Obtaining High-Resolution Chronologies of Submarine Lava Eruptions: Better Dating Through Radiochemistry

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Seafloor volcanic eruptions can be wonderfully useful events, providing windows to study magmatic, hydrothermal, and biological processes in the crust and opportunities to observe punctuated changes in deep-sea environments and ecosystems, which is one basis for Ridge 2000 Time Critical Studies. Because eruption-related phenomena tend to be highly transient, with most signals decaying over days to months, we will describe here how the community can best take advantage of radiometric techniques to date eruptions.

Two issues plague the time-critical studies of submarine eruptions: (1) detecting events and (2) establishing chronologies for detected or suspected events. At the University of Hawai'i, we have successfully used radiometric methods for dating lavas as one means to establish eruption chronologies, including a recent eruption in 2003 at 10°44'N on the EPR [*Voight et al.,* 2004]. We discuss our experience to illustrate the limitations and logistical constraints on the application of radiochemistry to this problem. Our goal in this article is to alert the community that the capability exists, and to pass along information that will maximize the quality of results when the next opportunity arises.

Submarine Eruptions—When did they occur?

It is difficult to detect volcanic eruptions on the global submarine ridge system, and trickier still to obtain observations immediately following one [e.g., see review in *Perfit and Chadwick,* 1998]. Historically, such eruptions have either been detected acoustically [e.g., *Fox et al.,* 1995] or by fortuitous arrival of research teams at a recent eruption site [e.g., *Haymon et al.,* 1993]. In either case, rock radiometric dating can establish high-resolution eruption chronologies, which are particularly useful for interpreting subsequent evolution of the volcanic system and related environmental changes. In addition, for eruptions not detected acoustically, radiometric dating provides an unambiguous means to confirm if and when a suspected eruption occurred.

During a November 2003 biological sampling visit to the EPR at 10°44'N [*the FIELD cruise, J. Voight, PI*], *Alvin* divers expected to be revisiting an established hydrothermal vent field. Instead, they found fresh rock, bacterial mats, and diffuse snow blower vents issuing from lava collapses, and they suspected a recent eruption [*Voight et al.,* 2004]. Not sure of how "old" the event was, the science team acted quickly after the cruise to send our Hawai'i group lava samples for dating. We determined that an eruption had occurred within 1 to 2 months prior to their visit to the site, which is in the midst of the 8-11°N ISS [*van der Zander et al.,* 2004]. This area has been covered by the N-EPR hydrophone array since 1996, which is not monitored in real time, and unfortunately, no data was recorded during the 2002-2004 deployment due to a hardware glitch (Bob Dziak, pers. comm., 2004). Although we have missed an opportunity to compare the two records, the serendipitous eruption discovery and radiometric dating provided the first opportunity to study such an event at a magmatically starved fast-spreading ridge crest.

Radiometric Lava Dating Methods, Timescales, and Resolution

Ages for lavas erupted within the past 1.5 to 2 yrs can be determined with the ^{210}Po-^{210}Pb dating method [*Rubin et al.,* 1994]. To use this method, analyses should begin as soon as logistically possible after samples are collected from suspected eruption locales. Radioactive disequilibrium is largest and temporal resolution of the method is highest immediately following eruption.

Here is how the dating system works: Polonium is volatile at magmatic temperatures and degasses from magmas when they erupt. This creates an initial ^{210}Po (half life=138.4 day) deficit relative to grand parental ^{210}Pb in freshly erupted magmas (Figure 1). This deficit is subsequently erased with time via radioactive ingrowth toward secular equilibrium. Repeated analyses of ^{210}Po are conducted by alpha-spectrometry of a dissolved sample solution over 1 to 1.5 yrs, and the eruption age is determined by best-fit regression to a radioactive ingrowth curve. Dating resolution depends on a clock that starts with eruption and winds down in just a couple of years. Errors from extent of initial Po degassing and how well spaced analyses are on the ingrowth curve are explained in the Figure 1 caption. In essence, the sooner after eruption analysis begins (a function of sampling infrastructure availability, sample processing speed, and luck), the better the ingrowth regression is. Sample requirements are described below.

The ^{210}Po-^{210}Pb dating method was originally developed in response to unprecedented biological and volcanological observations by submersible divers at 9°50'N on the EPR in 1991 [*Haymon et al.,* 1993]. Since then, it has been applied successfully to eruptions on the EPR, Gorda Ridge, Loihi Seamount, Boomerang Seamount (SE Indian Ridge), and Rota seamount in the Marianas [*Rubin et al.,* 1998; *Garcia et al.,* 1998; *Johnson, et al.,* 2000; *van der Zander et al.,* 2004]. Temporal resolutions of these results have been variable (<2 to 3 months), largely related to when analyses were begun relative to the eruption date.

The Gorda and Loihi studies were responses to seismically detected eruptions (Gorda by SOSUS and Loihi by the USGS seismic net on land at nearby Kilauea volcano). Thanks to NSF support provided with

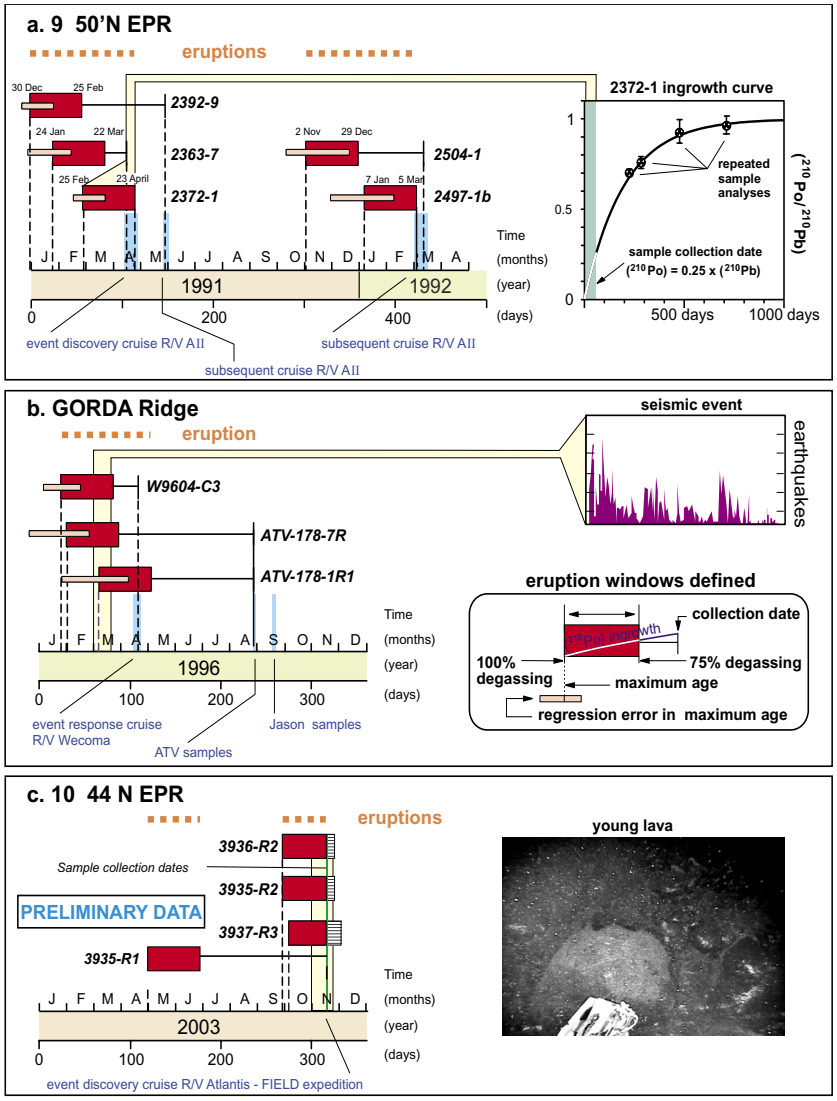

Fig. 1. ^{210}Po-^{210}Pb dating results from 3 eruptions on the EPR and Gorda Ridges. Ages are given as eruption windows (black bars), which represent unavoidable uncertainty in the extent of initial Po degassing. Heavy dashed lines show likely eruption intervals. Po is completely degassed upon eruption at subaerial and shallow submarine volcanoes [see review by *Rubin,* 1997]. We are not certain this occurs at oceanic depths of 2-3 km, so we report an "eruption window" based on a conservative minimum degassing estimate and 100% degassing. The 2-month window we currently report is based on observations at 9°50'N EPR (panel a), although the still preliminary data from 10°44'N EPR (panel c) may allow us to narrow eruption window widths because 3 of 4 samples were >75% degassed of Po upon sample collection. Errors in maximum age (gray horizontal bars) reflect data regression and analytical errors (see the eruption window inset). Sample collection dates are depicted by a --I, coinciding with cruises to those areas (vertical gray bars). Absolute and relative times are given at the base of the plot. Note the difference in error on maximum ages for Gorda samples taken in April and August 1996 (ages overlap for all samples in panel B but early sampling led to much higher resolution ages). The young lava flow image is a video frame grab from *Alvin* dive 3935 of the FIELD expedition [*provided by Robert Zierenberg*]. An example ingrowth curve and the seismic record that led to the Gorda event response are also shown, tied to calendar time and sample ages.

record-breaking speed, response cruises to these events were mounted within weeks, and fresh lava samples were recovered for ^{210}Po-^{210}Pb dating. The Gorda radiometric dates fell within the detected dates of the seismic swarm, but at Loihi seamount (Hawaii), dating showed that lavas were erupted several months before the seismically detected event, which formed a new pit crater on the summit and brecciated the young lava flow.

The other studies came about from fortuitous arrival of research teams at recent eruption sites. In each case, shipboard scientists insightfully interpreted seafloor or near bottom observations as probable indicators of a submarine eruption. Since none of these events were detected remotely, the subsequent radiometric age dates provided the only quantitative eruption timing data.

Collectively, these studies indicate that ^{210}Po-^{210}Pb dating can do more than confirm visually based indications of suspected eruptions. At 9°50'N EPR, for example, we also documented in the same area two discrete eruptive events separated by about 6 to 12 months [*Rubin et al.,* 1994; see Figure 1]. The radiometric eruption dates are consistent with rapid changes in vent water chemistry seen in time-series analyses, including a reset of the system in early 1992 [*Von Damm et al.,* 1995].

A similar story of prolonged eruption is emerging from work still in progress on the 2003 eruption at 10°44'N EPR, where the time between eruption and first sample analysis is so short that we may get the highest resolution dates yet [*van der Zander et al.,* 2004].

We also employ a second, lower-resolution dating approach, which does not require rapid-response sampling. It uses ^{210}Pb-^{226}Ra radioactive disequilibria (half life = 22 yrs) to date eruptive events over the past century at decadal to semi-decadal resolution [*Rubin et al.,* 2001; *Bergmanis,* 2003; *van der Zander et al.,* 2003]. This method is useful for determining eruption recurrence intervals (e.g., at recent eruption sites by comparing the youngest lava and samples of antecedent lava flows). Unlike ^{210}Po-^{210}Pb where the clock is set by eruption, ^{210}Pb-^{226}Ra radioactive disequilibria are petrogenetic. This and the generally small radioactive disequilibria in MORB (<15%) add to the uncertainty.

How To Obtain Dates, and Associated Costs

Because of the short half-life, ^{210}Po-^{210}Pb dating should be considered for at least 1-3 samples as soon as suspected lava flows are sampled. ^{210}Po dating is a race against the clock and each delay (avoidable or not) takes resolution away from resulting dates. Any radiometric counting

facility should be able to conduct the analyses for ^{210}Po-^{210}Pb dating. Each eruption is different (timing, sampling, sample composition), but it is generally best for investigators who are thinking of having some dating work done to contact their laboratory of choice as soon as possible to plan for the work, so that sample condition, quantity, and transportation logistics can be discussed. At present, the SOEST Isotope Laboratory at the University of Hawai'i, with funding from NSF-MGG, can provide the radiometric dating to PIs at no charge. For almost 8 years, NSF-MGG has funded radiometric dating analyses via the RREADI (Recent Ridge Eruptions And Dating Investigations) and RREADI-2 projects. As a result, the SOEST Isotope lab has in place the infrastructure and prior experience needed to achieve a quality date in short turnaround. NSF-MGG has indicated a preference to fund analyses on a case-by-case basis via supplements to existing projects, a method we have recently used to date 4 lavas from the 10°44'N EPR event.

Analytical Details for Radiological Assays and Sample Requirements

Glass samples to be dated can be chipped from rock fragments or sent to the lab still attached to the rocks. In the SOEST lab, we dissolve 2-5 grams of microscopically inspected clean (unaltered-phenocryst free) normal MORB glass for a complete high-resolution assay. It is easiest and fastest to pick glass from a large sample pool (~25 grams). Our experience is that adequate material can be picked from a very fresh MORB sample in ~2-3 weeks. Sample prep and analyses are conducted in our clean laboratory. Minimal sample cleaning and handling outside of such a lab is preferable. Material for analysis can be rinsed in de-ionized or millipore water and dried at <75°C, but other common shipboard and/or lab-based sample "cleaning" methods for petrologic analysis (water or acid washing in sonic baths) should be avoided. If enough sample is available, it is useful to make additional U-series analyses (^{238}U-^{230}Th-^{226}Ra-^{210}Pb-^{232}Th) by thermal ionization mass spectrometry, and to apply the ^{210}Pb-^{226}Ra chronometer, which uses the longer-lived isotopes to measure petrogenetic timescale variations and seawater alteration signatures. At SOEST, these analyses are conducted on the same glass dissolutions as the ^{210}Po analyses and use about 25% of the total material.

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