A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006
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Chapter 37

Timing of Degassing and Plagioclase Growth in Lavas Erupted from Mount St. Helens, 2004–2005, from ^{210}Po-^{210}Pb-^{226}Ra Disequilibria

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Abstract

Disequilibrium between ^{210}Po, ^{210}Pb, and ^{226}Ra was measured on rocks and plagioclase mineral separates erupted during the first year of the ongoing eruption of Mount St. Helens. The purpose of this study was to monitor the volatile fluxing and crystal growth that occurred in the weeks, years, and decades leading up to eruption. Whole-rock samples were leached in dilute HCl to remove ^{210}Po precipitated in open spaces. Before leaching, samples had variable initial (^{210}Po) values, whereas after leaching, the groundmasses of nearly all juvenile samples were found to have had (^{210}Po) ≈ 0 when they erupted. Thus, most samples degassed ^{210}Po both before and after the magmas switched from open- to closed-system degassing. All juvenile samples have (^{210}Pb)/(^{226}Ra) ratios within 2σ of equilibrium, suggesting that the magmas involved in the ongoing eruption did not have strong, persistent fluxes of ^{222}Rn in or out of magmas during the decades and years leading to eruption. These equilibrium values also require a period of at least a century after magma generation and the last significant differentiation of the Mount St. Helens dacites. Despite this, the elevated (^{210}Pb)/(^{226}Ra) value measured in a plagioclase mineral separate from lava erupted in 2004 suggests that a significant proportion of this plagioclase grew within a few decades of eruption. The combined dataset suggests that for most 2004–5 lavas, the last stage of open-system degassing of the dacite magmas at Mount St. Helens is confined to the period between 1–2 years and 1–2 weeks before eruption, whereas plagioclase large enough to be included in the mineral separate grew around the time of the 1980s eruption or earlier.

Introduction

Open- and closed-system degassing occurring during the century before an eruption can be monitored by measuring the relative activities of short-lived radionuclides, such as polonium-210 (^{210}Po; $t_{1/2}$ = 138.4 days), lead-210 (^{210}Pb; $t_{1/2}$ = 22.6 years), and radium-226 (^{226}Ra; $t_{1/2}$ = 1,599 years) in lavas. For example, Po partitions efficiently into exsolving volatile phases and commonly degasses from both mafic and silicic lavas, which results in (^{210}Po)/(^{210}Pb) << 1.0 in erupted lavas. Examples of lavas that have (^{210}Po)/(^{210}Pb) < 0.15 include those erupted from Etna (Lambert and others, 1985; Le Cloarec and Pennisi, 2001), Hawai‘i (Gill and others, 1985), Arenal (Gill and others, 1985; Reagan and others, 2006), Mount St. Helens in 1980 (Bennett and others, 1982), and Anatahan (Reagan and others, 2005). Excesses of ^{210}Po over ^{210}Pb have been observed in some phreatomagmatic tephras because of condensation of ^{210}Po from gases streaming through the shallow conduit system of a volcano before eruption (Reagan and others, 2005).

Radon-222 (^{222}Rn), which lies between ^{226}Ra and ^{210}Pb in the ^{238}U decay series and has a half-life of 3.82 days, strongly partitions into the gas phase (Gill and others, 1985), whereas about 99 percent of Pb stays within the melt (Gauthier and others, 2000). Nevertheless, significant deficits of ^{210}Pb with respect to ^{226}Ra have been observed in magmas with widely varying compositions. Such deficits can result from differential partitioning of these elements between coexisting mineral and melt phases (Williams and others, 1986; Gill and Williams, 1990; Condomines and others, 1995; Sigmarsson, 1996), and/or from persistent (year- to decade-scale) losses of ^{222}Rn by degassing (Gauthier and Condomines, 1999; Gauthier

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and others, 2000; Le Cloarec and Pennisi, 2001; Le Cloarec and Gauthier, 2003; Turner and others, 2004; Berlo and others, 2004). Deficits in (^{210}Pb) with respect to (^{226}Ra) in midocean-ridge basalts have been attributed to lower partition coefficients for Ra compared to Pb during magma generation (Rubin and others, 2005).

Although large excesses of ^{210}Pb with respect to ^{226}Ra have been reported at some arc volcanoes, including the 1980s lavas and tephras from Mount St. Helens (Berlo and others, 2004), (^{210}Pb/^{226}Ra) values for lavas erupting at many other arc volcanoes are within 2σ error of equilibrium when the error is propagated back to the age of eruption. These near-equilibrium lavas include the silicic andesite tephras erupted from Anatahan in 2004 (Reagan and others, 2005), basalts and andesites erupted from Klyuchevskoy and Bezymianny in Kamchatka (Turner and others, 2007), and most of the basaltic andesites that have erupted from Arenal since 1968 (Reagan and others, 2006). The frequency of near-equilibrium (^{210}Pb)/(^{226}Ra) values in lavas probably reflects the special circumstances needed to supply enough ^{222}Rn to accumulate significant ^{210}Pb excesses (Reagan and others, 2006).

The regular sampling of the ongoing eruption of Mount St. Helens by the U.S. Geological Survey has provided an exceptional suite of samples for applying ^{226}Ra-^{210}Pb-^{210}Po disequilibria to constrain the time scales of degassing and other magmatic processes that have occurred within the century before eruption. Silicic glass inclusions from lavas erupted at Mount St. Helens have as much as 6 weight percent H_2O (Blundy and Cashman, 2005), and degassing of this water has the potential to generate significant disequilibrium between these short-lived nuclides.

Samples and Analytical Procedures

Whole-rock powders analyzed here span the period of the ongoing eruption from October 2004 to December 2005. Most samples are solid juvenile dome samples, but the samples include the phreatomagmatic tephra erupted in October 4, 2004, and March 8, 2005, and two samples of the dome-coating gouge. All dome samples were collected within 2 months of venting at the surface. Other chapters in this volume describe the mineral contents, textures, and chemical compositions of the samples analyzed here in detail (Pallister and others, this volume, chap. 30; Thornber and others, this volume, chap. 32). Briefly, all juvenile samples are dacites with approximately 65 percent SiO_2, 1.4 percent K_2O, and FeO*/MgO ≈2. These samples are highly porphyritic, with approximately 50 percent plagioclase, 3–5 percent hornblende and orthopyroxene, and 1 percent or less each of magnetite and augite phenocrysts, typically in a microlite-choked groundmass. Gabbroic to granodioritic inclusions, some in varying stages of disaggregation, are present in varying amounts in the dacites. These inclusions were avoided in the sampling for this study.

The October 2004 tephra sample (MSH04E2A03_A2) consists of finely pulverized rock fragments, with a variety of mineral textures, reflecting sources for the particles in older Mount St. Helens rocks, as well as juvenile dacite (Rowe and others, this volume, chap. 29). This sample also had organic debris that was removed by hand picking before analysis. The March 2005 tephra sample (MSH05DRS_3_9_4) consisted entirely of fragmented young dome debris and had a high proportion of clasts with lengths from 2 to 6 mm. The coarseness of this sample allowed us to hand-pick fragments for additional fragmentation in a ceramic rotary-ring mill and analysis.

Dome sample preparation began by fragmentation to particle lengths of several millimeters to 2 cm. Unaltered fragments were hand picked for ultrasonic washing in purified water and coarse grinding in a ceramic rotary mill. Gouge sample SH307-2A was indurated, whereas SH314-1G consisted of a collection of particles ranging from silt to about 2 mm in length. The SH307-2A sample was broken up and then coarsely ground. Sample SH314-1G was not additionally comminuted. Except for the initial tephra sample and the first dome sample, all samples were leached with 0.5 N HCl for 10–15 minutes in an ultrasonic agitator, followed by centrifuging and rinsing and centrifuging twice in purified water. This was done to remove ^{210}Po that condensed on surfaces of cracks and vesicles, which proved crucial for determining the initial groundmass (^{210}Po) value.

Plagioclase was separated from sample SH304-2A using standard density and magnetic techniques after grinding and sieving to segregate particles between 170 mesh and 80 mesh. This separate was washed with a 0.5 N HCl–2 percent H_2O_2 mixture for 10 minutes, followed by washing in purified water before analysis.

Analytical techniques for ^{210}Po are discussed in detail elsewhere (Reagan and others, 2005; Reagan and others, 2006). Initial (^{210}Po) and (^{210}Pb) values and errors for samples were calculated using exponential regressions through multiple analyses employing a half-life for ^{210}Po of 138.4 days (Holden, 1990). Rock standard RGM-1 was analyzed six times over the period of analysis. The weighted mean (^{210}Po) value and standard deviation for these analyses are 4.20±0.04 (1σ) decays per minute per gram (dpm/g), which is similar to the measured values for (^{238}U) for this standard (Le Fevre and Pin, 2002). The concentrations of ^{226}Ra in samples discussed here are from Cooper and Donnelly (this volume, chap. 36).

Other Time-Series Data

The variation in major-element, trace-element, and long-lived radiogenic isotopic compositions for juvenile lavas from the ongoing eruption has been minimal (Pallister and others, this volume, chap. 30). However, (^{230}Th)/(^{238}U) values vary from 0.93 to 1.10 at a nearly constant Th isotopic composition in dome samples, which has been attributed to fractionation of U from Th during melting to generate the Mount St. Helens

dacites (Cooper and Donnelly, this volume, chap. 36). This Th isotopic composition is similar to the values measured for lavas erupted from Mount St. Helens in the middle 1980s, suggesting that there is a genetic link between the lavas. However, the Th isotopic compositions of plagioclase separates from lavas from the ongoing eruption range from 1.026 to 1.306 (whole-rock values are 1.26–1.28), and some of these values are different than any values measured for 1980s and 2004–5 lavas, indicating that an additional older magma component is involved in the ongoing eruption (Cooper and Donnelly, this volume, chap. 36). A wide range for the average ages of plagioclase mineral separates is supported by their (^{226}Ra)/(^{230}Th) values, which range from 1.51 for plagioclase from sample SH304-2A to 1.04 for a plagioclase from SH305-1 (Cooper and Donnelly, this volume, chap. 36).

^{210}Po-^{210}Pb-^{226}Ra disequilibria

Whole tephras erupted on October 4, 2004, were enriched in ^{210}Po over ^{210}Pb by more than a factor of 2, indicating that significant magmatic ^{210}Po had condensed in the shallow hydrothermal system before the phreatomagmatic explosions began (Reagan and others, 2005). This contrasts with tephras ejected during the phreatomagmatic explosions of March 8, 2005 (MSH05DRS_3_9_4), which were largely degassed of ^{210}Po when they erupted and had very little leachable ^{210}Po (table 1; fig. 1).

The first lavas ejected at the vent (for example, sample SH301-1A7, table 1) had a small excess of ^{210}Po over ^{210}Pb values and (^{210}Pb) that approximately matched (^{210}Pb) values for samples erupted in the 1980s. We interpret these data to indicate that this sample was rock excavated from the dome materials erupted in the 1980s that were in the vent area. The small excess of ^{210}Po for this sample was likely deposited in open spaces from fumarolic gases streaming through the vent area just before eruption. This observation was one of the first indications that this material was not juvenile 2004 material but was excavated from the 1980s dome (see Pallister and others, this volume, chap. 30).

All of the dome samples that were erupted and analyzed after sample SH301-1A7 represented new juvenile magma, and multiple analyses of leached samples produced radioactive equilibration curves that generally demonstrated complete degassing of ^{210}Po before eruption (fig. 1). Plagioclase crystals in sample SH304-2A had initial (^{210}Po) and (^{210}Pb) values of about 0.29 dpm/g (table 1). Assuming that plagioclase in all of the 2004–5 samples have this same (^{210}Po), that plagioclase crystals make up 50 percent of whole rock, and that other coarsely crystalline phases have near zero (^{210}Po), samples with groundmasses that are entirely degassed of ^{210}Po would have (^{210}Po)≈0.14 dpm/g. Therefore, the "no-Po" line on figure 1 is used to represent the approximate value of a whole rock whose groundmass had been entirely degassed of ^{210}Po.

Representative values of (^{210}Po) for whole rocks are compared with the values for leached samples in figure 2. In all cases, the whole-rock values exceed the leached values. For most samples, the values for unleached samples analyzed within two months of eruption are between 5 and 20 percent higher than for the leached samples. For sample SH305-1, the unleached values are more than 50 percent higher; for sample SH316-1A, these values are highly variable and as much as several times higher. These data indicate that a significant amount of ^{210}Po resides in open pore spaces, which indicates that a fraction of the ^{210}Po in all samples degassed into bubbles that never escaped from the magmas. This observation is important from an analytical point of view because it demonstrates the importance of leaching samples in dilute acid to obtain intrinsic ^{210}Po activities in lavas after all gas is lost from the magma. It also is important because it can allow the change from open- to closed-system degassing to be constrained temporally.

Nearly all dome whole-rock samples analyzed had initial (^{210}Po)/(^{210}Pb) ratios near the no-Po value when they vented. That is, the last day of complete degassing of ^{210}Po from the Mount St. Helens dacite, which is represented by the date of intersection of the ^{210}Po ingrowth curves with the no-Po line on figure 1, generally corresponds with their day of eruption within error of analysis and knowledge of eruption day (fig. 3). An exception to this is sample SH305-1, which erupted in mid-November 2004 but apparently had last degassed Po in September 2004.

Like the dome samples, the lithified gouge sample SH307-2A degassed ^{210}Po until the time that it vented to the surface. In contrast, the nonlithified gouge sample SH314-1G either ceased degassing ^{210}Po about a month before it erupted, or gas derived from underlying magma added ^{210}Po to this sample (fig. 3).

All of the calculated initial (^{210}Pb)/(^{226}Ra) values for whole rocks from the ongoing eruption are within 2σ analytical error of equilibrium (table 1). This is in marked contrast with samples erupted from Mount St. Helens in 1980, which had widely varying (^{210}Po)/(^{226}Ra) values (0.8 to 1.4) when they erupted (Berlo and others, 2004).

Discussion

^{210}Po-^{210}Pb Disequilibrium

The tephra sample ejected near the beginning of the ongoing eruption on October 4, 2004, was strongly enriched in ^{210}Po over ^{210}Pb, demonstrating that magmatic Po had condensed on surfaces in the pore space of the shallow fumarolic system shortly before eruption and had erupted along with the pulverized rock fragments. In contrast, the hand-picked tephra fragments erupted on March 8, 2005, during active dome building had low initial (^{210}Po) values, indicating that these fragments were mostly or entirely pieces of shallow dome material that had been emplaced about two weeks before their involvement in the phreatomagmatic explosions (fig. 3).

Table 1. Activities of ^{210}Po and initial (^{210}Pb)/(^{226}Ra) values for samples erupted in 2004–2005 from Mount St. Helens, Washington.

[Eruption day (month/day/year) from Pallister and others (this volume, chap. 30). Day of analysis is number of days after October 1, 2004. Initial (^{210}Pb) values calculated by regressing a best-fit radioactive equilibration curve through leached sample analyses. Values for (^{226}Ra) in dpm/g (disintegrations per minute per gram) from Cooper and Donnelly (this volume, chap. 36).]

Sample No.	Sample type	Eruption day	Analytical treatment	Analysis day	(^{210}Po) dpm/g	±1σ	(^{210}Pb)	(^{210}Pb)/(^{226}Ra)	±1σ
MSH04E2A03_A2	Tephra	10/4/04	whole	10	2.361	0.052	~1.17		
			whole	99	1.927	0.044			
			whole	134	1.806	0.041			
SH301-1A7	Dome	1980s	whole	30	1.191	0.026	1.04		
			whole	150	1.131	0.026			
			whole	559	1.043	0.025			
SH304-2A	Dome	10/18/04	whole	42	0.359	0.018	1.19	0.958	0.027
			whole	99	0.574	0.019			
			whole	126	0.642	0.030			
			whole	298	0.966	0.025			
			leached	126	0.593	0.021			
			leached	298	0.949	0.024			
			leached	369	1.015	0.024			
SH304-2A	Plagioclase	10/18/04	leached	66	0.298	0.010	0.29	4.4	0.1
			leached	188	0.285	0.011			
SH305-1	Dome	11/20/04	whole	99	0.907	0.024	1.17	1.023	0.039
			whole	112	0.845	0.040			
			whole	253	1.036	0.076			
			leached	112	0.621	0.021			
			leached	218	0.863	0.021			
			leached	253	0.913	0.025			
			leached	475	1.061	0.023			
			leached	475	1.084	0.024			
SH306	Dome	12/15/04	whole	126	0.384	0.014	1.15	0.974	0.031
			whole	141	0.486	0.015			
			whole	211	0.708	0.030			
			leached	141	0.445	0.014			
			leached	211	0.681	0.021			
			leached	396	0.938	0.021			
SH307-2A	Gouge	2/12/05	whole	159	0.288	0.030	1.17	1.038	0.033
			whole	218	0.487	0.023			
			leached	159	0.251	0.010			
			leached	218	0.464	0.015			
			leached	475	0.980	0.024			
SH311-1B	Ballistic fragment	1/16/05	whole	159	0.467	0.030	1.15	1.056	0.033
			leached	159	0.438	0.013			
			leached	216	0.611	0.019			
			leached	475	1.001	0.023			
MSH05DRS_3_9_4	Hand-picked clasts	3/8/05	whole	202	0.405	0.028	1.15	1.018	0.032
			leached	202	0.394	0.011			
			leached	483	0.982	0.025			
SH314-1G	Gouge	4/17/05	whole	211	0.360	0.043	1.13		
			leached	211	0.311	0.012			
			leached	396	0.810	0.020			
SH315-1	Dome	4/1/05	whole	211	0.370	0.070	1.13		
			leached	211	0.323	0.013			
			leached	396	0.812	0.020			
			leached	965	1.116	0.022			

Table 1. Activities of ^{210}Po and initial (^{210}Pb)/(^{226}Ra) values for samples erupted in 2004–2005 from Mount St. Helens, Washington.—Continued

[Eruption day (month/day/year) from Pallister and others (this volume, chap. 30). Day of analysis is number of days after October 1, 2004. Initial (^{210}Pb) values calculated by regressing a best-fit radioactive equilibration curve through leached sample analyses. Values for (^{226}Ra) in dpm/g (disintegrations per minute per gram) from Cooper and Donnelly (this volume, chap. 36).]

Sample No.	Sample type	Eruption day	Analytical treatment	Analysis day	(^{210}Po) dpm/g	±1σ	(^{210}Pb)	(^{210}Pb)/(^{226}Ra)	±1σ
SH316-1A	Dome	4/15/05	whole	253	3.642	0.121	1.14	1.028	0.033
			whole	465	1.617	0.076			
			leached	334	0.671	0.018			
			leached	559	0.968	0.024			
			leached	965	1.143	0.023			
SH317-1A	Dome	5/1/05	whole	290	0.543	0.019	1.11	0.973	0.031
			whole	465	1.005	0.068			
			leached	298	0.459	0.014			
			leached	483	0.846	0.022			
			leached	965	1.087	0.020			
MSH319-1	Dome	5/15/05	whole	298	0.534	0.013	1.14		
			whole	465	0.818	0.042			
			leached	298	0.428	0.011			
			leached	516	0.895	0.022			
			leached	978	1.122	0.022			

Although initial whole-rock ^{210}Po activities are variable for dacite lavas from Mount St. Helens, these activities drop to near zero in nearly all samples when ^{210}Po is removed from surfaces by leaching with dilute acid (table 1). Thus, like most other lavas (Gill and others, 1985; Lambert and others, 1985; Le Cloarec and Pennisi, 2001; Bennett and others, 1982; Reagan and others, 2006), the intrinsic initial ^{210}Po activities of Mount St. Helens dacites are near zero. The presence of significant ^{210}Po in pore spaces of the Mount St. Helens dacites implies that the magmas continued to partition ^{210}Po into the gas phase until the magmas arrived at the vent and cooled below the blocking temperature of ^{210}Po.

The activities of ^{210}Po in whole dacite samples were significantly more variable and higher on the day the samples vented to the surface compared with the activities of ^{210}Po in leached samples. These differences probably reflect variations in the depth at which magmas ceased being able to vent gas to their surroundings; that is, when degassing changed from being open-system to closed-system. For most samples, the initial quantity of ^{210}Po in pore spaces was small, which is consistent with closed-system degassing beginning no more than 1–2 weeks before eruption (fig. 2). At an eruption rate of 5–10 meters per day, which is the approximate ascent rate of magmas in the shallow conduit (LaHusen and others, this volume, chap. 16), this switch from open- to closed-system degassing must have typically occurred between about 35 and 150 meters depth, which is similar to the depth where magmas are becoming rheological solids (Moran and others, this volume, chap. 2). However, sample SH305-1, which is unaltered and significantly more vesicular and more glassy than other samples, had much higher leachable ^{210}Po values than less vesicular samples. This sample also has the greatest difference between its eruption day and last degassing day (fig. 3). Therefore, assuming that this sample's velocity was the same as the velocity for other dome dacites, sample SH305-1 might have begun closed-system degassing as much as 200 days before eruption (corresponding to 1–2 km depth) and ceased degassing altogether about 2 months before it erupted (corresponding to about 0.5 km depth). If these assumptions are correct, this dacite chilled deeper within the edifice than other dacites from the ongoing eruption, which also might explain why sample SH305-1 contains fewer groundmass crystals than other samples from the 2004–5 eruption (see Cashman and others, this volume, chap. 19).

One sample with exceptionally high leachable ^{210}Po was sample SH316-1A, which had a whole rock (^{210}Po)/(^{210}Pb) value significantly greater than unity when it erupted. This sample had significant orange staining on fracture surfaces; although these surfaces were avoided during hand picking before analysis, extraneous ^{210}Po from underlying magmas appears to have been deposited heterogeneously in pore spaces throughout this sample. Nevertheless, this extraneous Po did not diffuse into the magma or solidified dacite, because the eruption and Po-degassing dates for sample SH316-1A are within error of each other.

Like the whole-dome samples, the lithified gouge sample SH307-2A degassed ^{210}Po approximately until the day that it vented. Thus, despite its position along the conduit walls, where it quenched to a solid and was ground to gouge, this sample maintained a temperature that was high enough for ^{210}Po to degas completely until it vented. The loose gouge sample SH314-1G appears to have cooled below the ^{210}Po

blocking temperature about a month before eruption, which corresponds to a depth of about 150–300 m below the surface.

^{210}Pb-^{226}Ra Equilibrium

As demonstrated above, the dacites from the ongoing eruption of Mount St. Helens reach the surface nearly degassed of ^{210}Po. Nevertheless, all lavas from the ongoing eruption had near-equilibrium (^{210}Pb)/(^{226}Ra) values when they erupted. Both because ^{222}Rn is a noble gas and because ^{210}Po appears to partition entirely into the gas phase at magmatic temperatures at Mount St. Helens, we assume that ^{222}Rn also strongly partitions from magma into a separate gas phase. If so, then the lack of a measurable ^{210}Pb deficit indicates that open-system degassing of dacites erupting at Mount St. Helens must be confined to the time period between about 1–2 years (the minimum time to produce a measurable ^{210}Pb deficit) before eruption and the start of closed-system degassing near the surface. These equilibrium values also indicate that the lavas from the ongoing eruption did not experience persistent streaming of ^{222}Rn from large volumes of underlying magma, which contrasts with lavas and tephras erupted from Mount St. Helens in 1980 (compare Berlo and others, 2004). Finally, these equilibrium (^{210}Pb)/(^{226}Ra) values indicate that the melting processes that created ^{226}Ra excesses over ^{230}Th (and probably ^{210}Pb) in all of the dacites from the ongoing eruption (Cooper and Donnelly, this volume, chap. 36), as well as the majority of plagioclase fractionation, occurred more than a century before eruption.

The contrast between the lack of (^{210}Pb)/(^{226}Ra) disequilibria during this eruption and the significant disequilibria encountered in samples from the eruption in 1980 (Berlo and others, 2004) is noteworthy. This difference is in stark contrast to Li concentration data, which indicate that plagioclase is enriched in Li at the beginning of both eruptions (compare Berlo and others, 2004; Kent and others, 2007) compared with subsequently erupted samples. The Li data suggest that a Li-enriched fluid pervasively infiltrated the first-erupted magmas and raised Li concentrations in plagioclase through

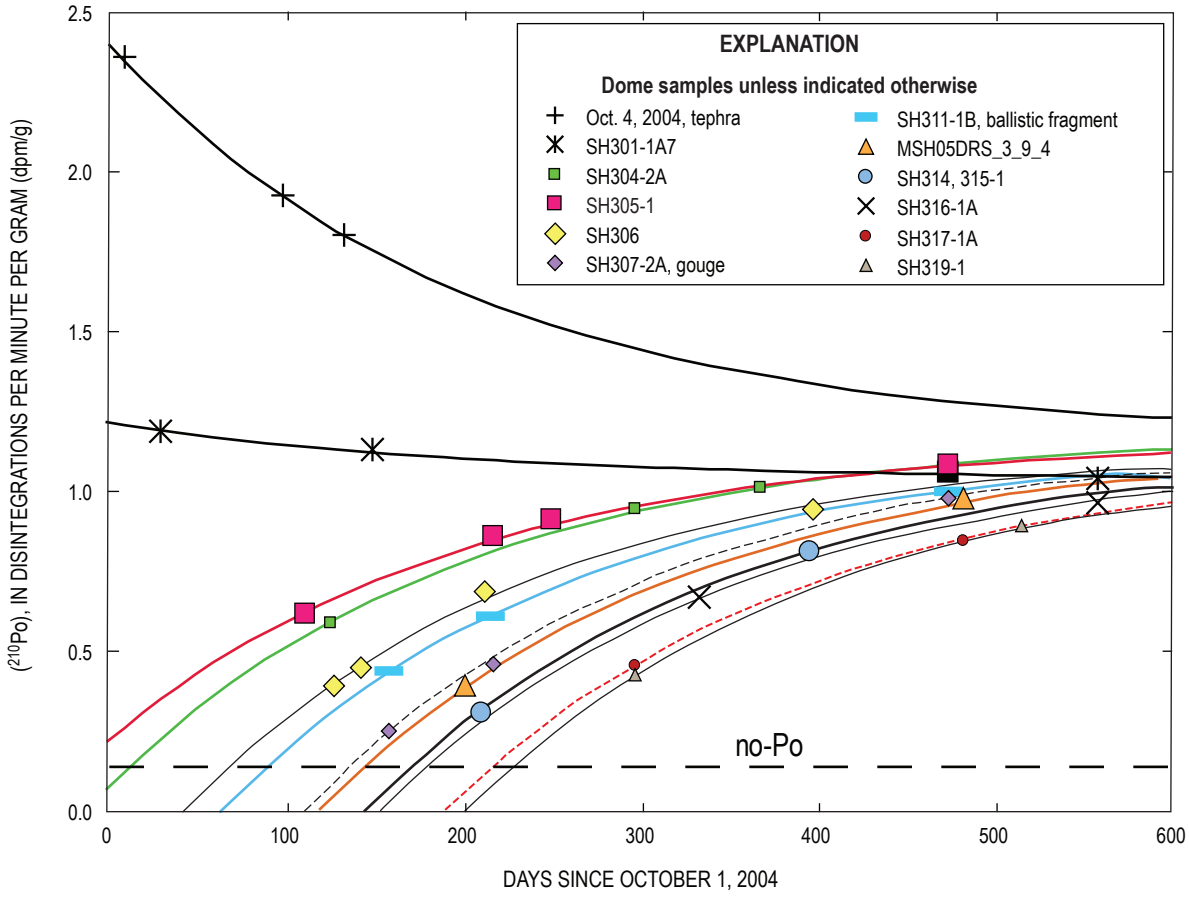

Figure 1. Plot of ^{210}Po activities for leached samples recently erupted from Mount St. Helens, Washington. ^{210}Po ingrowth curves drawn by choosing the day when (^{210}Po) = 0 and the initial (^{210}Pb) value that produced best-fit line through data points for each sample. The "no Po" line represents the approximate whole-rock value when groundmass was entirely degassed of ^{210}Po. Analyses completed more than 600 days after October 1, 2004, are not shown, although they were used to determine the best-fit ingrowth curves. See text for further explanation.

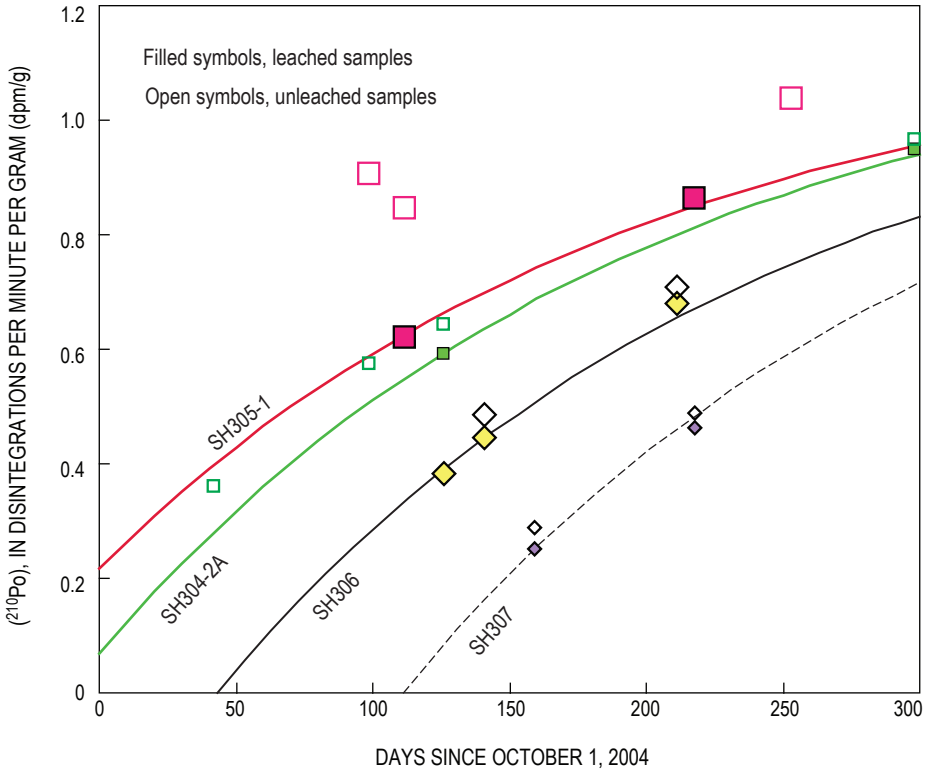

Figure 2. Plot of ^{210}Po activity versus date of analysis in days after Oct. 1, 2004, for representative whole-rock powders from Mount St. Helens, Washington, before (open symbols) and after (filled symbols) leaching (symbols match those in figure 1).

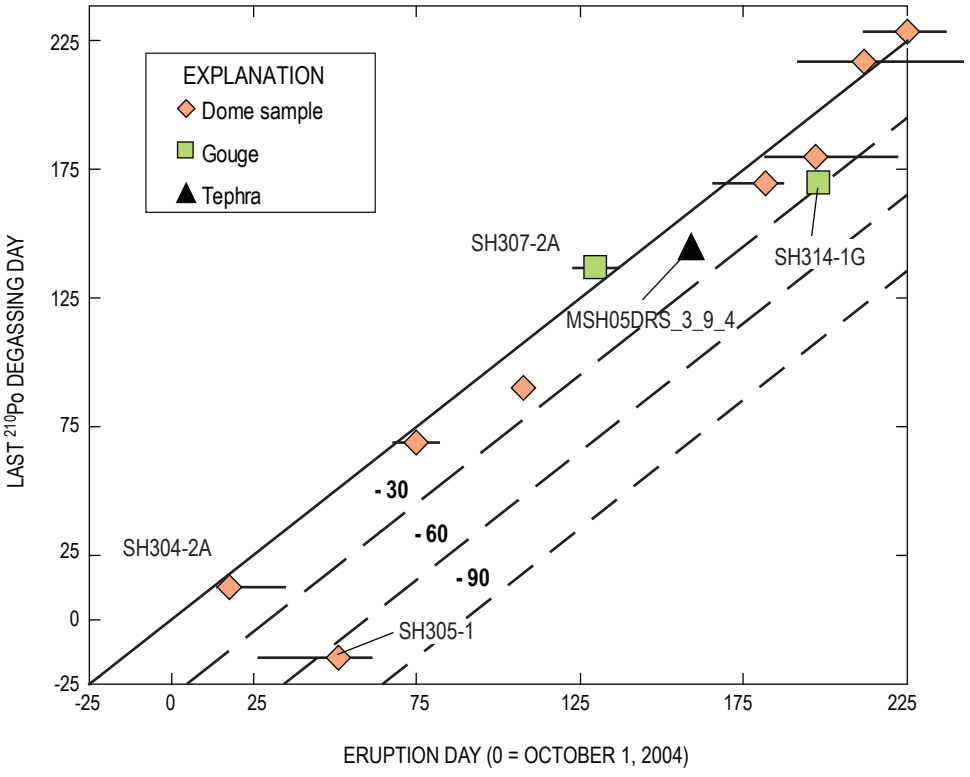

Figure 3. Plot of the last day of ^{210}Po degassing (date of intersection of ^{210}Po ingrowth curves with no-Po line on figure 1) versus the date of eruption for samples from the ongoing eruption of Mount St. Helens, Washington. Numbers for samples mentioned in the text are shown. Symbols show best guess for a sample's eruption date, and lines indicate the range of potential eruption dates. The solid diagonal line marks equivalent last ^{210}Po degassing day and eruption day (^{210}Po ceases degassing on eruption day). Dashed lines show calculated effect if ^{210}Po ceased degassing 30, 60, or 90 days before eruption. Note that most samples of all types degas ^{210}Po by closed- or open-system processes until the magmas are within two weeks of arriving at the surface.

diffusion, whereas this fluid either did not infiltrate subsequent magmas for both eruptions, or it did so for too short a time to affect Li concentrations in plagioclase (Kent and others, 2007). The ^{210}Pb enrichment found in the cryptodome and pumice samples erupted in 1980 was attributed to a Rn flux accompanying the Li flux (Berlo and others, 2004). If so, and if the ^{222}Rn excess required to ingrow ^{210}Pb also was associated with Li-bearing fluid for the current eruption, then this fluxing must have occurred during a much shorter time period before the current eruption than was the case in 1980 (Kent and others, 2007). An alternative possibility is that the ^{222}Rn flux required for the high (^{210}Pb)/(^{226}Ra) values in the 1980 magmas was separate from the Li-bearing fluid. In that case, the ^{222}Rn flux may have been associated with the order-of-magnitude higher rates of gas emission in 1980 compared with emission rates of the ongoing eruption (Gerlach and others, this volume, chap. 26).

The plagioclase mineral separate from sample SH304-2A has (^{210}Po)/(^{210}Pb)≈1, indicating that very little of this plagioclase grew within 1–2 years before eruption. However, comparing the (^{210}Pb) value with the (^{226}Ra) value reported in Cooper and Donnelly (this volume, chap. 36) gives a (^{210}Pb)/(^{226}Ra) value of about 4.4, indicating that a significant proportion of the plagioclase crystals in this lava grew within several decades of eruption. Assuming t=850°C and an average plagioclase An value of 0.5, the D_{Pb}/D_{Ra} value in plagioclase would have been about 9.3 based on the lattice strain method of Blundy and Wood (1994) to calculate D_{Ra} and the partitioning model of Bindeman and others (1998) to calculate D_{Pb}. Reconciling the (^{210}Pb)/(^{226}Ra) values and D_{Pb}/D_{Ra} values produces a model average age of the plagioclase in the mineral separate of about 30 years. Cooper and Donnelly (this volume, chap. 36) show that this plagioclase mineral separate has a (^{226}Ra)/(^{230}Th) value similar to that of the whole rock but a Th isotope ratio that is less than that of the whole rock by about 25 percent. These data were interpreted to suggest that 60–80 percent of the plagioclase is "zero-age" and the rest is older than 10 ka. Assuming that 70 percent of the plagioclase is young and that it grew in a single pulse, the (^{210}Pb)/(^{226}Ra) ratio in the newly grown material would have been about 5.9, which gives a model age of about 17 years, consistent with a large proportion of the plagioclase growing at about the time of the 1980–86 eruption.

Conclusions

1. Leaching of powdered whole-rock samples by dilute acid to remove ^{210}Po deposited in pore spaces is necessary to allow measurement of magmatic ^{210}Po values.

2. ^{210}Po degasses from lavas associated with the ongoing eruption of Mount St. Helens until they vent at the surface. The change from open- to closed-system degassing generally occurs within 150 m of the surface, which is about the depth at which the exterior dome samples become solid. Nevertheless, closed-system degassing began as deep as 1–2 km for some magmas.

3. Our sample of indurated gouge, collected from the surface of the lava dome, continued to degas ^{210}Po until it reached the surface, whereas our sample of loose, more interior gouge appears to have ceased degassing ^{210}Po at a depth of 150–300 m.

4. Magmas erupted in 2004–5 from Mount St. Helens were generated and underwent differentiation more than a century before eruption on the basis of equilibrium (^{210}Pb)/(^{226}Ra) values, but less than a few thousand years before eruption on the basis of disequilibrium (^{226}Ra)/(^{230}Th) values (see Cooper and Donnelly, this volume, chap. 36).

5. The near-equilibrium (^{210}Pb)/(^{226}Ra) ratios for all of the dacites erupted in 2004–5 from Mount St. Helens suggest that the last stage of open-system degassing of these magmas was confined to the time period between about a year before eruption and the start of closed-system degassing near the surface. These values further indicate that persistent streaming of excess ^{222}Rn gas through the magmas did not occur before this eruption, despite Li enrichments observed in plagioclase erupted in October and November 2004 (Kent and others, 2007).

6. The combined dataset of short- and long-lived U-series nuclides suggests that a significant proportion of the coarse plagioclase in a sample erupted in November 2004 grew at about the time of the 1980s eruptions of Mount St. Helens, and not during this last stage of magma rise and degassing.

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References Cited

Bennett, J.T., Krishnaswami, S., Turekian, K.K., Melson, W.G., and Hopson, C.A., 1982, The uranium and thorium decay series nuclides in Mt. St. Helens effusives: Earth and Planetary Science Letters, v. 60, no. 1, p. 61–69.

Berlo, K., Blundy, J., Turner, S., Cashman, K., Hawkesworth, C., and Black, S., 2004, Geochemical precursors to volcanic activity at Mount St. Helens, USA: Science, v. 306, p. 1167–1169.

Blundy, J., and Cashman, K., 2005, Rapid decompression-driven crystallization recorded by melt inclusions from Mount St. Helens volcano: Geology, v. 33, no. 10, p. 793–796, doi:10.1130/G21668.1.

Cashman, K.V., Thornber, C.R., and Pallister, J.S., 2008, From dome to dust; shallow crystallization and fragmentation of conduit magma during the 2004–2006 dome extrusion of Mount St. Helens, Washington, chap. 19 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Condomines, M., Tanguy, J.-C., and Michaud, V., 1995, Magma dynamics at Mt Etna; constraints from U-Th-Ra-Pb radioactive disequilibria and Sr isotopes in historical lavas: Earth and Planetary Science Letters, v. 132, p. 25–41.

Cooper, K.M., and Donnelly, C.T., 2008, ^{238}U-^{230}Th-^{226}Ra disequilibria in dacite and plagioclase from the 2004–2005 eruption of Mount St. Helens, chap. 36 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Gauthier, P.-J., and Condomines, M., 1999, ^{210}Pb-^{226}Ra radioactive disequilibria in recent lavas and radon degassing; inferences on the magma chamber dynamics at Stromboli and Merapi volcanoes: Earth and Planetary Science Letters, v. 172, p. 111–126.

Gauthier, P.-J., Le Cloarec, M.-F., and Condomines, M., 2000, Degassing processes at Stromboli volcano inferred from short-lived disequilibria (^{210}Pb-^{210}Bi-^{210}Po) in volcanic gases: Journal of Volcanology and Geothermal Research, v. 102, p. 1–19.

Gerlach, T.M., McGee, K.A., and Doukas, M.P., 2008, Emission rates of CO_2, SO_2, and H_2S, scrubbing, and preeruption excess volatiles at Mount St. Helens, 2004–2005, chap. 26 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Gill, J., Williams, R., and Bruland, K., 1985, Eruption of basalt and andesite lava degasses ^{222}Rn and ^{210}Po: Geophysical Research Letters, v. 12, p. 17–20.

Holden, N.E., 1990, Total half-lives for selected nuclides: Pure and Applied Chemistry, v. 62, p. 941–958.

Kent, A.J.R., Blundy, J., Cashman, K.V., Cooper, K.M., Donnelly, C., Pallister, J.S., Reagan, M., Rowe, M.C., and Thornber, C.R., 2007, Vapor transfer prior to the October 2004 eruption of Mount St. Helens, Washington: Geology, v. 35, no. 3, p. 231–234, doi:10.1130/G22809A.1.

LaHusen, R.G., Swinford, K.J., Logan, M., and Lisowski, M., 2008, Instrumentation in remote and dangerous settings; examples using data from GPS "spider" deployments during the 2004–2005 eruption of Mount St. Helens, Washington, chap. 16 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume) .

Lambert, G., Le Cloarec, M.F., Ardouin, B., and Le Roulley, J.C., 1985, Volcanic emission of radionuclides and magma dynamics: Earth and Planetary Science Letters, v. 76, p. 185–192.

Le Cloarec, M.-F., and Gauthier, P.-J., 2003, Merapi volcano, central Java, Indonesia; a case study of radionuclide behavior in volcanic gases and its implications for magma dynamics at andesitic volcanoes: Journal of Geophysical Research, v. 108, no. B5, doi:10.1029/2001JB001709, 14 p.

Le Cloarec, M.-F., and Pennisi, M., 2001, Radionuclides and sulfur content in Mount Etna plume in 1983–1995: new constraints on the magma feeding system: Journal of Volcanology and Geothermal Research, v. 108, nos. 1–4, p. 141–155, doi:10.1016/S0377-0273(00)00282-1.

Le Fevre, B., and Pin, C., 2002, Determination of Zr, Hf, Th and U by isotope dilution and inductively coupled plasma-quadrupole mass spectrometry after concomitant separation using extraction chromatography: Geostandards Newsletter, v. 26, p. 161–170.

Moran, S.C., Malone, S.D., Qamar, A.I., Thelen, W.A., Wright, A.K., and Caplan-Auerbach, J., 2008, Seismicity associated with renewed dome building at Mount St. Helens, 2004–2005, chap. 2 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Pallister, J.S., Thornber, C.R., Cashman, K.V., Clynne, M.A., Lowers, H.A., Mandeville, C.W., Brownfield, I.K., and Meeker, G.P., 2008, Petrology of the 2004–2006 Mount St. Helens lava dome—implications for magmatic plumbing and eruption triggering, chap. 30 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Reagan, M., Tepley, F.J., III, Gill, J.B., Wortel., M., and Hartman, B., 2005, Rapid time scales of basalt to andesite differentiation at Anatahan volcano, Mariana Islands: Journal of Volcanology and Geothermal Research, v. 146, nos. 1–3, p. 171–183, doi:10.1016/j.jvolgeores.2004.10.022.

Reagan, M.K., Tepley, F.J., III, Gill, J.B., Wortel., M., and Garrison, J., 2006, Timescales of degassing and crystallization implied by ^{210}Po-^{210}Pb-^{226}Ra disequilibria for andesitic lavas erupted from Arenal volcano: Journal of Volcanology and Geothermal Research, v. 157, p. 135–146, doi:10.1016/j.jvolgeores.2006.03.044.

Rowe, M.C., Thornber, C.R., and Kent, A.J.R., 2008, Identification and evolution of the juvenile component in 2004–2005 Mount St. Helens ash, chap. 29 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Rubin, K.H., van der Zander, I., Smith, M.C., and Bergmanis, E.C., 2005, Minimum speed limit for ocean ridge magmatism from ^{210}Pb-^{226}Ra-^{230}Th disequilibria: Nature, v. 437, p. 534–538.

Sigmarsson, O., 1996, Short magma residence time at an Icelandic volcano inferred from U-series disequilibria: Nature, v. 382, p. 440–442.

Thornber, C.R., Pallister, J.S., Lowers, H.A., Rowe, M.C., Mandeville, C.W., and Meeker, G.P., 2008, Chemistry, mineralogy, and petrology of amphibole in Mount St. Helens 2004–2006 dacite, chap. 32 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Turner, S., Black, S., and Berlo, K., 2004, ^{210}Pb-^{226}Ra and ^{228}Ra-^{232}Th systematics in young arc rocks: Earth and Planetary Science Letters, v. 227, p. 1–16.

Turner, S., Sims, K.W.W., Reagan, M., and Cook, C., 2006, A ^{210}Pb-^{226}Ra-^{230}Th-^{23}8U study of Klyuchevskoy and Bezymianny volcanoes, Kamchatka: Geochimica et Cosmochimica Acta, v. 71, p. 4771-4785, doi:101016/j.gca.2007.08.006.

Williams, R.W., Gill, J.B., and Bruland, K.W., 1986, Ra-Th disequilibria systematics; timescale of carbonatite magma formation at Oldoinyo Lengai volcano, Tanzania: Geochimica et Cosmochimica Acta, v. 50, p. 1249–1259.