DATA REPOSITORY

THERMAL AND ZHe-DIFFUSION MODEL

Thermal Diffusion Model

Using a solution for diffusion in a sphere (Crank, 1975), we calculate the temperature from $r_i/x = 0$ to $r_i/x = 1$, where x is the radius of the xenolith in meters, r_i is any point along that radius, and where i is any integer from 0 (the center of the sphere) to 1000 (the outer edge of the sphere):

$$T = T_x + (T_m - T_x)\left[1 + \left(\frac{2x}{\pi r_i}\right)\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\sin\frac{n\pi r_i}{a}\,e^{-Dn^2\pi^2 t/x^2}\right]$$

For the singular case $r_i/x \rightarrow 0$, we use:

$$T = T_x + (T_m - T_x)\left[1 + 2\sum_{n=1}^{\infty}(-1)^n e^{-Dn^2\pi^2 t/x^2}\right]$$

Each r_i corresponds to a spherical shell outer radius and the corresponding spherical shell volume between $r_{(i-1)}$ and r_i. Within each shell volume, we assume a homogenous distribution of zircons and *T-t* history. Assuming a thermal diffusivity for granite, $\kappa = 1\text{x}10^{-2}$ cm^2/s, typical basalt temperatures of 1150, 1200, and 1250 ºC, an estimated xenolith temperature of 100 ºC, and a spherical xenolith with typical BPVF xenolith radii of 2.5, 5.0, 7.5, and 10 cm, we calculate the temperature at the outer radius of each of the 1000 spherical shells (zircon locations) for a range of times.

He Loss Model

Using the calculated time-temperature histories for each location in the xenolith, we then calculate the fractional He loss for a representative tetragonal zircon prism at each location, and for a range of magmatic residence durations. By assuming a typical zircon width, W, of 100 µm and a length, L of $3W$, we calculate the radius of a sphere, a, with a corresponding surface-area to volume ratio (β) (Meesters and Dunai, 2002a, b), using the relationship: $a = R_{sphere} = 3 / \beta_{zirc}$, where β_{zirc} is calculated based on a tetragonal prism with bipyramidal tips (Reiners, 2005) We model diffusive fractional He loss from this sphere for a range of times (Crank, 1975; McDougall and Harrison, 1999) using the following equation:

$$f = 1 - (6/\pi^2)\sum_{n=1}^{\infty}(1/n^2)\exp(-n^2\pi^2 Dt/a^2)$$

where

$$D = D_0 \exp(-E_a / RT)$$

and $D_0 = 0.46$ cm^2/s and $E_a = 40.4$ kcal/mol (Reiners et al., 2004). The calculated xenolith temperature, T, is used to determine Dt/a^2 for a given crystal, which we then use to calculate fractional He loss using the above equation. For this model, we require 99.99% degassing for a zircon to be considered fully degassed. In the case of a preeruption ZHe age of 100 Ma, this represents only 10 kyr (0.01%) worth of remaining He left in the zircon, or 10% of a 100-ka eruption age. If the resulting fractional loss is less than the required 0.9999 to be considered fully degassed, then we consider the zircons within that shell to only be partially reset. Knowing the volume of each spherical shell, we then use the volume fraction of shells with partially reset zircons to give an estimate of the percent of xenolithic zircons with retained He for a given temperature, xenolith size and residence time in the melt (Fig 2).

If a 10-cm radius xenolith in a 1150 ºC magma is allowed to heat for 1000 s, ~68% of zircon crystals will retain He ($f < 0.9999$) (Fig 2). As a first order approximation of the potential effect of prolonged cooling in post-eruptive lava, we hold each grain at 600 ºC after 1000 s for extended durations. If the same xenolith now remains entrained in a 600 ºC lava at the surface for one year, ~34% of the xenolith zircon crystals still will retain He. Thus the He loss on the time-scale of cooling lava at low temperatures is minimal compared to the xenolith's residence at high (magmatic) temperatures.

SAMPLE LOCATIONS AND PETROLOGY

The BPVF comprises several Pleistocene basaltic (and one rhyolitic) vents and flows in Owens Valley, CA, some of which have been previously dated using $^{40}Ar/^{39}Ar$ and K/Ar techniques. The Oak Creek basalts are the southernmost flows of the volcanic field, originate in the Eastern Sierra, and outcrop on the west side of the valley. Due to the extent of erosion and alluviation, and their position beneath a Tahoe glacial moraine, at least some of the Oak Creek basalts are thought to be the oldest in the BPVF (Darrow, 1972). Previous $^{40}Ar/^{39}Ar$ Oak Creek measurements of four whole-rock basalts and six feldspar xenolith separates gave a mean eruption age of 1.18 ± 0.05 Ma (2σ) (Gillespie et al., 1983). Four K/Ar ages from distinct outcrops in the eastern part of Oak Creek yielded ages of 0.10 Ma, 0.24 Ma, 0.33 Ma, and 0.42 Ma (Turrin and Gillespie, 1986; Connor and Conway, 2000). The sample used in this study (N 36°50.846'; W 118°17.433') is near the $^{40}Ar/^{39}Ar$ dated site A of Gillespie et al. (1983), to the east of $^{40}Ar/^{39}Ar$ dated sites B and C of Gillespie et al. (1983), and to the west of the K/Ar dated Oak Creek outcrops (Turrin and Gillespie, 1986; Connor and Conway, 2000). The wide range of ages and the discontinuous outcrops suggest that the Oak Creek region has multiple vents. Obvious vent locations have been removed by erosion, making dating of the separate outcrops the most reliable method of determining whether they belong to one or many eruptions. The flow dated by ZHe is the youngest age found in the immediate vicinity, so it was not likely reset by later eruptions. Both ultramafic and granitoid xenoliths are present. In hand sample, many of the felsic xenoliths, such as the one used in this study, appear lithologically similar to the Eastern Sierran granodiorite exposed at the surface.

The Fish Springs cinder cone (N 37°04.601'; W 118°15.670') of the BPVF is also located on the west side of Owens valley, north of Oak Creek. The previous $^{40}Ar/^{39}Ar$ age determined for this cone using two K-feldspars crystals from one xenolith is 0.314 ± 0.036 Ma (2σ) (Martel et al., 1987; Connor and Conway, 2000). Abundant ultramafic and granitic xenoliths are present, and have much more pronounced alteration textures than any other xenolith suite in the BPVF. As a monogenetic vent, there are no overlying flows that might reset the He ages. The xenolith used in this study was granodioritic in composition.

Prindle volcano (N 63º43.2'; W 141º37.2') is in eastern-most central Alaska, near the Yukon border, and represents the western-most extent of alkaline magmatism in the northern Cordilleran volcanic province (NCVP; Edwards and Russell, 2000). It is a basanitic scoria cone (Foster et al., 1966; Prescott, 1983) comprising a rim of agglutinated spatter and spindle bombs, breached on the southern end by a ~10 km long lava flow. The lava is olivine-phyric and contains a diverse population of feldspathic granulitic and peridotitic xenoliths (Foster et al., 1966; Prescott, 1983; Roughly et al., 2000; Ghent et al., 2004). The xenolith used for this study is a felsic granulite from the upper rim of the pyroclastic cone, and is not overlain by any flows that might reset the He age. Because the surficial rocks around Prindle are dominantly amphibolite-facies (Dusel-Bacon, 1994), it is likely that the granulite-facies xenoliths are derived from greater crustal depths. Ghent et al. (2004) reported equilibration temperatures and pressures of 770-1015 °C and 10-11 kb respectively for granulite xenoliths from Prindle. The Prindle granulite temperature estimates are considerably higher than those reported for surrounding amphibolites by Dusel-Bacon et al. (1995), which range from 570-700

°C. Assuming a median temperature of 635 °C for the amphibolites, a median temperature of 890 °C for the granulites, and a contemporaneous peak in metamorphic gradient for both rock types as part of a regional metamorphic sequence, we can calculate a minimum depth of in corporation. Using a conservatively cool geothermal gradient estimate of 25 °C/km the granulites would have formed approximately 10 km deeper in the crust than the amphibolites. Since the amphibolites are presently exposed at the surface, the granulites would have been incorporated into the Prindle basanite at a minimum depth of 10 km. The cone appears to be unmodified by glaciation or other erosional processes, and its age of formation has been estimated as Late Pleistocene (Foster et al., 1966). However, the only two attempts to date it gave inconsistent and anomalously old ages, 6.26 ± 0.15 Ma (2σ) and 3.57 ± 0.14 Ma (2σ) (Hunt and Roddick, 1992), which were attributed to either excess Ar or fractionation of the atmospheric argon component.

Little Bear Mountain volcano (N 56°49.2'; W 131°18.6') is immediately north of Hoodoo Mountain volcano (Edwards et al., 2002), near the southern end of the NCVP in western British Columbia. The alkaline basaltic volcano erupted mainly pyroclastic breccia, with minor amounts of massive lava, pillow lava, volcanic sandstone and hyaloclastite (Edwards et al., 1995; Edwards et al., 1999a). Its eruptions have been interpreted as subglacial, suggesting a pre-Holocene age (Edwards et al., 1995; Edwards, 1997). The massive basalt is olivine-, plagioclase-, and clinopyroxene-phyric and contains quartzose, gabbroic and syenitic xenoliths. The pyroxene syenite xenoliths used in this study show cross-cutting veinlets of obsidian indicating partial melting (Edwards, 1997). The analyzed xenolith was collected from near the top of the edifice, and nothing in the field relationships indicate that the sample would have ever been covered by younger lava flows. $^{40}Ar/^{39}Ar$ dating of a massive basalt sample gave an age of 0.253 ± 0.047 Ma (2σ) (Villeneuve et al., 1998; Edwards et al., 1999b; Edwards et al., 2002), though there is some excess ^{40}Ar and slight scatter in data. The basement geology surrounding the volcano is dominated by metasedimentary, metavolcanic, and meta-igneous rocks of the Mesozoic Stikine terrane (Edwards et al., 1999a). The xenolith is thought to have originated from mid-crustal depths, although no geobarometric constraints are available for the sample.

Table DR 1. (U-Th)/He AGES FOR INDIVIDUAL ZIRCONS OF THE FOUR VOLCANIC CENTERS. 1σ REPRESENTS FORMAL ANALYTICAL ERROR OF INDIVIDUAL RUNS

sample name	U ppm	Th ppm	Th/U (atomic)	^{4}He (nmol/g)	mass (ug)	half-width (um)	HAC (Ft)	corrected age (ka)	± 1σ analyt. error
Oak Creek, BPVF									
01zA	329	148	0.46	0.312	15.6	60.8	0.833	191	3.9
01zC	238	105	0.45	0.201	11.6	51.3	0.810	176	4.6
01zE	242	129	0.55	0.218	12.5	48.5	0.806	184	5.0
01zF	291	132	0.47	0.282	25.6	69.8	0.857	189	6.7
01zG	329	139	0.43	0.318	12.5	59.5	0.826	198	9.0
01zH	448	173	0.40	0.482	11.5	55.5	0.819	224	8.5
01zI	364	192	0.54	0.302	13.7	55.5	0.822	167	4.0
01zJ	240	109	0.47	0.203	25.1	82.8	0.865	163	3.4
01zK	306	170	0.57	0.272	17.1	63.3	0.837	174	3.6
01zL	315	125	0.41	0.273	21.2	71.0	0.852	173	3.6
01zM	309	156	0.52	0.279	15.6	55.0	0.825	182	4.4
01zN	435	192	0.45	0.373	10.1	43.8	0.786	184	4.5
01zO	376	205	0.56	0.311	9.3	50.0	0.800	170	4.3
01zP	363	137	0.39	0.292	16.6	64.0	0.840	163	3.9
01zQ	274	122	0.46	0.275	44.7	92.3	0.885	190	3.7
01zR	353	130	0.38	0.368	9.1	53.5	0.806	221	5.1
Fish Springs, BPVF									
24zA	510	473	0.95	0.789	4.1	32.3	0.717	328	8.7
24zB	479	163	0.35	0.581	1.9	30.8	0.685	305	12.3
24zD	1089	456	0.43	1.318	7.0	44.8	0.781	261	5.9
24zF	3124	30	0.01	4.841	6.2	47.8	0.787	365	11.8
24zG	1106	488	0.45	1.163	3.6	32.5	0.718	246	11.0
24zH	3852	2183	0.58	6.566	3.6	35.8	0.732	381	11.8
24zI	2830	1566	0.57	4.334	11.4	49.8	0.807	312	5.9
24zJ	492	413	0.86	0.864	13.2	61.0	0.828	329	6.4
24zK	2970	1626	0.56	4.660	30.8	70.3	0.857	301	5.7
24zL	189	153	0.83	0.243	12.7	59.8	0.825	243	6.1
24zM	1098	334	0.31	1.173	8.1	45.5	0.790	234	5.2
24zO	675	434	0.66	0.824	5.2	37.5	0.750	262	6.1
24zP	836	1543	1.89	1.497	5.6	34.5	0.730	317	6.4
24zQ	1076	474	0.45	1.171	5.8	42.5	0.771	238	4.7
24zR	812	416	0.53	0.909	9.1	47.0	0.794	233	4.5
Prindle volcano, Alaska									
595-1a	964	318	0.34	0.688	2.5	37.3	0.729	169	3.3
595-1b	542	188	0.36	0.453	3.2	37.0	0.732	196	4.0
595-1c	64	159	2.56	0.073	9.0	54.5	0.804	166	2.9
595-1d	468	213	0.47	0.348	2.9	34.0	0.713	175	3.9
595-1f	1189	376	0.32	0.940	2.6	35.3	0.719	190	4.2

Little Bear Mountain, British Columbia									
595-4a	2421	598	0.25	1.946	51.3	104.5	0.898	157	3.3
595-4b	1587	436	0.28	1.220	12.6	59.8	0.829	162	3.4
595-4z	1449	412	0.29	0.954	3.6	33.3	0.722	159	3.3
595-4y	1571	570	0.37	1.103	4.4	45.0	0.772	155	3.4
595-4c	1977	622	0.32	1.423	13.7	59.3	0.827	151	3.0
595-4d	1672	610	0.37	1.268	7.9	48.0	0.795	163	3.2
595-4e	1558	464	0.31	1.189	16.9	63.8	0.841	158	3.2
595-4f	1721	489	0.29	1.324	29.0	79.3	0.868	154	3.0

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