Chapter 22

Petrology and geochemistry of lavas

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"This continuity disappears, however, if one considers individual parts of the [Central American] chain and examines separate groups of volcanoes within a restricted volcanic field. It then becomes apparent that the continuity of the province as a whole is the result of grouping excessively large segments of the chain." A.R. McBirney: Compositional variations in Cenozoic calc-alkaline suites of Central America. Intern. Upper Mantle Sci. Rept. 16, 1969.

22.1 INTRODUCTION

Since the elegant summary of Central American geology by Weyl [1] in 1980, petrological and geochemical studies unveiled large variations in the Tertiary and Quaternary volcanics both along the volcanic chain and across it. The active volcanoes define an abrupt volcanic front, located 165 to 190 km inland from the Middle America trench (MAT). The front consists of 39 distinct centers or clusters of vents that occur in 100 to 300 km long lineaments or segments. Most of the active volcanic centers are complexes constructed primarily of basaltic to andesitic lavas. Several centers include calderas that erupted extensive silicic fall and flow deposits. Throughout most of Central America, the active volcanoes lie on the trenchward side of an extensive plateau of Tertiary volcanics, comprising primarily voluminous ignimbrite sheets that dominate the Tertiary topography. Mafic composite volcanoes, the predecessors of the active volcanic front, are recognizable in many areas and should ultimately be useful for defining the past positions of the volcanic front. Relatively few studies of the Tertiary volcanics have expanded the stratigraphic and petrologic knowledge base since Weyl's review in 1980.

This chapter will first describe the tectonic and geologic settings of the diverse Quaternary volcanoes of Central America. Some aspects of their petrology and petrography are then reviewed. In 1969, McBirney [2] recognized a few regional variations in petrology and geochemistry but advances in analytical instruments allowed us to define a large number of geochemical variations both along the Quaternary volcanic front and across it. Reviewing these geochemical results is the primary focus of this chapter. Finally, the chapter briefly describes advances in Tertiary volcanic stratigraphy and new geochemical and geochronological studies of the Tertiary volcanics in Nicaragua and Costa Rica.

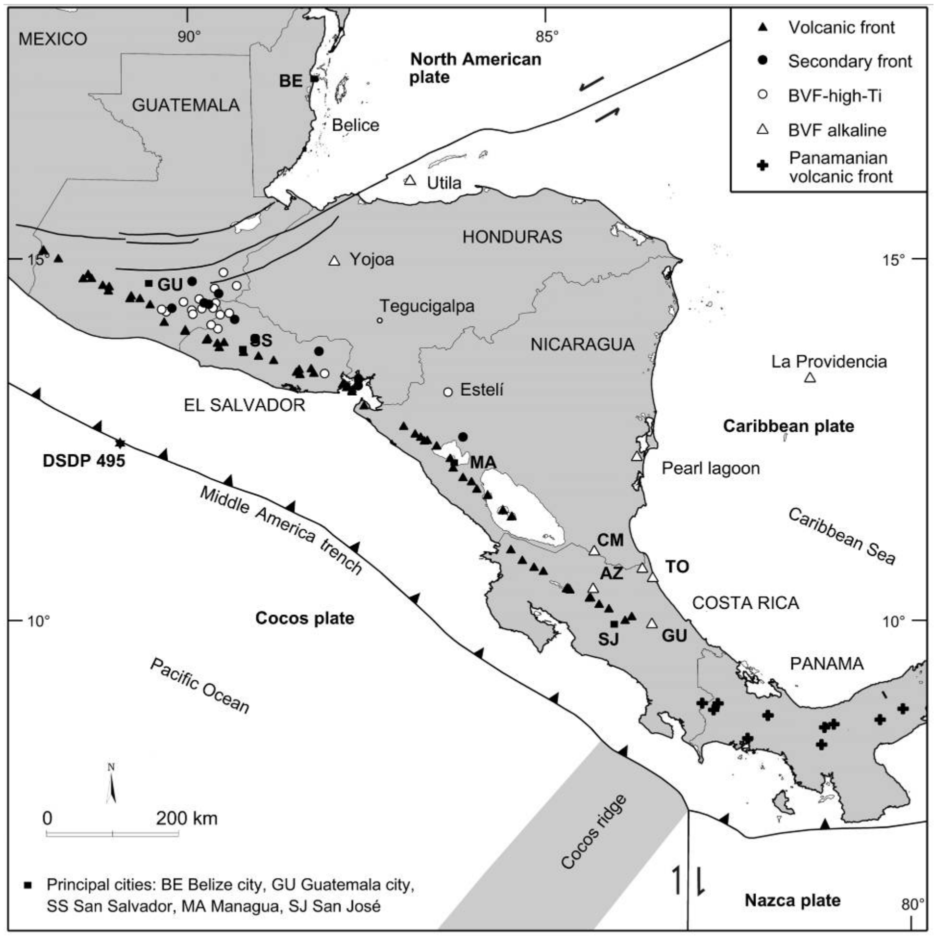

Figure 22.1. Volcanological framework of Central America. The letters refer to back arc volcanos; CM is Cerro Mercedes, AZ is Aguas Zarcas, GU is Guayacán and TO is Tortugero.

22.2 TECTONIC AND GEOLOGIC SETTING OF VOLCANOES

The historically active Central American volcanoes occur above the convergent plate boundary between the subducting Cocos plate and the overriding Caribbean plate, whereas, the volcanoes in Panama are the result of Nazca-Caribbean plate convergence (Fig. 22.1). Because the volcanoes of Panama are derived via a different plate convergence process from the rest of Central America and because they have very little recent activity, they are not considered in detail here. However, substantial progress has been made on the tectonic setting and geochemistry of Panamanian volcanoes. De Boer *et al.* [3] defined the plate tectonic setting of the Tertiary and Quaternary volcanoes of western Panama and provided evidence for active subduction below western Panama. The geochemistry of the volcanism in western Panama reveals strong similarities to central Costa Rica but is distinguished by the discovery of adakitic rocks in several localities in western Panama [4]. Recently, the similarities between the volcanism in western Panama and the northernmost segment of the Cascades arc were related to the subduction in both areas of young and hot lithosphere [5].

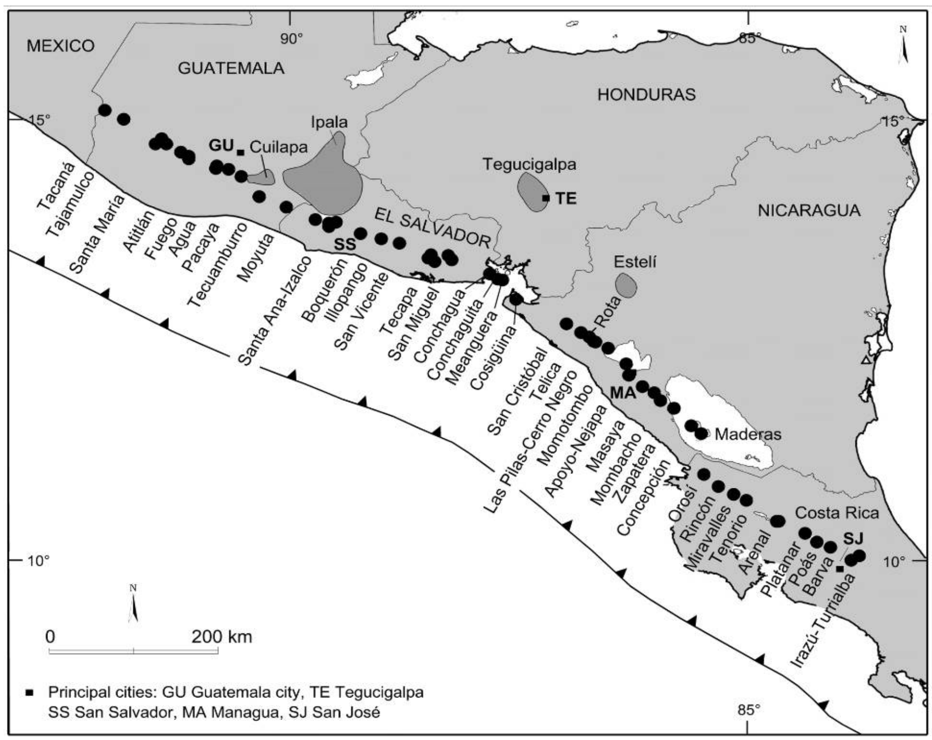

Figure 22.2. Locations of volcanic centers and subalkaline BVF fields. The dark grey areas show approximate extents of the BVF volcanic fields with subalkaline and high-TiO_2 character.

The Cocos-Caribbean plate convergence that gives rise to the highly active and closely spaced Central American volcanic front is bounded by tectonically complex areas that obscure the triple junctions required by simple plate tectonic theory. To the northwest, a zone of strike slip faults, cutting across Guatemala, separates the Caribbean and North American plates, but the curvature of the faults is opposite what would be expected from the North American-Caribbean pole of rotation. Volcanism ceases as the strike slip fault zone disappears near the volcanic front at the Mexico-Guatemala border. There is no convincing explanation for why volcanism ends near this plate boundary or for the long volcanic gap that extends all the way to El Chichón volcano in Mexico.

At the southeast end of the Central American volcanic front, the subduction of the Cocos ridge coincides with the substantial volcanic gap between central Costa Rica and western Panama (Fig. 22.1). Buoyant hot spot tracks commonly cause gaps in volcanism and so the termination of volcanism here is qualitatively explained by subduction of relatively dry and over-thickened oceanic crust and by reduction in thickness of the mantle wedge. However, the detailed plate boundaries in the area from central Costa Rica to western Panama are not universally agreed on because of the development of microplates fragmenting the overriding Caribbean plate.

The geochemistry of Central American lavas varies substantially with changing tectonic setting along and across the plate margin. Current understanding of the relationships between tectonics and volcanism indicate three distinguishable volcanic systems (Figs. 22.1 and 22.2). The two major ones, the volcanic front and the back-arc, appear to form by substantially different melting processes and both have substantial geochemical zonations. The discussion of petrology and geochemistry below will focus on the regional and local variations in geochemistry discovered within both the volcanic front and the back-arc.

Along the Cocos-Caribbean plate margin, the majority of volcanic output occurs at a narrow volcanic front comprising 39 distinct clusters or centers with overlapping volcanoes. Most centers are complex massifs with multiple cones, domes, calderas and numerous minor vents. Only a few centers are simple cones (e.g. Agua in Guatemala). The Cocos-Caribbean volcanic front is divided into distinct lineaments, 100 to 300 km long, a pattern that was pointed out by Dollfus and Montserrat [6] more than 100 years ago. Most of the lineaments or segments are separated by right steps of 10 km to 40 km, marked with O's in Figure 22.3. At several of these breaks in the arc, there are changes in strike as well as the right-stepping offsets. The southeastern Guatemala segment is separated from the El Salvador segment to the southeast only by a change in strike (S in Fig. 22.3), even though there is also active transverse faulting along the volcanic front at this break [7]. A minimum in volcanic output (M in Fig. 22.3) occurs at the Arenal-Chato-Los Perdidos volcanic center in Costa Rica. This complex is in the middle of substantial gaps in the Upper Quaternary volcanism that separate the Central cordillera volcanic range to the southeast and the Guanacaste volcanic range to the northwest. Both of these ranges are made of large volcanic centers that overlap each other, so the gaps surrounding Arenal are pronounced. Geochemically, Arenal appears to belong with the Central cordillera range [8, 9].

Estimates of the volumes of the active volcanic centers [10] indicate that the majority of volcanic products have been basaltic to dacitic lavas and related epiclastic deposits of various types. The volume estimates (Fig. 22.3) are biased in favor of the more erosion resistant lavas and so the actual amounts of lavas and tephras may be comparable. The volumes of the volcanic centers are lognormally distributed, as has been found in other arc settings [12]. The mean spacing between volcanic centers is about 30 km, but there is no regular periodicity. Instead, the spacings between volcanoes have a Poisson distribution with a λ of about 24 km. This fact argues for a random distribution, which may be the result of multiple generations of diapirs rising independently [13]. However, by considering volcanic production as well as location, a regular pattern emerges. In Figure 22.3, there are several regular progressions from very large volcanic centers to small ones. The seven largest centers are all flanked on one or both sides by progressively smaller centers whose spacing becomes closer as their size decreases. This distribution suggests that the volcanic centers have different ages, proportional to size. First came an initial generation of seven centers, which are now the largest ones, with an average spacing of 150 km (the range is from 100 to 190 km). Subsequent generations emerged adjacent to the previous generation but at smaller spacing. The later generations have a smaller area to draw magma from and are substantially smaller. Geochronological tests are currently underway to determine if the oldest lavas at progressively smaller volcanic centers are in fact progressively younger. Regardless, there are profound differences in the rate of volcanic production on a 150 km wavelength.

In addition to the volcanic front, there are a few volcanoes of similar morphology (large, polygenic composite cones) and geochemistry (calc-alkaline with a significant LIL enrichment and Nb depletion) that are located 20 to 75 km behind the volcanic front (Fig. 22.1). This secondary line is weakly developed in Central America and has not been the site of any historic eruptions. It is not yet well studied, although some results for Zacate Grande volcano in Honduras are available [14].

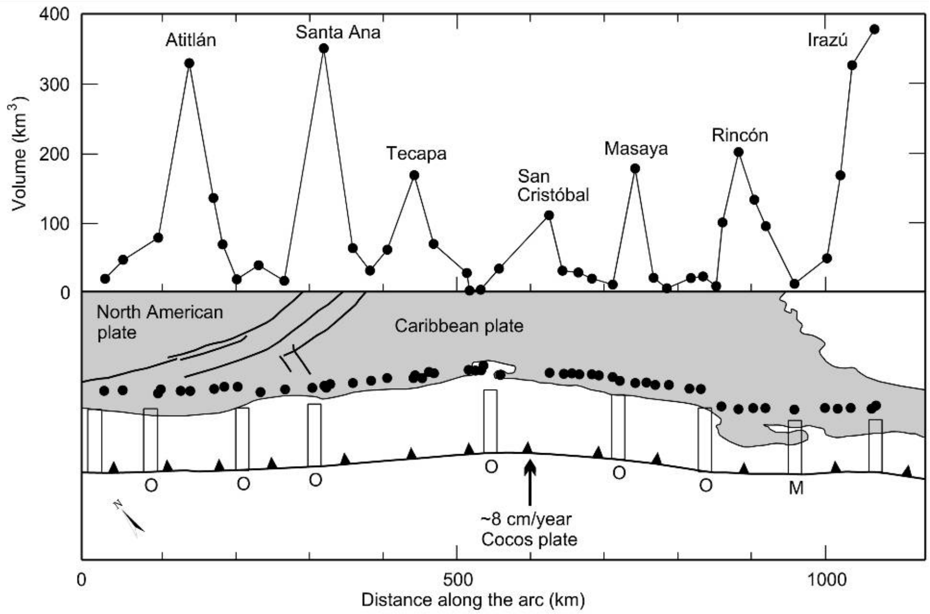

Figure 22.3. Distribution of Quaternary volcanic production along the volcanic front. Upper panel shows volumes of 39 volcanic centers. The large volcanic centers that are labeled may represent the earliest generation of volcanoes in the Quaternary volcanic episode. The lower panel shows the distribution of major Quaternary cones and calderas. The grey bars point to abrupt changes in the distribution of volcanoes along the front; either right-stepping offsets (O), changes in strike (S), minima in the volume distribution (M) or the ends of the volcanic chain. These breaks in the volcanic chain define eight volcanic segments.

A much more robust volcanic system occurs behind the volcanic front in areas of extensional tectonics. These volcanoes, termed *"behind the front"* (BVF) by Walker [15], are a type of back-arc volcanism. The major focus of BVF volcanism is the Ipala graben region of Guatemala and El Salvador (Fig. 22.2). Smaller examples of this type of volcanism include Tegucigalpa, Honduras [14], and Estelí, Nicaragua [16]. Most of the back-arc volcanism in northern Central America occurs in areas of obvious E–W extension. A major cause of the extension is the strike-slip plate boundary between the Caribbean and North American plates that extends through Guatemala [17]. In Honduras, near this strike slip boundary, there are two alkaline volcanoes, one at Yojoa and another at Utila island (Fig. 22.1). However, in most of northern Central America the back-arc volcanism is subalkaline and the dominant morphologic feature is a cinder cone with its associated lava field. In the Ipala region, more than 100 cinder cones have been identified [18, 19]. Ipala also includes several obsidian domes and flows all of which are nearly identical in chemical composition [20]. Less obvious are several shield volcanoes with very low slopes that are not visually striking but make a substantial contribution to the volcanic production. Several of the Ipala cinder cones could be Holocene based on their morphology and lack of weathering.

The back-arc volcanism in southern Central America is substantially different. Along the Caribbean coasts of Nicaragua and Costa Rica there are scattered occurrences of back-arc alkaline volcanism (Fig. 22.1). In Costa Rica, Pliocene alkaline magmatism of the Guayacán Formation (5 Ma) occurs near the volcanic front east of Turrialba volcano [21–24]. Similarly, at Platanar volcano, Quaternary cinder cones with shoshonite affinity occur just North of the volcano [25] and a few shoshonitic lavas have been sampled on the volcano's north flank [26]. Other alkaline vents in this region include Cerro Tortugero and Lomas Azules [27]. Cerro Mercedes, an eroded alkaline volcano, located along the Rio San Juan and the border with Nicaragua, is especially notable because its lavas have abundant ultramafic xenoliths of dunite, lherzolite and pyroxenite [28].

22.3 PETROLOGY AND PETROGRAPHY OF VOLCANIC FRONT LAVAS

The petrology of Central American volcanics has been much less studied than the geochemistry but several stratigraphic studies of volcanic sections demonstrate the importance of crystal fractionation, magma mixing and assimilation in creating substantial change in major elements. Stratigraphic sections of exposed lava piles have been sampled at many volcanoes with highly variable results. At Santa María volcano in Guatemala, a section of the caldera wall formed in the massive Plinian eruption of 1902 revealed a progressive increase in SiO_2 with higher stratigraphic position [29]. A substantially different evolutionary pattern for SiO_2 occurs at Izalco volcano, a small composite cone that erupted nearly continuously for 200 years after its first eruption in 1770. The SiO_2 contents of Izalco's lavas vary with the level of preceding eruptive activity [30]. After periods of low activity, lavas have higher than average SiO_2 content, whereas after periods of high activity, lavas have lower than average SiO_2 content. The walls of the deep crater of Boquerón volcano revealed yet another pattern, a change from calc-alkaline fractionation style at the base of the section to a tholeiitic fractionation style (FeO enrichment) at the top of the section and in the historic flank eruptions [31]. Separating the two lava sequences is a thick tephra section which suggests that a major explosive period led to the creation of a shallow magma chamber that, in turn, generated the tholeiitic fractionation.

The three stratigraphic sections described above can be explained by simple fractional crystallization and magma mixing involving a single source. Physical mechanisms, such as the time interval between eruptions or the depth of fractionation provide plausible explanations for the variations discovered. The three sections above are the most comprehensive stratigraphic sections available that appear constructed from the same or very similar magma batches. Each is unique, which suggests that the variety of patterns of magmatic evolution is very large in Central America.

The stratigraphy of Fuego volcano in Guatemala adds a different level of complexity. Lava sections at Fuego appear to consist of several similar but slightly different magma batches, perhaps derived from the same source but with different degrees of melting [32]. Distinct magma batches from a common source but with different incompatible element contents that indicate different degrees of melting are likely present at all the Central American volcanoes and await discovery through careful sampling and modern high resolution trace element measurements.

Compared with other arc systems, there have been relatively few detailed mineralogical studies and no experimental studies. One prominent exception is the remarkable definition of the detailed history of mineral growth prior to and during the 1974 eruption of Fuego volcano in Guatemala [33]. Arenal volcano in Costa Rica has phenocryst rich lavas and a variety of mafic inclusions that have been interpreted as remnants of buried oceanic crust by Cigolini and Kudo [34] and as comagmatic inclusions by Beard *et al.* [35]. Sachs and Alvarado [36] describe lower crustal xenoliths of mafic metaigneous rocks and made a preliminary crustal model based on Arenal xenoliths. Substantial petrologic data exists for individual volcanoes, including Irazú [37], Concepción [38] and Arenal [39]. Tournon [23] obtained petrologic results for several Costa Rican volcanoes, making this thesis an excellent starting point for understanding the petrology of Costa Rican lavas.

The volcanic front is characterized by an abundance of phenocrysts of plagioclase, pyroxene, magnetite and olivine [40]. The phenocrysts typically contain complex zoning, including reversed zones and bands of disturbed growth with abundant resorption features. Cerro Negro volcano in Nicaragua has erupted lavas and pyroclastics with particularly large and abundant phenocrysts. One reason may be the high water content of the pre-eruptive magma. Roggensack *et al.* [41] found pre-eruptive water contents as high as 5% in glass inclusions within olivine phenocrysts. High water content lowers magma viscosity and helps increase crystal growth rates. Sisson and Lane [42] measured high water contents in melt inclusions from phenocrysts erupted by Fuego volcano in Guatemala in 1974 using infrared spectroscopy. Roggensack [43] examined melt inclusions from small crystals in Fuego's 1974 tephra to recover some of the degassing history of that eruption.

The high percentages of phenocrysts commonly found in volcanic front basalts in Central America are, in some cases, clearly the result of phenocryst accumulation. Cerro Negro lavas from eruptions during 1950 to 1962 have unusually high FeO and MgO contents, consistent with accumulation of pyroxene and olivine [44]. Volcanics with very high Al_2O_3 (20 wt% or more) are likely caused by plagioclase accumulation. Fuego's 1974 eruption is a good example of such phenocryst sorting during a single eruption [45]. In this case, the less dense plagioclase phenocrysts were abundant in the earliest phase of the eruption, whereas olivine and pyroxene were more abundant in the last stage of the eruption.

Magma mixing and mingling occurs in a variety of scales in Central American lavas. Typical lavas contain complexly zoned phenocrysts of plagioclase that have a large calcic core and two or more layers of normal zoning, separated by resorbed and inclusion rich zones. Several specific instances of magma mixing have been documented in the active volcanoes that have long series of historic flows or stratigraphically related flows. Reagan *et al.* [46] described an early Al_2O_3 rich phase of the ongoing eruption of Arenal. This magma is similar to the lavas that erupted during the previous eruption of Arenal and appears to be a remnant of that previous episode. The subsequent lavas at Arenal are remarkably uniform in major elements but have subtle changes in incompatible elements that have been explained by ongoing magma mixing [39, 46, 47]. The stratigraphic history of Masaya volcano includes oscillatory variations in both compatible and incompatible elements that can be explained by a combination of continuing crystal fractionation coupled with fresh input of two magma types; a basalt, rich in TiO_2, like those found at the nearby Nejapa and Apoyo vents, and a calc-alkaline basalt [48].

The magma mixing described at Arenal and Masaya is cryptic and elucidated primarily by high precision chemical analyses. More obvious mixing occurs at Irazú volcano [37] which has a variety of magma combinations, ranging from well mixed to obvious blends that are better described as commingled. For example, the most recent eruption of Irazú, during 1963–1965, was a basaltic andesite that is a combination of two separate magmas present in the pre-eruption tephra and lava stratigraphy [37]. These tephras contain bimodal distributions of plagioclase and phenocrysts of olivine that are reacting with the groundmass. The two plagioclase populations can be recognized in thin section and microprobe analysis.

Throughout Central America, the most obvious examples of mingled magmas occur in the large silicic tephras that occur all along the arc. Upon close examination, most silicic tephras will have at least some dark colored component, either basaltic or andesitic. It is common to find individual blocks with the two magmas interswirled. Examples of mingled magmas or the co-eruption of two distinct magmas have been described at almost all the large caldera complexes: Atitlán [49–51], Coatepeque [52], Ilopango [53, 54], Apoyo [55]; at several of the stratovolcanoes; Santa Ana [52], Rincón de la Vieja [56], Arenal [46], Plantanar [26], Irazú [37] and El Valle [57]; and even at the small cones of Nejapa and Granada [58].

Representative thin sections of Central American lavas are shown in Figure 22.4. Rock sample Gu-C33 (Fig. 22.4a) shows a lava from a BVF vent with an olivine phenocryst in a groundmass dominated by plagioclase laths. BVF lavas are characterized by nearly aphyric texures with some small olivine and plagioclase phenocrysts. Rock Sal-SV4 (Fig. 22.4b) shows a typical pyroxene andesite from San Vicente volcano in El Salvador with a high percentage of plagioclase, pyroxene and magnetite phenocrysts in a pilotaxitic groundmass. The glomeroporphyritc clot of pyroxene and magnetite is a common feature of basaltic andesites and andesites. Rock Sal-II4 (Fig. 22.4c) is from the 1879–1880 eruption of the Islas Quemadas dome in the Ilopango caldera in El Salvador. It is a mixture of a rhyodacite (below) and a basaltic andesite. Highly corroded plagioclase crystals, like the one near the magma contact and just above the center of the image, are common. Mafic clots in generally silicic magmas, like the example shown, are not particularly common in Central American lavas.

Rock samples Nic-AP3 and Nic-AP5 (Figs. 22.4d and 22.4e) are lavas exposed in the wall of the Apoyo caldera in Nicaragua. Sample Nic-AP3 (22.4d) is an example of a high-TiO_2 basalt and, like many examples of this magma type, it has few phenocrysts and a fine grained texture. The larger phenocrysts are pyroxenes and olivines, whereas plagioclase is present in smaller laths. Sample Nic-AP5 (4e) is highly porphyritic and contains crystal clots and large corroded plagioclase phenocrysts. Not surprisingly, it has a high Al_2O_3 content (> 20 wt%).

The rock sample Cr-AR82 (Fig. 22.4f) is from a vesicular basaltic andesite lava erupted in 1982 from Arenal volcano in Costa Rica. Note the zoned plagioclase crystal in the upper left. Plagioclases with multiple zones of corrosion and subsequent growth are common throughout Central America, especially in the typical, low-TiO_2 lavas.

22.4 GEOCHEMISTRY OF THE VOLCANIC FRONT

The mantle and crustal sources for Central American volcanism (Figs. 22.5 and 22.6a) are outlined by two arrays in Sr and Nd isotope space [8]. Most of the volcanic front samples (closed symbols) define an array with an unusual positive slope. At the upper right end of this array are lavas from the volcanic front of Nicaragua that have Nd isotopes similar to MORB, but are elevated in $^{87}Sr/^{86}Sr$ because of incorporation of Sr from marine sediment. The sediment has both high $^{87}Sr/^{86}Sr$ (0.7090) and high Sr (1200 ppm). Mixing a small amount of fluid derived from this sediment with the mantle creates a horizontal array of increasing $^{87}Sr/^{86}Sr$ with virtually no change in $^{143}Nd/^{144}Nd$. The lower left end of the positively sloping array intersects the MORB-OIB mantle array.

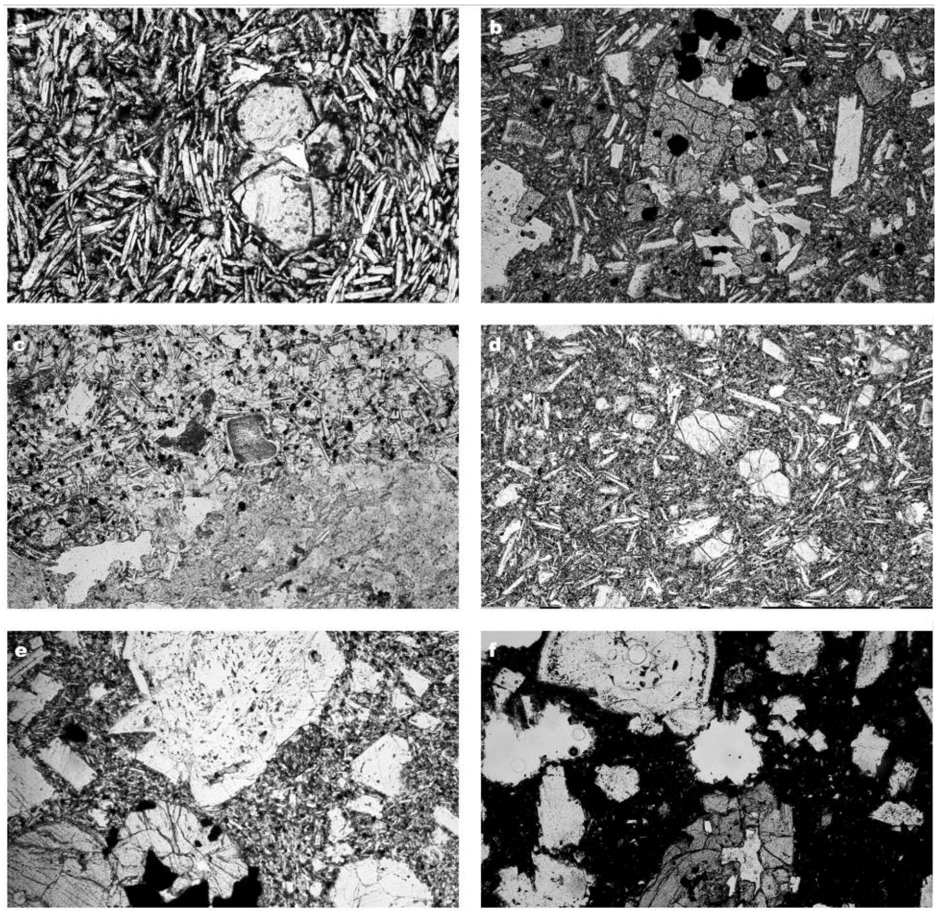

Figure 22.4. Thin sections of Central American lavas imaged in plain polarized light: (a) Gu-C33; (b) Sal-SV4; (c) Sal-II4; (d) Nic-AP3; (e) Nic-Ap5; (f) Cr-AR82. The long axis of each panel is 2.8 mm.

The second array has the negative slope of the MORB-OIB mantle trend and is composed primarily of back-arc samples from Guatemala and Honduras (open circles and triangles respectively) with a few volcanic front samples from western Guatemala (filled circles). The existence of a depleted-MORB mantle signature in the wedge is indicated by the isotopic composition of lavas from behind the volcanic front (BVF) in Guatemala and Honduras, which trend toward low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$. A crustal isotopic signature is apparent in many lavas from Guatemala and Honduras, whose isotopic ratios fall along the mantle array toward low Nd and high Sr isotopic values. These samples plot along mixing lines between depleted-MORB source mantle and metamorphic or granitic basement. The isotopic data show that crustal contamination is significant just in the areas that have Paleozoic basement: the volcanic front in central and western Guatemala and in some back-arc regions of Guatemala and Honduras.

The unusual array with a positive slope that is defined by most of the volcanic front data (filled symbols) reveals a variable subducted component, whose upper right end has a strong sediment signature. Although the Sr and Nd arrays outline the basic

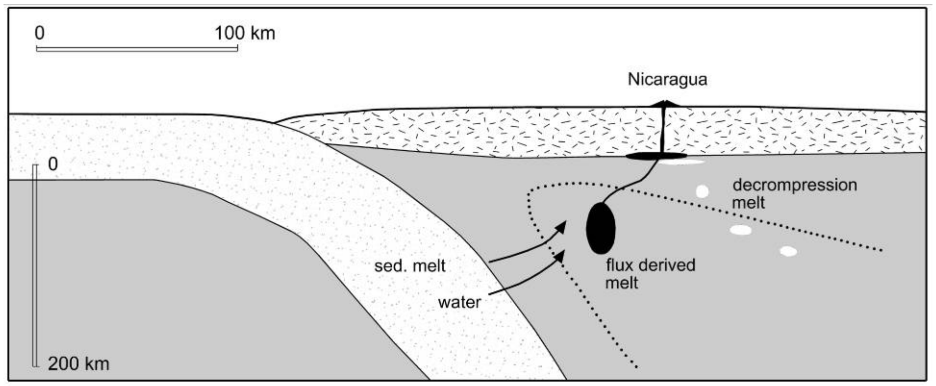

Figure 22.5. Cross section through Nicaragua showing plausible melt sources. Possible triggers for melting in the mantle wedge include; a hydrous fluid from the slab interior, a silicic hydrous melt from the sediments at the top of the subducting plate and decompression (upwelling) in the back arc. A flux derived melt (black) and a decompression derived melt (white) are shown in the mantle along with possible paths to the volcanic front. The dotted line shows schematic mantle flow into and then away from the wedge corner.

structure of the mantle and crustal sources of Central American volcanism, Pb isotope data (discussed below) will reveal an additional component in southern Central America which has OIB characteristics.

Central American magmas come from at least three distinct melting processes. The dominant magma type at the Central American volcanic front has the LIL-enrichment and HFS-depletion typically found at convergent margins [60]. The low contents of heavy REEs and TiO_2 imply a high degree of melting. Furthermore, the samples with the highest degree of melting also have high values for subducted sediment tracers, such as Ba/La. The combination of high degree of melting and high sediment signal indicates that a flux rises into the mantle wedge and triggers extensive melting. At many volcanic centers there is a second magma type that has elevated HREEs and TiO_2 and modest, if any, LIL enrichment. This magma appears to form in a separate melting process where decompression melting plays a significant or dominant role. Figure 22.5 is a cartoon showing three different melting triggers. Two separate fluxes evolve from the descending slab, one from the sediment at the upper surface of the slab and another, dominated by water, from the slab interior, as suggested by Ruepke *et al.* [59]. These flux derived melts combine and rise towards the volcanic front. Another melt originates in the region behind the volcanic front where asthenosphere is drawn inward and upwards toward the mantle wedge corner. Decompression melting occurs because of the upward component of asthenospheric movement. In Nicaragua, where the slab dip is very steep, the flux and decompression melts are mingled because they commonly erupt from the same vent. In the rest of the arc, a less steep dip of the slab appears to allow separation of flux derived melts into the volcanic front and decompression melts into the back-arc.

22.4.1 Regional variations

McBirney [2] outlined regional variations in geochemistry along the Central American volcanic front using major element data. He found that alkalis decreased from Guatemala to Nicaragua and that silicic tephras are rhyolite in Guatemala, dacite in

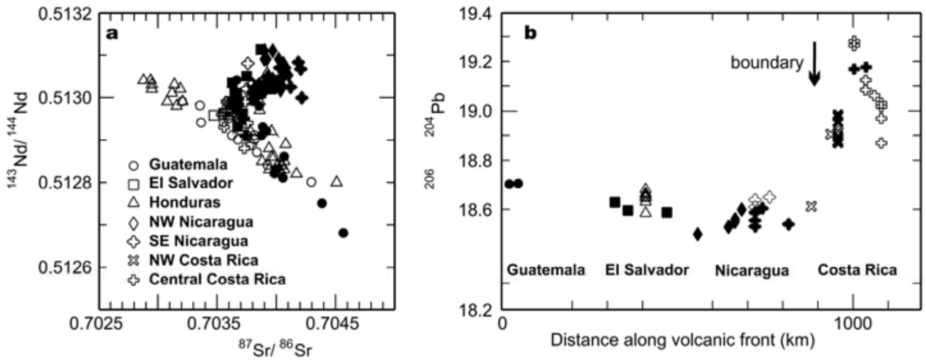

Figure 22.6a. Sr-Nd isotopes for Central American volcanics: Most volcanic front samples (solid symbols) show a positive correlation (except for crustally contaminated Guatemalan lavas); back-arc samples trend along the mantle array —Nicaraguan samples are displaced farthest from the array, showing the maximum influence of subducted slab components; (b) $^{206}Pb/^{204}Pb$ versus distance along the Central American volcanic front: distance is measured from the Guatemala/Mexico border; all samples are from the volcanic front. $^{206}Pb/^{204}Pb$ decreases from Guatemala to a minimum in Nicaragua —there is a notably abrupt increase in NW Costa Rica, marked by an arrow.

Nicaragua and ferrodacite in Costa Rica. The first comprehensive regional study based on trace elements and isotopes [60] defined strong gradients in Sr and Nd isotope ratios and in Ba/La and La/Yb. The discovery of high $^{10}Be/^{9}Be$ in Nicaragua [61] and regional gradients in this ratio that paralleled those of Ba/La and La/Yb, made clear that Central America is an excellent place to examine the role of subducted input in arc magmagenesis. The discovery of strong regional gradients in geochemistry both along and across the Central American volcanic chain is the major development in petrology-geochemistry since 1980.

Many of the spatial geochemical variations discovered in Central America are reproduced in Figures 22.6b, 22.7 and 22.8 and Table 22.1 is a brief overview of the more robust margin-wide variations. Most of these regional variations are attributed to a subducted origin, primarily from the subducted Cocos plate sediments. However, a variation in Pb isotopes (Fig. 22.6b) and a corresponding change in LIL and REE geochemistry in central Costa Rica is caused by the occurrence of OIB source material in this area.

22.4.2 Anomalous mantle in central Costa Rica

Unusual trace element contents and isotopic ratios occur in volcanic rocks from central Costa Rica and northern Panama. The magmas of central Costa Rica are distinct from those of the rest of Central America and have ocean-island basalt (OIB) character [25, 65, 69, 70]. Specifically, lavas in this region have geochemical similarities to lavas from the Galápagos hot spot. The distinctive trace element feature is a steep REE profile that contrasts sharply with the much flatter profiles found elsewhere along the margin and interpreted as evidence for a MORB source mantle [71]. Reagan *et al.* [61] showed that the distinction between the central Costa Rican lavas and the lavas in western Costa Rica and Nicaragua was clear in U-series isotopes as well.

The volcanoes with clear OIB character are the volcanoes of the Central cordillera;

Table 22.1. Regional geochemical variations along the length of the volcanic front.

Crustal origin	
alkalies	● McBirney [1] suggested the lower alkalies at active volcanoes in Nicaragua were related to the more extensive Tertiary volcanism that occurred there.
Na_2O	● Carr [62] found that Na_2O decreases from Guatemala to a minimum in Nicaragua and then increases into central Costa Rica. He correlated this to crustal thickness and proposed greater differentiation where the crust was thicker.
FeO and CaO	● Plank and Langmuir [63] found that FeO varied inversely to Na_2O. They attributed the regional variation in these elements to variable degrees of melting caused by crustal thickness. Thus high Na_2O and low FeO occur where the crust is thicker because partially molten mantle diapirs have less room to rise and therefore melt to lower degrees.
Sr, Nd isotopes	● NW across Guatemala, Feigenson and Carr [64] found increasing Sr and decreasing Nd isotopes that correlated with increasing crustal thickness and the presence of Paleozoic rocks beneath the volcanic front and attributed this to small amounts of crustal contamination.
Mantle or subducted plate origin	
	● From Central Costa Rica (Central cordillera) and NW at least as far as Arenal, recent volcanics have an OIB signature similar to the Galápagos (approaching HIMU). Many hypotheses compete to explain this fact (see [8] for a recent summary).
Subducted plate origin	
Ba/La and La/Yb	● Ba/La peaks in Nicaragua and decreases to the NW into Guatemala and to the SE into Costa Rica. La/Yb variation is inverse to Ba/La. Carr *et al.* [60] attributed high Ba/La to increased slab sediment component that led to higher extents of melting and lower La/Yb.
B/La	● B/La correlates positively with Ba/La and has a larger range of variation [65].
$^{10}Be/^{9}Be$	● $^{10}Be/^{9}Be$ correlates positively with Ba/La but traces recent mantle metasomatism given the short half-life of ^{10}Be [61].
Ba/Th, U/Th	● These ratios correlate positively with Ba/La [66].
Sr, Nd isotopes	● Outside of Guatemala, there is an unusual positive correlation between Sr and Nd isotopes, furthermore, these Sr and Nd isotopes correlate positively with Ba/La [64].
Mo, Cu	● Noll *et al.* [67] show that siderophile and chalcophile elements show regional variation similar to that of Ba/La.
Iodine	● From Iodine isotopes, Snyder and Fehn [68] inferred that the volcanic zone returns subducted Iodine, making the volcanoes an important part in the overall marine cycle of iodine and similar

Irazú, Barva, Poás, and Platanar. The northwestern boundary of the OIB geochemical region has not been definitively located because it varies with the geochemical data used. If the REE pattern is the standard, then Arenal, which lies between the Central cordillera and the Guanacaste range lacks the OIB signature. This places the OIB/MORB mantle boundary between Arenal and Platanar. On the basis of U-series isotopes, Reagan *et al.*, [61] make a strong case that this boundary is gradational across northwestern Costa Rica and possibly may extend into eastern Nicaragua. However, in Pb isotope space, the boundary appears sharp (Fig. 22.6b). Most Central American lavas have $^{206}Pb/^{204}Pb$ values between 18.4 and 18.7, similar to MORB-source mantle.

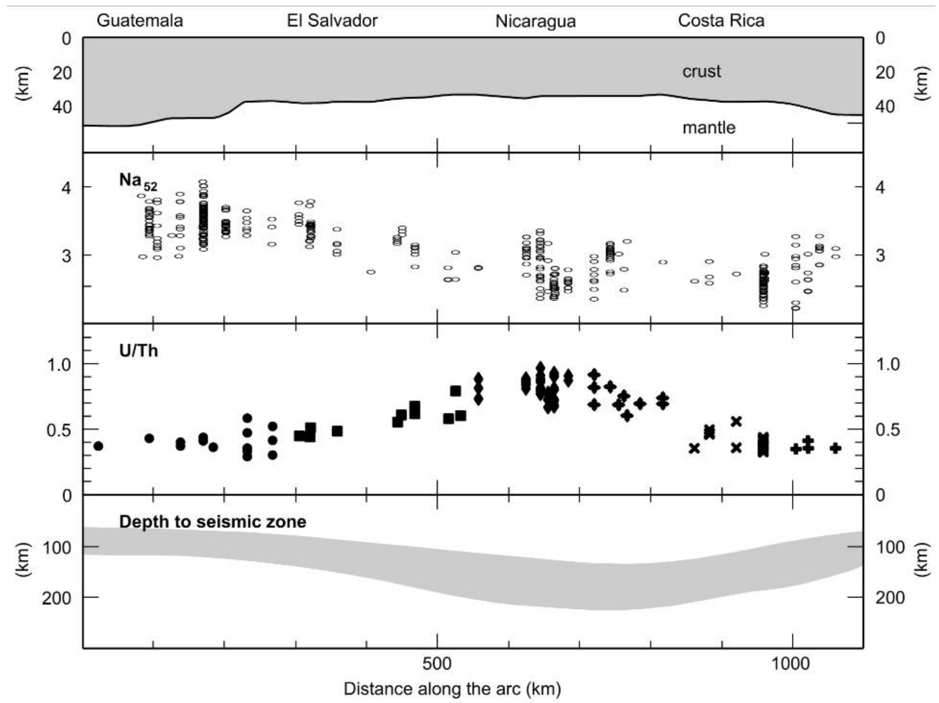

Figure 22.7. Geochemical variations along the Central American volcanic front. Crustal thickness was estimated from the regional variation in Bouguer gravity measurements. All the geochemical samples are from the volcanic front. Na_{52} is Na_2O content of lavas with SiO_2 contents between 48 wt% and 55 wt%, corrected to 52% SiO_2 via $Na_{52} = Na_2O - (SiO_2 - 52)*0.14$. The symbols in the U/Th diagram are the same as those in Figure 22.6a. The depth to the seismic zone beneath the volcanic front is not well determined but the several existing estimates seem to agree that the depth beneath the volcanoes is greatest in Nicaragua and decreases to the NW and SE.

In central Costa Rica, $^{206}Pb/^{204}Pb$ values are sharply higher from Arenal to Irazú, with values of 18.8 to 19.3. For Pb isotopes, the boundary between the OIB-like mantle in central Costa Rica and the MORB-like mantle in the rest of the margin to the northwest appears to lie between Arenal and Tenorio volcanoes [8].

Most studies of central Costa Rican magmas agree that the mantle source has OIB or Galápagos hot spot characteristics, but there are many ideas on how that source gets into the present volcanic system. These hypotheses are not mutually exclusive and most cannot be ruled out using existing evidence. Herrstrom *et al.* [70] cite S-wave splitting evidence for mantle flow parallel to the Andes that brings unusual mantle from the southeast. Abratis and Wörner [72] cite a window in the subducting Cocos plate, inferred from plate reconstructions [73] that allows Galápagos mantle to rise into central Costa Rica. The Galápagos signature is present in Eocene to Quaternary lavas in easternmost Nicaragua and on islands in the Caribbean well behind the arc [8], such as La Providencia (Fig. 22.1). Wherever the Galápagos signature occurs in young volcanoes, it coincides with the track of the Galápagos hotspot during the last 133 Ma [74, 75]. Feigenson *et al.* [8] conclude that the hotspot added its geochemical signature to the mantle that passed over it and Galápagos-like magma erupts where this mantle is currently involved in melting.

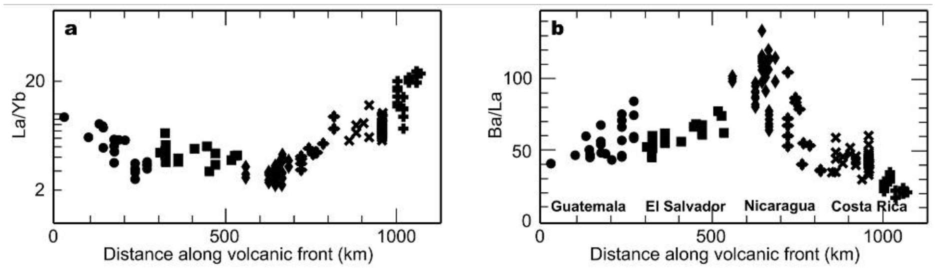

Figure 22.8. Fundamental geochemical variation along the Central American volcanic front. The inverse relationship between Ba/La, an indicator of slab flux, and La/Yb, an indicator of degree of melting, strongly argues that higher concentrations of flux (Ba/La) cause higher degrees of melting (lower La/Yb) in a regionally systematic manner.

22.4.3 Subducted component

At the volcanic front, there is a pronounced gradient in the strength of the slab signal that varies in a symmetric pattern centered on a maximum located in western to central Nicaragua. U/Th (Fig. 22.7) and Ba/La (Fig. 22.8) show this regional variation most comprehensively and clearly. These ratios are both nearly constant throughout the Cocos plate sediment stratigraphy. Ba/La has a lower variance in the sediment column and is therefore considered a more precise tracer of the strength of the slab signal [10]. Other ratios that show this pattern are listed in Table 22.1. The maxima in this regional variation occur in Nicaragua between Telica volcano, which has the maximum Ba/La, and Masaya volcano, which has the maximum $^{10}Be/^{9}Be$ and maximum $^{87}Sr/^{86}Sr$, outside of Guatemala. The intensity of the slab signal varies by at least a factor of four in Ba/La. Ba/La and U/Th correlate positively ($r > 0.80$) with $^{10}Be/^{9}Be$ and therefore are unambiguous, easily measured indicators of subducted sediment.

The working hypothesis for the regional variation in intensity of slab signal is based on one central observation. There is a positive correlation between slab signal (estimated by Ba/La) and apparent degree of melting (estimated from the slope of REE patterns). The mirror image in the along strike variations of La/Yb and Ba/La (Fig. 22.8) shows a regionally consistent, positive correlation between slab signal and degree of melting. The La/Yb plot has a log scale to allow for the anomalously high La/Yb values in central Costa Rica derived from the Galápagos-like mantle in this area. Even excluding the central Costa Rican data (crosses at distances of 1000 km and greater in Fig. 22.8), there is a convincing mirror image between La/Yb and Ba/La. The positive correlation between slab signal and degree of melting may be explained by a more concentrated flux producing higher degree melts [60].

Carr *et al.* [60] proposed an additional constraint; a crude negative correlation between degree of melting and volumes of erupted volcanics. Nicaragua, which has the lowest La/Yb and thus the highest degree of melting, also has smaller volcanoes; just the opposite of what would be expected. A major problem with this proposal is lack of knowledge of the ages of the volcanoes, much less their actual eruption rates. Recent extensive dating of Costa Rican volcanics [76–78] proves that the Costa Rican volcanoes are substantially older than Carr *et al.* [60] or Patino *et al.* [66] assumed, 1.0 to 0.5 Ma instead of 0.1 Ma. Therefore, this proposal does not hold and elemental flux calculations [66] need to be redone after obtaining extensive geochronological control on the ages of Central American volcanoes.

22.4.4 Geochemical variations within volcanoes

Many Central American volcanic centers have geochemical variations that indicate different sources (isotopically different mantle domains or different mixes of subducted sources). These geochemical variations within one volcanic center can be very substantial, as at the relatively small Telica volcanic center [66], or limited, as is the case for the lavas at the very large Masaya volcanic center, where magma mixing plays a substantial role in homogenizing the volcanic output [48]. Qualitatively, the greatest extremes in geochemical end members (isotope ratios or incompatible element ratios) are found at small volcanoes with multiple vents. Large centers with few vents seems to have greater probability of maintaining large, long-lived magma chambers that obscure the diverse magma types that feed into the system. Two separate types of intravolcano geochemical variations are commonly found: the first concerns TiO_2 and HFS elements and the second concerns U/La and Ba/Th, ratios that emphasize the end member compositions of the subducted Cocos plate sedimentary section.

22.4.5 Bimodal distribution of TiO_2 and HFS elements in volcanic front lavas

Throughout Central America there are many examples of volcanic centers; e.g. Telica [66]; Platanar [26] or individual vents Irazú [37]; Turrialba, [79] that erupt two or more distinct magma types that cannot be related via fractional crystallization but instead require a different source and or different degree of melting. The major element that most consistently separates different magma types in Central America is TiO_2. Figure 22.9 shows the persistence of a bimodal distribution of TiO_2 along most of the arc. The distributions of the high and low-TiO_2 groups overlap so they can not be uniquely separated. In general, the mode of the low-TiO_2 lavas is < 1.0 wt% and the mode for the high-TiO_2 lavas is > 1.0 wt%. In each segment of the arc, the proportion of samples with higher TiO_2 is small. There is no consistent field observation that allows one to predict what lava will have elevated TiO_2. However, in some instances, the lavas with high-TiO_2 are distinctly low in phenocrysts and in a few cases the lavas have a pahoehoe texture, suggesting high temperature and low viscosity. These characteristics may have allowed a small sampling bias in favor of the high-TiO_2 lavas.

On the global spectrum of basaltic volcanism, the Central American high-TiO_2 lavas actually have normal TiO_2 contents. It is only in comparison with the more abundant calc-alkaline arc magmas, most of which are derived by high degrees of melting and have the characteristic arc depletion in HFS elements, that the high-TiO_2 magmas are notable.

The lavas with low-TiO_2 appear derived by a high degree of melting from a MORB source (e.g. [66]). During differentiation of these magmas by fractional crystallization, TiO_2 is extracted by phenocrysts of titaniferrous magnetite, which are common at the volcanic front. Therefore, there is no increase in TiO_2 as there is in the tholeiitic style of differentiation [80].

The lavas with high-TiO_2 vary considerably along Central America [10]. In general, they appear derived by lower degrees of melting. In many instances, especially in the back-arc, where most lavas are the high-TiO_2 type, the high-TiO_2 magmas appear derived by decompression melting with either a small or a negligible component of slab-derived flux [14, 24, 46, 81, 82]. The origin of the most extreme high-TiO_2 lavas, the Nejapa-Granada basalts (NG basalts), is controversial. Reagan *et al.* [61] emphasize sequential melting processes and derive the high-TiO_2 lavas from the same source as the low-TiO_2 lavas. Walker *et al.* [83] explain the high variability in the NG basalts using variable contributions from the subducting slab.

In Guatemala and El Salvador the separation between the low-TiO_2 mode and the high-TiO_2 mode is not large. In eastern Nicaragua, the largest volcano, Masaya, is extensively sampled and is interpreted as a mixture of low-TiO_2 and high-TiO_2 magma types [48]. Therefore, in the southeastern Nicaragua panel of Figure 22.9 the Masaya lavas obscure the bimodal distribution that occurs in the smaller volcanoes. At this time, no high-TiO_2 lavas have been discovered in the northwestern Costa Rica segment, the Guanacaste range.

22.4.6 Local variations in magma type and in flux composition

Patino *et al.* [66] discovered a binary mixing array at individual volcanoes that is parallel to the mixing array between the two sediment layers on the subducting Cocos plate. The apparent mixing arrays for volcanoes Telica and Arenal are shown in Figure 22.10. One endpoint has high Ba/Th and low U/La, similar to the carbonate sediments or to a hydrous fluid that interacted with altered MORB [84]. The very high Ba/Th found at this endpoint suggests that both these components are present. The other endpoint has low Ba/Th, high U/La and slightly elevated K_2O. These characteristics suggest a substantial contribution from the uppermost stratigraphic layer on the Cocos plate, the hemipelagic sediments. Geochemical models of this endpoint [66, 81, 85] are not definitive but must include several components. First, a hemipelagic component is essential to bring in ^{10}Be and K_2O but can be either a hydrous fluid or a melt. A hydrous fluid that interacts with subducted MORB is essential to explain the elevated Sr contents but only mildly elevated Sr isotopes; low oxygen isotopes in olivine crystals imply a serpentinite source for some of the water [86], possibly from deep fractures in the subducted Cocos plate [87]. Finally, a contribution from the subducted carbonate sediments is allowed but may not be required.

The local array varies along the arc. At Arenal, where the sediment signal is small the array is closer to typical mantle values. At Telica, where the sediment signal is strong, the array is further from typical mantle values and closer to the bulk sediment mixing line, which lies outside the figure. The local array at Telica may not reach the most extreme possible endpoints but it does cover most of the possible range. At Arenal, the hemipelagic contribution to the mixing array is much less than at Telica, suggesting a much reduced hemipelagic contribution to the Arenal products.

The local array suggests that two fluxes emerge from the subducted slab and subsequently mix, one from carbonate plus MORB and another dominated by the hemipelagic muds. Moreover, the local arrays for different volcanic centers, such as Telica and Arenal, are subparallel. This indicates that, at any individual volcano, the two fluxes have similar magnitude, that some overriding process delivers the two components in consistently the same proportions. Reagan *et al.* [61] argued for a similar requirement of consistently similar mixing proportions between a fluid dominated component and a melt dominated component. Their data showed that slab tracers, presumed the result of fluid transport, correlated well with Th addition, even though Th should be immobile in a hydrous fluid.

Several possibilities can be proposed for the two components needed for the local arrays. The carbonate end likely involves a hydrous fluid from the subducted MORB that interacted with some of the carbonate section. The hemipelagic end may be a melt

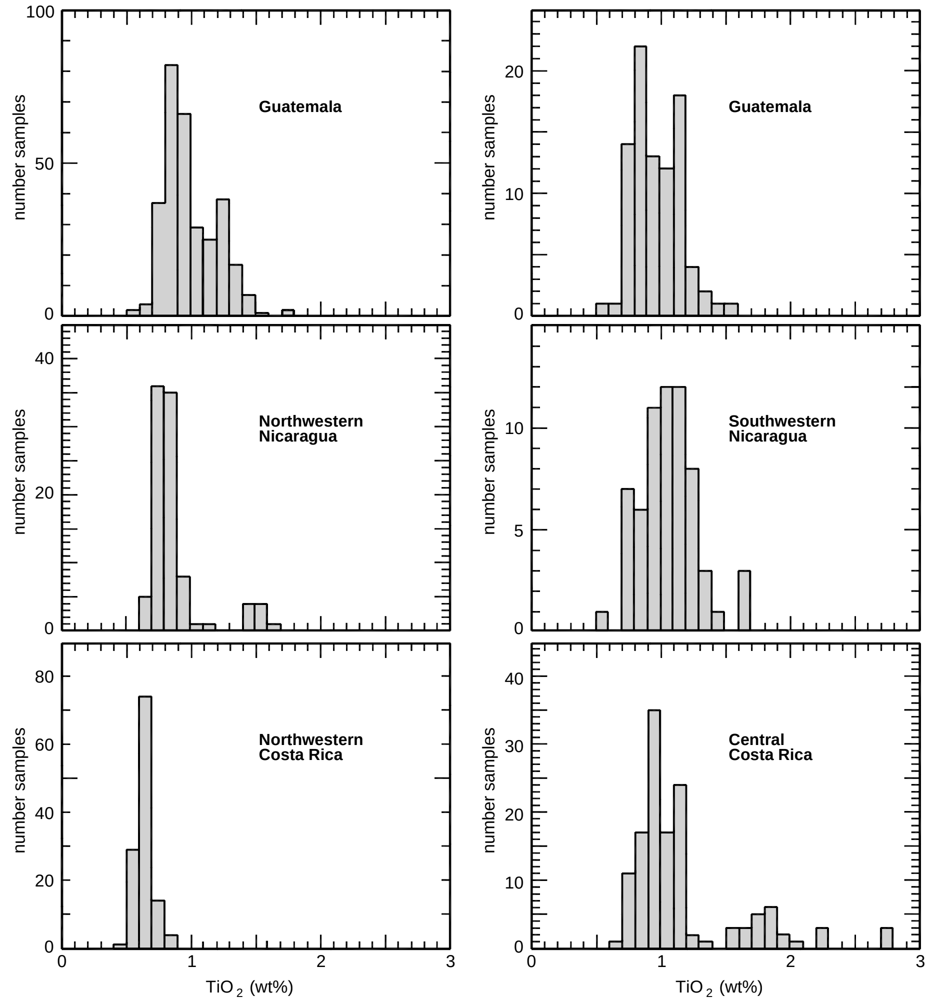

Figure 22.9. Histograms of TiO_2 contents of lavas. Most segments of the Central American margin have a bimodal distribution of TiO_2 with a dominant low-TiO_2 mode and a small secondary mode with somewhat higher TiO_2. Samples shown have SiO_2 contents between 46 and 56 wt%.

or a hydrous fluid. There may be two hydrous fluids, one from the devolatilization of the subducted sediments and MORB and another from devolatilization of mafic and ultramafic rocks deep in the subducted plate [59], especially in areas where the lithosphere underwent through going fracturing as it bent into the trench [87]. Did the two fluxes originate together or at distinctly different times? The U-series patterns of Central American lavas [61, 88] suggest several different time scales for producing Central American lavas.

22.5 PETROLOGIC CHARACTERISTICS OF SUBALKALINE BACK-ARC LAVAS

The subalkaline BVF volcanism in northern Central America [14, 15, 89] has a simple mineralogy that can be explained by rapid eruption of magma after a period of storage that allowed phenocrysts to effectively separate from the remaining liquid. The great majority of these lavas are aphyric except for rare, small phenocrysts of olivine and, occasionally, plagioclase. Clinopyroxenes are not usually found. However, a suite of these lavas that spans a moderate range of fractionation shows CaO/Al_2O_3 decreasing with MgO. The positive correlation of these two parameters implies that clinopyroxene was being fractionated prior to eruption, probably during deep storage, where the olivine primary phase volume is shrunken by pressure. The subsequent crystallization of only olivine and plagioclase can be explained by a rapid rise to shallow pressure where the stability fields of these two minerals expands at the expense of pyroxene [15].

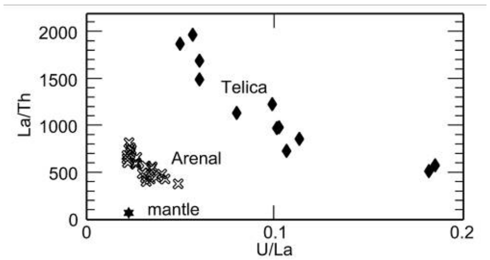

Figure 22.10. Local or intravolcano geochemical variation. Low-TiO_2 lavas at Arenal and Telica volcanoes define arrays that are subparallel to the array defined by the Cocos plate sediment section. The Arenal samples (X's) are closer to the mantle and thus have a lower subducted sediment component. The Telica samples (diamonds) are closer to the sediment array which lies outside the diagram.

22.6 GEOCHEMICAL VARIATIONS TRANSVERSE TO THE ARC

Halsor and Rose [11] provided several examples of short (< 10 km) cross-arc volcanic lineaments in northern Central America along which there are substantial physical and geochemical gradients. These lineaments, called *"paired volcanoes"*, are within the volcanic front. The general pattern is for the volcano closest to the trench to be more explosive and have lower incompatible elements and higher Ba/La, indicating a higher degree of melting and a higher input of flux from the subducted slab. The volcano on the back-arc side of the center has a higher proportion of lavas than ash and a higher level of incompatible elements, consistent with less water and a lower degree of melting. Ba/La is also low, suggesting less flux from the subducting plate. One way of looking at this gradient is that flux triggered melting in the mantle wedge creates the seaward volcano, whereas the volcano closest to the back-arc has a substantial component of back-arc magma caused by decompression melting that has a lower degree of melting and a lower flux component [10]. The cross-arc gradient described above is common but by no means universal. At Poás volcano in Costa Rica, the more TiO_2 and incompatible element rich lavas, which would be expected on the back-arc side of the volcano, instead appear on the trenchward side [90].

Extensional tectonics has allowed the eruption of extensive fields of recent monogenetic volcanism in southeastern Guatemala (the Cuilapa region) and along the Guatemala-El Salvador boundary (the Ipala region). A less well preserved but equally extensive area of back-arc volcanism occurs near Tegucigalpa, Honduras and there are smaller, less well investigated areas of back arc volcanism, like the flows just north of Estelí, Nicaragua. Table 22.2 summarizes several studies of cross-arc variations in geochemistry. All these studies focus on the two areas where cross arc traverses are possible, the southeast Guatemala-Ipala graben traverse and the Gulf of Fonseca-Honduras traverse. Both cross-arc traverses include the volcanic front and back-arc fields of monogenetic volcanism. The Honduras traverse [14] is richer because there are two second line volcanoes, El Tigre and Zacate Grande, and the distal alkaline volcanic field at Yojoa lake.

Table 22.2. Geochemical variations across the arc.

Element or ratio	Interpretation
alkalies	● Low-K subalkaline basalts occur at the arc; moderate-K subalkaline basalts occur just behind the arc and alkaline basalts occur well behind the arc. No systematic change in K_2O content occurs with depth to the seismic zone [91].
Ba/La	● Cuilapa and Ipala graben: Ba/La drops sharply immediately behind the volcanic front but does not change across the back-arc region [89]. Honduras: some evidence for progressive change across the volcanic front and into the back-arc [14].
$^{10}Be/^{9}Be$	● Honduras: $^{10}Be/^{9}Be$ decreases across the Gulf of Fonseca [14].
Sr, Nd isotopes	● Honduras: Sr, Nd isotope ratos decrease across the Gulf of Fonseca [14].
Pb isotopes	● Cuilapa and Ipala graben: Pb isotopes become more radiogenic across the arc because of assimilation of increasingly older continental crust [89].
Ba/La in melt inclusions	● Cuilapa and Ipala graben: a decrease in Ba/La across the back-arc region [83]. Apparently, a subtle decrease in a subduction signal.

The available evidence suggests that the volcanic front [11] and second line [14] have a gradient of decreasing slab signal with distance behind the volcanic front, a feature found in many arcs. In contrast, the back-arc subalkaline volcanic fields extend from the volcanic front to distances well behind the current Wadati-Benioff zone but show no obvious internal gradients in isotopic or incompatible element ratios that would be expected if a flux from the descending slab was the main trigger for melting. The only exception is a cross-arc decrease in Ba/La in melt inclusions hosted by olivine crystals in a few Ipala graben cinder cones [83]. These subalkaline volcanic fields do have a definite subduction signal [89] which is substantially below that of the volcanic front and somewhat higher than the Yojoa lake basalts that appear to have very little subduction related component [14].

The volcanic front and second line are made of composite volcanoes with calc-alkaline fractionation style. Within these groups there are cross arc decreases in subduction component and in degree of melting with distance from the trench. The subalkaline monogenetic fields have a subduction component but show little evidence of change in that component proceeding away from the volcanic front.

22.7 TERTIARY VOLCANISM

The current framework for the Tertiary volcanic stratigraphy in Central America was clearly described in Salvador [92] and summarized by Weyl [1]. Reynolds [93] found the same stratigraphic sequence in southeast Guatemala and proposed a regional stratigraphic framework by including previous studies from Honduras, Nicaragua and other areas of Guatemala. Ehrenborg [94] proposed that some formations in central

Nicaragua could be subdivided on the basis of volcanic facies. This approach is useful in regions of mafic volcanism as highly eroded cones may lack mapable layers, but can be divided into different proximal and distal volcanic facies.

Much remains to be learned about the timing and extent of Tertiary volcanism. The ability of field geologists to define separate units suggests a discontinuous production of magma. McBirney at al. [95] used K/Ar dating and estimates of the volumes of volcanic units to propose pulses in magma production with a time scale of roughly 5 Ma in Central America. In contrast, the distribution of silicic tephras in Caribbean cores offshore of eastern Central America [96] show that volcanic productivity has distinct peaks in the Eocene (50 Ma) and the Middle Miocene (15 Ma). For stratospheric winds, the Caribbean sites are downwind of Central American volcanoes. In contrast, the prevailing winds in the troposphere are to the west, driving small, low ash plumes into the Pacific. Thus, the Caribbean cores predominantly record the history of very large silicic eruptions.

Rogers *et al.* [97] propose a tear in the subducted Cocos plate that results in a gap in the downgoing plate, through which aesthenosphere rises, causing heating and uplift of the Tertiary volcanic plateau. The argument for substantial uplift is based on hypsometry and on extensive entrenched river channels that cut the Tertiary ignimbrite plateau. New seismic tomography for the region shows the descending Cocos plate as an inclined high velocity region extending from the surface to a depth of about 200 km [97]. Below this is a region that lacks the high velocities expected for a subducting slab, creating an apparent gap of 300 km. At a depth of about 500 km, tomography again images high velocities consistent with a descending slab. The late Tertiary uplift is directly above the apparent gap in the slab, suggesting a tear in the slab caused by the arrival of young, hot and buoyant oceanic crust from the East Pacific rise (EPR). This buoyant crust formed during a period of very fast EPR spreading in the interval between 19 and 10 Ma. The age of the uplift, though not well constrained, is between about 4 Ma and 10 Ma.

The degree of continuity in magma production remains an important problem. The land record and the marine record agree that there were major increases in the Middle Miocene and Eocene. Are the smaller scale pulses described by McBirney *et al.* [95] real or are they a function of sparse and unrepresentative sampling? The answer will come after much more extensive study of the Tertiary geology.

22.7.1 Tertiary geochemistry

Plank *et al.* [98] built on the work of Nyström *et al.* [99] to define the first along arc variation in incompatible element ratios for Tertiary lavas. They found opposite results for Ba/La and U/Th, the two ratios that best define the modern, subduction related variations along the arc. For Ba/La, the late Tertiary (Miocene and Pliocene) regional variation in Nicaragua was identical to the modern variation pattern. However, the regional variation in U/Th, which is parallel to Ba/La in recent lavas, is absent in the late Tertiary lavas, which have low and constant U/Th, near the normal magmatic value. The Ba/La and U/Th subduction signals originate in the sediment section, but the sediment has changed drastically with time [66]. Prior to about 10 Ma, the sediments were carbonate oozes. A change in marine geochemistry in the eastern Pacific, called the *"carbonate crash"* [100] resulted in a profound change in marine sedimentation. From 10 my to the present, the dominant sediment near the Middle America trench has been hemipelagic mud. The U content of this mud has increased over time. For at least the last 5 Ma, the U content of subducting sediments has been high and the U/Th ratio has been anomalously high, about 1.5. Subduction of these U rich sediments is the cause of the elevated values of U/Th that define the modern regional variation. The lack of a regional variation in this ratio in the late Tertiary is simply a reflection of the very different sedimentary input.

The similarity between late Tertiary and modern Ba/La values reflects the near constancy of the Ba content and Ba/La ratio over the last 20 Ma in the Cocos plate sediment section [66]. The extremely high Ba content of these sediments is the result of continuously high biological productivity in this subtropical region. For the Tertiary volcanics, the regional variation in Ba/La discovered in Nicaragua has been extended northwest across El Salvador [101] and southeast across Costa Rica ([69] and Gans, *pers. comm.*, 2003). The temporal stability of the regional variation in Ba/La is quite surprising given the large shifts in the volcanic front over time [98]. This clearly is an important problem to guide future study of the mafic lavas in the Tertiary.

22.8 IMPORTANT CHARACTERISTICS OF VOLCANISM AND GEOCHEMISTRY

Central America is one of the best places in the world to study volcanoes because there are many volcanic centers and they are closely spaced and easy to reach. The level of volcanic activity is high, allowing a mixture of investigations on time scales ranging from the active process to the long term geological and geochemical evolution of the arc.

Volcanism is concentrated in a narrow volcanic front that extends approximately 1100 km and includes 39 volcanic centers. Volcanism extends across the volcanic front to as much as 200 km into the back arc. The back-arc volcanism allows assessment of cross-arc geochemical variations and provides insight into the components mixing in at the roots of the volcanic centers. In general, the volcanic front has phenocryst rich lavas, high Al_2O_3 contents and high ratios of fluid mobile/fluid immobile elements. These characteristics imply a water-rich flux as the cause of most volcanic front magmas. The back-arc lavas have moderate to quite low contents of slab-derived elements. Their eruption sites are primarily in areas of crustal extension, suggesting that the major factor causing melting is decompression. The separation between decompression melts in the back-arc and flux melts at the volcanic front is by no means rigorous; there is much overlap.

Remarkable regional variations in geochemical parameters make Central America a useful testing ground for theories for the origin of many features of arc geochemistry. Nicaraguan lavas have some of the globally highest levels of slab tracers such as $^{10}Be/^{9}Be$ and Ba/La. The area of high slab signal extends across Nicaragua between the volcanoes Cosigüina and Masaya. Northwest of Cosigüina, the slab signal decreases gradually across El Salvador and Guatemala. In contrast, the slab signal drops precipitously to the southeast from Masaya to Concepción volcanoes. Across Costa Rica, the slab signals are low and an isotopically distinct source occurs between Arenal and Irazú volcanoes in central Costa Rica.

The fundamental geochemical variation along the Central American volcanic front is the inverse relationship between Ba/La, an indicator of slab flux, and La/Yb, an indicator of degree of melting. Higher concentrations of flux (Ba/La) cause higher degrees of melting (lower La/Yb) in a regionally systematic manner. The underlying tectonic cause of this variation has not yet been convincingly explained.

An apparent binary mixing array, the local array, occurs at most volcanic centers in U/La versus Ba/Th space. These two ratios provide maximum separation between the two sediment layers on the Cocos plate; the lower carbonate section and the upper hemipelagic section. The array found in the volcanoes is parallel to the mixing array between the two sediment layers. The local array varies along the arc. Where the sediment signal is small, the array shrinks and moves closer to typical mantle values. Where the sediment signal is strong, the array expands and moves closer to the bulk sediment mixing line. The local array suggests that two fluxes emerge from the subducted slab and subsequently mix, one that has MORB-carbonate input and another that has an additional strong input from the hemipelagic sediments. Moreover, the local arrays for different volcanic centers are subparallel, indicating that, at any individual volcano, the two fluxes have similar magnitude, as if some overriding process delivers the two components in consistently the same proportions.

The methodology recommended by McBirney [2] to consider individual parts of the volcanic chain and examine separate groups of volcanoes within a restricted volcanic field has proven to be the key to uncovering the diversity of Central American magmas and discovering their remarkable geographic variations.

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