Petrogenesis and $^{230}\text{Th} - ^{238}\text{U}$ disequilibrium at Mt. Shasta, California, and in the Cascades

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Abstract. Petrogenesis at Mt. Shasta is dominated by mixing of magmas and/or assimilation of wall rock, as is shown by petrographic, major and trace element chemistry, and $^{234}\text{U} - ^{230}\text{Th}$ disequilibrium data. At least three end-members are involved in these mixing processes. Lavas of very young Cascades lavas, from Mt. Garibaldi in the north to Lassen Peak in the south, are characterized by a large range of thorium isotopic ratios, although series of samples from single volcanoes are characterized by approximately constant $^{230}\text{Th}/^{232}\text{Th}$. There is a monotonic decrease in this ratio from Crater Lake south through Lassen Peak, perhaps reflecting increasing thickness of the underlying crust. Th/U fractionation in Cascades lavas, as evidenced by $^{230}\text{Th}/^{238}\text{U} \geq 1$, is in the opposite sense to that in most island arc lavas. This trend suggests that fluid transport, which is thought to produce uranium enrichment in island arc lavas, is lacking or somehow modified in the petrogenesis of the Cascades lavas.

1. Introduction

The Cascades range of the northwestern United States and southwestern Canada (Fig. 1) is a classic example of continental volcanism. Although the current lack of intermediate and deep focus earthquakes suggests that active subduction is not occurring seaward of the High Cascades, the abundant Holocene and Recent volcanism together with heat flow patterns typical of subduction zones indicate that this process may still be operative (e.g., Blackwell et al. 1982).

The geologic history of the Cascades region is one of tectonic accretion of crustal blocks of various sizes, formed in various environments, to the North American plate (e.g., Simpson and Cox 1977; Beck 1980; Duncan 1982). Following the erosion of products of several earlier phases of volcanism, the modern High Cascades were built up very quickly, mostly since the Brunhes-Matuyama magnetic polarity reversal 730,000 years ago (McBirney 1968, 1978; Berggren et al. 1980).

Trends in the chemistry of modern Cascades lavas reflect this history. The volcanoes of central Oregon are built on thin mafic oceanic-like crust whereas the basement underlying Washington and northern California volcanoes is thicker sial (McBirney 1978; White and McBirney 1978). Condie and Swenson (1973), McBirney (1978), and White and McBirney (1978) have noted that the compositions of lavas from cones along the belt follow systematic trends. Although the cones themselves are quite uniform in rock type with pyroxene andesite generally being dominant, most LIL [large ion lithophile] element concentrations are highest at Mt. Rainier in the north, intermediate to high at Mt. Shasta in the south, and lower at Mt. Jefferson in the central region. This pattern is roughly inverse to that of the thickness of the crust in these regions.

Although many processes, including fractional crystallization, assimilation, and mixing, have been important in controlling variations in the compositions of cogenetic lavas in the Cascades, petrogenetic trends appear to be dominated by mixing (e.g., Condie and Swenson 1973; Eichelberger 1975; Anderson 1976; Heiken and Eichelberger 1980; Grove et al. 1982).

Isotopic evidence suggests that sources involved in magmatogenesis in the High Cascades must include mantle material. Gases from two hot springs at Lassen Peak have $^3\text{He}/$


In this paper we present chemical and Th–U isotopic data pertinent to the petrogenesis of the High Cascades Range. The $^{230}$Th–$^{238}$U disequilibrium method is appropriate for studying a rapidly growing continental arc because it can be used both as a geochronological tool and as a geochemical tracer. The geochronological application has been used successfully to follow the evolution of magma systems (Allegre and Condomines 1976; Condomines and Allegre 1980; Bennett et al. 1982; Condomines et al. 1982) and to date individual lavas (e.g., Allegre 1968; Baranowski and Harmon 1978). The method is applicable to systems which are less than approximately 250,000 and older than approximately 10,000 years old, these limitations being imposed by the half-life of $^{235}$U (75,200 years) and the statistical uncertainties of the measurements. Any lava less than about 10,000 years old can be considered to be of zero-age. The isochron equation describing the closed system behavior of $^{232}$Th and $^{238}$U, normalized to $^{232}$Th and expressed in activities (activity = $2N$; activities indicated by parentheses) is:

$$\left(\frac{^{230}Th}{^{232}Th}\right) = \left(\frac{^{230}Th}{^{232}Th}\right)_0 e^{-\lambda_{230}t} + \left(\frac{^{238}U}{^{232}Th}\right) (1-e^{-\lambda_{232}t}),$$

where $\left(\frac{^{230}Th}{^{232}Th}\right)_0$ is the initial ratio (at time of eruption).

The geochemical tracer application, using the $\left(\frac{^{230}Th}{^{232}Th}\right)$ activity ratio, is analogous to the use of Sr, Nd, Pb, and He isotopic ratios and allows study of parent-daughter ($^{234}$U–$^{230}$Th) fractionation (Oversby and Gast 1968; Condomines et al. 1981; Allegre and Condomines 1982). However, because $^{230}$Th is radioactive, $\left(\frac{^{230}Th}{^{232}Th}\right)_0$ does not integrate over the entire lifetime of the source region but rather reflects its current Th/U ratio, provided that: 1) the source region is in radioactive equilibrium with respect to $^{230}$Th and $^{232}$Th, and 2) the time between Th–U fractionation and eruption has been very short relative to the half-life of $^{230}$Th. Where a long-lived magma chamber is thought to exist, secular variations in $\left(\frac{^{230}Th}{^{232}Th}\right)$ can give information about its evolution caused by such processes as new injections of magma and magma mixing (e.g., Condomines et al. 1982).

In the sections that follow, we discuss data for samples from along the length of the High Cascades Range, from Mt. Garibaldi in British Columbia to Lassen Peak in California (Fig. 1), which we studied to investigate spatial variations in "present-day" $^{230}$Th–$^{238}$U disequilibrium systematics. In addition, a detailed study of Mt. Shasta in northern California was conducted in order to examine temporal evolution at a single volcano.

### 2. Analytical methods

Uranium and thorium concentrations and isotopic compositions were determined by isotope dilution alpha spectrometry, following ion exchange and solvent extraction of U and Th fractions from the rocks. A discussion of the methods and errors of sample preparation, chemical separation of U and Th, and calculation of concentrations and isotopic compositions is presented elsewhere (Newman 1983; Newman et al. 1984a). Comparison of results from separately collected and prepared samples of two flows from Mt. St. Helens analyzed by Bennett et al. (1982) and by us demonstrates good agreement between these two laboratories (Newman et al. 1984a). Major element compositions were measured by electron microprobe on polished fused glass chips. Trace elements were measured by X-ray fluorescence of pressed powder pellets.

### 3. Results

#### 3.1 General features of the $^{230}$Th–$^{238}$U data

When data from all of the zero-age (<10,000 years old) Cascades lavas are plotted on the $^{230}$Th/$^{232}$Th versus $^{235}$U/$^{232}$Th diagram (Fig. 2, Table 1), several characteristics are observed. First, many of the lavas exhibit an excess of $^{230}$Th over $^{238}$U, i.e. the data fall to the left of the equiline. Second, there is a large range of $^{235}$U/$^{232}$Th; however, where several very young samples from the same volcano have been analyzed, they exhibit constant thorium isotopic compositions, together with significant variations in $^{235}$U/$^{232}$Th. This suggests that the reservoir(s) feeding the eruptions at a single volcano are homogeneous with respect to $^{230}$Th/$^{232}$Th. Finally, there is a correlation between geographical location and $^{230}$Th/$^{232}$Th among the lavas of the southern Cascades. From Crater Lake south to Mt. Lassen there is a monotonic decrease in $^{230}$Th/$^{232}$Th. Th/U ratios in the same rocks increase from Crater Lake through Mt. Lassen. North of Crater Lake no coherent trend exists.

The observation of significant disequilibrium between $^{230}$Th and $^{238}$U in some of the lavas contrasts with the equilibrium observed for all fresh samples by Krishnaswami et al. (1984), including Mt. St. Helens (Bennett et al. 1982). Disequilibrium has been reported for fresh young volcanic rocks by other workers (e.g., Allegre and Condomines 1982; Nishimura 1970; Oversby and Gast 1968). The Yale group has proposed that any disequilibrium found is the result