf | | 44.5 | | 37.6 | | 40.5 | | 39.2 | | 29.6 |
| Thermometry | Ln (Zr) | | 7.63 | | 6.99 | | 7.51 | | 7.29 | | 6.80 |
| | P (Kbars) | | 12 | | 12 | | 12 | | 12 | | 12 |
| | Temperature (°C) | 36 | 846 | 40 | 776 | 36 | 832 | 37 | 807 | 38 | 756 |
| Distance from grain boundary (μm) | | | 26 | | 39 | | 58 | | 50 | | 47 |
| | GROD | | 0.385 | | 0.565 | | 0.125 | | 0.335 | | 0.255 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | Elements (ppm) (MDL filtered) | 23 | | No U-Pb | | No U-Pb | | No U-Pb | | 25 | |
|--|----------------------------------|---------------|--------|---------------|--------|---------------|-------|---------------|--------|---------------|--------|
| | | $\pm 2\sigma$ | 6_J1-1 | $\pm 2\sigma$ | 6_J5-1 | $\pm 2\sigma$ | 7_B-1 | $\pm 2\sigma$ | 7_C-1 | $\pm 2\sigma$ | 7_G1-3 |
| Analyses | Si | 160 | 939 | 270 | 753 | 230 | 406 | 160 | 278 | 130 | 553 |
| | Fe | 810 | 4110 | 700 | 5390 | 980 | 4510 | 1000 | 3830 | 860 | 5000 |
| | U | 1.3 | 7.96 | 1.6 | 5.60 | 1.1 | 1.86 | 0.50 | 0.0643 | 0.020 | 8.18 |
| | V | 190 | 725 | 150 | 746 | 150 | 486 | 130 | 229 | 58 | 814 |
| | Zr | 190 | 2300 | 440 | 1620 | 320 | 1400 | 350 | 811 | 200 | 872 |
| | Hf | 6.6 | 46.7 | 9.0 | 42.0 | 8.2 | 38.6 | 9.8 | 23.2 | 5.7 | 24.2 |
| | Cr | 16 | 57.4 | 12 | 46.5 | 9.8 | 47.4 | 13 | 8.4 | 2.6 | 51.1 |
| | Nb | 180 | 1450 | 280 | 1420 | 280 | 975 | 250 | 893 | 220 | 903 |
| | Ta | 6.5 | 68.1 | 13 | 61.6 | 12 | 45.9 | 12 | 69.3 | 17 | 40.9 |
| | Zn | 3.8 | 4.76 | 4.0 | 8.08 | 4.4 | 3.35 | 4.3 | 4.50 | 4.3 | 4.45 |
| | Mo | 11 | 49.5 | 9.6 | 75.4 | 15 | 65.2 | 16 | 14.4 | 3.6 | 81.9 |
| | W | 11 | 62.4 | 13 | 52.4 | 11 | 40.0 | 11 | 54.2 | 14 | 47.1 |
| | Sb | 0.32 | 1.90 | 0.44 | 1.69 | 0.40 | 1.27 | 0.38 | 1.74 | 0.50 | 1.11 |
| | Sn | 2.8 | 12.0 | 2.5 | 13.4 | 2.8 | 13.7 | 3.7 | 8.12 | 2.1 | 15.9 |
| Ratios | Nb/Ta | | 21.3 | | 23.0 | | 21.2 | | 12.9 | | 22.1 |
| | Zr/Hf | | 49.3 | | 38.6 | | 36.3 | | 34.9 | | 36.0 |
| Thermometry | Ln (Zr) | | 7.74 | | 7.39 | | 7.24 | | 6.70 | | 6.77 |
| | P (Kbars) | | 12 | | 12 | | 12 | | 12 | | 12 |
| | Temperature (°C) | 35 | 859 | 37 | 819 | 36 | 803 | 42 | 747 | 37 | 754 |
| Distance from grain boundary (μm) | | | 29 | | 34 | | 46 | | 12 | | 147 |
| | GROD | | 0.385 | | 0.335 | | 4.52 | | 2.38 | | 2.43 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | Elements (ppm) (MDL filtered) | 25 | | 26 | | 26 | | No U-Pb | | 27 | |
|--|----------------------------------|---------------|--------|---------------|--------|---------------|--------|---------------|-------|---------------|--------|
| | | $\pm 2\sigma$ | 7_G1-8 | $\pm 2\sigma$ | 7_G2-1 | $\pm 2\sigma$ | 7_G2-2 | $\pm 2\sigma$ | 7_K-2 | $\pm 2\sigma$ | 7_L1-3 |
| Analyses | Si | 190 | 610 | 210 | 341 | 140 | 197 | 120 | 403 | 160 | 695 |
| | Fe | 1100 | 4680 | 1000 | 4750 | 1000 | 4690 | 1000 | 4010 | 860 | 8170 |
| | U | 2.0 | 7.94 | 2.0 | 13.1 | 3.3 | 9.52 | 2.4 | 0.483 | 0.12 | 10.6 |
| | V | 200 | 789 | 190 | 506 | 130 | 510 | 130 | 627 | 150 | 735 |
| | Zr | 210 | 1160 | 280 | 1940 | 470 | 1720 | 420 | 1350 | 320 | 1500 |
| | Hf | 5.8 | 31.9 | 7.6 | 46.1 | 11 | 44.3 | 11 | 33.3 | 7.8 | 39.0 |
| | Cr | 13 | 44.2 | 11 | 53.6 | 14 | 62.2 | 16 | 20.0 | 5.2 | 52.5 |
| | Nb | 210 | 921 | 220 | 992 | 240 | 1050 | 250 | 462 | 110 | 996 |
| | Ta | 9.8 | 41.3 | 10 | 43.4 | 11 | 42.1 | 10 | 18.3 | 4.3 | 44.6 |
| | Zn | 4.2 | b.d.l. | 4.1 | 2.27 | 4.0 | 0.641 | 4.1 | 11.6 | 5.3 | 9.38 |
| | Mo | 19 | 76.1 | 18 | 86.4 | 21 | 80.9 | 19 | 35.2 | 8.2 | 86.7 |
| | W | 12 | 41.6 | 10 | 48.2 | 12 | 48.1 | 12 | 18.9 | 4.6 | 48.9 |
| | Sb | 0.32 | 1.19 | 0.34 | 0.895 | 0.26 | 0.91 | 0.26 | 1.23 | 0.34 | 1.22 |
| | Sn | 4.0 | 14.8 | 3.8 | 13.9 | 3.5 | 13.9 | 3.6 | 15.1 | 3.7 | 15.5 |
| Ratios | Nb/Ta | | 22.3 | | 22.9 | | 24.9 | | 25.3 | | 22.3 |
| | Zr/Hf | | 36.4 | | 42.1 | | 38.9 | | 40.5 | | 38.5 |
| Thermometry | Ln (Zr) | | 7.06 | | 7.57 | | 7.45 | | 7.21 | | 7.31 |
| | P (Kbars) | | 12 | | 12 | | 12 | | 12 | | 12 |
| | Temperature (°C) | 36 | 783 | 38 | 839 | 42 | 825 | 42 | 799 | 39 | 810 |
| Distance from grain boundary (μm) | | | 71 | | 51 | | 89 | | 15 | | 88 |
| | GROD | | 2.22 | | 0.805 | | 1.25 | | 0.535 | | 0.125 |

Table S2 - LA-ICP-MS trace element analyses from rutile of leucocratic domains

| Grain number** | 28 | | | |
|--|----------------------------------|---------------|--------|---------------|
| | Elements (ppm) (MDL filtered) | $\pm 2\sigma$ | 7_L2-1 | $\pm 2\sigma$ |
| Analyses | Si | 230 | 674 | 220 |
| | Fe | 1710 | 4330 | 900 |
| | U | 2.5 | 8.69 | 2.1 |
| | V | 170 | 536 | 130 |
| | Zr | 340 | 1680 | 390 |
| | Hf | 8.9 | 40.2 | 9.3 |
| | Cr | 13 | 50.3 | 12 |
| | Nb | 230 | 1030 | 240 |
| | Ta | 10 | 44.5 | 10 |
| | Zn | 4.9 | 5.40 | 4.2 |
| | Mo | 20 | 77.9 | 18 |
| | W | 12 | 48.5 | 12 |
| | Sb | 0.34 | 0.932 | 0.26 |
| | Sn | 3.8 | 14.3 | 3.5 |
| Ratios | Nb/Ta | | 23.1 | |
| | Zr/Hf | | 41.8 | |
| Thermometry | Ln (Zr) | | 7.43 | |
| | P (Kbars) | | 12 | |
| | Temperature (°C) | 39 | 823 | 40 |
| Distance from grain boundary (μm) | | | 64 | |
| | GROD | | 0.325 | |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology Type Analyses | Amphibolite | | | | | |
|---|-------------|-------------|-------------|-------------|-------------|-------------|
| | 17FJ05_R1_1 | 17FJ05_R1_2 | 17FJ05_R2_1 | 17FJ05_R2_2 | 17FJ05_R2_3 | 17FJ05_R2_4 |
| Wt% oxide | | | | | | |
| SiO ₂ | 0.200 | 0.758 | 0.415 | 0.0636 | 0.652 | 0.137 |
| TiO ₂ | 99.1 | 96.3 | 99.7 | 101 | 96.6 | 98.9 |
| Al ₂ O ₃ | 0.0227 | 0.0610 | 0.144 | 0.0138 | 0.153 | 0.0375 |
| Cr ₂ O ₃ | b.d.l. | b.d.l. | 0.0658 | 0.0556 | 0.0469 | 0.0393 |
| FeO | 0.485 | 0.606 | 0.376 | 0.276 | 0.337 | 0.322 |
| MnO | 0.0160 | 0.0152 | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| NiO | b.d.l. | 0.00736 | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| CaO | 0.709 | 1.05 | 0.698 | 0.463 | 1.12 | 0.714 |
| Nb ₂ O ₅ | 0.0275 | 0.0179 | 0.0184 | 0.0123 | 0.0133 | 0.0167 |
| ZrO ₂ | 0.0527 | 0.0456 | 0.0276 | 0.0234 | 0.0305 | 0.0197 |
| HfO ₂ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V ₂ O ₃ | 0.0464 | b.d.l. | 0.0824 | 0.0914 | 0.0569 | 0.0931 |
| Total | 101 | 98.8 | 102 | 102 | 99.0 | 100 |
| Elements (ppm) | | | | | | |
| Si | 936 | 3540 | 1940 | 297 | 3050 | 640 |
| Al | 120 | 323 | 762 | 73 | 808 | 199 |
| Cr | b.d.l. | b.d.l. | 451 | 381 | 321 | 269 |
| Fe | 3770 | 4710 | 2930 | 2150 | 2620 | 2500 |
| Ni | b.d.l. | 57.8 | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V | 260 | b.d.l. | 462 | 512 | 319 | 522 |
| Nb | 192 | 125 | 129 | 86.0 | 92.7 | 117 |
| Zr | 390 | 337 | 205 | 173 | 226 | 146 |
| Thermometer (Tomkins et al 2007) | | | | | | |
| In (Zr ppm) | 5.97 | 5.82 | 5.32 | 5.15 | 5.42 | 4.98 |
| P (Kbar) | 13 | 13 | 13 | 13 | 13 | 13 |
| Temperature (°C) | 685 | 672 | 632 | 620 | 640 | 607 |
| Error (2σ)* | 19 | 20 | 24 | 25 | 23 | 27 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology Type | | | | | | | | |
|--------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|---------|
| Analyses | 17FJ05_R2 | 17FJ05_R2 | 17FJ05_R3 | 17FJ05_R3 | 17FJ05_R3 | 17FJ05_R3 | 17FJ05_R3 | H2 R15 |
| Wt% oxide | | | | | | | | |
| SiO ₂ | 0.0807 | 0.878 | 0.0546 | 0.0428 | 0.0385 | 0.0429 | 0.361 | 0.581 |
| TiO ₂ | 99.8 | 99.3 | 100 | 101 | 101 | 101 | 99.8 | 98.3 |
| Al ₂ O ₃ | 0.00519 | 0.306 | 0.0198 | b.d.l. | 0.00781 | 0.0103 | 0.110 | 0.254 |
| Cr ₂ O ₃ | 0.0539 | 0.0404 | 0.0505 | 0.0415 | 0.0708 | 0.0583 | 0.0533 | b.d.l. |
| FeO | 0.413 | 0.667 | 0.383 | 0.359 | 0.327 | 0.323 | 0.387 | 0.421 |
| MnO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | 0.0106 | 0.00611 | b.d.l. | 0.00693 |
| NiO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | 0.00988 |
| CaO | 0.548 | 0.744 | 0.314 | 0.270 | 0.268 | 0.286 | 0.557 | 1.00 |
| Nb ₂ O ₅ | 0.0182 | 0.0156 | 0.0196 | 0.0140 | 0.0191 | 0.0152 | 0.0130 | 0.0447 |
| ZrO ₂ | 0.0254 | 0.0209 | 0.0557 | 0.0340 | 0.0291 | 0.0469 | 0.0564 | 0.0712 |
| HfO ₂ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V ₂ O ₃ | 0.0974 | 0.0610 | 0.0573 | 0.0757 | 0.0732 | 0.0600 | 0.0667 | 0.0187 |
| Total | 101 | 102 | 101 | 101 | 102 | 102 | 101 | 101 |
| Elements (ppm) | | | | | | | | |
| Si | 377 | 4110 | 255 | 200 | 180 | 201 | 1690 | 2720 |
| Al | 27.5 | 1620 | 105 | b.d.l. | 41.3 | 54.5 | 582 | 1340 |
| Cr | 369 | 276 | 346 | 284 | 485 | 399 | 364 | b.d.l. |
| Fe | 3210 | 5180 | 2970 | 2790 | 2550 | 2510 | 3010 | 3270 |
| Ni | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | 77.7 |
| V | 545 | 342 | 321 | 424 | 410 | 336 | 374 | 105 |
| Nb | 128 | 109 | 137 | 97.9 | 134 | 106 | 90.8 | 313 |
| Zr | 188 | 155 | 412 | 252 | 216 | 347 | 418 | 527 |
| Thermometer (Tomki) | | | | | | | | |
| In (Zr ppm) | 5.24 | 5.04 | 6.02 | 5.53 | 5.37 | 5.85 | 6.03 | 6.27 |
| P (Kbar) | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| Temperature (°C) | 626 | 612 | 689 | 648 | 636 | 675 | 690 | 715 |
| Error (2σ)* | 25 | 26 | 19 | 22 | 24 | 20 | 19 | 18 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology Type Analyses | Strained amphibolite | | | | | | | |
|--------------------------------|----------------------|----------|----------|----------|----------|----------|----------|-----------|
| | H2 R16 | FJ7-2 R1 | FJ7-2 R2 | FJ7-2 R2 | FJ7-2 R7 | FJ7-2 R9 | FJ7-2 R6 | FJ7-2 R10 |
| Wt% oxide | | | | | | | | |
| SiO ₂ | 0.0997 | 0.0416 | 0.0411 | 0.0859 | 0.274 | 0.104 | 0.254 | 0.0853 |
| TiO ₂ | 100 | 100 | 101 | 101 | 99.4 | 100 | 101 | 101 |
| Al ₂ O ₃ | 0.00759 | b.d.l. | b.d.l. | 0.0198 | 0.0912 | 0.0361 | 0.0745 | 0.0247 |
| Cr ₂ O ₃ | b.d.l. | 0.0370 | b.d.l. | 0.0254 | 0.0341 | 0.0621 | 0.0248 | 0.0378 |
| FeO | 0.385 | 0.412 | 0.396 | 0.504 | 0.637 | 0.480 | 0.650 | 0.564 |
| MnO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | 0.00988 | 0.0114 | b.d.l. |
| NiO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| CaO | 1.00 | 0.0244 | 0.0276 | 0.0398 | 0.513 | 0.244 | 0.525 | 0.334 |
| Nb ₂ O ₅ | 0.0476 | 0.0890 | 0.0681 | 0.218 | 0.0899 | 0.142 | 0.0878 | 0.1635 |
| ZrO ₂ | 0.0772 | 0.0196 | 0.0261 | 0.0100 | 0.0175 | 0.0241 | 0.0334 | 0.0112 |
| HfO ₂ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V ₂ O ₃ | b.d.l. | 0.0234 | 0.0329 | 0.0165 | 0.0267 | 0.0341 | b.d.l. | b.d.l. |
| Total | 102 | 101 | 101 | 102 | 101 | 101 | 103 | 103 |
| Elements (ppm) | | | | | | | | |
| Si | 466 | 195 | 192 | 401 | 1280 | 486 | 1190 | 399 |
| Al | 40.2 | b.d.l. | b.d.l. | 105 | 482 | 191 | 394 | 131 |
| Cr | b.d.l. | 253 | b.d.l. | 174 | 233 | 425 | 170 | 259 |
| Fe | 2990 | 3200 | 3080 | 3920 | 4950 | 3730 | 5060 | 4390 |
| Ni | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V | b.d.l. | 131 | 184 | 92.4 | 149 | 191 | b.d.l. | b.d.l. |
| Nb | 333 | 622 | 476 | 1530 | 628 | 994 | 614 | 1140 |
| Zr | 572 | 145 | 193 | 73.9 | 129 | 178 | 247 | 83 |
| Thermometer (Tomki) | | | | | | | | |
| In (Zr ppm) | 6.35 | 4.97 | 5.26 | 4.30 | 4.86 | 5.18 | 5.51 | 4.42 |
| P (Kbar) | 13 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| Temperature (°C) | 727 | 603 | 624 | 557 | 595 | 618 | 655 | 580 |
| Error (2σ)* | 17 | 26 | 24 | 35 | 27 | 25 | 22 | 34 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology Type Analyses | Fracture type-I halo | | | | |
|--------------------------------|----------------------|--------------|--------------|--------------|--------------|
| | 17FJ02A_R2_1 | 17FJ02A_R2_2 | 17FJ02A_R2_3 | 17FJ02A_R3_1 | 17FJ02A_R3_2 |
| Wt% oxide | | | | | |
| SiO ₂ | 0.0446 | 0.0352 | 0.0444 | 0.0598 | 0.0522 |
| TiO ₂ | 98.4 | 99.7 | 100 | 99.7 | 101 |
| Al ₂ O ₃ | b.d.l | b.d.l | b.d.l | b.d.l | b.d.l |
| Cr ₂ O ₃ | 0.140 | 0.139 | 0.165 | 0.0861 | 0.0853 |
| FeO | 0.322 | 0.299 | 0.322 | 0.383 | 0.377 |
| MnO | 0.0107 | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| NiO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| CaO | 0.304 | 0.250 | 0.311 | 0.261 | 0.222 |
| Nb ₂ O ₅ | 0.0351 | 0.0252 | 0.0211 | 0.0657 | 0.0573 |
| ZrO ₂ | 0.0198 | 0.0291 | 0.0336 | 0.0276 | 0.0265 |
| HfO ₂ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V ₂ O ₃ | 0.0435 | 0.0503 | 0.0559 | 0.0876 | 0.0703 |
| Total | 99.4 | 100 | 101 | 101 | 102 |
| Elements (ppm) | | | | | |
| Si | 208 | 165 | 207 | 279 | 244 |
| Al | b.d.l | b.d.l | b.d.l | b.d.l. | b.d.l. |
| Cr | 959 | 952 | 1130 | 589 | 584 |
| Fe | 2500 | 2320 | 2500 | 2980 | 2930 |
| Ni | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V | 244 | 282 | 313 | 491 | 394 |
| Nb | 245 | 176 | 148 | 459 | 401 |
| Zr | 147 | 215 | 249 | 204 | 196 |
| Thermometer (Tomki) | | | | | |
| In (Zr ppm) | 4.99 | 5.37 | 5.52 | 5.32 | 5.28 |
| P (Kbar) | 11 | 11 | 11 | 11 | 11 |
| Temperature (°C) | 599 | 628 | 639 | 624 | 621 |
| Error (2σ)* | 27 | 23 | 22 | 24 | 24 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology Type | 17FJ02A_R3_3 | 17FJ02A_R3_4 | 17FJ02A_R3_7 | 17FJ02A_R3_8 | 17FJ02A_R4_2 |
|--------------------------------|--------------|--------------|--------------|--------------|--------------|
| Analyses | | | | | |
| Wt% oxide | | | | | |
| SiO ₂ | 0.0532 | 0.0514 | 0.109 | 0.0972 | 0.0423 |
| TiO ₂ | 100 | 99.0 | 99.8 | 98.4 | 101 |
| Al ₂ O ₃ | b.d.l. | b.d.l. | 0.0106 | b.d.l. | b.d.l. |
| Cr ₂ O ₃ | 0.108 | 0.105 | 0.0813 | 0.0992 | 0.101 |
| FeO | 0.369 | 0.373 | 0.424 | 0.495 | 0.372 |
| MnO | b.d.l. | 0.00920 | b.d.l. | b.d.l. | b.d.l. |
| NiO | b.d.l. | 0.00615 | b.d.l. | b.d.l. | b.d.l. |
| CaO | 0.212 | 0.210 | 0.557 | 0.495 | 0.206 |
| Nb ₂ O ₅ | 0.0512 | 0.0635 | 0.0482 | 0.0729 | 0.0283 |
| ZrO ₂ | 0.0169 | 0.0242 | 0.0328 | 0.0622 | 0.0337 |
| HfO ₂ | b.d.l. | b.d.l. | 0.0233 | b.d.l. | 0.0102 |
| V ₂ O ₃ | 0.0814 | 0.0797 | 0.0586 | 0.0720 | 0.0843 |
| Total | 101 | 99.9 | 101 | 99.8 | 101 |
| Elements (ppm) | | | | | |
| Si | 249 | 240 | 511 | 454 | 198 |
| Al | b.d.l. | b.d.l. | 55.96 | b.d.l. | b.d.l. |
| Cr | 737 | 719 | 556 | 679 | 690 |
| Fe | 2870 | 2900 | 3290 | 3850 | 2890 |
| Ni | b.d.l. | 48.3 | b.d.l. | b.d.l. | b.d.l. |
| V | 456 | 446 | 328 | 404 | 472 |
| Nb | 358 | 444 | 337 | 509 | 198 |
| Zr | 125 | 179 | 242 | 460 | 249 |
| Thermometer (Tomki) | | | | | |
| In (Zr ppm) | 4.83 | 5.19 | 5.49 | 6.13 | 5.52 |
| P (Kbar) | 11 | 11 | 11 | 11 | 11 |
| Temperature (°C) | 588 | 614 | 637 | 690 | 639 |
| Error (2σ)* | 28 | 25 | 23 | 18 | 22 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology | | | | | |
|--------------------------------|--------------|--------------|--------------|--------------|--------------|
| Type | | | | | |
| Analyses | 17FJ02A_R4_3 | 17FJ02A_R4_4 | 17FJ02A_R4_5 | 17FJ02A_R4_6 | 17FJ02A_R4_7 |
| Wt% oxide | | | | | |
| SiO ₂ | 0.0406 | 0.0597 | 0.0920 | 0.0794 | 0.0867 |
| TiO ₂ | 100 | 101 | 99.5 | 101 | 101 |
| Al ₂ O ₃ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| Cr ₂ O ₃ | 0.105 | 0.102 | 0.0983 | 0.0888 | 0.0933 |
| FeO | 0.364 | 0.439 | 0.473 | 0.480 | 0.511 |
| MnO | b.d.l. | b.d.l. | 0.00622 | 0.0125 | b.d.l. |
| NiO | b.d.l. | b.d.l. | 0.00603 | b.d.l. | b.d.l. |
| CaO | 0.252 | 0.320 | 0.441 | 0.413 | 0.467 |
| Nb ₂ O ₅ | 0.0326 | 0.0345 | 0.0397 | 0.0353 | 0.0513 |
| ZrO ₂ | 0.0486 | 0.0325 | 0.0373 | 0.0290 | 0.0505 |
| HfO ₂ | b.d.l. | 0.0168 | b.d.l. | b.d.l. | b.d.l. |
| V ₂ O ₃ | 0.0837 | 0.0648 | 0.0433 | 0.0669 | 0.0733 |
| Total | 101 | 102 | 101 | 103 | 102 |
| Elements (ppm) | | | | | |
| Si | 190 | 279 | 430 | 371 | 405 |
| Al | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| Cr | 717 | 695 | 673 | 607 | 638 |
| Fe | 2830 | 3410 | 3680 | 3730 | 3970 |
| Ni | b.d.l. | b.d.l. | 47.4 | b.d.l. | b.d.l. |
| V | 469 | 363 | 242 | 375 | 411 |
| Nb | 228 | 241 | 278 | 246 | 359 |
| Zr | 360 | 241 | 276 | 215 | 374 |
| Thermometer (Tomki) | | | | | |
| In (Zr ppm) | 5.89 | 5.48 | 5.62 | 5.37 | 5.92 |
| P (Kbar) | 11 | 11 | 11 | 11 | 11 |
| Temperature (°C) | 669 | 637 | 647 | 628 | 672 |
| Error (2σ)* | 19 | 23 | 22 | 23 | 19 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology | | | | | |
|--------------------------------|--------------|--------------|--------------|--------------|--------------|
| Type | | | | | |
| Analyses | 17FJ02A_R4_8 | 17FJ02A_R4_9 | 17FJ02A_R5_2 | 17FJ02A_R5_3 | 17FJ02A_R6_3 |
| Wt% oxide | | | | | |
| SiO ₂ | 0.0752 | 0.0582 | 0.106 | 0.186 | 0.0662 |
| TiO ₂ | 100 | 99.5 | 101 | 98.9 | 101 |
| Al ₂ O ₃ | 0.00592 | b.d.l | 0.00713 | 0.0169 | b.d.l |
| Cr ₂ O ₃ | 0.0832 | 0.0754 | 0.231 | 0.252 | 0.307 |
| FeO | 0.475 | 0.525 | 0.390 | 0.430 | 0.325 |
| MnO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| NiO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| CaO | 0.392 | 0.385 | 0.475 | 0.567 | 0.380 |
| Nb ₂ O ₅ | 0.0502 | 0.0380 | 0.0539 | 0.0615 | 0.0282 |
| ZrO ₂ | 0.0407 | 0.0293 | 0.0421 | 0.0624 | 0.0331 |
| HfO ₂ | b.d.l. | 0.0198 | b.d.l. | b.d.l. | b.d.l. |
| V ₂ O ₃ | 0.0684 | 0.0337 | 0.0456 | 0.0653 | 0.0654 |
| Total | 102 | 101 | 102 | 101 | 102 |
| Elements (ppm) | | | | | |
| Si | 352 | 272 | 497 | 871 | 310 |
| Al | 31.34 | b.d.l | 37.74 | 89.64 | b.d.l. |
| Cr | 569 | 516 | 1578 | 1724 | 2100 |
| Fe | 3690 | 4080 | 3030 | 3340 | 2530 |
| Ni | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V | 383 | 189 | 255 | 366 | 366 |
| Nb | 351 | 266 | 377 | 430 | 197 |
| Zr | 301 | 217 | 312 | 462 | 245 |
| Thermometer (Tomki) | | | | | |
| In (Zr ppm) | 5.71 | 5.38 | 5.74 | 6.14 | 5.50 |
| P (Kbar) | 11 | 11 | 11 | 11 | 11 |
| Temperature (°C) | 654 | 629 | 657 | 690 | 638 |
| Error (2σ)* | 20 | 23 | 20 | 18 | 23 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology Type Analyses | Fracture type-II halo | | | | |
|--------------------------------|-----------------------|--------------|--------------|--------------|--------------|
| | 17FJ02A_R6_4 | 17FJ02A_R6_5 | 17FJ06B_R1_1 | 17FJ06B_R1_2 | 17FJ06B_R1_3 |
| Wt% oxide | | | | | |
| SiO ₂ | 0.0831 | 0.105 | 0.0827 | 0.0330 | 0.0501 |
| TiO ₂ | 99.4 | 99.5 | 101 | 99.5 | 99.4 |
| Al ₂ O ₃ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| Cr ₂ O ₃ | 0.271 | 0.279 | 0.0288 | b.d.l. | 0.0361 |
| FeO | 0.338 | 0.383 | 0.465 | 0.437 | 0.453 |
| MnO | b.d.l. | b.d.l. | b.d.l. | 0.0114 | b.d.l. |
| NiO | b.d.l. | b.d.l. | 0.0102 | b.d.l. | b.d.l. |
| CaO | 0.408 | 0.524 | 0.594 | 0.543 | 0.582 |
| Nb ₂ O ₅ | 0.0321 | 0.0279 | 0.0808 | 0.0772 | 0.0731 |
| ZrO ₂ | 0.0178 | 0.0431 | 0.0322 | 0.0394 | 0.0485 |
| HfO ₂ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V ₂ O ₃ | 0.0766 | 0.0444 | 0.0305 | 0.0268 | 0.0268 |
| Total | 101 | 101 | 102 | 101 | 101 |
| Elements (ppm) | | | | | |
| Si | 388 | 489 | 387 | 154 | 234 |
| Al | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| Cr | 1853 | 1910 | 197 | b.d.l. | 247 |
| Fe | 2630 | 2980 | 3610 | 3400 | 3520 |
| Ni | b.d.l. | b.d.l. | 80.2 | b.d.l. | b.d.l. |
| V | 429 | 249 | 171 | 150 | 150 |
| Nb | 225 | 195 | 565 | 539 | 511 |
| Zr | 132 | 319 | 238 | 291 | 359 |
| Thermometer (Tomki) | | | | | |
| In (Zr ppm) | 4.88 | 5.77 | 5.47 | 5.67 | 5.88 |
| P (Kbar) | 11 | 11 | 12 | 12 | 12 |
| Temperature (°C) | 592 | 659 | 640 | 656 | 673 |
| Error (2σ)* | 27 | 20 | 23 | 22 | 19 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology Type | Leucocratic domain | | | | |
|--------------------------------|--------------------|--------------|--------------|--------------|-----------|
| | Small | | | | |
| Analyses | 17FJ06B_R1_4 | 17FJ06B_R1_5 | 17FJ06B_R2_2 | 17FJ06B_R2_3 | FJ6a-1 R2 |
| Wt% oxide | | | | | |
| SiO ₂ | 0.0951 | 0.204 | 0.722 | 0.188 | 0.0513 |
| TiO ₂ | 98.8 | 99.5 | 99.9 | 100 | 101 |
| Al ₂ O ₃ | 0.0140 | 0.155 | b.d.l | 0.0316 | 0.00889 |
| Cr ₂ O ₃ | 0.0320 | 0.0127 | 0.0177 | 0.101 | 0.0304 |
| FeO | 0.496 | 0.500 | 0.194 | 0.193 | 0.342 |
| MnO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| NiO | b.d.l. | b.d.l. | 0.0586 | 0.0125 | b.d.l. |
| CaO | 0.887 | 0.840 | 0.410 | 0.515 | 0.129 |
| Nb ₂ O ₅ | 0.0706 | 0.0723 | 0.0102 | 0.0197 | 0.166 |
| ZrO ₂ | 0.0379 | 0.0423 | 0.0635 | 0.0530 | 0.0223 |
| HfO ₂ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V ₂ O ₃ | 0.0513 | 0.0396 | 0.0834 | 0.114 | 0.127 |
| Total | 101 | 101 | 102 | 102 | 102 |
| Elements (ppm) | | | | | |
| Si | 444 | 953 | 3370 | 877 | 240 |
| Al | 74.18 | 822.18 | b.d.l | 167.10 | 47.07 |
| Cr | 219 | 87.0 | 121 | 692 | 208 |
| Fe | 3860 | 3890 | 1510 | 1500 | 2660 |
| Ni | b.d.l. | b.d.l. | 461 | 98.6 | b.d.l. |
| V | 287 | 222 | 467 | 637 | 710 |
| Nb | 493 | 506 | 71.6 | 138 | 1160 |
| Zr | 281 | 313 | 470 | 392 | 165 |
| Thermometer (Tomki) | | | | | |
| In (Zr ppm) | 5.64 | 5.75 | 6.15 | 5.97 | 5.11 |
| P (Kbar) | 12 | 12 | 12 | 12 | 12 |
| Temperature (°C) | 653 | 662 | 696 | 681 | 612 |
| Error (2σ)* | 22 | 20 | 18 | 19 | 25 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology | | | | | | | | |
|------------------------------------|-----------|-----------|-----------|------------|------------|------------|------------|------------|
| Type | Large | Large | Large | Large | Large | LAB | LAB | LAB |
| Analyses | FJ6a-1 R5 | FJ6a-1 R7 | FJ6a-1 R9 | FJ6a-1 R10 | FJ6a-1 R11 | FJ6a-1 R14 | FJ6a-1 R15 | FJ6a-1 R17 |
| Wt% oxide | | | | | | | | |
| SiO₂ | b.d.l. | 0.00691 | 0.0134 | 0.0147 | 0.0116 | b.d.l. | 0.00778 | b.d.l. |
| TiO₂ | 101 | 101 | 101 | 101 | 101 | 101 | 100 | 101 |
| Al₂O₃ | b.d.l. | b.d.l. | b.d.l. | 0.0292 | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| Cr₂O₃ | 0.0282 | 0.0456 | 0.0501 | 0.0570 | 0.0334 | 0.0349 | 0.0269 | 0.0293 |
| FeO | 0.550 | 0.441 | 0.446 | 0.372 | 0.288 | 0.381 | 0.384 | 0.363 |
| MnO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | 0.00894 |
| NiO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | 0.00288 | 0.00593 | b.d.l. |
| CaO | 0.00440 | 0.00467 | 0.0202 | 0.0145 | 0.0246 | 0.00362 | 0.0180 | 0.00312 |
| Nb₂O₅ | 0.205 | 0.191 | 0.193 | 0.190 | 0.176 | 0.0685 | 0.0728 | 0.0612 |
| ZrO₂ | 0.1230 | 0.1173 | 0.0445 | 0.0440 | 0.122 | 0.110 | 0.122 | 0.0698 |
| HfO₂ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V₂O₃ | 0.109 | 0.119 | 0.140 | 0.134 | 0.195 | 0.257 | 0.278 | 0.269 |
| Total | 102 | 102 | 101 | 102 | 102 | 102 | 101 | 102 |
| Elements (ppm) | | | | | | | | |
| Si | b.d.l. | 32.3 | 62.7 | 68.7 | 54.3 | b.d.l. | 36.3 | b.d.l. |
| Al | b.d.l. | b.d.l. | b.d.l. | 154.59 | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| Cr | 193 | 312 | 343 | 390 | 229 | 239 | 184 | 201 |
| Fe | 4270 | 3430 | 3470 | 2890 | 2240 | 2960 | 2990 | 2820 |
| Ni | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | 22.6 | 46.6 | b.d.l. |
| V | 613 | 667 | 783 | 751 | 1090 | 1440 | 1560 | 1510 |
| Nb | 1440 | 1340 | 1350 | 1330 | 1230 | 479 | 509 | 428 |
| Zr | 911 | 869 | 329 | 326 | 906 | 813 | 903 | 516 |
| Thermometer (Tomki) | | | | | | | | |
| In (Zr ppm) | 6.81 | 6.77 | 5.80 | 5.79 | 6.81 | 6.70 | 6.81 | 6.25 |
| P (Kbar) | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| Temperature (°C) | 758 | 753 | 666 | 665 | 758 | 747 | 757 | 705 |
| Error (2σ)* | 16 | 16 | 20 | 20 | 16 | 16 | 16 | 18 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology | LAB | | Large | | Small | | Large |
|------------------------------------|------------|------------|------------|------------|-----------|-----------|-----------|
| Type | FJ6a-1 R19 | FJ6a-1 R20 | FJ6a-1 R21 | FJ6a-1 R22 | FJ6a-1 R1 | FJ6a-1 R3 | FJ6a-1 R4 |
| Analyses | | | | | | | |
| Wt% oxide | | | | | | | |
| SiO₂ | 0.0132 | 0.00717 | 0.0148 | 0.0238 | 0.0246 | 0.0387 | 0.0250 |
| TiO₂ | 101 | 100 | 100 | 101 | 102 | 102 | 101 |
| Al₂O₃ | b.d.l | b.d.l | b.d.l | b.d.l | b.d.l | b.d.l | 0.00635 |
| Cr₂O₃ | 0.0420 | 0.0064 | b.d.l | 0.0191 | 0.0585 | 0.0205 | 0.0591 |
| FeO | 0.440 | 0.407 | 0.316 | 0.315 | 0.354 | 0.362 | 0.493 |
| MnO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | 0.00767 | 0.00859 | 0.00822 |
| NiO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| CaO | 0.0088 | 0.0143 | 0.0587 | 0.0524 | 0.0189 | 0.0823 | 0.0141 |
| Nb₂O₅ | 0.0720 | 0.0718 | 0.0383 | 0.0224 | 0.121 | 0.0970 | 0.186 |
| ZrO₂ | 0.123 | 0.104 | 0.0439 | 0.0310 | 0.0353 | 0.0131 | 0.0855 |
| HfO₂ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V₂O₃ | 0.250 | 0.250 | 0.162 | 0.163 | 0.150 | 0.132 | 0.117 |
| Total | 102 | 101 | 101 | 101 | 103 | 103 | 102 |
| Elements (ppm) | | | | | | | |
| Si | 61.6 | 33.5 | 69.2 | 111 | 115 | 181 | 117 |
| Al | b.d.l | b.d.l | b.d.l | b.d.l | b.d.l | b.d.l | 33.6 |
| Cr | 287 | 43.7 | b.d.l | 131 | 400 | 140 | 404 |
| Fe | 3420 | 3170 | 2460 | 2450 | 2750 | 2810 | 3830 |
| Ni | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V | 1400 | 1400 | 908 | 915 | 838 | 738 | 657 |
| Nb | 503 | 502 | 268 | 157 | 845 | 678 | 1300 |
| Zr | 909 | 767 | 325 | 230 | 262 | 97.1 | 633 |
| Thermometer (Tomki) | | | | | | | |
| In (Zr ppm) | 6.81 | 6.64 | 5.78 | 5.44 | 5.57 | 4.58 | 6.45 |
| P (Kbar) | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| Temperature (°C) | 758 | 741 | 665 | 637 | 669 | 598 | 755 |
| Error (2σ)* | 16 | 17 | 20 | 23 | 22 | 32 | 17 |

Table S3 - EMPA major and trace element data for all lithologies

| Lithology | | | | | |
|------------------------------------|-----------|------------|------------|------------|------------|
| Type | Large | LAB | LAB | LAB | LAB |
| Analyses | FJ6a-1 R6 | FJ6a-1 R12 | FJ6a-1 R13 | FJ6a-1 R16 | FJ6a-1 R18 |
| <i>Wt% oxide</i> | | | | | |
| SiO₂ | 0.0120 | 0.0146 | 0.00742 | b.d.l. | 0.00590 |
| TiO₂ | 101 | 101 | 102 | 101 | 101 |
| Al₂O₃ | b.d.l. | 0.00627 | b.d.l. | b.d.l. | 0.0175 |
| Cr₂O₃ | 0.0346 | 0.0530 | 0.0332 | 0.0177 | 0.0289 |
| FeO | 0.478 | 0.311 | 0.257 | 1.13 | 0.381 |
| MnO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| NiO | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| CaO | 0.0160 | 0.0143 | 0.00788 | 0.00346 | 0.00253 |
| Nb₂O₅ | 0.192 | 0.0534 | 0.0584 | 0.0282 | 0.0651 |
| ZrO₂ | 0.0650 | 0.0472 | 0.0788 | 0.0390 | 0.0928 |
| HfO₂ | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V₂O₃ | 0.151 | 0.281 | 0.273 | 0.293 | 0.296 |
| Total | 102 | 102 | 102 | 102 | 102 |
| <i>Elements (ppm)</i> | | | | | |
| Si | 56.2 | 68.3 | 34.7 | b.d.l. | 27.6 |
| Al | b.d.l. | 33.2 | b.d.l. | b.d.l. | 92.7 |
| Cr | 236 | 362 | 227 | 121 | 198 |
| Fe | 3720 | 2410 | 2000 | 8790 | 2960 |
| Ni | b.d.l. | b.d.l. | b.d.l. | b.d.l. | b.d.l. |
| V | 845 | 1570 | 1530 | 1640 | 1660 |
| Nb | 1340 | 373 | 408 | 197 | 455 |
| Zr | 481 | 350 | 584 | 288 | 687 |
| Thermometer (Tomki) | | | | | |
| In (Zr ppm) | 6.18 | 5.86 | 6.37 | 5.66 | 6.53 |
| P (Kbar) | 12 | 12 | 12 | 12 | 12 |
| Temperature (°C) | 734 | 710 | 761 | 702 | 786 |
| Error (2σ)* | 18 | 19 | 17 | 21 | 17 |

Table S4a - LA-ICP-MS U-Pb data for large rutile grains in leucocratic domains

| Grain | Analyses | Distance from grain boundary (μm) | U (ppm) | Pb_c | Ratios | | | | | | Ages | |
|-------|----------|--|---------|---------------|-------------|----------------------------------|---------------|----------------------------------|---------------|-----------------------------------|------|---------------|
| | | | | | $f_{206\%}$ | $^{207}\text{Pb}/^{235}\text{U}$ | $\pm 2\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $\pm 2\sigma$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | | $\pm 2\sigma$ |
| 1 | 1_1-1 | 77 | 8.99 | 4.9 | 0.477 | 0.040 | 0.0644 | 0.0020 | 0.0537 | 0.0041 | 0.37 | 402 |
| | 1_1-2 | 69 | 4.96 | 8.0 | 0.470 | 0.056 | 0.0643 | 0.0019 | 0.0530 | 0.0061 | 0.25 | 402 |
| 2 | 1_2-1 | 31 | 5.06 | 7.5 | 0.488 | 0.062 | 0.0645 | 0.0018 | 0.0549 | 0.0068 | 0.22 | 403 |
| | 1_2-2 | 167 | 8.70 | 4.1 | 0.480 | 0.047 | 0.0637 | 0.0024 | 0.0547 | 0.0049 | 0.39 | 398 |
| | 1_2-3 | 173 | 10.5 | 3.6 | 0.483 | 0.036 | 0.0641 | 0.0021 | 0.0546 | 0.0037 | 0.43 | 401 |
| | 1_2-4 | 10 | 8.6 | 4.8 | 0.479 | 0.038 | 0.0645 | 0.0019 | 0.0538 | 0.0040 | 0.37 | 403 |
| | 1_2-5 | 10 | 8.01 | 5.8 | 0.472 | 0.051 | 0.0626 | 0.0026 | 0.0548 | 0.0055 | 0.38 | 391 |
| 3 | 1_3-1 | 55 | 3.39 | 6.8 | 0.570 | 0.079 | 0.0734 | 0.0030 | 0.0563 | 0.0075 | 0.30 | 456 |
| | 1_3-2 | 95 | 7.80 | 3.7 | 0.508 | 0.053 | 0.0667 | 0.0041 | 0.0553 | 0.0047 | 0.59 | 416 |
| 4 | 1_4-1 | 97 | 23.5 | 1.7 | 0.458 | 0.038 | 0.0584 | 0.0037 | 0.0569 | 0.0030 | 0.77 | 366 |
| | 1_4-2 | 114 | 3.72 | 8.9 | 0.628 | 0.076 | 0.0715 | 0.0024 | 0.0637 | 0.0074 | 0.28 | 445 |
| 5 | 1_5-1 | 80 | 6.25 | 5.4 | 0.476 | 0.071 | 0.0634 | 0.0027 | 0.0545 | 0.0077 | 0.29 | 396 |
| | 1_5-2 | 126 | 8.12 | 3.9 | 0.484 | 0.043 | 0.0647 | 0.0023 | 0.0542 | 0.0044 | 0.40 | 404 |
| | 1_5-3 | 105 | 7.94 | 3.9 | 0.489 | 0.041 | 0.0645 | 0.0029 | 0.0550 | 0.0039 | 0.53 | 403 |
| | 1_5-4 | 10 | 5.22 | 5.9 | 0.494 | 0.057 | 0.0650 | 0.0038 | 0.0550 | 0.0054 | 0.50 | 406 |
| 6 | 1_5-5 | 64 | 8.68 | 6.0 | 0.451 | 0.045 | 0.0613 | 0.0023 | 0.0534 | 0.0050 | 0.37 | 383 |
| | 1_5-6 | 154 | 9.32 | 3.8 | 0.487 | 0.037 | 0.0650 | 0.0023 | 0.0543 | 0.0037 | 0.46 | 406 |
| | 1_5-8 | 92 | 7.03 | 4.4 | 0.488 | 0.044 | 0.0641 | 0.0037 | 0.0552 | 0.0038 | 0.65 | 401 |
| 7 | 2_D-5 | 36 | 13.8 | 2.7 | 0.479 | 0.040 | 0.0645 | 0.0041 | 0.0538 | 0.0029 | 0.77 | 403 |
| 8 | 2_G-1 | 90 | 7.51 | 4.9 | 0.480 | 0.032 | 0.0639 | 0.0018 | 0.0545 | 0.0034 | 0.41 | 399 |
| 9 | 3_C-2 | 80 | 5.12 | 5.9 | 0.542 | 0.068 | 0.0641 | 0.0047 | 0.0613 | 0.0062 | 0.58 | 401 |
| 10 | 3_G2-2 | 84 | 7.74 | 4.0 | 0.499 | 0.056 | 0.0660 | 0.0033 | 0.0549 | 0.0055 | 0.44 | 412 |
| | 3_G2-3 | 40 | 8.47 | 3.3 | 0.498 | 0.050 | 0.0660 | 0.0029 | 0.0547 | 0.0050 | 0.43 | 412 |
| 11 | 3_K-1 | 86 | 7.78 | 3.9 | 0.525 | 0.040 | 0.0686 | 0.0021 | 0.0556 | 0.0039 | 0.39 | 428 |
| | 3_K-2 | 142 | 6.95 | 4.3 | 0.519 | 0.061 | 0.0698 | 0.0024 | 0.0539 | 0.0060 | 0.30 | 435 |
| | 3_K-3 | 89 | 5.42 | 6.0 | 0.502 | 0.068 | 0.0654 | 0.0026 | 0.0557 | 0.0073 | 0.29 | 408 |
| 12 | 4_BI-3 | 22 | 4.35 | 8.8 | 0.508 | 0.059 | 0.0667 | 0.0039 | 0.0552 | 0.0056 | 0.50 | 417 |
| 13 | 4_I-1 | 33 | 5.26 | 6.9 | 0.562 | 0.066 | 0.0726 | 0.0038 | 0.0562 | 0.0059 | 0.44 | 451 |

Table S4a - LA-ICP-MS U-Pb data for large rutile grains in leucocratic domains

| | | <i>f</i> 206% | | ²⁰⁷ Pb/ ²³⁵ U | ±2σ | ²⁰⁶ Pb/ ²³⁸ U | ±2σ | ²⁰⁷ Pb/ ²⁰⁶ Pb | ±2σ | rho | ²⁰⁶ Pb/ ²³⁸ U | |
|----|---------|---------------|------|-------------------------------------|-------|-------------------------------------|--------|--------------------------------------|--------|--------|-------------------------------------|-----|
| 14 | 4_M-2 | 69 | 4.33 | 4.6 | 0.458 | 0.054 | 0.0643 | 0.0044 | 0.0517 | 0.0049 | 0.59 | 402 |
| 15 | 4_N-5 | 33 | 8.74 | 3.9 | 0.485 | 0.046 | 0.0674 | 0.0020 | 0.0523 | 0.0048 | 0.31 | 420 |
| | 4_N-6 | 74 | 7.22 | 4.7 | 0.510 | 0.051 | 0.0699 | 0.0019 | 0.0529 | 0.0051 | 0.27 | 436 |
| 16 | 4_NII-2 | 36 | 8.00 | 5.0 | 0.541 | 0.048 | 0.0712 | 0.0034 | 0.0552 | 0.0041 | 0.54 | 443 |
| 17 | 5_D-1 | 47 | 11.3 | 3.0 | 0.497 | 0.044 | 0.0646 | 0.0034 | 0.0558 | 0.0040 | 0.59 | 404 |
| | 5_D-2 | 49 | 3.42 | 9.9 | 0.496 | 0.072 | 0.0671 | 0.0029 | 0.0536 | 0.0074 | 0.30 | 419 |
| | 5_D-3 | 160 | 17.4 | 2.3 | 0.492 | 0.042 | 0.0656 | 0.0026 | 0.0544 | 0.0041 | 0.47 | 410 |
| | 5_D-4 | 20 | 6.50 | 4.7 | 0.573 | 0.046 | 0.0738 | 0.0029 | 0.0563 | 0.0039 | 0.49 | 459 |
| | 5_D-5 | 46 | 13.0 | 2.9 | 0.484 | 0.030 | 0.0682 | 0.0025 | 0.0516 | 0.0026 | 0.60 | 425 |
| 18 | 6_B-2 | 43 | 4.35 | 7.7 | 0.603 | 0.079 | 0.0773 | 0.0036 | 0.0566 | 0.0069 | 0.36 | 480 |
| 19 | 6_G2-2 | 27 | 10.9 | 3.1 | 0.544 | 0.029 | 0.0718 | 0.0017 | 0.0550 | 0.0026 | 0.45 | 447 |
| | 6_G2-3 | 36 | 6.13 | 5.2 | 0.544 | 0.048 | 0.0704 | 0.0022 | 0.0560 | 0.0046 | 0.36 | 439 |
| | 6_G2-4 | 28 | 4.43 | 7.1 | 0.577 | 0.088 | 0.0742 | 0.0022 | 0.0564 | 0.0084 | 0.19 | 461 |
| 20 | 6_H1-1 | 24 | 12.0 | 2.7 | 0.526 | 0.040 | 0.0687 | 0.0015 | 0.0555 | 0.0041 | 0.29 | 428 |
| | 6_H1-2 | 73 | 12.6 | 2.8 | 0.521 | 0.029 | 0.0672 | 0.0019 | 0.0563 | 0.0027 | 0.50 | 419 |
| | 6_H1-3 | 70 | 14.4 | 2.5 | 0.530 | 0.032 | 0.0686 | 0.0026 | 0.0560 | 0.0026 | 0.63 | 428 |
| | 6_H1-4 | 67 | 14.0 | 2.6 | 0.555 | 0.038 | 0.0684 | 0.0023 | 0.0589 | 0.0036 | 0.48 | 426 |
| 21 | 6_H1-6 | 46 | 9.90 | 3.4 | 0.526 | 0.043 | 0.0691 | 0.0029 | 0.0552 | 0.0039 | 0.51 | 431 |
| | 6_H1-7 | 9 | 12.1 | 3.0 | 0.523 | 0.041 | 0.0686 | 0.0020 | 0.0553 | 0.0041 | 0.37 | 427 |
| 22 | 6_H3-1 | 33 | 9.93 | 3.5 | 0.493 | 0.030 | 0.0683 | 0.0021 | 0.0523 | 0.0028 | 0.50 | 426 |
| | 6_H3-3 | 46 | 13.7 | 2.7 | 0.503 | 0.044 | 0.0699 | 0.0049 | 0.0522 | 0.0027 | 0.81 | 435 |
| 23 | 6_J1-2 | 37 | 11.9 | 3.4 | 0.491 | 0.057 | 0.0642 | 0.0053 | 0.0555 | 0.0045 | 0.71 | 401 |
| | 6_J1-3 | 73 | 5.37 | 7.1 | 0.497 | 0.068 | 0.0647 | 0.0028 | 0.0558 | 0.0072 | 0.32 | 404 |
| 24 | 7_E-1 | 34 | 4.35 | 6.2 | 0.526 | 0.058 | 0.0670 | 0.0025 | 0.0570 | 0.0059 | 0.34 | 418 |
| 25 | 7_G1-3 | 252 | 9.79 | 4.8 | 0.445 | 0.031 | 0.0622 | 0.0013 | 0.0520 | 0.0034 | 0.31 | 389 |
| | 7_G1-4 | 144 | 8.31 | 3.1 | 0.530 | 0.037 | 0.0697 | 0.0025 | 0.0552 | 0.0033 | 0.51 | 434 |
| | 7_G1-5 | 60 | 12.5 | 2.2 | 0.483 | 0.027 | 0.0639 | 0.0025 | 0.0548 | 0.0023 | 0.68 | 400 |
| | 7_G1-6 | 170 | 9.28 | 2.8 | 0.500 | 0.032 | 0.0648 | 0.0021 | 0.0560 | 0.0030 | 0.52 | 405 |
| | 7_G1-7 | 71 | 9.09 | 3.1 | 0.447 | 0.034 | 0.0598 | 0.0019 | 0.0541 | 0.0038 | 0.42 | 375 |
| 26 | 7_G2-1 | 35 | 7.36 | 3.8 | 0.521 | 0.044 | 0.0653 | 0.0020 | 0.0578 | 0.0045 | 0.37 | 408 |
| | 7_G2-2 | 56 | 5.80 | 4.9 | 0.484 | 0.038 | 0.0642 | 0.0018 | 0.0547 | 0.0040 | 0.37 | 401 |

Table S4a - LA-ICP-MS U-Pb data for large rutile grains in leucocratic domains

| | | f206% | | $^{207}\text{Pb}/^{235}\text{U}$ | $\pm 2\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $\pm 2\sigma$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $\pm 2\sigma$ | rho | $^{206}\text{Pb}/^{238}\text{U}$ |
|-----------|-----|--------------|-----|----------------------------------|---------------|----------------------------------|---------------|-----------------------------------|---------------|------|----------------------------------|
| 7_G2-3 | 62 | 12.2 | 2.3 | 0.511 | 0.026 | 0.0679 | 0.0017 | 0.0546 | 0.0024 | 0.50 | 424 |
| 7_G2-4 | 33 | 3.90 | 7.8 | 0.538 | 0.060 | 0.0711 | 0.0020 | 0.0549 | 0.0059 | 0.25 | 443 |
| 27 7_L1-1 | 56 | 7.07 | 3.4 | 0.484 | 0.045 | 0.0643 | 0.0033 | 0.0546 | 0.0042 | 0.55 | 402 |
| 7_L1-2 | 21 | 12.4 | 2.5 | 0.472 | 0.037 | 0.0665 | 0.0026 | 0.0515 | 0.0035 | 0.51 | 415 |
| 7_L1-3 | 143 | 13.9 | 2.1 | 0.499 | 0.040 | 0.0660 | 0.0030 | 0.0548 | 0.0037 | 0.56 | 412 |
| 7_L1-4 | 26 | 12.1 | 2.4 | 0.518 | 0.031 | 0.0679 | 0.0020 | 0.0553 | 0.0028 | 0.50 | 423 |
| 7_L1-6 | 6 | 9.21 | 2.6 | 0.489 | 0.038 | 0.0650 | 0.0036 | 0.0546 | 0.0031 | 0.70 | 406 |
| 28 7_L2-1 | 30 | 8.04 | 3.4 | 0.617 | 0.050 | 0.0788 | 0.0026 | 0.0568 | 0.0042 | 0.41 | 489 |
| 7_L2-2 | 60 | 12.1 | 2.8 | 0.542 | 0.045 | 0.0708 | 0.0044 | 0.0555 | 0.0031 | 0.74 | 441 |

Table S4a - LA-ICP-MS U-Pb data for large rutile grains in leucocratic domains

| Grain | Analyses | Discordance (%) | | | Peak age on radial plot (Fig. 10e) | Mean grain age | Mean grain age | | | Mean ratios | |
|-------|----------|-----------------|----------------------------------|---------------|------------------------------------|----------------|----------------------------------|---------------|----------------------------------|-------------|---------------|
| | | $\pm 2\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ | $\pm 2\sigma$ | | | $^{207}\text{Pb}/^{235}\text{U}$ | $\pm 2\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | | $\pm 2\sigma$ |
| 1 | 1_1-1 | 12 | 396 | 27 | 1.6 | 1 | 394 | 22 | 402 | 8.3 | 0.475 |
| | 1_1-2 | 11 | 391 | 39 | 2.7 | 1 | | | | | |
| 2 | 1_2-1 | 11 | 403 | 43 | -0.15 | 1 | 398 | 14 | 400 | 5.7 | 0.480 |
| | 1_2-2 | 15 | 398 | 32 | -0.024 | 1 | | | | | |
| | 1_2-3 | 12 | 400 | 25 | 0.19 | 1 | | | | | |
| | 1_2-4 | 11 | 397 | 26 | 1.5 | 1 | | | | | |
| | 1_2-5 | 16 | 393 | 35 | -0.42 | 1 | | | | | |
| 3 | 1_3-1 | 18 | 458 | 51 | -0.33 | 2 | 431 | 29 | 442 | 15 | 0.527 |
| | 1_3-2 | 25 | 417 | 36 | -0.27 | 1 | | | | | |
| 4 | 1_4-1 | 23 | 383 | 26 | -4.6 | exc. | 409 | 23 | 422 | 12 | 0.490 |
| | 1_4-2 | 15 | 495 | 48 | -11 | 1 | | | | | |
| 5 | 1_5-1 | 17 | 396 | 49 | 0.10 | 1 | 403 | 17 | 402 | 8.5 | 0.487 |
| | 1_5-2 | 14 | 400 | 29 | 0.9 | 1 | | | | | |
| | 1_5-3 | 18 | 404 | 28 | -0.34 | 1 | | | | | |
| | 1_5-4 | 23 | 407 | 38 | -0.27 | 1 | | | | | |
| 6 | 1_5-5 | 14 | 378 | 32 | 1.4 | 1 | 393 | 20 | 396 | 8.9 | 0.477 |
| | 1_5-6 | 14 | 403 | 25 | 0.77 | 1 | | | | | |
| | 1_5-8 | 23 | 404 | 30 | -0.75 | 1 | | | | | |
| 7 | 2_D-5 | 25 | 397 | 27 | 1.5 | 1 | 397 | 27 | 403 | 25 | 0.479 |
| 8 | 2_G-1 | 11 | 398 | 22 | 0.29 | 1 | 398 | 22 | 399 | 11 | 0.480 |
| 9 | 3_C-2 | 28 | 440 | 45 | -9.8 | exc. | 440 | 45 | 401 | 28 | 0.542 |
| 10 | 3_G2-2 | 20 | 411 | 38 | 0.13 | 1 | 411 | 25 | 412 | 13 | 0.499 |
| | 3_G2-3 | 17 | 410 | 34 | 0.46 | 1 | | | | | |
| 11 | 3_K-1 | 12 | 429 | 27 | -0.28 | 2 | 427 | 22 | 425 | 8.1 | 0.519 |
| | 3_K-2 | 15 | 425 | 40 | 2.4 | 2 | | | | | |
| | 3_K-3 | 16 | 413 | 46 | -1.2 | 1 | | | | | |
| 12 | 4_BI-3 | 24 | 417 | 40 | -0.21 | 1 | 417 | 40 | 417 | 24 | 0.508 |
| 13 | 4_I-1 | 23 | 453 | 43 | -0.34 | 2 | 453 | 43 | 451 | 23 | 0.562 |

Table S4a - LA-ICP-MS U-Pb data for large rutile grains in leucocratic domains

| | $\pm 2\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ | $\pm 2\sigma$ | $\frac{^{207}\text{Pb}/^{235}\text{U}}{(^{206}\text{Pb}/^{238}\text{U})}$ | | $^{207}\text{Pb}/^{235}\text{U}$ | $\pm 2\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $\pm 2\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ |
|------------|---------------|----------------------------------|---------------|---|------|----------------------------------|---------------|----------------------------------|---------------|----------------------------------|
| 14 4_M-2 | 27 | 383 | 37 | 4.7 | 1 | 383 | 37 | 402 | 27 | 0.458 |
| 15 4_N-5 | 12 | 402 | 32 | 4.4 | 2 | 409 | 23 | 428 | 8.2 | 0.496 |
| 4_N-6 | 11 | 418 | 34 | 4.0 | 2 | | | | | |
| 16 4_NII-2 | 21 | 439 | 32 | 0.88 | 2 | 439 | 32 | 443 | 21 | 0.541 |
| 17 5_D-1 | 20 | 410 | 30 | -1.5 | 1 | 415 | 13 | 411 | 10 | 0.504 |
| 5_D-2 | 17 | 409 | 49 | 2.3 | 1 | | | | | |
| 5_D-3 | 16 | 407 | 29 | 0.77 | 1 | | | | | |
| 5_D-4 | 17 | 460 | 30 | -0.26 | 2 | | | | | |
| 5_D-5 | 15 | 401 | 21 | 5.6 | exc. | | | | | |
| 18 6_B-2 | 22 | 479 | 50 | 0.16 | 2 | 479 | 50 | 480 | 22 | 0.603 |
| 19 6_G2-2 | 10 | 441 | 19 | 1.3 | 2 | 443 | 16 | 449 | 7.0 | 0.547 |
| 6_G2-3 | 13 | 441 | 32 | -0.51 | 2 | | | | | |
| 6_G2-4 | 13 | 463 | 57 | -0.27 | 2 | | | | | |
| 20 6_H1-1 | 9.1 | 429 | 27 | -0.15 | 2 | 433 | 11 | 426 | 5.8 | 0.531 |
| 6_H1-2 | 11 | 426 | 19 | -1.6 | 2 | | | | | |
| 6_H1-3 | 15 | 432 | 21 | -0.92 | 2 | | | | | |
| 6_H1-4 | 14 | 448 | 25 | -5.1 | exc. | | | | | |
| 21 6_H1-6 | 17 | 429 | 29 | 0.30 | 2 | 428 | 20 | 429 | 10 | 0.524 |
| 6_H1-7 | 12 | 427 | 28 | 0.13 | 2 | | | | | |
| 22 6_H3-1 | 13 | 407 | 21 | 4.5 | 2 | 409 | 17 | 424 | 11 | 0.496 |
| 6_H3-3 | 30 | 414 | 30 | 5.0 | exc. | | | | | |
| 23 6_J1-2 | 32 | 406 | 39 | -1.2 | 1 | 407 | 30 | 403 | 15 | 0.494 |
| 6_J1-3 | 17 | 410 | 46 | -1.5 | 1 | | | | | |
| 24 7_E-1 | 15 | 429 | 39 | -2.7 | 1 | 429 | 39 | 418 | 15 | 0.526 |
| 25 7_G1-3 | 8.1 | 374 | 22 | 3.8 | 1 | 398 | 10 | 390 | 5.5 | 0.479 |
| 7_G1-4 | 15 | 432 | 24 | 0.50 | 2 | | | | | |
| 7_G1-5 | 15 | 400 | 19 | -0.15 | 1 | | | | | |
| 7_G1-6 | 13 | 412 | 21 | -1.8 | 1 | | | | | |
| 7_G1-7 | 12 | 375 | 24 | -0.086 | 1 | | | | | |
| 26 7_G2-1 | 12 | 426 | 29 | -4.3 | 1 | 418 | 12 | 419 | 7.8 | 0.509 |
| 7_G2-2 | 11 | 401 | 26 | 0.042 | 1 | | | | | |

Table S4a - LA-ICP-MS U-Pb data for large rutile grains in leucocratic domains

| | $\pm 2\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ | $\pm 2\sigma$ | $\frac{^{207}\text{Pb}/^{235}\text{U}}{(^{206}\text{Pb}/^{238}\text{U})}$ | | $^{207}\text{Pb}/^{235}\text{U}$ | $\pm 2\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $\pm 2\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ |
|-----------|---------------|----------------------------------|---------------|---|--|----------------------------------|---------------|----------------------------------|---------------|----------------------------------|
| 7_G2-3 | 10 | 419 | 17 | 1.1 | | 2 | | | | |
| 7_G2-4 | 12 | 437 | 40 | 1.3 | | 2 | | | | |
| 27 7_L1-1 | 20 | 401 | 31 | 0.16 | | 1 | 409 | 11 | 415 | 8.3 |
| 7_L1-2 | 16 | 393 | 26 | 5.3 | | exc. | | | | |
| 7_L1-3 | 18 | 411 | 27 | 0.24 | | 1 | | | | |
| 7_L1-4 | 12 | 424 | 21 | -0.11 | | 2 | | | | |
| 7_L1-6 | 22 | 404 | 26 | 0.39 | | 1 | | | | |
| 28 7_L2-1 | 16 | 488 | 31 | 0.22 | | 2 | 462 | 22 | 477 | 13 |
| 7_L2-2 | 26 | 440 | 30 | 0.32 | | 2 | | | | |

Table S4a - LA-ICP-MS U-Pb data for large rutile grains in leucocratic domains

| Grain | Analyses | | Mean rho | Grain diameter (μm) | Grain orientation spread (°) | | |
|-------|----------|---------------|----------------------------------|---------------------|------------------------------|-----|------|
| | | $\pm 2\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $\pm 2\sigma$ | | | |
| 1 | 1_1-1 | 0.032 | 0.064 | 0.001 | 0.310 | 352 | 0.35 |
| | 1_1-2 | | | | | | |
| 2 | 1_2-1 | 0.020 | 0.064 | 0.001 | 0.356 | 660 | 0.3 |
| | 1_2-2 | | | | | | |
| | 1_2-3 | | | | | | |
| | 1_2-4 | | | | | | |
| | 1_2-5 | | | | | | |
| 3 | 1_3-1 | 0.044 | 0.071 | 0.041 | 0.442 | 366 | 0.44 |
| | 1_3-2 | | | | | | |
| 4 | 1_4-1 | 0.860 | 0.068 | 0.077 | 0.524 | 512 | 4.4 |
| | 1_4-2 | | | | | | |
| 5 | 1_5-1 | 0.025 | 0.064 | 0.001 | 0.432 | 481 | 0.38 |
| | 1_5-2 | | | | | | |
| | 1_5-3 | | | | | | |
| | 1_5-4 | | | | | | |
| 6 | 1_5-5 | 0.024 | 0.063 | 0.005 | 0.490 | 679 | 3.7 |
| | 1_5-6 | | | | | | |
| | 1_5-8 | | | | | | |
| 7 | 2_D-5 | 0.040 | 0.065 | 0.004 | 0.765 | 511 | 3.0 |
| 8 | 2_G-1 | 0.032 | 0.064 | 0.002 | 0.415 | 396 | 0.88 |
| 9 | 3_C-2 | 0.068 | 0.064 | 0.005 | 0.585 | 337 | 0.82 |
| 10 | 3_G2-2 | 0.037 | 0.066 | 0.002 | 0.439 | 459 | 0.53 |
| | 3_G2-3 | | | | | | |
| 11 | 3_K-1 | 0.030 | 0.068 | 0.005 | 0.327 | 666 | 2.1 |
| | 3_K-2 | | | | | | |
| | 3_K-3 | | | | | | |
| 12 | 4_BI-3 | 0.059 | 0.067 | 0.004 | 0.503 | 224 | 6.1 |
| 13 | 4_I-1 | 0.066 | 0.073 | 0.004 | 0.444 | 368 | 0.42 |

Table S4a - LA-ICP-MS U-Pb data for large rutile grains in leucocratic domains

| | $\pm 2\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $\pm 2\sigma$ | | | |
|------------|---------------|----------------------------------|---------------|-------|-----|------|
| 14 4_M-2 | 0.054 | 0.064 | 0.004 | 0.589 | 361 | 0.54 |
| 15 4_N-5 | 0.034 | 0.069 | 0.016 | 0.288 | 428 | 1.5 |
| 4_N-6 | | | | | | |
| 16 4_NII-2 | 0.048 | 0.071 | 0.003 | 0.541 | 229 | 0.16 |
| 17 5_D-1 | 0.043 | 0.068 | 0.004 | 0.490 | 471 | 0.38 |
| 5_D-2 | | | | | | |
| 5_D-3 | | | | | | |
| 5_D-4 | | | | | | |
| 5_D-5 | | | | | | |
| 18 6_B-2 | 0.079 | 0.077 | 0.004 | 0.357 | 276 | 1.4 |
| 19 6_G2-2 | 0.024 | 0.072 | 0.004 | 0.333 | 311 | 0.52 |
| 6_G2-3 | | | | | | |
| 6_G2-4 | | | | | | |
| 20 6_H1-1 | 0.017 | 0.068 | 0.001 | 0.474 | 464 | 0.34 |
| 6_H1-2 | | | | | | |
| 6_H1-3 | | | | | | |
| 6_H1-4 | | | | | | |
| 21 6_H1-6 | 0.030 | 0.069 | 0.002 | 0.440 | 315 | 1.5 |
| 6_H1-7 | | | | | | |
| 22 6_H3-1 | 0.025 | 0.069 | 0.002 | 0.654 | 392 | 0.51 |
| 6_H3-3 | | | | | | |
| 23 6_J1-2 | 0.044 | 0.065 | 0.002 | 0.516 | 328 | 0.52 |
| 6_J1-3 | | | | | | |
| 24 7_E-1 | 0.058 | 0.067 | 0.003 | 0.343 | 376 | 0.5 |
| 25 7_G1-3 | 0.042 | 0.063 | 0.004 | 0.490 | 774 | 4.7 |
| 7_G1-4 | | | | | | |
| 7_G1-5 | | | | | | |
| 7_G1-6 | | | | | | |
| 7_G1-7 | | | | | | |
| 26 7_G2-1 | 0.018 | 0.067 | 0.005 | 0.371 | 588 | 1.1 |
| 7_G2-2 | | | | | | |

Table S4a - LA-ICP-MS U-Pb data for large rutile grains in leucocratic domains

| | $\pm 2\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$ | $\pm 2\sigma$ | | | |
|-----------|---------------|----------------------------------|---------------|-----|------|--|
| 7_G2-3 | | | | | | |
| 7_G2-4 | | | | | | |
| 27 7_L1-1 | 0.017 | 0.066 | 0.537 | 521 | 0.38 | |
| 7_L1-2 | | | | | | |
| 7_L1-3 | | | | | | |
| 7_L1-4 | | | | | | |
| 7_L1-6 | | | | | | |
| 28 7_L2-1 | 0.480 | | 0.740 | 320 | 0.29 | |
| 7_L2-2 | | | | | | |

Table S4b - SHRIMP U-Pb data for large rutile grains in leucocratic domains

| Grain | Analyses | U (ppm) | Pb _c | Ratios | | | | | | Ages | | | |
|-------|--------------|---------|-----------------|---------------|-------------------------------------|--------|-------------------------------------|--------|--------------------------------------|------|-----|-------------------------------------|-----|
| | | | | <i>f</i> 206% | ²⁰⁷ Pb/ ²³⁵ U | ±2σ | ²⁰⁶ Pb/ ²³⁸ U | ±2σ | ²⁰⁷ Pb/ ²⁰⁶ Pb | ±2σ | rho | ²⁰⁶ Pb/ ²³⁸ U | ±2σ |
| 29 | N17-44A1-3 | 12.3 | 0.41 | 0.524 | 0.013 | 0.0659 | 0.0011 | 0.0577 | 0.0011 | 0.64 | 411 | 6.4 | 428 |
| | N17-44A.1-6 | 8.90 | 0.58 | 0.484 | 0.013 | 0.0644 | 0.00097 | 0.0545 | 0.0013 | 0.52 | 402 | 5.9 | 401 |
| | N17-44A.1-7 | 8.47 | 0.79 | 0.506 | 0.014 | 0.0659 | 0.00099 | 0.0556 | 0.0013 | 0.50 | 411 | 6.0 | 416 |
| | N17-44A.1-9 | 8.70 | 0.81 | 0.456 | 0.013 | 0.0636 | 0.00095 | 0.0521 | 0.0013 | 0.49 | 397 | 5.8 | 381 |
| | N17-44A.1-11 | 9.01 | 0.77 | 0.504 | 0.015 | 0.0665 | 0.0014 | 0.0549 | 0.0013 | 0.63 | 415 | 8.4 | 414 |
| 30 | N17-44B.2-2 | 6.92 | 1.2 | 0.500 | 0.024 | 0.0642 | 0.0013 | 0.0565 | 0.0024 | 0.38 | 401 | 7.8 | 412 |
| | N17-44B.2-10 | 5.11 | 1.1 | 0.515 | 0.043 | 0.0675 | 0.0014 | 0.0554 | 0.0044 | 0.25 | 421 | 8.6 | 422 |
| 31 | N17-44C.1-2 | 10.9 | 0.92 | 0.491 | 0.021 | 0.0669 | 0.0013 | 0.0532 | 0.0020 | 0.42 | 417 | 8.1 | 406 |
| | N17-44C.1-3 | 11.0 | 0.60 | 0.508 | 0.014 | 0.0672 | 0.0012 | 0.0549 | 0.0012 | 0.61 | 419 | 7.3 | 417 |
| | N17-44C.1-4 | 7.89 | 0.73 | 0.517 | 0.020 | 0.0663 | 0.0021 | 0.0565 | 0.0014 | 0.76 | 414 | 12 | 423 |
| | N17-44C.1-5 | 7.14 | 0.75 | 0.509 | 0.020 | 0.0652 | 0.0019 | 0.0566 | 0.0016 | 0.68 | 407 | 11 | 418 |
| | N17-44C.1-6 | 6.25 | 0.95 | 0.520 | 0.023 | 0.0662 | 0.0030 | 0.0570 | 0.0018 | 0.76 | 413 | 18 | 425 |
| | N17-44C.1-8 | 7.75 | 1.1 | 0.522 | 0.017 | 0.0673 | 0.0015 | 0.0562 | 0.0015 | 0.64 | 420 | 9.4 | 426 |
| | N17-44C.1-9 | 5.27 | 1.3 | 0.516 | 0.019 | 0.0654 | 0.0016 | 0.0572 | 0.0018 | 0.53 | 408 | 9.5 | 422 |
| | N17-44C.1-16 | 9.47 | 0.73 | 0.518 | 0.017 | 0.0674 | 0.0017 | 0.0557 | 0.0012 | 0.72 | 420 | 10 | 424 |
| 32 | N17-44E.1-2 | 13.6 | 0.51 | 0.476 | 0.019 | 0.0636 | 0.0014 | 0.0543 | 0.0018 | 0.53 | 397 | 8.5 | 395 |
| | N17-44E.1-3 | 13.8 | 0.46 | 0.498 | 0.020 | 0.0649 | 0.0015 | 0.0556 | 0.0018 | 0.56 | 405 | 9.0 | 410 |
| | N17-44E.1-4 | 13.0 | 0.66 | 0.474 | 0.018 | 0.0606 | 0.0011 | 0.0567 | 0.0019 | 0.44 | 379 | 6.6 | 394 |
| | N17-44E.1-5 | 13.5 | 0.66 | 0.489 | 0.030 | 0.0634 | 0.0016 | 0.0559 | 0.0031 | 0.42 | 396 | 10 | 404 |
| 33 | N17-44G.1-10 | 10.2 | 0.65 | 0.553 | 0.017 | 0.0706 | 0.0016 | 0.0569 | 0.0013 | 0.77 | 440 | 9.4 | 447 |
| | N17-44G.1-12 | 10.8 | 0.66 | 0.524 | 0.013 | 0.0689 | 0.0010 | 0.0551 | 0.0011 | 0.37 | 430 | 6.2 | 428 |
| | N17-44G.1-13 | 8.44 | 0.43 | 0.544 | 0.013 | 0.0703 | 0.0012 | 0.0561 | 0.0010 | 0.31 | 438 | 7.2 | 441 |
| | N17-44G.1-16 | 7.59 | 0.41 | 0.533 | 0.011 | 0.0711 | 0.0010 | 0.0543 | 0.00087 | 0.51 | 443 | 6.0 | 434 |
| | N17-44G.1-17 | 11.1 | 0.38 | 0.528 | 0.011 | 0.0704 | 0.00092 | 0.0544 | 0.00082 | 0.66 | 439 | 5.5 | 430 |
| | N17-44G.1-2 | 8.24 | 1.3 | 0.526 | 0.023 | 0.0697 | 0.0013 | 0.0547 | 0.0021 | 0.67 | 434 | 8.0 | 429 |
| | N17-44G.1-3 | 9.58 | 1.1 | 0.523 | 0.017 | 0.0690 | 0.0019 | 0.0550 | 0.0012 | 0.56 | 430 | 11 | 427 |
| | N17-44G.1-4 | 11.7 | 0.50 | 0.521 | 0.019 | 0.0685 | 0.0013 | 0.0552 | 0.0019 | 0.68 | 427 | 7.9 | 426 |
| | N17-44G.1-5 | 15.2 | 1.4 | 0.532 | 0.024 | 0.0732 | 0.0014 | 0.0527 | 0.0023 | 0.63 | 455 | 8.4 | 433 |
| | N17-44G.1-6 | 15.8 | 0.89 | 0.527 | 0.014 | 0.0706 | 0.0024 | 0.0541 | 0.0016 | 0.64 | 440 | 14 | 430 |

Table S4b - SHRIMP U-Pb data for large rutile grains in leucocratic domains

| Grain | Analyses | U (ppm) | Pb _c | Ratios | | | | | | | Ages | | |
|-------|-------------|---------|-----------------|---------------|-------------------------------------|--------|-------------------------------------|--------|--------------------------------------|------|------|-------------------------------------|-----|
| | | | | <i>f</i> 206% | ²⁰⁷ Pb/ ²³⁵ U | ±2σ | ²⁰⁶ Pb/ ²³⁸ U | ±2σ | ²⁰⁷ Pb/ ²⁰⁶ Pb | ±2σ | rho | ²⁰⁶ Pb/ ²³⁸ U | ±2σ |
| | N17-44G.1-7 | 9.46 | 0.86 | 0.578 | 0.016 | 0.0719 | 0.0015 | 0.0583 | 0.0012 | 0.40 | 448 | 9.1 | 463 |

Table S4b - SHRIMP U-Pb data for large rutile grains in leucocratic domains

| Grain | Analyses | Discordance (%) | | Mean grain age | Grain diameter (µm) | Grain orientation spread (°) |
|-------------|--------------|-----------------|--|----------------------------------|---------------------|------------------------------|
| | | $\pm 2\sigma$ | $(^{206}\text{Pb}/^{238}\text{U} - ^{207}\text{Pb}/^{235}\text{U}) / (^{206}\text{Pb}/^{238}\text{U})$ | $^{206}\text{Pb}/^{238}\text{U}$ | | |
| 29 | N17-44A1-3 | 8.7 | -4.0 | 406 | 384 | 3.9 |
| | N17-44A.1-6 | 8.9 | 0.38 | | | |
| | N17-44A.1-7 | 9.6 | -1.1 | | | |
| | N17-44A.1-9 | 8.9 | 4.0 | | | |
| | N17-44A.1-11 | 10 | 0.15 | | | |
| 30 | N17-44B.2-2 | 16 | -2.6 | 410 | n.m | n.m |
| | N17-44B.2-10 | 29 | -0.17 | | | |
| 31 | N17-44C.1-2 | 14 | 2.8 | 416 | 896 | 2.8 |
| | N17-44C.1-3 | 9.2 | 0.52 | | | |
| | N17-44C.1-4 | 14 | -2.3 | | | |
| | N17-44C.1-5 | 13 | -2.6 | | | |
| | N17-44C.1-6 | 16 | -2.9 | | | |
| | N17-44C.1-8 | 12 | -1.6 | | | |
| | N17-44C.1-9 | 13 | -3.5 | | | |
| | N17-44C.1-16 | 11 | -0.79 | | | |
| 32 | N17-44E.1-2 | 13 | 0.54 | 393 | n.m | n.m |
| | N17-44E.1-3 | 14 | -1.2 | | | |
| | N17-44E.1-4 | 12 | -3.9 | | | |
| | N17-44E.1-5 | 20 | -2.0 | | | |
| 33 | N17-44G.1-10 | 11 | -1.6 | 437 | 483 | 0.69 |
| | N17-44G.1-12 | 8.7 | 0.40 | | | |
| | N17-44G.1-13 | 8.6 | -0.71 | | | |
| | N17-44G.1-16 | 7.4 | 2.0 | | | |
| | N17-44G.1-17 | 7.0 | 1.8 | | | |
| | N17-44G.1-2 | 15 | 1.2 | | | |
| | N17-44G.1-3 | 12 | 0.69 | | | |
| | N17-44G.1-4 | 13 | 0.30 | | | |
| N17-44G.1-5 | 16 | 4.9 | | | | |
| N17-44G.1-6 | 9.5 | 2.3 | | | | |

Table S4b - SHRIMP U-Pb data for large rutile grains in leucocratic domains

| Grain | Analyses | Discordance (%) | Mean grain age | Grain diameter (μm) | Grain orientation spread (°) |
|-------------|----------|--|----------------------------------|---------------------|------------------------------|
| | | $\frac{(^{206}\text{Pb}/^{238}\text{U} - ^{207}\text{Pb}/^{235}\text{U})}{(^{206}\text{Pb}/^{238}\text{U})}$ | $^{206}\text{Pb}/^{238}\text{U}$ | | |
| | | $\pm 2\sigma$ | $\pm 2\sigma$ | | |
| N17-44G.1-7 | 10 | -3.5 | | | |