PLIOCENE TO PRESENT MIGRATION OF THE VOLCANIC FRONT, ANDEAN SOUTHERN VOLCANIC ZONE

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ABSTRACT

Between the Pliocene and the Present the volcanic belt from 33-34°S, at the northern end of the Southern Volcanic Zone (SVZ) of the Andes, narrowed into a single chain of volcanos as the volcanic front migrated 35 km to the east and the boundary separating the volcanically quiescent zone to the north from the SVZ moved 25 km southward. These changes can be related to progressive flattening of the angle of subduction of oceanic lithosphere below the northern end of the SVZ. This resulted in **1.** an increase in the rate of tectonic erosion of the continental margin causing eastward migration of the axis of the Chile Trench; and **2.** a decrease in the volume and cooling of the asthenospheric mantle wedge above the subducted slab, and consequently, an increase in the depth of magma generation in the subarc mantle below this region. In contrast, the volcanic belt from 38-39°S, near the middle of the SVZ, broadened as the volcanic front migrated 35-80 km to the west over the same time period.

At the northern end of the SVZ, increased crustal thickness caused by compressive deformation accentuated the decrease in the volume and the cooling of the subarc mantle associated with flattening of the angle of subduction. Increased importance of tectonic erosion of the continental crust towards the northern end of the SVZ, combined with the smaller volume and cooler subarc mantle wedge, resulted in **1.** an increase in the importance of continental crust in the subducted slab-derived components added to the subarc mantle; **2.** an increase in the relative importance of the slab-derived components in the smaller subarc mantle; and **3.** conditions of greater depths and smaller degrees of partial melting, and consequently, increased significance of residual garnet in the subarc mantle. These conditions are $^{87}Sr/^{86}Sr$ ratios in magmas erupted at the northern end compared to farther south in the SVZ, and they may have been important factors in producing both the Pliocene porphyry copper deposits between 33-34°S as well as other Cenozoic porphyry copper mega-deposits farther north in the Chilean Andes.

Key words: Andean volcanism, Pliocene, Quaternary, Volcanic front, Subduction geometry, Tectonic erosion, Subarc mantle, Porphyry copper.

RESUMEN

Desde el Plioceno al Presente el cinturón volcánico comprendido entre 33° y 34°S, en el extremo norte de la Zona Volcánica Sur (ZVS) de los Andes, se enangostó hasta formar una sola cadena volcánica a medida que el frente volcánico migraba 35 km hacia el este y el límite que separaba la zona volcánica inactiva al norte de la ZVS se movía 25 km hacia el sur. Estos cambios podrían estar relacionados con la disminución del ángulo de subducción de la litósfera oceánica bajo el extremo norte de la ZVS. Esta disminución en el ángulo de subducción resultó en: **1.** un aumento en la velocidad de la erosión tectónica del margen continental causando la migración hacia el este del eje de la Fosa Chilena; y **2.** una disminución en el volumen y el enfriamiento de la cuña del manto astenosférico sobre la placa subductada y, consecuentemente, un aumento de la profundidad de la zona de generación de magmas en el manto, bajo el arco en esta región. En contraste, el cinturón volcánico desde 38-39°S, cerca de la mitad de la ZVS, se ensanchó a medida que el frente volcánico migraba 35-80 km hacia el oeste durante el mismo período.

En el extremo norte de la ZVS, el aumento del espesor de la corteza causado por deformación compresiva acentuó la disminución en el volumen y enfriamiento del manto bajo el arco asociado a la disminución del ángulo de subducción.

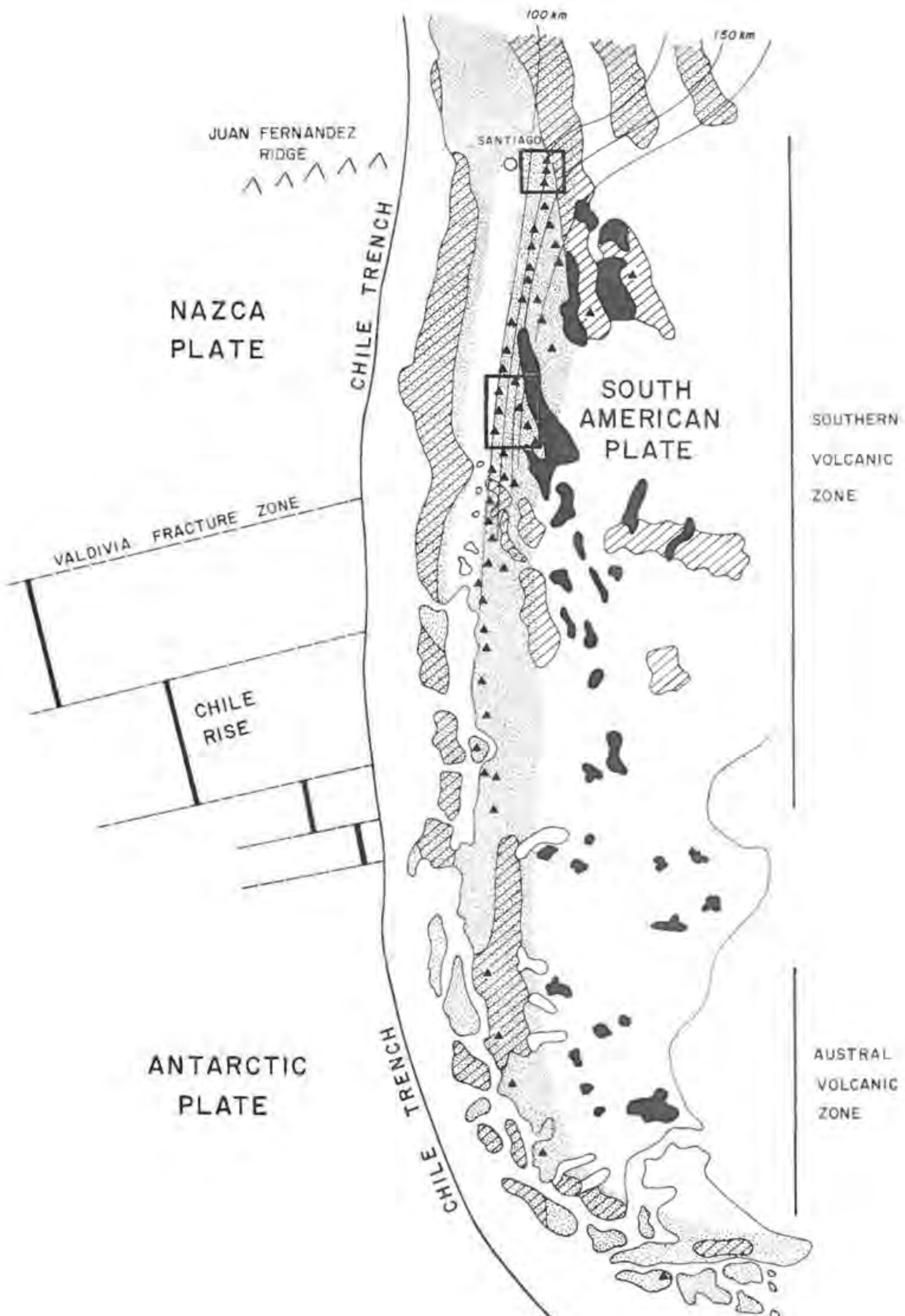

FIG. 1. Schematic map of the distribution of late Quaternary volcanic centers of the Andean orogenic arc (triangles) forming the Southern and Austral Volcanic Zones. The figure also shows plates and plate boundaries, depth in kilometers to the center of the Benioff zone of seismic activity (Bevis and Isacks, 1984), and the outcrop of Quaternary back-arc basalts (black) and Paleozoic and Lower Mesozoic pre-Andean basement (diagonally lined). Uplifted area, including the Coastal and Main Andean cordilleras and the Sierras Pampeanas Ranges, are shaded. The areas within the boxes, between 33-34°S and 38-39°S, are shown in more detail in figures 2 and 3.

El aumento de la importancia de la erosión tectónica de la corteza continental hacia el extremo norte de la ZVS, junto a un volumen menor y al enfriamiento de la cuña del manto bajo el arco, resultó en: **1.** un aumento en la importancia de la corteza continental en la componente derivada de la placa subductada añadida al manto bajo el arco; **2.** un aumento en la importancia relativa de los componentes derivados de la placa subductada en el manto disminuido bajo el arco; y **3.** condiciones de mayor profundidad y grados menores de fusión parcial y, consecuentemente, un aumento del granate residual en el manto bajo del arco. Estas condiciones son consistentes con un modelo de contaminación de la fuente en el manto propuesto para explicar el contenido alto de Sr y las razones altas de La/Yb y $^{87}Sr/^{86}Sr$ en magmas que hicieron erupción en el extremo norte en comparación con los de más al sur en la ZVS. Ellos podrían haber sido factores importantes en la génesis de los depósitos de pórfido cuprífero pliocenos entre 33° y 34°S y también de otros mega-depósitos cenozoicos de pórfido cuprífero más al norte en los Andes de Chile.

Palabra claves: Volcanismo andino, Plioceno, Cuaternario, Frente volcánico, Geometría de subducción, Erosión tectónica, Manto, Pórfido cuprífero.

INTRODUCTION

Barazangi and Isacks (1976) showed that in regions of the South American continental margin below which the angle of subduction is very low (less than 20 degrees), active volcanism is absent. Volcanism in the Andes is currently occurring only in those regions below which the subduction angle is somewhat greater (20-30 degrees). These differences suggest a close relation between the generation of Andean volcanism and the geometry of subduction of oceanic lithosphere, as does the near uniformity of the depth to the Benioff zone of seismic activity below the volcanic front within the volcanically active segments of the Andes.

Accordingly, changes in the location of the Andean volcanic front with time have been interpreted to indicate changes in the geometry of subduction. For example, Kay *et al.* (1987, 1988) attribute the eastward migration, between the Miocene and the Pliocene, of the locus of Andean volcanism at latitude 30°S, to progressive flattening of the angle of subduction below this region during this time period.

This paper discusses the migration of the volcanic front from the Pliocene to the Present within two segments of the Southern Volcanic Zone of the Andes (SVZ, 33-46°S, Fig. 1): between 33-34°S at the northern end of the SVZ (Fig. 2) and between 38-39°S near the middle of the SVZ (Fig. 3). In these two regions the volcanic front has migrated as much as 30-80 km over the last 1 to 2 Ma, but in different directions. Both the differences in the sense of migration of the volcanic front, as well as differences in the chemistry of the magmas erupted along the current front within these two regions, can be related to changes occurring in the geometry of subduction below these different portions of the SVZ of the Andes.

THE VOLCANIC FRONT BETWEEN 33-34°S

GENERAL TECTONIC SETTING

The northern end of the SVZ, at 33°S, corresponds to a major Andean tectonic segment boundary spatially associated with the impingement of the Juan Fernández Ridge upon the Chile Trench (Fig. 1). North of this latitude Quaternary volcanism is absent, the Chilean Central valley disappears, and the Sierras Pampeanas structural province of compressive crystalline basement uplifts appears in the Argentine foreland (Fig. 1; Jordan *et al.*, 1983). These changes across this segment boundary have been related to differences in the angle of dip of the subduction of the Nazca plate, which becomes significantly shallower to the north, possibly due to the subduction of the Juan Fernández Ridge (Barazangi and Isacks, 1976; Pilger, 1984; Bevis and Isacks, 1984).

Bevis and Isacks (1984) concluded that the change in the angle of subduction of the Nazca Plate in the vicinity of 33°S does not reflect an abrupt tear in the subducted oceanic plate, but

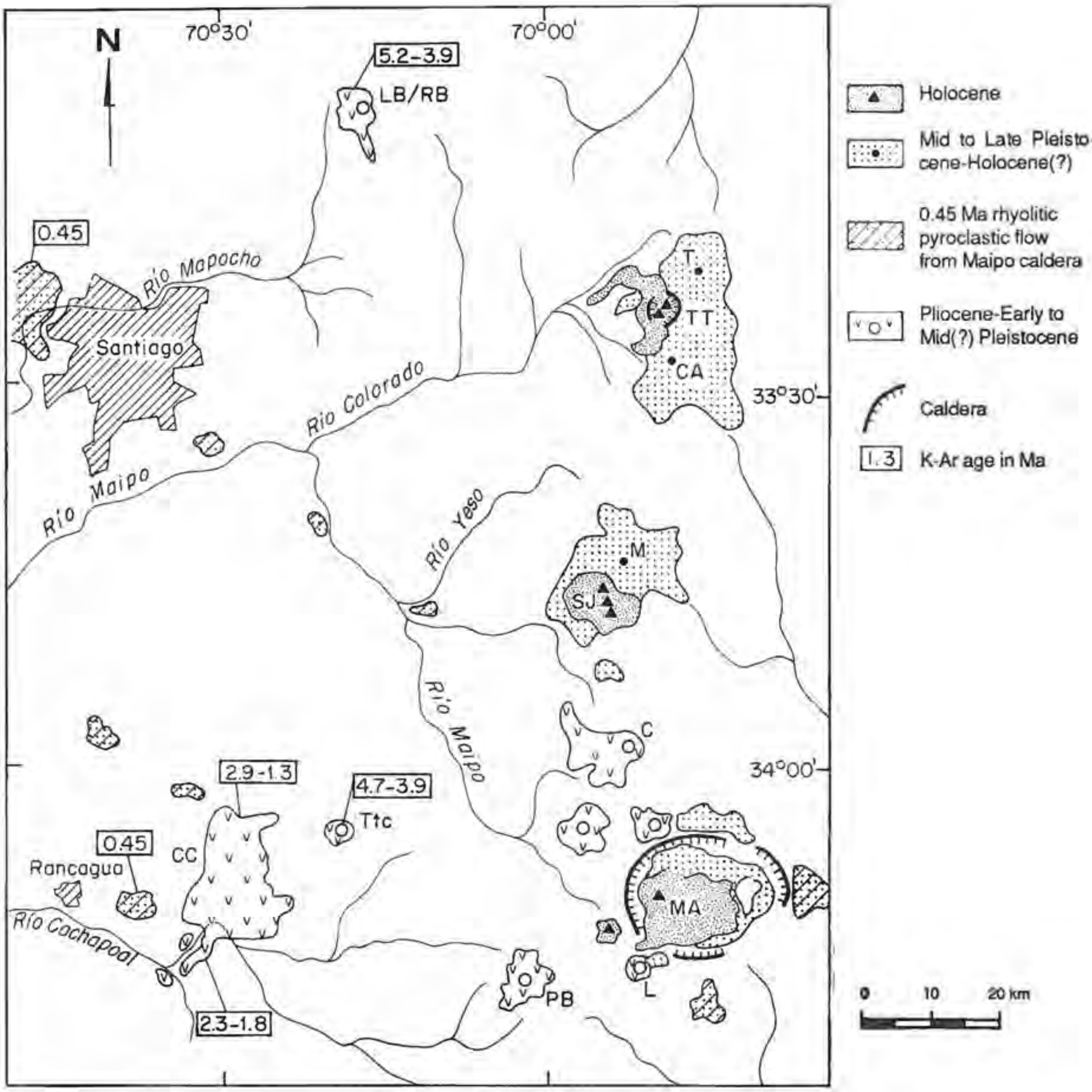

FIG. 2. Map of the Pliocene/early to mid(?) Pleistocene, mid to late Pleistocene/Holocene(?), and Holocene volcanic units between 33-34°S. The figure shows the location of the Holocene volcanos: **TT.** Tupungatito; **SJ.** San José de Maipo; **MA.** Maipo. Mid to late Pleistocene/Holocene(?) centers: **T.** Tupungato; **CA.** Cerro Alto; **M.** Marmolejo, as well as the outcrop of the late Pleistocene rhyolitic ashflow from the Maipo caldera (diagonally lined). Pliocene/early to mid(?) Pleistocene centers: **LB/RB.** Los Bronces-Río Blanco; **Ttc.** El Teniente; **C.** Cerro Castillo; **L.** Listado; and **PB.** Picos de Barroso, and outcrop of **CC.** Formation Colón-Coya. Ages shown in boxes are K-Ar and fission-track determinations, in Ma, from Charrier and Munizaga (1979), Stern *et al.* (1984a); Warnaars *et al.* (1985), and Cuadra (1986).

rather a smooth transition achieved by flexure of a coherent slab. The contours of the depth to the deeper parts of the Benioff zone east of below the volcanic front (Fig. 1) indicate that the northward flattening of the angle of subduction may, in fact, begin as far south as 36°S. Crustal deformation, thickening, and uplift north of 33°S have been related to the development of the low angle of subduction below this region (Jordan *et al.*, 1983) and the gradual northward increase in elevation of the Main Cordillera north of 36°S (Hildreth and Moorbath, 1988) is presumably caused by crustal thickening related to the gradual flattening of the angle of subduction towards the northern end of the SVZ.

THE CURRENT VOLCANIC FRONT

Between 33-34°S the current volcanic front, and in fact the entire volcanic belt, consists of the four predominantly andesitic volcanic complexes Tupungato/Tupungatito, Cerro Alto, Marmolejo/Espíritu Santo/San José de Maipo, and Maipo/Casimiro (Fig. 2; Thiele and Katsui, 1969; López-Escobar *et al.*, 1977, 1985; Stern *et al.*, 1984a, b; Hickey *et al.*, 1984,1986; Futa and Stern, 1988; Stern, 1988, and in press; Hildreth and Moorbath, 1988). These volcanos are located along the crest of the Andes, 288 ± 8 km east of the axis of the Chile Trench and approximately 100 ± 10 km above the top of the Benioff zone of seismic activity (Bevis and Isacks, 1984; Hildreth and Moorbath, 1988). South of 34°S the volcanic belts widens (Fig. 1) to include both the volcanic front and an eastern belt of Andean stratovolcanos, as well as fields of scattered and fissure aligned alkali basalt cones and flows to the east of the Main Cordillera (Muñoz and Stern, 1988, 1989).

The age of the oldest volcanic activity in the regions of the Tupungato/Tupungatito, Cerro Alto, and Marmolejo/Espíritu Santo/San José de Maipo volcanic centers is not well determined. Thiele and Katsui (1969) suggested that the Tupungato and Marmolejo volcanos may have begun to be active in the Pliocene. The Maipo volcano occurs within, and thus post-dates, a 15 by 20 km caldera depression formed 450,000 years ago (Stern *et al.*, 1984a). Mid Pleistocene pre-caldera lavas are exposed in the wall of the Maipo caldera (Harrington and Stern, 1987), and these lavas overlie and post-date older volcanic rocks associated with the Nevado de Argüelles, Listado, and Picos de Barroso volcanic centers which may be early Pleistocene or Pliocene in age (Schneider *et al.*, 1988).

THE PLIOCENE AND EARLY PLEISTOCENE VOLCANIC FRONT

The Pliocene and early Pleistocene volcanic front between 33-34°S was located to the west of the current volcanic front (Fig. 2). Andesite and dacite lavas, rhyolite pyroclastic flows, and subvolcanic intrusions of dacite, latite, and quartz porphyries, tourmaline breccias, and andesite and lamprophyre dikes, which have been dated by K-Ar techniques as being Pliocene and early Pleistocene in age, occur in the vicinity of the Río Blanco and Los Bronces mines (4.9 - 3.9 Ma; Quirt *et al.*, 1971; Drake *et al.*, 1976; López-Escobar and Vergara, 1982; Vergara and Latorre, 1984; Warnaars *et al.*, 1985; Blondel *et al.*, 1988), the El Teniente mine (4.7 - 2.9 Ma; Quirt *et al.*, 1971; Clark *et al.*, 1983; Cuadra, 1986), and in the valley of the Río Cachapoal (2.3 - 1.8 Ma; Charrier and Munizaga, 1979). The Pliocene and early Pleistocene volcanic rocks near the latter two localities have been grouped together as the Formation Colón-Coya (Cuadra, 1986). This formation includes lava flows, laharic deposits, and layers of volcanic ash. Cuadra (1986) reported a mid Pleistocene age (1.3 Ma) for a sample of ash intercalated within the formation. Although the source of this ash is uncertain, and it may have been derived from a volcanic center along the current volcanic front as were the 0.45 Ma rhyolitic pyroclastics which rest on the Formation Colón-Coya near Coya (Stern *et al.*, 1984a) this date indicates that lava flows within the Formation Colón Coya may range in age to as young as mid Pleistocene.

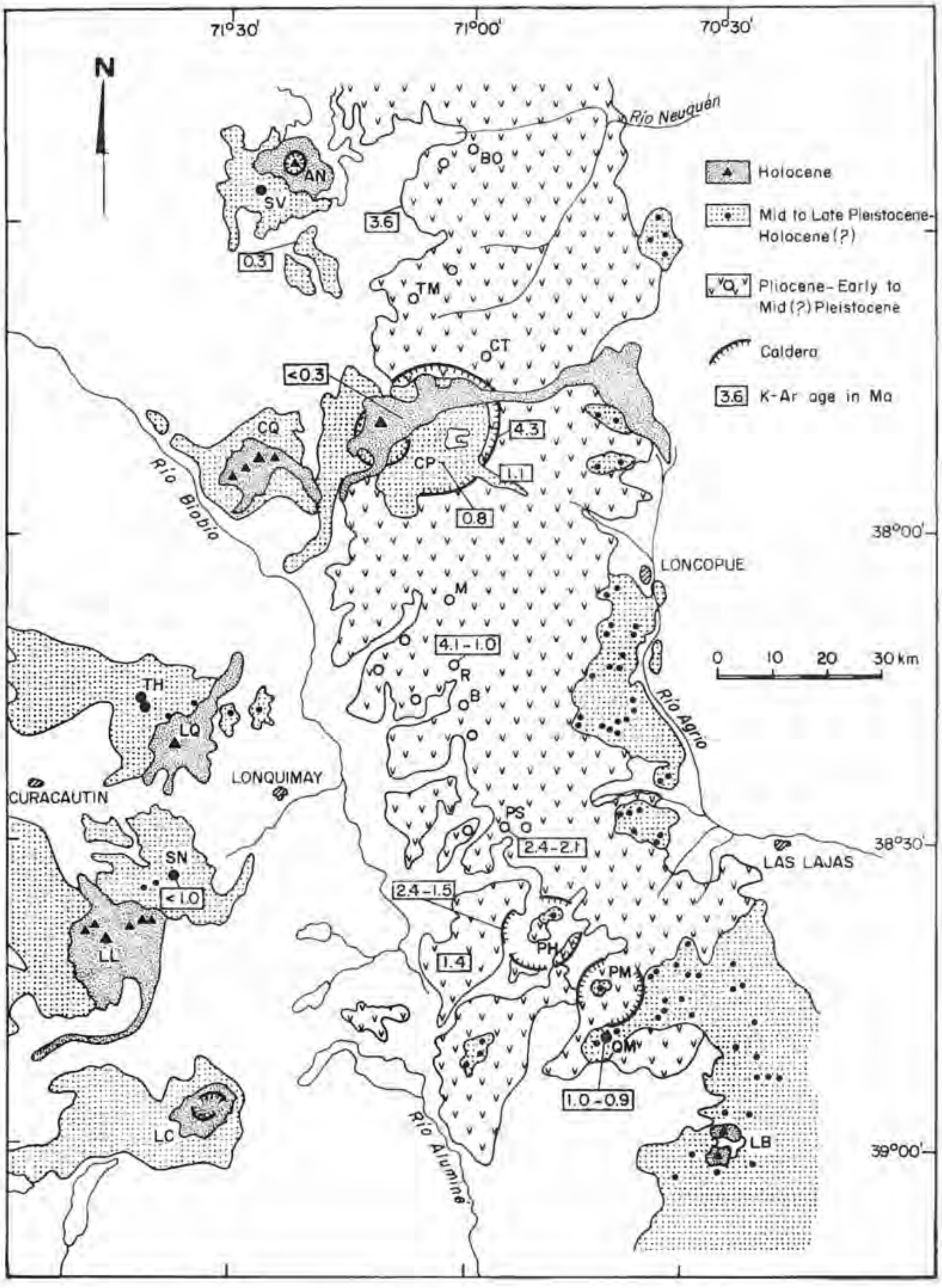

FIG. 3. Map, modified after Muñoz and Stern (1989), of the Pliocene/early to mid(?) Pleistocene, mid to late Pleistocene/Holocene(?), and Holocene volcanic units between 37°30'-39°S. The figure shows the location of the Holocene volcanos: **AN.** Antuco; **CP.** Copahue; **CQ.** Callaqui; **LQ.** Lonquimay; **LL.** Laima; **LC.** Llallicupe; and cones near **LB.** Laguna Blanca. Mid to late Pleistocene/Holocene(?) centers: **SV.** Sierra Velluda; **TH.** Tolhuaca; **SN.** Sierra Nevada; **PM.** Palao Mahuida; QM. Queli Mahuida. Pliocene/early to mid(?) Pleistocene centers: **BO.** Bonete; **TM.** Trocoman; **CT.** Cerro Trolon; **M.** Las Monjas; **R.** Rahue; **B.** Butahuao; **PS.** Pino Solo/Tralihue; **PH.** Pino Hachado. Ages shown in boxes are K-Ar determinations, in Ma, from Drake (1976), Drake *et al.* (1976), Muñoz and Stern (1988, 1989), and Muñoz *et al.* (1989).

THE VOLCANIC FRONT BETWEEN 38-39°S

GENERAL TECTONIC SETTING

The region between 38-39°S occurs at the southern boundary of the segment 34-39°S of the volcanic belt of the southern Andes which is characterized by intra-arc extension (Fig. 1; Muñoz and Stern, 1988 and 1989; Muñoz *et al.*, 1989). North of 39°S, orogenic arc volcanos occur both in the Main Cordillera and to the east on precordilleran uplifts separated from the Main Cordillera and from each other by extensional valleys within which intra-arc alkali basaltic volcanism is occurring (Muñoz and Stern, 1988, 1989). South of 39°S, the orogenic arc is restricted to the Main Cordillera while back-arc basaltic volcanism occurs well to the east. This change near 39°S has been attributed to the change in age, from older to younger respectively, of the oceanic lithosphere being subducted below the regions north and south of the intersection of the Valdivia Fracture Zone with the Chile Trench (Muñoz and Stern, 1988).

THE VOLCANIC FRONT

The current volcanic front between 38-39°S consists of the three predominantly basaltic through andesitic volcanic centers Callaqui, Lonquimay, and Llaima (Fig. 3; López-Escobar *et al.*, 1977; Hickey *et al.*, 1984, 1986; Muñoz and Stern, 1988, 1989). These volcanos are located within but to the west of the crest of the Andes, 285 ± 5 km east of the axis of the Chile Trench and approximately 90 ± 10 km above the top of the Benioff zone of seismic activity, which is slightly shallower than at the northern end of the SVZ (Bevis and Isacks, 1984). The Holocene volcanic belt between 38-39°S also includes stratovolcanos east of the volcanic front, such as the Copahue volcano, and fields of small fissure aligned and scattered cones of alkali basalts to the east of the Main Cordillera (Muñoz and Stern, 1988).

Lonquimay volcano is located just to the southeast of an older inactive(?) center, the Tolhuaca volcano, and the Llaima volcano is located just to the southwest of an older inactive volcano, Sierra Nevada. A sample from Sierra Nevada has been dated as being less than 1 Ma, implying a mid Pleistocene age for this center (Muñoz and Stern, 1988). The Holocene Antuco volcano, located on the volcanic front at 37°30'S, also rests on the edge of an older volcanic edifice, Sierra Velluda, a lava from the base of which has been dated as late Pleistocene (0.3 Ma; Drake, 1976a, b). These relations suggest that, near the middle of the SVZ, volcanic activity in the vicinity of the current volcanic front was initiated in the mid to late Pleistocene and the volcanic front has not significantly changed its position since that time (Drake, 1976 b; Muñoz and Stern, 1988, 1989). The Tolhuaca volcano and the base of the Callaqui, Lonquimay, and Llaima volcanos are assumed to be mid to late Pleistocene in age as well (Fig. 3).

Drake (1976b) described outcrops, which occur to the west of the current volcanic front at latitude 35°30'S, of Pliocene and early Pleistocene lavas belonging to what Vergara and Munizaga (1974) termed the 'andesitic plateau series' and which more recently have been included in the Formation Cola de Zorro (Vergara and Muñoz, 1982). The eruptive centers for these and other Pliocene and early Pleistocene lavas in central-south Chile have been shown to occur to the east of the current volcanic front, as described in more detail below (Drake, 1976b; Pesce, 1987; Muñoz and Stern, 1988, 1989).

THE PLIOCENE AND EARLY PLEISTOCENE VOLCANIC FRONT

The Pliocene and early Pleistocene volcanic front between 38-39°S was located well to the east of the current volcanic front along the Copahue-Pino Hachado precordilleran uplift (Fig. 3; Muñoz and Stern, 1988, 1989; Muñoz *et al.*, 1989). Basaltic through andesitic lava flows and rhyolitic pyroclastic deposits dated by K-Ar techniques as being Pliocene and early-mid Pleistocene in age have been described from the base of the inner wall of the Copahue caldera (4.3 Ma; Muñoz and Stern, 1988), from the pyroclastic outflow related to the formation of this caldera (1.1 Ma; Muñoz and Stern, 1988), and from the Rahue volcanic center (4.1-1.0 Ma; Muñoz and Stern, 1988) the Tralihue/Pino Solo volcano (2.4-2.1 Ma; Muñoz and Stern, 1988; Muñoz *et al.*, 1989), the Pino Hachado volcanic complex (2.45-1.4 Ma; Vergara and Munizaga, 1974; Muñoz and Stern, 1988; Muñoz *et al.*, 1989), and the Queli Mahuida volcano (1.0-0.9 Ma;

Muñoz and Stern, 1988).

Other volcanic centers which formed the Pliocene and early Pleistocene volcanic front along the Copahue-Pino Hachado uplift between 38-39°S include the Butahuao, Huarenchenque, and Palao Mahuida volcanic complexes (Pesce, 1987; Muñoz and Stern, 1988), while to the north this chain includes the Cerro Trolon, Trocoman, Bonete, Guanaco, and Los Niches (37°S) volcanic centers (Pesce, 1987), and even further north Volcán Campanario (36°S) and Cerro San Francisquito (Drake, 1976a, b). Pliocene and early to mid Pleistocene lavas outcropping at Paso Pichachen (37°30'S; 3.6 Ma; Muñoz *et al.*, 1989) and in the region north of Laguna del Maule (36°S; 4.2-0.6 Ma; Drake, 1976b) were derived from these centers which all occur east of the current volcanic front.

DISCUSSION

The chronological information summarized above indicates that between 33-34°S, at the northernmost end of the SVZ, and between 38-39°S, near the middle of the SVZ, the Andean volcanic front has changed its position significantly, but in different directions, from the Pliocene to the Present.

Between 38-39°S the front has migrated westward, a distance which ranges from 30-80 km over the last 1-2 Ma (Fig. 3), as was recognized previously by Vergara and Munizaga (1974), Drake (1976a, b), and Muñoz and Stern (1988, 1989). In contrast, between 33-34°S the volcanic front has migrated eastward, approximately 35 km, over this same time period, and the boundary between the volcanically inactive zone to the north and the SVZ to the south has migrated southward at least 25 km (Fig. 2).

Changes in the position of the Andean volcanic front with time are likely to reflect changes in **1.** the angle of subduction of oceanic lithosphere below the western margin of the continent; **2.** the position of the trench relative to the continental margin; and/or **3.** the thermal regime in the mantle wedge above the subducted oceanic crust which determines the depth of magma generation below the volcanic front. These changes may be caused by **1.** the subduction of bouyant features such as aseismic ocean ridges; **2.** changes in the rate and/or orientation of plate convergence; **3.** accretion to or tectonic erosion of the continental margin; and **4.** changes in the vigor of convection in the asthenospheric mantle wedge above the subducted oceanic plate (Cross and Pilger, 1982). The probable causes for the migration - from the Pliocene to the Present during which time the convergence rate and direction between the Nazca and South American plates apparently was constant - of the volcanic fronts at 33-34°S and 38-39°S are discussed below, along with their possible role in producing the petrochemically distinct magmas erupted in these two regions of the SVZ of the Andes.

MIGRATION OF THE VOLCANIC FRONT AT 33-34°S

The eastward migration, between the Pliocene and the Present, of the volcanic front at 33-34°S, could be related to **1.** a decrease in the angle of subduction of the oceanic plate; **2.** eastward migration of the Chile Trench due to tectonic erosion of the continental margin; and/or **3.** cooling of the mantle wedge overlying the subducted plate, resulting in a deepening of the zone of magma generation below the volcanic front (Fig. 4). As discussed below it is likely that all three of these processes are occurring at the northern end of the SVZ of the Andes.

Flattening of the angle of subduction of oceanic lithosphere below the Andean segment north of 33°S began in the mid Tertiary and continued into the Pliocene, with a major change occurring between 11-8 Ma as indicated by eastward migration and ultimate cessation of volcanism in this region (Kay *et al.*, 1988). Flattening of the angle of subduction north of 33°S must have affected the geometry of subduction to the south, if, as suggested by Bevis and Isacks (1984), the subducted oceanic lithosphere below these adjacent regions forms a coherent slab. Continued flexture and flattening of the angle of subduction below the northern end of the SVZ is consistent with the southward migration of the boundary between the volcanically quiescent zone to the north and the SVZ to the south, as well as the eastward migration of the

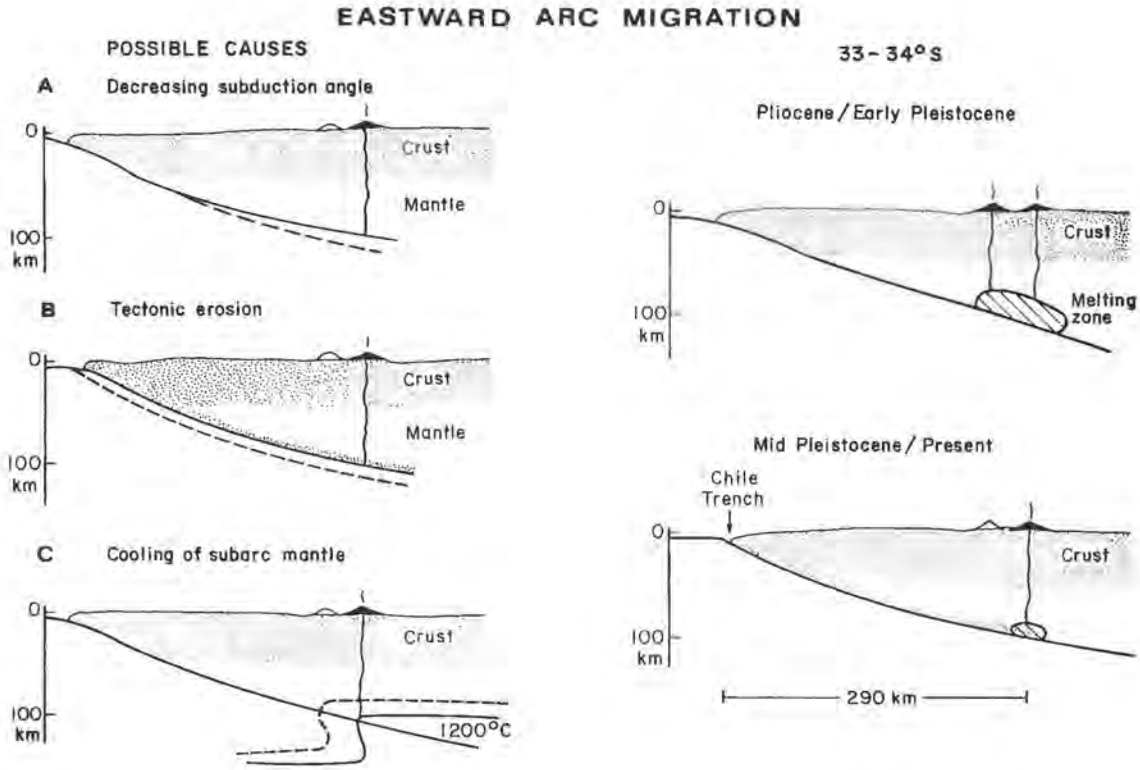

FIG. 4. Schematic diagram of the factors influencing the eastward migration of the volcanic front at 33-34°S. **Possible causes:** A, B, and C show, respectively, the effect on the location of the volcanic front of **A.** decreasing angle of subduction; **B.** eastward migration of the trench axis relative to the coast caused by tectonic erosion along the inner trench wall; and **C.** cooling in the asthenosphere wedge overlying the subducted slab as represented by the change in position of the 1200°C isotherm. In diagrams A and B the original position of the top subducted slab is indicated by dashed lines and the final position by heavy solid lines. In C the original position of the 1200°C isotherm is represented by a dashed line and the final position by a thin solid line. The combined effect of these three factors is likely to have caused shrinking and deepening of the zone of subarc melting (horizontally lined area) and the eastward migration, between the Pliocene and the Present, of the volcanic front below the SVZ at 33-34°S as discussed in the text and illustrated on the right side of the diagram.

volcanic front observed between the Pliocene and the Present.

Tectonic erosion of the continental margin, causing the trench axis to migrate eastward with time, is likely to be a more significant factor at the northern end compared to farther south in the SVZ because of both **1.** the lower subduction angle below the northern end of the SVZ, and **2.** the lower sediment supply to the Chile Trench caused by the increasingly arid climate towards the northern end of the SVZ. Ziegler *et al.* (1981), Shreve and Cloos (1986), and Cloos and Shreve (1988) have suggested that lower subduction angle and decreased sediment supply to the trench will increase the probability of tectonic erosion along the inner trench wall. Sediment subduction and tectonic erosion, during the Mesozoic and Cenozoic development of the Andes, of the south American continental margin of central and northern Chile, north of about 33° S, is suggested by the **1.** the lack of any Mesozoic or Cenozoic accretionary complex and the almost complete absence of sediment within the Chile Trench north of this latitude (Scholl *et al.*, 1970, 1977; Rutland, 1971; Plafker, 1972; Kulm *et al.*, 1977; Ziegler *et al.*, 1981; Hussong and Wipperman, 1981; Lowrie and Hay, 1981; Thornburg and Kulm, 1987); **2.** the north-northwest strike into the trench and essential disappearance, north of 33°S, of the pre-Andean upper Paleozoic subduction-related accretionary terrain and Upper Paleozoic to Lower Jurassic plutonic belts which make up the western portion of the Coastal Cordillera in south-central Chile (Fig. 1; Hervé *et al.*, 1988); and **3.** the progressive eastward migration of the mid Jurassic to Cenozoic Andean plutonic belts of Central Chile (Parada and Hervé, 1987).

Allmendinger *et al.* (in press) recently concluded that the total amount of observed crustal shortening occurring over the last 15 Ma at 30°S, within the Andean segment just north of the SVZ, is probably greater than can be accounted for with reasonable crustal thicknesses, thus implying the likelyhood of tectonic erosion along the convergent plate boundary. They consider 170 km of observed structural shortening at this latitude to be a conservative estimate, while they calculate, by crustal area balance assuming a maximum reasonable value of 45 km for present crustal thickness, only 137 km of horizontal shortening. The difference in these two estimates suggests the removal, by tectonic erosion, of a minimum of 33 km of 38 km thick crust over the last 15 Ma, implying a minimum average rate of 84 km^3/Ma of tectonic erosion per km along the trench. This value is within the range reported by Bourgois (1989) of 75-535 km^3/Ma of crust removed over the last 6 Ma by tectonic erosion per km along the Peruvian Trench between 5-12°S. Apparently subduction of the Nazca Ridge below this region of southern Perú locally accelerated rates of tectonic erosion (Von Huene *et al.*, 1988). The abrupt thinning of the trench sediments and disappearance of the pre-Andean basement north of 33°S suggests that the subduction of the Juan Fernández Ridge below the Andean segment just north of the SVZ may have had a similar effect, which would be currently focused at the northern end of the SVZ.

Subduction of oceanic lithosphere will lower the temperature in the mantle below the over-riding plate unless convection in the asthenosphere wedge above the subducted slab causes the influx of hot mantle. The overall decrease in the volume of the asthenospheric wedge above the subducted slab at the northern end of the SVZ, caused by the progressive flattening of the angle of subduction, probably acts to inhibit the extent of convection and influx of hot asthenosphere into this region. This effect may be accentuated by increasing crustal thickness towards the northern end of the SVZ. The lack of back-arc volcanism and extension east of the arc between 33-34°S (Fig. 1) is consistent with a lack of convection in the asthenosphere wedge below this region. Kay *et al.* (1987) also suggested that beginning in the mid Tertiary, a combination of crustal thickening and progressively decreasing angle of subduction below the Andean segment north of 33°S resulted in a decrease in the volume and cooling of the asthenosphere wedge above the subducted slab. The evolution of the volcanic belt at the northern end of the SVZ, between the Pliocene and the present, from a broad zone, involving magmatic activity both along the volcanic front and to the east as well (Fig. 2), into the single belt of volcanic centers which currently forms the volcanic belt at this latitude, is consistent with cooling of the subarc mantle over this time period. The restriction of the volcanic belt at 33-34°S to a single chain of volcanos, the lower magma production rates estimated for these centers compared to farther south in the SVZ (Stern *et al.*, 1984a; Stern, 1988, and in press), and the slightly greater depths to the Benioff zone beneath the front below the northern end of the SVZ are all consistent with a cooler subarc mantle below this region compared to farther south in the SVZ.

MIGRATION OF THE VOLCANIC FRONT AT 38-39°S

The westward migration, between the early Pleistocene and the present, of the volcanic front at 38-39°S, could be related to **1.** an increase in the angle of subduction of the oceanic plate; **2.** westward migration of the trench axis due to accretion along the inner trench wall; and/or **3.** heating of the mantle wedge overlying the subducted slab resulting in a shallowing of the zone of magma generation below the volcanic front (Fig. 5). All three of these processes may have occurred to some extent, but the importance of the latter is particularly clear. Extensive back-arc volcanism east of the Main Cordillera between 38-39°S implies active convection and influx of hot asthenospheric material into the mantle wedge below this region (Muñoz and Stern, 1988, 1989). Both the broad volcanic belt and the shallower depths to the Benioff zone of seismic activity below the volcanic front suggest a hotter subarc mantle below this region compared to the northern end of the SVZ. Also, although no accretionary complexes have been described within the trench, the morphology of the trench at this latitude is masked by sedimentary infill (Lowrie and Hay, 1981; Thornburg and Kulm, 1987). This implies that

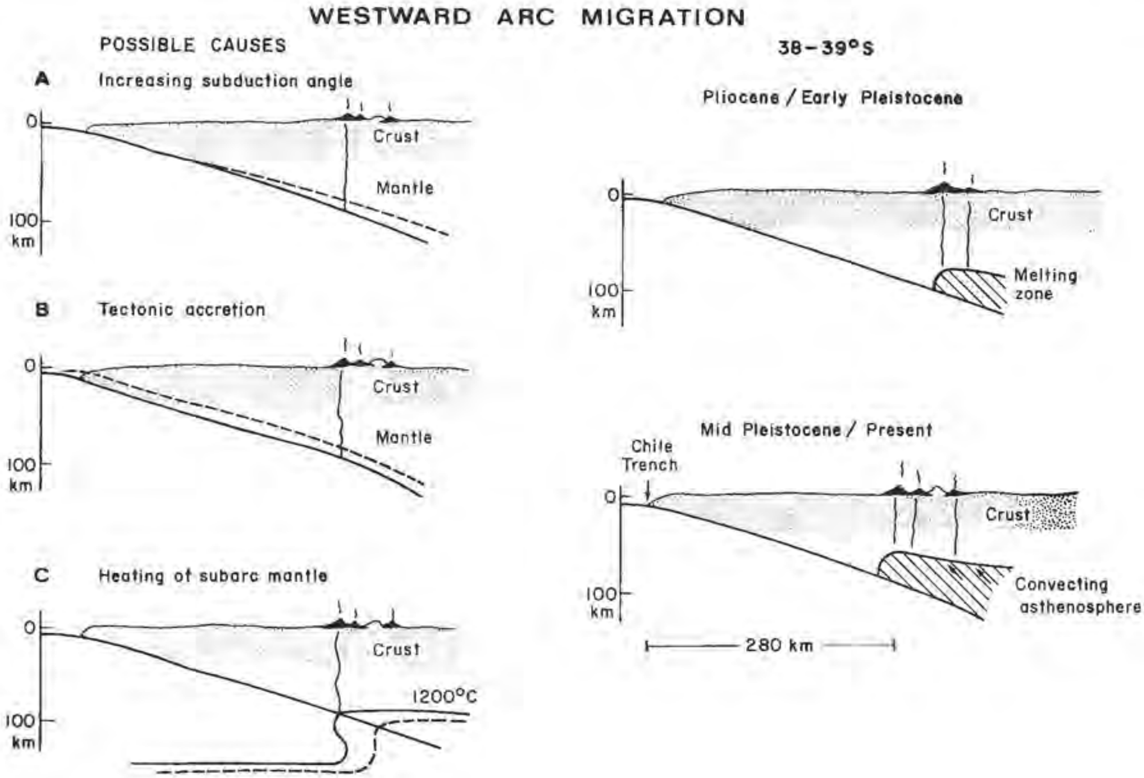

FIG. 5. Schematice diagram illustrating the factors influencing the westward migration of the volcanic front at 38-39°S. **Possible causes**: A, B, and C show, respectively, the effect on the location of the volcanic front of **A.** increasing angle of subduction; **B.** westward migration of the trench axis relative to the coast caused by accretion of material to the inner trench wall; and **C.** heating in the asthenosphere wedge overlying the subducted slab due to convective input of hot material. The combined effect of these three factors is likely to have caused the expansion of the zone of subarc melting and westward migration, between the Pliocene and the Present, of the volcanic front below the SVZ from 38-39°S as discussed in the text and illustrated on the right side of the diagram. Symbols as in figure 4.

the current rate of sediment supply to the trench is greater than the rate of sediment subduction, which may be in part responsible for causing the trench axis at this latitude to be significantly further from the coast compared to the region north of 34°S where tectonic erosion is believed to be more significant. Finally, progressive steepening of the angle of subduction below this region may be a geometric response to the flattening of the angle of subduction taking place to the north, or to the subduction of older oceanic lithosphere as the intersection of the Valdivia Fracture Zone and the Chile Trench migrates southward.

IMPLICATIONS FOR ANDEAN MAGMA GENESIS

Compared to farther south along the current volcanic front, the four volcanic centers at the northern end of the SVZ have distinctive petrochemical characteristics (López-Escobar *et al.*, 1977, 1985; Stern *et al.* 1984b; Hickey *et al.*, 1984, 1986; Futa and Stern, 1988; Stern, 1988, and in press; Hildreth and Moorbath, 1988), including **1.** the relative scarcity of mafic lavas resulting in a higher average SiO_2; **2.** higher incompatible element concentrations for samples of similar SiO_2; **3.** higher La/Yb (Fig. 6); and **4.** higher $^{87}Sr/^{86}Sr$ (Figs. 7, 8), lower $^{143}Nd/^{144}Nd$, more variable Pb isotopic composition, but similar δ180 compared to the volcanic centers farther south in the SVZ. These data have been interpreted by Stern *et al.* (1984b), Futa and Stern (1988), Stern (1988, and in press) and Hildreth and Moorbath (1988) to imply that, relative to farther south in the SVZ, **1.** a greater proportion of components derived from the continental crust are

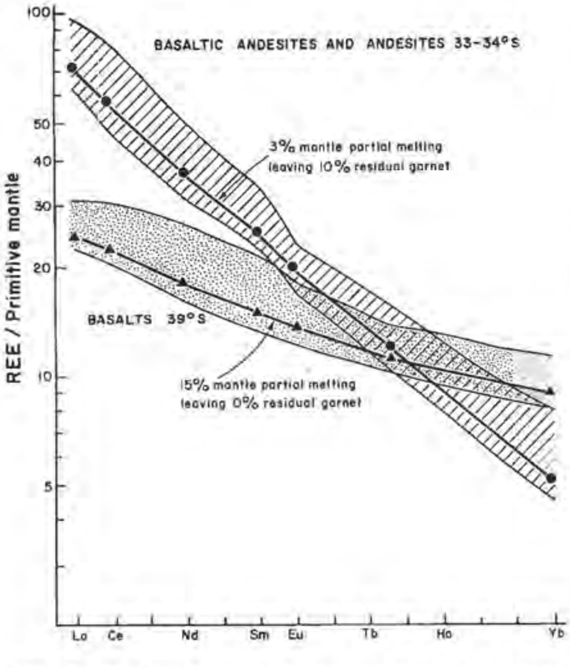

FIG. 6. Rare earth element concentrations, normalized relative to primitive upper mantle (La/0.315; Ce/0.813; Nd/0.597; Sm/0.192; Eu/0.072; Tb/0.049; Yb/0.208), for basalts from the Llaima volcano at 39°S in the middle of the SVZ (data from Hickey *et al.*, 1986) and basaltic andesites and andesites from the Tupungato, Marmolejo, and Maipo/Casimiro volcanos located between 33-34°S at the northern end of the SVZ (data from López-Escobar *et al.*, 1977, 1985; Stern, 1988). Also shown are models, developed and described in detail by López-Escobar *et al.* (1977), involving 3% and 15% partial mantle melting with garnet persisting as a residual phase only in the first model. These models suggest that the higher La and La/Yb of the volcanic centers at the northern end of the SVZ reflect lower degrees of mantle partial melting combined with a more significant role of garnet as a residual phase after melting.

incorporated in the magmas at the northern end of the SVZ; and **2.** garnet plays a more important role in the evolution of the magmas at the northern end of the SVZ. López-Escobar *et al.* (1977), and Stern (1988, and in press) conclude that lower degrees of subarc mantle partial melting is also a significant factor in increasing both the La/Yb (Fig. 6) and incompatible element concentrations, particularly the Sr contents (Fig. 8), of the magmas erupted at the northern end compared to farther south in the SVZ.

The relatively high Sr contents and high $^{87}Sr/^{86}Sr$ values of the andesites from the northern end compared to basalts from farther south in the SVZ indicate that the process of incorporation of crustal components in the more mafic magmas erupted at the northern end of the SVZ did not occur in the mid to upper crust where combined assimilation and crystal-liquid fractionation are expected to lower rather than increase the Sr content of more evolved magmas (Fig. 7). Hildreth and Moorbath (1988) suggested that crustal contamination of all SVZ magmas occurs in the lower continental crust, and that the significance of such intracrustal contamination increases towards the northern end of the SVZ because of the greater crustal thickness below this region. Alternatively, Stern *et al.* (1984b), Futa and Stern (1988), and Stern (1988, and in press) have argued that crustal components are incorporated in all SVZ magmas by the subduction of these materials into the subarc mantle source region, and that the significance of such source region contamination increases towards the northern end of the SVZ because of a greater rate of sediment subduction and tectonic erosion in this region. As discussed above, the eastward migration, between the Pliocene and the Present, of the volcanic front at the northern end of the SVZ is consistent with increased importance of tectonic erosion in this region compared to farther south in the SVZ.

Stern (in press) calculated that a typical SVZ basalt would have to assimilate at least its own weight in postulated high-Sr lower crustal lithologies to raise both its Sr content and Sr-isotopic composition to the values observed in the andesites erupted at the northern end of the SVZ (Fig. 8). Such large amounts of intra-crustal assimilation might be expected to significantly modify the δ18O and trace element composition of the basalt, but the andesites erupted at the northern end of the SVZ have δ18O and trace element ratios nearly similar to typical SVZ basalts. In contrast, addition to the subducted oceanic lithosphere of only 1% of tectonically eroded Paleozoic basement could raise the $^{87}Sr/^{86}Sr$ of the subarc mantle to the value of 0.705 observed in the andesites erupted at the northern end of the SVZ (Fig. 8). For the subduction of a 100 km thick oceanic lithosphere at 10 cm/yr, such as is occurring below the SVZ of the Andes, this corresponds to tectonic erosion and subduction of 100 km^3/Ma of Paleozoic basement per km of trench. This rate is similar to that calculated to have occurred over the last 15 Ma in the Andean segment just north of the SVZ, and is at the lower end of the range occurring along the coast of southern Perú.

Progressive decrease in the angle of subduction and the resultant decrease in volume and cooling of the subarc asthenosphere, which have been identified above as important factors in causing the eastward migration of the volcanic front at the northern end of the SVZ, are also consistent with the conditions - involving not only more significant source region contamination, but also lower percents of partial melting and increased participation of garnet - that have been invoked by López *et al.* (1977), Stern *et al.* (1984b), and Stern (1988, and in press) to explain the distinctive petrochemical characteristics of the volcanos in this region. As discussed previously by Stern *et al.* (1984b), and Stern (1988, and in press), the decreased volume of the subarc mantle below the northern end of the SVZ, due to a combination of both thicker crust and lower angle of subduction, increases the relative proportion of slab-derived components in the integrated slab + mantle contribution to magma genesis in this region. Cooling in the subarc mantle would deepen the zone of magma generation and lower the extent of partial melting, thus increasing the importance of residual garnet. The importance of residual garnet would increase in the deeper magma generation zone associated with a cooler subarc mantle because **1.** lower temperatures and higher pressures act to increase the proportion of mantle garnet relative to spinel; **2.** lower degrees of mantle partial melting increase the probability of garnet as a residual phase since garnet is one of the first mantle phases to enter a melt; and **3.** as discussed by Stern (in press), the experimental results of Johnston and Wyllie (1989) indicate that garnet will crystallize and increase in modal abundance as a slab-derived melt hydridizes at near isothermal conditions with peridotite within a relatively cool subarc mantle wedge.

Kay *et al.* (1987, 1988) also noted the increasing importance, between the Mid and Late Miocene, of garnet in the petrogenesis of Andean magmas near 30°S as the angle of dip of the subducted slab flattened and the crust thickened below this region, thus decreasing the volume and cooling the subarc mantle. They suggested that garnet may have increased in importance not only in the mantle, but at the base of the thickened

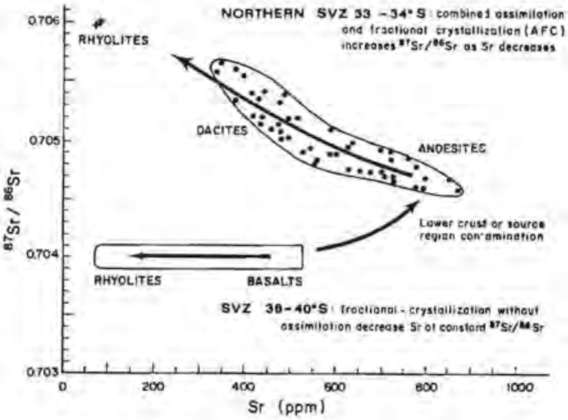

FIG. 7. **Sr content** *versus* $^{87}Sr/^{86}Sr$ for samples from the volcanic centers at the northern end (data from López-Escobar *et al.*, 1977, 1985; Stern *et al.*, 1984a; Stern, 1988; Hildreth and Moorbath, 1988) compared to the southern part of the SVZ of the Andes. The trend observed through the sequence basalt to rhyolite in the southern part of the SVZ, with constant $^{87}St/^{86}Sr$ as Sr decreases, is interpreted to result from fractional crystallization either without crustal assimilation or with assimilation of young granitic rocks with low $^{87}Sr/^{86}Sr$ similar to the SVZ basalts (Hickley *et al.*, 1984, 1986; Futa and Stern, 1988). The trend observed through the sequence basaltic andesite to rhyolite at the northern end of the SVZ, with increasing $^{87}Sr/^{86}Sr$ as Sr decreases, can be modeled by assimilation -of upper crustal lithologies with relatively low Sr and high $^{87}Sr/^{86}Sr$ - combined with fractional crystallization (AFC, see figure 6 of Hildreth and Moorbath, 1988). The higher Sr and $^{87}Sr/^{86}Sr$ of basaltic andesites and andesites from the northern end of the SVZ compared to basalts from farther south in the SVZ can not be explained by either of these processes, but must result instead from either (see Fig. 8) assimilation of high-Sr lithologies in the lower crust, as suggested by Hildreth and Moorbath (1988), or by changes in both the degree of partial melting as well as contamination process in the subarc mantle source region, as suggested by Stern *et al.* (1984b), Futa and Stern (1988), and Stern (1988, and in press).

crust as well. Hildreth and Moorbath (1988) also suggested that the increased importance of garnet in the petrogenesis of the magmas at the northern end compared to farther south in the SVZ reflects the thicker crust below this region. Thickened crust and increased compressive stress, such as occur at the northern end compared to farther

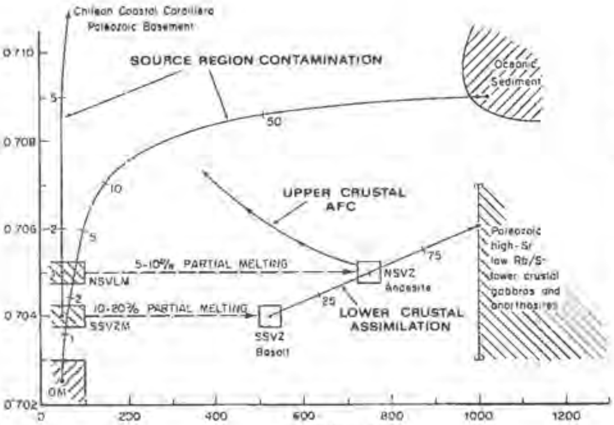

FIG. 8. Sr content *versus* $^{87}Sr/^{86}Sr$ for basalts from the southern part of the SVZ (SSVZ) and andesites from the northern end of the SVZ (NSVZ), taken from figure 7, and materials possibly involved in the generation of these rocks, including **1.** oceanic mantle (OM; Sr = 50 ppm and 87Sr/86Sr = 0.7025); **2.** oceanic sediment (Sr =1000 ppm and $^{87}Sr/^{86}Sr$ = 0.709); **3.** high-Sr lower crustal lithologies (Sr - 1000 ppm and $^{87}Sr/^{86}Sr$=0.706); and **4.** Paleozoic basement of the Chilean Coastal Cordillera (Sr = 200 ppm and $^{87}Sr/^{86}Sr$=0.73). The figure shows mixing curves between these materials, with percent of mixing indicated by the small numbers next to tick marks. These mixing curves show that a mantle source for the SSVZ basalts (SSVZM) can form by the contamination of oceanic type mantle with 1.5% of oceanic sediment. NSVZ andesites can form by either **1.** assimilation, by an SSVZ basalt within the lower crust, of an equal weight of high-Sr gabbro or anorthosite; or **2.** by melting of a mantle source region (NSVZM) which, compared to the mantle farther south in the SVZ, has been further modified by the addition of 1% subducted Paleozoic Coastal Cordillera basement. As discussed in a separate publication (Stern, in press) in which the details of each model and the values of Sr and $^{87}Sr/^{86}Sr$ used in their construction are described in more detail, the author concludes that the source region contamination model, involving as it does only a small change in the composition of subducted materials, is a more appropiate model for explaining the generation of andesites at the northern end of the SVZ since these andesites have δ18O and trace element ratios very similar to the basalts erupted farther south in the SVZ.

south in the SVZ and developed across the continental margin at 30°S in the Mid to Late Miocene, may increase the extent to which mantle derived magmas evolve as they rise through the crust, thus increasing the proportion of evolved intermediate and silicic magmas erupted relative to more mafic magmas (Stern *et al.*, 1984b). However, the fundamental petrochemical features of all Andean magmas, as well as magmas from other convergent plate boundaries both along continental margins and in intra-oceanic regions, is established in the intergrated subarc slab + mantle system (Stern, in press).

In contrast to the northern end of the SVZ, a model involving relatively high degrees of partial melting (Figs. 6, 8) of a subarc mantle contaminated by components derived dominantly from subducted pelagic sediment and/or sea-water altered oceanic crust, has been proposed for the generation of the basalts erupted from along the volcanic front near the middle of the SVZ (López-Escobar *et al.*, 1977; Hickey *et al.*, 1984, 1986; Futa and Stern, 1988). The decreased probability of tectonic erosion within a trench filled with sediment (Ziegler *et al.*, 1981; Shreve and Cloos, 1986; Cloos and Shreve, 1988) and the hotter temperatures in the subarc mantle below the middle as compared to the northern end of the SVZ - as indicated by the presence of backarc basaltic volcanism and the shallower depth to the Benioff zone below the arc in this region - are consistent with the conditions implied by these models.

IMPLICATIONS FOR ANDEAN METALLOGENESIS

Mineralized subvolcanic tourmaline breccia pipes within the Río Blanco-Los Bronces and El Teniente porphyry copper deposits (33-34°S; Fig. 2) have been dated as Pliocene in age (5.2-3.9 Ma and 4.7-4.5 Ma, respectively; Quirt *et al.*, 1971; Drake *et al.*, 1976; Clark *et al.*, 1983; Warnaars *et al.*, 1985; Cuadra, 1986). These deposits are hosted in older Miocene Farellones Formation volcanic rocks and their plutonic equivalents (18.5-7 Ma; Vergara *et al.*, 1988), which were erupted and emplaced in the region between 31°30'-34°35'S prior to the establishment of the current tectonic and magmatic segmentation of the Andes. Fluid inclusion data indicate a period of uplift following the cooling of the plutons of the San Francisco batholith (20.1-8.6 Ma; Warnaars *et al.*, 1985) and proceeding the subsequent intrusion of the Los Bronces tourmaline breccias (Holmgren *et al.*, 1988; M.A. Skewes, personal commun.). These data, as well as the lack of important Pliocene porphyry copper deposits north of 33°, suggest that the metal-rich tourmaline breccia pipes at Río Blanco-Los Bronces and El Teniente do not represent a late stage in the process of solidification of the plutons associated with the Miocene Farellones Formation, as suggested by Warnaars *et al.* (1985), but rather that the magmas responsible for this mineralization belong to the Pliocene phase of volcanism which developed after the current segmentation of the Andes near latitude 33°S had been established.

Apparently the generation of these Pliocene metal-rich tourmaline breccia pipes is closely related in time to the initiation of the flattening of the angle of subduction below the northern end of the SVZ. The late Miocene Los Pelambres porphyry copper at 32°S also formed as subduction angle decreased below the Andean segment just north of the SVZ (Skewes and Stern, 1988). As discussed above, decreasing angle of subduction led to a decrease in the volume and cooling of the subarc mantle, an increase in the rate of tectonic erosion, and eventually the eastward migration of the arc in these regions (Fig. 4). In this article it is suggested that two effects of decreasing angle of subduction - the increased relative importance of slab-derived components in the integrated slab + mantle magma source region as the volume of the subarc mantle decreases and the increased proportion of continental components added into the subarc mantle as the rate of tectonic erosion increases - are significant processes, not only in the generation of the distinctive petrochemical characteristics of the magmas erupted along the current volcanic front between 33-34°S, but also in the genesis of the late Miocene and Pliocene porphyry copper deposits of Los Pelambres, Río Blanco-Los Bronces, and El Teniente located between 32-34°S.

Maksaev and Zentilli (1988) showed that porphyry copper deposits farther north in Chile formed following episodes of crustal deformation, uplift, and thickening, and just prior to the eastward migration or cessation of igneous activity. They identified relatively low degrees of mantle partial melting in the presence of garnet as important factors in the generation of the magmas with which these deposits are associated and suggested that these conditions are meet after episodes of crustal thickening due to the consequent decrease in the volume and cooling of the subarc mantle and subsequent deepening of the zone of magma generation. As noted above, another important effect related to any decrease in the volume of the subarc mantle, caused by either crustal thickening or a decrease in the angle of slab subduction, is an increase in the relative importance of slab-derived components in the integrated slab + mantle source of Andean magmas. Thus, as the volume of the subarc mantle shrinks, the 'geostill' (Sillitoe, 1972) processes a greater proportion of subducted material relative to mantle peridotite. It is here suggested that this effect, in association with the decrease in the extent of melting as the subarc mantle source region cools and deepens after periods of either crustal thickening or in responce to the flattening of subduction angle, was one of the key processes in generating the magmas that led to the development of mega-porphyry systems, not only between 32-34°S, but in northern Chile as well.

The extent to which flattening of subduction angle and tectonic erosion were also important factors in the generation of the porphyry copper deposits in northern Chile, as it has here been suggested for those deposits between 32-34°S, remains speculative, but a clear correlation exists between the regional distribution of Chilean porphyry copper deposits and the zone of extensive tectonic erosion delineated by Ziegler *et al.* (1981). Unfortunately, because tectonic erosion destroys rather than produces rock units, determining whether tectonic erosion was an episodic process like crustal deformation, uplift and thickening, and whether episodes of increased rates of tectonic erosion correlate with porphyry copper genesis, remains problematic.

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