U-series disequilibria in Guatemalan lavas, crustal contamination, and implications for magma genesis along the Central American subduction zone

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[1] New U-series results indicate that Guatemalan volcanic rocks display both ^{238}U and ^{230}Th excesses. ^{230}Th excess is restricted to volcanoes in central Guatemala, both along and behind the front. ^{230}Th excess correlates with a number of incompatible element ratios, such as Th/Nb and Ba/Th. It also shows a negative correlation with MgO. Guatemalan volcanic rocks have ($^{230}Th/^{232}Th$) ratios that overlap those of Costa Rican volcanics and are therefore considerably lower than the unusually high ratios characterizing volcanic rocks from Nicaragua. Along-arc variations in ($^{230}Th/^{232}Th$) therefore mirror those of a number of diagnostic geochemical parameters, such as Ba/La, which are symmetrical about a peak in west central Nicaragua. The one siliceous lava analyzed, from the Cerro Quemado dome complex, has a recognizable crustal imprint, distinguished, for instance, by high Th/Nb and low Ba/Th. In mafic samples, ^{238}U excess is attributed to addition of a U-enriched fluid component from the subducting Cocos plate. Our preferred explanation for ^{230}Th excess in Guatemalan mafic samples, on the other hand, is crustal contamination, consistent with the relatively high Th/Nb and low Ba/Th ratios in these samples. We suspect, however, that crustal contamination only exerts a sizable control over the U-series disequilibrium of mafic magmas in Guatemala, and not elsewhere along the Central American volcanic front. This agrees with previously published trace element and isotopic evidence that throughout Central America, with the exception of Guatemala, mafic magmas are largely uncontaminated by crustal material.

1. Introduction

[2] Magma generation and evolution at subduction zones is unique and complex [*Ringwood*, 1974; *Gill*, 1981; *Davidson*, 1996; *Stern*, 2002]. U-series isotopic analyses of recently erupted subduction zone lavas have provided increasingly valuable constraints on the complexities inherent in subduction zone melting and differentiation and on the time scales over which they operate [*Gill and Williams*, 1990; *Gill et al.*, 1993; *Reagan et al.*, 1994, 2003; *Elliott et*

al., 1997; *Bourdon et al.*, 1999, 2003; *Turner et al.*, 2000a; *Turner and Foden*, 2001; *Peate et al.*, 2001; *Thomas et al.*, 2002; *George et al.*, 2003]. For example, many subduction zone lavas have ^{238}U excesses [*Newman et al.*, 1984; *Elliott*, 2003; *Turner et al.*, 2003a]. Such excesses, rare in lavas from other tectonic settings, are universally attributed to the preferential transport of U in a fluid component from the subducting plate to the melting region within the mantle wedge [*Allègre and Condomines*, 1982; *Newman et al.*, 1984; *Gill and Williams*, 1990; *Elliott et al.*, 1997; *Bourdon et al.*, 2003; *Elliott*, 2003; *Turner et al.*, 2003a]. Thus the common occurrence of ^{238}U excesses in subduction zone lavas adds support to the general belief that fluid-induced, or flux, melting is the predominant mechanism for generating primary, basaltic magmas in subduction zones [*Ringwood*, 1974; *Tatsumi*, 1986; *McCulloch and Gamble*, 1991; *Davies and Stevenson*, 1992; *Tatsumi and Eggins*, 1995; *Iwamori*, 1998; *Kincaid and Hall*, 2003]. The Central American subduction zone displays singular along-arc geochemical variations in erupted basaltic magmas [*Carr*, 1984; *Feigenson and Carr*, 1986; *Carr et al.*, 1990, 2003; *Feigenson and Carr*, 1993; *Leeman et al.*, 1994; *Patino et al.*, 2000; *Feigenson et al.*, 2004]. Many of these variations

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have been attributed to systematic regional changes in magma generation, specifically in the degree and nature of inputs from the subducting Cocos plate, or slab [*Carr et al.*, 1990, 2003; *Feigenson and Carr*, 1993; *Leeman et al.*, 1994; *Patino et al.*, 2000; *Snyder et al.*, 2001; *Thomas et al.*, 2002; *Fischer et al.*, 2002; *Rüpke et al.*, 2002; *Cameron et al.*, 2002; *Shaw et al.*, 2003; *Eiler et al.*, 2005]. Slab inputs clearly peak in Nicaragua and fall off toward both ends of the subduction zone [*Carr et al.*, 1990, 2003; *Leeman et al.*, 1994; *Patino et al.*, 2000; *Eiler et al.*, 2005]. Taken together, previous studies provide geochemical evidence to support slab inputs from two sources: (1) subducted sediments; and (2) subducted oceanic crust/mantle [e.g., *Eiler et al.*, 2005]. The sediment input, however, includes contributions from two distinct sedimentary units: hemipelagic muds and clays; and carbonate-rich oozes [*Patino et al.*, 2000]. Sediment input has been alternatively attributed to the transfer of a fluid [*Leeman et al.*, 1994], or a siliceous melt [*Cameron et al.*, 2002; *Eiler et al.*, 2005], component. Input from the subducted Cocos crust/mantle, by contrast, has been consistently imputed to transfer of a fluid component [*Carr et al.*, 1990; *Cameron et al.*, 2002; *Rüpke et al.*, 2002; *Eiler et al.*, 2005]. Previous isotopic and trace element studies have also concluded that basaltic magmas erupted along the Central American volcanic front are not significantly influenced by crustal contamination, except perhaps in Guatemala where older pre-Cenozoic crust may extend beneath the front [*Feigenson and Carr*, 1986; *Carr et al.*, 1990; *Cameron et al.*, 2002; *Rogers*, 2003; *Feigenson et al.*, 2004; *Eiler et al.*, 2005].

[3] In this paper we present U-series isotope data on young volcanic rocks erupted in Guatemala, including lavas from small cinder cones behind the volcanic front. The new U-series data may provide additional evidence for crustal influence on Guatemalan basaltic magmas. In addition, they also allow us to critically re-examine some of the geochemical variations along the entire Central American subduction zone and their relationship to slab inputs.

2. Central American Subduction Zone

[4] The Central American subduction zone is an active continental margin associated with subduction of the Cocos plate beneath the Caribbean plate (Figure 1). The convergence rate between the two plates gradually increases to the southeast from about 7 to 9 cm/yr [*DeMets*, 2001]. The age of the subducting Cocos lithosphere is approximately constant (about 26 Ma) along most of the subduction zone, except along its southeasternmost segment in central Costa Rica where slightly younger (~17 to 25 Ma) lithosphere, generated at the Cocos-Nazca spreading center, is being subducted [*Harry and Green*, 1999; *von Huene et al.*, 2000; *Barckhausen et al.*, 2001]. The sedimentary section crowning the subducting Cocos plate is also thought to be relatively uniform along the length of the subduction zone, broadly consisting of: pelagic carbonates overlain by hemipelagic oozes [*Aubouin et al.*, 1982; *Kimura et al.*, 1997]. Both units are geochemically distinct and both are believed to substantially contribute to the slab signal seen in erupted basaltic magmas, except perhaps in central Costa Rica [*Morris et al.*, 1990; *Plank and Langmuir*, 1993; *Reagan*

et al., 1994; *Patino et al.*, 2000; *Walker et al.*, 2000, 2001; *Carr et al.*, 2003].

[5] Most of the volcanism related to subduction in Central America has been concentrated at the large polygenetic volcanic centers comprising the volcanic front, the trenchward limit of volcanism (Figure 1). One tectonic parameter not constant along strike is the dip of the subducting Cocos plate beneath the volcanic front [*Carr*, 1984; *Carr et al.*, 1990]. The dip is relatively shallow beneath Guatemala, increases to a maximum in Nicaragua, and abruptly shoals in central Costa Rica at an apparent tear termed the Quebrada Sharp Contortion [*Protti et al.*, 1995; *Leeman et al.*, 1994; *Carr et al.*, 2003].

[6] Crustal thickness below the volcanic front (VF) also exhibits regular variation along the Central American subduction zone [*Carr*, 1984; *Carr et al.*, 1990, 2003]. The crust is thickest (>40 km) at the edges of the subduction zone, in central-northwestern Guatemala and central Costa Rica, and is thinner (≤40 km) throughout the remainder of the arc [*Carr et al.*, 2003]. In the northern part of the subduction zone, Guatemala is bisected by strike-slip faults marking the Caribbean-North America plate boundary (Figure 1). Motion along this boundary has contributed to the unusual arc-normal back-arc extension experienced across northern Central America [*Burkart and Self*, 1985]. Back-arc extension has been accompanied by scattered back-arc, or behind-the-front (BVF), volcanism, which is most voluminous in southeastern Guatemala (Figure 1) [*Walker*, 1981].

3. Samples and Analytical Techniques

[7] Six new samples of lava and tephra (Gua1–Gua9) from Guatemala were collected for U-series analysis: four from the volcanic front and two from behind the front in southeastern Guatemala (Table 1 and Figure 2). Sample Gua7 is included as part of the volcanic front although it comes from Cerro Quemado, a Holocene dome complex slightly (5 km) "behind" one of the large stratovolcanoes (Santa María) defining the front [*Conway et al.*, 1992]. Gua7 has abundant fine-grained mafic inclusions which are interpreted as blobs of mafic, possibly hybrid, magma quenched in their more silicic host [*Eichelberger*, 1980; *Bacon and Metz*, 1984; *Bacon*, 1986; *Koyaguchi*, 1986; *Grove and Donnelly-Nolan*, 1986; *Linneman and Myers*, 1990; *Varga et al.*, 1990; *Nakada et al.*, 1994; *Feeley and Dungan*, 1996; *Clynne*, 1999; *Murphy et al.*, 2000; *Saito et al.*, 2002]. We attempted to completely exclude these inclusions from the powdered sample, but were probably unsuccessful (see below). Gua5 is from a cinder cone (Cuilapa Sur II) in the Cuilapa area about 15 km behind the front. Gua8 is from a cinder cone from the Ipala Graben (Cerro Colorado) about 80 km behind the front (Figure 2). Recent $^{40}Ar/^{39}Ar$ incremental heating measurements indicate that monogenetic volcanism in southeastern Guatemala ranges in age from 1070 ± 22 ka to 19 ± 10 ka (*Walker et al.* [2005] and unpublished results). Lava from Cuilapa Sur II has yielded an Ar/Ar plateau age of 47 ± 20 ka (unpublished result). Lava from Cerro Colorado has yet to be dated.

[8] We also undertook U-series analyses of four lavas previously collected from the Guatemalan portion of the volcanic front (Table 2). Sample GPA07 is from the 1987 lava flow of the frequently active Pacaya volcano [*Cameron*,
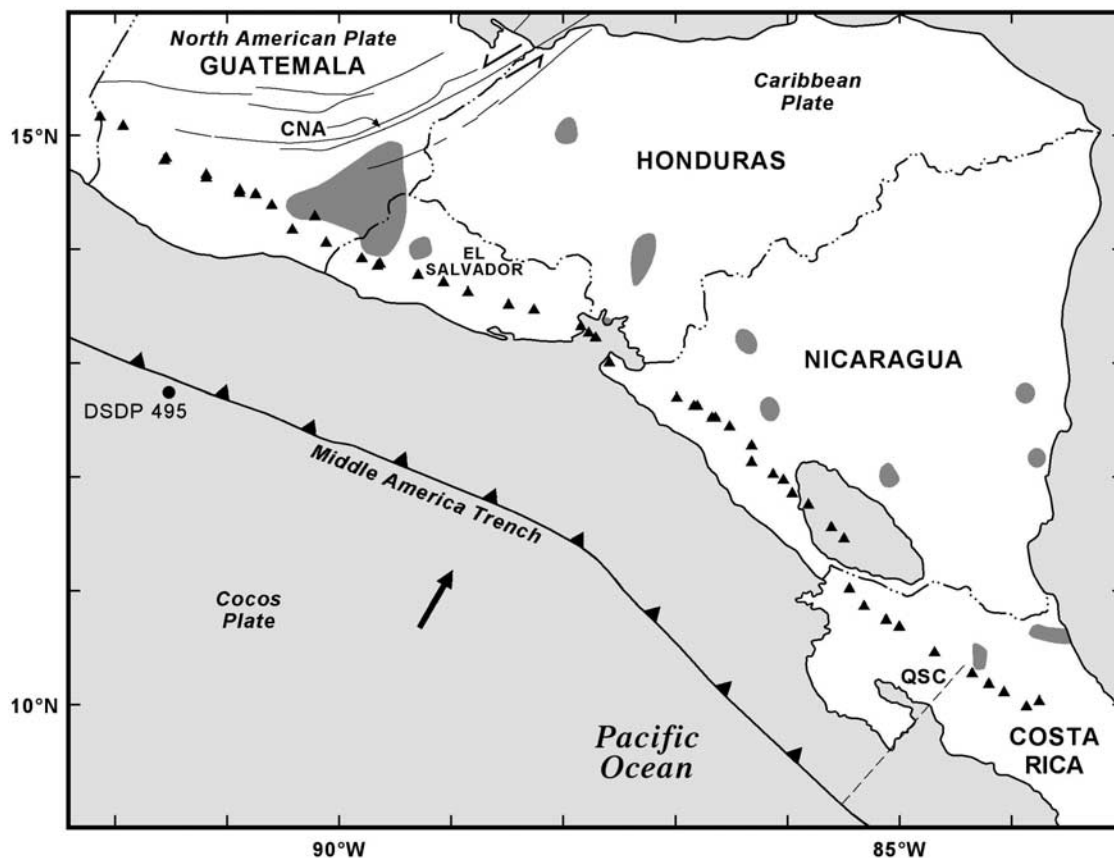
Figure 1. The Central American subduction zone. Arrow shows approximate direction of Cocos-Caribbean convergence. Triangles are volcanic front (or VF) volcanoes. Shaded areas are regions of behind-the-front (or BVF) volcanism. The solid lines in Guatemala and northwesternmost Honduras are strike-slip faults associated with the Caribbean-North American plate boundary (CNA). The Middle America trench marks the Cocos-Caribbean plate boundary. Dot on Cocos plate shows approximate location of DSDP drill hole 495. Dashed line represents the surface trace of the Quebrada Sharp Contortion, a proposed tear in the subducting Cocos plate [*Protti et al.*, 1985].

1998]. SM114 and SM126 are cone-building lavas from Santa María volcano [*Rose et al.*, 1977; *Rose*, 1987]. Paleomagnetic evidence suggests cone construction is younger than approximately 30 ka [*Rose et al.*, 1977; *Conway et al.*, 1994]. TCB302 is a porphyritic lava from Tecuamburro volcano, a relatively youthful stratovolcano from southeastern Guatemala (Figure 2), whose origins are believed to postdate 38 ka [*Duffield et al.*, 1992].

[9] Methods of crushing and powdering rock samples were identical to those described by *Cameron et al.* [2002]. Major elements of the newly collected samples were determined by XRF spectrometry at Northern Illinois University using a low dilution fusion technique on homogeneous glass fusion discs [*Eastell and Willis*, 1990; *Cameron et al.*, 2002]. The same discs were then analyzed for trace element concentrations via laser ablation inductively coupled plasma mass spectrometry at Michigan State University [e.g., *Cameron et al.*, 2002].

[10] Uranium and thorium were separated, concentrated and spiked using the procedures described by *Thomas et al.* [2002] and *Shen et al.* [2002]. Purified thorium separates were loaded on single Re filaments with graphite [*Asmerom and Edwards*, 1996]. The ^{230}Th measurements were made on a Finnigan MAT 262 thermal ionization mass spectrom-

eter with a retarding quadrupole energy filter at the University of Minnesota. The ^{230}Th measurements are accurate to better than 2.2 %. The ^{238}U and ^{232}Th measurements were made via magnetic sector inductively coupled plasma mass spectrometry using a Finnigan Element, equipped with a double-focusing sector-field magnet in reversed Nier-Johnson geometry and a single MasCom multiplier, also at the University of Minnesota. Separate dissolutions of Table Mountain Latite (TML), an interlaboratory standard

Table 1. Sample Descriptions[a]

Sample	Volcano	VF/BVF	Lithology	Eruption Age
Gua 1	Pacaya	VF	basaltic tephra	A.D. 2000
Gua 3	Pacaya	VF	basaltic lava	A.D. 1998
Gua 5	Cuilapa Sur II	BVF	basaltic tephra	47 ± 20 ka
Gua 7	Cerro Quemado	VF	andesitic lava	A.D. 1818
Gua 8	Cerro Colorado	BVF	basaltic lava	??
Gua 9	Fuego	VF	basaltic tephra	A.D.1999
GPA 07	Pacaya	VF	basaltic lava	1987
SM 114	Santa María	VF	basaltic lava	<30 ka?
SM 126	Santa María	VF	basaltic lava	<30 ka?
TCB 302	Tecuamburro	VF	andesitic lava	<38 ka?

[a]VF = volcanic front; BVF = behind-the-volcanic front. Gua 5 eruption age is unpublished Ar/Ar plateau age (see text).
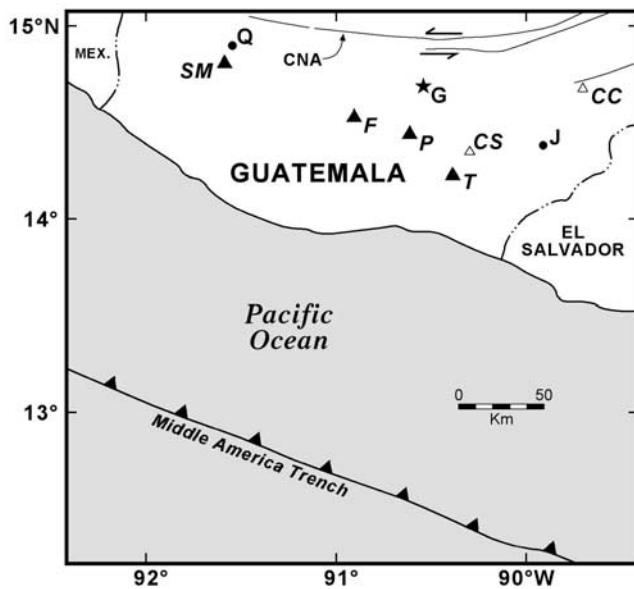
Figure 2. Volcanoes sampled in Guatemala. Volcanic front: SM = Santa María; F = Fuego; P = Pacaya; T = Tecuamburro. Behind-the-volcanic front: CS = Cuilapa Sur II; CC = Cerro Colorado. Q, G, and J are the Guatemalan cities of Quezaltenango, Guatemala City and Jutiapa, respectively. CNA is the Caribbean-North American plate boundary.

in secular equilibrium, were run to test the precision and accuracy of the isotopic results. The mean $(^{230}Th/^{238}U)$ value for TML is given in Table 3 and is within the range of values reported in the literature [*Asmerom and Edwards*, 1995; *Asmerom et al.*, 2000; *Cheng et al.*, 2000; *Thomas et al.*, 2002; *Pietruszka et al.*, 2002].

[11] No other isotopic measurements have been carried out on newly collected samples, and of the previously collected samples only SM126 has been analyzed for Sr and Nd isotopes: $^{87}Sr/^{86}Sr = 0.703990$; and $^{143}Nd/^{144}Nd = 0.512820$ (from the Centam database http://www.rci.rutgers.edu/~carr/index.html).

4. Results

[12] Major and trace element concentrations of the ten volcanic rocks studied are given in Table 2. Eight of the samples are basalts and two are andesites (Figure 3). All are very representative of their respective VF stratovolcanoes, or of BVF cinder cones [*Mickelson*, 2003]. The acid andesite from Cerro Quemado falls at the Si-poor end of previously analyzed lavas from the dome complex (including samples of the 1818 lava) suggesting mafic inclusions were not entirely removed prior to powdering Gua7 (Figure 3). All of the samples, including those from behind the front, show similar arc-like incompatible trace element patterns (Figure 4). The acid andesite from Cerro Quemado, however, stands out in Figure 4, exhibiting more prominent positive spikes in Pb and K, and greater fractionation between highly and mildly incompatible elements. We will argue below that these and other trace element distinctions of the Cerro Quemado

Table 2. Major and Trace Element Compositions of Analyzed Volcanic Rocks[a]

	Gua 1	Gua 3	Gua 5	Gua 7	Gua 8	Gua 9	GPA 07	SM 114	SM 126	TCB 302
SiO_2	49.2	47.12	50.13	58.26	49.83	51.68	50.46	51.90	51.40	53.87
TiO_2	11.14	1.09	1.30	0.60	1.17	0.93	1.12	0.90	0.95	0.74
Al_2O_3	19.07	18.86	17.28	16.31	17.31	20.21	20.18	18.25	18.69	17.95
FeO^T	8.90	8.63	8.96	5.61	9.11	8.22	8.80	9.11	8.28	7.52
MnO	0.16	0.15	0.16	0.12	0.16	0.15	0.15	0.19	n.d.	0.14
MgO	3.38	3.18	6.65	3.02	7.87	4.05	3.39	5.40	5.20	5.43
CaO	9.91	10.30	8.73	5.74	9.41	9.10	10.18	8.47	9.35	8.59
Na_2O	3.59	3.47	3.76	4.06	3.26	3.60	3.48	3.64	3.60	3.39
K_2O	0.85	0.81	1.07	1.92	0.83	0.77	0.82	0.87	0.76	0.62
P_2O5	0.22	0.20	0.30	0.12	0.28	0.14	0.24	0.23	0.22	0.15
Sr	607.0	610.0	584.0	412.0	545.0	604.0	636.0	558.0	630.0	466.0
Ba	419.0	403.0	419.0	733.0	383.0	396.0	441.0	451.0	429.0	315.0
Y	22.8	20.9	26.5	13.2	24.8	19.7	20.9	18.4	19.6	14.7
Nb	3.49	3.29	6.57	5.05	6.92	2.47	n.d.	3.05	3.37	2.43
La	10.24	9.66	14.14	11.78	12.29	7.34	n.d.	8.36	8.73	5.83
Ce	23.06	21.84	32.35	29.70	27.78	17.05	n.d.	19.67	20.27	14.07
Pr	3.35	3.19	4.58	3.31	3.88	2.56	n.d.	2.96	3.02	2.07
Nd	15.89	14.86	20.48	12.63	17.32	12.50	n.d.	14.20	14.22	9.45
Sm	4.09	3.78	4.84	2.92	4.17	3.37	n.d.	3.53	3.56	2.35
Eu	1.33	1.26	1.53	0.91	1.14	1.16	n.d.	1.12	1.17	0.80
Gd	4.14	3.79	4.76	2.62	4.16	3.47	n.d.	3.55	3.54	2.92
Tb	0.64	0.60	0.74	0.40	0.66	0.54	n.d.	0.55	0.56	0.48
Dy	4.10	3.76	4.68	2.36	4.23	3.49	n.d.	3.47	3.57	2.82
Ho	0.77	0.71	0.93	0.42	0.82	0.67	n.d.	0.64	0.69	0.59
Er	2.25	2.06	2.55	1.43	2.34	1.94	n.d.	1.94	2.02	1.68
Yb	2.10	1.88	2.68	1.11	2.33	1.75	n.d.	1.86	n.d.	1.62
Lu	0.33	0.30	0.40	0.17	0.37	0.28	n.d.	0.28	n.d.	0.24
Pb	4.55	4.23	4.29	16.73	3.45	3.57	n.d.	n.d.	4.82	3.27
Th	1.51	1.34	1.49	3.88	1.16	0.96	n.d.	0.99	1.23	0.45
U	0.59	0.54	0.61	2.26	0.46	0.37	n.d.	0.42	0.51	0.25
Hf	2.43	2.17	3.27	2.59	3.10	2.12	n.d.	2.84	2.53	2.08
Ta	0.34	0.32	0.70	0.46	0.60	0.28	n.d.	0.34	0.34	0.14

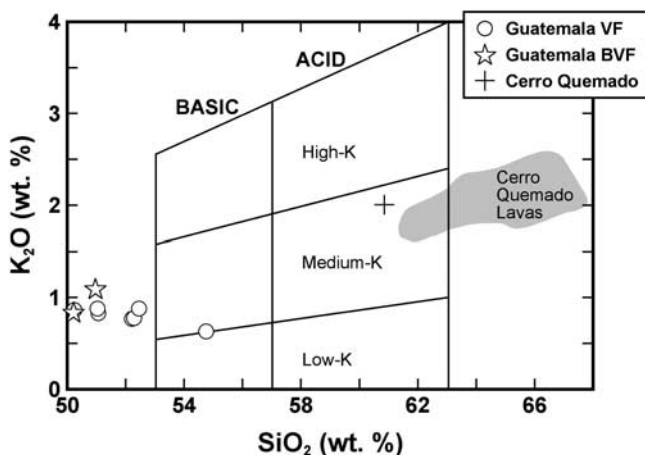[a]FeO^T = total Fe as FeO; n.d. = not determined.

Figure 3. K_2O versus SiO_2 for volcanic rocks studied. Compositions have been normalized to 100% on a volatile free basis. Quadrilaterals subdividing basic and acid orogenic andesites into low-K, medium-K, and high-K regions from *Gill* [1981]. Analyses defining field for Cerro Quemado lavas from *Conway et al.* [1992] and *Johns* [1975].

andesite are indicative of a significant crustal imprint. The new U-Th isotope data are presented in Table 3. Table 3 also gives the age-corrected ($^{230}Th/^{232}Th$) and ($^{230}Th/^{238}U$) values for sample Gua5. It is possible that the U-series data for the samples from Santa María, Tecuamburro and Cerro Colorado should also be age-corrected, but $^{40}Ar/^{39}Ar$ eruption ages are not available for these samples. For this reason, and since the age corrections will be relatively small, as shown for Gua5, we have chosen to utilize only the measured U-series data throughout the remainder of the paper. This slight limitation does not affect any of the major conclusions to come.

[13] In detail, the Guatemalan volcanic rocks separate into three groups (Figure 5). Lavas from Santa María, Cerro Quemado and one of the BVF cinder cones have ^{238}U excesses and the lowest ($^{230}Th/^{232}Th$). Volcanic rocks from Fuego, Pacaya and the other BVF cinder cones have higher ($^{230}Th/^{232}Th$) and small ^{230}Th excesses. And finally, the lava from Tecuamburro has ^{238}U excess and the highest ($^{230}Th/^{232}Th$) (Figure 5). Overall the magnitude of disequilibrium shown by Guatemalan volcanics is largely <10%, smaller than amounts seen in some Nicaraguan lavas and many volcanic rocks from the Tonga island arc (Figure 6). ^{230}Th excess, although the norm for mid-ocean ridge basalts [*Condomines and Sigmarsson*, 1993; *Bourdon et al.*, 1996; *Lundstrom et al.*, 1998, 2000], is less common than ^{238}U excess in subduction zone volcanic rocks [*Gill and Williams*, 1990; *McDermott and Hawkesworth*, 1991; *Condomines and Sigmarsson*, 1993; *Hawkesworth et al.*, 1997; *Bourdon et al.*, 2003; *Elliott*, 2003]. In Guatemala, ^{230}Th excess is restricted to central Guatemala (Figure 7): Fuego and Pacaya stratovolcanoes on the VF, and the Cuilapa Sur II cinder cone behind the front. Also, within both the VF and BVF realms, and excluding the distinctive Cerro Quemado acid andesite from the former, ^{230}Th excess correlates positively with Ba/Hf, Th/Nb, and TiO_2; and negatively with Ba/Th and MgO (Figure 8). Correlations between incompatible element ratios and U-Th disequilibrium in subduction zone suites containing both ^{238}U and ^{230}Th excesses have been

noted elsewhere and have furnished important insights into the causes of the disequilibrium [*Reagan et al.*, 1994; *Elliott et al.*, 1997; *Bourdon et al.*, 2000; *Thomas et al.*, 2002; *Turner et al.*, 2003b; *Dosseto et al.*, 2003]. *Dosseto et al.* [2003] have reported a similar correlation between ^{230}Th excess and lower MgO amongst lavas from the Kamchatka arc. Like TiO_2, most incompatible elements exhibit good to fair positive correlations with ^{230}Th excess, with notable exceptions such as Nb (Figure 8). The latter correlations are consistent with the general observation that ^{238}U excesses are greatest in the most depleted arc basalts [*Condomines and Sigmarsson*, 1993; *Reagan et al.*, 1994; *Elliott*, 2003].

[14] The ($^{230}Th/^{232}Th$) values for Guatemalan volcanic rocks are somewhat intermediary between values determined for Costa Rica and El Salvador, all of which are lower than the elevated ($^{230}Th/^{232}Th$) ratios of Nicaraguan volcanics (Figure 6). As previously pointed out by *Reagan et al.* [1994], Nicaraguan volcanic rocks are characterized by some of the highest ($^{230}Th/^{232}Th$) ratios reported for any terrestrial volcanic rocks. Variation in the ($^{230}Th/^{232}Th$) ratios of mafic volcanic rocks along the Central American subduction zone is quite systematic and mimics along-arc changes in a number of geochemical parameters, such as Ba/La (Figure 9). ($^{238}U/^{232}Th$) ratios exhibit an identical pattern, symmetrical about a peak in west-central Nicaragua (Figure 9).

5. Crustal Imprint in the 1818 Lava From Cerro Quemado

[15] The Cerro Quemado acid andesite erupted in 1818 (Gua7) has higher La/Yb and Th/Nb, and lower Ba/Th, ratios than mafic magmas erupted in Guatemala (Figure 10). The incompatible element ratios of Gua7 are teasingly similar to those of analyzed Mesozoic metamorphic rocks from Guatemala (Figure 10), rocks identified by *Walker et al.* [1995] and *Cameron* [1998] as likely crustal contaminants of some recent basaltic and andesitic magmas in northernmost southeastern Guatemala. A number of the siliceous ignimbrites from Guatemala analyzed by *Vogel et al.* [2004] also have high La/Yb and Th/Nb, as well as low Ba/Th (Figure 10). The curves in Figure 10 demonstrate
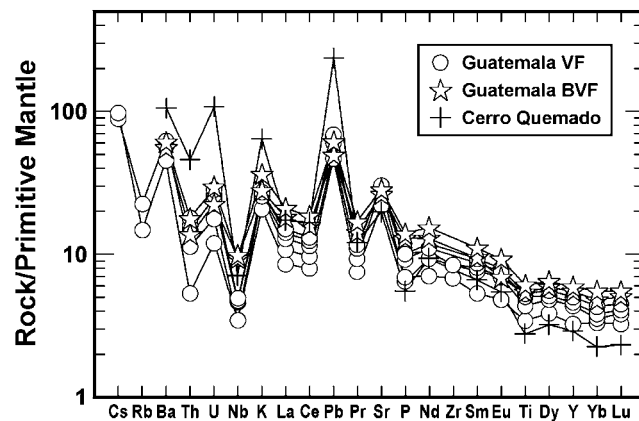

Figure 4. Primitive mantle normalized [*Sun and McDonough*, 1989] spidergrams for volcanic rocks studied save GPA 07 and SM 126. GPA 07 was excluded because it has not been analyzed for most trace elements (Table 2), while SM 126 shows a nearly identical pattern to SM 114.

Table 3. U-Series Data[a]

Sample	(^{230}Th/^{232}Th)	(^{238}U/^{232}Th)	(^{230}Th/^{238}U)
Gua 1	1.302 ± 0.016	1.224 ± 0.004	1.064 ± 0.018
Gua 3	1.280 ± 0.050	1.219 ± 0.004	1.050 ± 0.057
Gua 5	1.349 ± 0.018	1.313 ± 0.006	1.028 ± 0.019
	(1.368 ± 0.018)		(1.042 ± 0.018)
Gua 7	1.107 ± 0.010	1.147 ± 0.005	0.965 ± 0.011
Gua 8	1.126 ± 0.043	1.285 ± 0.005	0.877 ± 0.047
Gua 9	1.293 ± 0.028	1.232 ± 0.005	1.049 ± 0.032
GPA 07	1.313 ± 0.010	1.226 ± 0.006	1.071 ± 0.012
SM 114	1.110 ± 0.014	1.214 ± 0.006	0.914 ± 0.014
SM 126	1.169 ± 0.015	1.255 ± 0.004	0.931 ± 0.016
TCB 302	1.479 ± 0.018	1.607 ± 0.005	0.920 ± 0.015
TML	1.073 ± 0.018	1.070 ± 0.006	1.003 ± 0.018

[a]TML = Table Mountain Latite standard. Values in parentheses are age-corrected values.

that the crustal imprint borne by Gua7, and by some of the Guatemalan ignimbrites, could be produced by combined assimilation/fractional crystallization (AFC), starting from a Santa María-like mafic parental composition, although only with high ratios of assimilation/crystallization and very extensive fractionation, both 0.5. The reduced ^{238}U excess in Gua7 and the general trend toward reduced ^{238}U excesses with SiO$_2$ (Figure 11), are also consistent with an origin by extensive crustal differentiation from a Santa María-like parent that had a larger ^{238}U excess [*Turner and Foden*, 2001; *Reagan et al.*, 2003; *Zellmer et al.*, 2005]. The small ^{238}U excess in Gua7 could also be an acquisition from a relatively recent mixing event with mafic mantle-derived magma [e.g., *Hughes and Hawkesworth*, 1999]. The abundant mafic inclusions in Gua7 may document this event. Alternatively, Gua7 could represent an little adulterated crustal melt [*Hawkesworth et al.*, 1982; *Smith and Leeman*, 1987; *de Silva*, 1989; *Beard and Lofgren*, 1991; *Costa and Singer*, 2002]. If so, the 4% ^{238}U excess in Gua7 would need to be explained; perhaps by a residual Th-rich accessory phase, such as allanite [*Heumann et al.*, 2002] or by

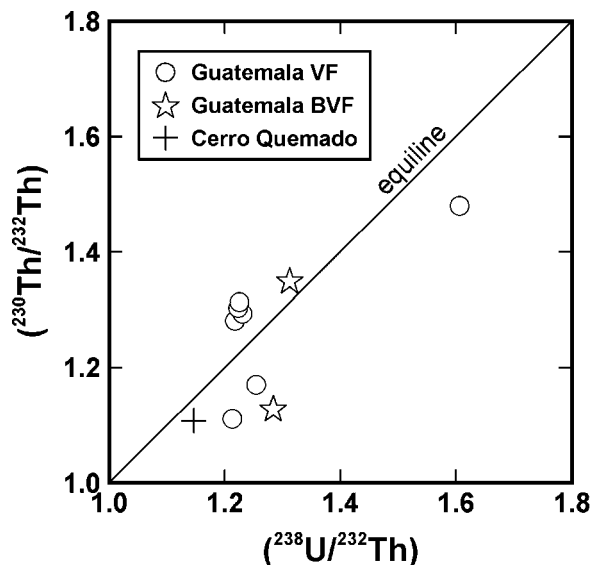flux-melting of the crust [*Keppler and Wyllie*, 1990; *Black et al.*, 1997]. However, below we suggest that crustal signatures in Guatemala may be characterized by ^{230}Th, not ^{238}U, excess. The crustal signature of Gua7 and some Guatemalan ignimbrites supports the previous assertions by *Feigenson and Carr* [1986], *Carr et al.* [2003] and *Feigenson et al.* [2004] that a crustal overprint is recognizable in some Guatemalan magmas. Note that an obvious crustal signature appears to be lacking in ignimbrites from El Salvador (Figure 10). This may be further evidence that
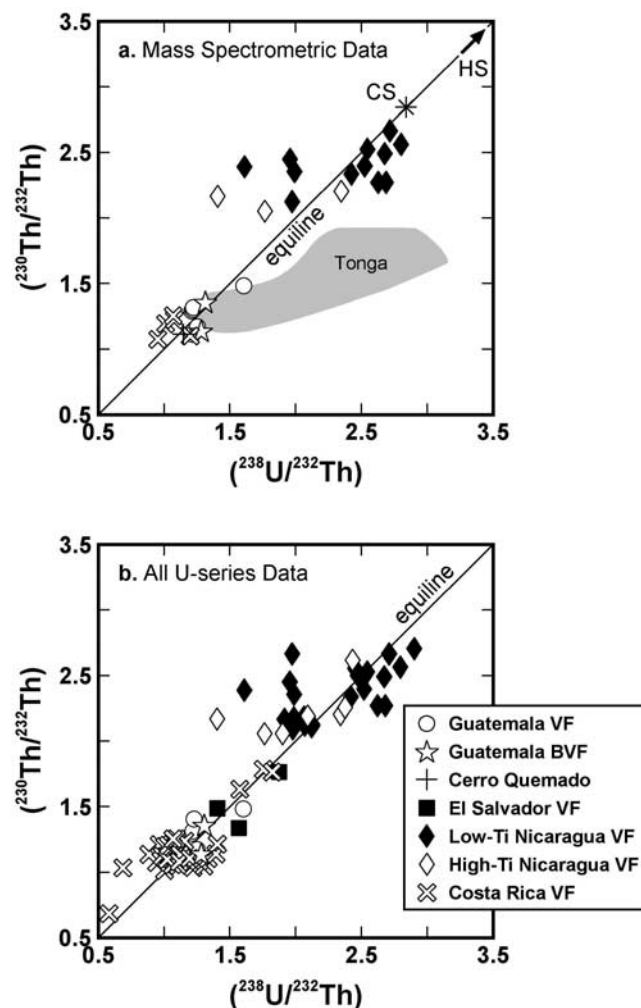

Figure 6. Comparison of U-series data from Guatemala with that from the rest of the Central American subduction zone. (a) Mass spectrometric data for Central America from *McDermott and Hawkesworth* [1991], *Reagan et al.* [1994], and *Thomas et al.* [2002] and (b) symbol legend. U-series data for Tonga lavas from *Turner et al.* [1997]. CS and HS represent calculated (^{230}Th/^{232}Th) from mean U/Th ratios of carbonate and hemipelagic sediments being subducted along the Central American subduction zone. Mean U/Th ratios from *Patino et al.* [2000]. Also shown in Figure 6b is alpha spectrometry + mass spectrometric data for Central America. Added alpha spectrometry data from *Allegre and Condomines* [1976], *Condomines and Sigmarsson* [1993], *Reagan et al.* [1994], *Herrstrom et al.* [1995], *Herrstrom* [1998], and *Clark et al.* [1998].
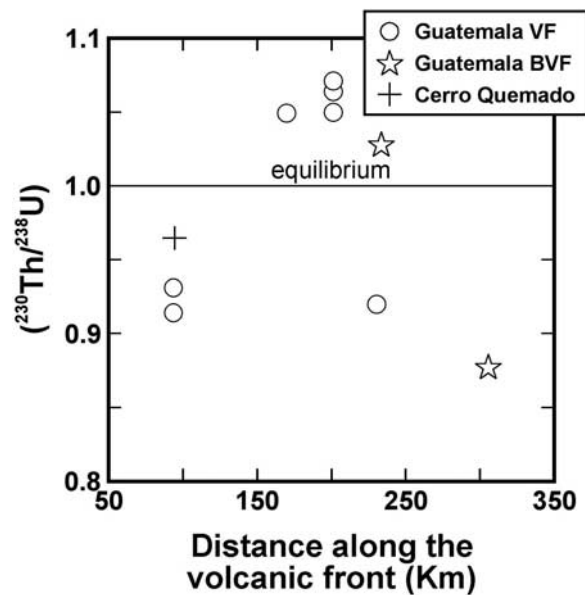

Figure 5. U-series results for Guatemalan volcanic rocks on standard equiline diagram.

Figure 7. (^{230}Th/^{238}U) disequilibrium along the Guatemalan portion of the Central America volcanic front (although not included on plot, Pacaya sample from *Herrstrom* [1998] has (^{230}Th/^{238}U) = 1.25).

older, Mesozoic and Paleozoic, continental crust does not extend beneath the modern volcanic front south of Guatemala [*Rogers*, 2003].

6. Causes of U-Th Disequilibrium in the Remaining Guatemalan Basalts and Andesites

[16] As stated in the introduction, the ^{238}U excesses that commonly occur in subduction zone lavas have been ascribed to the preferential transport of U, relative to Th, in a fluid component from subducting lithosphere into the overlying mantle wedge [e.g., *Elliott*, 2003]. Indeed, this has been the general explanation advanced to produce the ^{238}U excesses observed in Central American lavas from Nicaragua and Costa Rica [*Reagan et al.*, 1994; *Herrstrom et al.*, 1995; *Thomas et al.*, 2002]. For ^{238}U excesses to be maintained fluid transfer must have occurred within the past 350 kyr or so. *Cameron et al.* [2002] have presented forward models that suggest the involvement of a fluid component, or components, in the source region of Guatemalan lavas. Hence, we assume that the ^{238}U excesses recorded in about one half of Guatemalan basalts and andesites are the result of fluid fluxing from either subducted sediments, subducted oceanic crust/mantle, or both. What are more difficult to explain, and hence, much more interesting, are the ^{230}Th excesses in the remaining Guatemalan volcanic rocks. There are four possible explanations for these ^{230}Th excesses: (1) wedge melting in the garnet stability field; (2) addition of a eclogitic melt component from subducted oceanic crust; (3) addition of a sediment melt component; and (4) crustal contamination. We will evaluate each of these possibilities in turn, particularly in light of the observed correlations between U-Th disequilibrium and various elemental concentrations and ratios (Figure 8).

[17] Garnet has a well-documented preference for U over Th, so that having it control the U-Th fractionation during mantle melting has been a key cog of many models for the common ^{230}Th excess found in oceanic basalts [*Beattie*, 1993; *LaTourrette et al.*, 1993; *Hauri et al.*, 1994; *Salters and Longhi*, 1999; *Salters et al.*, 2002]. Thus the ^{230}Th excesses in Guatemala could be due to the presence of residual garnet during melt generation in the mantle wedge. ^{230}Th excesses may be enhanced if melting occurs by decompression with ^{230}Th ingrowth during upwelling. Recent studies have suggested a greater role for decompression melting in the mantle wedge of a number of subduction zones [*Pearce and Parkinson*, 1993; *Pearce and Peate*, 1995; *Sisson and Bronto*, 1998; *Bourdon et al.*, 1999; *Conder et al.*, 2002; *Kincaid and Hall*, 2003; *Cervantes and Wallace*, 2003], including southeastern Guatemala [*Cameron et al.*, 2002]. Regardless of the exact melting mechanism, *Turner and Foden* [2001] and *Turner et al.* [2003b] suggest that mantle-wedge melts generated with residual garnet should also have high Tb/Yb ratios (0.4). The Tb/Yb ratios of Guatemalan basalts and andesites, however, are all around 0.3. A further problem is that mantle melting with (or without) residual garnet, should not greatly fractionate Th from Ba or Nb [e.g., *Hauri et al.*, 1994] and therefore cannot explain the observed correlations between ^{230}Th excess and Th/Nb and Ba/Th (Figure 8).

[18] ^{230}Th excesses could also be delivered to the Guatemalan mantle wedge by melts of subducted, eclogitic oceanic crust [*Sigmarsson et al.*, 1998; *Dosseto et al.*, 2003]. Such melts should obviously bear a strong garnet signature: e.g., high Tb/Yb, La/Yb and Sr/Y [*Sigmarsson et al.*, 1998; *Dosseto et al.*, 2003; *Kelemen et al.*, 2003]. Thus, ^{230}Th excess would be expected to exhibit positive correlations with these, and analogous, parameters, in any subsequent melts of the mantle wedge. However, (^{230}Th/^{238}U) shows no correlation with either La/Yb or Sr/Y, and only a weak positive correlation with Tb/Yb, for our Guatemalan basaltic-andesitic samples. Invoking melts of subducted oceanic crust is also problematic in that previous geochemical studies throughout Central America have shown no evidence for an eclogitic melt component [*Carr et al.*, 1990, 2003; *Leeman et al.*, 1994; *Cameron et al.*, 2002; *Feigenson et al.*, 2004; *Eiler et al.*, 2005].

[19] Recent geochemical studies in Central America have, however, advocated that melts of subducted sediment may be an important slab component, particularly in Guatemala [*Cameron et al.*, 2002; *Eiler et al.*, 2005]. Whether a sediment melt contains a ^{230}Th excess or not is critically dependent on the sediment mineralogy at depth, which is not well constrained. Nevertheless, attributing the ^{230}Th excesses seen in Guatemala to a sediment melt component is not feasible as all of the sediments subducting in Central America are characterized by exceedingly high (^{230}Th/^{232}Th) (Figure 6a). As a result, melts of such sediment would also have equivalently high (^{230}Th/^{232}Th), much higher than those of any Guatemalan (or Costa Rican) lavas, and ^{230}Th excess should exclusively correlate with higher (^{230}Th/^{232}Th), which it does not (Figure 5).

[20] Our preferred cause of the ^{230}Th excesses present in some Guatemalan lavas is crustal contamination. *Bourdon et al.* [2000], *Garrison et al.* [2006], and *Jicha et al.* [2006] have all suggested that crustal contamination can explain observed ^{230}Th excesses in some volcanic rocks from
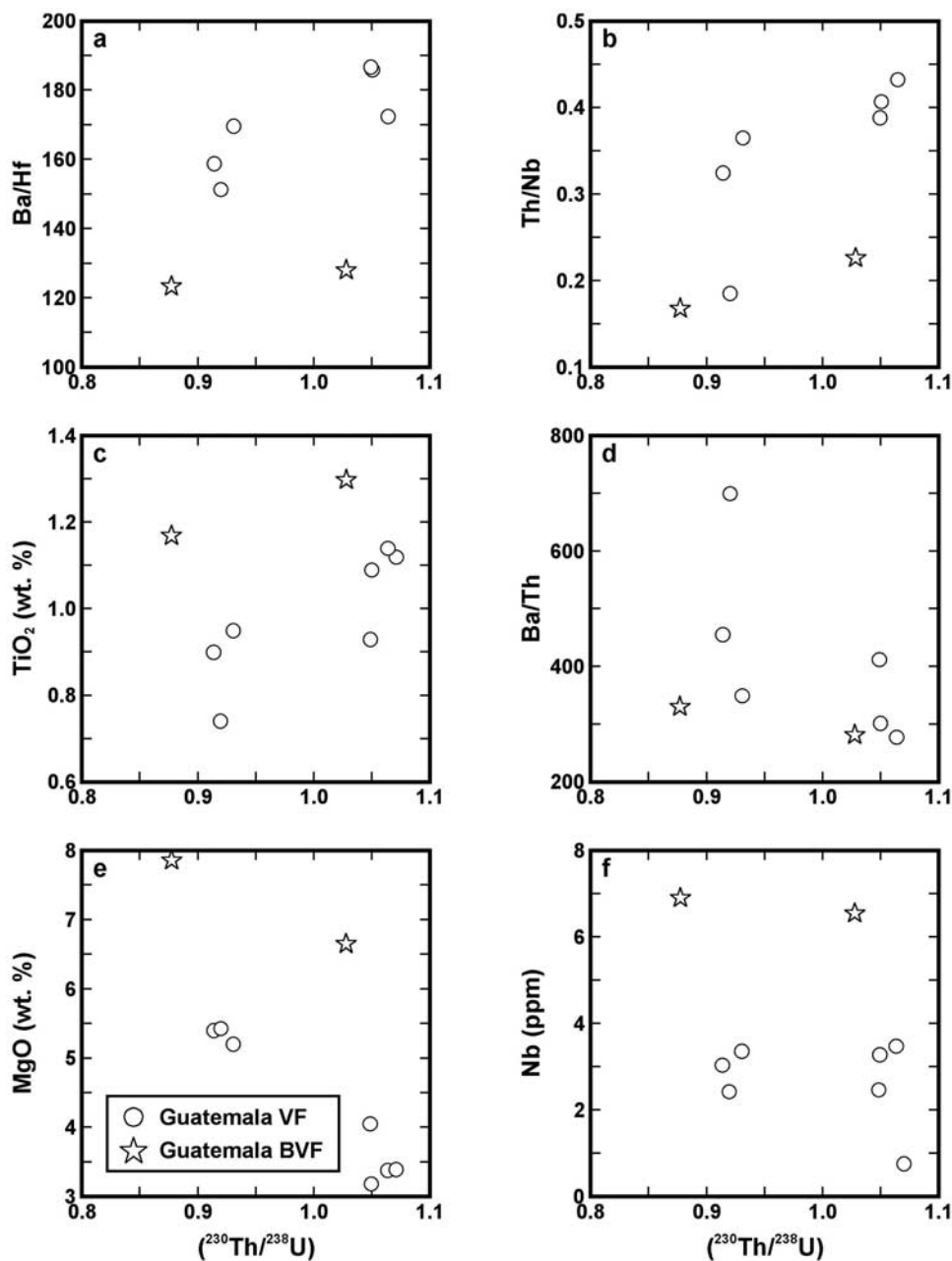
Figure 8. Observed correlations between (^{230}Th/^{238}U) disequilibrium and incompatible element ratios, major elements and trace elements for Guatemalan volcanic rocks of this study, excluding the acid andesite from Cerro Quemado.

Andean subduction zone volcanoes. In detail, the development of ^{230}Th excess requires that parental magmas from the mantle mix with crustal melts that have a substantial ^{230}Th excess [*Bourdon et al.*, 2000; *Garrison et al.*, 2006; *Jicha et al.*, 2006]. In addition, mixing/contamination must have occurred in the past 300 ka in order to preserve the ^{230}Th excess. Residual source mineralogy is crucial in determining whether crustal melts have Th or U excesses [*Bourdon et al.*, 2000; *Berlo et al.*, 2004; *Dufek and Cooper*, 2005; *Garrison et al.*, 2006; *Jicha et al.*, 2006]. For crustal melts, residual garnet is once again thought to be a major cause of the production of ^{230}Th excesses [*Bourdon et al.*, 2000; *Berlo et al.*, 2004; *Dufek and Cooper*, 2005; *Garrison*

et al., 2006]. However, partial melting with residual zircon, and perhaps magnetite, may also generate ^{230}Th excesses [*Berlo et al.*, 2004; *Jicha et al.*, 2006]. Crustal melting without residual garnet appears to be a requisite in Guatemala because the lavas bearing ^{230}Th excesses lack an obvious garnet signature. We pointed out above that contamination with Guatemalan Mesozoic crust leads to high Th/Nb and low Ba/Th ratios (Figure 10). Both high Th/Nb and low Ba/Th correlate with Th excess (Figure 8). Th excess also correlates with high Ba/Hf (Figure 8a). Gua 7, our contaminated lava from Cerro Quemado, has a very high Ba/Hf ratio of 283, suggesting that crustal contamination in Guatemala may generate high Ba/Hf ratios, as is the
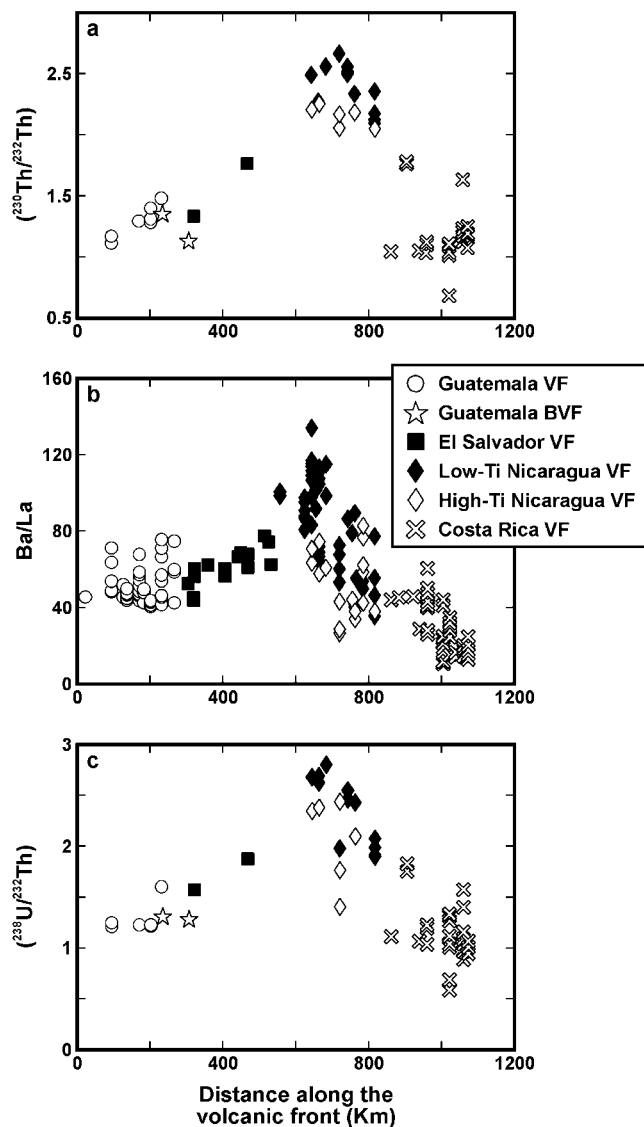
Figure 9. (^{230}Th/^{232}Th), Ba/La, and (^{238}U/^{232}Th) variations along the Central American volcanic front for lavas with SiO$_2$ < 55 wt.%. Includes both mass spectrometric and alpha spectrometric data for U-series activities. Also includes new U-series results for two BVF samples from Guatemala. Ba/La ratios from slightly modified version of the Centam database (http://www-rci.rutgers.edu/~carr/index.html).

Carr, 1986; Carr et al., 1990; Walker et al., 1995]. There are a number of possible reasons for enhanced crustal contamination beneath central Guatemala. The first is the presence of abnormally high crustal temperatures because of greater magmatic input, as reflected in the persistent recent activity at both Fuego and Pacaya [Martin and Rose, 1981;
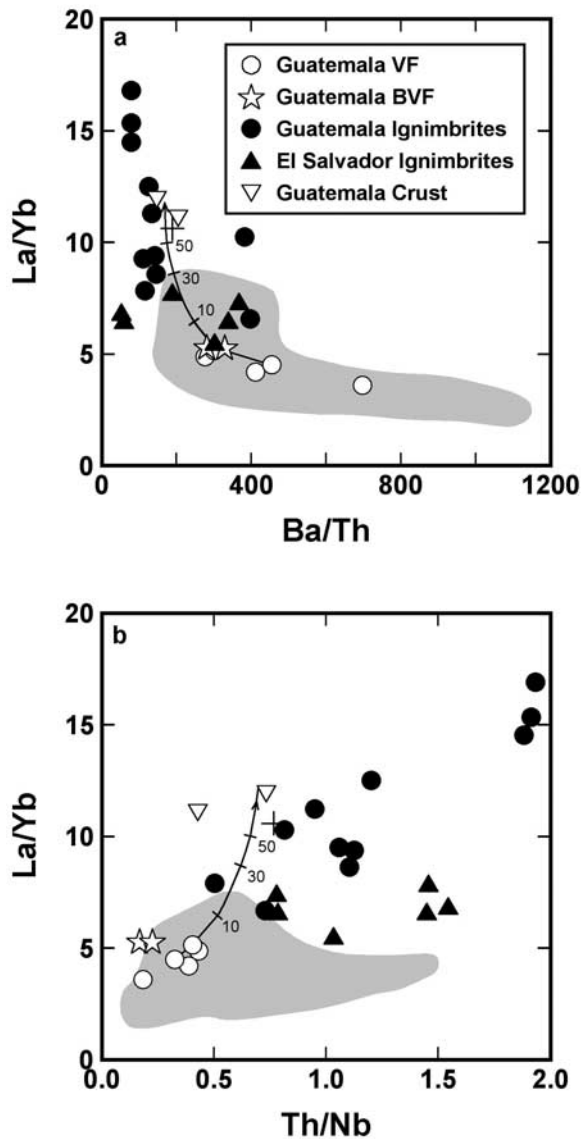

Figure 10. La/Yb versus Ba/Th (a) and Th/Nb (b) for volcanic rocks of this study; Guatemalan mafic VF volcanic rocks (shaded field; SiO$_2$ < 55 wt.%; modified Centam database); and siliceous ignimbrites from Guatemala and El Salvador. Trace element data for siliceous ignimbrites from unpublished results of T. Vogel and L. Patino. Inverted triangles are compositions of Mesozoic metamorphic rocks from southeastern Guatemala. Solid lines in Figures 10a and 10b are calculated trace element changes resulting from combined assimilation/fractional crystallization (AFC) starting from parental composition of SM 114. Tic marks show extent of crystallization (to 50%). Other parameters assumed in the model: D$_{Th}$ = 0.01; D$_{Nb}$ = 0.02; D$_{La}$ = 0.01; D$_{Yb}$ = 0.10; rate of assimilation/rate of crystallization = 0.50.

case below Parinacota volcano in Chile [Bourdon et al., 2000]. Thus, contamination with Mesozoic crust appears capable of producing all of the requisite trace element and isotopic characteristics of the magmatic end member with ^{230}Th excess. Moreover, crustal contamination would likely lead to lower MgO contents, also an attribute of the lavas exhibiting ^{230}Th excess (Figure 8e).

[21] Mafic lavas erupted in central (and western) Guatemala have slightly higher ^{87}Sr/^{86}Sr, and slightly lower ^{143}Nd/^{144}Nd than those erupted in westernmost El Salvador and southeastern Guatemala (Figure 12), providing further support for increased crustal contamination, with more radiogenic Mesozoic crust, in this region [Feigenson and
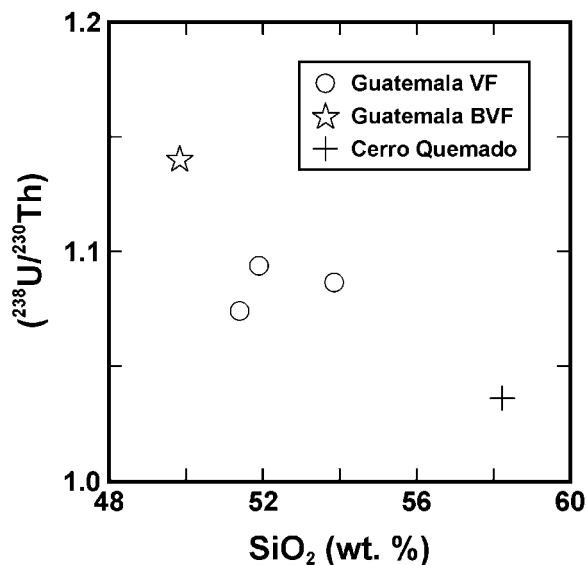
Figure 11. $(^{238}U/^{230}Th)$ versus SiO_2 for Guatemalan volcanic rocks with ^{238}U excess.

Kitamura and Matías, 1995; *Venzke et al.*, 2006]. A second possibility is that arc-normal extension related to North American-Caribbean plate interactions is propagating westward into central Guatemala as predicted by *Burkart and Self* [1985]. In such a tectonic setting with incipient extension, crustal contamination should be maximized [*Glazner and Ussler*, 1989]. And lastly, recent eruptive activity at Fuego and Pacaya may reflect newly developed magmatic conduit systems, which according to the models of *Myers et al.* [1985] and *Singer et al.* [1989] would be more susceptible to crustal contamination.

7. Is ^{230}Th Excess in Central American Basalts and Andesites Always Caused By Crustal Contamination?

[22] Above we have suggested that the ^{230}Th excess in Guatemalan basalts and andesites is the result of crustal contamination. Within subduction zone basalts and andesites worldwide, ^{230}Th excess is generally restricted to those erupted at continental margins [*Newman et al.*, 1984; *Gill and Williams*, 1990; *Davidson et al.*, 2005; *Garrison et al.*, 2006]. This suggests that crustal contamination could be the general cause of Th excess at subduction zones, as previously suggested by *Newman et al.* [1984] and *Davidson et al.* [2005]. A broad discussion of this suggestion is beyond the scope of this paper and the knowledge of the authors. However, we can address this issue for the Central American subduction zone as a whole. Selected lavas from Nicaragua and Costa Rica also exhibit ^{230}Th excess (Figure 6).

[23] If ^{230}Th excess is related to crustal contamination we might expect lessened disequilibrium in Nicaraguan magmas because they pass through thinner crust [*Carr*, 1984; *Carr et al.*, 2003]. Although ^{238}U excesses are indeed more common in Nicaragua [*Reagan et al.*, 1994; *Thomas et al.*, 2002], significant ^{230}Th excess is seen in andesitic lavas from Concepcion volcano [*McDermott and Hawkesworth*, 1991; *Thomas*, 2002] and in high-Ti basaltic lavas

from the Nejapa cinder cone alignment [*Reagan et al.*, 1994], focusing on only higher quality mass spectrometric data. The high-Ti basalts are quite primitive compositions, with Mg#'s of 60 and 63, suggesting limited crustal contamination. This is consistent with their trace element and isotopic compositions [*Walker et al.*, 1990; *Carr et al.*, 1990, 2003; *Feigenson et al.*, 2004]. The Concepcion lavas are less well studied, however, the Pb isotopic composition of one of them shows no evidence for contamination with more radiogenic crust [*Feigenson et al.*, 2004]. Hence, we feel that current data is weighted against the production of ^{230}Th excesses in Nicaragua via crustal contamination, particularly in the case of the high-Ti basalts, although we cannot completely rule out the possibility of some form of cryptic contamination with mafic crustal melts. In contrast, *Thomas et al.* [2002] attribute the ^{230}Th excesses in the Nicaraguan (and Costa Rican) lavas to a combination of: a
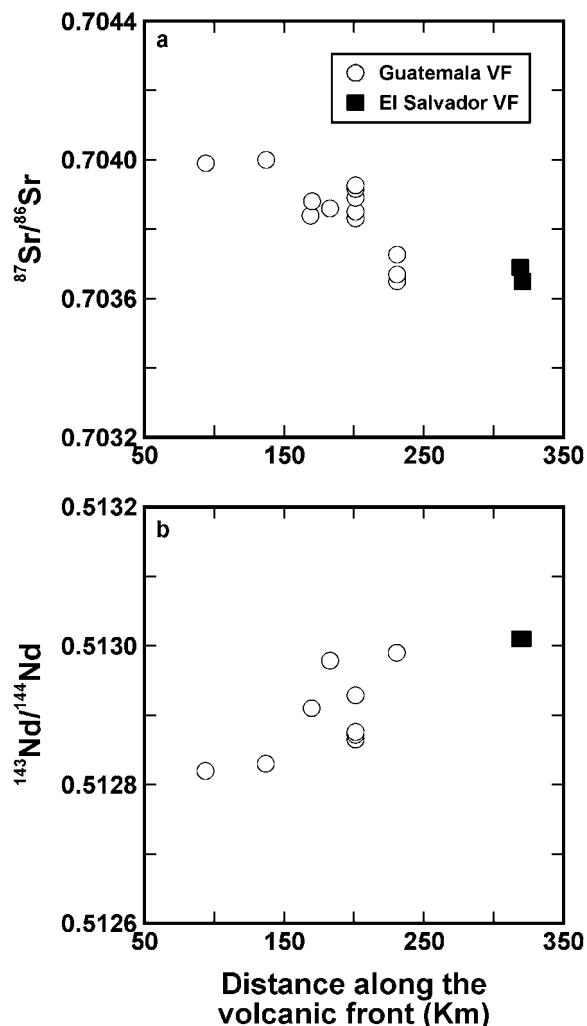

Figure 12. Variations in (a) $^{87}Sr/^{86}Sr$ and (b) $^{143}Nd/^{144}Nd$ along the northern portion of the Central American volcanic front (Guatemala and westernmost El Salvador) for volcanic rocks with $SiO_2 < 55$ wt.% (from modified Centam database). Note that slightly more radiogenic values begin to appear in central Guatemala moving northwestward from El Salvador.
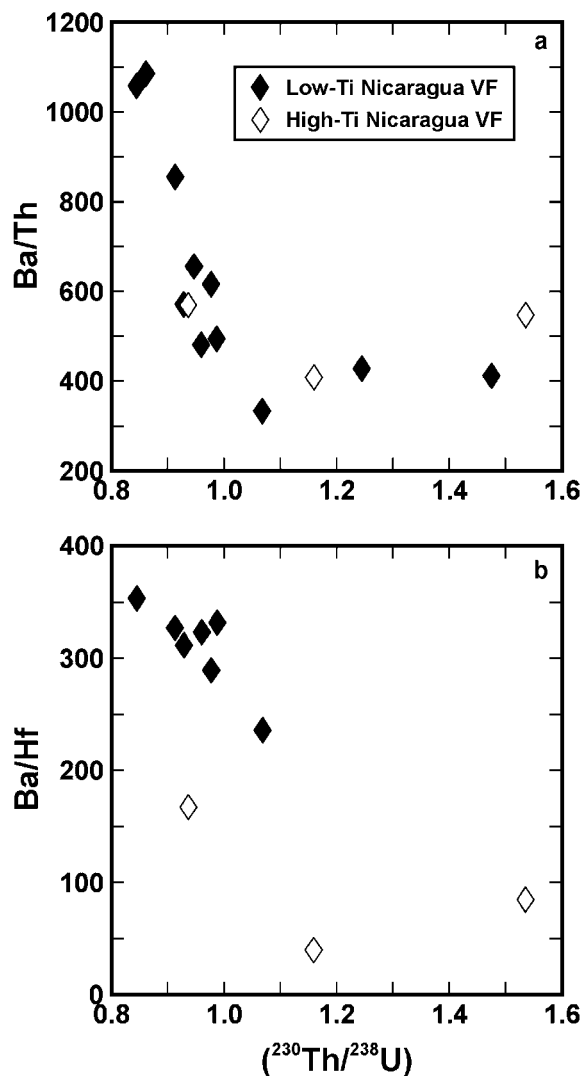
Figure 13. (a) Ba/Th and (b) Ba/Hf versus (^{230}Th/^{238}U) for Nicaraguan volcanic rocks (mass spectrometric data only as in Figure 6a).

pyroxene, in which $D_U > D_{Th}$ [*Wood et al.*, 1999; *Turner et al.*, 2000b; *Landwehr et al.*, 2001].

[24] ^{230}Th excess is common in basaltic lavas erupted in Costa Rica, particularly in central Costa Rica, southeast of Arenal volcano (Figures 6 and 14). This terminal segment of the volcanic front, southeast of the Quebrada Sharp Contortion, is characterized by shallower subduction [*Protti et al.*, 1995; *Peacock et al.*, 2005], thickened underlying crust [*Carr*, 1984; *Carr et al.*, 2003], and eruption of magmas from a geochemically distinct source [*Carr et al.*, 1990; *Feigenson and Carr*, 1993; *Leeman et al.*, 1994; *Herrstrom et al.*, 1995; *Abratis and Wörner*, 2001; *Feigenson et al.*, 2004]. ^{230}Th excess in this region shows no correlation with degree of differentiation (Figure 15), which again suggests minimal contamination, unless the contaminant has a mafic composition. Minimal contamination is also consistent with the Sr, Nd, Pb and O isotopic compositions of Costa Rican basalts [*Feigenson and Carr*, 1986; *Carr et al.*, 1990; *Cameron et al.*, 2002; *Feigenson et al.*, 2004; *Eiler et al.*, 2005]. Th enrichment in Costa Rica can instead be successfully modeled with a reduced slab fluid component, ^{230}Th ingrowth, and residual garnet in the mantle wedge [*Thomas et al.*, 2002]. The presence of increased residual garnet in central Costa Rica is consistent with the elevated Tb/Yb of erupted lavas (Figure 16) [*Turner et al.*, 2003b; *Kokfelt et al.*, 2003; *George et al.*, 2003] and with inverse modeling of rare-earth elements [*Feigenson and Carr*, 1993].

[25] In sum, ^{230}Th excesses in both Nicaraguan and Costa Rican basic magmas can be attributed to subcrustal processes and cannot be linked to contamination with older, radiogenic crust, as in Guatemala. Although we cannot eliminate a possible role of mafic crustal melts, we suspect that ^{230}Th excesses found in the southern half of the Central American subduction zone are not always caused by crustal contami-
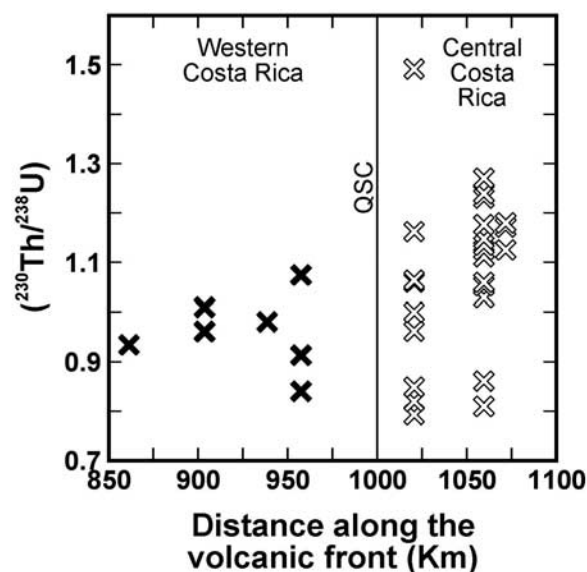
much reduced slab component, ^{230}Th ingrowth and garnet control during melting. A much reduced slab component is consistent with the lower Ba/Th, Ba/Hf and Th/Nb ratios of the Nicaraguan lavas that bear ^{230}Th excesses (Figure 13) [*Thomas et al.*, 2002]. Garnet control, on the other hand, is hard to reconcile with the unusually low LREE/HREE ratios of the high-Ti basalts [*Feigenson and Carr*, 1993; *Reagan et al.*, 1994]. *Reagan et al.* [1994] alternatively suggested that preferential melting of amphibole could explain the Th enrichment in the Nicaraguan high-Ti basalts. However, the experimental results of *Tiepolo et al.* [2000] indicate that amphibole is incapable of producing significant fractionation of U from Th during partial melting in the mantle. These problems lead us to suggest that the high-Ti lavas, who clearly have an unusual history [*Walker et al.*, 1990, 2001], originate largely by decompression melting of the mantle wedge. Since the high-Ti lavas lack a garnet signature, we would attribute the observed ^{230}Th excesses to ingrowth during upwelling and residual aluminous clino-

Figure 14. (^{230}Th/^{238}U) along the Costa Rican portion of the Central American volcanic front. All U-series data is included (sources of data as in Figure 6). Vertical line shows approximate location of Quebrada Sharp Contortion (or QSC). Western Costa Rican samples filled to highlight their greater uniformity and relative lack of ^{230}Th excess.
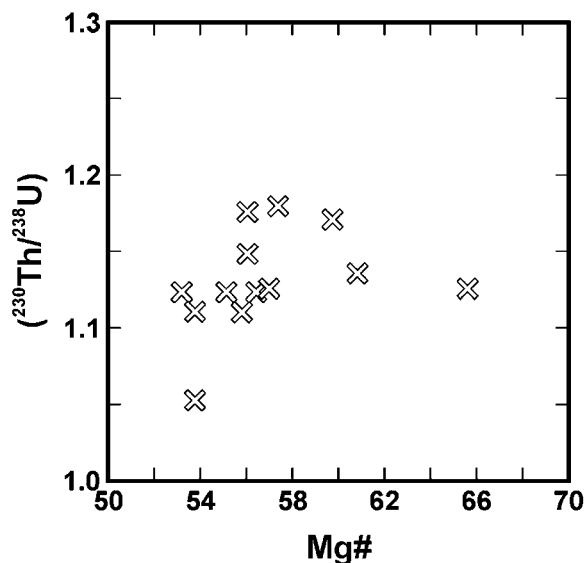
Figure 15. $(^{230}Th/^{238}U)$ versus Mg# for volcanic rocks from central Costa Rica. Includes all samples where both U-series and major element data are available.

nation. This suspicion needs to be tested at a local scale in some individual volcanoes in Nicaragua and Costa Rica.

8. $(^{230}Th/^{232}Th)$ Variations Along the Central American Volcanic Front

[26] The new U-Th disequilibrium data for Guatemalan lavas serve to complete the picture of $(^{230}Th/^{232}Th)$ variations along the Central American volcanic front (Figure 9). The resulting pattern is identical to that shown by a number of geochemical tracers, such as Ba/La, showing peak values in west-central Nicaragua and lowest values at the extremities of the arc (Figure 9). The accepted explanation of these along-arc variations is that they track magmatic contributions, or signals, from the subducted Cocos "slab" which are maximized in west-central Nicaragua and minimized at
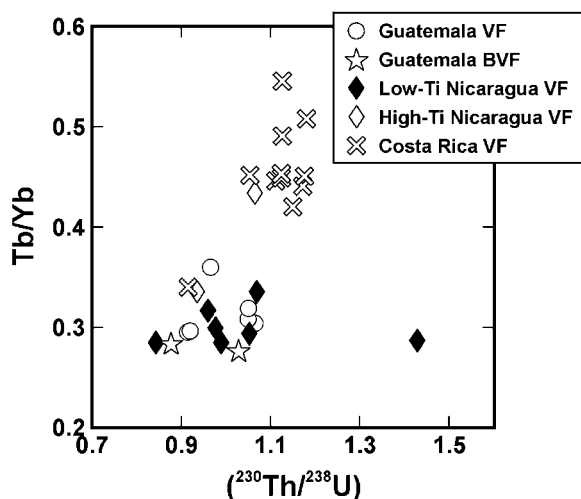
both extremities of the subduction zone [*Carr et al.*, 1990; *Carr et al.*, 2003]. Slab signals in Central American lavas are a complex amalgam of two to three components [*Patino et al.*, 2000; *Carr et al.*, 2003; *Eiler et al.*, 2005]. [10]Be, because of its half-life of about 1.5 Ma, is an unambiguous tracer of one of these components, namely the upper, hemipelagic portion of the sedimentary veneer subducting in Central America [*Reagan et al.*, 1994]. As previously discussed by *Reagan et al.* [1994], the positive correlation between [10]Be and $(^{230}Th/^{232}Th)$ (Figure 17) strongly implicates this hemipelagic component as a major contributor to the unusually high $(^{230}Th/^{232}Th)$ ratios in Nicaragua. Subducting sediment is also believed to control the Th isotopic composition of lavas in the Sunda arc [*Turner and Foden*, 2001]. These case studies support the contention of *Plank and Langmuir* [1993] that Th outputs in subduction zones are directly tied to sedimentary inputs. The unusually high $(^{230}Th/^{232}Th)$ ratios in Nicaragua may also reflect an extended history of U enrichment via a fluid component from the subducting Cocos plate [*Reagan et al.*, 1994]. The fluid likely comes from the altered oceanic crust [e.g., *Elliott*, 2003] and is characterized by elevated Ba/Th ratios given the positive correlation between Ba/Th and ^{238}U excess (Figure 13a). Thus, the Ba/Th ratio may, at times, be more useful as a tracer of the fluid component in Central America, as recently suggested by *Eiler et al.* [2005], and not of a subducted carbonate sedimentary component as advocated by *Patino et al.* [2000]. This would also be more in keeping with global surveys of subduction zones that utilize Ba/Th ratios for identifying a fluid component from subducted, altered oceanic crust [*Hawkesworth et al.*, 1997; *Elliott*, 2003]. Our suspicion, however, is that the peaks in slab input to Nicaraguan magmas actually reflect increased contributions from both sedimentary and fluid components. Thus, regional models that stress the relative importance of
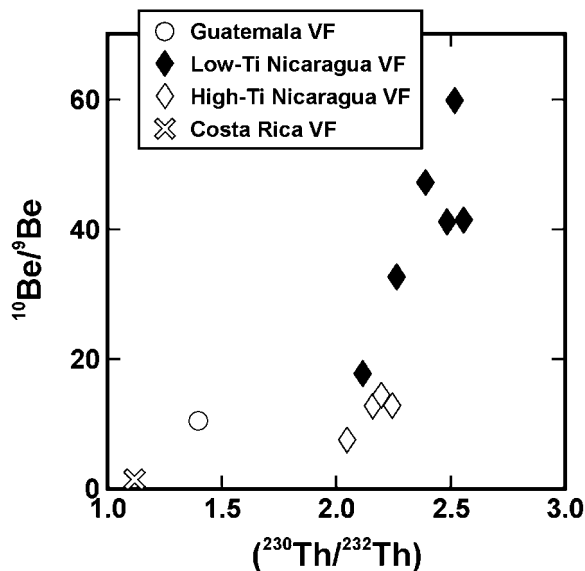

Figure 16. Tb/Yb versus $(^{230}Th/^{238}U)$ for Central American volcanic rocks. Includes alpha spectrometry data.

Figure 17. [10]Be/[9]Be versus $(^{230}Th/^{232}Th)$ for Central American volcanic rocks. Includes alpha spectrometry data. [10]Be/[9]Be ratios originally from *Morris et al.* [1990] and *Reagan et al.* [1994].

one over the other for Nicaragua [e.g., *Eiler et al.*, 2005] are probably oversimplified.

9. Conclusions

[27] Guatemalan lavas exhibit both ^{238}U and ^{230}Th excesses. The latter are restricted to central Guatemala. As in other subduction zones, ^{238}U excess is attributed to the preferential transport of U in metasomatizing hydrous fluids released from the subducting plate. The ^{230}Th excesses in lavas from central Guatemala, on the other hand, we relate to crustal contamination, given the observed correlations between ^{230}Th excess, various trace element ratios and MgO. The trace element ratios and radiogenic isotope compositions of lavas from central Guatemala suggest that crustal contamination involved, to some extent, radiogenic Mesozoic crust. Thus, the U-series data affirm that differentiation in the crust is an important cause of some of the regional geochemical variations along the Central American volcanic front, particularly in Guatemala where the crust is relatively thick and old. Some lavas from Nicaragua and Costa Rica also exhibit ^{230}Th excesses, but most of these, we feel, are more credibly linked to melting processes in the mantle wedge, not to crustal contamination. The (^{230}Th/^{232}Th) ratios of Guatemalan lavas are much lower than those seen in Nicaragua, instead overlapping those of Costa Rican lavas. Hence, variations of (^{230}Th/^{232}Th) along the Central American volcanic front resemble those of a number of isotopic and trace ratios, such as Ba/La and U/Th. All such variations indicate that slab contributions to the mantle wedge are maximized below west-central Nicaragua. The unusually high (^{230}Th/^{232}Th) ratios in west-central Nicaragua are clearly tied to maximized inputs from subducted sediments [*Reagan et al.*, 1994].

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