



Deposited via The University of Leeds.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/89971/>

Version: Accepted Version

Article:

Chamberlain, KJ, Morgan, DJ and Wilson, CJN (2014) Timescales of mixing and mobilisation in the Bishop Tuff magma body: Perspectives from diffusion chronometry. *Contributions to Mineralogy and Petrology*, 168 (1). 1034. ISSN: 0010-7999

<https://doi.org/10.1007/s00410-014-1034-2>

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Contributions to Mineralogy and Petrology

Timescales of mixing and mobilisation in the Bishop Tuff magma body: perspectives from diffusion chronometry --Manuscript Draft--

Manuscript Number:	
Full Title:	Timescales of mixing and mobilisation in the Bishop Tuff magma body: perspectives from diffusion chronometry
Article Type:	Original Paper
Keywords:	diffusion chronometry; Bishop Tuff; two-feldspar thermometry; Ba in sanidine; Sr in sanidine; Ti in quartz; Fe-Mg in orthopyroxene
Corresponding Author:	Katy Jane Chamberlain Victoria University of Wellington Wellington, NEW ZEALAND
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Victoria University of Wellington
Corresponding Author's Secondary Institution:	
First Author:	Katy Jane Chamberlain
First Author Secondary Information:	
Order of Authors:	Katy Jane Chamberlain Daniel J Morgan Colin J N Wilson
Order of Authors Secondary Information:	
Abstract:	<p>We present two-feldspar thermometry and diffusion chronometry from sanidine, orthopyroxene and quartz from multiple samples of the Bishop Tuff, California, to constrain the temperature stratification within the pre-eruptive magma body and the timescales of magma mixing prior to its eruption. Two-feldspar thermometry yields estimates that agrees well with previous Fe-Ti oxide thermometry and gives a ~80 °C temperature difference between the earlier- and later-erupted regions of the magma chamber. Using this thermometry, we model diffusion of Ti in quartz, and Ba and Sr in sanidine as well as Fe-Mg interdiffusion in orthopyroxene to yield timescales for the formation of overgrowth rims on these phenocryst phases. Diffusion profiles of Ti in quartz and Fe-Mg in orthopyroxene diffusion both yield timescales of <150 years for the formation of overgrowth rims. In contrast, both Ba and Sr diffusion in sanidine yield nominal timescales 1-2 orders of magnitude longer than these two methods. The main cause for this discrepancy is inferred to be an incorrect assumption for the initial profile shape for Ba and Sr diffusion modelling (i.e., growth zoning). Utilising the divergent diffusion behaviour of Ba and Sr, we place constraints on the initial width of the interface and can refine our initial conditions considerably, bringing Ba and Sr data into alignment, and yielding timescales closer to 500 years, the majority of which are then within uncertainty of timescales modelled from Ti diffusion in quartz. Care must be thus taken when using Ba-in-sanidine geospeedometry in evolved magmatic systems where no other phases or elements are available for comparative diffusion profiling. Our diffusion modelling reveals piecemeal rejuvenation of the lower parts of the Bishop Tuff magma chamber at least 500 years prior to eruption. Timescales from our mineral profiling imply either that diffusion coefficients currently used are uncertain by 1-2 orders of magnitude, or that the minerals concerned did not experience a common history, despite being extracted from the same single pumice clasts. Introduction of the magma initiating crystallization of the contrasting rims on sanidine, quartz, orthopyroxene and zircon was prolonged, and may be a marker of other processes that initiated the Bishop Tuff eruption rather than the trigger itself.</p>

1 **Timescales of mixing and mobilisation in the Bishop Tuff magma body:**
2
3 **perspectives from diffusion chronometry**
4
5
6
7
8
9

10 Katy J. Chamberlain^{1,*}; Daniel J. Morgan² and Colin J. N. Wilson¹
11
12
13
14
15
16

17 ¹ School of Geography, Environment and Earth Sciences, Victoria University, PO Box 600,
18 Wellington 6140, New Zealand
19
20
21

22 ² School of Earth and Environment, University of Leeds, Leeds LS6 2JT, United Kingdom
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43

44 Manuscript for: *Contributions to Mineralogy and Petrology*
45
46

47 Running title: Diffusion in Bishop crystals
48
49

50 Keywords: diffusion chronometry, Bishop Tuff, two-feldspar thermometry, Ba in sanidine, Sr
51 in sanidine, Ti in quartz; Fe-Mg in orthopyroxene
52
53

54 Final Version: Jan 2014
55
56

57 *Corresponding author: Email katy.chamberlain@vuw.ac.nz, Phone (+64) 4 463 6595, Fax
58 (+64) 4 463 5186.
59
60
61
62
63
64
65

1
2 **Abstract**
3

4 We present two-feldspar thermometry and diffusion chronometry from sanidine, orthopyroxene and
5 quartz from multiple samples of the Bishop Tuff, California, to constrain the temperature stratification
6 within the pre-eruptive magma body and the timescales of magma mixing prior to its eruption. Two-
7 feldspar thermometry yields estimates that agree well with previous Fe-Ti oxide thermometry and
8 gives a ~80 °C temperature difference between the earlier- and later-erupted regions of the magma
9 chamber. Using this thermometry, we model diffusion of Ti in quartz, and Ba and Sr in sanidine as
10 well as Fe-Mg interdiffusion in orthopyroxene to yield timescales for the formation of overgrowth
11 rims on these phenocryst phases. Diffusion profiles of Ti in quartz and Fe-Mg in orthopyroxene
12 diffusion both yield timescales of <150 years for the formation of overgrowth rims. In contrast, both
13 Ba and Sr diffusion in sanidine yield nominal timescales 1-2 orders of magnitude longer than these
14 two methods. The main cause for this discrepancy is inferred to be an incorrect assumption for the
15 initial profile shape for Ba and Sr diffusion modelling (i.e., growth zoning). Utilising the divergent
16 diffusion behaviour of Ba and Sr, we place constraints on the initial width of the interface and can
17 refine our initial conditions considerably, bringing Ba and Sr data into alignment, and yielding
18 timescales closer to 500 years, the majority of which are then within uncertainty of timescales
19 modelled from Ti diffusion in quartz. Care must be thus taken when using Ba-in-sanidine
20 geospeedometry in evolved magmatic systems where no other phases or elements are available for
21 comparative diffusion profiling. Our diffusion modelling reveals piecemeal rejuvenation of the lower
22 parts of the Bishop Tuff magma chamber at least 500 years prior to eruption. Timescales from our
23 mineral profiling imply either that diffusion coefficients currently used are uncertain by 1-2 orders of
24 magnitude, or that the minerals concerned did not experience a common history, despite being
25 extracted from the same single pumice clasts. Introduction of the magma initiating crystallization of
26 the contrasting rims on sanidine, quartz, orthopyroxene and zircon was prolonged, and may be a
27 marker of other processes that initiated the Bishop Tuff eruption rather than the trigger itself.
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Introduction

Understanding the role of recharge in the assembly, stratification and evacuation of magma chambers has been a long standing question in the study of large-scale silicic magma systems, particularly those generating supereruptions. These eruptions, of $>10^{15}$ kg (~ 450 km³) magma (Self 2006; Miller and Wark 2008), have the potential to cause massive destruction, as well as having catastrophic effects on global climate (Self and Blake 2007). In terms of mitigating potential hazards, the more that can be determined regarding the timescales of the processes occurring in the parental magma systems (regardless of size), the more information that can be fed into monitoring programs at currently-active silicic volcanoes.

Recharge of volcanic systems has often been cited as a trigger for eruptions (e.g. Sparks et al. 1977; Jellinek and DePaolo 2003; Wark et al. 2007; Arienzo et al. 2011; Matthews et al. 2012a; Saunders et al. 2012) whether due to direct increase in volume causing failure of the magma chamber wall rocks (e.g. Jellinek and DePaolo 2003), or by indirectly causing changes in volume of saturated gases and crystal cargo which eventually leads to eruption (e.g. Snyder 2000; Wark et al. 2007). Evidence of magmatic recharge or mixing is commonly preserved as zonations within crystal phases already present in the magma chamber (e.g. Morgan et al. 2004; Ginibre et al. 2007; Wark et al. 2007; Martin et al. 2008; Humphreys et al. 2009; Allan et al. 2013). However, two factors make interpretation complex. The first is whether the crystal phases are recording consistently the same event, resolution of which is hampered (in general) by use of single mineral phases for study (e.g. Wark et al. 2007; Gualda et al. 2012a). The second is whether evidence for recharge or magma mixing is automatically evidence for an eruption trigger (e.g. Wark et al. 2007), when other, external factors may be important in causing both the recharge and the eruption (e.g. Allan et al. 2012; 2013)..

Diffusional geochronometry aims to model the evolution of compositional profiles within zoned crystals to determine the time elapsed since compositional variations were introduced. Typically, an initial starting profile shape is assumed – usually a sharp, step-change – and this is modelled forwards in time until it matches the observed profile. The timescale determined via this method can be regarded as a maximum, as the exact initial condition is not known. We will return to the validity of this initial assumption later in this paper. Although diffusion modelling of single or

1 multiple elements has been frequently utilised to explore timescales of crystal residence in magma
2 chambers (e.g. Zellmer et al. 1999; Costa et al. 2003; Morgan et al. 2004; Costa and Dungan 2005;
3 Morgan et al. 2006; Wark et al. 2007; Gualda et al. 2012a; Saunders et al. 2012; Till et al. 2012; Allan
4 et al. 2013), multiple phases from the same sample have not been routinely investigated. Here we
5 compare and contrast the timescales inferred from Fe-Mg interdiffusion in orthopyroxene, Ti
6 diffusion in quartz (cf. Wark et al. 2007; Gualda et al. 2012a), Sr diffusion in sanidine and Ba
7 diffusion in sanidine (cf. Morgan and Blake 2006) from samples of the Bishop Tuff, eastern
8 California. We also compare our data with alternative information on timescales of the processes
9 involved from high-precision U-Pb chronometry and textural studies in co-erupted zircon
10 (Chamberlain et al. 2014).

21
22 The Bishop Tuff (eruption age of 767 ka; Rivera et al. 2011) is an iconic example of a
23 supereruption which displays evidence of magma mixing preserved as zonation in quartz, sanidine
24 and orthopyroxene crystals (Hildreth 1977, 1979; Anderson et al. 2000; Peppard et al. 2001; Morgan
25 and Blake 2006; Wark et al. 2007; Gualda et al. 2012a). Whilst the Bishop Tuff has been the subject
26 of many volcanological and geochemical investigations (see Hildreth and Wilson 2007, for review),
27 the timescales associated with magma chamber assembly, residence and pre-eruptive mobilisation
28 remain controversial. For example, early radiogenic isotopic studies on crystal and glass separates
29 from the Bishop Tuff pointed to a long residence time for the magma (300 – 1300 kyr: Christensen
30 and Halliday 1996; Davies and Halliday 1998), apparently supported by theoretical models of felsic
31 magma genesis (Fowler and Spera 2010). However, more recent studies of zircon U-Pb ages and
32 crystal size distribution (CSD) modelling indicate that this is unrealistic and infer timescales of
33 between ~160 kyr to a few thousand years (e.g. Gualda et al. 2012a; Pamukcu et al. 2012; Reid and
34 Schmitt 2012; Chamberlain et al. 2014) for crystals residing in the melt-dominant magma body.
35 Previous workers have investigated the timescales for magma mobilisation within the Bishop Tuff
36 magma chamber, primarily by modelling Ti diffusion with quartz (Wark et al. 2007; Gualda et al.
37 2012a) which yields timescales of <100 yr (for the ‘bright-rim’ [in CL imagery] overgrowths) to
38 ~2700 yr (for core-interior zonation). However, no comprehensive combined study of the diffusion
39 records of multiple phenocryst phases within the Bishop Tuff has been undertaken. Here we examine
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 the rim-forming overgrowths on sanidine, quartz and orthopyroxene crystals from multiple samples of
2 multiple units of the Bishop Tuff. We examine how comparable each of these timescales are, if they
3 are tracing the same magmatic evolution, and reveal the relatively short-lived magmatic intrusions
4 occurring prior to eruption.
5
6
7

8 9 10 **Geological setting**

11 The Bishop Tuff eruption was the culmination of ~3.8 Myr of magmatic development in the Long
12 Valley region and is the product of one of the largest eruptions on Earth in the last 1 Myr. Over 600
13 km³ of magma was erupted to generate fall deposits and ignimbrite, along with voluminous infill from
14 the formation of Long Valley caldera (Fig. 1; Bailey et al. 1976; Hildreth 1979, 2004; Wilson and
15 Hildreth 1997; Hildreth and Wilson 2007). The volume of rhyolite erupted as the Bishop Tuff is
16 greater than all other felsic eruptions combined in the Long Valley area before or since (Hildreth
17 2004), and so questions arise as to how, and over what time period, such a large body of magma was
18 accumulated and what the triggering processes were for the eruption.
19
20
21
22
23
24
25
26
27
28
29
30

31 Proximal deposits of the eruption consist of nine fall units (F1-9) and eleven ignimbrite
32 packages (Wilson and Hildreth 1997; Fig.1). A systematic change from ‘early’, crystal poor, more-
33 evolved (78.2 – 74.8 wt.% SiO₂ whole rock; Hildreth and Wilson 2007) to ‘late’, crystal rich, less-
34 evolved (77.8 – 73.4 wt.% SiO₂ whole rock; Hildreth and Wilson 2007) compositions is observed
35 within the stratigraphy of the Bishop Tuff. (In the context of this paper, ‘early’ refers to fall units F1-
36 F8 and their coeval Ig1 ignimbrite packages; ‘late’ refers to Ig2N and Ig2NW; and ‘intermediate’ to
37 the Ig2E ignimbrite packages and fall unit F9). Changes in pumice composition accompany an overall
38 change in volatile contents and species in quartz hosted melt inclusions from water-richer, CO₂-poorer
39 to water-poorer, CO₂-richer (Dunbar & Hervig 1992; Wallace et al. 1999) magma. For this study,
40 single pumice samples were collected from every ignimbrite unit of the Bishop Tuff, and pumices
41 covering the range of crystallinities were sampled (Fig. 1). Pumice clasts are categorised within two
42 spectra: the ‘normal’ crystal-poor (xp) to crystal-rich (xr) scale, and the ‘variant’ types, following
43 Hildreth and Wilson (2007). The latter are of particular interest because they often show evidence of
44 physical mixing on millimetre to centimetre scales, and so eight samples of the ‘swirly’ and
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 'chocolate' variant pumice types of Hildreth and Wilson (2007) were inspected from packages Ig1Eb
2 through to Ig2Nb.
3
4
5

6 **Methods**

7 **Sample preparation**

8
9 Single pumices were selected, washed to remove adhering matrix, and then crushed to chips using a
10 Boyd crusher at Victoria University of Wellington. Crushed material was sieved and the sample was
11 water-panned to separate glass from crystals. Quartz and sanidine phenocrysts were then hand-picked
12 under optical microscope from the 1 – 2 mm size fraction. Orthopyroxene was hand-picked from the
13 250 – 500 μm size fraction (the sieved fraction in which orthopyroxene crystals were most common).
14
15 Sanidine and orthopyroxene crystals were orientated with the crystal *b*- and *c*- axes in the plane of the
16 section, so that these axes were exposed once the epoxy mount was ground and polished for imaging
17 and analysis.
18
19
20
21
22
23
24
25
26
27
28
29
30

31 **BSE imaging**

32
33 Zoning patterns in sanidine and orthopyroxene were imaged by back-scattered electron (BSE)
34 methods on a JEOL JXA 8230 Electron Microprobe (EPMA) at Victoria University of Wellington.
35
36 Due to the dependence of BSE brightness on the effective atomic number of the sample per unit
37 volume, changes in BSE brightness correspond to compositional changes within the crystal (Reed
38 2005). In sanidine the major element affecting BSE brightness is Ba, and therefore brighter BSE tones
39 relate, in these samples, to areas of higher Ba concentration. Sanidine compositions vary by less 0.5
40 mol% anorthite, < 3 mol% albite and < 3 mol% orthoclase, though typically this does not exceed ~
41 0.2, ~0.8 and ~1 mol%, respectively. In orthopyroxene, BSE brightness is controlled largely by
42 changing Fe-Mg content. Ca can have a minor effect, but this can be neglected in this case (see
43 Electronic Appendix 3 and Allan et al. 2013). All crystals were imaged completely and any zoning
44 identified, before high-resolution images of the boundaries in the crystal were acquired to give
45 improved spatial resolution across boundaries of interest. Image acquisition time was ~ 2 minutes,
46 with a single integration.
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2 CL imaging
3

4 Quartz zoning patterns were gathered by cathodoluminescence (CL) imaging, where the brightness of
5 the image directly corresponds to Ti concentration (Wark et al. 2007; Matthews et al. 2012a, b).
6

7
8 Initial lower quality whole-crystal images were acquired at Stanford University using a JEOL LV
9 5600 Scanning Electron Microscope (SEM) so that a large number of crystals could be evaluated for
10 their zoning patterns prior to detailed analysis. High-resolution CL images of Ti boundaries in quartz
11 crystals were obtained on a FEI Quanta 650 FEG-SEM (Field Emission Gun- Scanning Electron
12 Microscope) with a KE Centaurus panchromatic CL detector at the University of Leeds, with a dwell
13 time of 100 μ s per pixel.
14
15
16
17
18
19
20
21
22
23

24 Quantitative analyses

25
26 Quantitative major, minor and selected trace element analyses were undertaken on a JEOL JXA 8230
27 SuperProbe at Victoria University of Wellington. For all elements apart from Sr and Ba an
28 accelerating voltage of 15 kV, a beam current of 12 nA and a spot size of \sim 1 μ m was used. Elements
29 were analysed with a 30 s count on-peak. For Sr and Ba in sanidines a 20 kV accelerating voltage and
30 40 nA beam current was used (following the method of Ginibre et al. 2002) with a defocused beam
31 diameter of 5 μ m. Spots were placed at a 7 μ m spacing so as to avoid significant convolution issues.
32
33 Sr was analysed with a 240 s peak count, and background was measured within 2 mm of the peak
34 location (unlike 5 mm for other elements) to remove the effect of Si. Ba was analysed with a 120 s
35 count time on-peak.
36
37
38
39
40
41
42
43
44
45

46 Trace element analyses from the EPMA were compared with trace element concentrations
47 measured using laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at Victoria
48 University of Wellington. *In situ* measurements were undertaken using a New Wave deep UV laser
49 (193 nm solid state) coupled to an Agilent 7500cs ICPMS.
50
51
52
53
54
55
56
57

58 Modelling parameters
59
60
61
62
63
64
65

Greyscale profiles of Ba in sanidine, Fe-Mg in orthopyroxene and Ti in quartz were extracted from BSE or CL images using ImageJ[®] software. Sr profiles in sanidine were taken directly from EPMA measurements at 7 μm spacing. For all profiles an initial condition of a step-function was assumed. Sanidine and quartz modelling was carried out using a simple 1D model (e.g. Morgan et al. 2006). This assumption can hold due to the relatively small extent of diffusion relative to grain size, and follows the method of Morgan et al. (2006) and Morgan and Blake (2006). Diffusion anisotropy was considered small for Ti in quartz, and Ba and Sr in sanidine, as previous studies have not noted marked anisotropy in these systems (Cherniak 2002, 2010; Cherniak and Watson 1992; Cherniak et al. 2007). The modelling parameters used for each species are presented in Table 1. Given the high temperature dependence of elemental diffusion, the uncertainty on every timescale was calculated using ± 30 °C in the temperature input, based on common uncertainties in FeTi oxide thermometry (e.g. Hildreth and Wilson 2007), and that associated with the two-feldspar thermometry (see Results section).

In order to model diffusion for Ti in quartz, Sr in sanidine and Ba in sanidine, the diffusivity of the element (D_i) being considered must be calculated. In many systems (including those listed above) where there is no compositional or oxygen fugacity dependence, these diffusivities are expressed in the form:

$$D_i = D_{i,0} e^{\left(\frac{-E}{RT}\right)} \quad (\text{Equation 1; see e.g. Crank 1975; Zhang 2010}),$$

where $D_{i,0}$ is the D_0 for species i given in Table 1, E is the activation energy given in Table 1, R is the gas constant, and T is temperature in Kelvins. Having calculated the appropriate values of D for each elemental system at the appropriate temperature, the following equation was solved for time:

$$C = C_0 + \frac{(C_1 - C_0)}{2} \left[\operatorname{erfc} \left(\frac{x}{2\sqrt{D_i t}} \right) \right] \quad (\text{Equation 2; Morgan et al. 2004}),$$

where C is the normalised concentration of Ti, Sr or Ba, C_0 and C_1 refer to the initial amounts of the element on each side of an initial interface, D_i is the calculated diffusivity in m^2s^{-1} , t is the diffusion time, and x is the position measured in metres along the profile and centred on the interface (the midpoint of the profile). The best-fit profiles were then determined by using a macro to minimise the

1 difference between modelled profile shape and the input profile, yielding a timescale for the best-fit
2 profile.
3

4 For modelling in orthopyroxene, Fe-Mg profiles were obtained along the crystallographic a -
5 or b -axis, to be internally consistent and to avoid anisotropy effects. This is comparable with other
6 Fe-Mg orthopyroxene interdiffusion chronometry where growth effects along the c -axis could be
7 demonstrated to have occurred (e.g. Allan et al. 2013). Due to an expected fO_2 dependence of D_{Fe-Mg}
8 in orthopyroxene (Ganguly and Tazzoli 1994), the formula of Ganguly and Tazzoli (1994) modified
9 as in Allan et al. (2013) is used to calculate D_{Fe-Mg} :

$$17 \log_{10} D_{Fe-Mg} = \left(-5.54 + 2.6X_{Fe} - \frac{12530}{T} \right) + \frac{1}{6} \log_{10} \left(\frac{fO_2 (sample, T)}{fO_2 (IW\ buffer, T)} \right)$$

21 (Equation 3),
22

23 where X_{Fe} is the molar proportion of the Fe end member (ferrosilite), T is temperature in Kelvins, and
24 fO_2 is oxygen fugacity. In order to then model a timescale, finite difference methods were used, as
25 detailed in Allan et al. (2013). We revisit the potential accuracy of this expression in the discussion.
26
27

28 In order to test that all profiles extracted were statistically significant, and to what degree
29 variation on either end of the profile is significant, statistical analyses were conducted across every
30 profile extracted from images. The uncertainty on the greyscale profile, being essentially random
31 thermal noise in the BSE or CL detector, scales as $\frac{1}{\sqrt{n}}$ where n is the number of pixels being averaged
32 together; yielding a standard error (s.e.). If diffusion is the cause of the sigmoidal concentration
33 profile, the plateaux at either end of the profile should be flat. Profiles which had variation in the
34 plateaux that exceeded the calculated 2 s.e. were therefore rejected.
35
36
37
38
39
40
41
42
43
44
45
46
47
48

49 **Results**

50 Two-feldspar thermometry

51 Where present, major element analyses of sanidine inclusions in plagioclase crystals (and *vice versa*)
52 were used in combination with the Elkins and Grove (1990) calibration of the two-feldspar
53 thermometer to iteratively calculate the temperatures at which these feldspars crystallised. We
54
55
56
57
58
59
60
61
62
63
64
65

1 present 26 new temperature calculations from the early Bishop Tuff (Ig1Eb- Fig. 1) through to the
2 latest Bishop Tuff (Ig2Nc- Fig. 1). The full results are presented in Table 2. All inclusions measured
3 are within BSE-‘dark’ cores of crystals, showing that the temperature stratification of ~80 °C
4 calculated by two-feldspar thermometry was present prior to any mixing with the contrasting magma
5 composition that gave rise to the BSE-bright crystal rims. The ‘bright-rim’ forming magma is
6 inferred to have been of slightly higher temperature than the ‘normal’ Bishop Tuff magma due to its
7 less-evolved melt composition and as indicated by increases in Fe-Ti oxide and oxygen-isotope model
8 temperatures with inferred depth in the system (Hildreth 1979; Wallace et al. 1999; Bindeman and
9 Valley 2002; Hildreth and Wilson 2007).

10 We then use these temperature results, in consideration with previously published Fe-Ti oxide
11 thermometry (Hildreth and Wilson 2007), to estimate temperatures at which diffusion occurred (Table
12 3). Samples from units Ig2Na yield cooler temperatures than those of the overlying Ig2Nb and Ig2Nc
13 packages (Fig. 1; Table 2), and are thus modelled at 770 °C, representing a rounded average of the
14 calculated model temperatures. Samples from Ig2Nb and Ig2Nc appear indistinguishable based on the
15 feldspar thermometry and thus are modelled at 790 °C, representing again a rounded average of the
16 results. Samples from Ig2Nwa and Ig2Nwb are modelled at 815 °C due to their higher model
17 temperatures than Ig2N packages. Where zoning is present, crystals from the F9 sample are modelled
18 using an average of 780 °C represented by the results from Ig2N. Some quartz crystals from Ig2SW
19 preserved Ti zonation, and this diffusion was modelled at 753 °C, that is, an average of Ig2E and
20 Ig2Na modelled temperatures. In all cases a ± 30 °C (1σ) uncertainty on thermometry is assumed
21 which is then propagated through to uncertainties on the diffusive timescales. The actual temperature
22 controlling diffusion is, however, likely to have been slightly hotter than those modelled here from the
23 cores of crystals due to the crystals being subsequently immersed in the ‘bright-rim’ forming melt
24 (Hildreth 1979; Hildreth and Wilson 2007; Chamberlain et al. 2014: see Table 3 for temperatures
25 used).

26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58 Ti-in-quartz
59
60
61
62
63
64
65

1 Quartz from 16 samples from F1 (earliest erupted) to Ig2Nc (latest erupted: Fig. 1) were imaged, of
2 which 11 samples showed bright rim overgrowths on quartz crystals suitable for modelling (Fig. 2).
3
4 The 11 samples came from units Ig2Na, Ig2Nb, Ig2Nc, Ig2NcWa, Ig2NcWb, F9 as well as 3 boundaries
5
6 from a sample of Ig2SW (Fig. 1). As previously shown, only quartz crystals from ‘late’ in the Bishop
7
8 Tuff eruption sequence (and therefore from deeper in the magma chamber: Wallace et al. 1999) have
9
10 a high-Ti rim. ‘Early’ samples (which constitute ~ 2/3 of the eruptive volume, Hildreth and Wilson
11
12 2007) still retain some complex oscillatory zoning (Peppard et al. 2001; Wark et al. 2007; Gualda et
13
14 al. 2012a), but this is not investigated further here.
15
16

17
18 One hundred and seventy four timescales were modelled, using the feldspar thermometry
19
20 results detailed above. Of these timescales, fifteen were rejected for not having a statistically
21
22 significant contrast along the profile (see Methods). The boundaries between higher and lower Ti-
23
24 bearing quartz range in width from ~5 μm to ~30 μm , yielding maximum timescales which range
25
26 from as little as 15 days (+37/-8 days uncertainty) to 226 years (+556/-97 yrs uncertainty) with a
27
28 mean value of 24 years which is skewed by the dominance of shorter timescales. The best timescale
29
30 resolution achievable from CL images was calculated by modelling the fictive apparent timescale
31
32 across a known sharp contact, in this case, a crack within a quartz crystal. This yielded a “timescale”
33
34 of 0.56 years (at 815 °C), and therefore any timescales shorter than this are effectively unresolvable
35
36 via CL imaging and are discounted. The shortest resolvable timescale is thus 1.0 years (+2.4/-0.45
37
38 yrs) (Fig 3). All timescales are referred to as “maximum” due to the assumption that the initial
39
40 boundary between the horizontal concentration profiles was both sharp and oriented perpendicular to
41
42 the sample surface (see Fig. 2 dotted lines), as no angular correction has been applied (Matthews et al.
43
44 2012a; Costa and Morgan 2010). Changing these assumptions would serve only to shorten the
45
46 modelled timescales further.
47
48
49
50

51
52 There is no systematic difference in timescales obtained from individual samples or packages,
53
54 although note that of the eighteen quartz crystals imaged from Ig2SW only two showed a bright
55
56 overgrowth. In all other late-erupted packages the bright rim development was far more common (see
57
58 Electronic Appendix 1 for compiled, low resolution images of representative samples; Electronic
59
60 Appendix 2 for all modelled boundaries in quartz). This pattern is matched in Bishop zircons
61
62
63
64
65

1 (Chamberlain et al. 2014) where samples from Ig2SW show only sparsely developed bright rim
2 overgrowths when compared with other late-erupted material from the northern and north-western
3 vents.
4
5

6 7 8 Fe-Mg in orthopyroxene 9

10 There were twelve samples from which orthopyroxene could be extracted (from packages Ig2Nb,
11 Ig2Nc, Ig2Nwa and Ig2Nwb; note that there was a lack of significant orthopyroxene in Ig2Na). Of
12 these, nine produced zoned crystals suitable for modelling for diffusive timescales. The zoning
13 textures in orthopyroxene are not as systematic as those in quartz, but can be split into three groups:
14 unzoned (Fig. 4a); darker (i.e. Mg-richer) rims (Fig. 4b); and brighter (i.e. Fe-richer) rims (Fig. 4c).
15
16 There is a direct correlation between BSE brightness and Fe-Mg content (e.g. Allan et al. 2013) and is
17 demonstrated for the Bishop samples in Electronic Appendix 3. The variation in Mg content across
18 the zones is relatively small, only up to 5.4 mol% enstatite, with the minimum resolvable change for
19 diffusive modelling in this way being 0.5 mol% enstatite
20
21

22
23
24
25
26
27
28
29
30
31 Thirty-six timescales were obtained from diffusive modelling within orthopyroxene crystals
32 following the method of Allan et al. (2013), where different oxygen fugacities (+0.48 log units to
33 +1.11 log units, relative to NNO) were used in combination with the range in temperatures (790 °C or
34 815 °C). Oxygen fugacity data was taken from Hildreth and Wilson (2007) and calculated relative to
35 NNO using the formulation from Huebner and Sato (1970). The maximum resolution for
36 orthopyroxene boundaries was calculated in the same way as for quartz crystals using a crystal edge
37 as the known sharp boundary. The shortest time resolvable by this technique is equivalent to ~0.04
38 years, shorter than that from CL images of Ti in quartz due to the better spatial resolution of BSE
39 imaging and the different values of D calculated for different diffusion regimes. Boundaries between
40 lower Fe and higher Fe vary in full width from ~4 µm to ~30 µm, giving ranges in maximum
41 timescales of 0.1 year (+0.1/-0.05 yrs) to 14 years (+13/-6.7 yrs: Fig. 3). The mean value of Fe-Mg
42 interdiffusion timescales is 2.8 years, an order of magnitude shorter than that of Ti in quartz, and
43 again shows a dominance of very short timescales (<4 years). Although different textural groups are
44 observed, the timescales do not vary systematically with absolute rim compositions, relative changes
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 in Mg content (i.e. lighter versus darker rims), or eruptive package. This observation implies that
2 although the resulting rims have slightly different compositions, the process(es) causing the
3 overgrowths occurred over similar timescales (Electronic Appendix 3).
4
5
6
7

8 Ba-in-sanidine 9

10 A total of 54 samples of sanidine crystals were imaged, spanning the entire eruptive sequence from F1
11 to Ig2Nc (Fig. 1). Of these, 15 samples showed sanidine crystals with a bright (higher Ba, Sr)
12 overgrowth (Fig. 5). These crystals were found dominantly in samples from the Ig2N and Ig2NW
13 packages (plus single samples from F9 and Ig2SW). As with quartz CL images (see above) the
14 Ig2SW sanidines generally lack bright rims, with only two of twelve crystals having a bright
15 overgrowth. All other early-erupted samples show no zonation (Fig. 5a). We cannot replicate the
16 observations by Gualda (2007) and Pamukcu et al. (2012) that some feldspars from Ig2E have bright
17 rims in our ten sample suite from Ig2E pumices (representing a range in crystallinities). The minimum
18 resolvable timescale for Ba in sanidine was calculated using the same method as for orthopyroxene,
19 yielding a value of ~30 years.
20
21
22
23
24
25
26
27
28
29
30
31
32

33 Fifty-four timescales were modelled from the statistically significant profiles (see Methods
34 section) between higher- and lower-Ba zones in sanidine crystals. The width of these boundaries
35 varied from ~4 μm to ~40 μm , yielding maximum timescales that range from 44 years (+138/-33 yrs)
36 to 150,000 years (+540,000 /-114,000 yrs), although most are commonly on the order of 100s to
37 10,000s of years (Fig. 3; Electronic Appendix 4 for all modelled timescales). The mean value of
38 timescales for Ba diffusion in sanidine is 6770 years, but if the two longest values are removed this is
39 reduced to 600 years. The median value of timescales for Ba diffusion in sanidine is 350 years. Even
40 though these timescales are considered maxima there remains substantial differences from the
41 modelled timescales of Ti diffusion in quartz and Fe-Mg interdiffusion in orthopyroxene. Ba diffusion
42 timescales in sanidine appear to be between one and three orders of magnitude longer than those from
43 other two phases (Fig. 3).
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59

60 Sr-in-sanidine 61 62 63 64 65

1 In order to assess if the contrast in Ba-in-sanidine model ages is due to sanidine having a different
2 crystallisation history to quartz and orthopyroxene, or due to some problem related to the modelling
3 of Ba behaviour, we undertook comparative modelling of Sr diffusion in sanidine. Strontium
4 distribution in these sanidines is known to mimic that of Ba (Hildreth 1977, 1979; Lu 1991; Lu et al.
5 1992; Anderson et al. 2000; Hildreth and Wilson 2007). With the more rapid diffusion rates of Sr in
6 alkali feldspar (Cherniak and Watson 1992), it would be expected that Sr profiles could be measured
7 via EPMA or LA-ICPMS. Ten of the 15 examples of Ba-zoned sanidine were selected for
8 investigation. Initial LA-ICPMS measurements were conducted to confirm that the correlations of Sr
9 and Ba in zoned sanidines noted by earlier authors (Lu 1991; Anderson et al. 2000) were widespread
10 throughout the Bishop Tuff (Fig. 6: R^2 values of 0.87 for LA-ICPMS and 0.74 for EPMA). Given
11 these positive correlations, a range of diffusion boundaries previously analysed for Ba were selected
12 for Sr analysis. Due to the relatively narrow width of the diffusion boundaries ($<50 \mu\text{m}$), LA-ICPMS
13 lacked the spatial resolution to definitively measure Sr changes across the boundary without serious
14 convolution problems. Although use of Nano-SIMS (Saunders et al. 2014) would have been
15 preferable in terms of spatial precision, the short time required to measure a Sr profile by EPMA (~1.5
16 hrs) meant that modelling of maximum timescales (reflecting the spatial resolution) across multiple
17 boundaries was relatively straightforward. By using a 40 nA current and long (240 s) count time, our
18 measurement uncertainties were improved to ± 75 ppm (2 sd), with a detection limit of 150 ppm (4
19 sd), sufficient to define profiles in 19 grains.

20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Boundaries for Sr were located using the BSE images, as Sr and Ba were directly correlated (Figs. 5, 6). Although many boundaries were analysed, only seventeen yielded Sr profiles which were deemed appropriate for diffusion modelling with acceptable definition, and lower degrees of analytical noise (e.g. Fig. 5d [i]). Only Sr profiles that were matched by changes in Ba concentration (from EPMA analyses) were used for modelling, to ensure that the change in Sr concentration was not an artifact of sub-optimal analytical procedures. The maximum width of these profiles varied between $\sim 5 \mu\text{m}$ and $\sim 50 \mu\text{m}$ which yielded maximum timescales of 19 years (+65/-14 yrs) to 1710 years (+5790/-1290 yrs: Fig. 3), with a mean timescale of 430 years. With analysis by EPMA and a

1 defocused beam, these results will necessarily include some convolution, and so these timescales are
2 effectively overestimates but at least provide upper limits for comparative purposes.
3
4
5

6 **Discussion**

7
8 Temperature stratification within the Bishop magma body
9

10 Many estimates have been presented of magmatic temperatures of the Bishop Tuff. These
11 thermometry calculations have utilised Fe-Ti oxides (Hildreth, 1977, 1979; Hildreth and Wilson 2007;
12 Evans and Bachmann 2013), Ti concentrations in quartz (Wark et al. 2007; Thomas et al. 2010;
13 Thomas and Watson 2012; Wilson et al. 2012), Ti concentrations in zircon (Reid et al. 2011;
14 Chamberlain et al. 2014), $\Delta^{18}\text{O}$ fractionation between crystal phases (Bindeman and Valley 2002),
15 and 2-pyroxene compositions (Hildreth 1979; Frost and Lindsley 1992) all of which yield ~ 100 °C
16 temperature difference between upper and lower regions in the magma chamber. In contrast,
17 thermodynamic modelling of the Bishop Tuff system has been used to propose a very uniform
18 temperature range (Gualda et al. 2012b). Calculations for thermometry can be somewhat limited as
19 they often involve assumptions about the uniformity of pre-eruptive melt conditions (e.g. a_{TiO_2} for
20 Ti-in-quartz and Ti-in-zircon), or reveal only the most recent thermal stratification within the magma
21 chamber [e.g. Fe-Ti oxides re-equilibrate rapidly and so cannot preserve evidence of any longer-term
22 history (Buddington and Lindsley 1964; Hammond and Taylor 1982; Ghiorso and Sack 1991)]. By
23 utilising two-feldspar thermometry we avoid entering into ongoing debates over the use of Fe-Ti
24 oxide and Ti in quartz thermometry (cf. Thomas et al. 2010; Wilson et al. 2012; Evans and Bachmann
25 2013; Ghiorso and Gualda 2013), although our conclusions are similar to those previously proposed
26 regarding thermal gradients within the Bishop magma body (Bindeman and Valley 2002; Hildreth
27 and Wilson 2007). Our two-feldspar thermometry does not make any assumptions other than that the
28 two feldspars were in equilibrium with each other at the time of inclusion. The feldspar thermometer
29 is not reset quickly due to the relatively slow diffusion timescales for Ca, Na and K within feldspar
30 crystals and the need for coupled substitution of Al and Si for charge balance (Cherniak 2010). We
31 therefore infer that our temperatures accurately record the magmatic temperatures at the point of
32 crystallisation. All inclusion pairs analysed were within the cores of crystals, and have therefore been
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 unaffected by the late-stage mixing with the ‘bright-rim’ magma (Wark et al. 2007; Chamberlain et al.
2 2014). As such we can thus investigate any temperature stratification within the Bishop Tuff magma
3 body *prior* to formation of the bright-rim overgrowths seen on quartz, sanidine and zircon.
4
5

6 Our results show that the ‘early’ units from Ig1Eb through to Ig2Eb (Fig. 1) have relatively
7 uniform model temperatures of 740 – 760 °C (except for two analyses from Ig2Eb, Table 2). This is
8 up to 30 °C hotter than the reported Fe-Ti oxide and $\Delta^{18}\text{O}$ (qtz-mt) temperatures of 714 °C (Bindeman
9 and Valley 2002; Hildreth and Wilson 2007), but is more comparable (when the ± 30 °C uncertainty
10 is considered) with Ti-in-quartz analyses which yield temperatures of 720 – 750 °C (Wark et al. 2007;
11 Kularatne and Audetat, 2014). Temperatures then start to increase in Ig2Na, which appears to play a
12 transitional role between the cooler, upper and hotter, lower regions of the magma chamber. We
13 observe a general progression within the northern and north-western units to the hottest model
14 temperature of 821 °C (Table 2). The temperatures calculated for cores of late-erupted northern and
15 northwestern units are broadly similar to temperatures calculated from FeTi oxide, $\Delta^{18}\text{O}$ (qtz-mt) and
16 Ti-in-quartz thermometry (Hildreth 1977, 1979; Bindeman and Valley 2002; Hildreth and Wilson
17 2007; Wark et al. 2007), all of which are subject to late stage re-equilibration due to mixing with the
18 less-evolved ‘bright-rim’ magma (for example, in the case of Ti-in-quartz the analyses are from
19 within the bright, Ti rich rims). These similarities in model temperatures imply that the ‘bright-rim’
20 magma was not in fact significantly hotter than the pre-existing ‘normal’ Bishop magma. Our data
21 thus support the notion that a general temperature and compositional stratification (Hildreth and
22 Wilson 2007, and references therein) existed within the unitary magma chamber prior to introduction
23 of the ‘bright-rim’ magma.
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45

46 In contrast, recent thermodynamic modelling (Gualda et al. 2012b) has led to the assertion
47 that there was no significant thermal gradient through the Bishop Tuff magma chamber (and that in
48 fact there existed two separate magma chambers: Gualda and Ghiorso 2013). This modelling suggests
49 that the ‘late’ Bishop Tuff magma was held at ~ 760 °C and that there was a <30 °C gradient across
50 the ‘late’ north and north-western units. We do not find evidence of crystallisation at 760 °C for any
51 of our ‘late’ ternary feldspar pairs, apart from those in Ig2Na (which fills a transitional role from the
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 with respect to model temperatures), and in turn see evidence for ~80 °C variation across the erupted
2 Bishop compositions.
3

4 5 6 Uncertainties in Diffusion Chronometry 7

8 The single most important factor in calculating the uncertainties associated with diffusion
9 chronometry is temperature, which has an exponential effect (see equations 1 and 2) on the timescales
10 modelled via the Arrhenius relationship in equation 1 (e.g. Morgan et al. 2006; Allan et al. 2013).
11 Given uncertainties of ± 30 °C in our thermometry estimates, this leads to an asymmetric uncertainty
12 which, for the longer (+) timescale uncertainty, can be numerically more than double the calculated
13 timescale (from modelling at the low temperature from uncertainties: see Electronic Appendix 6 for
14 all timescales and their uncertainties). Uncertainties in D_0 and fO_2 are second order, but still play a
15 considerable role. fO_2 uncertainty is only considered in relation to Fe-Mg interdiffusion modelling,
16 and an uncertainty of ± 0.3 log units is assumed (following Allan et al. 2013). In the case of Ti in
17 quartz, Ba in sanidine and Sr in sanidine we calculate uncertainties of ± 0.06 , 0.12 and 0.03 log units
18 (for Ti, Ba and Sr, respectively) for D_0 and E (Electronic Appendix 6). For further discussion on the
19 effects of T and fO_2 variation on orthopyroxene Fe-Mg interdiffusion modelling see Allan et al.
20 (2013).
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36

37 Timescales in this paper are referred to as maximum timescales due to the spatial limitations
38 of constraining the maximum profile width of the zone across which diffusion has occurred. Due to
39 either pixel size (a more limited effect) or spot size and spacing (for Sr) the maximum distance across
40 which diffusion has occurred is always likely to be slightly over-estimated. Similarly, by assuming an
41 initial step-change concentration profile, the full width of the profile is assumed to be caused by
42 diffusion, yielding the maximum timescale (see Equation 2). These assumptions will be discussed
43 later in relation to sanidine diffusion modelling.
44
45
46
47
48
49
50
51
52

53 Trends in Diffusion Profiles 54

55 Three distinct categories of profile shape are evident on visual inspection of all modelled profiles
56 from all four modelled systems (Fig. 7). They can be defined as class 1: ideal diffusion shape, good
57
58
59
60
61
62
63
64
65

1 sigmoid and close fit to modelled profile shape; class 2: profiles with a spike on the side of one
2 boundary, which sets an initially high/low condition on half of the profile; class 3: slightly
3
4 asymmetric profiles, where one side of the measured profile deviates away from the modelled profile.
5

6 We interpret that the class 2 and class 3 profiles generally represent some relict growth zoning
7 which has been over printed by diffusion and are not ideal for modelling. By their shape they indicate
8 that our initial assumption of the starting profile shape was not correct, and the profile must have
9 started with a width somewhat greater than zero, i.e., less sharp than the modelled step-change. Whilst
10 this is problematic in terms of absolute timescale determination, the true timescale of such a profile
11 cannot exceed the timescale from a simple step profile diffused to the same width. Again, therefore,
12 our choice of model starting condition leads us to an overestimate in timescale, and we can
13 confidently regard the class 2 and class 3 profiles as maxima in the light of this knowledge. Whilst
14 class 2 profiles seem to be quite reproducible in terms of their end results, giving answers close to the
15 more ideal class 1 profiles, we are less confident about class 3, and there is no *a priori* method to
16 determine how much growth versus diffusion these represent. Whilst they do represent a maximum
17 time constraint, we regard this as very loose, and so the class 3 profiles have been excluded from our
18 accumulated data (but can be found in Electronic Appendices 4 and 6 due to the significant proportion
19 of sanidine crystals which have these class 3 profiles).
20
21

22 The recognition of all three boundary types in Sr, Ba, Ti and Fe-Mg profiles raises the
23 question as to what processes have caused the preservation of the class 2 and 3 profiles, and may yield
24 insights into the precursory processes occurring in the Bishop Tuff magma chamber. Class 2 profiles,
25 with their distinctive peak prior to the diffusion sigmoid, could represent evidence of relict growth
26 zoning due to slow diffusion of cations to the crystal-melt interface (Margaritz and Hoffman 1978) or
27 due to depletion in Ba/Ti/Sr/Fe/Mg in the boundary layer of melt at the crystal face. They are
28 typically most extreme in Ba profiles, which would suggest the involvement of zone-refining and
29 boundary depletion effects due to the extreme partition coefficient of Ba in sanidine (28.4: Lu 1991).
30 Class 3 profiles raise more challenging issues but, again, are most evident in Ba profiles from
31 sanidine, and thus are likely to preserved evidence of an initial profile which had some component of
32 growth zoning, possibly even caused by Ba retention during dissolution of the core prior to rim
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 growth. Although these three classes of profiles have significantly different appearances, there is no
2 systematic difference in the range of timescales modelled from each mineral-element pair. The
3 identification of all three boundary types in all phases investigated here strongly suggests that the
4 zoning reflects common origins, and that the timescales modelled should be roughly comparable
5 across all phases.
6
7
8
9

10 Contrasts in modelled timescales between crystal phases

11 *Modelling diffusion in sanidine*

12 It is apparent that diffusion modelling of both Ba and Sr in sanidine yields much longer timescales, by
13 up to 3 orders of magnitude, than modelling of Ti in quartz and Fe-Mg in orthopyroxene. This result
14 matches other studies, for example from profiles obtained from Nano-SIMS analyses (Till et al.
15 2012). One interpretation could be that timescales from modelling of Ba and Sr diffusion in sanidine
16 are overestimates (Figs. 3 and 5). Based on consideration of the applicable diffusivities, the width of
17 Sr boundaries should be ~10 times wider than those of Ba (Cherniak 2002), had these elements been
18 diffusing for similar amounts of time (Table 1). This is not always the case (Fig. 5; Electronic
19 Appendices 4 and 5) and the widths of the boundaries can be similar. Given the variable nature of the
20 relationship between Ba and Sr profile widths, and the longer timescales from Ba and Sr in sanidine
21 diffusion modelling, there are several possible factors that could cause this discrepancy.
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39

40 (1). Ba and Sr are not always being affected in the same way, sometimes not being correlated during
41 crystal growth across the boundary between darker core and brighter rim, and their behaviour may not
42 be related to the change in Ti content in quartz crystals.
43
44
45

46 (2). The very high activation energy and D_0 of Ba and Sr diffusion in sanidine (Table 1) is sensitive to
47 small thermal perturbations (although variably sensitive, due to differences in their diffusion
48 coefficients: Table 1), so that short periods of time at elevated temperatures could allow Ba and Sr to
49 diffuse rapidly, making their timescales appear unusually long.
50
51
52
53
54

55 (3). The initial Ba and Sr profiles were not step-like as assumed, and modelling requires a different
56 initial condition with some gradient across the boundary as an initial state from which to model.
57
58
59
60
61
62
63
64
65

1 All three of these factors could contribute towards yielding longer timescales, but in practice we can
2 rule out some of these possibilities. If Ba and Sr were unrelated in their behaviour, then the overall
3 trends seen in graphs of Ba versus Sr in ICPMS and EPMA data would not be so clear (Fig. 6). Glass
4 trace element data shows coupled increases in Ti, Ba and Sr (Hildreth and Wilson 2007; KJ
5 Chamberlain unpub data) implying that the high-Ti rims on quartz are related to the high Ba and Sr
6 rims on sanidine. These lines of evidence suggests that option (1) is unlikely.
7
8
9
10
11
12

13 The second option, that the high activation energy of Ba and Sr could allow the diffusion
14 behaviours to decorrelate, is also demonstrably unlikely. The high resolution EPMA data shows that
15 the steps are correlated in space, occurring across the same regions. The difference in timescales
16 between sanidine, quartz and orthopyroxene is more reflective of differences in diffusion speed than
17 discrepancies in profile width. For Ba diffusion to overtake Ti diffusion would require temperatures
18 around 1100 °C, which is wholly implausible for a rhyolitic magma in which plagioclase-sanidine
19 pairs survived (and lacking any other mineral textural evidence for such high temperatures).
20
21
22
23
24
25
26
27
28

29 Ti-in-quartz profiles are comparable in width to Ba-in-sanidine profiles, again showing that
30 these Ba profiles are artificially wide (Ti diffuses faster in quartz than Ba in sanidine at these
31 conditions: Cherniak 2002; Cherniak et al. 2007). Given the wide profile of Ba in sanidine it would
32 thus seem likely that the initial assumption of a sharp step function is incorrect for the case of Ba and
33 Sr diffusion in sanidine. The timescales modelled are therefore a combination of Ba and Sr diffusion,
34 superposed on initially curved Ba and Sr starting profiles. This raises questions as to how initially
35 curved Ba and Sr profiles can be generated in sanidine, but not in other phases, with the effect much
36 more noticeable in Ba profiles than those of Sr concentration.
37
38
39
40
41
42
43
44
45
46

47 The highly compatible nature of Ba in Bishop Tuff sanidine ($K_d \sim 22$: KJ Chamberlain unpub
48 data; ~ 28.4 : Lu 1991) means that any partial dissolution of sanidine will lead to an interfacial layer of
49 melt that is enriched in Ba. This interfacial layer will have Ba concentrations similar to those in the
50 crystal, rather than the lower levels found in the ambient melt, and as a consequence the sanidine
51 crystal cannot be in equilibrium. In response to this situation, the remaining sanidine phenocryst will,
52 by diffusion, scavenge the Ba from the melt interface, leading to an enriched zone in the sanidine
53 crystal prior to growth of the Ba-rich bright rim on sanidine, that is, a zone-refining process. Sr, with a
54
55
56
57
58
59
60
61
62
63
64
65

1 K_d of ~9 (KJ Chamberlain, unpub data); ~11.4 (Lu 1991) will be similarly affected. The more rapid
2 diffusion of Sr in sanidine means, however, that this initially curved Sr profile will be broader and less
3 well preserved than for Ba. The curvature of the initial starting profile will also have less effect on
4 timescales from diffusion modelling of Sr, as the initial curvature represents less equivalent diffusion
5 time for Sr than for Ba. From this inference we conclude that both Ba and Sr in sanidine will yield
6 over-estimates of time for diffusion, but that for Ba the timescales recovered will be dominated by the
7 growth curvature, while the Sr profile would contain appreciable components of both diffusion and
8 growth. This conclusion agrees with the trends seen in timescales from Ba and Sr diffusion compared
9 with those timescales from Fe-Mg interdiffusion in orthopyroxene and Ti in quartz (Fig. 3). Evidence
10 for dissolution of quartz is preserved in CL imagery, where interior zones are truncated against the
11 bright rim overgrowth (Electronic Appendix 1; Peppard et al. 2001; Wark et al. 2007). This texture is
12 replicated in sanidine BSE images, which commonly reveal rounded corners on grains, inferring a
13 similar resorptive process.

14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
In systems where partial dissolution of sanidine could have occurred prior to rim overgrowth, and until its effects on the initial profile of Ba (and to a lesser extent Sr) can be constrained, Ba and Sr geospeedometry in low temperature rhyolitic systems (i.e. <900 °C: Till et al. 2012) yields discrepancies at ~800-840 °C and should be treated with caution. It is necessary to bear in mind that *a step change in composition is a model assumption*, and that at one extreme, diffusion and growth are comparable processes at sub-micron lengthscales, placing a limit on how sharp a profile junction can be. This limit in turn controls how far spatial resolution can reasonably be pushed before the assumptions of diffusion modelling have to be considered for their reliability.

Removing the “growth” effect

66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000

1 boundary within the same crystal, the modelled timescale due to diffusion alone should be the same,
2 and thus by exploiting differential diffusion speeds, the combined modelling of both Ba and Sr
3 diffusion simultaneously should allow for removal of the variable growth component. Twelve paired
4 profiles of Ba and Sr were used to test this model, with all the modelled timescales being significantly
5 reduced when compared to the timescales for either Ba or Sr alone (Table 4). Modelled timescales
6 range from 24 years to 1540 years, with ten of the twelve modelled boundaries yielding timescales of
7 <500 years. These values are within an order of magnitude of those from Ti-in-quartz modelling
8 (Figs. 8, 9). Prior to the combined modelling the average model timescales in these crystals were 1500
9 (Ba) and 540 years (Sr), ~63 times and ~23 times longer (respectively) than the average Ti-in-quartz
10 model timescales, respectively. The average from combined modelling is now 440 years (~19 times
11 longer than the Ti-in-quartz average), but with the two longest timescales removed this is shortened to
12 only 230 years (~10 times longer than the Ti-in-quartz average).

13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Given the very high activation energy of both Ba and Sr diffusion in sanidine when compared with Ti diffusion in quartz, small temperature changes from those at which diffusion is modelled, could allow for even greater agreement between the combined Ba and Sr timescales and those modelled from Ti in quartz. This is due to modelled sanidine timescales decreasing with increasing temperature much faster than timescales from Ti diffusion in quartz. In fact, as the uncertainties on our two-feldspar thermometry are $\sim \pm 30$ °C, we model both Ti in quartz diffusion and Ba and Sr diffusion at 827 °C (within uncertainty of all but the Ig2Na temperature estimates; Table 2). This shortens the mean Ti in quartz timescale to 10 years, but shortens the average from combined modelling in sanidine to ~ 100 years (with all 12 timescales) or 57 years when the two longest timescales are ignored, only ~6 times as long as Ti in quartz timescales at 827 °C. This arbitrary temperature of 827 °C is within the upper limits of temperature estimates from FeTi oxides (Hildreth & Wilson., 2007) and is therefore not implausible for a diffusive temperature, however we consider this as means to highlight the large thermal effect in diffusion within sanidine, and not a revised estimate for the late Bishop Tuff magma. In order to properly constrain the role of growth zoning, the thermal effect on diffusion in sanidine, and to properly quantify how closely sanidine and quartz timescales agree, further investigation using techniques such as Nano-SIMS is needed.

Comparisons of modelled timescales between crystal phases

Using the current calibration of the Fe-Mg interdiffusion coefficient within orthopyroxene, diffusion timescales for the Bishop Tuff are extremely short (<20 years: Fig. 3). Given the comparable profile groups observed in orthopyroxene, quartz and sanidine (Fig. 7), and the phase stability relationships of Naney (1983) it seems valid to infer that the orthopyroxene timescales should be comparable with those from sanidine and quartz. In order for this to be the case, the value of the diffusion coefficients for Fe-Mg interdiffusion would have to be over-estimated by about an order of magnitude (Fig. 9). This is not surprising in the light of the large range in orthopyroxene diffusion coefficients and calibrations used in the literature (Ganguly and Tazzoli 1994; Schwandt et al. 1998; Saunders et al. 2012). Using the Ganguly and Tazzoli (1994) calibrations, D values used here are $\sim 1 \times 10^{-19} \text{ m}^2 \text{ s}^{-1}$ to $\sim 1 \times 10^{-20} \text{ m}^2 \text{ s}^{-1}$. In contrast, using the calibration of Schwandt et al. (1998) D values at the relevant temperatures used here range from $\sim 1 \times 10^{-22} \text{ m}^2 \text{ s}^{-1}$ to $\sim 6 \times 10^{-22} \text{ m}^2 \text{ s}^{-1}$, two to three orders of magnitude smaller. Use of the latter figures would result in timescales which are two to three orders of magnitude longer than that calculated in this paper, i.e. up to $\sim 14\,000$ years, and which are comparable with the un-corrected Ba-in-sanidine diffusion timescales we derive.

In order to bring the orthopyroxene timescales into alignment with those obtained from Ti diffusion in quartz, the value of D would need to be $\sim 1/5$ of that currently used: $\sim 1\text{-}2 \times 10^{-20} \text{ m}^2 \text{ s}^{-1}$ depending on the model temperature (790 or 815 °C). Following discussion with those conducting experimental research, preliminary findings suggest that the Ganguly and Tazzoli (1994) formulation with added oxygen dependence we have used may well yield an overestimate of diffusion speed (S Chakraborty and R Dohmen, pers comm). Our work suggests that regarding orthopyroxene, the quantification of D_0 and E for Fe-Mg interdiffusion in rhyolitic systems warrants further investigation, as it has significant impacts on the compatibility of timescales modelled from different phases in the Bishop Tuff.

Pyroxenes and their textural implications

1 The diversity of textures observed in orthopyroxene (normal-zoned, bright rim grains, to reversely-
2 zoned, dark rim grains, to those which are unzoned) is not matched by changes in timescales. In
3
4 addition, the rim compositions do not converge towards a single composition, unlike that seen in the
5
6 Oruanui example (Allan et al. 2013). These features raise the issue as to how the process that caused
7
8 the growth of Fe-richer rims was occurring over the same timescales as that which caused growth of
9
10 Mg-richer rims. Orthopyroxene with contrasting rim compositions revealing similar timescales has
11
12 been previously noted at Mt St. Helens (Saunders et al. 2012) where compositional differences were
13
14 larger than those recorded here (8 to 15 mol% enstatite variation from cores to rims compared with
15
16 0.5 to 5.4 mol% enstatite variation in the Bishop orthopyroxenes: Electronic Appendix 3). Saunders
17
18 et al. (2012) cited intrusion of a more mafic component to cause growth of both reversely-zoned and
19
20 normally-zoned orthopyroxene, due to changes not only in melt composition, but also volatile
21
22 contents and fO_2 . For the Bishop Tuff, there appears to be multiple options for the formation of both
23
24 Fe-rich and Mg-rich rims (Fig. 10), as follows.

25
26
27
28
29 Option (1). Mg-richer cores grew at depth within the Bishop magma reservoir, possibly
30
31 within a crystal-rich mush zone (e.g. Hildreth and Wilson 2007) and consequently are slightly more
32
33 enstatite-rich. Concurrently, a Fe-richer population of crystals were growing within the shallower
34
35 melt-dominant magma chamber from the slightly more evolved melt (Fig. 10). When the ‘bright-rim’
36
37 magma intruded the Bishop melt-dominant magma body, it either originated in, or entrained crystals
38
39 from, the underlying mush zone, bringing the Mg-richer cores into the melt-dominant body. Chaotic,
40
41 piecemeal mixing within the lower parts of this body (Figs. 3 and 10) with this ‘bright-rim’ magma
42
43 could produce rims of marginally higher or lower Mg content to crystallise simultaneously, depending
44
45 on the sense of entrainment from Mg-richer to Mg-poorer melt, or vice versa.

46
47
48
49 Option (2). The ‘bright-rim’ magma was not compositionally different in Fe or Mg
50
51 concentrations, but had higher fO_2 values and CO_2 contents (Wallace et al. 1999). In this scenario,
52
53 there would be interplay between rapid crystallisation of more magnesian orthopyroxene from melts
54
55 with higher CO_2 (Fig. 10: Blundy et al. 2010) and the increased fO_2 resulting in crystallisation of more
56
57 Fe-rich rims. The interplay between these two factors and the degree of mixing would produce
58
59 magma which has orthopyroxene with both Fe- and Mg-rich rims.

1
2 Option (3). The orthopyroxene crystallised as a result of mixing between the dominant
3 'normal' Bishop Tuff magma and the 'bright-rim' magma (Fig. 10). This would, however, appear to
4 be a less likely explanation, as this would require extremely rapid crystallisation of orthopyroxene
5 (and associated clinopyroxene). Although the timescales for Fe-Mg interdiffusion in orthopyroxene
6 (and associated clinopyroxene). Although the timescales for Fe-Mg interdiffusion in orthopyroxene
7 are relatively short (using the Ganguly and Tazzoli [1994] calibration), current investigation suggests
8 that the inaccuracies in constraining the diffusion coefficients could be the cause of these apparently
9 short timescales (S Chakraborty pers comm). In order to distinguish between options (1) and (2), more
10 detailed investigation into the composition (major and trace elements) of orthopyroxene and other
11 phases in the Bishop Tuff is required.
12
13
14
15
16
17
18

19
20 A major question has been raised in previous studies over the occurrence of pyroxene (both
21 ortho- and clino-) in the Bishop Tuff, with some suggesting that the pyroxenes are not in equilibrium
22 with other phenocrysts (e.g. Ghiorso and Sack 1991; Frost and Lindsley 1992; Evans and Bachmann
23 2013). The euhedral appearance of orthopyroxene (and clinopyroxene) phenocrysts (Fig. 4), the
24 similar compositions of inclusions within the orthopyroxenes when compared with free crystals
25 (Hildreth 1977, 1979) and phase stability relations based on the two-feldspar thermometry presented
26 here (Naney 1983) counts against them being 'foreign'. In addition, the similarity in groups of
27 diffusion profiles (Fig. 7) from all three crystal phases modelled here could be used to suggest that
28 Bishop pyroxene, sanidine and quartz crystals experienced similar controls on growth and diffusion.
29
30
31
32
33
34
35
36
37
38
39
40
41

42 Rejuvenation of the Bishop magma body

43
44 Many explanations have been put forward for the bright rim overgrowths on quartz and sanidine.
45 Initially it was proposed that these rims grew from sinking of the crystals into less evolved, Ba-, Sr-
46 and Ti-richer magma within the magma chamber (Anderson et al. 2000; Peppard et al. 2001). Studies
47 on melt inclusion entrapment pressures and compositions have however, shown that core and rim
48 inclusions crystallised at comparable pressures, but within varying melt compositions (Wallace et al.
49 1999; Roberge et al. 2013). These observations imply that introduction of a melt with a slightly
50 different composition underlies the growth of bright rims on quartz and sanidine (Wark et al. 2007;
51 Roberge et al. 2013). The short timescales presented here support this hypothesis of shortly pre-
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 eruptive rejuvenation of lower parts of the Bishop magma chamber by interaction with a melt
2 enriched in Ti, Ba, Sr and CO₂ (Wallace et al. 1999; Hildreth and Wilson 2007; Wark et al. 2007;
3
4 Roberge et al. 2013).
5

6 Our timescales from quartz, sanidine and orthopyroxene diffusion profiles do not provide any
7
8 evidence for long-lived (>1000 year) interaction between the ‘bright-rim’ magma and the resident
9
10 melt-dominant body. However, zircons from the same samples or eruptive units as those studied in
11
12 this paper have parallel records of the presence or absence of bright-rim overgrowths, plus sparse
13
14 numbers of grains wholly formed from the ‘bright-rim’ magma (Chamberlain et al. 2014). Age data
15
16 from sectors of the crystal cores just inside the bright rims suggest that growth of these rims could
17
18 have commenced up to ~10 kyr before eruption. It is plausible that the longer history of zircon
19
20 interaction with the ‘bright-rim’ magma may be tracing crystal growth within the ‘bright-rim’ magma
21
22 prior to its later interaction with the main Bishop magma body, and thus provides a maximum time
23
24 constraint for interaction of the ‘bright-rim’ magma in the Bishop magma system. In addition, the
25
26 contrasting timescales recorded of interaction between the zircon, sanidine, quartz and orthopyroxene
27
28 and the ‘bright-rim’ magma may reflect a more gradual sequence of events than any immediately pre-
29
30 eruptive triggering event.
31
32
33
34

35 In the sanidine, quartz and orthopyroxene records, intrusion of the ‘bright-rim’ magma into
36
37 the main Bishop melt-dominant magma body seems to have consisted of multiple events (at least
38
39 three, from preserved crystal zonation: Electronic Appendices 2 – 5) which began ~500 years prior to
40
41 eruption, as shown by the fairly continuous distribution of timescales that can be calculated from
42
43 sequentially higher Ba/Sr/Ti profiles within sanidine and quartz phenocrysts (e.g. Fig. 3; Electronic
44
45 Appendices 2 and 4). The modelled timescales appear to cluster towards eruption age (Figs. 3, 9),
46
47 with 50% of the timescales being <18 years (Ti-in-quartz), <250 years (combined Ba and Sr in
48
49 sanidine) and <2.5 years (Fe-Mg in orthopyroxene). Although the three suites of model ages have
50
51 varying absolute values, their cumulative frequency distributions and textural boundary features are
52
53 closely comparable.
54
55
56

57 The apparent clustering of timescales closer to eruption could be due to exponential increases
58
59 in the volume and frequency of magmatic intrusion into the lower magma chamber immediately prior
60
61
62
63
64
65

1 to eruption, which would favour the concept of mixing as an eruptive trigger (Wark et al. 2007).
2 Another possibility, however, is that although rates of ingress of the external ‘bright-rim’ magma
3 stayed relatively constant, magmatic overturn and increased thermal contrasts between the less-
4 evolved magma and the ‘normal’ Bishop magma caused increases in mixing within the lower regions
5 of the magma chamber. This would then expose more crystals to a less-evolved melt than that which
6 they initially resided in, generating the shorter timescales and apparent increases in mixing, even if
7 there was not an increasing rate of intrusion into the magma body. Whatever the cause, it is still
8 apparent that rejuvenation (recorded from diffusion modelling in the major mineral phases) and
9 mixing with a melt that was marginally hotter, but enriched in Ti, Sr and Ba occurred over a short
10 timescale (<500 yrs) and continued to cause compositional variation within the Bishop magma
11 chamber until quenched by eruption.
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26

27 **Implications and conclusions**

28 We show that timescales calculated from simplistic diffusion modelling of Sr and Ba in sanidine are
29 1-3 orders of magnitude longer than Ti diffusion in quartz, which are in turn an order of magnitude
30 longer than timescale from Fe-Mg interdiffusion in orthopyroxene. There are no *a priori* reasons as
31 such for supposing which of the three systems yields the ‘correct’ result. Recognition of the role of
32 growth zoning in sanidine highlights an incorrect initial assumption of an initially sharp step in Ba
33 and Sr contents in this mineral. We have used combined Ba and Sr diffusion modelling to remove this
34 growth effect, and the resulting timescales are shortened to become more comparable (to within
35 roughly an order of magnitude) of those modelled from Ti diffusion in quartz. Given the similar
36 nature of diffusion profiles extracted from orthopyroxene images to those from quartz and sanidine
37 images we suggest that modelling of Fe-Mg interdiffusion in orthopyroxene may produce artificially
38 short timescales. In order for orthopyroxene timescales to align with those in modelled from Ti
39 diffusion in quartz, for example, the calculated values of D would have to be approximately an order
40 of magnitude smaller than those using the Ganguly and Tazzoli (1994) calibration with fO_2
41 dependence at $T = \sim 800$ °C, but 1-2 orders of magnitude larger than that of the Schwandt et al. (1998)
42 calibration. Adoption of the latter values would then align the orthopyroxene timescales more closely
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 with those derived from the growth-corrected profiles for Ba and Sr in sanidine. These gross
2 disparities highlight the very pressing need in particular for calibration of Fe-Mg interdiffusion at
3 temperatures and pressures representative of evolved (particularly rhyolitic) compositions, in order to
4 extract viable and consistent timescales.
5
6
7

8 Two-feldspar thermometry shows that a temperature stratification of ~80 °C existed between
9 the upper and lower reaches of the Bishop Tuff magma chamber, and that this stratification is not
10 simply a result of the late-stage intrusion at the base of the magma chamber. This temperature range is
11 similar to that suggested by Fe-Ti oxide and oxygen-isotopic thermometry, and supports the model of
12 Hildreth and Wilson (2007) for a unitary zoned magma chamber for the Bishop Tuff. An important
13 implication arising from the similarity of the temperature estimates is that the intruding 'bright-rim'
14 magma was not significantly hotter than the basal parts of the Bishop magma chamber. Instead it
15 would appear that the intruding magma was enriched in Ba, Ti, Sr and CO₂ (e.g. Wallace et al. 1999;
16 Wark et al. 2007) which has affected crystallisation conditions to cause growth of the bright rims on
17 orthopyroxene, quartz and sanidine (and zircon: Chamberlain et al. 2014).
18
19
20
21
22
23
24
25
26
27
28
29
30

31 The similarity of diffusion profile shapes between quartz, orthopyroxene and sanidine and the
32 order of magnitude agreement between sanidine and quartz geospeedometry, indicates that for at least
33 ~500 years prior to eruption, these phases shared a common history and experienced magmatic
34 intrusion causing the overgrowth of compositionally contrasting rims. It remains an open question as
35 to whether the three major phases are actually recording events with closely similar timings, and that
36 the diversity in model-age ranges reflects systematic errors in the diffusion parameters available at
37 present. An important conclusion of our work is that application of diffusion modelling over multiple
38 co-erupted mineral species is restricted by uncertainties over values for diffusion coefficients in such
39 evolved, relatively low-temperature magmatic systems. The alternative end-member inference to
40 explain the diverse zoning patterns and contrasting diffusive timescales is that the crystals are
41 recording different timescales because gradational interaction with the 'bright-rim' magma affected
42 different mineral species now found together within single pumices at different times. The great
43 ranges in proportions of zircon crystals with bright rims, and the diversity of development of zircon
44 overgrowths from the 'bright-rim' magma (Chamberlain et al. 2014) support this alternative inference
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 to some extent. These observations would imply that the zircons found within single pumices are
2 mixtures that did not all grow *in situ* from the host melt represented in that pumice (cf. Hildreth
3 1979), and such inferences may also apply to the major mineral phases, at least in the lower portion of
4 the magma chamber which is pyroxene-bearing and has other phases with bright rims.
5
6

7
8 We show from textural proportions that rejuvenation of the Bishop magma chamber had only
9 noticeable effects on mineral phases found in the northern and north-western ignimbrite packages,
10 inferred to represent the deeper, less-evolved parts of the magma body. Rejuvenation by the ‘bright-
11 rim’ magma was not a single event and, from the timescales measured here in the common mineral
12 phases, occurred over a period of ~500 years right up to eruption. The longer timescale for interaction
13 of the ‘bright-rim’ magma (up to ~10,000 years) indicated by zircon age spectra from cores to bright-
14 rimmed crystals would imply that the intruding magma was in itself probably not the trigger for the
15 eruption. Instead, its rise into and interaction with the Bishop magma chamber may have reflected
16 other processes, such as changes in the regional stress conditions (cf. Allan et al. 2013) or disturbance
17 of the mush zone by extraction of large volumes of melt. As such the ‘bright-rim’ magma could be
18 regarded as the marker for processes leading to eruption, rather than the trigger. Our study has
19 important implications not only for models of the Bishop Tuff magma chamber, but also raises
20 significant issues regarding the application of systematic diffusion chronometry to other rhyolitic
21 systems.
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41

42 **Acknowledgements**

43 We thank Richard Walshaw (University of Leeds) and Joe Wooden (Stanford University) for
44 assistance during CL imaging, and Aidan Allan and George Cooper for discussions. KJC was
45 supported by an NZ International Doctoral Research Scholarship administered by Education New
46 Zealand, a Jack Kleinman Award administered by the U.S. Geological Survey, and two Victoria
47 University of Wellington Faculty Strategic Research Grants. CJNW thanks the Royal Society of New
48 Zealand for support through Marsden Fund grant VUW0813 (which also facilitated participation of
49 DJM) and a James Cook Fellowship. Analyses at Leeds were part-funded by DJM through School of
50 Earth and Environment start-up funds.
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2 **References**
3

4 Allan ASR, Wilson CJN, Millet M-A, Wysoczanski RJ (2012) The invisible hand: tectonic triggering
5 and modulation of a rhyolitic supereruption. *Geology* 40:563-566
6

7
8 Allan ASR, Morgan DJ, Wilson CJN, Millet M-A (2013) From mush to eruption in centuries:
9 assembly of the super-sized Oruanui magma body. *Contrib Mineral Petrol* 166:143-164
10

11 Anderson AT, Davis AM, Lu F (2000) Evolution of Bishop Tuff rhyolitic magma based on melt and
12 magnetite inclusions and zoned phenocrysts. *J Petrol* 41:449-473
13

14 Arienzo I, Heumann A, Wörner G, Civetta L, Orsi G (2011) Processes and timescales of magma
15 evolution prior to the Campanian Ignimbrite eruption (Campi Flegrei, Italy). *Earth Planet Sci*
16 *Lett* 306:217-228
17

18 Bailey RA, Dalrymple GB, Lanphere MA (1976) Volcanism, structure, and geochronology of Long
19 Valley caldera, Mono County, California. *J Geophys Res* 81:725-744
20

21 Bindeman IN, Valley JW (2002) Oxygen isotope study of the Long Valley magmatic system,
22 California: isotope thermometry and convection in large silicic magma bodies. *Contrib Mineral*
23 *Petrol* 144:185-205
24

25 Blundy J, Cashman KV, Rust A, Witham F (2010). A case for CO₂-rich arc magmas. *Earth Planet Sci*
26 *Lett* 290:289-301
27

28 Buddington AF, Lindsley DH (1964) Iron-titanium oxide minerals and synthetic equivalents. *J Petrol*
29 5:310-357
30

31 Chamberlain KJ, Wilson CJN, Wooden JL, Charlier BLA, Ireland TR (2014) New perspectives on the
32 Bishop Tuff from zircon textures, ages and trace elements. *J Petrol* 55:(in press)
33

34 Cherniak DJ (2002) Ba diffusion in feldspar. *Geochim Cosmochim Acta* 66:1641-1650
35

36 Cherniak DJ (2010) Cation diffusion in feldspars. *Rev Mineral Geochem* 72:691-733
37

38 Cherniak DJ, Watson, EB (1992) A study of strontium diffusion in K-feldspar, Na-K feldspar and
39 anorthite using Rutherford backscattering spectroscopy. *Earth Planet Sci Lett* 113:411-425
40

41 Cherniak DJ, Watson EB, Wark DA (2007) Ti diffusion in quartz. *Chem Geol* 236:65-74
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1 Christensen JN, Halliday AN (1996) Rb-Sr ages and Nd isotopic compositions of melt inclusions
2 from the Bishop Tuff and the generation of silicic magma. *Earth Planet Sci Lett* 144:547-561
3
- 4 Costa F, Dungan M (2005) Short time scales of magmatic assimilation from diffusion modeling of
5 multiple elements in olivine. *Geology* 33:837-840
6
7
- 8 Costa F, Morgan D (2010) Time constraints from chemical equilibration in magmatic crystals. In:
9 Dosseto A, Turner SP, Van Orman JA (eds) *Timescales of magmatic processes: from core to*
10 *atmosphere*. John Wiley & Sons, Chichester, UK, pp 125-159
11
12
13
14
- 15 Costa F, Chakraborty S, Dohmen R (2003) Diffusion coupling between trace and major elements and
16 a model for calculation of magma residence times using plagioclase. *Geochim Cosmochim*
17 *Acta* 67:2189-2200
18
19
20
21
- 22 Crank J (1975) *The Mathematics of Diffusion* (2nd ed), Oxford University Press, Oxford, UK, 414 pp
23
- 24 Davies GR, Halliday AN (1998) Development of the Long Valley rhyolitic magma system: strontium
25 and neodymium isotope evidence from glasses and individual phenocrysts. *Geochim*
26 *Cosmochim Acta* 62:3561-3574
27
28
29
30
- 31 Dunbar NW, Hervig RL (1992) Petrogenesis and volatile stratigraphy of the Bishop Tuff: evidence
32 from melt inclusion analysis. *J Geophys Res* 97:15129-15150
33
34
- 35 Elkins LT, Grove TL (1990) Ternary feldspar experiments and thermodynamic models. *Am Mineral*
36 *75:544-559*
37
38
39
- 40 Evans BW, Bachmann O (2012) Implications of equilibrium and disequilibrium among crystal phases
41 in the Bishop Tuff. *Am Mineral* 98:271-274
42
43
- 44 Fowler SJ, Spera FJ (2010) A metamodel for crustal magmatism: phase equilibria of giant
45 ignimbrites. *J Petrol* 51:1783-1830
46
47
48
- 49 Frost BR, Lindsley DH (1992) Equilibria among Fe-Ti oxides, pyroxenes, olivine, and quartz. Part II.
50 Application. *Am Mineral* 77:1004-1020
51
52
- 53 Ganguly J, Tazzoli V (1994) Fe²⁺-Mg interdiffusion in orthopyroxene: retrieval from the data on
54 intracrystalline exchange reaction. *Am Mineral* 79:930-937
55
56
57
58
59
60
61
62
63
64
65

- 1
2 Ghiorso MS, Gualda GAR (2013) A method for estimating the activity of titania in magmatic liquids
3 from the compositions of coexisting rhombohedral and cubic iron-titanium oxides. Contrib
4 Mineral Petrol 165:73-81
5
- 6 Ghiorso MS, Sack RO (1991) Fe-Ti oxide geothermometry: thermodynamic formulation and the
7 estimation of intensive variable in silicic magmas. Contrib Mineral Petrol 108:485-510
8
- 9 Ginibre C, Wörner G, Kronz A (2002) Minor- and trace-element zoning in plagioclase: implications
10 for magma chamber processes in Paríacota volcano, northern Chile. Contrib Mineral Petrol
11 143:300-315
12
- 13 Ginibre C, Wörner G, Kronz A (2007) Crystal zoning as an archive for magma evolution. Elements
14 3:261-266
15
- 16 Gualda GAR (2007) Crystal and bubble populations in the early-erupted Bishop rhyolitic magma:
17 Microscopy, x-ray tomography and microanalysis of pumice clasts. PhD Thesis: The University
18 of Chicago, Chicago, Illinois.
19
- 20 Gualda GAR, Ghiorso MS (2013) The Bishop Tuff giant magma body: an alternative to the Standard
21 Model. Contrib Mineral Petrol 166:755-775
22
- 23 Gualda GAR, Pamukcu AS, Ghiorso MS, Anderson AT, Sutton SR, Rivers ML (2012a) Timescales of
24 quartz crystallization and the longevity of the Bishop giant magma body. Plos ONE 7:e37492
25
- 26 Gualda GAR, Ghiorso MS, Lemons RV, Carley TL (2012b) Rhyolite-MELTS: a modified calibration
27 of MELTS optimized for silica-rich, fluid-bearing magmatic systems. J Petrol 53:875-890
28
- 29 Hammond PA, Taylor LA (1982) The ilmenite/titano-magnetite assemblage: kinetics of re-
30 equilibration. Earth Planet Sci Lett 61:143-150
31
- 32 Hildreth EW (1977) The magma chamber of the Bishop Tuff: gradients in temperature, pressure, and
33 composition. PhD thesis, University of California, Berkeley, CA
34
- 35 Hildreth W (1979) The Bishop Tuff: evidence for the origin of compositional zonation in silicic
36 magma chambers. In Chapin CE, Elston WE (eds) Ash-flow tuffs. Geol Soc Am Spec Pap
37 180:43-75
38
- 39 Hildreth W (2004) Volcanological perspectives on Long Valley, Mammoth Mountain, and Mono
40 Craters: several contiguous but discrete systems. J Volcanol Geotherm Res 136:169-198
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
- Hildreth W, Wilson CJN (2007) Compositional zoning of the Bishop Tuff. *J Petrol* 48:951-999
- Huebner JS, Sato M (1970) The oxygen fugacity-temperature relationships of manganese oxide and nickel oxide buffers. *Am Mineral* 55:934-952
- Humphreys MCS, Christopher T, Hards V (2009) Microlite transfer by disaggregation of mafic inclusions following magma mixing at Soufriere Hills volcano, Montserrat. *Contrib Mineral Petrol* 157:609-624
- Jellinek AM, DePaolo DJ (2003) A model for the origin of large silicic magma chambers: precursors of caldera-forming eruptions. *Bull Volcanol* 65:363-381
- Kularatne K, Audétat A (2014) Rutile solubility in hydrous rhyolite melts at 750 – 900 °C and 2 kbar, with application to titanium-in-quartz (TitaniQ) thermobarometry. *Geochim Cosmochim Acta* 125:196-209
- Lu F (1991) The Bishop Tuff: origins of the high-silica rhyolite and its thermal and chemical zonations. PhD thesis, The University of Chicago, Chicago, IL
- Lu F, Anderson AT, Davis AM (1992) Melt inclusions and crystal-liquid separation in rhyolitic magma of the Bishop Tuff. *Contrib Mineral Petrol* 110:113-120
- Margaritz M, Hofmann AW (1978) Diffusion of Sr, Ba and Na in obsidian. *Geochim Cosmochim Acta* 42:595-605
- Martin VM, Morgan DJ, Jerram DA, Caddick MJ, Prior DJ, Davidson JP (2008) Bang! Month-scale eruption triggering at Santorini volcano. *Science* 321:1178
- Matthews NE, Huber C, Pyle DM, Smith VC (2012a) Timescales of magma recharge and reactivation of large silicic systems from Ti diffusion in quartz. *J Petrol* 53:1385-1416
- Matthews NE, Pyle DM, Smith VC, Wilson CJN, Huber C, van Hinsberg V (2012b) Quartz zoning and the pre-eruptive evolution of the ~340-ka Whakamaru magma systems, New Zealand. *Contrib Mineral Petrol* 163:87-107
- Miller CF, Wark DA (2008) Supervolcanoes and their explosive supereruptions. *Elements* 4:11-16
- Morgan DJ, Blake S (2006) Magmatic residence times of zoned phenocrysts: introduction and application of the binary element diffusion modelling (BEDM) technique. *Contrib Mineral Petrol* 151:58-70

- 1
2 Morgan DJ, Blake S, Rogers NW, De Vivo B, Rolandi G, MacDonald R, Hawkesworth CJ (2004)
3 Time scales of crystal residence and magma chamber volumes from modelling of diffusion
4 profiles in phenocrysts: Vesuvius 1944. *Earth Planet Sci Lett* 222:933-946
5
6 Morgan DJ, Blake S, Rogers NW, De Vivo B, Rolandi G, Davidson JP (2006) Magma chamber
7 recharge at Vesuvius in the century prior to A.D. 79. *Geology* 34:845-848
8
9 Naney MT (1983) Phase equilibria of rock-forming ferromagnesian silicates in granitic systems. *Am J*
10 *Sci* 283:993-1033
11
12 Pamukcu AS, Gualda GAL, Anderson AT (2012) Crystallization stages of the Bishop Tuff magma
13 body recorded in crystal textures in pumice clasts. *J Petrol* 53:589-609
14
15 Peppard BT, Steele IM, Davis AM, Wallace PJ, Anderson AT (2001) Zoned quartz phenocrysts from
16 the rhyolitic Bishop Tuff. *Am Mineral* 86:1034-1052
17
18 Reed SJB (2005) *Electron microprobe analysis and scanning electron microscopy in geology.*
19 Cambridge University Press, Cambridge, UK
20
21 Reid MR, Schmitt AK (2012) Implications of Bishop Tuff zircon U-Pb ages for rates of zircon growth
22 and magma accumulation. Abstract V13F-07 presented at the 2012 Fall Meeting of the
23 American Geophysical Union, San Francisco, California, 3-7 December
24
25 Reid MR, Vazquez JA, Schmitt AK (2011) Zircon-scale insights into the history of a supervolcano,
26 Bishop Tuff, Long Valley, California, with implications for the Ti-in-zircon geothermometer.
27 *Contrib Mineral Petrol* 161:293-311
28
29 Rivera TA, Storey M, Zeeden C, Hilgen FJ, Kuiper K (2011) A refined astronomically calibrated
30 $^{40}\text{Ar}/^{39}\text{Ar}$ age for Fish Canyon sanidine. *Earth Planet Sci Lett* 311:420-426
31
32 Roberge J, Wallace PJ, Kent AJR (2013) Magmatic processes in the Bishop Tuff rhyolitic magma
33 based on trace elements in melt inclusions and pumice matrix glass. *Contrib Mineral Petrol*
34 165:237-257
35
36 Saunders K, Blundy J, Dohmen R, Cashman K (2012) Linking petrology and seismology at an active
37 volcano. *Science* 336:1023-1027
38
39 Saunders K, Buse B, Kilburn MR, Kearns S, Blundy J (2014) Nanoscale characterisation of crystal
40 zoning. *Chem Geol* 364:20-32
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1 Schwandt CS, Cygan RT, Westrich HR (1998) Magnesium self-diffusion in orthoenstatite. Contrib
2 Mineral Petrol 130:390-396
3
- 4 Self S (2006) The effects and consequences of very large explosive volcanic eruptions. Phil Trans R
5 Soc Lond A364:2073-2097
6
- 7 Self S, Blake S (2007) Consequences of explosive supereruptions. Elements 4:41-46
8
- 9 Snyder D (2000) Thermal effects of the intrusion of basaltic magma into a more silicic magma
10 chamber and implications for eruption triggering. Earth Planet Sci Lett 175:257-273
11
- 12 Sparks RSJ, Sigurdsson H, Wilson L (1977) Magma mixing: a mechanism for triggering acid
13 explosive eruptions. Nature 267:315-318
14
- 15 Thomas JB, Watson EB (2012) Application of the Ti-in-quartz thermobarometer to rutile-free
16 systems. Reply to: a comment on "Titaniq under pressure: the effect of pressure and
17 temperature on the solubility of Ti in quartz' by Thomas et al. Contrib Mineral Petrol 164:369-
18 374
19
- 20 Thomas JB, Watson EB, Spear FS, Shemella PT, Nayak SK, Lanzirotti A (2010) TitaniQ under
21 pressure: the effect of pressure and temperature on the solubility of Ti in quartz. Contrib
22 Mineral Petrol 160:743-759
23
- 24 Till CB, Vazquez JA, Boyce JW, Hitzman C (2012) Quantifying the interval between rejuvenation
25 and eruption of rhyolite at Yellowstone caldera using high-resolution NanoSIMS
26 geospeedometry. Abstract V43E-01 presented at the 2012 Fall Meeting of the American
27 Geophysical Union, San Francisco, California, 3-7 December
28
- 29 Wallace PJ, Anderson AT, Davis AM (1999) Gradients in H₂O, CO₂, and exsolved gas in a large-
30 volume silicic magma system: Interpreting the record preserved in melt inclusions from the
31 Bishop Tuff. J Geophys Res 104:20097-20122
32
- 33 Wark DA, Hildreth W, Spear FS, Cherniak DJ, Watson EB (2007) Pre-eruption recharge of the
34 Bishop magma system. Geology 35:235-238
35
- 36 Wilson CJN, Hildreth W (1997) The Bishop Tuff: new insights from eruptive stratigraphy. J Geol
37 105:407-439
38
- 39 Wilson CJN, Seward TM, Charlier BLA, Allan ASR, Bello L (2012) A comment on: 'TitaniQ under pressure:
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 the effect of pressure and temperature on the solubility of Ti in quartz', by Jay B. Thomas, E. Bruce

2 Watson, Frank S. Spear, Philip T. Shemella, Saroj K. Nayak and Antonio Lanzirotti. Contrib Mineral

3
4 Petrol 164:359-368

5
6 Zellmer GF, Blake S, Vance D, Hawkesworth C, Turner S (1999) Plagioclase residence times at two

7
8 island arc volcanoes (Kameni Islands, Santorini, and Soufriere, St. Vincent) determined by Sr

9
10 diffusion systematics. Contrib Mineral Petrol 136:345-357

11
12 Zhang Y (2010) Diffusion in minerals and melts: theoretical background. Rev Mineral Geochem

13
14 72:5-59

1
2 **Figure and Table Captions**
3

4 **Fig. 1 a** Map of the Long Valley area, eastern California, USA and **b** summary of the Bishop
5
6 Tuff stratigraphy, after Hildreth and Wilson (2007). **a** The topographic outline of Long
7
8 Valley caldera is shown as a dashed line, regions of Bishop ignimbrite are filled in grey.
9
10 The envelope enclosing mapped vent locations for the precursory Glass Mountain (GM)
11
12 eruptions is highlighted in light grey. The line marked ‘Fall deposition envelope’
13
14 marks the westerly limits of where Bishop fall deposits are found in this area. The lines
15
16 marked (i) and (ii) relate to the labels (i) and (ii) in panel **b**. (i) Shows a hypothetical
17
18 cross section from NW to NE across the northern ignimbrite lobes as viewed from the
19
20 centre of Long Valley caldera. (ii) Is a schematic proximal to distal cross section,
21
22 approximately along the line of the Owens River gorge. **b** Schematic stratigraphy of the
23
24 Bishop Tuff in its proximal area based on sections (i) and (ii). Ignimbrite units are
25
26 coloured; fall units are grey. Samples collected for this paper cover most of the
27
28 stratigraphic units (See Electronic Appendix 1).
29
30
31
32
33
34
35
36

37 **Fig. 2** CL images of representative quartz crystals from **a** ignimbrite packages Ig2NWb and **b**
38
39 Ig2Nb. Areas across which greyscale profiles were extracted are highlighted as red
40
41 boxes, and their corresponding profiles shown below the images. The modelled profile
42
43 (age given next to the associated profiles) is shown as a black line, overlying the data
44
45 (circles, connected by grey dashed line). The y axis for both graphs is relative greyscale
46
47 values, with 2σ uncertainty on greyscale value shown as the error bars. It is apparent
48
49 that no matter which axis the greyscale profile is extracted from, timescales are
50
51 comparable. White scale bars are 100 μm .
52
53
54
55
56

57 **Fig. 3** Compiled cumulative frequency plot of modelled timescales from Ti diffusion in
58
59 quartz (grey diamonds), Fe-Mg interdiffusion in orthopyroxene (yellow circles), Sr in
60
61
62
63
64
65

1 sanidine (green crosses), and Ba in sanidine (blue triangles). The 1 s.d. uncertainty on
2 each timescale modelled is shown as corresponding fields for each technique: yellow
3
4 for Fe-Mg in orthopyroxene, grey for Ti in quartz, green for Sr in sanidine and blue for
5
6 Ba in sanidine.
7
8
9

10 **Fig. 4** BSE images of orthopyroxene showing the three zoning categories, with Mg# labelled
11 in white. **a** unzoned; **b** those with a dark rim (more Mg-rich rim); **c** those with a light
12 (more Fe-rich rim). Areas across which greyscale profiles were extracted are shown by
13 red boxes, with the corresponding profiles labelled with (i), (ii) or (iii). The profiles
14 have been corrected to X_{Mg} and the modelled timescale is given next to the associated
15 profile. Extracted profiles are shown as circles (connected with a grey line), and the
16 modelled profiles are the black lines. 2σ uncertainty on greyscale value (corrected to
17 X_{Mg}) is shown as the error bars. White scale bar on all images is 100 μm .
18
19
20
21
22
23
24
25
26
27
28
29
30

31 **Fig. 5** BSE images of sanidine crystals showing representative examples of **a** those which are
32 unzoned and **b** those which have a bright, Ba- and Sr-rich rim. Sr and Ba contents are
33 labelled in white, from EPMA analyses. Areas over which greyscale profiles were
34 extracted are shown as red boxes, which are labelled to correspond to the profiles
35 shown below. All profiles are plotted as circles, connected with a grey dashed line; the
36 modelled profiles are plotted as black curves. Ba profiles from **b** are shown in **c** with
37 the y axis being relative grey-scale values, 2σ uncertainty on greyscale value plotted as
38 error bars. The associated Sr profiles from EPMA are plotted in **d**, with 2 s.d. EPMA
39 analytical uncertainties shown. Note the lack of a stable Sr plateau in (**d**, i) which
40 means that this timescale is not included in our results (see text for discussion of profile
41 classes and Fig. 7, below). White scale bars in images **a** and **b** are 100 μm .
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 **Fig. 6** Plot of Ba vs. Sr from LA-ICPMS (dark circles) and EPMA (light diamonds) analyses
2 of sanidine phenocrysts from samples investigated in this study. Error crosses show 2
3 s.d. uncertainties: the dark grey cross corresponds to LA-ICPMS analyses, the larger
4 light grey cross to EPMA analyses.
5
6
7
8
9

10 **Fig. 7** The three classes of diffusion profiles demonstrated in Ba profiles in sanidine (blue),
11 Ti profiles in quartz (grey), Mg# number profiles in orthopyroxene (yellow) and Sr
12 profiles in sanidine (green) (see text for details). All x axes are distance (in μm), y axes
13 are concentrations (absolute or inferred) of the element in question. Class 1 is the ideal
14 diffusion profile, being symmetrical and fitting the model (black line) well. Class 2
15 profiles reveal a false high/low on one side of the profile, where the “plateau” is not
16 horizontal as assume in the modelling (black line). Class 3 shows the asymmetric
17 boundaries which deviate away from the model (black line) within the concentration
18 gradient. This relict of growth zoning would cause timescales to be over-estimated.
19
20
21
22
23
24
25
26
27
28
29
30
31
32

33 **Fig. 8** Cumulative frequency plot comparing the timescales modelled from Ti diffusion in
34 quartz (diamonds), and the combined modelling of Ba and Sr in sanidine (red stars).
35 The 1 s.d. error window is shown as grey (Ti in quartz) or red (Ba and Sr in sanidine)
36 fields. The original timescales from Sr diffusion in sanidine (crosses) and Ba diffusion
37 in sanidine (triangles) from the crystals used in the combined modelling are also
38 plotted. This shows the significant reduction in Ba timescales once combined modelling
39 is used for sanidine diffusion zones.
40
41
42
43
44
45
46
47
48
49
50

51 **Fig. 9 a** Histogram of all combined diffusion timescales including those from Fe-Mg
52 interdiffusion in orthopyroxene, Ti diffusion in quartz, and combined Ba-Sr diffusion in
53 sanidine with **b** cumulative frequency chart showing the timescales and their
54 uncertainties for each method. All uncertainty bars are ± 1 s.d.
55
56
57
58
59
60
61
62
63
64
65

Fig. 10 Cartoons illustrating three possible model options (not to scale) for the origin of orthopyroxene and its associated zoning in the Bishop Tuff. Only a segment of the lower part of the magma chamber is depicted (in green) which is intruded by the ‘bright rim’ forming magma (white) from remelting of the underlying crystal mush (grey) by a more mafic magma (red). In all three models the end result is variably zoned orthopyroxene crystals, but the possible origins for these crystals is changeable. Note that in options 2 and 3 there must be limited convection within the melt-dominant magma body [consistent with the views of Hildreth (1979) and Hildreth & Wilson (2007)] in order to preserve small-scale heterogeneities within the melt-dominant magma body prior to late-stage mingling upon eruption.

Figure 1
[Click here to download high resolution image](#)

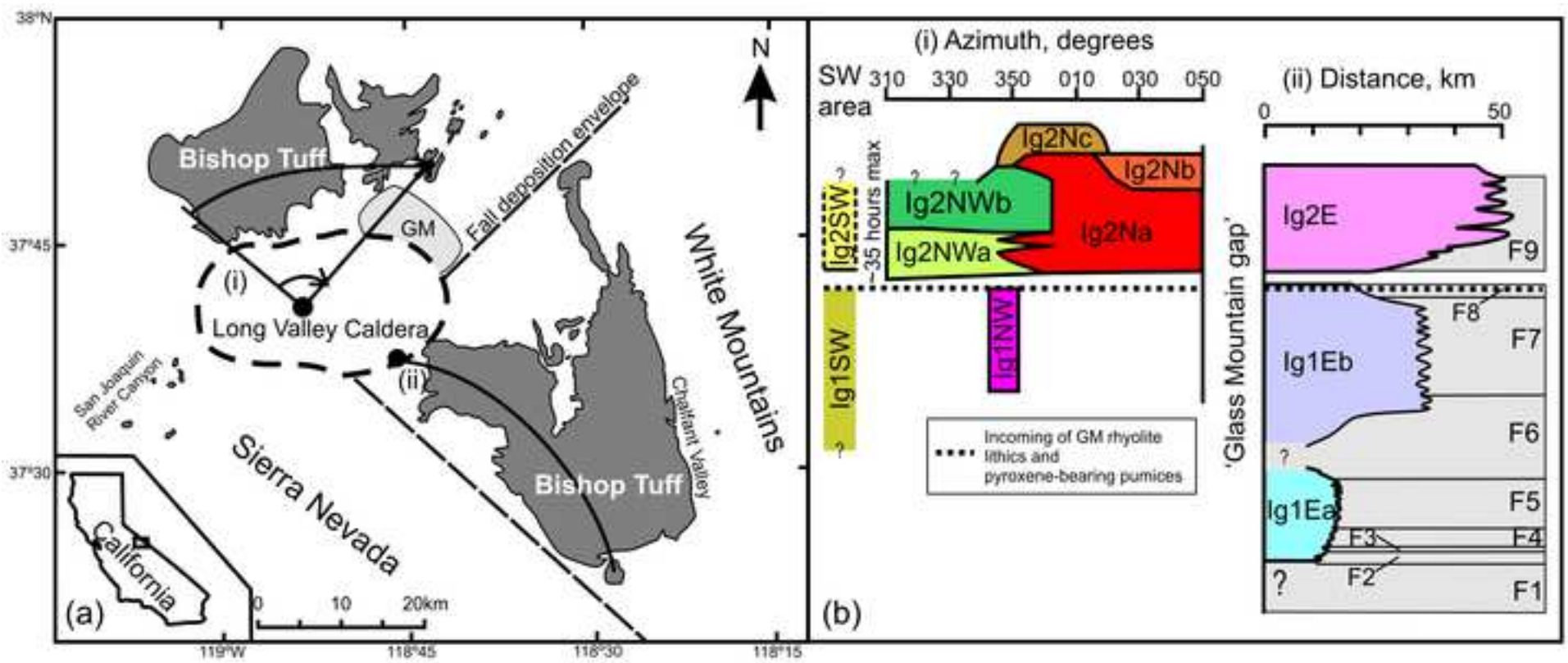


Figure 2
[Click here to download high resolution image](#)

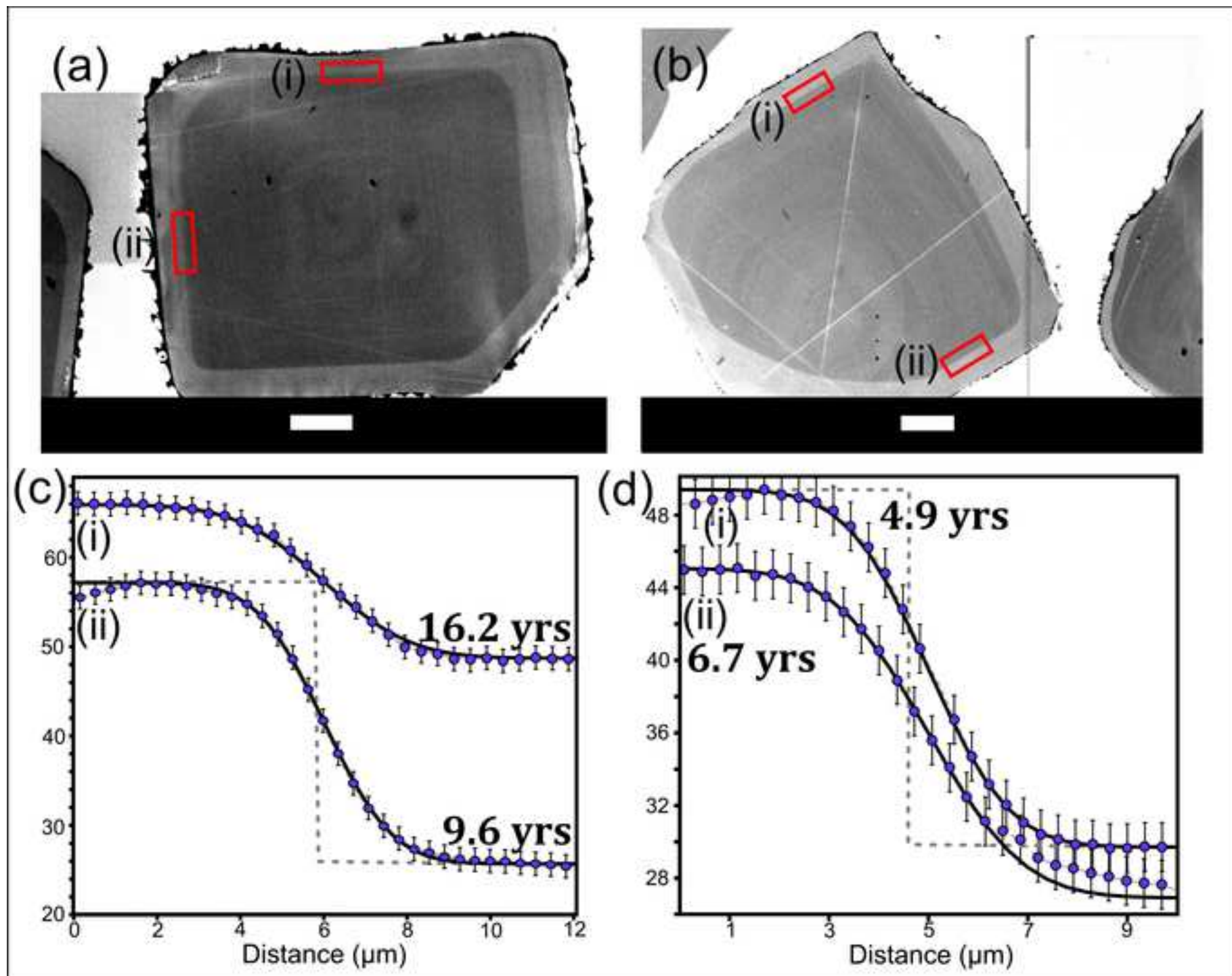


Figure 3
[Click here to download high resolution image](#)

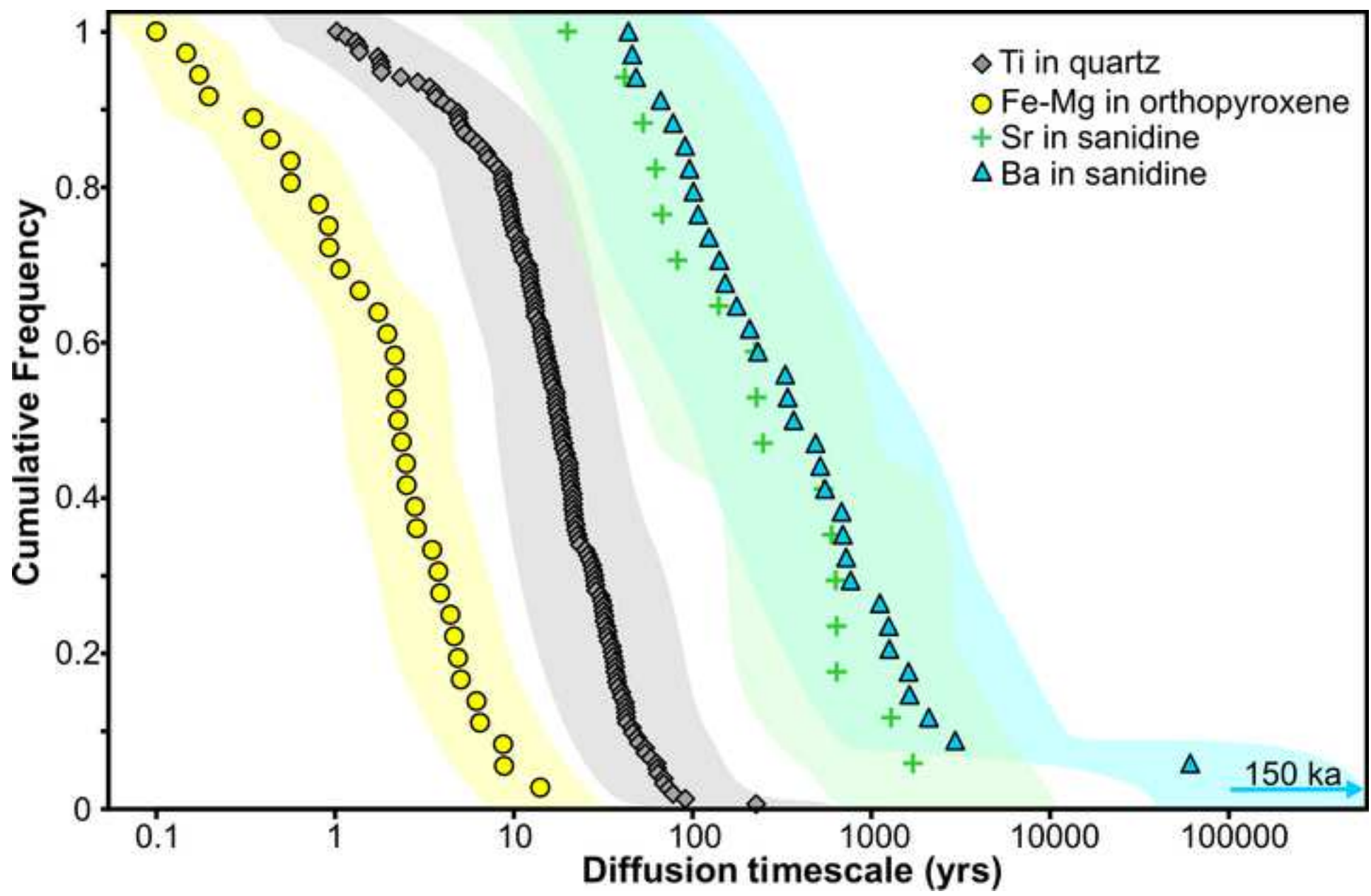


Figure 4
[Click here to download high resolution image](#)

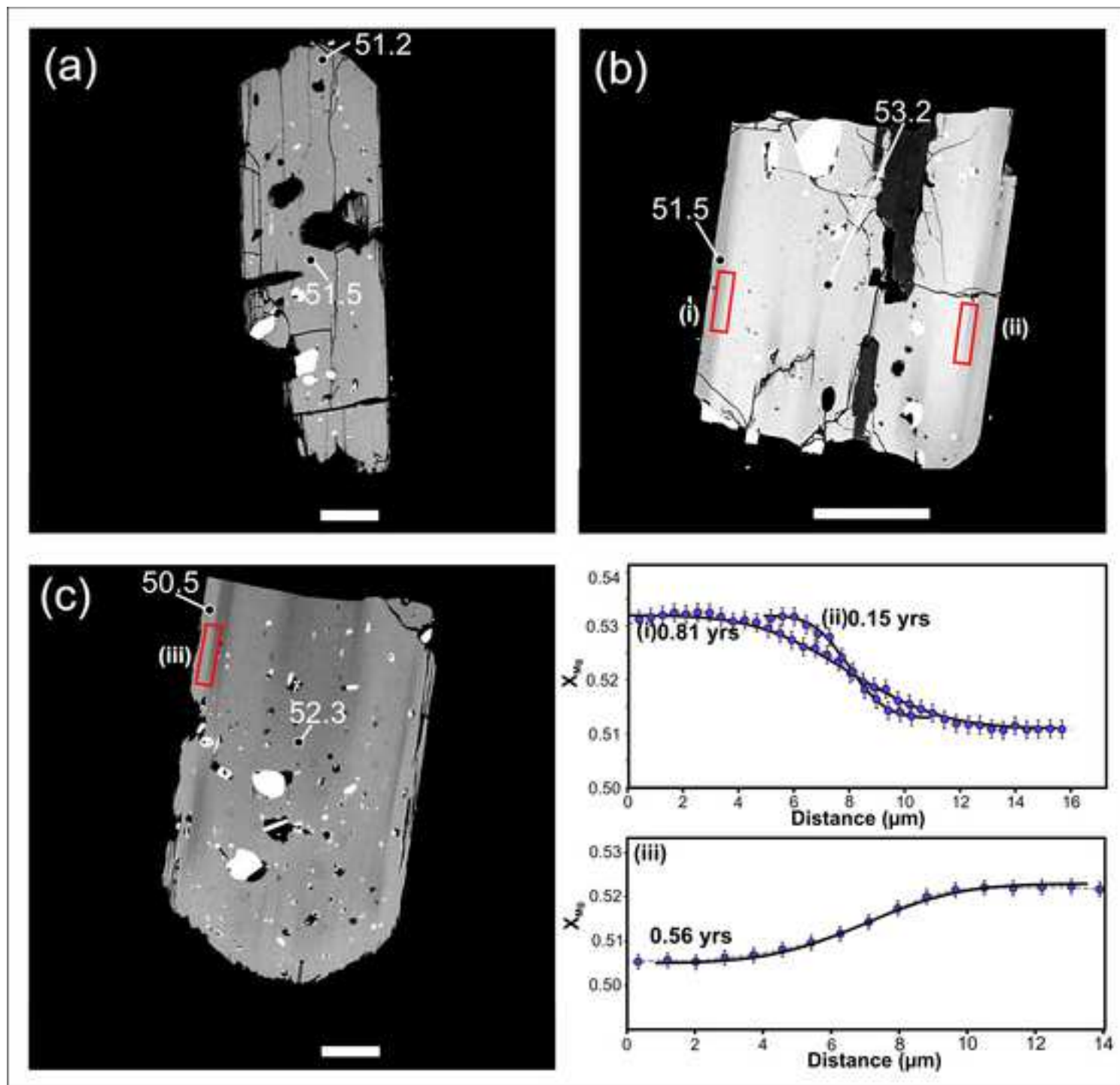


Figure 5
[Click here to download high resolution image](#)

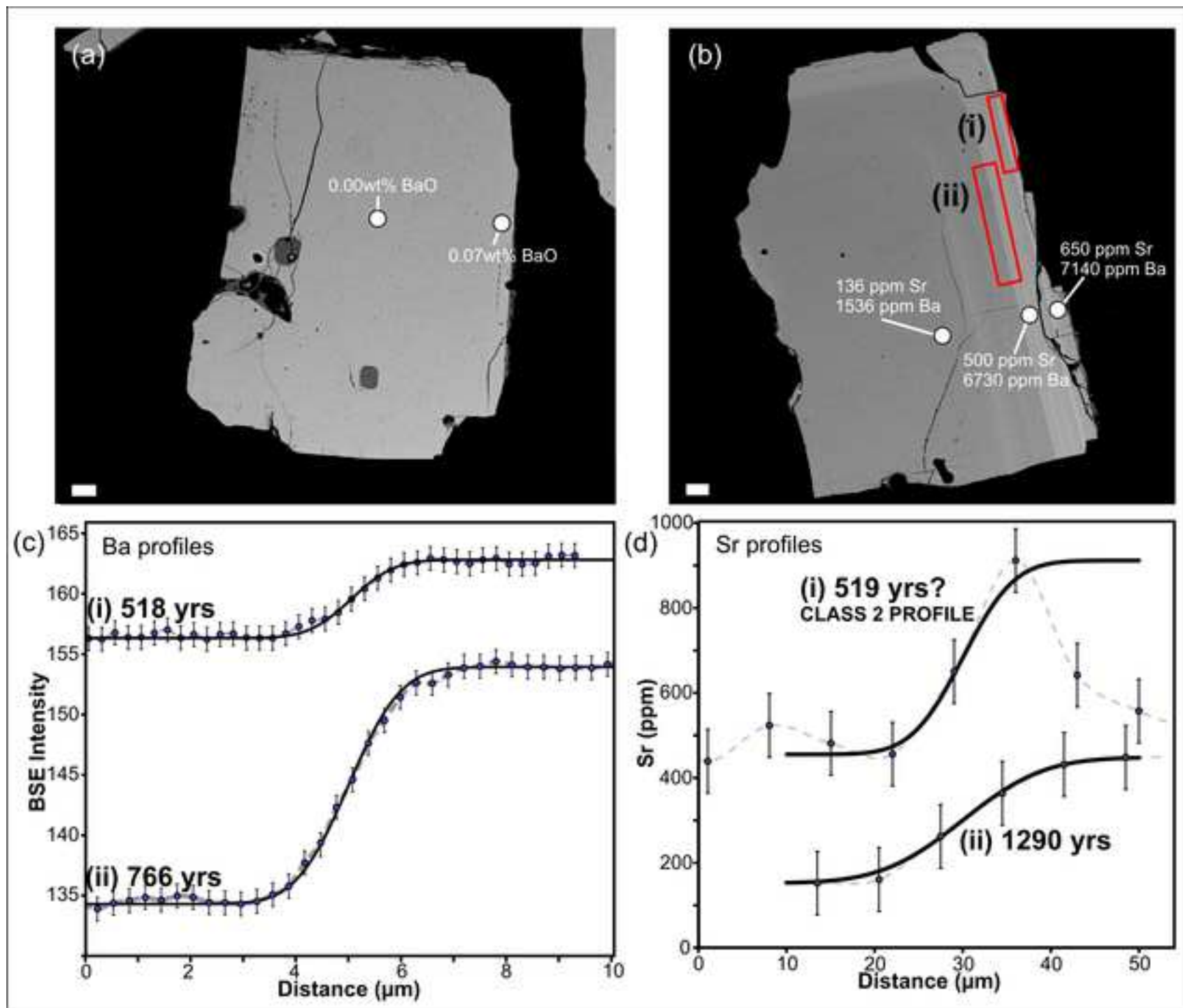


Figure 6
[Click here to download high resolution image](#)

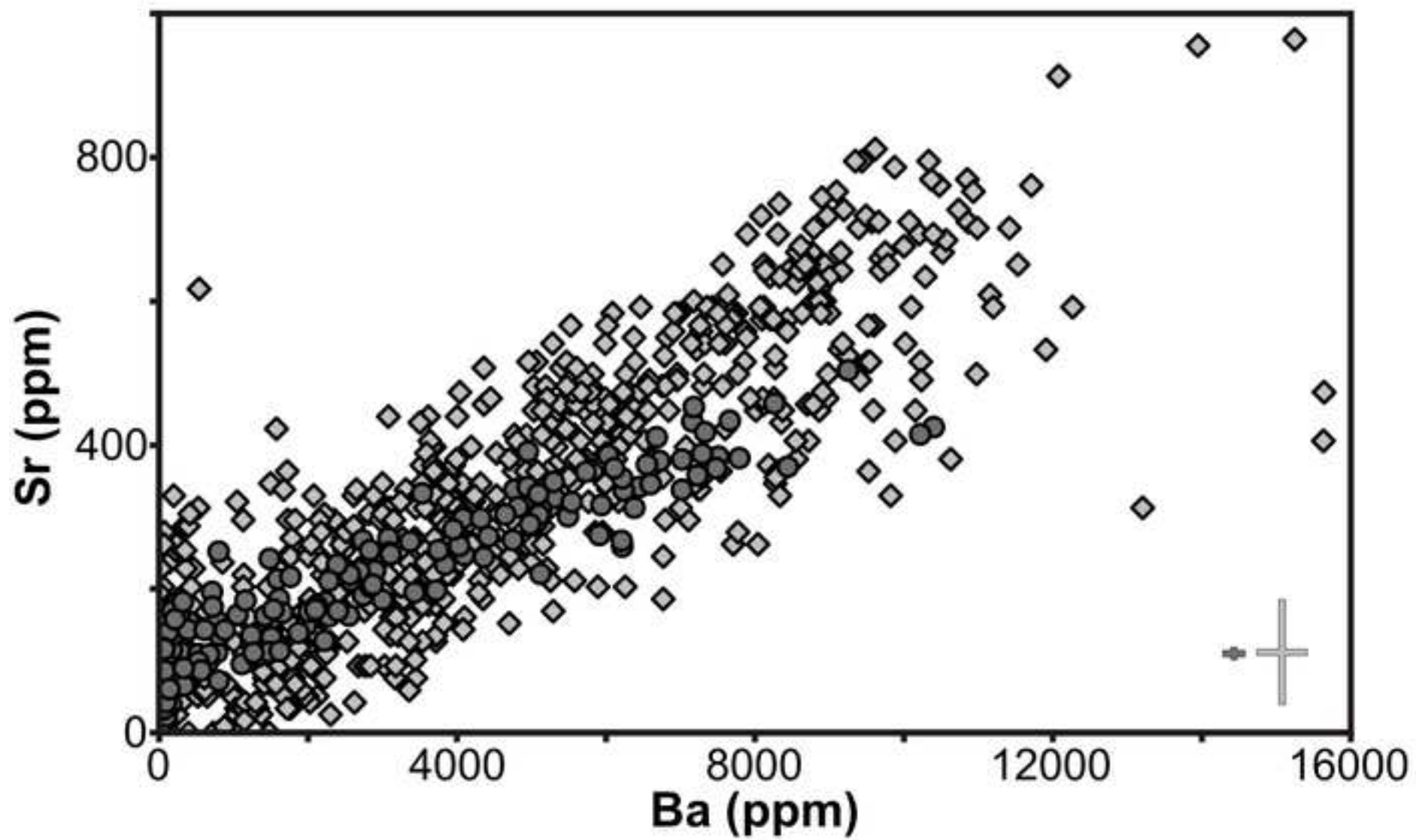


Figure 7
[Click here to download high resolution image](#)

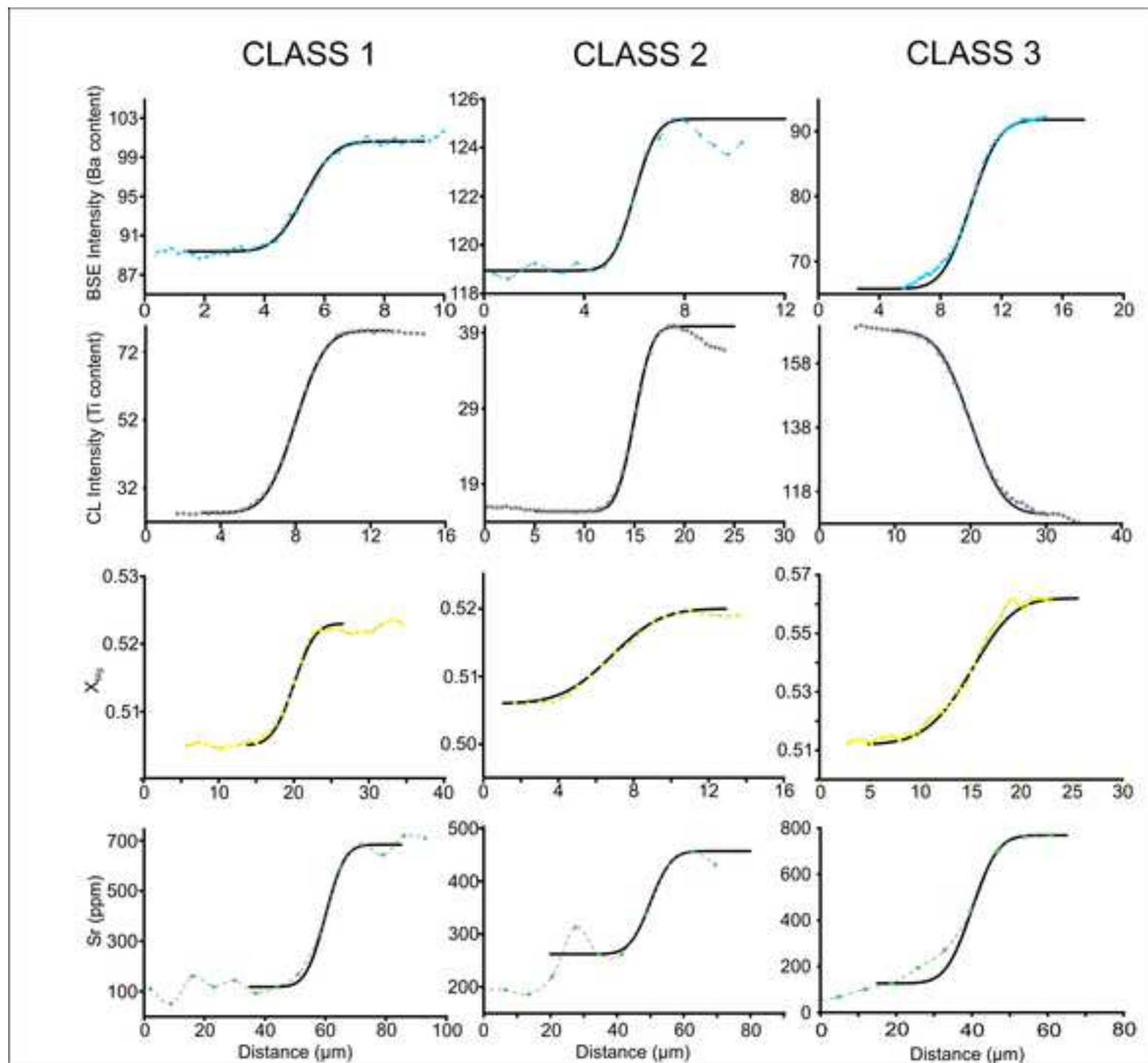


Figure 8
[Click here to download high resolution image](#)

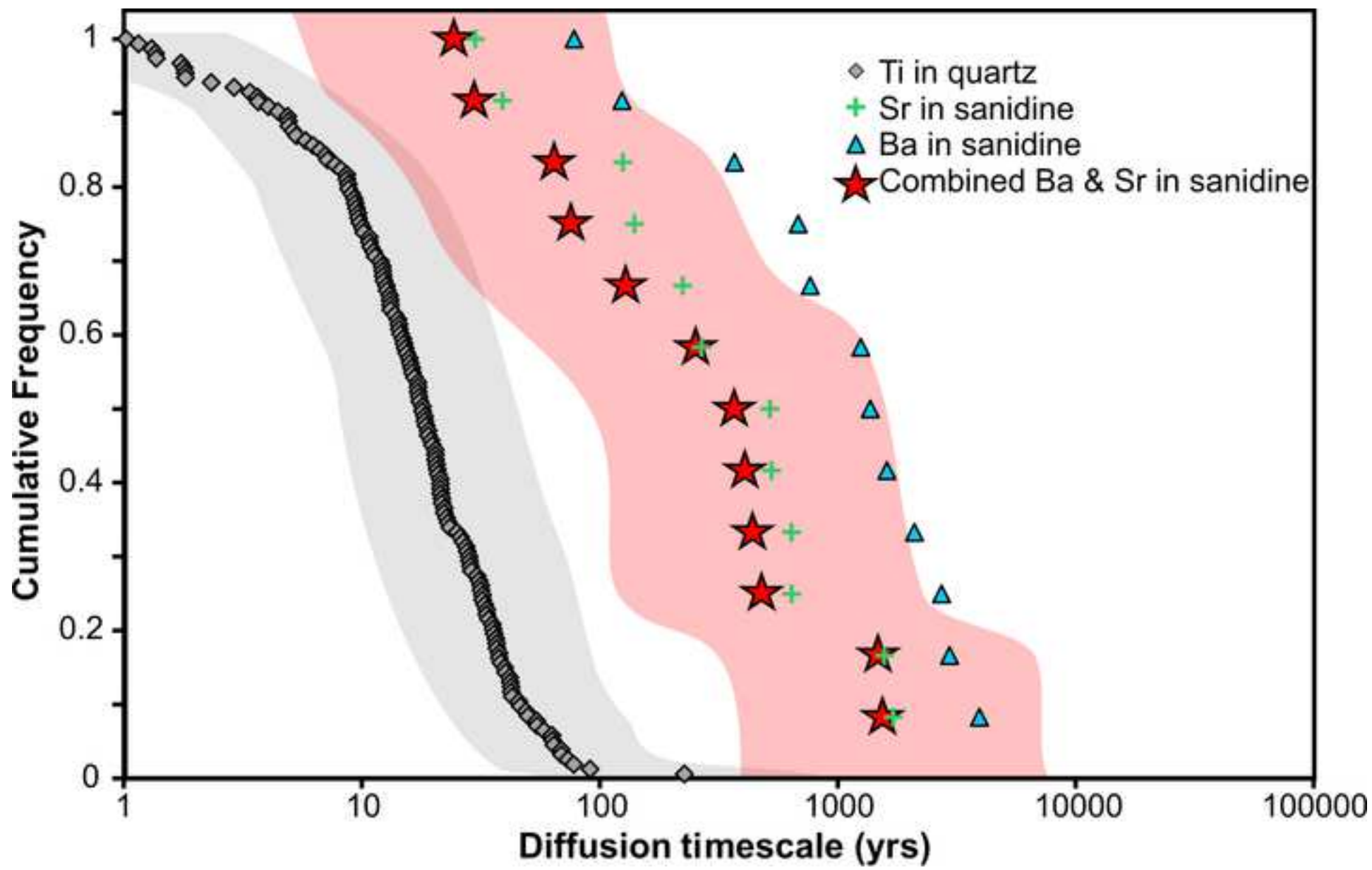


Figure 9

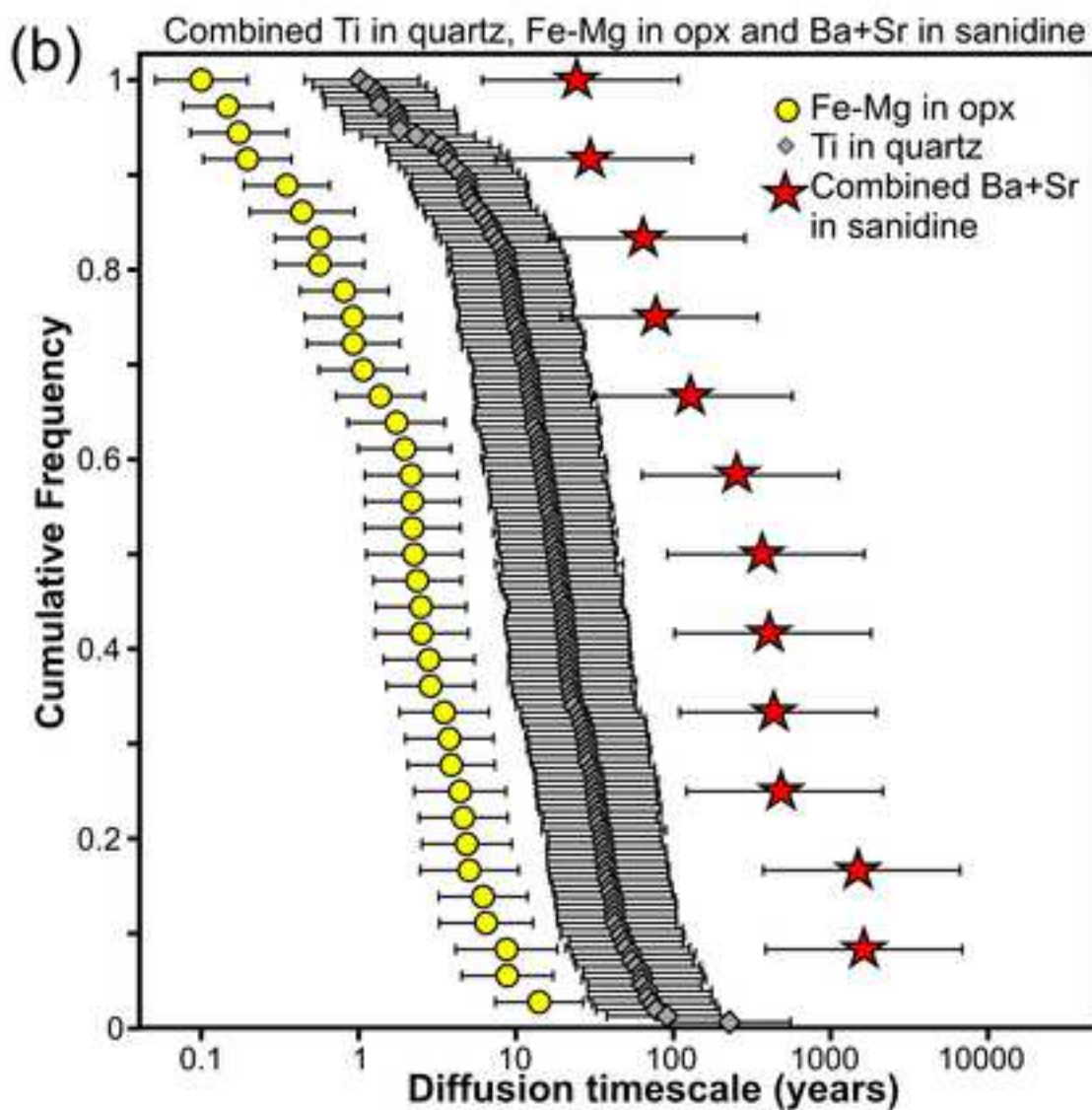
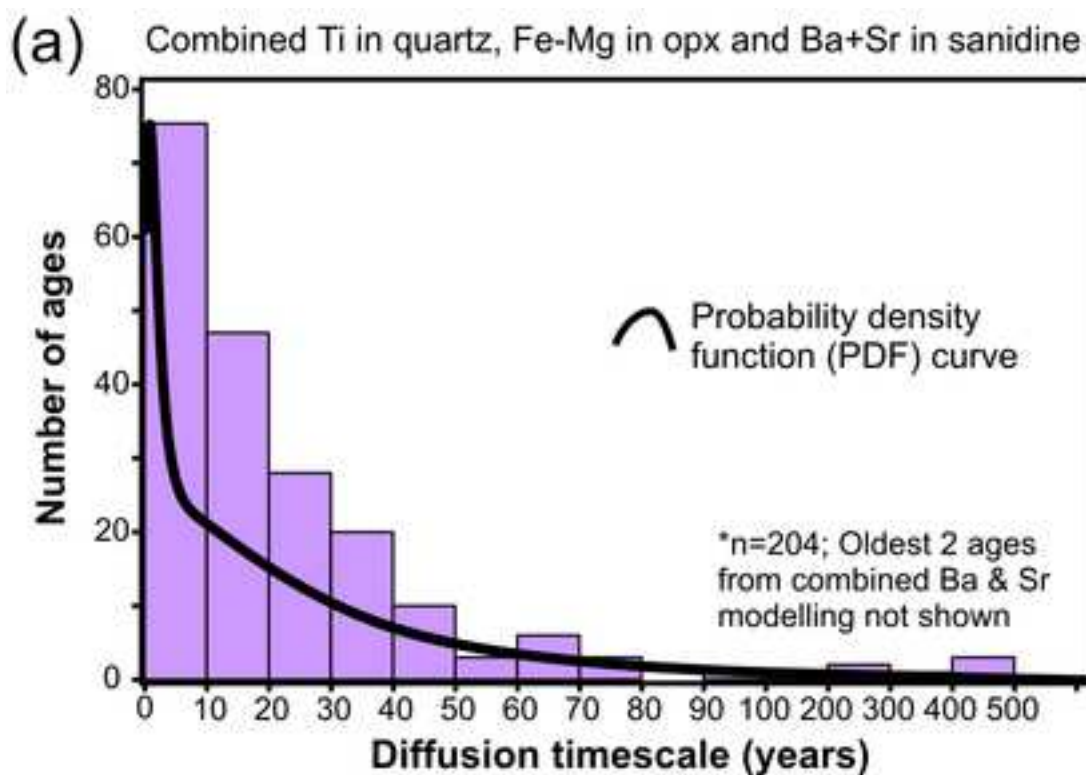
[Click here to download high resolution image](#)

Figure 10
[Click here to download high resolution image](#)

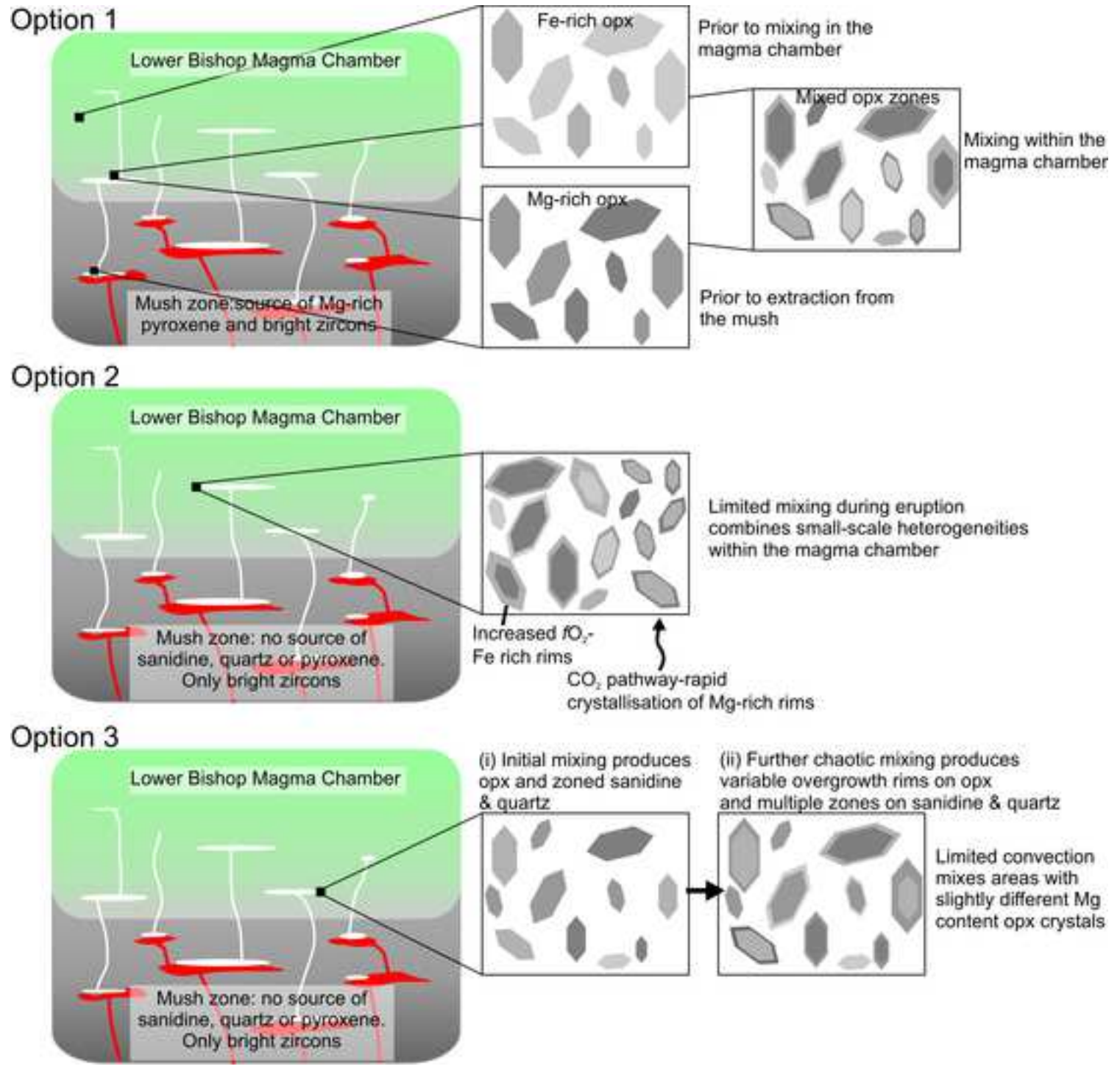


Table 1 Listing of diffusion constants used for all species modelled

Phase	Diffusing Species	D_0 (ms^{-2})	E_{act} (J/mol)	$f\text{O}_2$ (Δ NNO; range)	T ($^{\circ}\text{C}$; range)
Orthopyroxene	Fe-Mg	0.00000288 ^A		0.483 – 1.111 ^B	790 – 815
Quartz	Ti	0.00000007 ^C	273000 ^C	NA	753 – 815
Sanidine	Ba	0.29 ^D	455000 ^D	NA	753 – 815
Sanidine	Sr	8.4 ^E	450000 ^E	NA	770 – 815

Sources of values used. A: Ganguly & Tazzoli 1994; B: Hildreth & Wilson 2007; C: Cherniak et al. 2007; D: Cherniak 2002; E: Cherniak 1996. NA = Not applicable.

Table 2 Major element analyses (wt. %) and resulting two-feldspar temperatures from sanidine and plagioclase crystals in the Bishop Tuff

Sample	Phase	Eruptive unit	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	BaO	Total	An (%)	Ab (%)	Or (%)	Calculated T (°C)
BP080	plag inc	Ig1Eb	65.53	0.00	22.66	0.13	0.00	2.90	8.56	1.75	0.33	101.87	14.16	75.68	10.16	738
	san xtl		66.39	0.01	18.34	0.08	0.00	0.16	4.13	11.12	0.00	100.21	0.78	35.80	63.43	
BP087	plag inc	Ig1Eb	65.01	0.00	23.16	0.14	0.00	3.41	8.33	1.52	0.00	101.57	16.79	74.29	8.92	741
	san xtl		66.64	0.01	18.45	0.11	0.00	0.18	4.11	11.02	0.01	100.51	0.87	35.84	63.29	
BP098	plag inc	Ig1Eb	65.13	0.00	22.66	0.15	0.00	3.04	8.26	1.77	0.01	101.01	15.16	74.38	10.46	755
	san xtl		67.01	0.00	18.47	0.06	0.00	0.15	4.14	11.10	0.00	100.94	0.73	35.91	63.35	
BP032	plag inc	Ig1Eb (chocolate)	64.78	0.00	23.09	0.17	0.00	3.21	8.32	1.90	0.00	101.47	15.63	73.33	11.04	747
	san xtl		66.10	0.00	18.18	0.11	0.00	0.19	4.05	11.03	0.00	99.67	0.90	35.47	63.63	
BP036	plag xtl	Ig1Eb (Sherwin)	64.93	0.00	22.43	0.11	0.00	3.07	8.44	1.82	0.00	100.80	14.98	74.44	10.58	737
	san inc		66.30	0.00	18.45	0.11	0.00	0.22	4.32	10.65	0.02	100.06	1.04	37.73	61.23	
BP040	plag inc	Ig1Eb (Sherwin)	63.93	0.02	23.98	0.17	0.00	4.17	8.11	1.08	0.00	101.45	20.73	72.90	6.37	754
	san xtl		67.01	0.00	18.47	0.06	0.00	0.15	4.14	11.10	0.00	99.62	0.87	35.49	63.64	
BP040	plag inc	Ig1Eb (Sherwin)	64.28	0.03	22.64	0.17	0.00	3.32	8.19	1.88	0.00	100.94	15.02	73.53	11.45	746
	san xtl		65.91	0.00	18.16	0.08	0.00	0.18	3.85	11.05	0.02	99.41	0.95	35.27	63.78	
BP040	plag inc	Ig1Eb (Sherwin)	64.75	0.00	22.41	0.13	0.00	3.08	8.33	1.97	0.27	100.52	16.28	72.72	11.01	758
	san xtl		65.82	0.00	18.31	0.08	0.00	0.20	4.00	11.00	0.00	99.25	0.86	34.34	64.80	
BP112	plag xtl	Ig1NW	65.16	0.00	22.92	0.12	0.00	2.98	8.29	1.81	0.00	100.79	15.91	74.88	9.21	746
	san inc		66.04	0.00	18.38	0.06	0.00	0.19	4.23	11.05	0.12	100.13	0.74	35.37	63.89	
BP112	plag inc	Ig1NW	64.59	0.00	22.61	0.15	0.00	3.19	8.02	2.17	0.00	101.29	14.79	74.50	10.71	753
	san xtl		65.86	0.00	18.10	0.10	0.00	0.22	3.88	11.19	0.00	100.08	0.91	36.45	62.64	
BP003	plag xtl	Ig2Ea	65.01	0.00	22.94	0.15	0.00	3.42	8.30	1.82	0.34	101.99	16.58	72.90	10.51	754
	san inc		66.49	0.02	18.31	0.09	0.00	0.21	4.15	11.15	0.03	100.45	1.01	35.77	63.23	
BP197	plag xtl	Ig2Ea	64.91	0.00	22.96	0.14	0.00	3.13	8.12	2.00	0.00	101.26	15.51	72.74	11.75	755
	san inc		66.31	0.00	18.35	0.11	0.00	0.20	3.99	11.13	0.07	100.15	0.95	34.96	64.09	
BP164	plag xtl	Ig2Eb	65.62	0.00	22.86	0.15	0.00	3.08	8.71	1.67	0.59	102.69	14.76	75.68	9.57	711
	san inc		66.21	0.00	18.29	0.06	0.00	0.16	4.10	11.08	0.00	99.90	0.77	35.74	63.48	

Table 2 cont.

Sample	Phase	Eruptive unit	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	BaO	Total	An (%)	Ab (%)	Or (%)	Calculated T (°C)
BP164	plag xtl	Ig2Eb	65.14	0.01	22.51	0.16	0.00	2.98	8.65	1.76	0.37	101.58	14.40	75.50	10.11	715
	san inc		66.33	0.01	18.56	0.06	0.00	0.16	4.03	11.16	0.00	100.31	0.79	35.18	64.03	
BP164	plag xtl	Ig2Eb	64.72	0.00	22.90	0.13	0.00	3.34	8.36	1.62	0.00	101.07	16.37	74.17	9.46	744
	san inc		66.33	0.00	18.47	0.09	0.00	0.19	4.09	11.08	0.03	100.27	0.90	35.59	63.50	
BP164	plag inc	Ig2Eb	64.21	0.02	22.67	0.14	0.00	3.27	8.28	1.59	0.63	100.81	16.23	74.35	9.42	750
	san xtl		66.04	0.00	18.36	0.07	0.00	0.15	4.14	11.08	0.07	99.92	0.74	35.99	63.27	
BP055	plag inc	Ig2Na	64.10	0.00	22.75	0.15	0.00	3.44	8.27	1.79	0.00	100.50	16.74	72.89	10.37	742
	san xtl		65.89	0.00	18.12	0.07	0.00	0.18	4.03	11.04	0.01	99.34	0.87	35.35	63.79	
BP055	plag inc	Ig2Na	64.23	0.00	22.48	0.14	0.00	3.16	8.20	2.02	0.00	100.23	15.50	72.75	11.76	750
	san xtl		65.83	0.00	18.28	0.10	0.00	0.18	3.98	11.14	0.00	99.52	0.89	34.89	64.23	
BP055	plag inc	Ig2Na	64.71	0.00	21.98	0.13	0.00	2.49	7.03	5.59	0.19	102.12	11.40	58.16	30.44	803
	san xtl		66.12	0.00	18.26	0.10	0.00	0.16	3.95	11.08	0.00	99.68	0.79	34.89	64.33	
BP060	plag inc	Ig2Na	64.74	0.00	22.35	0.15	0.00	3.17	7.98	2.38	0.00	100.77	15.49	70.64	13.87	767
	san xtl		65.67	0.00	18.08	0.11	0.00	0.19	3.64	11.27	0.00	98.95	0.94	32.60	66.46	
BP016	plag inc	Ig2Nb	62.30	0.02	24.14	0.23	0.01	5.19	7.42	1.56	0.49	101.36	25.35	65.58	9.07	802
	san xtl		66.01	0.00	18.12	0.08	0.00	0.24	3.77	11.22	0.17	99.60	1.19	33.42	65.39	
BP016	plag xtl	Ig2Nb	62.39	0.00	23.95	0.23	0.00	5.00	7.42	1.66	0.00	100.64	24.50	65.79	9.71	785
	san inc		65.31	0.01	18.28	0.10	0.00	0.34	3.51	11.60	0.31	99.45	1.64	30.97	67.39	
BP209	plag inc	Ig2Nc	62.75	0.00	23.86	0.31	0.00	4.83	7.59	1.50	0.00	100.85	23.75	67.47	8.78	790
	san xtl		65.31	0.00	17.97	0.08	0.00	0.21	3.78	11.19	0.12	98.68	1.02	33.60	65.37	
BP118	plag inc	Ig2NWa	64.72	0.00	22.64	0.12	0.00	3.26	8.47	1.58	0.00	100.72	15.72	71.57	12.72	769
	san xtl		66.36	0.00	18.38	0.11	0.00	0.15	4.03	11.07	0.03	99.35	1.06	34.14	64.81	
BP124	plag inc	Ig2NWb	64.09	0.00	23.75	0.21	0.00	4.52	7.70	1.99	0.15	102.41	21.69	66.92	11.39	812
	san xtl		66.41	0.00	18.27	0.07	0.00	0.26	3.86	11.46	0.07	100.41	1.26	33.43	65.31	
BP124	plag inc	Ig2NWb	63.08	0.00	24.05	0.22	0.00	4.89	7.42	1.87	0.46	101.99	23.79	65.36	10.85	821
	san xtl		66.41	0.00	18.27	0.07	0.00	0.26	3.86	11.46	0.07	100.41	1.26	33.43	65.31	

Eruptive units after Hildreth & Wilson (2007).

Table 3 Temperatures used for diffusion modelling in various units of the Bishop Tuff

Eruptive unit	T modelled at (°C)	Rationale
Ig2SW	753	Weighted Average of all Eastern and Ig2Na feldspar temperatures
F9	780	Average of Ig2Na, Ig2Nb and Ig2Nc feldspar temperatures
Ig2Na	770	Average of Ig2Na feldspar temperatures
Ig2Nb + c	790	Average of Ig2Nb and Ig2Nc feldspar temperatures
Ig2NWa + b	815	Average of Ig2NWb temperature only, due to "eastern" appearance of sanidine, zircon, and glass chemistry in sample BP118

Eruptive units after Hildreth & Wilson (2007).

Table 4 Differences in modelled timescales in sanidine between using combined Ba and Sr diffusion versus Sr or Ba diffusion alone

Sample	T used (K)	Boundary	Combined Timescale (yrs)	Sr timescale (yrs)	Ba timescale (yrs)
BP124-Ig2NWb	1088	k10 outer	24	30	78
BP126-Ig2NWb	1088	k13-outer	30	39	124
BP170- Ig2Nb	1063	k16-inner	64	140	1250
BP209-Ig2Nc	1063	k12	77	125	682
BP124-Ig2NWb	1088	k6	128	223	1370
BP115-Ig2NWa	1088	k4	253	268	368
BP124-Ig2NWb	1088	k10-inner	367	639	3940
BP061-Ig2Na	1043	k4-rhs	407	527	1610
BP016-Ig2Nb	1063	k12	438	640	2730
BP015-Ig2Nb	1063	k18-outer	484	519	766
BP060-Ig2Na	1043	k16	1490	1570	2100
BP015-Ig2Nb	1063	k10	1540	1710	2950

Sample numbers and boundaries relate to those used in Electronic Appendix 6.

Electronic supplementary material 1

[Click here to download Electronic supplementary material: EA1.pdf](#)

Electronic supplementary material 2

[Click here to download Electronic supplementary material: EA2_TI_IN_QUARTZ.pdf](#)

Electronic supplementary material 3

[Click here to download Electronic supplementary material: EA3_FE_MG_IN_OPX.pdf](#)

Electronic supplementary material 4

[Click here to download Electronic supplementary material: EA4_BA_IN_SANIDINE.pdf](#)

Electronic supplementary material 5

[Click here to download Electronic supplementary material: EA5_SR_IN_SANIDINE.pdf](#)

Electronic supplementary material 6

[Click here to download Electronic supplementary material: EA6.xlsx](#)