A detailed Pb isotopic study of crustal contamination/assimilation: The Edgumbe volcanic field, SE Alaska

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Abstract—To better understand the process of crustal contamination/assimilation, 23 Pb isotopic compositions and 12 concentrations have been measured on lavas and basement rocks from the Edgumbe volcanic field, SE Alaska. Measured isotopic ratios have the following ranges: $^{206}\text{Pb}/^{204}\text{Pb} = 18.477\text{--}19.161$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.562\text{--}15.679$; $^{208}\text{Pb}/^{204}\text{Pb} = 38.17\text{--}38.85$. While the data form well-constrained linear arrays on Pb-Pb diagrams, no simple correlation exists with major element composition. Basaltic lavas (≤ 51 wt% SiO_2) are characterized by two isotopic groups. The olivine basalt ($\leq 48\%$ SiO_2) is more radiogenic than the plagioclase basalt (48–51%) which also shows more heterogeneity. In the silica range 52–55%, Pb isotopic ratios increase significantly but remain fairly constant in the range 55–70% SiO_2 . Lead concentrations vary from 1 ppm in the basalts to 7 ppm in the rhyodacites. Analyzed basement rocks are more radiogenic than any of the lavas ($^{206}\text{Pb}/^{204}\text{Pb} = 19.20$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.65$; $^{208}\text{Pb}/^{204}\text{Pb} = 38.86$). The Pb isotopic data are qualitatively consistent with the contamination process described by MYERS *et al.* (1984). However, because of fundamental differences in the mixing relations between the Sr system studied earlier and the Pb system, the new Pb data have revealed details of the process not apparent from the Sr data alone. In particular, it has been shown that the parent magma was more primitive than originally assumed, and that two contamination events are recorded in the lavas. The first event, involving a mafic parent and different crustal contaminants, produced the intermediate and siliceous hybrids in cupolas located above the main basaltic chamber. The types of country rock intruded as well as the degree of partial fusion achieved in individual cupolas controlled the range of hybrid compositions produced while the eruption sequence was determined by the order in which the cupolas were tapped. The second contamination event produced the plagioclase basalt, the most voluminous basaltic unit, by mixing the mafic parent with the olivine basalt, an independent, primary magma. Our results suggest crustal contamination models that assume bulk assimilation of crustal end members may be too simplistic.

INTRODUCTION

Pb ISOTOPIC DATA have been used extensively to study the origin and evolution of young volcanic rocks. Since their age precludes appreciable accumulation of radiogenic Pb, linear Pb-Pb arrays defined by young volcanics are generally interpreted as mixing lines connecting isotopically distinct end members and not as secondary isochrons (ARMSTRONG and COOPER, 1971). Two unique characteristics of the Pb system make it especially useful in unraveling the evolution of young volcanic suites. First, because the isotopic ratios plotted against each other (*i.e.*, $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ or $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$) have a common denominator (*i.e.*, ^{204}Pb), mixing curves are always straight lines (LANGMUIR *et al.*, 1978). In contrast, mixing curves on diagrams utilizing different isotopic ratios (*e.g.*, $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$) are straight only in very special cases. Secondly, the character of the mixing lines provides a direct means of estimating the end members involved (ARMSTRONG and COOPER, 1971). Because they must lie at the extremes of the arrays or along their extensions, possible end members are readily identifiable. An additional useful characteristic of the

Pb system combines the nature of its straight mixing lines with the fact that they are not influenced by fractionation. Mixing curves on the other plot that produces straight lines (*i.e.*, isotopic ratios versus reciprocal concentration) can be destroyed or modified by fractionation (FAURE, 1977; LANGMUIR *et al.*, 1978). Their interpretation is, therefore, more involved than that of Pb-Pb diagrams (BRIQUEU and LANCELOT, 1979; MYERS *et al.*, 1984). Because of these characteristics, Pb isotopic data are useful for studying igneous processes responsible for the generation of young volcanic suites. Accordingly, the lead isotopic signatures of very young volcanic rocks have been used to characterize mantle or crustal source heterogeneity, to identify different mantle sources, to understand crustal contamination of mantle-derived magmas as well as to place constraints on the sediment component involved in the generation of island arc magmas. Unfortunately, many of these studies have been regional in nature and often lack the detailed petrologic control required for the close examination of a particular process.

In an attempt to better understand crustal contamination, we have selected a single, well-studied volcanic center for a detailed lead isotopic investigation. In

particular, we were interested in determining the range of Pb isotopic values produced by basalt-crust interaction, the degree of coupling between lead and strontium isotopic systems during such a process as well as how crustal partial melts (*i.e.*, magma contaminants) varied. If magma contamination occurs by interaction between two silicate liquids, then coupling between the two isotopic systems should be complete and parent/mixture ratios derived independently from Pb and Sr systematics similar. Disagreement between these ratios would suggest a decoupling of the two isotopic systems and hence a more complex contamination process. Earlier studies (MYERS *et al.*, 1984) have also revealed a strong effect on hybrid strontium isotopic systematics by the behavior of Sr-rich (and Sr-poor) phases undergoing partial fusion. Because different crustal minerals control Pb and Sr concentrations, a Pb isotopic study should help determine how melting controls contaminant Pb concentrations and hence hybrid lava isotopic compositions.

THE EDGE CUMBE VOLCANIC FIELD

The Edgecumbe volcanic field is located in southeastern Alaska on the southern end of Kruzof Island (Fig. 1). Tectonically, the center occurs along the plate margin separating the North America and Pacific plates (TOBIN and SYKES, 1968). Except for two anomalous events (MILNE *et al.*, 1978), all the earthquakes along this boundary are consistent with movement of the Pacific plate northward along a transform fault extending from 49°N to almost 60°N (GAWTHROP *et al.*, 1973; CHANDRA, 1974; MILNE *et al.*, 1978). Consequently, neither the primary Edgecumbe magmas nor the compositional ranges of the volcanic suite could have been produced by subduction related processes.

FIG. 1. Location map of the Edgecumbe volcanic field and analyzed samples. After MYERS and MARSH (1981).

Lavas exposed in the Edgecumbe field range from basalts through rhyodacites, however, nearly 70% of the volcanics are basaltic and a compositional gap exists between the dacites and rhyodacites (BREW *et al.*, 1969; KOSCO, 1981; MYERS and MARSH, 1981). In the basaltic lavas, phenocryst phases consist of plagioclase and olivine whereas plagioclase, orthopyroxene and minor clinopyroxene are the primary phases in the intermediate and siliceous lavas. Phenocryst zoning is strong in the intermediate lavas, but nearly absent in the basalts and rhyodacites (KOSCO, 1981; MYERS and MARSH, 1981). Small granitic clasts occur in the volcanic ejecta (BREW *et al.*, 1969; MYERS and MARSH, 1981).

Chemically, the lavas, which are alumina-rich and lack an iron enrichment trend, range from 47 to 72 wt% SiO₂ (BREW *et al.*, 1969; KOSCO, 1981; MYERS and MARSH, 1981). With increasing silica, CaO, MgO, Al₂O₃ and FeO decrease while alkalis increase. Strontium increases from 155 ppm in the basalts to 370 ppm in an olivine andesite and then decreases to about 130 ppm in the most siliceous lavas. In contrast, Rb (1–70 ppm) and Ba (50–500 ppm) increase with silica content. Initial strontium isotopic ratios range from 0.70291 to 0.70410, however, no simple correlation with silica or other components exists (MYERS *et al.*, 1984). The two basaltic units have measurably different ⁸⁷Sr/⁸⁶Sr ratios (olivine basalt: 0.70322–0.70323; plagioclase basalt: 0.70291–0.70301). In the silica range 58–60 wt%, there are two ⁸⁷Sr/⁸⁶Sr groupings. One group has strontium isotopic ratios around 0.70370 while the other has considerably higher values (0.70400–0.70410). The rhyodacites are characterized by measurable isotopic variability. Lavas from the Shell Mountain cinder cone have uniform ratios averaging 0.70373. In contrast, volcanics from the vicinity of the Crater Ridge caldera are more variable. Samples from the caldera rim and its associated dome have relatively low values (0.70356–0.70363) when compared to those from the rhyodacitic domes directly to the east (0.70386). Unlike strontium, $\delta^{18}\text{O}$ increases steadily from a low in the plagioclase basalt (5.9‰) to a high in the rhyodacites (7.9‰, MYERS and MARSH, 1981). In the intermediate lavas, high $\delta^{18}\text{O}$ correlates with high ⁸⁷Sr/⁸⁶Sr, however, such a correlation is absent in the rhyodacites.

ANALYTICAL PROCEDURES

Samples chosen for study cover the petrographic and compositional range of the volcanics and were previously analyzed for major elements (MYERS and MARSH, 1981) and strontium isotopic compositions (MYERS *et al.*, 1984). Powders were acid washed in cold, quartz-distilled 0.5 N HCl and dissolved overnight in a 48% HF-16 N HNO₃ mixture using 5 ml Savillex containers. One gram of sample was used for isotopic composition determinations while 400–500 mg were dissolved for Pb concentration measurements. The lead fraction was separated using analytical grade 200 mesh anion exchange resin, 1 ml quartz columns and the HBr separation procedure. Total lead blanks measured during this study ranged from 1 to 2 ng. Given the

Pb concentrations measured (>0.7 ppm), blank corrections are within analytical error and, accordingly, have not been made. Isotopic ratios were measured using a 35 cm radius, 90° sector mass spectrometer, the silica gel-phosphate method of CAMERON *et al.* (1969) and zone refined rhenium filaments. Utilizing a two point linear interpolation between peaks, ratios were calculated at the ^{206}Pb peak. All measurements were made on a 1V range (largest peak at $\sim 80,000$ cps) using a $10^{11} \Omega$ resistor in the vibrating reed electrometer. Repeated cycling of the isotopic spectrum and the collection of between 50 and 60 ratios yielded internal precision of 0.05% or better for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$. Inter-run accuracy and precision were continually monitored by running CIT isotopic standard and performing duplicate analyses as well as analyzing USGS standard BCR-1. Nineteen analyses of CIT gave the following means: $^{206}\text{Pb}/^{204}\text{Pb} = 16.604 \pm 5$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.551 \pm 5$; $^{208}\text{Pb}/^{204}\text{Pb} = 36.15 \pm 2$ (2σ errors are standard errors of the mean). Normalization of our data to absolute CIT values (CATANZARO, 1967) yielded a per mass unit fractionation correction factor of 0.124%. Duplicate analyses (listed in Table 1) gave percent variations of 0.12, 0.18 and 0.20 for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$, respectively. Lead concentrations and isotopic compositions for the Edgumbe lavas as well as BCR-1 are reported in Table 1. Also presented in Table 1 are corresponding silica values and strontium isotopic ratios.

RESULTS

Although lead isotopic ratios show a range in values ($^{206}\text{Pb}/^{204}\text{Pb} = 18.477\text{--}19.161$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.562\text{--}15.679$; $^{208}\text{Pb}/^{204}\text{Pb} = 38.17\text{--}38.85$), no simple correlation exists with SiO_2 (Fig. 2). At low SiO_2 , two Pb isotopic groupings occur. The more radiogenic group is the olivine basalt (<48 wt% SiO_2). The other group, the plagioclase basalt of MYERS and MARSH (1981), has much lower values (*e.g.*, $^{206}\text{Pb}/^{204}\text{Pb} = 18.477\text{--}18.786$) and is the least radiogenic of the volcanic units. In contrast to $^{87}\text{Sr}/^{86}\text{Sr}$ (MYERS *et al.*, 1984), this petrographic unit is characterized by some Pb isotopic heterogeneity. These two basaltic units are also distinguished by differences in petrography and major element chemistry (MYERS and MARSH, 1981) as well as initial strontium isotopic ratios (MYERS *et al.*, 1984). The $^{87}\text{Sr}/^{86}\text{Sr}$ difference between these two units is in the same sense as the Pb isotopic variation (*i.e.*, the olivine basalt is more radiogenic). Pb isotopic ratios increase from those characteristic of the plagioclase basalt to more radiogenic values in

TABLE 1: LEAD ISOTOPIC COMPOSITIONS AND CONCENTRATIONS OF EDGUMBE LAVAS

Sample Number	SiO_2^1	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}^2$	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{208}\text{Pb}}{^{204}\text{Pb}}$	Pb (ppm)
ED-30	47.54	0.70323	18.989 $\pm$ 10	15.618 $\pm$ 9	38.60 $\pm$ 2	1.0
ED-25	48.81	0.70322	19.055 $\pm$ 13	15.656 $\pm$ 9	38.77 $\pm$ 2	
ED-44	48.8	0.70292	18.786 $\pm$ 8	15.592 $\pm$ 6	38.42 $\pm$ 1	
ED-48	49.5	0.70298	18.694 $\pm$ 19	15.565 $\pm$ 17	38.30 $\pm$ 1	
ED-43	49.6	0.70301	18.648 $\pm$ 7	15.573 $\pm$ 5	38.27 $\pm$ 1	
ED-33	49.77	0.70293	18.750 $\pm$ 16	15.622 $\pm$ 15	38.40 $\pm$ 3	
			18.760 $\pm$ 10	15.581 $\pm$ 9	38.41 $\pm$ 3	
		avg.	18.755	15.602	38.41	
ED-70	50.2	0.70299	18.477 $\pm$ 11	15.562 $\pm$ 8	38.17 $\pm$ 2	0.8
ED-47	51.02	0.70326	18.867 $\pm$ 13	15.602 $\pm$ 12	38.55 $\pm$ 4	
			18.864 $\pm$ 14	15.593 $\pm$ 12	38.46 $\pm$ 3	
			18.835 $\pm$ 9	15.592 $\pm$ 7	38.45 $\pm$ 2	
		avg.	18.855	15.596	38.49	
ED-55	52.04	0.70328	18.813 $\pm$ 19	15.598 $\pm$ 6	38.42 $\pm$ 2	2.6
567b	52.76	0.70351	19.006 $\pm$ 5	15.635 $\pm$ 3	38.69 $\pm$ 7	
725a	54.29	0.70358	18.945 $\pm$ 9	15.618 $\pm$ 8	38.61 $\pm$ 2	
ED-1	55.69	0.70405	19.148 $\pm$ 8	15.679 $\pm$ 7	38.85 $\pm$ 2	
			19.085 $\pm$ 9	15.620 $\pm$ 3	38.64 $\pm$ 2	
		avg.	19.117	15.650	38.75	
ED-130	55.45 ³	0.70410	19.158 $\pm$ 8	15.621 $\pm$ 11	38.77 $\pm$ 2	5.6
			19.161 $\pm$ 7	15.626 $\pm$ 3	38.78 $\pm$ 1	
		avg.	19.160	15.624	38.78	
ED-80	57.0	0.70402	19.058 $\pm$ 58	15.590 $\pm$ 43	38.71	4.7
ED-78	59.2	0.70407	19.096 $\pm$ 29	15.649 $\pm$ 19	38.70 $\pm$ 6	
			19.073 $\pm$ 12	15.618 $\pm$ 9	38.69 $\pm$ 3	
		avg.	19.085	15.634	38.70	
ED-20	58.48	0.70362	19.047 $\pm$ 9	15.626 $\pm$ 7	38.69 $\pm$ 2	1.8
ED-18	58.96	0.70373	18.965 $\pm$ 8	15.590 $\pm$ 6	38.57	
			18.971 $\pm$ 43	15.613 $\pm$ 24	38.74 $\pm$ 7	
		avg.	18.968	15.602	38.66	
723	61.36	0.70374	19.063 $\pm$ 9	15.621 $\pm$ 7	38.70 $\pm$ 2	
			19.042 $\pm$ 7	15.617 $\pm$ 4	38.67 $\pm$ 1	
		avg.	19.053	15.619	38.68	
ED-2	61.63	0.70363	18.998 $\pm$ 53	15.628 $\pm$ 47	38.65 $\pm$ 1	3.8
			18.981 $\pm$ 7	15.611 $\pm$ 6	38.58 $\pm$ 2	
		avg.	18.990	15.620	38.62	
ED-12	70.48	0.70356	19.065 $\pm$ 8	15.606 $\pm$ 6	38.64 $\pm$ 1	7.0
ED-8	70.60	0.70386	18.825 $\pm$ 6	15.558 $\pm$ 9	38.44 $\pm$ 2	7.1
ED-77	70.54	0.70372	19.086 $\pm$ 11	15.627 $\pm$ 10	38.73 $\pm$ 3	
ED-42	66.15	0.70529	19.202 $\pm$ 12	15.652 $\pm$ 8	38.86 $\pm$ 3	5.1
ED-139	62.10 ³		19.207 $\pm$ 11	15.650 $\pm$ 8	38.80 $\pm$ 2	
BCR1						
(750 mg)			18.850 $\pm$ 18	15.678 $\pm$ 17	38.85 $\pm$ 4	
(500 mg)			18.812 $\pm$ 12	15.630 $\pm$ 8	38.72 $\pm$ 2	12.3

1. From MYERS and MARSH (1981)

2. From MYERS *et al.* (1984)

3. MYERS (1984, unpub. data)

FIG. 2. Pb concentrations and isotopic ratios versus SiO_2 . Note the increase in isotopic ratios in the 52–54 wt% silica range and the relatively constant ratios for lavas with $\text{SiO}_2 > 55\%$. The intermediate lavas are characterized by variable Pb concentrations. Symbols: ●—olivine basalt, ○—plagioclase basalt, □—aphyric andesitic basalt, ■—porphyritic andesitic basalt, △—olivine andesite, ▲—pyroxene andesite, *—Shell Mountain hypersthene andesite, ⊕—Mount Edgecumbe hypersthene andesite, ▼—Cape Edgecumbe dacite, ◇—Crater Ridge rhyodacite, ◆—Shell Mountain rhyodacite. Petrographic units as defined by MYERS and MARSH (1981).

the intermediate and siliceous lavas (Fig. 2). These changes are most pronounced for $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$. In the silica range 52 and 55 wt%, $^{206}\text{Pb}/^{204}\text{Pb}$ increases from 18.8 to ~19.0 and $^{208}\text{Pb}/^{204}\text{Pb}$ from 38.4 to 38.6. Although $^{207}\text{Pb}/^{204}\text{Pb}$ also increases with silica, the increase is not as large. At silica contents greater than 55 wt%, the Pb isotopic compositions are fairly constant (e.g., all cluster around 19.0 for $^{206}\text{Pb}/^{204}\text{Pb}$ and 38.7 for $^{208}\text{Pb}/^{204}\text{Pb}$). This trend is different from that for $^{87}\text{Sr}/^{86}\text{Sr}$ versus SiO_2 (MYERS *et al.*, 1984). In the intermediate silica range (55–59%), lavas with both high (≥ 0.7040) and low (≤ 0.7038) strontium isotopic ratios occur. The more radiogenic lavas do have slightly higher Pb isotopic ratios but the difference between the two groups is not significant. Rhyodacites from the Crater Ridge caldera rim as well as from the Shell Mountain cinder cone (Fig. 1) have relatively high ratios whereas samples from the rhyodacitic dome immediately east of the caldera rim are less radiogenic (Fig. 2). Although the isotopic differences of the rhyodacites are also reflected by the strontium isotopes, this variation is

in the opposite sense (MYERS *et al.*, 1984). Despite these differences, there is a striking similarity between the Pb isotope-silica trends and that for $^{87}\text{Sr}/^{86}\text{Sr}$ (compare Fig. 2 to Fig. 5 of MYERS *et al.*, 1984).

On Pb-Pb diagrams, the Edgecumbe volcanics define linear trends that are terminated at the lower ends by the plagioclase basalt and at the upper ends by the olivine andesite (Fig. 3). Also plotting near the arrays' upper ends are the pyroxene and hypersthene andesites of the Shell Mountain region. All of these lavas are characterized by $^{87}\text{Sr}/^{86}\text{Sr}$ ratios greater than 0.7040 (MYERS *et al.*, 1984). For a given $^{206}\text{Pb}/^{204}\text{Pb}$, the lavas plot along the MORB trend for $^{208}\text{Pb}/^{204}\text{Pb}$, but are slightly elevated in $^{207}\text{Pb}/^{204}\text{Pb}$ (Fig. 3).

While Pb concentrations increase with SiO_2 , they do not do so in a linear fashion (Fig. 2). Both basaltic units are characterized by extremely low Pb contents (≤ 1 ppm) that are similar to those of many mantle-derived basalts (TATSUMOTO, 1978). In the intermediate lavas, Pb content correlates with Pb and Sr isotopic composition. Radiogenic lavas have relatively high Pb contents (> 4 ppm) while the less radiogenic volcanics are characterized by lower concentrations (< 2 ppm). Such a correlation does not hold, however, for the rhyodacites. Regardless of isotopic composition, these siliceous lavas have high (~ 7 ppm), nearly constant Pb contents.

FIG. 3. $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams for the Edgecumbe volcanics. For both diagrams, the data define linear trends. The arrays are terminated at the lower ends by the plagioclase basalt and the upper ends by the crustal rocks. Vertical lined bands are the trends for MORB. Data sources: HAMELIN *et al.* (1984); VIDAL and CLAUER (1981); COHEN *et al.* (1980); DUPRÉ and ALLÈGRE (1980); DUPRÉ *et al.* (1981); WHITE and SCHILLING (1978); TATSUMOTO (1978); SUN *et al.* (1975); COHEN and O'NIONS (1982b); CHURCH and TATSUMOTO (1975). ●—Kruzof Island Plutonics. Other symbols as in Fig. 2.

The crustal rocks through which the volcanics were erupted (MYERS and MARSH, 1981) also plot along the linear Pb-Pb arrays but at isotopic ratios slightly higher than those of the lavas (Fig. 3). The Pb contents of these rocks average ~ 5 ppm and are less than those of the rhyodacites (Table 1).

Pb MIXING SYSTEMATICS

Since the Edgumbe lavas are very young, the linear Pb-Pb trends defined by the volcanics probably represent mixing lines. The position of the basement rocks at the upper ends of these arrays suggest contamination of a basaltic magma by crustal basement, a conclusion consistent with petrography and major element chemistry (MYERS and MARSH, 1981) as well as strontium isotopic data (MYERS *et al.*, 1984). Two possible mafic parental magmas (*i.e.*, the olivine and plagioclase basalts) are represented in the volcanic suite. Based on petrography, major element composition and preliminary Sr isotopic results, MYERS and MARSH (1981) concluded that the volcanic suite could not have been derived from the olivine basalt by fractionation, assimilation or a combination of these processes. This conclusion was supported by a later, more detailed strontium isotopic investigation (MYERS *et al.*, 1984). Because no genetic relationship has been established between the two basalts, the olivine basalt appears to represent an independent primary magma that played no role in the evolution of the intermediate and siliceous Edgumbe volcanics. The position of this basalt along the Pb-Pb arrays is, therefore, merely fortuitous. At the same time, our earlier conclusion that the hybrid volcanics are the result of contamination of a basaltic magma by crustal melts is qualitatively consistent with the Pb data.

If the hybrid lavas have not been modified by fractionation, contamination/assimilation can be studied using plots of isotopic composition *versus* reciprocal concentration (*e.g.*, $^{207}\text{Pb}/^{204}\text{Pb}$ *versus* $1/^{204}\text{Pb}$; BRIQUEU and LANCELOT, 1979). On such plots, interaction of two isotopically distinct end members produces straight lines (FAURE, 1977; LANGMUIR *et al.*, 1978). Given the limited Pb concentrations characteristic of the Edgumbe lavas, straight mixing lines are also closely approximated by substituting Pb for ^{204}Pb . Because the Edgumbe volcanics have undergone little fractionation (MYERS and MARSH, 1981), diagrams of this type have proved useful in understanding the contamination/assimilation process. Using a $^{87}\text{Sr}/^{86}\text{Sr}$ -1/Sr diagram, MYERS *et al.* (1984) suggested that the hybrid lavas resulted from the contamination of the plagioclase basalt by crustal melts of differing major and trace element compositions but constant $^{87}\text{Sr}/^{86}\text{Sr}$. If the Pb system behaves in a similar fashion, on a Pb isotopic ratio *versus* 1/Pb diagram a series of mixing lines should radiate from the plagioclase basalt and pass through the hybrid lavas. Assuming the crustal melts were isotopically the same as the basement rocks (*i.e.*,

equilibrium melting), contaminant Pb contents are fixed by the intersections of the mixing lines with a horizontal line through the isotopic composition of the crustal rocks (Fig. 5a). Errors in Pb concentrations calculated in this manner are strongly controlled by the slopes of the mixing lines as well as the positions of the intersection points. When the slope is steep, small analytical errors do not shift the intersection point significantly. For mixing lines with low slopes, small errors produce large horizontal shifts in the intersection points. The effect of such horizontal shifts on calculated Pb content depends on the position of the intersection point. Small errors in intersection point position at large 1/Pb (*i.e.*, low Pb) do not produce significant changes in Pb content. At small 1/Pb (*i.e.*, high Pb), Pb content varies substantially with minor horizontal displacement of the intersection point.

Despite their basic similarities, Pb and Sr mixing systematics are distinguished by three fundamental differences. First, whereas Pb has three isotopic ratios ($^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$), strontium has only one ($^{87}\text{Sr}/^{86}\text{Sr}$). Since they are the products of the same process, results from the three Pb isotopic ratios should be similar. Secondly, the Pb isotopic ratios of crustal contaminants are more varied than $^{87}\text{Sr}/^{86}\text{Sr}$ compositions and, accordingly, mixing line slopes may be of the opposite sense. Generally, crustal contaminants are lower in Sr and more radiogenic than mantle-derived magmas; therefore, $^{87}\text{Sr}/^{86}\text{Sr}$ -1/Sr mixing lines have positive slopes and resultant hybrid lavas have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios greater than their parent. Since Pb content is greater in crustal contaminants and isotopic compositions may be either more or less radiogenic, Pb mixing lines may have either positive or negative slopes. Assimilation of undepleted crustal rocks with high Pb concentrations will produce negative Pb mixing lines. Because of the manner in which concentrations vary across mixing diagrams, differences in the sign of mixing line slopes have a significant effect on the calculation of contaminant concentrations. As reciprocal concentration approaches zero, elemental contents asymptotically approach infinity. Since the intersection points for mixing lines with negative slopes lie close to zero (*i.e.*, the Pb system), it is, therefore, difficult to resolve contaminant concentrations. In contrast, Sr mixing lines are generally positive; therefore, their intersection points occur on the right of the mixing diagram. In this region, elemental concentrations are easier to resolve. Lower parent and contaminant Pb contents relative to Sr, and hence differences in 1/Pb and 1/Sr ranges, is the third major difference between Pb and Sr systematics. In the Edgumbe lavas, 1/Pb ranges from 0.08 to 1.25 (Pb < 15 ppm) while 1/Sr varies from 0.002 to 0.008 (Sr > 100 ppm). Compared to Pb, the more limited 1/Sr range permits much more accurate determinations of contaminant Sr contents. Because of these three fundamental differences, combining Pb and Sr data may reveal details

of the contamination/assimilation process not readily apparent from the study of one system alone.

Due to the limited range in measured $^{207}\text{Pb}/^{204}\text{Pb}$ ratios (Table 1), mixing lines are difficult to identify using this isotopic ratio (Fig. 4). Consequently, our discussion is restricted to $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ mixing systematics. As expected, the data do not define one single mixing line (Fig. 4). More importantly, all the mixing lines drawn from the plagioclase basalt through the various hybrids do not intersect the isotopic composition of the proposed contaminant at positive values of $1/\text{Pb}$. Since negative Pb contents are impossible, the contamination/assimilation process must have been more complex than originally proposed. The calculated negative Pb concentrations could be explained by (Fig. 5b-d): 1) the isotopic variability of the parental magma; 2) the interaction of a contaminant(s) isotopically distinct from the observed basement rocks; or 3) rotation of the primary mixing lines.

Although it is isotopically variable, we have used an average to represent the plagioclase basalt (*i.e.*, the parent). Since the slope of a mixing line defined using an average composition is less than that constructed using the least radiogenic sample, the negative contaminant Pb contents may result from an incorrect parent isotopic composition (Fig. 5b). Mixing lines constructed with the least radiogenic plagioclase basalt

FIG. 4. Pb mixing diagram for the Edgecumbe volcanics. While two mixing lines suggest positive contaminant Pb contents, most intersect the isotopic composition of the contaminant (dashed horizontal line) at negative Pb concentrations. Also shown is the isotopic range of the plagioclase basalt. Light dotted line illustrates mixing lines constructed assuming the most primitive basaltic sample as the parental magma. See text for further discussion. Symbols as in Fig. 2.

FIG. 5. Schematic diagram illustrating processes that may have been operative during the evolution of the Edgecumbe volcanics. (A) Contamination by crustal contaminants of fixed isotopic compositions but variable Pb content. (B) Effect of parental magma isotopic variability on mixing line slopes and Pb concentrations. Using an average value for the parent decreases the slope of the "mixing line". (C) Generation of hybrids from crustal contaminants with differing isotopic compositions. While a contaminant with isotopic composition 1 would require a negative Pb content to produce hybrid 2, both hybrids could be generated from a less radiogenic contaminant (*e.g.*, 2). (D) Rotation of mixing lines due to fractionation and/or secondary contamination after the main contamination event. Significant counterclockwise rotation will yield negative contaminant Pb contents. See text for discussion. Symbols: ○—parental magma, ●—modified mafic magma, □—primary hybrid magmas, ■—evolved hybrid magma; ————true mixing lines, - - - - -fictitious mixing lines, ⇨—fractionation, Pb_1^c , Pb_2^c , Pb_3^c —lead contents of different contaminants, $-\text{Pb}_c$ —hypothetical negative Pb contents.

Pb isotopic ratios, however, still yield negative Pb contents (Fig. 4).

Since a lower contaminant Pb isotopic composition would produce intersection points all to the right of zero (Fig. 5c), the negative Pb contents may indicate the crustal end member was, in fact, less radiogenic than the observed basement rocks. Because the presumed contaminant has Pb isotopic ratios only slightly higher than those of the volcanics (Fig. 3), assimilation of less radiogenic crustal end members could produce only a portion of the hybrid volcanics. Generation of the more radiogenic lavas would require a second component with higher isotopic ratios. While such a two-stage contamination process could explain the Pb data, no strong geologic evidence exists to suggest alternative or additional crustal contaminants (MYERS and MARSH, 1981). Alternatively, nonequilibrium partial melting of the observed crustal rocks could produce contaminants of different isotopic signatures. Because the actual process of partial fusion has not been observed, disequilibrium melting has not been documented and is not considered further.

Since most petrologic processes will alter parent and/or hybrid Pb concentrations, the negative contaminant Pb contents may indicate that the mixing lines constructed with the analyzed lavas do not, in

fact, represent the original contamination event. Significant counterclockwise rotation of the original mixing lines could produce intersection points to the left of zero (Fig. 5d). Three processes (or combinations thereof) are capable of rotating mixing lines in such a fashion (Fig. 6). They are: (1) fractionation of the hybrid magma; (2) contamination of the hybrid magmas by depleted crustal rocks (*e.g.*, granulites with low U/Pb and variable Th/Pb); or (3) contamination of the parent magma by evolved rocks (*i.e.*, high U/Pb-Th/Pb). It is unlikely, however, that either of the processes acting on the hybrid magmas is the cause of the negative contaminant Pb contents. As mentioned earlier, MYERS and MARSH (1981) showed that fractionation played only a minor role in the evolution of this volcanic suite. At the same time, contamination of the hybrid magmas by depleted crustal rocks would have shifted the resultant liquids off the linear Pb-Pb arrays. Since neither fractionation nor contamination of the hybrid magmas appears to have occurred, the negative contaminant Pb contents are probably due to contamination of the parent by a more radiogenic end member *after* the original hybrid magmas (*i.e.*, basaltic andesite → rhyodacite) were formed.

THE PARENT MAGMA

If the original mixing lines have been rotated, then the plagioclase basalt is itself a hybrid lava and the

FIG. 6. Schematic diagram illustrating the various processes capable of rotating mixing lines. Upper diagram shows effect of processes operative on parent magma while lower diagram depicts the same processes acting on primary hybrid magmas. See text for discussion. Symbols as in Fig. 5.

FIG. 7. Schematic diagram illustrating how the Pb isotopic compositions of the parent and secondary contaminant are constrained by mixing systematics. The two end members most likely plot in the lined regions. See text for detailed discussion.

true parent is not represented in the sampled volcanics. Because the volcanics fall along linear Pb-Pb arrays, the parent and its contaminant must also lie along these trends but on opposite sides of the plagioclase basalt. Since the contaminants that produced the intermediate and siliceous volcanics had positive Pb contents, on a Pb isotope *versus* 1/Pb diagram the intersection points for these hybrid lavas must lie to the right of zero. Mixing lines that produce such intersection points have slopes greater than that of a line (the limiting mixing line) through the intersection of the crustal contaminant's isotopic composition and zero and the most Pb-rich, hybrid lava (Fig. 7). The parent will plot below this line at isotopic ratios less than those of the plagioclase basalt. Since the plagioclase basalt, itself a hybrid, is relatively "primitive", the parent magma probably had low Pb contents (≤ 1 ppm, TATSUMOTO, 1978) and, accordingly, plots in a small triangle below the limiting mixing line (Fig. 7). In contrast, the parent's contaminant must plot above the limiting mixing line and at Pb isotopic ratios greater than those of the plagioclase basalt. Four possible contaminants can be identified: (1) any of the hybrid magmas; (2) the crustal contaminant; (3) residuals from partial fusion of the crustal rocks; or (4) the olivine basalt. Because of the significant compositional differences between mafic magmas and the first three possible contaminants, interaction between any of these and a mafic liquid is unlikely to have produced a "primitive" magma such as the plagioclase basalt. On the other hand, contamination of a mafic magma by the olivine basalt would significantly alter the parent's Pb isotopic ratios but affect $^{87}\text{Sr}/^{86}\text{Sr}$ and major element compositions only slightly. Indeed, these are the major characteristics of the plagioclase basalt (MYERS and MARSH, 1981; MYERS *et al.*, 1984). Consequently, we believe that

the plagioclase basalt was produced when the olivine basalt contaminated an unobserved mafic magma.

The parent's maximum Pb isotopic composition is marked by the intersection of the olivine basalt-plagioclase basalt mixing line and the limiting mixing line (Fig. 7). If the average of the Crater Ridge rhyodacites is used to define the limiting mixing line, maximum isotopic ratios are $^{206}\text{Pb}/^{204}\text{Pb} = 17.41$ and $^{208}\text{Pb}/^{204}\text{Pb} = 36.75$, a composition that plots well below the Edgecumbe Pb-Pb trend. The two samples analyzed from this unit have, however, distinctly different Pb isotopic signatures. The sample from the dome east of the caldera (ED-8) is non-radiogenic and different from the other rhyodacites analyzed. The cause of this difference is presently unknown. In contrast, the sample from the caldera rim (ED-12) is more radiogenic and along with the aphyric andesitic basalt defines a limiting mixing line that suggests maximum parent isotopic ratios of 18.26 and 37.91. A magma of this composition lies along the $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ trend and would comprise 30–70% of the plagioclase basalt. Employing these volume proportions and the olivine and plagioclase basalt averages (MYERS *et al.*, 1984), mass balance calculations suggest the parental magma must have had the following major element composition: $\text{SiO}_2 \leq 51\%$; $\text{Al}_2\text{O}_3 \leq 17\%$; $\text{CaO} \sim 11\text{--}12\%$ and $\text{MgO} > 3\%$. Calculated Sr contents vary between 333 and 509 ppm and average 420 ppm while $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.70277 to 0.70290 (average ~ 0.70282). Although these isotopic ratios are only slightly lower ($\sim 0.02\%$) than those originally assumed for the parent, the calculated Sr contents are significantly higher

FIG. 8. $^{87}\text{Sr}/^{86}\text{Sr}$ versus $1/\text{Sr}$ mixing diagram constructed using the calculated parent magma. Compare this figure to Fig. 15 of MYERS *et al.* (1984) where the plagioclase basalt average ($\star$) was used as the parent magma. The new parent magma lowers contaminant Sr contents while increasing parent/mixture ratios. Solid lines are mixing lines and labelled with contaminant Sr content (in ppm); dashed lines indicate constant parent/mixture ratios. Dash-dot line is mixing line between calculated parental magma and the olivine basalt. Symbols as in Fig. 2.

FIG. 9. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $1/\text{Pb}$ mixing diagrams using the calculated parent magma. Solid lines are mixing lines and are labelled with contaminant Pb contents (in ppm). Dotted lines represent parent/mixture ratios. See text for discussion. Symbols as in Fig. 2. Star—upper limit of parent magma.

(MYERS *et al.*, 1984). Because the estimates of the parent's Pb isotopic compositions are maximums, the compositional ranges calculated are maximums and volume proportions minimums.

GENERATION OF THE INTERMEDIATE AND SILICEOUS LAVAS

Although the basic contamination process originally outlined by MYERS *et al.* (1984) is still valid, recognition that the plagioclase basalt was not the parent magma warrants a reexamination of the details of the process. Accordingly, mixing diagrams using the new parental magma have been constructed (Figs. 8 and 9). In the strontium system, the new mixing lines are not significantly different from those originally defined (MYERS *et al.*, 1984). Changing the parent decreases the mixing line slopes, thereby reducing the Sr content of individual contaminants by 30–70 ppm (Fig. 8). At the same time, the more primitive character of the new parent requires a greater proportion of crustal component. For example, using the new parent the Mount Edgecumbe hypersthene andesite consists of approximately 60% crustal

component with a Sr content of ~ 150 ppm. Previously, MYERS *et al.* (1984) had calculated that this hybrid lava contained 40% contaminant that had a strontium content of 200 ppm. Because of where the hybrids plot on the Pb mixing diagrams, resolution of contaminant Pb contents and parent/mixture ratios is somewhat difficult (Fig. 9). Estimates for contaminant Pb concentrations range from 2 to 14 ppm and parent/mixture ratios between 0.2 and 0.6. Since both Pb mixing diagrams suggest similar contaminant Pb contents as well as parent/mixture ratios, the Pb data are, at least, internally consistent.

Agreement between parent/mixture ratios calculated from the two systems is variable with ratios derived from the Pb system always higher. For the olivine and Mount Edgecumbe hypersthene andesites, the two systems yield similar results but estimates for other hybrids (*e.g.*, pyroxene andesite, Shell Mountain hypersthene andesite, Cape Edgecumbe dacite) differ by as much as 50% (Figs. 8 and 9). The largest differences occur for the Crater Ridge rhyodacite. According to Sr systematics this unit is nearly all crustal component ($x = 0.2$), yet its average Pb isotopic ratio suggests this component comprises less than 20% of the hybrid. If individual rhyodacite analyses are plotted, the radiogenic sample falls near the convergence of the contour lines and given the uncertainties associated with this region of the diagram could contain a significant crustal component. In contrast, the non-radiogenic sample requires almost no crustal contribution. The reasons for the anomalous behavior of this sample are not understood. Some of the disagreement between the Pb and Sr systems probably results from the inability to estimate Pb parent/mixture contours as accurately as those for strontium. Given the errors inherent in the Pb system, the overall good agreement between Sr and Pb mixing systematics is quite encouraging.

PHYSICAL EVOLUTION OF THE MAGMA CHAMBER

While the Pb isotopic data modify the petrologic model of MYERS *et al.* (1984) only slightly, they require a major revision of the physical model of contamination. MYERS and MARSH (1981) suggested that hybrid magmas were derived sequentially and that the magma chamber need not have contained more than one hybrid liquid at any given time. Because they rest on a basal shield of plagioclase basalt (itself a hybrid), the intermediate and siliceous lavas must have been formed before the generation and eruption of this basalt. All of the hybrid liquids must have, therefore, existed in the magma chamber before the eruptive cycle was initiated.

Any physical model describing the evolution of the Edgecumbe volcanics must explain the: 1) complex relationship between eruption sequence and magma composition; 2) nearly simultaneous eruption in different parts of the field of compositionally dissimilar magmas; 3) small volume of hybrid magmas relative

to basaltic liquid; 4) generation of intermediate and siliceous hybrids before contamination of the parent; and 5) larger volumes of hybrid lavas in the center of the volcanic field than at the margins. Such features can not be explained by the rapid emptying of a vertically zoned magma chamber (HILDRETH, 1979, 1981; MAHOOD, 1981; SMITH, 1979). For example, formation of the basal shield from such a chamber would have required magmatic conduits to tap the lower portions of the chamber while bypassing the stratigraphically higher, more evolved liquids.

MYERS and MARSH (1981) suggested that at least 36 km^3 of basaltic liquid was intruded beneath the Edgecumbe volcanic field. Assuming the area defined by the volcanic field ($24 \text{ km} \times 12 \text{ km}$; Fig. 10a) approximates that of the magma chamber, a chamber with this volume would be less than a kilometer thick. Since such a body would cool extremely rapidly, the original estimate for the volume of the chamber appears to be too small. Subsequent field work (MYERS, 1982, unpublished data) has also shown that the volume of erupted basaltic lava was underestimated by a factor of 4–5. Assuming the magma chamber had a thickness of $\sim 3 \text{ km}$, its volume would be approximately 450 km^3 . Although such a volume seems high, this large volume is almost essential for the magma to reach the surface before solidification (MARSH, 1978). Since the hybrids were formed before the injection of the olivine basalt, the chamber outlined by the major hybrid eruptive centers probably corresponds to that for the parent magma before it was contaminated by the olivine basalt. Based on Pb data, the plagioclase basalt contains approximately 40% olivine basalt; therefore, this liquid must have had a total volume of 180 km^3 . These volume estimates are based on only two assumptions: 1) the areal extent of the chamber is approximately delineated by the major eruptive centers; and 2) the chamber is 3 km thick.

Evolution of this volcanic suite is envisioned to have occurred in the following manner. At depths of $\sim 100 \text{ km}$, the mafic parent was generated by partial fusion probably related to movement along the plate margin (MYERS, 1979). As the crystal-liquid mush rose, it underwent further melting and a magma was ultimately extracted (MARSH, 1984). This magma rose diapirically as a sphere with a diameter of 9 km. (Alternately, the basaltic magma may have been emplaced as several smaller bodies that each rose independently and were injected into a common chamber.) As it approached the surface, the magma body began to flatten and pancake (Fig. 10b; OLSON *et al.*, 1984). At approximately 6 km, the magma reached its depth of emplacement (MYERS and MARSH, 1981), and lateral spreading accelerated. Localized stoping of the roof, probably controlled by small-scale ($\leq 1 \text{ km}$) crustal heterogeneities (jointing, faults, etc.), produced cupolas above the main basaltic chamber (FURLONG and MYERS, 1985). Fusion of

FIG. 10. Scaled schematic diagram illustrating the evolution of the Edgumbe magma chamber. (A) Major eruptive centers of the volcanic field and inferred extent of the magma chamber before (dashed dotted line) and after (dotted line) injection of the olivine basalt. (B) Initial flattening of the magma body as it approaches the surface. (C) Continued flattening of the body at its final emplacement depth (~ 6 km). At this stage, the first cupolas have formed. (D) Additional lateral extension of the magma chamber. The original cupolas have increased in size and new ones have begun developing near the chamber margins. The olivine basalt is approaching the shallower chamber. (E) Injection of the olivine basalt into the original chamber. (F) Hybridization of the mafic magmas has been completed and eruption of the hybrid mafic liquid produces the basal shield. (G) Eruption from the central cupolas generates the Crater Ridge and Mount Edgumbe volcanoes. (H) Tapping of the smaller, distal cupolas produces the eruptive centers at Cape Edgumbe and Shell Mountain. For detailed discussion see text.

stoped blocks within these cupolas produced small batches of crustal melt that contaminated the original mafic parent and yielded hybrid liquids (Fig. 10c). Since each is spatially isolated, hybrid magmas produced in different cupolas do not necessarily have any genetic relationship. Compositions produced at each site are a function of the degree of partial fusion achieved and the local character of the country rock.

As the lower part of the magma body continued to rise, the chamber extended further laterally (Fig. 10d). In the early formed cupolas, melting continued and relatively large volumes of crustal contaminant were produced. At the same time, stoping, partial fusion and hybridization were initiated at additional sites (Fig. 10d). Because of the density differences between the hybrid magmas of the cupolas and the basaltic liquid of the main chamber, little mass transfer occurred between these two regions. Heat was, however, transferred from the main body to the cupolas by conduction at their bases and distributed within their interiors by convection. This heat provided the energy for stoping, partial melting and hybridization. At the same time, convection within the basaltic reservoir maintained a relatively constant temperature at the base of the cupolas.

While the near surface magma chamber evolved, the olivine basalt, derived independently, was ascend-

ing as a sphere 7 km in diameter (Fig. 10d). In all likelihood, this body followed the ascent path of the earlier magma. At a depth of 6 km, the olivine basalt was injected into the main chamber thereby increasing its volume to over 600 km^3 (Fig. 10a). If the original aspect ratios were maintained, the dimensions of the enlarged chamber ($27 \text{ km} \times 14 \text{ km} \times 3.5 \text{ km}$) were only slightly larger than those of the original body. Similarities in magma density, viscosity and temperature facilitated rapid dispersal and homogenization of the olivine basalt. (A small volume of this basalt was also erupted without being compositionally modified.) Because they were effectively isolated, this magmatic event did not effect the hybrid magmas in the cupolas. Sometime after hybridization of the mafic magmas, the volcanic cycle was initiated by the eruption of the basaltic lavas that formed the basal shield (Fig. 10f). Since the hybrid magmas occupied only a small fraction of the main chamber's upper surface, numerous conduits were able to tap the mafic magma. After formation of the basal shield, hybrid magmas were erupted from the cupolas (Fig. 10g, h). Because each contained compositionally different hybrids, the eruptive cycle was determined by the sequence in which the cupolas were tapped.

In terms of the types of hybrid compositions produced as well as the sequence in which they are

erupted, this model possesses a great degree of flexibility. Liquid compositions are a function of the heterogeneity of the country rock intruded as well as the degree of melting achieved within individual cupolas. Because the hybrid magmas are developed independently as small batches within individual cupolas, there is no *a priori* reason for a continuum in magma compositions and the erupted lavas may be characterized by compositional gaps of different magnitudes and at different silica ranges. The eruption sequence is controlled by the order in which the cupolas are tapped. In addition, since the cupolas occupy only a small, discontinuous volume above the mafic chamber, basaltic liquid can be erupted almost anywhere in the volcanic field at any point in the volcanic cycle.

DISCUSSION

Many continental volcanic suites may have been derived by as complex a contamination process as that operative at Edgecumbe. Unfortunately, quantitatively testing for such a process may be extremely difficult or even impossible. At Edgecumbe, the geologic setting is relatively simple and the types of basement rocks limited. Knowing the probable crustal end member, it was possible to show that assimilants varied in major and trace element composition. For most continental volcanic suites, identifying the crustal end member is not as straightforward (CHURCH and TILTON, 1973; CHURCH, 1976; HALLIDAY *et al.*, 1983). Once a crustal end member has been tentatively identified, most studies have also assumed it was assimilated in bulk (*i.e.*, the composition of the contaminant was the same as the bulk rock) and volume proportions calculated accordingly. If, however, the crustal rocks were only partially melted, then contaminants could have varied significantly in major and trace element composition from the observed crustal rocks. Accordingly, calculated crustal contributions to the volcanics would be incorrect. For example, the Edgecumbe rhyodacites are composed of over 70% crustal component and yet their strontium isotopic ratios are only 0.70370–0.70380. If the bulk composition of the crustal rocks had been used as the contaminant, the amount of crustal contamination would have been assumed to be minor. Although HALLIDAY *et al.* (1983) have suggested that volcanics from Mount St. Helens contain only a small crustal component, Sr and Pb isotopic ranges similar to those for the Edgecumbe lavas may indicate that they have been derived by a similar evolutionary process and they record significant crustal contamination. Because the crustal end members cannot be confidently identified, testing for such a process is probably impossible. The possibility that such complex contamination processes may have occurred must be recognized when crustal contamination mechanisms are evaluated.

Pb isotopic data have also been used extensively to determine the sediment component in arc magmas

(GILL, 1981; HAWKESWORTH, 1982). Mass balance calculations have suggested that sediment makes up less than 5% of arc magmas (BARRIERO, 1983; COHEN and O'NIONS, 1982a). These calculations assume bulk assimilation of the sediment (*i.e.*, complete melting yields a liquid of the same composition as the original sediment). Our results show that if melting is not total, the actual component contributed to the magma may differ appreciably from the sediments. Because of the influence of concentration on isotopic composition (LANGMUIR *et al.*, 1978; MYERS *et al.*, 1984), such a process could significantly alter conclusions derived assuming bulk assimilation. Although the elevated $^{207}\text{Pb}/^{204}\text{Pb}$ ratios of some island arc lavas have been attributed to a sediment component, our study of Edgecumbe suggests that such isotopic characteristics can also be generated, especially along continental margins, by assimilation of very young material derived from evolved sources.

CONCLUSIONS

1. The Edgecumbe volcanics, which are characterized by Pb isotopic variability, define linear arrays on Pb-Pb diagrams. Because basement rocks plot at the radiogenic end of these linear arrays, the data are qualitatively consistent with crustal assimilation/contamination.

2. Negative contaminant Pb contents calculated from Pb isotopes *versus* 1/Pb indicate the contamination model proposed by MYERS *et al.* (1984) must be revised. The new Pb data suggest the plagioclase basalt, the parent of MYERS *et al.* (1984), is, in fact, a hybrid magma and the volcanics record two separate contamination events. One, involving a mafic parent and different crustal contaminants, produced the intermediate and siliceous lavas. The later contamination event produced the plagioclase basalt by mixing the mafic parent with the olivine basalt.

3. Mass-balance calculations using the new parent alter the Sr mixing proportions of MYERS *et al.* (1984) only slightly but reduce contaminant Sr contents by 30–70 ppm. Agreement between parent mixture ratios calculated from the two isotopic systems is generally good and suggest a close coupling between the two systems.

4. The Pb data require a major revision of the physical model for the magma chamber. In particular, all the hybrid magmas must have existed in the magma chamber before the volcanic cycle began. Hybrid magmas were generated in cupolas above the main basaltic reservoir. Resultant compositions were controlled by the types of country rock intruded and the degree of partial fusion achieved in individual cupolas. Since they were spatially isolated, no direct relationship need exist between hybrid magmas from different cupolas. Finally, the order in which the cupolas were tapped determine how lava composition evolved with time.

5. Differences in Sr and Pb isotopic mixing systematics are useful in studying contamination/assim-

ilation. In particular, the negative mixing line slopes in the Pb system are helpful in identifying possible rotation of original mixing lines. Due to positive mixing line slopes, such rotation may go unnoticed when only strontium isotopic relations are investigated.

6. The Pb isotopic ranges of the Edgecumbe volcanics are similar to those of many Aleutian volcanic centers. Because of this similarity in isotopic ratios and the absence of subduction at Edgecumbe, Pb isotopes alone are probably not good indicators of the sediment component in arc magmas.

7. The present study also suggests that questions of magma genesis and crustal assimilation are best studied using an integrated petrologic approach combining detailed field mapping, extensive petrographic study and numerous geochemical and isotopic analyses. Reconnaissance Pb isotopic studies utilizing one or two analyses per volcanic center lack the detail necessary to understand the complex petrologic processes of magma genesis and evolution.

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