

1 **Rapid assembly and rejuvenation of a large silicic magmatic**
2 **system: insights from mineral diffusive profiles in the Kidnappers**
3 **and Rocky Hill deposits, New Zealand**

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26 **Abstract**

27 The timescales over which magmas in large silicic systems are reactivated, assembled and
28 stored remains a fundamental question in volcanology. To address this question, we study
29 timescales from Fe-Mg interdiffusion in orthopyroxenes and Ti diffusion in quartz from the
30 caldera-forming 1200 km³ Kidnappers and 200 km³ Rocky Hill eruptions from the
31 Mangakino volcanic centre (Taupo Volcanic Zone, New Zealand). The two eruptions came
32 from the same source area, have indistinguishable ⁴⁰Ar/³⁹Ar ages (~1.0 Ma) and zircon U-Pb
33 age spectra, but their respective deposits are separated by a short period of erosion.
34 Compositions of pumice, glass and mineral species in the collective eruption deposits define
35 multiple melt dominant bodies but indicate that these shared a common magmatic mush zone.
36 Diffusion timescales from both eruptions are used to build on chemical and textural crystal
37 signatures and interpret both the crystal growth histories and the timing of magma
38 accumulation. Fe-Mg interdiffusion profiles in orthopyroxenes imply that the three melt-
39 dominant bodies, established through extraction of melt and crystals from the common source,
40 were generated within 600 years and with peak accumulation rates within 100 years of each
41 eruption. In addition, a less-evolved melt interacted with the Kidnappers magma, beginning
42 ~30 years prior to and peaking within 3 years of the eruption. This interaction did not directly
43 trigger the eruption, but may have primed the magmatic system. Orthopyroxene crystals with
44 the same zoning patterns from the Kidnappers and Rocky Hill pumices yield consistently
45 different diffusion timescales, suggesting a time break between the eruptions of ~20 years
46 (from core-rim zones) to ~10 years (outer rim zones). Diffusion of Ti in quartz reveals
47 similarly short timescales and magmatic residence times of < 30 years, suggesting quartz is
48 only recording the last period of crystallization within the final eruptible melt. Accumulation
49 of the eruptible magma for these two, closely successive eruptions was accomplished over
50 centuries to decades, in contrast to the gestation time of the magmatic system of ~200 kyr, as

51 indicated by zircon age patterns. The magmatic system was able to recover after the
52 Kidnappers eruption in only ~10-20 years to accumulate enough eruptible melt and crystals
53 for a second ~200 km³ eruption. Our data support concepts of large silicic systems being
54 stored as long-lived crystal mushes, with eruptible melts generated over extraordinarily short
55 timescales prior to eruption.

56

57 Keywords

58 Diffusion chronometry; Fe-Mg in orthopyroxene; Ti in quartz; magmatic timescales;
59 supereruption; Taupo Volcanic Zone

60

61 **1. Introduction**

62 Establishing the timescales of magmatic processes associated with large explosive eruptions
63 provides important insights into the dynamics of large-scale crustal magmatic systems and the
64 processes that lead up to eruption. There are two contrasting, but complementary, approaches
65 to measuring these time scales, both of which utilise mineral phases in the eruption products.
66 The first involves direct age dating of crystallization events through such techniques as U-
67 series or U-Pb dating of suitable accessory mineral phases, such as zircon, allanite, or titanite
68 (e.g. Schmitt, 2011) or the use of parent-daughter isochrons, such as Rb/Sr techniques in
69 feldspars (e.g. Davies et al., 1994). The second approach is that of indirect age dating through
70 diffusion modelling of inferred step-changes in compositional characteristics in minerals (e.g.
71 Costa et al., 2008; Chakraborty, 2008; Costa and Morgan, 2010). Rather than dating the age
72 of crystals themselves, this approach measures the time elapsed at magmatic temperatures
73 following periods of renewed growth and formation of crystal zonation within individual
74 grains.

75 For those eruptive units where both of these approaches have been undertaken, there is
76 an apparent contrast between the respective results. Crystal-specific ages indicate histories of
77 typically 10^3 to $>10^5$ years, whereas diffusion modelling yields estimates in the 10^1 to 10^3
78 years range (e.g. Turner and Costa, 2007; Cooper and Kent, 2014) . This contrast can be
79 linked to the inference that the chemical processes leading to these magmas (and growth of
80 their crystal cargo, particularly the zircons that are dated) can be prolonged and magma within
81 large silicic systems may be stored at near-solidus conditions for long periods of time (Cooper
82 and Kent, 2014). This concept involves the waxing and waning of a crystal-rich, melt-poor
83 (mush) system and the generation of large volumes of melt of given composition through
84 fractionation, controlled by the rates at which material and heat are added and heat can be lost
85 (e.g. Hildreth, 2004; Bachmann and Bergantz, 2004). On the other hand, processes involved
86 in the mobilisation and extraction of that melt into eruptible bodies can occur much more
87 rapidly because they only involve the physical transportation of melt \pm crystals (Wilson and
88 Charlier, 2009; Gualda et al., 2012; Allan et al., 2013; Barker et al., 2016).

89 The textures, compositions and thicknesses of growth zones within crystals can be
90 used to discriminate between different magmatic processes responsible for the zonation
91 (Saunders et al., 2012; Allan et al., 2013; Kahl et al., 2013). Each crystal interior may have a
92 diverse and complex growth history, but zoning features that are common to a substantial
93 proportion of all crystals allow for the distinction to be made between localised versus
94 system-wide crystal histories. In the case of the Oruanui and post-Oruanui rhyolites from
95 Taupo volcano the zoning in phenocryst phases records common magmatic histories and
96 suggests rapid rejuvenation of crystal mushes and melt accumulation (Allan et al., 2013;
97 Barker et al., 2016). In addition, there may be disparities in the timescales estimated from
98 different phases recording seemingly common processes (e.g. Chamberlain et al., 2014) and
99 so if zoning within the crystals permits, it is important to consider the timescales from

100 multiple phases. Here we present pre-eruptive timescales for assembly of the final erupted
101 melt-dominant bodies inferred from Fe-Mg interdiffusion in orthopyroxene and Ti diffusion
102 in quartz from pumices in two eruptions, the Kidnappers and Rocky Hill events from
103 Mangakino volcanic centre, New Zealand (Tables 1 and 2). We also use the difference in
104 timescales from common growth zones within orthopyroxenes from the Kidnappers and
105 Rocky Hill deposits to constrain the time break, inferred from field evidence to be
106 geologically short, between the two eruptions.

107

108 **2. Kidnappers and Rocky Hill eruptions**

109 The Kidnappers and Rocky Hill eruptions occurred from the Mangakino volcanic
110 centre, a composite caldera system in the Taupo Volcanic Zone, New Zealand (Fig. 1; Wilson
111 et al., 2009). The Kidnappers eruption (~1200 km³ DRE) generated a large, fine-grained
112 phreatomagmatic fall deposit (Carter et al., 2004; Cooper et al., 2012), followed by an
113 exceptionally widespread, non-welded ignimbrite (Wilson et al., 1995). It was followed, after
114 a short interval of erosion, by the ~200 km³ Rocky Hill eruption which mostly generated a
115 partly-welded ignimbrite (Cooper et al., 2016). The two deposits yield identical ⁴⁰Ar/³⁹Ar
116 ages within uncertainty at ~1.0 Ma (Wilson et al., 1995) and their zircon U-Pb age spectra are
117 also closely similar, ranging back to between 100 and 200 kyr prior to the eruption age
118 (Cooper et al., 2014).

119 Textural and compositional records from the major mineral phases (plagioclase, quartz,
120 amphibole, orthopyroxene), coupled with thermobarometric model constraints suggest that
121 both eruption deposits were sourced from a common magmatic system with crystals
122 originating from a shared mush zone (Cooper et al., 2016). However, compositions of glass
123 shards and glass-selvedged crystals from the fine grained Kidnappers fall deposit (Cooper et
124 al., 2012) and pumices, matrix glass and crystal phases from the Kidnappers and Rocky Hill

125 ignimbrites (Cooper et al., 2016) show variations consistent with there being multiple discrete
126 melt-dominant magma bodies tapped during the collective events. There are three
127 distinguishable glass compositions in the Kidnappers fall deposit (KF-A, KF-B and KF-C),
128 three pumice groups in the Kidnappers ignimbrite (KI-1, KI-2, KI-3), and two pumice groups
129 in the Rocky Hill ignimbrite (RH-1, RH-2). Of these, modal abundances and glass and
130 mineral chemistries link the two most voluminous as (i) KF-A = KI-1 = RH1 and (ii) KF-B =
131 KI-2 = RH-2. The two other magma types are (iii) glass type KF-C, which forms a minor
132 proportion of the Kidnappers fall deposit and is compositionally overlapped by glass from
133 pumice type KI-1 and (iv) the lower silica pumice type KI-3 found only in the Kidnappers
134 ignimbrite (see Cooper et al., 2016, for full descriptions).

135 Within the Kidnappers and Rocky Hill deposits, it is particularly relevant to identify
136 compositional zones within crystals that record the same apparent processes in both eruptions,
137 with the aim of assessing the differences in model timescales during the lead up to the
138 respective eruptions. Orthopyroxene is the ideal choice within this system, as simple zoning
139 patterns are present which, together with an extensive textural and geochemical dataset
140 (Cooper et al., 2016), strongly suggest that orthopyroxene shares common growth histories
141 with the other crystal phases. We compare the diffusive timescales from orthopyroxene with
142 those from quartz in order to see if the crystal phases, from multiple magma bodies, are
143 recording the same chamber-wide magmatic events.

144

145 **3. Samples**

146 Orthopyroxene and quartz crystals were picked from representative pumices from
147 each of the compositional groups in the Kidnappers and Rocky Hill ignimbrites (Cooper et
148 al., 2016). Kidnappers pumices were sampled from Litchfield Quarry ~30 km from source at
149 NZMG grid reference 2758837m E, 6339943m N (Fig. 1). Diffusion profile determinations

150 were made from orthopyroxenes in Kidnappers samples P1655 and P17XX from KI-3;
151 P1607, P1609, P2006 and P2015 from KI-1; and P1646, P1649 and P2011 from KI-2. Rocky
152 Hill pumices were sampled from exposures in the Waipa Valley, ~50 km from source (Fig. 1).
153 Diffusive age determinations were made from orthopyroxenes in Rocky Hill samples P2000,
154 P2029, P2042, P2049 and P2050 from RH-1 and sample P2046 from RH-2. Ti-in-quartz
155 diffusion ages were determined from one Kidnappers KI-2 pumice (P2006), the zircons in
156 which were dated by U-Pb techniques (Cooper et al., 2014), and one Rocky Hill RH-1 pumice
157 (P2050).

158

159 **4. Methods**

160 **4.1. Measurement techniques**

161 *Orthopyroxene*

162 Orthopyroxenes were orientated in epoxy blocks with the crystal (*a*- or *b*-) and *c*-axes
163 exposed. High resolution backscattered electron (BSE) images of each orthopyroxene crystal
164 were taken to investigate crystal zonation features and mark the location of individual
165 analyses. Crystal cores, rims and any prominent zonation features (intermediate domains)
166 were targeted for analysis by EPMA using a JEOL JXA-8230 Superprobe at Victoria
167 University of Wellington. Crystals were analysed with a 15 kV accelerating voltage and a 12
168 nA focused beam. A strong negative linear relationship ($R^2 = 0.95$) was observed between
169 BSE greyscale values and the Mg/(Mg+Fe) content of multiple orthopyroxene crystals, and
170 therefore the zoning observed in BSE images was inferred to be an accurate reflection of the
171 Fe-Mg content (Supplementary Fig. 1). This relationship allowed the gradients in Fe-Mg
172 concentrations to be investigated at a higher spatial resolution than is possible from spot
173 analyses alone (Morgan et al., 2004; Martin et al., 2008; Saunders et al., 2012; Allan et al.,
174 2013). The software package *Image J* (<http://rsb.info.nih.gov/ij/>) was used to extract spatially

175 resolved profiles of BSE intensity across crystal zonation boundaries. The linear relationship
176 between the Fe-Mg content of the orthopyroxenes and intensity of backscattering (greyscale
177 value: Supplementary Fig. 1) was used to quantify Mg/(Mg+Fe) concentration gradients
178 between the EPMA analytical spots on either side of the diffusion profile. It is assumed that
179 the boundaries chosen for modelling initially had step-wise concentration gradients, which
180 over time at magmatic temperatures were modified by Fe-Mg interdiffusion, and that
181 diffusion ceased upon quenching on eruption, resulting in sigmoidal concentration gradients.
182 Finite-difference software was used to generate a database of simulated sigmoidal diffusion
183 profiles, which obey composition-dependent diffusion under a 1-D (linear) diffusion
184 geometry; these were then adapted to the samples via application of scaling laws using Excel.

185 Dohmen et al. (2016) provided a new set of experimentally determined interdiffusion
186 coefficients. However, this study only used highly magnesian compositions (En₉₁₋₉₈) that are
187 well outside the compositional range of the Kidnappers/Rocky Hill orthopyroxenes (En₄₁₋₆₈).
188 Therefore, to calculate orthopyroxene $D_{\text{Fe-Mg}}$ we employed the parameterization of Ganguly
189 and Tazzoli (1994) who utilised compositions close to those of this study and also determined
190 a more significant compositional dependence. Indeed, our observation of asymmetric
191 diffusion profile shapes as a function of the composition dependence is completely consistent
192 with the composition dependence proposed by Ganguly and Tazzoli (1994). In terms of
193 oxygen fugacity, Dohmen et al. (2016) suggest a much lower $f\text{O}_2$ dependence than that found
194 in olivine (exponent of $1/6$, e.g. Dohmen and Chakraborty, 2007), This result does contradict
195 the value of oxygen fugacity dependence suggested (in the absence of experimental
196 constraints) by Ganguly and Tazzoli (1994) based on analogy with olivine. We have
197 therefore, for the purposes of this study, used the equation of Ganguly and Tazzoli (1994) but
198 without an oxygen fugacity component.

199

200 *Quartz*

201 Cathodoluminescence (CL) imaging was used to show zoning within quartz grains,
202 where the brightness of the image element is inferred to directly correspond to the Ti
203 concentration (Wark et al., 2007; Matthews et al., 2012a, b). High-resolution CL images of Ti
204 variations in quartz grains were obtained on a FEI Quanta 650 FEG-SEM (field emission
205 gun—scanning electron microscope) with a KE Centaurus panchromatic CL detector at the
206 University of Leeds.

207 Ti in quartz diffusivities can be calculated in the following way from the
208 parameterisation of Cherniak et al. (2007):

$$D_{Ti} = D_{Ti,0} e^{\left(\frac{-E}{RT}\right)},$$

209 where $D_{Ti,0}$ is the D_0 for Ti ($7 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$), E is the activation energy ($273 \pm 12 \text{ kJ mol}^{-1}$), R is
210 the gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$) and T is temperature (in Kelvin). Having calculated the
211 appropriate values of D for each elemental system at the appropriate temperature, the
212 following equation was solved for time (Crank, 1979; Morgan et al., 2004):

$$213 \quad C = C_0 + \frac{(C_1 - C_0)}{2} \left[\operatorname{erfc} \left(\frac{x}{2\sqrt{D_i t}} \right) \right],$$

214 where C is the normalised concentration of Ti, C_0 and C_1 refer to the initial amounts of the
215 element on each side of an initial interface, D_i is the calculated diffusivity in $\text{m}^2 \text{ s}^{-1}$, t is the
216 diffusion time and x is the position measured in metres along the profile and centred on the
217 interface (the mid-point of the profile). The difference between modelled profile shape and
218 the input profile were minimised using an Excel macro to get a best-fit profile from which a
219 model timescale could be calculated.

220

221 **4.2. Parameters and uncertainties**

222 It is essential to consider the sources and magnitude of uncertainties in diffusion modelling

223 (Chakraborty, 2008; Costa and Morgan, 2010). Calculations for $D_{\text{Fe-Mg}}$ are insensitive to
224 pressure (Dohmen and Chakraborty, 2007), but highly sensitive to temperature (diffusion data
225 of Besancon, 1981, and Schwandt et al., 1998). Here we adopt different magmatic
226 temperatures for each compositional group within the Kidnappers and Rocky Hill (Table 1),
227 based on estimates from measured amphibole rim compositions (Cooper et al., 2016) and
228 using the model of Ridolfi et al. (2010: Table 1). Regardless of the model used to estimate
229 absolute temperature values, the relative difference between compositional groups is always
230 consistent (Cooper et al., 2016). Amphiboles used in this study have common final growth
231 histories with orthopyroxenes (Cooper et al., 2016) and therefore temperatures estimated from
232 amphibole rims are inferred to also represent the corresponding temperatures during
233 orthopyroxene growth. Within the low-SiO₂ Kidnappers group (KI-3) a significant number of
234 crystals have up-temperature rim signals and therefore a higher temperature (based on
235 corresponding up-temperature amphibole rims) is adopted for this group. In the other
236 compositional groups where down-temperature rim signals dominate, the temperature used is
237 lower, yielding maximum age estimates. For uncertainty calculations on single model-age
238 determinations, temperature uncertainties of ± 30 °C (1σ) were used, based on common
239 thermometry uncertainties (Blundy and Cashman, 2008). It is possible that temperature
240 fluctuated during the diffusion process, which would have the effect of shortening (higher
241 temperatures) or lengthening (lower temperatures) the modelled timescales. However, there is
242 no evidence from any crystal phase (e.g. oscillatory zoning) for a significant shift in
243 temperature during diffusion of the modelled boundaries and therefore all modelled
244 timescales in this study assume an isothermal history.

245 The uncertainties associated with profile shapes (i.e. the compositional integrity of the
246 BSE images) and the profile lengths (based upon the absolute reliability of the magnification
247 provided by microprobe imaging) were also taken into account, and a conservative value of

248 ± 3 % was adopted as a maximum uncertainty on profile lengths. The validity of estimates
249 based on crystal zonation boundaries that display sigmoidal profiles over short ($< \sim 5 \mu\text{m}$)
250 length scales, implying very short timescales of ≤ 3 years at the conditions relevant to this
251 study (Table 1), needs to be considered with caution. Such boundaries may reflect a tangible
252 record of very short-lived processes in the magma, but may potentially also be an artifact of
253 pixel size and effects of convolution in the BSE imaging and during image rotation steps or
254 sampling of an image along an inclined traverse. Convolution can be particularly problematic
255 where image pixel size is very small ($\sim 0.25 \mu\text{m}$) compared to the spatial resolution and
256 excitation volume of the electron beam ($< 1 \mu\text{m}$), potentially smearing out a genuinely sharp
257 stepwise boundary and generating an artificial diffusion profile (Morgan et al., 2004). To test
258 for this effect, the resolution limit was estimated by taking a BSE profile across the edge of
259 orthopyroxene crystals and into the glass selvage at different image magnifications and
260 resolutions (Fig. 2). The lower magnification (x120) and resolution image shows a $\pm 1 \mu\text{m}$
261 smearing over the edge of the crystal (assumed to be a stepwise boundary). At higher
262 magnification (x370) and resolution this effect is reduced to $\pm 0.25 \mu\text{m}$ (Fig. 2). These lengths
263 are $\sim 12\%$ and $\sim 5\%$, respectively, of the measured diffusion profile lengths, and thus yield
264 uncertainties that are considerably smaller than those associated with the temperature
265 estimates. However, to account for possible convolution effects, the youngest ages (0-3 years)
266 are grouped here as ' < 3 years'.

267 The finest-scale time scale resolution available for CL images of quartz was estimated
268 by modelling a known sharp contact (crystal edge or crack). This yielded a timescale of 0.5
269 years (at $780 \text{ }^\circ\text{C}$), which is thus the shortest resolvable age via CL imaging. Any diffusion-
270 based age estimates of < 0.5 years are thus unresolvable using CL imaging and are rejected.
271 As with orthopyroxene, all timescales can be considered as maximum ages due to the
272 assumption that the initial boundary had a step-wise concentration gradient. Changing this

273 assumption would only serve to shorten the timescales further.

274

275 **5. Results**

276 **5.1. Textural characteristics of Kidnappers and Rocky Hill orthopyroxenes**

277 The zoning within individual orthopyroxene crystals in the Kidnappers and Rocky Hill
278 samples can be complex. There are, however, key overarching textural features that allow
279 crystals to be classified into distinct populations (Table 1 and Supplementary Fig. 2). Four
280 main orthopyroxene crystal populations (referred to here as normal, unzoned, reverse and
281 patchy) are present, based on the simplified textural characteristics observed in BSE images.
282 In addition, these populations can have a dark outer zone (within 100 μm of the outermost
283 rim, or forming the outermost rim itself) that may overprint any of the above textures
284 (Supplementary Fig. 2). Here, boundaries from both normal- and reverse-zoned grains are
285 utilised for modelling. Grains with an overprinted dark outer zone (higher Mg#) are of
286 particular interest for modelling timescales, as they are found in orthopyroxene crystals from
287 both eruptions. Textures of plagioclase grains and the chemistry of amphiboles from the
288 Kidnappers and Rocky Hill eruptions have features consistent with those of the
289 orthopyroxenes and thus all these phases are inferred to share a common magmatic history for
290 the modelled period of time prior to eruption (Cooper et al., 2016).

291 To assess both the primary zonation and diffusion-affected zonation, elemental
292 mapping of selected crystals using EPMA was carried out (Supplementary Figs. 3, 4). In
293 orthopyroxene, Al has a very slow diffusion rate, Ca is slow, and Fe and Mg have relatively
294 fast diffusion rates (Sautter et al., 1988). Al can be considered to be effectively immobile over
295 timescales of <10,000 years at the magmatic temperatures applicable to the
296 Kidnappers/Rocky Hill system (Smith and Barron, 1991) and thus closely records the original
297 growth zonation of the orthopyroxene. Blurring in Al content across boundaries parallel to the

298 *c*-axis is evident, which cannot realistically be attributed to diffusion. Therefore, we conclude
299 that growth must have exerted a strong control parallel to the *c*-axis when compared to the
300 sharper boundary along the *a*- or *b*-axes, which have negligible blurring, and, we infer,
301 negligible growth effects to interfere with the diffusion profiles.

302

303 **5.2. Fe-Mg diffusion timescales in Kidnappers and Rocky Hill orthopyroxenes**

304 Within Kidnappers orthopyroxenes, timescales were modelled across the boundaries
305 perpendicular to the *c*-axis both between cores and rims, and between intermediate domains
306 and dark outer zones (the latter are common in the KI-3 compositional group). The
307 corresponding boundaries were also modelled within Rocky Hill orthopyroxenes. Commonly,
308 Rocky Hill grains display an additional, BSE-lighter outer rim overgrowing the dark outer
309 zones, and therefore the additional intervening boundary was also modelled (Fig. 3). Core-rim
310 boundaries cover a spectrum from those with very dark cores found in the interior of the
311 crystal, to broader cores where the boundary is found towards the exterior of the crystal (Fig.
312 3). All modelled diffusion ages across the full range of core-rim boundaries were grouped
313 together, as definite textural distinctions that may represent unique events are difficult to
314 establish. All modelled boundaries were parallel to the *a*- or *b*-axes, which display
315 concentration gradients that are consistent with diffusive modification (Supplementary Figs.
316 2, 3).

317 Modelled diffusion timescales from core-rim boundaries within the Kidnappers
318 steadily increase in abundance from ~600-150 years, followed by a sharper increase within
319 150 years to a peak at ~20 years before eruption (Fig. 4). Modelled diffusion timescales from
320 analogous core-rim boundaries within the Rocky Hill show a continuous increase in
321 abundance from ~ 600 to 100 years, followed by a step change in gradient at <100 years to a
322 peak ~ 40 years before eruption (Fig. 4). There is a ~20 year difference in peak PDF ages of

323 core-rim zones between the Kidnappers (~20 years) and the Rocky Hill (~40 years). Only
324 three modelled boundaries across very dark cores from both eruptions return significantly
325 older pre-eruptive ages (>600 years).

326 All dark exterior zones from Kidnappers orthopyroxenes were modelled from within
327 the low-SiO₂ (KI-3) pumice group. The number of resulting time estimates range from 30
328 years to within one year of eruption, with a peak PDF age of ~3 years (Fig. 4). Notably fewer
329 orthopyroxene grains with dark exterior zones are found within the Rocky Hill (Table 1). The
330 grains displaying this texture in the Rocky Hill are inferred on compositional grounds to be
331 inherited from the common mush zone originally tapped during the Kidnappers eruption
332 (Cooper et al., 2016). Timescales from both the rim-side and core-side of dark exterior zones
333 in the Rocky Hill extend back further than those from the Kidnappers. Modelled ages are
334 between 240 and 10 years, and the PDF curve has a peak at ~13 years prior to eruption (Fig.
335 4). The peak PDF age difference between the dark outer zones of the Kidnappers (~3 years)
336 and Rocky Hill (~13 years) is ~10 years by this methodology.

337 All Fe-Mg interdiffusion timescales presented here suggest older ages are less
338 likely. This may be the result of an acceleration in the recorded process <100 years prior to
339 eruption (cf. Allan et al., 2013). Alternatively, these trends may be the result of older
340 boundaries being overwritten, settling and hence loss of older crystals, or dilution due to the
341 magma volume increasing through time.

342

343 **5.3. Textural characteristics of Kidnappers and Rocky Hill quartz**

344 In Kidnappers and Rocky Hill pumices, quartz forms euhedral, bipyramidal, but often
345 broken crystals up to ~2 mm across. CL imaging of quartz within the Kidnappers and Rocky
346 Hill pumices reveals oscillatory and complexly zoned grains with the greyscale intensity
347 inferred to reflect Ti concentrations (Wark et al., 2007; Matthews et al., 2012a, b; Fig. 5).

348 Oscillatory zoning is commonly truncated by (multiple) resorption surfaces and embayments
349 are also common (Fig. 5). CL-imaged quartz crystals from the Kidnappers and Rocky Hill
350 pumices were classified into three groups: (1) grains displaying darker rims (lower Ti) and (2)
351 lighter rims (higher Ti), and (3) those with no significant compositional change at the rim
352 (Table 2). Within a single KI-2 (high SiO₂) Kidnappers pumice, grains with darker rims
353 (lower Ti) dominate over those with lighter rims (Table 2) and thus provide evidence of an
354 apparent temperature decrease prior to eruption, consistent with the other mineral phases
355 (Cooper et al., 2016). This down-temperature signal is interpreted to represent movement of
356 the KI-2 magma to a shallower storage level prior to eruption (Cooper et al., 2016). In
357 contrast, grains within a single Rocky Hill (RH-1) pumice are dominated by lighter (higher
358 Ti) rims (in contrast to those with darker rims and those showing no change: Table 2),
359 reflecting an increase in apparent temperatures during growth prior to eruption. The
360 contrasting quartz histories reflect the multiple melt dominant bodies present in the
361 Kidnappers/Rocky Hill magmatic system and are in accord with the corresponding
362 orthopyroxene textural characteristics in the respective pumice types (Table 1).

363

364 **5.4. Ti diffusion timescales in Kidnappers and Rocky Hill quartz**

365 The complexity of the zoning within Kidnappers and Rocky Hill quartz did not allow
366 for a distinctive zone common to all grains to be modelled, so therefore all zones which
367 displayed a diffusive boundary were considered. Modelled Ti diffusion timescales across
368 boundaries ranging from the core to rim of Kidnappers quartz are all within 31 years of
369 eruption, with the exception of one at 130 yrs. The ages increase from 31 years to a peak at ~5
370 years before eruption (Fig. 6). Modelled Ti timescales from Rocky Hill quartz are all within
371 42 years of eruption and are very similar to the Kidnappers timescales. The ages peak at ~2

372 years prior to eruption (Fig. 6). The Ti-in-quartz timescales obtained are comparable to those
373 from orthopyroxene, in particular, those from dark outer zones (Fig. 7).

374

375 **6. Discussion**

376 **6.1. Implications of diffusion timescales from orthopyroxene dark exterior zones**

377 Evidence from the presence of BSE-darker exterior zones in orthopyroxene grains, as
378 well as the ‘up-temperature’ signals recorded in amphibole, plagioclase and matrix glass from
379 the low-SiO₂ Kidnappers (KI-3) pumice group is taken to represent mixing with, or
380 rejuvenation through interaction with, a less evolved and/or hotter melt (Fig. 8; Cooper et al.,
381 2016). Modelled timescales across the interior domain to darker exterior zone boundary thus
382 reflect the time (<50 yrs; Fig. 8) before eruption when this interaction occurred. Over the 50
383 year period, the number of crystal boundaries recording the interaction with the less-evolved
384 melt increased within the KI-3 magma volume up to the point of eruption, within the limits of
385 resolution of the imagery (PDF peak at <3 years; Fig. 4). The extent of interaction by the less-
386 evolved melt thus progressively increased in the <50 years before eruption, and might be
387 considered as a eruption triggering mechanism (cf. Wark et al., 2007). However, the
388 proportion of material with these signatures of interaction with the less-evolved melt is
389 relatively small (~3% of total erupted Kidnappers material). The magmatic rejuvenation
390 therefore seems unlikely to have had a system-wide influence. We infer that interaction of the
391 hotter and/or less evolved melt, possibly through underplating at the base of the mush
392 column, essentially primed a volume of material for eruption through thermal rejuvenation
393 and/or volatile exchange, rather than being the eruption trigger itself (cf. Chamberlain et al.,
394 2014).

395 Geochemical and petrological evidence from Kidnappers and Rocky Hill deposits
396 strongly suggests that both eruptions were derived from a common magmatic system (Cooper

397 et al., 2016). Consequently, orthopyroxene grains with a dark exterior zone (plus additional
398 rim growth) in the Rocky Hill can be inferred to record the same processes as seen within the
399 Kidnappers crystals that show the same pattern of zonation. The corresponding population of
400 Rocky Hill orthopyroxenes can thus be considered as remnants from the final melt dominant
401 bodies which were made more eruptible prior to, but not fully evacuated during, the
402 Kidnappers event. Consistent with this inference, the majority of modelled ages from the
403 dark exterior zone in Rocky Hill orthopyroxenes, including those from the dark zone to
404 outermost rim boundary, are greater than those from the Kidnappers. The offset in the peak
405 PDF value of ages derived for this common zonation (~10 years) therefore represents one
406 indirect estimate of the time break between the two eruptions (Figs. 4, 7). All crystals that
407 returned modelled ages of >10 years are therefore inferred to be inherited from Kidnappers
408 magma/mush. The textures and chemical zoning within the majority of Rocky Hill
409 orthopyroxenes (and other mineral phases) do not contain any evidence for a priming or
410 trigger mechanism for the eruption analogous to that seen in the Kidnappers KI-3 pumice
411 group.

412

413 **6.2. Implications of diffusion timescales from orthopyroxene core-rim boundaries**

414 Prominent core-rim boundaries within orthopyroxenes from the Kidnappers/Rocky
415 Hill samples are inferred to represent a transition from storage in a crystal mush to holding
416 and further crystallization within the melt-dominant bodies that were finally erupted (Cooper
417 et al., 2016). Timescales modelled across Kidnappers core-rim boundaries cover a large
418 range, but only one crystal returns an age of >600 years before eruption. 72 % of diffusion
419 profiles date to within 200 years of the eruption and suggests that a significant input of
420 orthopyroxene grains (those displaying normal zonation: Supplementary Fig. 2) to the final
421 melt-dominant body occurred within centuries (Fig. 8) and that this process peaked only

422 decades prior to the Kidnappers eruption (Fig. 4). The Fe-Mg modelled diffusion ages across
423 Kidnappers/Rocky Hill orthopyroxene core-rim boundaries cover similar timescales to those
424 inferred from those corresponding crystal boundaries recorded in the Oruanui (Allan et al.,
425 2013), which are also inferred to represent the timing of physical extraction and establishment
426 of the melt-dominant body. In the Oruanui case, ~90 % of orthopyroxenes record this
427 common history (Allan et al., 2013), but within the Kidnappers the proportion of crystals
428 recording this process is lower and varies between compositional groups (34-76 %) (Table 2),
429 suggesting that additional controls were operating within the Mangakino magmatic system.
430 The proportion of nominally unzoned grains within the Kidnappers ranges between 15 and 51
431 %. These crystals either entirely grew within a melt-dominant body prior to eruption or were
432 introduced into the melt-dominant bodies sufficiently close to the time of eruption so as not to
433 be able to grow a discernible contrasting rim.

434 Core-rim boundaries within Rocky Hill orthopyroxenes record a similar range of
435 timescales as in Kidnappers grains. The Rocky Hill core-rim model ages, which reflect the
436 timing of movement of orthopyroxene grains to the final erupted melt-dominant body, have a
437 peak PDF age at ~40 years (Fig. 4). This ~40 year peak is inferred to correspond to the same
438 peak input of grains ~20 years prior to the Kidnappers eruption. There is a continuity of core-
439 rim ages within this ~20 year window, suggesting that there was a sustained movement of
440 crystals from the mush zone to melt dominant bodies during the time break between the two
441 eruptions (Fig. 8). This feature is particularly marked in orthopyroxenes from the high-SiO₂
442 Rocky Hill (RH-2) pumice group, where 94 % of grains have normal zonation. This dominant
443 zonation pattern is coupled with lower amphibole rim model temperature and pressure
444 estimates, low-An plagioclase rims, and lower-Ca homogeneous glass (Cooper et al., 2016).
445 These distinctive characteristics of the RH-2 pumice group support the idea that a significant
446 proportion of magma was newly assembled into eruptible melt dominant bodies, with most of

447 the incorporated orthopyroxenes recording a post-Kidnappers magmatic history. Grains which
448 return core-rim model ages greater than a few hundred years are likely inherited from the
449 earlier Kidnappers system, and record common precursor processes within the common
450 magma system.

451 Differences in the model timescales from the core-rim boundaries between both
452 eruptions are consistent with the field evidence for a short time break between these
453 eruptions. Although the resolution of the data is lower than ages from the dark outer zones,
454 there is a ~20 year difference in core-rim model age peaks between the two eruptions, which
455 is the same, within uncertainties, as the independently estimated ~10 year time break
456 observed across dark outer zones. It is not possible to definitively estimate the time break
457 between the Kidnappers and Rocky Hill eruptions with diffusion timescales alone, due to
458 their inherent imprecision. Two further, independent lines of field evidence support such a
459 short time gap. (1) The erosional contact between the two ignimbrites has no associated
460 development of a soil horizon (Cooper et al., 2016). (2) The associated fall and reworked
461 material (collectively referred to as the Potaka Tephra: Shane, 1994; Carter et al., 2004), both
462 on land and in marine cores compositionally appears to be a single composite deposit of
463 primary and reworked Kidnappers and Rocky Hill material (Cooper et al., 2012).

464

465 **6.3. Consequences of short quartz diffusion timescales**

466 The similarity of Ti in quartz timescales and orthopyroxene Fe-Mg interdiffusion
467 timescales (Fig. 7) suggests that they are recording the same, or concurrent, processes within
468 the Kidnappers and Rocky Hill magmatic system prior to the eruption of the former. It is
469 remarkable that even intermediate domains within quartz return timescales within 30 years of
470 eruption. This supports the idea of rapid crystallization of quartz prior to eruption (Gualda and
471 Sutton, 2016), but is not consistent with the notion that the CL-brighter rims on the quartz

472 crystals are the result of syn-eruptive rapid growth associated with magma ascent (cf.
473 Pamukcu et al., 2016). Commonly, Kidnappers and Rocky Hill quartz grains record multiple
474 resorption episodes, suggesting that quartz can cycle many times between dissolution and
475 growth over geologically short timescales. Therefore we infer that the majority of quartz
476 timescales likely record only the latest episodes of crystal growth within the erupted magma
477 (at temperatures below the incoming of quartz in the crystallising assemblage and above the
478 solidus) prior to eruption. Quartz grains may have been stored in a mush over a much longer
479 timescale than is recorded by Ti-in-quartz diffusion prior to remobilization and dissolution
480 followed by rapid regrowth (Cooper and Kent, 2014).

481

482 **6.4. Timescale comparisons and considerations**

483 Values chosen for the parameters (particularly temperature) used in Fe-Mg diffusion
484 modelling calculations have a large influence on the modelled ages. All age estimates
485 reported here are maxima and the timescales discussed above are upper-bound limits, based
486 on an assumed initial sharp profile. In Rocky Hill orthopyroxenes, analogous zones were
487 modelled at conditions that reflected the outer rim growth of crystals and not necessarily the
488 original conditions under which the dark zone formed (Table 1). Therefore, we need to rule
489 out the possibility of using lower temperature estimates (765-795 °C) to artificially produce
490 larger age estimates in Rocky Hill orthopyroxenes. If 820 °C was used in calculations of
491 Rocky Hill darker exterior zone ages, the range of modelled ages would be reduced from 10-
492 238 to 5-128 years. All modelled Rocky Hill ages (peak PDF at ~7 years) would still be older
493 than the <3 yr peak within the Kidnappers, therefore halving the estimated time-break
494 between eruptions. Therefore the disparities in ages calculated using different temperature
495 estimates are not large enough to substantively change any of our conclusions.

496 Timescales from Fe-Ti interdiffusion within orthopyroxene and Ti-in quartz diffusion

497 calculated using the methods described above are comparable with one another (Fig. 7). This
498 is in contrast to crystals from the Bishop Tuff (Chamberlain et al., 2014), in which
499 orthopyroxene timescales were an order of magnitude shorter than those from quartz. This
500 difference between our results and those of Chamberlain et al. (2014) may be a consequence
501 of us removing the oxygen fugacity correction from the Fe-Mg interdiffusion equation, which
502 shifts timescales 0.75 log units towards longer timescales. There is a wide range of published
503 orthopyroxene partition coefficients (Ganguly and Tazzoli, 1994; Schwandt et al., 1998;
504 Dohmen et al., 2016), use of which result in correspondingly diverse timescales. The
505 similarity of the timescales determined for different mineral species in this study give us
506 confidence that the Fe-Mg interdiffusion coefficient used here is suitable for the
507 orthopyroxene compositions and conditions relevant for the Mangakino magmatic system.

508 The timescales obtained from orthopyroxenes and quartz are much shorter than the
509 inferred lifetime of the Kidnappers/Rocky Hill system from zircon U-Pb age spectra (Cooper
510 et al., 2014). The zircon age spectra suggest that the common system was developed over a
511 ~200 kyr period, with a peak crystallization age mode within uncertainty of the eruption age
512 at 1.0 Ma. The age contrasts are a consequence of the processes being recorded by each
513 technique. U-Pb zircon age spectra provide a ~200 kyr record for the overall assembly of the
514 magma system, specifically the time when zircon began crystallizing within the system. In
515 contrast, the orthopyroxene Fe-Mg interdiffusion and Ti in quartz diffusion timescales record
516 assembly of the final melt-dominant bodies and processes of recharge within the magma
517 system. The melt-dominant bodies were largely established <600 years before eruption, with
518 a significant input of material within centuries to decades of each eruption. The timescales we
519 present support the idea that magma in large silicic systems may only have a short time
520 window where it is in a melt-rich state during which it can erupt (e.g. Allan et al., 2013;
521 Cooper and Kent, 2014; Barker et al., 2016).

522 Timescales for the assembly of the Kidnappers/Rocky Hill system, as well as the
523 establishment of melt-dominant bodies are similar to contrasting timescales recorded in the
524 ~350 ka Whakamaru ignimbrite, New Zealand. Here zircon U-Pb age spectra indicate
525 magmatic residence times of 250 kyr prior to eruption, with periods of crystallization closer to
526 eruption following magmatic events (Brown and Fletcher, 1999). Saunders et al. (2010) and
527 Matthews et al. (2012a, b) investigated the timescales of quartz crystallization in the
528 Whakamaru deposits on the basis of Ti diffusion in quartz. They found that a significant
529 chemical change occurred in the Whakamaru system <300 yrs before eruption and peaked at
530 ~10-85 years. This change is interpreted to represent a rapid thermal pulse or pressure change
531 accompanying late-stage magma chamber recharge. Like the dark exterior zones within
532 orthopyroxene and up-temperature plagioclase and amphibole rims in the KI-3 compositional
533 group seen in the Kidnappers deposits, this late-stage Whakamaru quartz signal was attributed
534 by Matthews et al. (2012a, b) to open-system processes and the rejuvenation of rhyolitic
535 magma by interaction with underplated mafic magma. Comparable rejuvenation timescales
536 are also proposed in the ~61 ka Earthquake Flat eruption, Okataina, New Zealand and the ~74
537 ka Youngest Toba Tuff supereruption, Sumatra (Matthews et. al., 2012a; Budd et al., 2017).
538 Similarly short timescales for the physical remobilisation of felsic magmas are being reported
539 for eruptions of a range of scales at many other volcanoes worldwide for historic and
540 prehistoric eruptions, e.g. Vesuvius (Morgan et al., 2004, 2006), Santorini (Druitt et al.,
541 2012) and Huaynaputina (de Silva et al., 2008)

542 The acceleration of the magmatic system towards eruption implied by the Kidnappers
543 and Rocky Hill orthopyroxene and quartz timescales suggest that dynamic, open-system
544 processes occurred shortly before eruption and raises questions as to what the trigger
545 mechanism for each eruption was. It is hard to envisage how an exceptionally large silicic
546 system could erupt ~1200 km³ of material, before shutting down for 1-2 decades before the

547 evacuation of another $\sim 200 \text{ km}^3$ of material without an external control. There is growing
548 evidence for a strong tectonic control on magmatic systems within the TVZ (e.g. Rowland et
549 al., 2010; Allan et al., 2012) and we suggest that rifting-related tectonic processes may have
550 exerted a dominant control on both the triggering and intervening shutdown of the Kidnappers
551 and Rocky Hill eruptions.

552

553 **7. Conclusions**

554 Orthopyroxene and quartz from the Kidnappers and Rocky Hill contain textural and
555 chemical features that record open-system processes shortly before each eruption. Diffusion
556 modelling of textural zones within both mineral phases are concordant and suggest timescales
557 within centuries to years of the following processes.

558 (1) Movement of crystals and melt from a large-volume crystal mush to assemble the final
559 melt-dominant bodies occurred within centuries of the Kidnappers eruption. This process was
560 most prevalent only ~ 20 years prior to eruption.

561 (2) Interaction of a less-evolved melt with some part of the Kidnappers magma system
562 occurred within 30 years of eruption and was most prevalent in the decade prior to eruption.
563 This interaction, possibly through mafic underplating, remobilized a volume of crystal mush
564 which contributed crystals and melt towards the generation of the KI-3 eruptible magma just
565 prior to eruption.

566 (3) Difference in Fe-Mg interdiffusion model ages from dark exterior zones and core-rim
567 boundaries between samples from the Kidnappers and Rocky Hill deposits yield estimates of
568 the time break between the eruptions of one or two decades. This short time break,
569 represented by an erosion surface in the field, highlights the rapidity of magmatic
570 rejuvenation at Mangakino following the Kidnappers supereruption.

571 (4) The rapidity of quartz crystallization shown by diffusive modelling of internal zone

572 boundaries suggests that quartz is a transient phase in the Kidnappers/Rocky Hill magmatic
573 system. Quartz is always present, but textural evidence indicates individual crystals are
574 undergoing multiple resorption episodes, often to complete dissolution, followed by growth of
575 new zones or complete crystals. Diffusion timescales in quartz are thus only reflecting the
576 latest episodes of crystal growth prior to eruption, at temperatures below the incoming of
577 quartz in the crystallising assemblage and above the solidus.

578

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588

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720

721

722 **Figure captions**

723 **Fig. 1.** Map of the North Island, New Zealand showing the location of the Mangakino caldera
724 and extent of the Kidnappers and Rocky Hill ignimbrites. Sample site locations used
725 in this study are shown. Modified from Cooper et al. (2016).

726 **Fig. 2.** Back-scattered electron (BSE) images and associated profiles to assess the effect of
727 uncertainties due to image resolution and associated convolution. (a) image at x120
728 magnification and imaged at faster scan speeds ('Fine 1') which imparts a larger pixel
729 size on the area of the profile. (b) image at x370 magnification and slower scan speeds
730 ('Fine 2') resulting in smaller pixels. The effect of flaring across a demonstrably sharp
731 stepwise boundary (i.e. the edge of the crystal) is also shown.

732 **Fig. 3.** Selected examples of orthopyroxene BSE images of crystals extracted from pumices
733 within the Kidnappers (group KI-3) and Rocky Hill (groups RH-1 and RH-2) deposits
734 with corresponding modelled Fe-Mg diffusion profiles taken across boundaries
735 (yellow box areas). Profiles of greyscale intensity are taken from rotated BSE images,
736 and are converted to Mg #. The red line shows each modelled profile of an initially
737 sharp compositional boundary over the time presented for each profile, using the
738 parameters in Table 1.

739 **Fig. 4.** Histograms showing the range and frequency of maximum Fe-Mg interdiffusion ages
740 determined in orthopyroxene crystals for the core-rim boundaries from the Kidnappers
741 (a) and Rocky Hill (b), and from dark exterior zones in the Kidnappers (c) and Rocky
742 Hill (d). The PDF curve (Kidnappers in red, Rocky Hill in green) represents a
743 population probability of all age determinations with associated uncertainties resulting
744 from the precision of temperature estimates (± 30 °C).

745 **Fig. 5.** (a) An example of a quartz cathodoluminescence (CL) image from the Kidnappers
 746 (sample P2006 from KI-2) with corresponding modelled Ti-in-quartz diffusion
 747 profiles from two selected CL-defined boundaries (b & c).

748 **Fig. 6.** Histograms showing the range and frequency of maximum Ti in quartz ages
 749 determined for all quartz boundaries from the Kidnappers (a) and Rocky Hill (b).

750 **Fig. 7.** Summary stacked plots of the model ages derived from diffusion profiles in all
 751 samples analysed. (a) Orthopyroxene Fe-Mg interdiffusion ages and their absolute
 752 uncertainties (coloured bands: red – Kidnappers; yellow = Rocky Hill) from dark
 753 outer zones in the crystals. Note the distinct contrast between the values from the two
 754 deposits, interpreted to reflect the time gap between the two eruptions. (b) Fe-Mg
 755 interdiffusion ages and their absolute uncertainties from orthopyroxene core-rim
 756 boundaries. (c) Ti-in-quartz ages and uncertainties.

757 **Fig. 8.** Cartoon cross section of the Kidnappers/Rocky Hill magma system at two stages: (1)
 758 prior to eruption of the Kidnappers and (2) during the short time break between
 759 eruptions. The magmatic processes inferred from crystal textures and chemistry
 760 (discussed in the text), over the timescales modelled from Fe-Mg interdiffusion in
 761 orthopyroxene are shown.

762

763 **Table 1.** Summary of orthopyroxene textural populations.

764

Groups and samples	Temperature	f_{O_2} (ΔNNO)	Normal	Reverse	Unzoned	Patchy	Dark outer
Kidnappers							
KI-3 (low-SiO₂) P1655, P17XX	820 °C	0.1	34.0 %	7.6 %	51.4 %	6.9 %	41.0 %

KI-1 (mid-SiO₂)	785 °C	0.0	53.1 %	3.1 %	42.2 %	1.6 %	5.5 %
P1646, P1649, P2011							
KI-2 (high-SiO₂)	780 °C	0.2	76.2 %	1.2 %	15.2 %	7.3 %	2.4 %
P1607, P1609, P2006, P2015							

Rocky Hill

RH-1 (normal)	795 °C	0.1	54.7 %	6.6 %	38.1 %	0.6 %	13.2 %
P2000, P2029, P2042, P2049, P2050							
RH-2 (high SiO₂)	765 °C	0.0	94.3 %	1.1 %	4.6 %	0.0 %	1.1 %
P2046							

765 Temperatures presented were used to calculate orthopyroxene diffusive timescales from each
766 compositional group from the Kidnappers and Rocky Hill.

767

768 **Table 2.** Summary of quartz textural populations.

769

Groups and samples	Temperature	Dark rim	Light rim	No significant change
Kidnappers				
KI-2 (P2006)	780 °C	80 %	7 %	13 %
Rocky Hill				
RH-1 (P2050)	795 °C	19.5 %	61 %	19.5 %

770 Textural classification in based on CL intensities. Temperatures presented were used to calculate
771 quartz diffusive timescales.

772

773 **Supplementary figure captions**

774 **Fig. S1.** Plot to demonstrate the strong correlation between greyscale intensity and the Mg-Fe
775 proportions of orthopyroxenes analysed for this study. The correlation was measured
776 over 24 crystals, imaged under identical settings and analysed within a single
777 analytical session on a JEOL JXA-8230 electron microprobe at Victoria University of
778 Wellington.

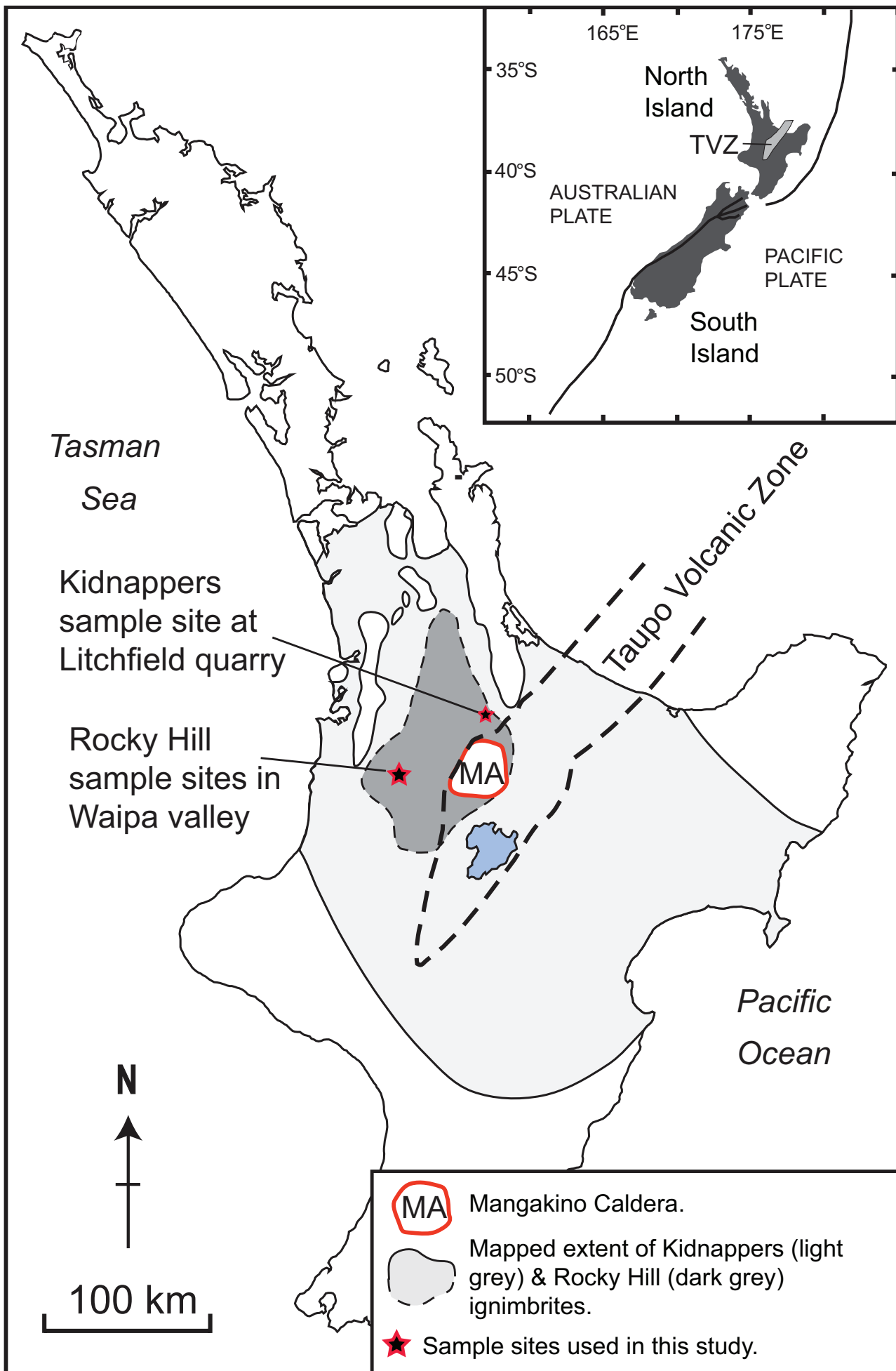
779 **Fig. S2.** Summary of textural features (based on BSE imaging) of Kidnappers and Rocky Hill
780 orthopyroxene grains in each pumice compositional group. The dark exterior zone
781 may be superimposed on any of the four other textures. Diagram modified from
782 Cooper et al. (2016).

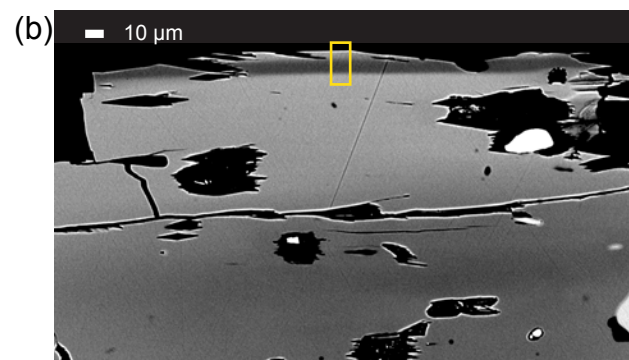
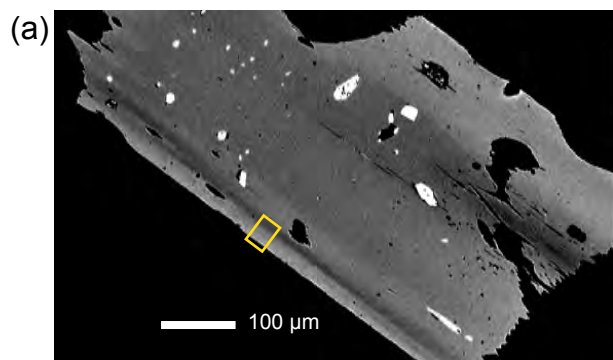
783 **Fig. S3.** Element maps of a representative normally zoned orthopyroxene crystal with a dark
784 core from the Rocky Hill (pumice P2046 from compositional group RH-2 [Cooper
785 et al., 2016]). The Al map shows blurring of the core-rim boundary parallel to the *c*-
786 axis compared to along the *a*-axis, suggesting a strong growth control parallel to the
787 *c*-axis. Slowly diffusing Ca shows dissolution of the core, and formation of melt
788 inclusions during recrystallization. Ca-poor haloes around melt inclusions within the
789 orthopyroxene represent secondary zonation caused by dissolution and formation of
790 Ca-rich melt inclusions, before crystallization resumed. Melt inclusions in the core
791 thus record a departure from equilibrium for a period of time and dissolution of the
792 crystal before growth was resumed and the crystal rim formed within the final
793 erupted melt dominant bodies. The Mg + Fe map highlights streaky zones, which are
794 often, but not always, visibly associated with inclusions and may represent the result
795 of diffusion from an inclusion above or beneath the plane of the polished surface, or
796 a recrystallization trail from a mobile melt inclusion.

797 **Fig. S4.** Element maps of a representative orthopyroxene crystal from the Rocky Hill
798 (pumice P2049 from compositional RH-1) with a dark exterior zone. Elements with
799 very slow (Al) and slow (Ca) diffusion rates preserve the original zonation to a
800 greater extent than faster diffusing Mg. The map of Mg content and BSE image
801 show increased blurring of the dark zone, parallel to the *c*-axis, compared to across
802 the *a*-axis, inferred to reflect a component of growth zonation along the *c*-axis.
803
804

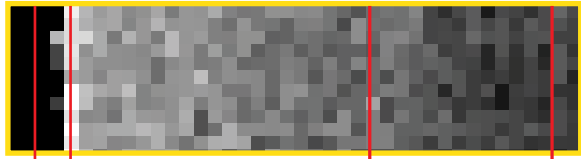
Figure 1

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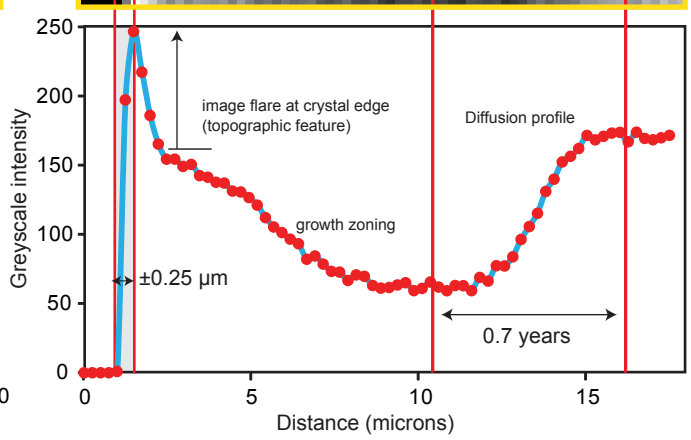
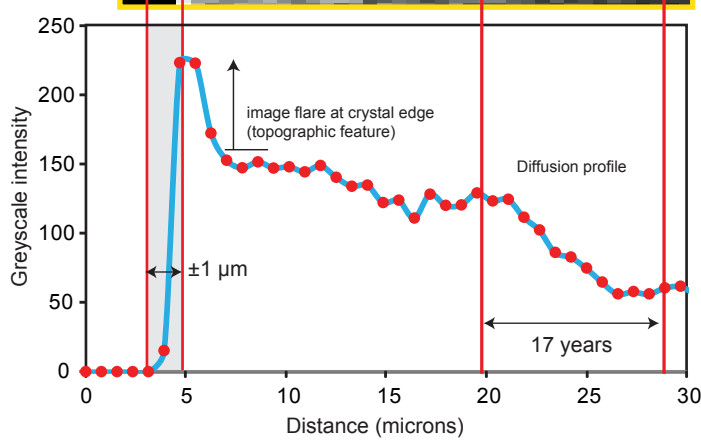
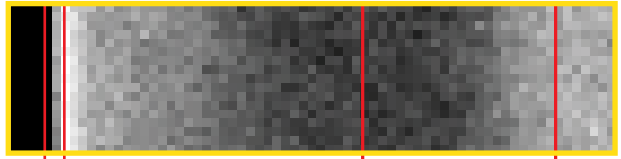




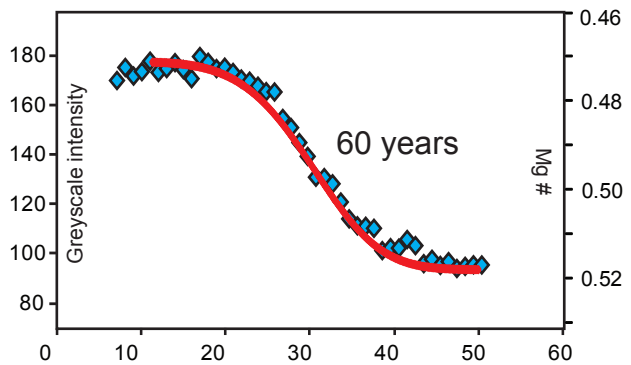
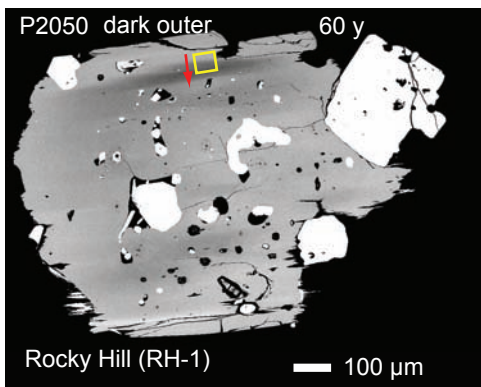
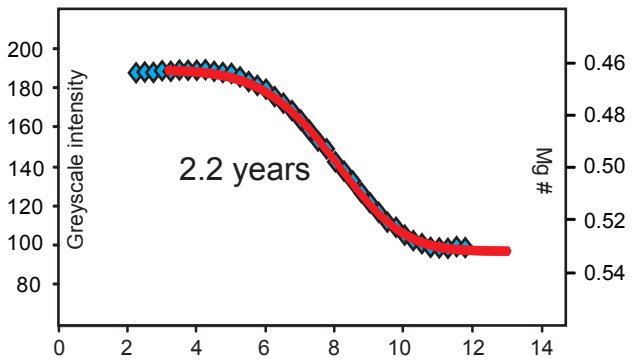
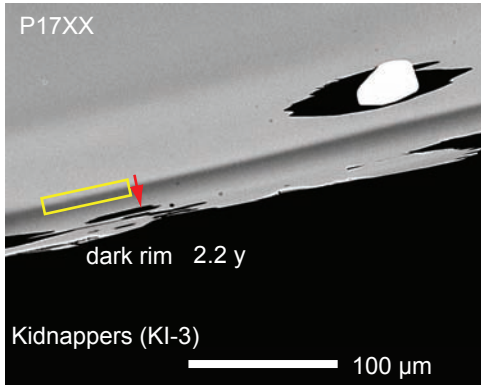
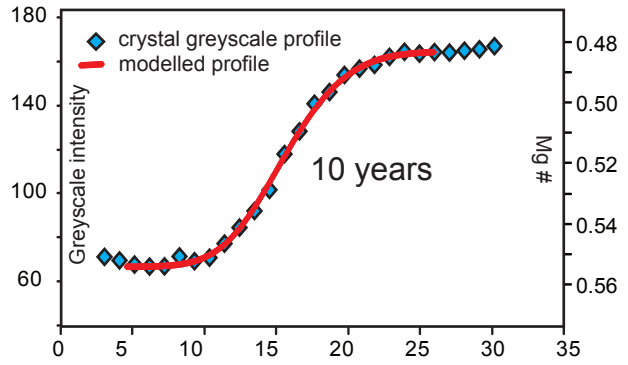
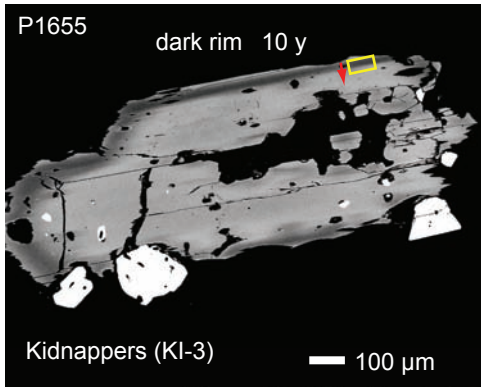
Area of image for profile:



Area of image for profile:



Dark exterior zones



Core-rim boundary

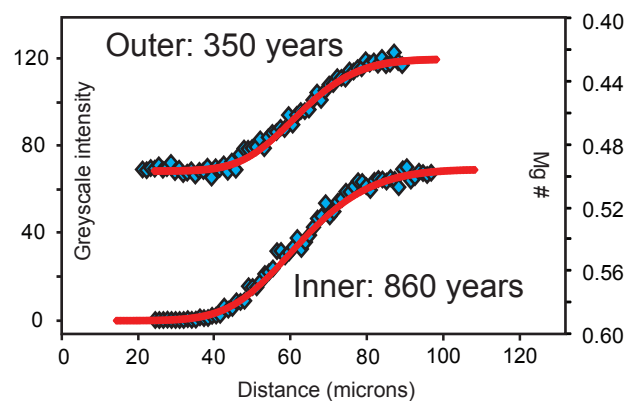
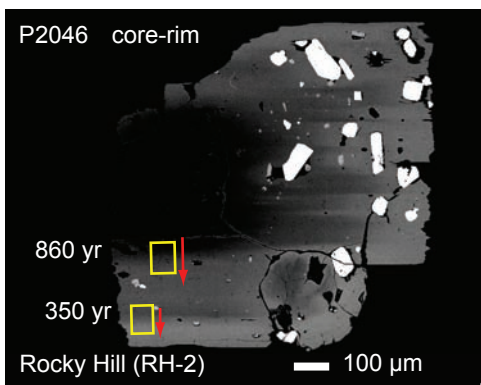
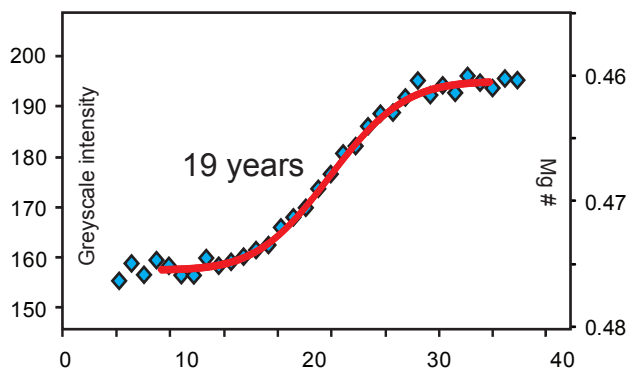
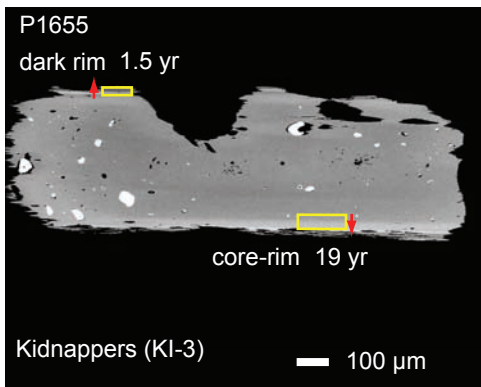


Figure 4
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 Fig. 4

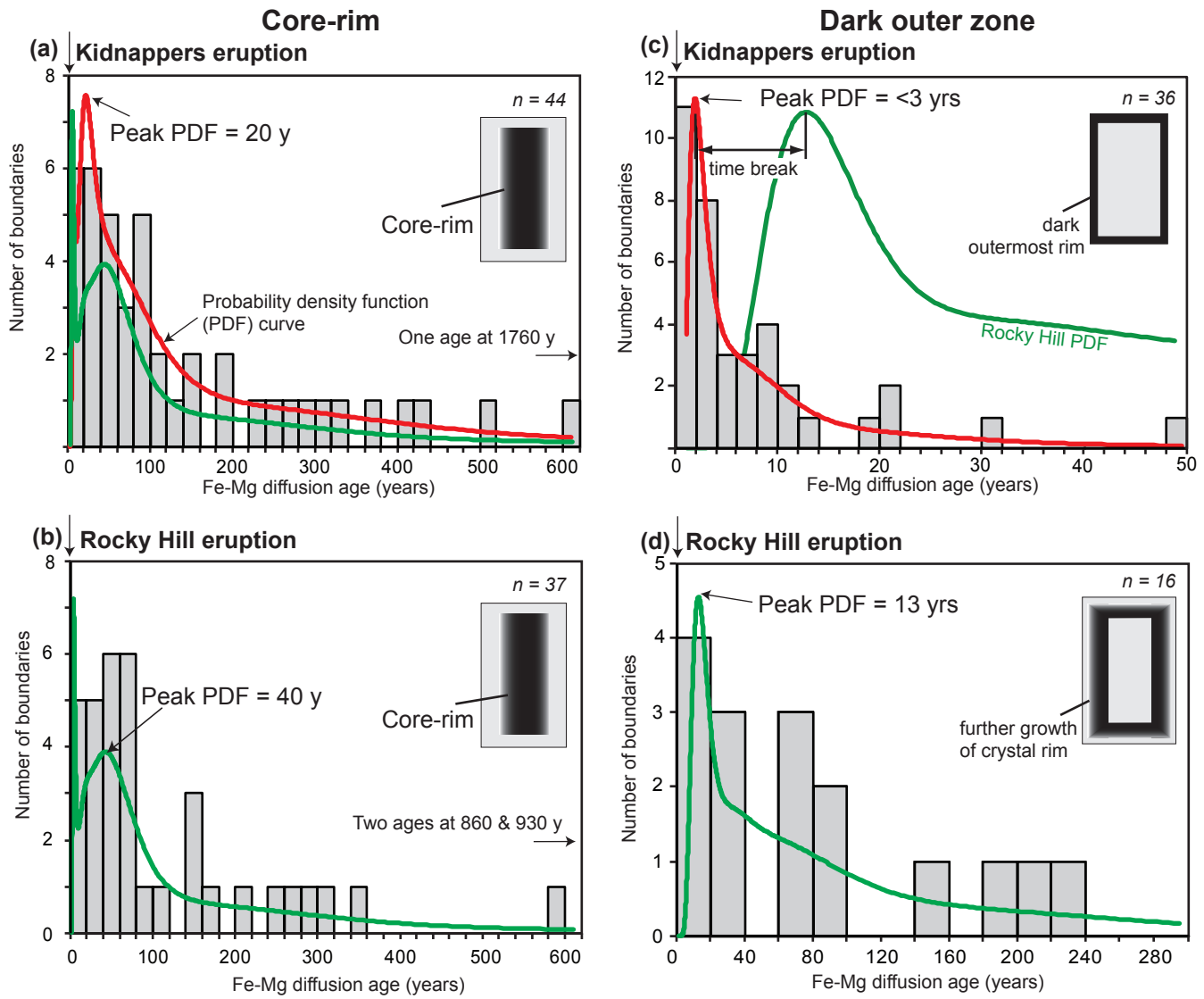
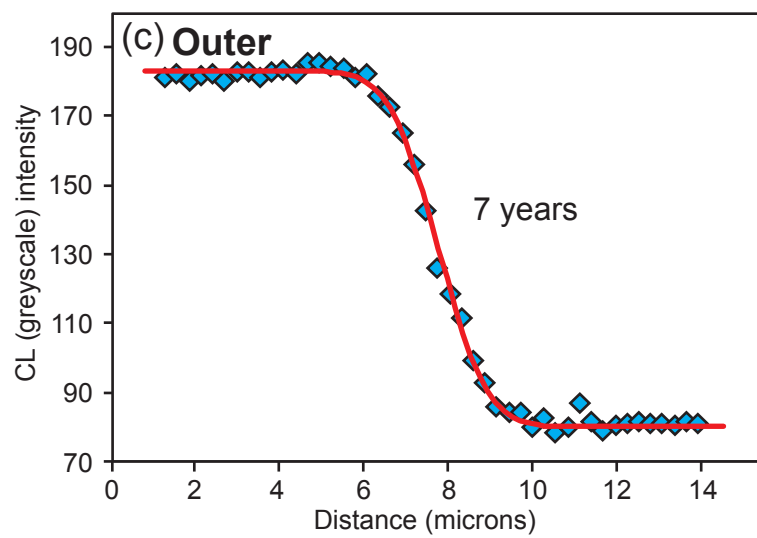
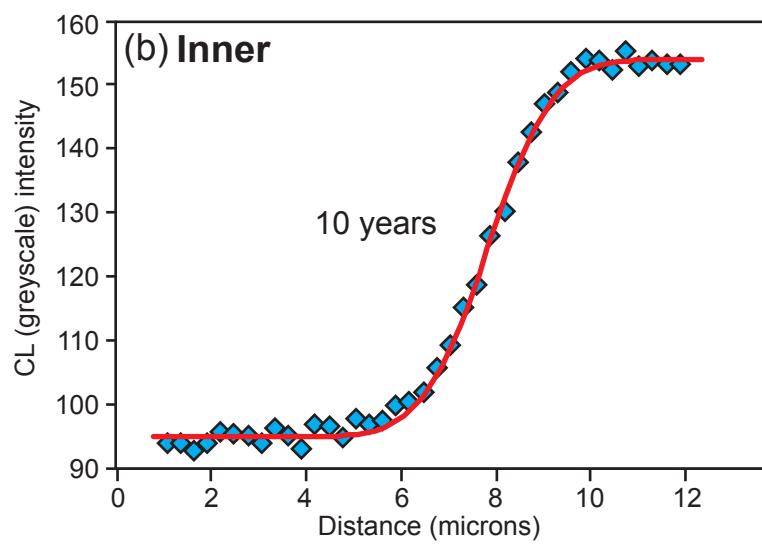
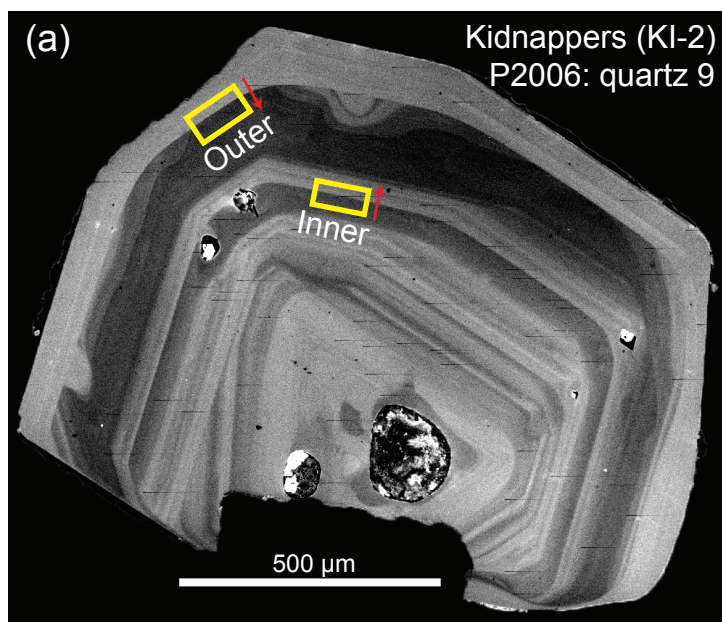


Figure 5
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Fig. 5



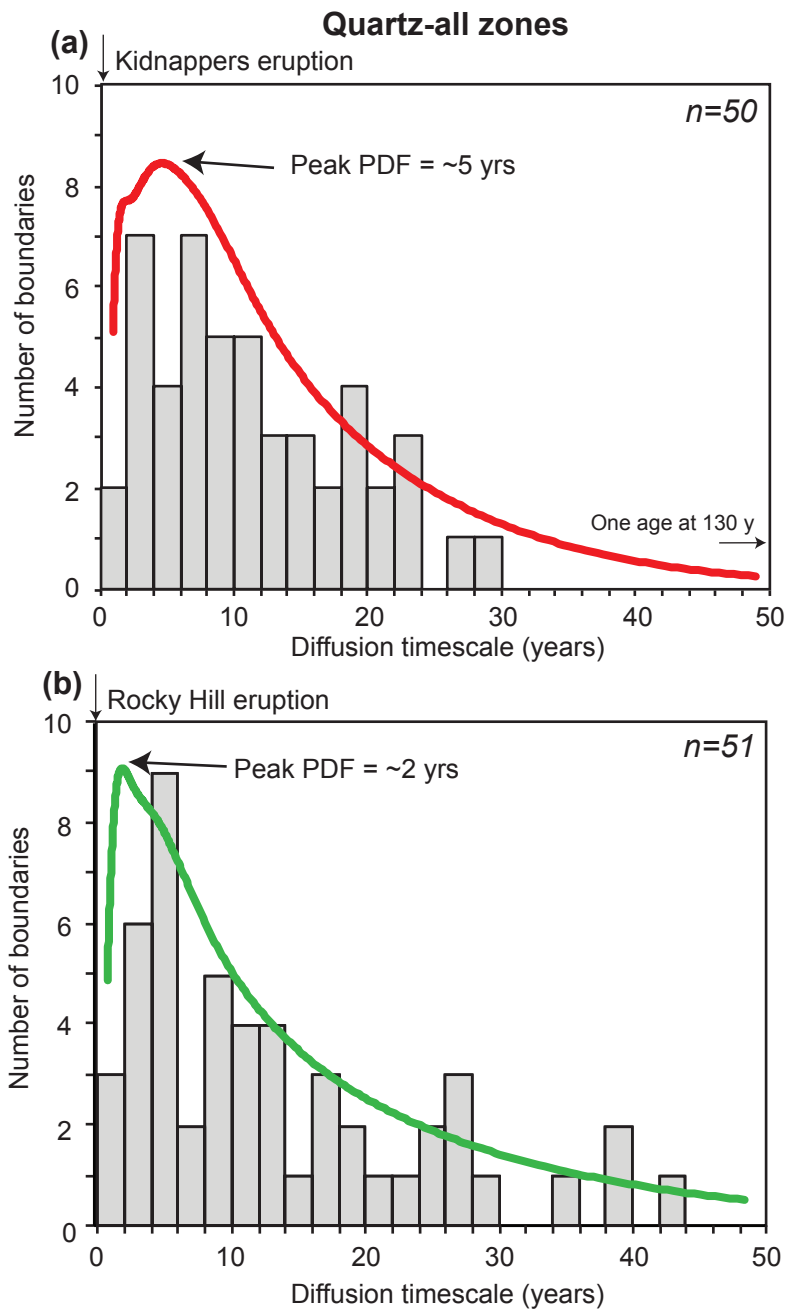


Figure 7
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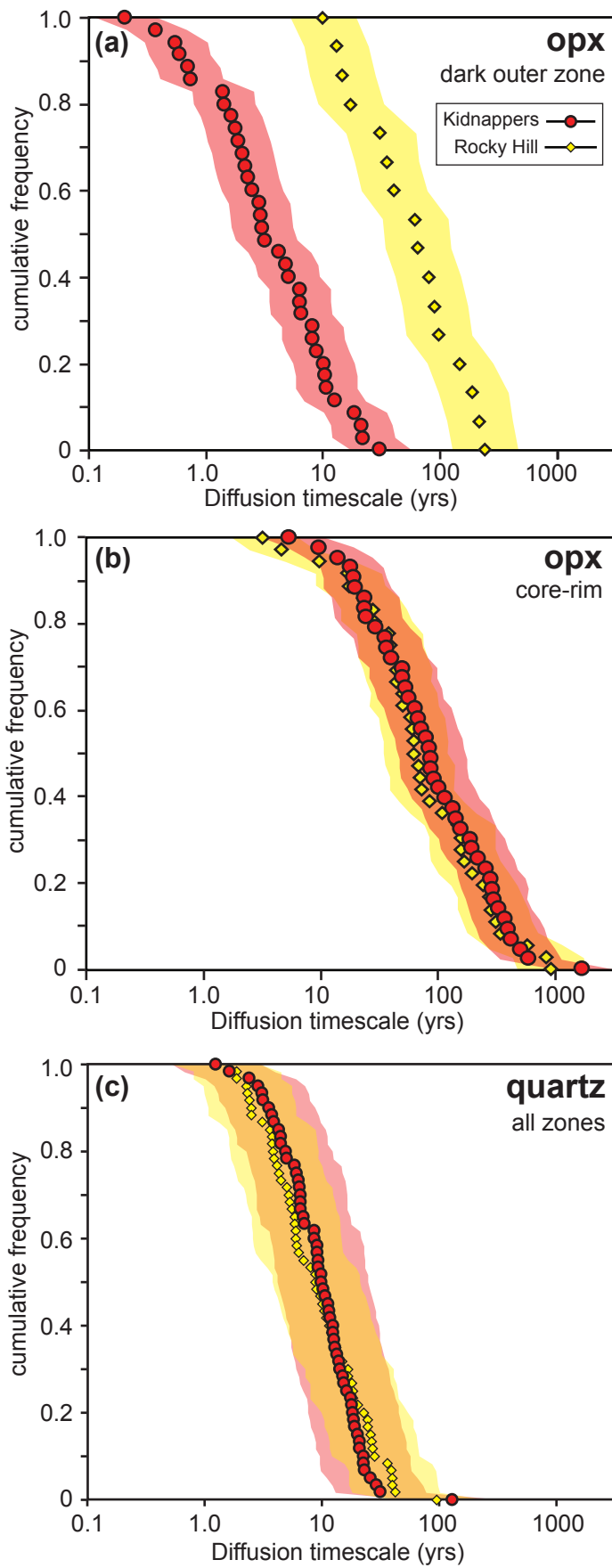


Figure 8

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Fig. 8

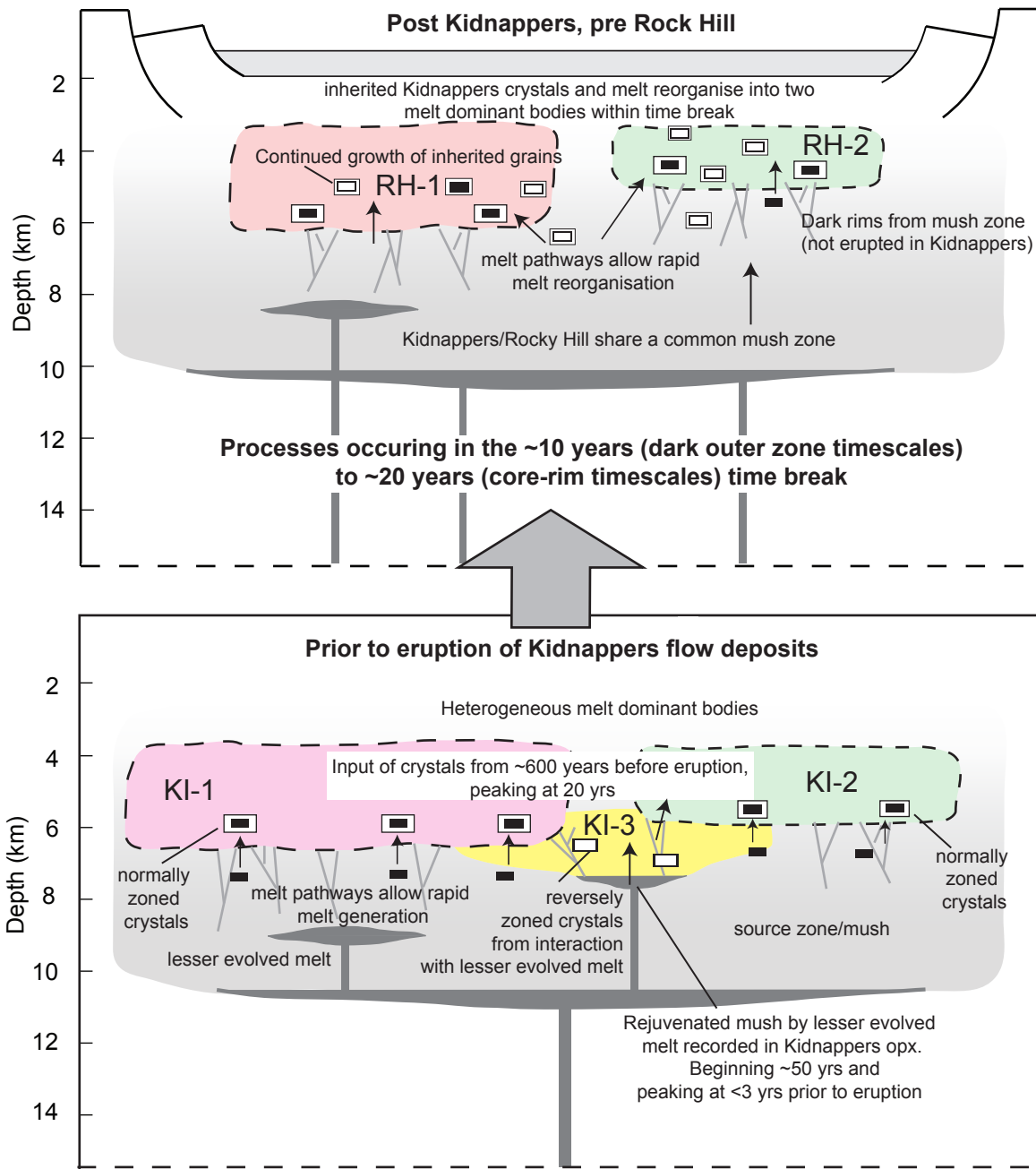


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Temperatures presented were used to calculate orthopyroxene diffusive timescales from each compositional group from the Kidnappers and Rocky Hill.

Table 2. Summary of quartz textural populations.

Groups and samples	Temperature	Dark rim	Light rim	No significant change
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KI-2 (P2006)	780 °C	80 %	7 %	13 %
Rocky Hill				
RH-1 (P2050)	795 °C	19.5 %	61 %	19.5 %

Textural classification in based on CL intensities. Temperatures presented were used to calculate quartz diffusive timescales.