Andean Geology 38 (1): 1-22. January, 2011

Andean Geology
formerly Revista Geológica de Chile
www.scielo.cl/andgeol.htm

Olivine-hornblende-lamprophyre dikes from Quebrada los Sapos, El Teniente, Central Chile (34°S): implications for the temporal geochemical evolution of the Andean subarc mantle

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ABSTRACT. Mafic Mg-olivine (Fo88)+hornblende lamprophyre dikes, with Ni ~190 ppm and Cr ~390 ppm, cut late Miocene lavas in the Quebrada los Sapos a few kilometers west of the El Teniente Cu-Mo mine. These dikes have petrochemical affinities with other less primitive, Pliocene (2.9-3.9 Ma), olivine-free lamprophyres previously described from both within and in the vicinity of El Teniente. The mafic mantle-derived lamprophyre dikes from Quebrada los Sapos have La/Yb ratios of 10-13, higher than the ratios of 4-9 for older Late Miocene El Teniente Mafic Complex olivine basalts, suggesting a temporal decrease in the percent of partial mantle melting, consistent with the observed decrease in the volume of igneous rocks through time at this latitude, as well as the ultimate cessation of magmatism and >40 km eastward arc migration by the Late Pliocene. Less primitive olivine-free lamprophyres have higher La and lower Yb, resulting in higher La/Yb ratios of 15-44, due to crystal-liquid fractionation involving hornblende, but not plagioclase, the crystallization of which is suppressed by the high H_2O contents of the lamprophyres. The lamprophyre dikes, as well as younger (1.8-2.3 Ma) olivine-bearing basaltic-andesite lava flows in the valley of the Cachapoal river, have $^{87}Sr/^{86}Sr$=0.7041 to 0.7049, ϵ_{Nd}=+1.2 to -1.1 and $^{206}Pb/^{204}Pb$=18.60 to 18.68, while Middle to Late Miocene (6.5-13.9 Ma) El Teniente Volcanic and Plutonic Complex igneous rocks have lower $^{87}Sr/^{86}Sr$=0.7039 to 0.7041 and $^{206}Pb/^{204}Pb$=18.56 to 18.59, and higher ϵ_{Nd}=+1.9 to +3.8, and older Oligocene to Early Miocene (>15 Ma) Abanico or Coya-Machalí Formation volcanic and plutonic rocks in the region have even lower $^{87}Sr/^{86}Sr$=0.7033 to 0.7039 and $^{206}Pb/^{204}Pb$=18.45 to 18.57, and higher ϵ_{Nd}=+3.8 to +6.2. The data indicate a significant progressive temporal evolution, between the Oligocene and the Pliocene, to higher $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$, and lower ϵ_{Nd} for mantle-derived mafic magmas, and by implication their mantle source region. Significantly Sr, Nd and Pb isotopic compositions are independent of SiO_2 content for rocks in each age group, which precludes contamination by isotopically heterogeneous Paleozoic and Mesozoic continental crust during evolution of intermediate and silicic rocks from mantle-derived mafic magmas. The Oligocene to Pliocene isotopic evolution of the mantle source of the mafic magmas may be explained by an increase from 1% to 6% in the extent of mantle source region contamination by subducted components, including continental crust tectonically eroded off the continental margin. We attribute this to both decreasing subduction angle and increasing rates of subduction erosion associated with the southward migration of the locus of subduction of the Juan Fernández Ridge. The lamprophyres also imply increased hydration of the mantle below this portion of the arc by the Pliocene, which may have played an important role in producing oxidized volatile-rich magmas and mineralization at El Teniente.

Keywords: El Teniente Cu-deposit, Lamprophyres, Subduction erosion, Subarc mantle, Isotopes.

RESUMEN. Diques lamprofídicos de olivino-hornblenda de la quebrada los Sapos, El Teniente, Chile central (34°S): implicancias para la evolución temporal de la geoquímica del manto subarco Andino. Diques de lamprófidos máficos, con fenocristales de olivino magnésicos (Fo88)+hornblendas y contenidos de Ni ~190 ppm y Cr 390 ppm, cortan lavas miocénicas superior en la quebrada los Sapos a escasos kilómetros al oeste del depósito de Cu-Mo El Teniente. Estos diques tienen afinidades petroquímicas con otros diques lamprofídicos del Plioceno (2,9-3,9Ma), menos primitivos y sin fenocristales de olivinos, los cuales han sido descritos tanto dentro como alrededor de El Teniente. Estos diques de lamprófidos máficos en la quebrada los Sapos, derivados del manto, tienen razones de La/Yb entre 10-13, más altas que la de los más antiguos basaltos de olivino (La/Yb entre 4 y 9) del Complejo Máfico El Teniente (CMET), sugerente de un decrecimiento temporal de la fusión parcial del manto, y esto es consistente con el volumen decreciente observado de las rocas ígneas en este período de tiempo, como también con el término del magmatismo y la migración hacia >40 km al este del arco magmático durante el Plioceno. Los lamprófidos menos primitivos, sin olivino, tienen contenidos más altos de La y menores de Yb, con razones más altas de La/Yb entre 15-44, debido al fraccionamiento cristal-líquido el cual involucra hornblenda, pero no plagioclasa. La cristalización de la plagioclasa es inhibida por el alto contenido de H_2O de los lamprófidos. Los lamprófidos y los flujos más jóvenes, del Plioceno (1,8-2,3 Ma), de lavas andesíticas-basálticas con olivino del valle del río Cachapoal tienen razones de $^{87}Sr/^{86}Sr$ entre 0,7041 y 0,7049, ϵ_{Nd} entre +1,2 y -1,1 y de $^{206}Pb/^{204}Pb$ entre 18,60 a 18,68, mientras que las rocas ígneas del Mioceno Medio a Superior (6,5-13,9 Ma) del Complejo Volcánico y Plutónico de El Teniente tienen razones más bajas de $^{87}Sr/^{86}Sr$=0,7039 a 0,7041 y de $^{206}Pb/^{204}Pb$=18,56 a 18,59, y más altas de ϵ_{Nd}= +1,9 y +3,8. Las rocas volcánicas y plutónicas del Oligoceno al Mioceno Inferior (>15 Ma) de la Formación Abanico o Coya-Machalí en la región tienen razones aún más bajas de $^{87}Sr/^{86}Sr$ entre 0,7033 a 0,7039 y de $^{206}Pb/^{204}Pb$ entre 18,45 a 18,57, y ϵ_{Nd} aún más alto entre +3,8 y +6,2. La información isotópica indica una evolución temporal entre el Oligoceno y el Plioceno hacia razones más altas de $^{87}Sr/^{86}Sr$ y $^{206}Pb/^{204}Pb$, y valores de ϵ_{Nd} más bajos para los magmas máficos derivados del manto y, por lo tanto, de su fuente en el manto. Notablemente las razones isotópicas de Sr, Nd y Pb son independientes del contenido de SiO_2 de las rocas de cada edad, lo que excluye contaminación por la corteza continental del Paleozoico y Mesozoico, la cual es isotópicamente heterogénea, durante la evolución de las rocas intermedias a ácidas generadas por los magmas máficos derivados del manto. La evolución isotópica de la fuente de magmas máficos en el manto durante el Oligoceno al Plioceno puede ser explicada por el aumento de 1% a 6% de contaminación en la región fuente de manto por material subductado, incluyendo corteza continental erosionado del margen continental. Atribuimos esto tanto a la disminución del ángulo de subducción como al aumento de las tasas de erosión por subducción asociada a la migración hacia el sur del centro de la subducción de la Dorsal Juan Fernández. La presencia de lamprófidos también implica un aumento de la hidratación del manto bajo esta zona del arco durante el Plioceno. Esta hidratación del manto podría haber jugado un rol importante en la producción de magmas ricos en volátiles y oxidados, y mineralización en El Teniente.

Palabras clave: El Teniente, Lamprófidos, Erosión por subducción, Manto, Isótopos.

1. Introduction

Studies of Cenozoic Andean magmatic activity in the vicinity of El Teniente (~34°S; Fig. 1), the world's largest Cu-Mo deposit (Skewes *et al.*, 2002, 2005), provide a relatively detailed chronologic (Charrier and Munizaga, 1979; Cuadra, 1986; Kurtz *et al.*, 1997; Maksaev *et al.*, 2004; Kay *et al.*, 2005) and petrochemical (Stern and Skewes, 1995; Nystrom *et al.*, 2003; Kay *et al.*, 2005; Muñoz *et al.*, 2006; Stern *et al.*, 2010) data base for understanding the temporal evolution of Andean magmas in this section of the Andes of central Chile. In fact, this is one of the best studied regions of the Andes with respect to the evolution of late Cenozoic igneous rocks, due in part to the interest in understanding the relation of igneous activity to the genesis of the giant El Teniente deposit. At this latitude, near the northern end of the volcanically active Andean Southern Volcanic Zone (Fig. 1), Andean magmatic activity migrated eastward to its current locus along the High Andean drainage divide during the Pliocene in association with decreasing subduction angle (Stern, 1989), which occurred in conjunction with crustal deformation, thickening and uplift (Skewes and Holmgren, 1993; Kurtz *et al.*, 1997; Kay *et al.*, 2005; Stern and Skewes, 2005).

This paper focuses on mafic to intermediate hornblende-bearing dikes in the vicinity of El Teniente, some of which have been previously dated as between 2.9 to 3.9 Ma (Table 1; Cuadra, 1986; Maksaev *et al.*, 2004; Kay *et al.*, 2005). Kay *et al.* (2005) referred to these dikes as Late Hornblende dikes, and Maksaev *et al.* (2004) referred to them as hornblende andesites based on major element compositions. However, they either completely

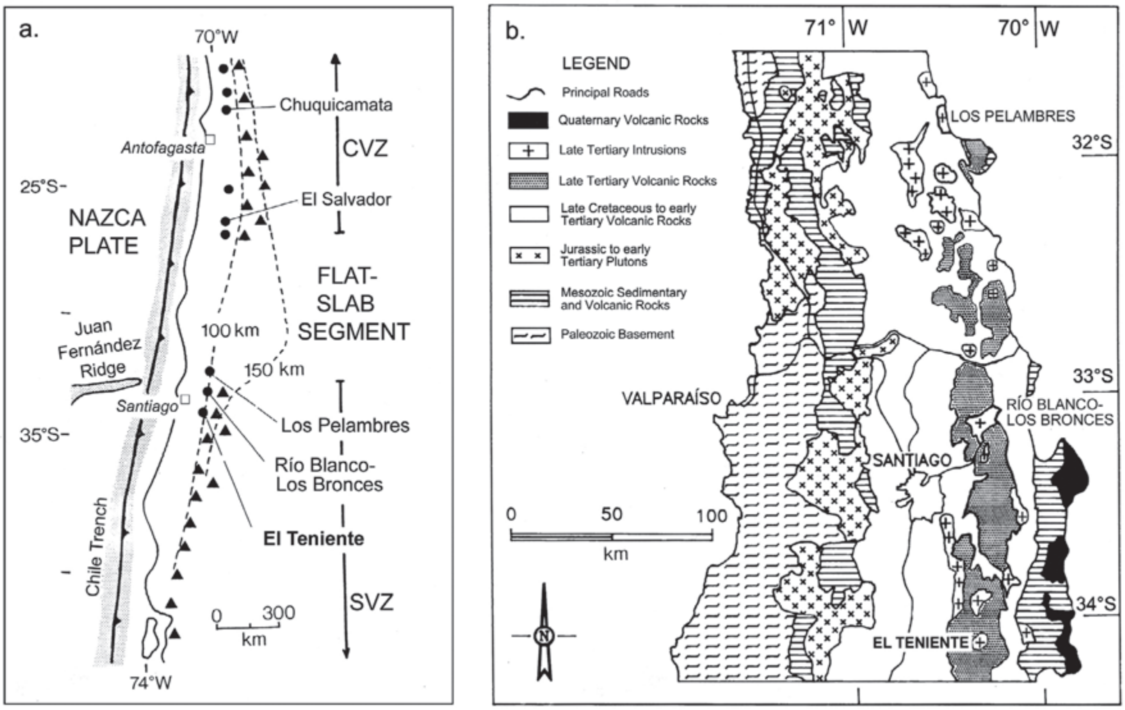

FIG. 1. **a.** Schematic regional map showing the general location of the study area, near El Teniente, in the context of Andean geotectonic features such as the volcanically inactive Flat-Slab Segment and northern end of the volcanically active Southern Volcanic zone (SVZ; Stern, 1989, 2004; Stern *et al.*, 2007a), the Juan Fernández Ridge, Chile trench, and depth to the Benioff zone of seismic activity which decreases rapidly to the north below the flat-slab segment; **b.** Simplified regional geology of central Chile. In this schematic map, the late Upper Oligocene to EarlyLower Miocene Coya-Machalí (Abanico) and Farellones (El Teniente Volcanic and Plutonic Complex) formations are included together in the belt of lateUpper Tertiary volcanic rocks. Other schematic regional geologic maps in the area around El Teniente have been published recently by Kay *et al.* (2005) and Muñoz *et al.* (2006).

lack or contain only scarce plagioclase feldspar phenocrysts and had, for this reason, been identified in the past as lamprophyres (Lindgren and Bastin, 1922; Howell and Molloy, 1960; Camus, 1975; Cuadra, 1986). Here we describe mafic olivine+hornblende-bearing dikes outcropping in the Quebrada los Sapos west of El Teniente mine (Fig. 2), which have not been previously studied. We suggest that these dikes are also best classified as olivine+hornblende lamprophyres, a lamprophyre being an igneous rock of mafic to intermediate composition, often containing hydrous phases such as amphibole or phlogopite mica, in which plagioclase feldspar occurs predominantly as microlites in the groundmass, and not as a common phenocryst phase as it does in more typical porphyritic, plagioclase-rich Andean olivine basalts and hornblende andesites (Figs. 3 and 4). This petrologic distinction between lamprophyres and typical porphyritic Andean olivine basalts and hornblende andesites, with abundant large plagioclase feldspar phenocrysts, is significant, because extensive experimental research had demonstrated that it requires relatively high water pressure to stabilize hornblende in basalts and to inhibit the early crystallization of plagioclase in both basalts and andesites (Moore and Carmichael, 1998; Blatter and Carmichael, 1998; Carmichael, 2002; Barcley and Carmichael, 2004).

Trace-element and isotopic data for the mafic olivine-bearing lamprophyre dikes in the Quebrada los Sapos provide insights into the geochemical evolution of the mantle source region of magmas in this section of the Andes just prior to eastward arc migration, and therefore help constrain the debate concerning the extent to which crustal

TABLE 1. LOCATION, AGE AND MINERALOGY OF HORNBLENDE-BEARING LAMPROPHYRE DIKES IN THE VICINITY OF EL TENIENTE.

Sample	UTM WGS-84 19 H N	UTM WGS-84 19 H E	Phenocrysts	Groundmass	Age Ma	Reference
Dikes in the Quebrada los Sapos						
AS2003-01	6,226,430	366,472	Ol(Fo88)>Cpx>Hbl>>Plag	Cpx, Hbl, Plag(An66), Fe-Ti oxides	-	This paper
AS2003-02	6,226,407	366,465	Ol>Cpx>Hbl>>Plag	Cpx, Hbl, Plag, Fe-Ti oxides	-	This paper
AS2003-03	6,226,324	367,214	Ol>Cpx>Hbl>>Plag	Hbl, Plag, Fe-Ti oxides	-	This paper
AS2003-04	6,226,260	367,218	Hbl>Cpx>Ol>>Plag	Hbl, Plag, Fe-Ti oxides	-	This paper
Dike at Caletones						
Ttc8	6,225,750	365,170	Hbl>>Plag	Hbl, Plag(An52), Fe-Ti oxides	-	Stern and Skewes, 1995
ET-5	-	-	Hbl>>Plag	Hbl, Plag, Fe-Ti oxides	-	Kay *et al*., 2005
BS-588	6,225,750	365,170	Hbl>>Plag	Hbl, Plag, Fe-Ti oxides	2.9±0.6	Cuadra, 1986
Dikes inside El Teniente mine						
TTc1	065S*	1,320E*	Hbl>Cpx>>Plag	Hbl, Plag, Fe-Ti oxides	-	Stern and Skewes, 1995
ET-2	-	-	-	-	-	Kay *et al*., 2005
KET-142B	6,223,900	375,300	-	-	3.1±0.8	Kay *et al*., 2005
KET-169	-	-	-	-	-	Kay, 1995
T3-22	065S*	1,320E*	Hbl>>Plag	Hbl, Plag, Fe-Ti oxides	3.8±0.3	Cuadra, 1986
TT-141	249.7S*	1,133.5E*	Hbl>>Plag	-	3.85±0.18	Maksaev *et al*., 2004
Dikes at other locations						
TTe71	-	-	-	-	-	Kay, 1995
ET-12C	-	-	-	-	-	Kay *et al*., 2005

***:** location given by mine coordinates; **Ol:** olivine; **Cpx:** clinopyroxene; **Plag:** plagioclase; **Hbl:** hornblende.

components are incorporated in Andean magmas by either intracrustal contamination (MASH; Hildreth and Moorbath, 1988), source region contamination (Stern, 1991, 2004; Stern and Skewes, 1995), or a combination of both (Kay *et al*., 2005). The lamprophyres also have interesting implications for understanding the evolution of magmas associated with the generation of the giant El Teniente Cu-Mo deposit (Stern *et al*., 2010).

2. Analytical Methods

Major and trace-element compositions for four samples from Quebrada los Sapos were determined by Actlabs, which used standard ICP-MS techniques to determined trace-elements. New trace-element analysis were also obtained from Actlabs for samples Ttc-1 and Ttc-8 to replace previous INAA data for these samples published by Stern and Skewes (1995). Mineral compositions were determined using a JOEL microprobe at the University of Colorado. The Sr, Nd and Pb isotopic compositions were determined by solid-source mass-spectrometry techniques (Farmer *et al.*, 1991) at the University of Colorado.

3. Sample Petrochemistry

Mafic, dark green to black in color, fresh or only weakly altered amphibole-bearing dikes occur within El Teniente mine (see map figure 1 in Cuadra, 1986), and also outcrop in the vicinity of the mine, both near Caletones (see map figure 3 in Cuadra, 1986), as well as in Quebrada los Sapos along the main road between Colon Alto and Sewell (Fig. 2; Table 1). These latter dikes are sub-vertical and strike east-west. They cut Late Miocene lavas of El Teniente Volcanic Complex and sills of El Teniente Mafic Complex and are younger

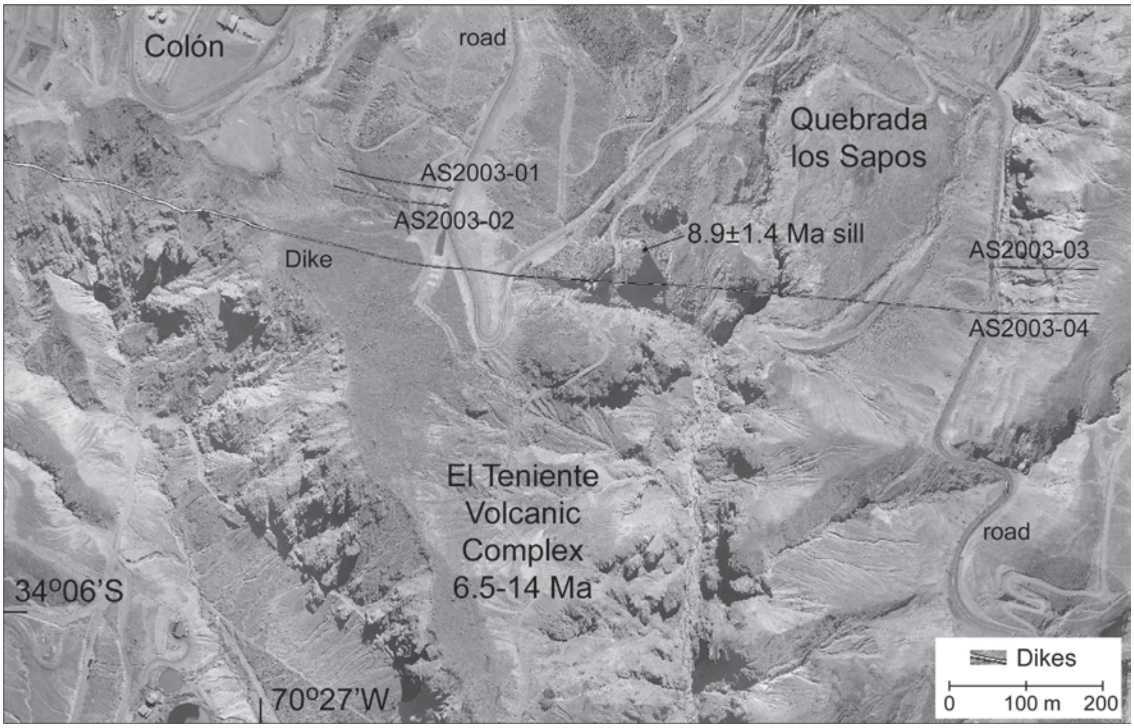

FIG. 2. Air photo showing the location of the lamprophyre dikes in the Quebrada los Sapos, along the main road from Colon to Sewell. This figure is essentially a geologic map, with only two units; upper Miocene lavas and pyroclastic flows of El Teniente Volcanic Complex (6.5 to 14 Ma; Kay *et al.*, 2005) intruded by sills of El Teniente Mafic Complex, one of which has been dated as 8.9±1.4 Ma (Stern *et al.*, 2010), and the mafic olivine + hornblende lamprophyre dikes which cut these units and are therefore younger than this latter age. For a larger geologic map of this area see figure 3 in Cuadra (1986). UTM locations of the sample sites of the dikes analyzed in this paper, which are indicated as the points where the dikes cross the road, are listed in table 1.

than these units. One olivine basalt sill in the Quebrada los Sapos, a distal unit of El Teniente Mafic Complex, has been dated as 8.9±1.4 Ma (Stern *et al.*, 2010), and other hornblende andesite sills, located less than 1 km to the north at Cerro Montura near the head of the Quebrada los Sapos, have been dated as 8.2±0.5 and 6.6±0.4 Ma (Cuadra, 1986).

The dikes in the Quebrada los Sapos contain abundant phenocyrsts of mafic minerals, including Mg-rich olivine (Fo88; Tables 1 and 2) up to 3x4.0 mm in size (Fig. 3a), pale-green augite clinopyroxene up to 1.5x1.5 mm in size, and red-brown Ti-rich hornblende up to 2x6 mm in size (Fig. 4a). However, they essentially lack plagioclase phenocrysts. Although some scarce plagioclase phenocrysts <1.0x<1.0 mm in size do occur occasionally (Fig. 3b), these are both smaller and far less abundant than the associated mafic phenocrysts. The textures of these rocks are for this reason notably different from typical phorphyritic, plagioclase-rich olivine basalts (Fig. 3d) of the older Late Miocene El Teniente Volcanic and El Teniente Mafic Complexes, in which plagioclase phenocrysts are in most cases larger than either the olivine or clinopyroxene phenocrysts and make up the dominant volume of the rock (Skewes *et al.*, 2002, 2005; Stern *et al.*, 2010), and hornblende is absent. We therefore suggest that the olivine+hornblende-bearing dikes are better classified as olivine+hornblende lamprophyres rather than olivine basalts, as elaborated further in the discussion. Calcic plagioclase microlites (An66) occur in the groundmass of the lamprophyre dikes along with hornblende, clinopyroxene and Fe-Ti oxides. Olivine is, in some cases, partially to completely altered to serpentine and calcite (Figs. 3a and 3b), but otherwise the original mineralogy and textures of these rocks has not been affected by alteration. Cognate gabbroic crystal agglomerates consisting of the phenocryst phases brown hornblende > clino-

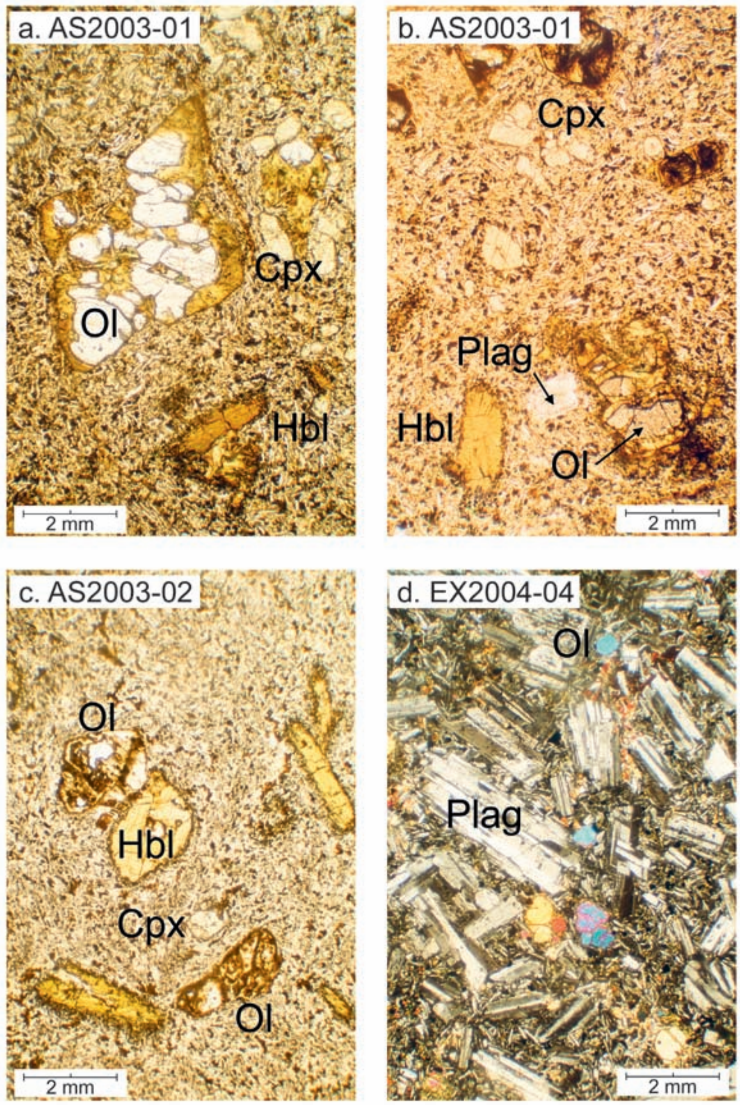

FIG. 3. Photomicrographs, all to the same scale, of mafic lamprophyres from Quebrada los Sapos compared to an older El Teniente Mafic Complex olivine basalt. **a**. and **b**. Mafic olivine+hornblende lamprophyre sample AS2003-01, with phenocrysts of olivine (partially replaced by serpentine and calcite), hornblende and clinopyroxene, along with plagioclase microlites and Fe-Ti oxides. A rare plagioclase phenocryst, the largest of only a few plagioclase grains that could be considered phenocrysts observed in two thin sections of this rock, is pictured in b. Despite the presence of this and a few other small phenocrysts of plagioclase in this rock, its classification as a lamprophyre, as defined by Carmichael (2002), is consistent with both the scarcity and small size of these plagioclase phenocrysts relative to those of olivine, clinopyroxene and hornblende; **c**. Mafic lamprophyre sample AS2003-02, which has a slightly greater proportion of hornblende relative to olivine than sample AS2003-01; **d**. A typical Upper Miocene El Teniente Mafic Complex olivine basalt, with abundant large phenocrysts of plagioclase along with olivine and clinopyroxene, but without hornblende.

pyroxene>olivine, along with minor plagioclase, Fe-Ti oxides±apatite, occur in samples AS2003-01 and AS2003-02, suggesting that these minerals crystallized deeper in the magmatic plumbing system through which their parental magmas moved towards the surface.

The mafic lamprophyre AS2003-01, the sample with the freshest olivine, has SiO_2=51 weight percent, and Ni ~190 ppm and Cr ~390 ppm (Table 3), indicating, along with the presence of Mg-olivine, that it crystallized from a primitive mantle-derived magma that had not undergone extensive crystal-liquid fractionation as it rose from the mantle towards the surface. The other three dikes in the Quebrada los Sapos are also relatively primitive, with SiO_2=50 to 53 weight percent and high Ni=70-130 ppm and Cr=280-310 ppm. As SiO_2 increases, the proportion of amphibole relative to olivine also increases (Figs. 3c and 4a).

Other dark colored post-mineralization dikes, which occur both inside El Teniente mine and at other locations in the vicinity of the mine (Table 1), also contain red-brown hornblende phenocrysts and calcic plagioclase microlites (An52; Tables 1 and 2; Figs. 4b and 4c), but lack olivine, plagioclase phenocrysts and/or orthopyroxene. Pale-green clinopyroxene occurs in some of the more mafic of these dikes (Ttc1; Table 1), but not in others. They range in composition from 55 to 67 weight percent SiO_2 and have lower Ni <100 and Cr <200 ppm (Table 3) than the more mafic olivine-bearing lamprophyres from Quebrada los Sapos. Their mineral assemblages and textures contrast significantly from typical Andean porphyritic hornblende andesites, such as occur in the Late Miocene El Teniente Volcanic Complex, which have abundant large plagioclase phenocrysts (Fig. 4d) and commonly contain orthopyroxene. Their textural and mineralogic characteristics suggest that they are genetically related to the more mafic mantle-derived olivine+hornblende lamprophyres in the Quebrada los Sapos, and that for this reason they are better classified as hornblende lamprophyres, as they were originally by Lindgren and Bastin (1922), Howell and Molloy (1960), Camus (1975) and Cuadra (1986), rather than as hornblende andesites.

Both the mafic and intermediate lamprophyre dikes have relatively high Sr=600 to 920 ppm (Table 3; except for the most silica-rich sample ET-12C for which Sr=340 ppm), low Y (12-17 ppm), and consequently high Sr/Y ratios (43-71), similar to adakitic andesites, but these rocks, which range from basaltic to dacitic in composition, are not adakites. The mafic lamprophyre

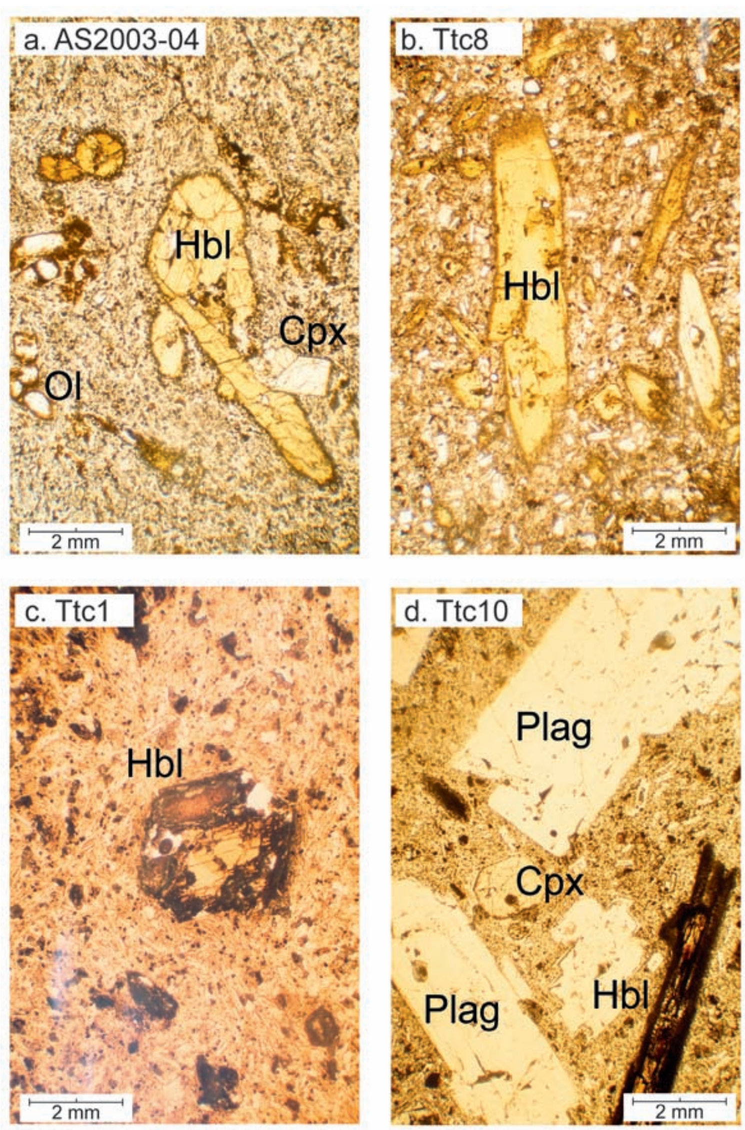

FIG. 4. **a**. Sample AS2003-04, the least primitive sample from the Quebrada los Sapos (Table 4), which has an even greater proportion of larger hornblende phenocrysts relative to olivine and clinopyroxene, but only microlites of plagioclase; **b**. Hornblende lamprophyre sample Ttc8 from Caletones (see map figure 3 in Cuadra, 1986). This sample, with greater than 60 wt% SiO_2 (Table 3), contains large hornblende phenocrysts, up to 2x8 mm in size, but no olivine, clinopyroxene or plagioclase phenocrysts. Compositionally it may be considered a hornblende andesite, but texturally it is significantly different than more typical plagioclase-rich andesites, an examples of which is shown in figure 4d; **c**. Sample Ttc1 from within El Teniente mine (Table 1). Cuadra (1986; see his 'Foto 4') present a photomicrograph of this same rocks in which he describes small acicular phenocryst of both hornblende and plagioclase, but both his picture and this one illustrate that hornblende phenocrysts in this rock may be significantly larger, up to 2x3 mm, than any plagioclase grains; **d**. Sample Ttc10, a 6.6±0.4 Ma sill from Cerro Montura just north of Quebrada los Sapos (sample E1233 from Cuardra, 1986; Stern and Skewers, 1995; Stern *et al.*, 2010), which is a plagioclase-rich, prophyritic hornblende +2-pyroxene andesite typical of the lavas and sills that form the Upper Miocene El Teniente Volcanic Complex cut by the younger mafic hornblende lamprophyre dikes in the Quebrada los Sapos.

TABLE 2. COMPOSITIONS OF MINERALS IN LAMPROPHYRE DIKES FROM THE VICINITY OF EL TENIENTE.

Sample Mineral of analysis	AS2003-01 Olivine 7	AS2003-01 Cpx 9	AS2003-01 Hbl 6	AS2003-01 Plag* 6	Ttc-8 Hbl 11	Ttc-8 Plag* 6
SiO_2	41.69	50.49	41.01	50.38	43.07	53.77
TiO_2	-	0.81	2.41	-	1.97	-
Al_2O_3	-	3.83	12.65	30.12	11.67	27.95
FeO	11.74	6.01	10.31	0.72	9.04	0.37
MnO	0.16	0.13	0.11	-	0.1	-
MgO	46.12	15.79	15.22	-	15.91	-
CaO	-	21.62	11.59	13.21	11.57	10.35
Na_2O	-	0.33	2.25	3.88	2.51	5.49
K_2O	-	-	0.34	0.12	0.41	0.16
Cr_2O_3	-	0.26	0.22	-	0.15	-
NiO	0.27	-	-	-	-	-
Total	99.99	99.27	96.11	98.43	96.41	98.09
Total cations	6	8	17	20	17	20
Si	2.08	3.72	6.68	9.3	6.85	9.87
Ti	-	0.09	0.31	-	0.24	-
Al	-	0.4	2.5	6.56	2.21	6.05
Fe	0.48	0.35	1.37	0.11	1.22	0.06
Mn	-	0.01	0.01	-	0.01	-
Mg	3.42	1.72	3.61	-	3.7	-
Ca	-	1.69	1.8	2.61	1.91	2.03
Na	-	0.1	0.65	1.39	0.78	1.95
K	-	-	0.07	0.03	0.09	0.04
Cr	-	0.09	-	-	-	-
Ni	0.2	-	-	-	-	-
	Fo88	-	-	An66	-	An52

Plag*: plagioclase microlites.

samples from the Quebrada los Sapos have low Yb (1.21 to 1.45 ppm), and La/Yb ratios (10-13; Fig. 5) that are somewhat higher than mafic rocks in even the youngest (Upper Sewell) units of the Upper Miocene El Teniente Volcanic Complex (5-8; Kay *et al.*, 2005) and plutonic rocks of El Teniente Mafic Complex (4-9; Skewes *et al.*, 2002; Stern *et al.*, 2010). The other less primitive olivine-free lamprophyre dikes have both lower Yb (0.42 to1.28 ppm) and higher La/Yb ratios (15-44; Table 3) compared to the more mafic lamprophyres in the Quebrada los Sapos (Fig. 5). However, Dy/Yb ratios decrease for the sequence from the most primitive (2.2 for samples AS2003-01; Table 3) to the more silica-rich samples (2.0 for sample Ttc8).

Both the mafic and intermediate lamprophyre dikes have initial $^{87}Sr/^{86}Sr$=0.70410 to 0.70435, ϵ_{Nd}=+1.2 to +0.2 (Table 4; Fig. 6), and $^{206}Pb/^{204}Pb$=18.60 to 18.61 (Table 5; Fig. 7). Their $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ isotopic values are higher, and ϵ_{Nd} values lower, than any Upper Miocene olivine basalts, andesites and dacites, as well as mafic and/or felsic plutonic rocks associated with El Teniente deposit ($^{87}Sr/^{86}Sr$=0.7039 to 0.7041, $^{206}Pb/^{204}Pb$=18.55 to 18.59 and ϵ_{Nd}=+3.6 to +1.9), but lower and higher, than the younger Upper Pliocene basaltic-andesite lavas from the Cachapoal

TABLE 3. COMPOSITIONS OF HORNBLENDE-BEARING LAMPROPHYRE DIKES IN THE VICINITY OF EL TENIENTE Cu DEPOSIT.

Location	Quebrada los Sapos				Inside El Teniente mine				Caletones		Other	
Sample No.	AS 2003-01	AS 2003-02	AS 2003-03	AS 2003-04	TTc-1	ET-2	KET142B	KET169	TTc-8	ET-5	TTE71	ET-12C
SiO_2	51.31	50.34	51.52	53.22	56.30	58.28	55.81	56.81	61.10	64.72	60.46	67.24
TiO_2	1.01	1.01	0.97	1.08	0.85	0.92	0.93	0.9	0.67	0.65	0.82	0.43
Al_2O_3	15.97	15.62	16.11	17.87	16.90	17.61	16.86	19.44	17.20	17.45	17.35	17.09
$Fe_2O_3^{++}$	7.82	7.62	6.97	6.79	3.60	-	-	-	2.60	-	-	-
FeO*	-	-	-	-	2.00	5.34	5.76	6.66	2.00	3.85	4.65	2.53
MnO	0.13	0.12	0.13	0.15	0.06	0.16	0.1	0.13	0.05	0.04	0.08	0.31
MgO	7.92	7.73	5.86	3.39	3.30	3.46	5.25	1.89	3.20	1.52	2.74	0.82
CaO	7.77	7.55	7.88	7.74	5.80	7.96	6.86	6.67	5.50	4.85	5.41	5.03
Na_2O	3.39	3.28	3.85	3.87	4.61	3.76	4.43	4.18	5.14	4.69	4.89	2.41
K_2O	1.06	1.08	1.25	1.38	1.60	2.19	1.67	1.49	2.00	2.01	2.02	4.02
P_2O_5	0.26	0.27	0.26	0.29	0.29	0.31	0.25	0.22	0.21	0.22	0.26	0.15
LOI	2.04	3.45	3.16	3.81	5.10	-	1.52	1.22	0.90	-	0.76	-
Total	98.66	98.08	97.97	99.58	100.41	100	99.44	99.61	100.57	100.00	99.44	100
Cs	8.5	10	7.9	13.5	7.7	15.6	-	-	13.9	-	-	6.4
Rb	21	22	20	47	40	-	36	34	39	-	39	-
Sr	680	642	767	835	916	762	860	670	871	867	920	341
Ba	345	340	363	390	460	461	520	440	628	654	580	871
Sc	23	22	19	22	11	12	16	6	9	12	10	4
Nb	5	4	4	5	5	-	-	-	5	-	-	-
Y	14	15	15	17	13	-	-	-	12	-	-	-
Zr	110	121	132	150	129	-	-	-	130	-	-	-
Hf	3.1	3	3.4	3.7	3.5	3.6	3.2	3.1	3.8	3.4	5.6	2.8
Th	2.6	2.8	2.7	3	2.4	2.6	2.6	3.8	3.5	3.3	4.4	3.5
U	0.7	0.8	0.7	0.9	1.9	0.7	0.6	0.8	1.8	1.3	1	1.5
Cr	387	310	280	300	77	77	200	17	72	39	74	11
Ni	188	130	100	70	78	49	82	12	86	35	35	5
Co	43	34	24	25	40	19	23	21	44	12	18	2
Cu	94	90	100	80	85	-	-	-	69	-	-	-
Zn	80	80	70	70	58	-	-	-	81	-	-	-
La	13.6	14.2	15.6	17.5	17.5	17.9	17.6	17.2	17.0	17.4	23.5	18.3
Ce	31.0	32.5	34.0	37.9	40.6	41.8	37.6	38.4	36.7	39	47.9	41
Pr	3.98	4.17	4.24	4.78	5.12	-	-	-	5.01	-	-	-
Nd	17.7	17.6	17	18.7	22.0	22.0	19.5	21.2	21.3	20.1	25.6	20.7
Sm	3.90	4.3	4.15	4.31	4.09	4.24	4.35	4.49	4.02	3.9	5.02	3.69
Eu	1.20	1.34	1.27	1.42	1.09	1.12	1.13	1.26	1.06	1	1.2	0.94
Gd	3.30	3.52	3.45	3.78	3.07	-	-	-	3.11	-	-	-
Tb	0.50	0.53	0.49.	0.54	0.38	0.41	0.39	0.45	0.38	04	0.47	0.27
Dy	2.82	2.93	2.57	2.91	1.71	-	-	-	1.85	-	-	-
Ho	0.50	0.58	0.48	0.56	0.31	-	-	-	0.34	-	-	-

Table 3. continued.

Location	Quebrada los Sapos				Inside El Teniente mine				Caletones		Other	
Sample No.	AS 2003-01	AS 2003-02	AS 2003-03	AS 2003-04	TTc-1	ET-2	KET142B	KET169	TTc-8	ET-5	TTE71	ET-12C
Tm	0.21	0.24	0.20	0.23	0.13	-	-	-	0.14	-	-	-
Yb	1.29	1.45	1.21	1.41	0.80	0.83	1.21	0.67	0.93	0.86	1.28	0.42
Lu	0.18	0.21	0.17	0.2	0.12	0.11	0.15	0.09	0.14	0.11	0.15	0.05
La/Yb	10	10	13	13	22	22	15	26	20	20	18	44
Dy/Yb	2.2	2.0	2.1	2.1	2.1	-	-	-	2.0	-	-	-
Sr/Y	49	43	51	49	70	-	-	-	71	-	-	-

Samples ET-2, Ket142B, KET169, ET-5, TTE71 and ET-12C from Kay *et al.* (2005).

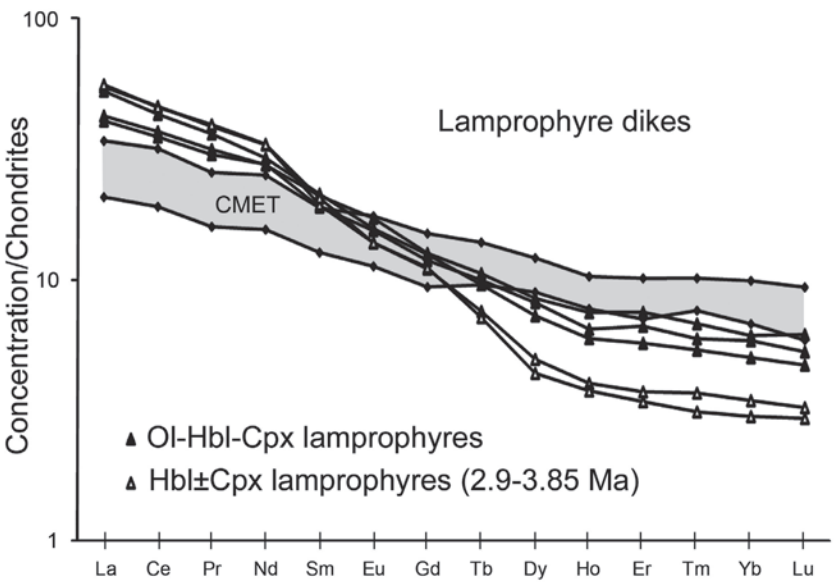

FIG. 5. Rare-earth-element contents, normalized to the compositions of chondritic meteorites, of mafic olivine-bearing lamprophyres (solid triangles; samples AS2003-01, -02 and 04; Table 3) and less primitive olivine-free lamprophyres (open triangles, samples Ttc1 and TTc8; Table 3) compared to samples of olivine basalts, diabases and gabbros of the older Upper Miocene El Teniente Mafic Complex (shaded field labeled CMET; Skewes *et al.*, 2002; Stern *et al.*, 2010).

river ($^{87}Sr/^{86}Sr$=0.70485, $^{206}Pb/^{204}Pb$=18.68 and ϵ_{Nd}=-0.9 to -1.1; Figs. 6 and 7). Sr, Nd and Pb isotopic compositions of all the igneous rocks in the vicinity of El Teniente changed significantly through time, but during any given time period their isotopic compositions are nearly constant and independent of SiO_2 content (Fig. 8), as previously noted by Stern and Skewes (1995), Kay *et al.* (2005) and Stern *et al.* (2010).

4. Discussion

The hornblende-bearing lamprophyre dikes represent one of the last phases of igneous activity in the vicinity of El Teniente prior to the >40 km eastward migration of the active Andean arc to its current location along the High Cordillera drainage divide between Chile and Argentina (Stern, 1989). They comprise only a very small volume of rock relative to the Upper Miocene El Teniente Volcanic and Plutonic Complex rocks that host El Teniente deposit, and the even greater volume of older Oligocene and Early Miocene Coya-Machalí (Abanico Formation) continental volcanics.

We discuss first the classification, age and origin of these dikes, next the implication of their isotopic compositions for the temporal evolution of the mantle source region below this region during the late

TABLE 4. Sr AND Nd ISOTOPIC COMPOSITIONS OF HORNBLENDE-BEARING LAMPROPHYRE DIKES IN THE VICINITY OF EL TENIENTE.

Sample	SiO_2	Rb	Sr	$^{87}Sr/^{86}Sr$	Nd	Sm	$^{143}Nd/^{144}Nd$	ϵ_{Nd}
AS2001-03	50.9	21	680	0.704252±13	17.7	3.90	0.512700±18	1.2
KET-142B	55.8	36	860	0.704350±7	19.5	4.35	0.512647±10	0.2
TTc-1	56.3	40	916	0.704250±7	22.0	4.09	0.51266±6	0.7
ET-2	58.3	-	762	0.704175±7	22.0	4.24	0.512689±10	1.0
TTc-8	61.1	39	871	0.704340±18	21.3	4.02	0.51267±7	0.7
ET-5	64.7	-	867	0.704098±7	20.1	3.90	0.512682±9	0.9

Samples KET-142B, ET-2, and ET-5 from Kay *et al.* (2005).

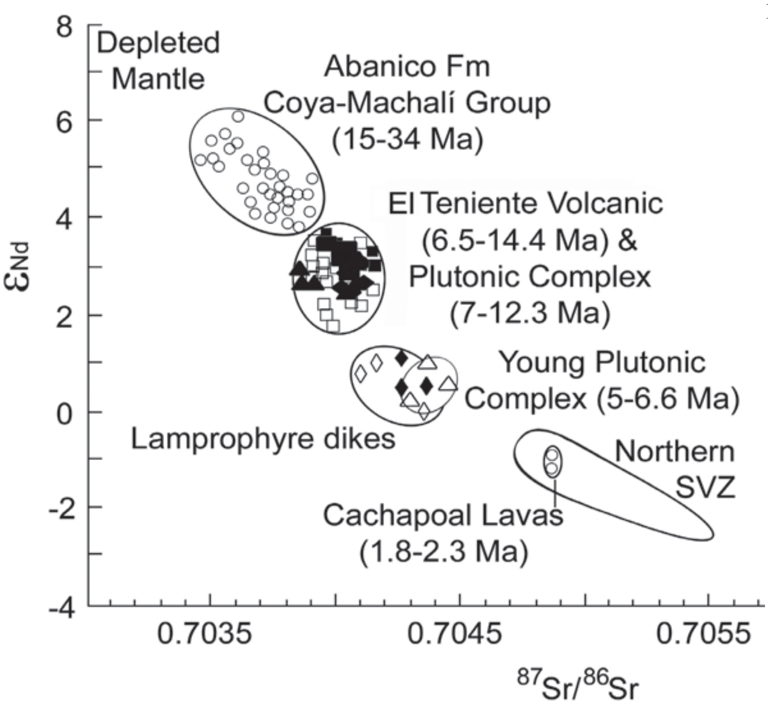

FIG. 6. $^{87}Sr/^{86}Sr$ *versus* ϵ_{Nd} for lamprophyre dikes (solid and open diamonds; Table 4) from the vicinity of El Teniente compared to older Coya-Machalí and Abanico Formation volcanics (circles; Nystrom *et al.*, 2003; Kay *et al.*, 2005; Muñoz *et al.*, 2006), El Teniente Volcanic and Plutonic Complex samples (open squares; Stern and Skewes, 1995; Kay *et al.*, 2005), the host plutons of El Teniente deposit (solid squares, circles and triangles; Skewes *et al.*, 2002; Stern *et al.*, 2010), the regionally defined Young Plutonic Complex (open triangles; Kay *et al.*, 2005), and younger Pliocene lavas from the valley of the Cachapoal River (circles; Stern and Skewes, 1995). The figure illustrated the progressive temporal increase in $^{87}Sr/^{86}Sr$ and decrease in ϵ_{Nd} from the Early Miocene to the Pliocene for igneous rocks at the latitude of El Teniente as pointed out previously by Stern and Skewes (1995), Kay *et al.* (2005) and Stern *et al.* (2010).

Cenozoic and the geotectonic factors that generated these changes, and finally their possible significance with regard to the formation of the giant El Teniente Cu-Mo deposit.

4.1. Petrochemical classification of the dikes

Because of the relatively small size and scarcity of plagioclase phenocrysts compared to mafic phenocrysts in both the mafic olivine+hornblende dikes in the Quebrada los Sapos (Fig. 3), as well as in the previously described intermediate dikes in El Teniente mine and elsewhere in the vicinity of El Teniente (Fig. 4), we suggest that these dikes are better classified as lamprophyres in order to distinguish them from typical richly porphyritic olivine basalts (Fig. 3d) and hornblende andesites (Fig. 4d) that are common in the Upper Miocene

TABLE 5. Pb ISOTOPES FOR LATE MIOCENE AND PLIOCENE SAMPLES NEAR 34°S.

Sample	Age Ma	SiO_2	206/204	207/204	208/204	Referencia
El Teniente Volcanic Complex						
KET143	10	53.6	18,556	15,579	38,330	Kay *et al*., 2005
KET126A	6.5	57.3	18,565	15,593	38,378	Kay *et al*., 2005
El Teniente Plutonic Complex						
ETP9	8.7	64.0	18,558	15,582	38,362	Kay *et al*., 2005
ETP7	8.4	67.6	18,577	15,587	38,388	Kay *et al*., 2005
ETP12	8.1	63.3	18,558	15,578	38,350	Kay *et al*., 2005
El Teniente Mafic Complex						
1411-1680	8.9	51.1	18,561	15,592	38,431	Skewes, 2006
AS99-1	8.9	59.8	18,554	15,584	38,422	Skewes, 2006
Sewell Tonalite						
Ttc5	7.1	63.7	18,565	15,589	38,435	Skewes, 2006
Young Plutonic Complex						
ETP11	6.6	62.8	18,588	15,577	38,378	Kay *et al*., 2005
Northern Quartz-Diorite Porphyry						
2370-159	6.1	64.0	18,584	15,586	38,453	Skewes, 2006
El Teniente Porphyry A microdiorite						
1446-266	5.7	56.3	18,578	15,578	38,386	Skewes, 2006
Lamprophyre Dikes						
AS2003-1	-	51.3	18,609	15,586	38,506	This paper
ET2	3.5	55.5	18,597	15,590	38,410	Kay *et al*., 2005
ET5	3.5	65.2	18,608	15,613	38,508	Kay *et al*., 2005
Río Cachapoal basaltic-andesites						
PVF2	2.3	55.4	18,680	15,596	38,507	This paper

El Teniente Volcanic Complex and El Teniente Mafic Complex. For the intermediate dikes this same classification was made by Lindgren and Bastin (1922), Howell and Molloy (1960), Camus (1975) and Cuadra (1986) for these same reasons.

This distinction is significant because the relatively small size, scarcity and/or lack of plagioclase phenocrysts compared to mafic phenocrysts implies that the early crystallization of plagioclase was inhibited. Extensive experimental work, discussed in more detail below, suggests that this is the result of relatively higher water pressure. This experimental work was conducted on samples from the active volcanic arc in Mexico, where Carmichael (2002) distinguished two varieties of lavas, one 'which may contain hornblende as the sole phenocryst, or be accompanied by sparse plagioclase' and the other which are 'richly porphyritic with minor hornblende and abundant plagioclase'. Both types may also contain olivine and pyroxenes. He suggested that the textural differences between these 'two heteromorphs' were due to the amount of dissolved water in their parental magmas. He referred to the type with sparse or no phenocrysts of plagioclase as lamprophyres. Our classification as lamprophyres of the dikes in and around El Teniente that contain abundant large

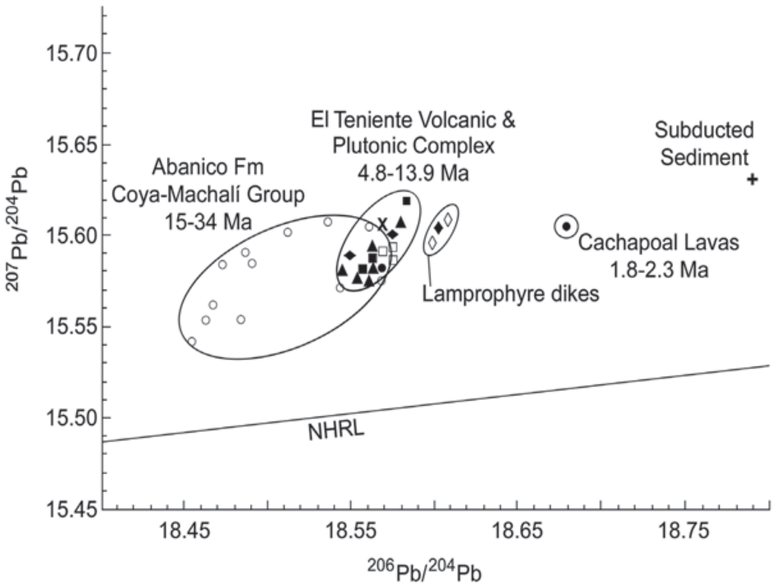

FIG. 7. $^{206}Pb/^{204}Pb$ *versus* $^{207}Pb/^{204}Pb$ for lamprophyre dikes (solid and open diamonds) from the vicinity of El Teniente deposit and basaltic andesite flows (solid circle) in the valley of the Cachapoal River (Table 5), compared to older Coya-Machalí and Abanico Formation volcanics, El Teniente Volcanic and Plutonic Complex samples, plutonic hosts of El Teniente deposit, and the regionally defined Young Plutonic Complex. Symbols and data sources are the same as in figure 6. Also shown is the Pb isotopic composition of El Teniente ores (X from Puig, 1988) and that of a model subducted sediment (+), including continental crust, as calculated by Macfarlane (1999). The data show a temporal trend of $^{206}Pb/^{204}Pb$ towards this value.

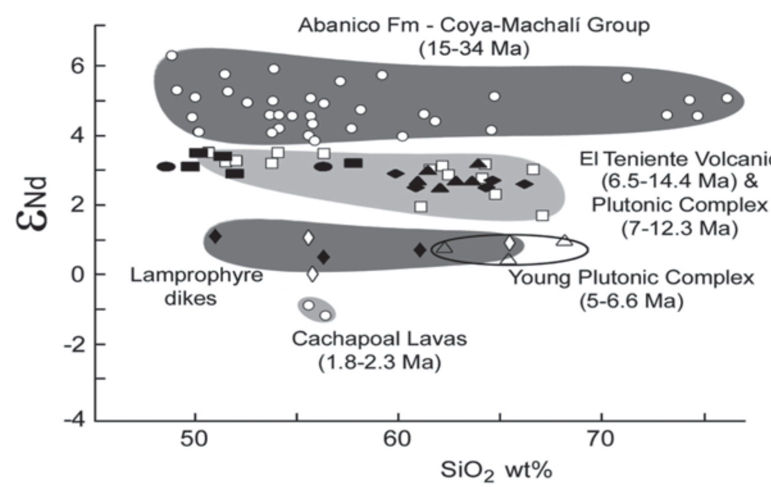

FIG. 8. SiO_2 *versus* ϵ_{Nd} for Abanico Formation volcanics, El Teniente Volcanic and Plutonic Complex samples, plutonic hosts of El Teniente deposit, the regionally defined Young Plutonic Complex, and younger lamprophyre dikes and Pliocene lavas from the valley of the Cachapoal River. Symbols and data sources are the same as in figure 6. The figure illustrates the progressive temporal decrease in ϵ_{Nd} from the Early Miocene to the Pliocene, and the independence during each specific time interval of isotopic composition and SiO_2 content of these rocks.

mafic phenocrysts of hornblende±olivine±clinopyroxene, but only small, sparse and/or no plagioclase phenocrysts (Figs. 3 and 4), is consistent with the classification of Carmichael (2002) for Mexican volcanic arc rocks. We suggest that whatever one would like to call these dikes, the significant point is that the experimental results obtained by Carmichael and co-workers (Moore and Carmichael, 1998; Blatter and Carmichael, 1998; Carmichael, 2002; Barcley and Carmichael, 2004) for rocks that they termed lamprophyres, as contrasted with porphyritic plagioclase-rich olivine basalts and andesites, applies as well to the essentially plagioclase phenocryst-free dikes in the vicinity of El Teniente.

4.2. Age of the mafic olivine lamprophyre dikes

Although the mafic olivine+hornblende lamprophyre dikes with the Quebrada los Sapos have not been dated directly, petrochemically similar hornblende lamprophyre dikes both within the El Teniente mine and in the vicinity of the mine have been dated as between 2.9 to 3.9 Ma (Table 1; Cuadra, 1986; Maksaev *et al.*, 2004; Kay *et al.*, 2005). The mafic olivine lamprophyre dikes in the Quebrada los Sapos cut lavas of the Upper Miocene El Teniente Volcanic Complex, and clearly post-date this complex, which regionally has been dated as 6.5 to 14 Ma (Kay *et al.*, 2005). Locally, a sill within the volcanic rocks cut by the mafic dikes in the Quebrada los Sapos has been dated as 8.9±1.4 Ma (Fig. 2; Stern *et al.*, 2010), and other sills at Cerro Montura, ~1 km to the north, have been dated as 8.2±0.5 and 6.6±0.4 Ma (Cuadra, 1986). Therefore, the lamprophyre dikes in Quebrada los Sapos are certainly <8.9 Ma, the age of El Teniente Mafic Complex, and most likely <6.6 Ma.

For two reasons we suggest that the lamprophyre dikes are most probably Pliocene in age, as are the previously dated intermediate lamprophyre dikes in the area. First is their petrochemical similarities to these intermediate lamprophyre dikes, similarities which include not only their textures (Figs. 3 and 4), but also their isotopic compositions (Figs. 6-8) and their trace element chemistry (relatively high Sr/Y and La/Yb; Fig. 5), both of which have been shown to vary with time in this region of the Andes (Stern and Skewes, 1995; Kay *et al.*, 2005; Stern *et al.*, 2010). Regionally, all the rocks of both El Teniente Volcanic and Plutonic Complex, which are >6.6 Ma, and all rocks directly associated with El Teniente mine, which are 8.9 to 4.8 Ma (Maksaev *et al.*, 2005), have lower $^{87}Sr/^{86}Sr$ (Fig. 6; Stern *et al.*, 2010) and $^{206}Pb/^{204}Pb$ (Fig. 7), and higher ϵ_{Nd} (Figs. 6 and 8), compared to both the mafic and intermediate lamprophyre dikes, which have isotopic compositions similar to each other. The ~5 to 6.6 Ma Younger Plutonic Complex rocks (Kay *et al.*, 2050), which outcrop in the larger region around El Teniente between 33-35°S, but not within El Teniente mine or the immediate vicinity of the mine (Stern *et al.*, 2010), have isotopic compositions similar to the lamprophyre dikes (Figs. 6-8). Taken together these data suggest that the mafic lamprophyre dikes are similar in age to the dated Pliocene intermediate dikes, or at least not older than 6.6 Ma, the oldest age for the Younger Plutonic Complex.

A second reason for suggesting a Pliocene age for the mafic lamprophyre dikes is their occurrence as dikes. Volcanism that formed El Teniente Volcanic Complex lasted until ~6.5 Ma, and between ~8.9 and ~6.2 Ma El Teniente Plutonic Complex rocks, such as El Teniente Mafic Complex, Sewell Tonalite and Cerro Montura sills, intruded as sills. Only after ~6.1 Ma did the rocks related to El Teniente, such as El Teniente Dacite Porphyry dike (~5.3 Ma) and Latite dikes (4.8 Ma; Maksaev *et al.*, 2004), intrude as small stocks and dikes. The occurrence of the mafic lamprophyres as dikes therefore suggests an age of <6.1 Ma. Furthermore, Stern and Skewes (2005) and Stern *et al.* (2010) have suggested that, as implied by its large amount of Cu ore, El Teniente was underlain by a large magma chamber, with a volume of >600 km^3, between at least 6.1 to 4.4 Ma, the period of Cu-Mo mineralization as determined by Re-Os ages (Maksaev *et al.*, 2004), and that mafic mantle-derived magmas recharged the base of this chamber, but did not reach the surface during this time as they were absorbed into this large chamber and mixed there with other more differentiated magmas. This would suggest that the intrusion of the mafic dikes in Quebrada los Sapos also occurred only after final solidification, at ~4.4 Ma, of this large magma chamber. Although these dikes occur ~5 km west of the Braden pipe, the center of El Teniente deposit, both El Teniente Mafic Complex (~50 km^3) and Sewell Tonalite (~30 km^3) sills extend further to the west than this and neither is more than 10% as large as the magma chamber underlying El Teniente must have been (~600 km^3; Stern *et al.*, 2010).

In summary, we suggest that the mafic sills in the Quebrada los Sapos are similar in age to other Pliocene lamprophyres in the area (2.9 to 3.9 Ma; Cuadra, 1986, Maksaev *et al.*, 2004; Kay *et al.*, 2005), or at least no older than the Younger Plutonic Complex rocks (~5 to 6.6 Ma; Kay *et al.*, 2005) which are isotopically similar, and they are certainly younger than the richly porphyritic, plagioclase-rich and hornblende-free, olivine basalts that form El Teniente Mafic Complex (~8.9 Ma), one distal sill of which is cut directly by the dikes.

4.3. Petrogenesis of the mafic olivine lamprophyres

The Mg-olivine phenocrysts, and their high MgO, Ni and Cr contents, imply a mantle origin for the mafic lamprophyre dikes from Quebrada los Sapos. Petrologically similar lamprophyres are found in the Mexican volcanic belt, and are considered to be the mantle-derived parent for the more typical richly porphyritic hornblende andesites that form the large central-vent stratovolcanoes in this belt (Carmichael, 2002). A mantle origin for the Mexican hornblende lamprophyres is confirmed by the presence of peridotite mantle xenoliths in one such rock (Blatter and Carmichael, 1998).

Experimental studies suggest that the phenocryst mineral assemblages of these Mexican lamprophyres, which are identical to those from the vicinity of El Teniente, with only sparse or no plagioclase phenocrysts, imply >6 wt% dissolved water in the lamprophyre magmas (Moore and Carmichael, 1998; Blatter and Carmichael, 1998; Barcley and Carmichael, 2004). This is consistent with a minimum of >5.2 wt% water in olivine-bearing Mexican magmas as indicated by the water content of melt inclusions in olivine (Cervantes and Wallace, 2003). Carmichael (2002) suggests that between 6 wt% (the minimum to reproduce the phenocryst mineral assemblage) to 16 wt% (the maximum to saturate the mantle at 10 kbars pressure) water, derived from the subducted oceanic lithosphere, was present in the mantle-source region of the Mexican lamprophyres.

In contrast, experimental constraints on richly porphyritic, plagioclase-rich but hornblende-free olivine-basalts similar in composition to the mafic rocks that form the Upper Miocene El Teniente Mafic Complex (Skewes *et al.*, 2002; Stern *et al.*, 2010), suggest that they formed from less hydrous magmas (2-6 wt% H_2O; Moore and Carmichael, 1998), by melting of mantle relatively less enriched by a fluid component derived from the subducted slab (Baker *et al.*, 1994). We conclude that the post-mineralization lamprophyre dikes in the vicinity of El Teniente, which as discussed above are clearly younger than the richly poprhyritic hornblende-free olivine-basalts of El Teniente Mafic Complex, imply a temporal increase in the extent of hydration of the sub-Andean mantle below this region between the Late Miocene and Pliocene.

The higher Sr and La/Yb, and the lower Y and Yb of the lamprophyres compared to Upper Miocene basaltic rocks of El Teniente Mafic Complex (Fig. 5), also suggest both a lower degree of partial mantle melting and/or a greater proportion of either garnet or hornblende in the mantle source of the lamprophyres. A lower degree of partial melting is consistent with the much smaller volume of Pliocene compared to the Upper Miocene igneous rock in the vicinity of El Teniente (Stern and Skewes, 2005; Stern *et al.*, 2010), and hornblende in the mantle source is consistent with both the presence of hornblende phenocrysts in the most mafic olivine-bearing dikes and the extensive hydration of their source as implied by the results of the experimental studies described above. Carmichael (2002) suggests that the source of Mexican lamprophyres is metasomatised mantle containing amphibole, similar to the mineralogy of the hornblende-lherzolite mantle xenoliths found in one such rock (Blatter and Carmichael, 1998).

4.4. Petrogenesis of the less mafic lamprophyres

The less mafic, olivine-free lamprophyre dikes at El Teniente are petrologically similar to the more mafic lamprophyres from Quebrada los Sapos, containing brown hornblende±clinopyroxene, but lacking plagioclase as a common phenocryst phases. We suggest that they are genetically associated with the more mafic lamprophyres based on their textural, mineralogical, isotopic and trace-element (high La/Yb and Sr/Y) similarities. Baker *et al.* (1994) concluded that magmas of intermediate silica content may form by low degrees of melting of hydrated (H_2O>6 wt%) mantle, but the lower MgO, Ni and Cr contents of these dikes suggests that it is more likely that they formed by crystal-liquid fractionation from more mafic lamprophyric magmas involving the phenocryst assemblage observed in the more mafic lamprophyres (olivine, clinopyroxene and Ti-rich hornblende), which also occur in the cognate gabbroic crystal agglomerates observed in some of these dikes.

Significantly, the less mafic, olivine-free lamprophyre dikes have similar or higher La, but lower Yb, resulting in significantly higher La/Yb compared to the mafic lamprophyres (Fig. 5). We suggest this is the product of amphibole fractionation, since heavy REE are compatible in amphiboles and amphibole is the most abundant observed phenocrysts in these lamprophyres. Decreasing Dy/Yb ratios (2.2 to 2.0) for lamprophyres that vary between 50.3 to 61.1 weight percent SiO_2 (Table 3) is also consistent with crystal-liquid fractionation involving amphibole rather than garnet (Davidson *et al.*, 2007). This conclusion suggests that amphibole fractionation is capable of increasing La/Yb ratios 4-fold, from 10 to >40, and that such high La/Yb ratios are not necessarily an indication of garnet fractionation in thickened continental crust as proposed by Kay *et al.* (2005).

Nearly constant Sr for the less mafic compared to the more mafic lamprophyres, and the lack of a negative Eu anomaly, indicate that plagioclase was not a significant fractionating crystal phase, consistent with it not being a common phenocryst phase. We suggest that the lack of plagioclase fractionation was due to the high H_2O content of the lamprophyre magma, which suppresses plagioclase crystallization and enhances the extent of amphibole crystallization, and it was not due to stabilization of garnet at the expense of plagioclase caused by high pressure in the magma source or crystal-fractionation region as suggested by Kay *et al.* (2005). Garnet may have existed in the mantle source region of the mafic lamprophyres, but we consider the trend to high La/Yb and low Yb observed between the more and less mafic lamprophyre samples to be due to crystal-fractionation involving amphibole and not to garnet fractionation. This reflects the increased importance of water in the mantle source of these rocks, and not an increase in depth and mineralogy of magma generation or evolution.

4.5. Temporal isotopic evolution

Relative to older Cenozoic igneous rocks in the vicinity of El Teniente, the lamprophyre dikes have higher $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$, and lower ϵ_{Nd} (Figs. 6-8). It is clear that these temporal isotopic changes, which are observed in the most mafic olivine-bearing mantle-derived samples, must reflect temporal isotopic changes that occurred in the subarc mantle source region of these rocks. Figure 9 presents a model for Sr and Nd isotopic variations caused by different amounts of contamination of the subarc mantle by subducted trench sediment containing both marine and terrigenous components (Table 6) as calculated by Macfarlane (1999). The model indicates that the Oligocene to Pliocene isotopic variations are consistent with increased mantle source region contamination.

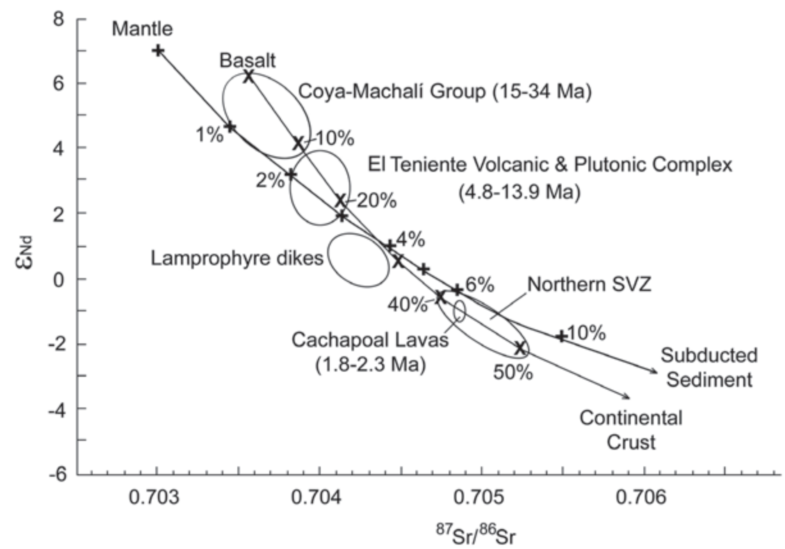

FIG. 9. Sr *versus* Nd isotopic values of the various groups of igneous rocks of different ages across a transect of the Andes at the latitude of El Teniente (34°S; fields and data sources from figure 6). The figure illustrates both a source region contamination model of primitive mantle (36 ppm Sr with $^{87}Sr/^{86}Sr$=0.703 and 1.8 ppm Nd with ϵ_{Nd}=+7; Sun and McDonough, 1989) mixed with various proportion of subducted sediment (380 ppm Sr with $^{87}Sr/^{86}Sr$=0.70763 and 42.3 ppm Nd with ϵ_{Nd}=-5.1; Macfarlane, 1999), and also an assimilation model, taken from Kay *et al.* (2005), for a Coya-Machalí basalt (450 ppm Sr with $^{87}Sr/^{86}Sr$= 0.7035 and 9 ppm Nd with ϵ_{Nd}=+6) assimilating various proportion of Paleozoic-Triassic Andean granite basement (350 ppm Sr with $^{87}Sr/^{86}Sr$=0.7075 and 20 ppm Nd with ϵ_{Nd}=-6; Kay *et al.*, 2005). Parameters for these models are listed in table 6. Both models reproduce the isotopic compositions of the progressively younger rocks in the transect, but the latter model requires assimilation of unacceptably high proportions of granite crust and is inconsistent with the generation of low SiO_2 primitive olivine-bearing mafic rocks in each age group, as well as the progressively higher Sr content of the progressively younger rocks, a feature that Stern (1991) suggested was due to decreasing degrees of partial mantle melting, which is consistent with the decreasing volumes of magma erupted through time at this latitude in the Andes.

TABLE 6. PARAMETERS USED FOR THE MANTLE + SEDIMENT MIXING AND BASALT + GRANITE ASSIMILATION MODELS.

	Mantle	Sediment	Basalt	granite
Sr ppm	36	380	450	350
$^{87}Sr/^{86}Sr$	0.703	0.708	0.704	0.708
Nd ppm	1.8	42.3	9	20
ε_{Nd}	7	-5.1	6	-6

Mantle: primitive mantle from Sun and McDonough (1989); **Sediment**: subducted sediment including crust from Macfarlane (1999); **Basalt**: Coya-Machalí basalt from Kay *et al.* (2005); **Granite**: Paleozoic-Triassic Andean granite basement from Kay *et al.* (2005).

The model suggests that Late Oligocene to Early Miocene Coya Machalí magmas could form from a mantle contaminated by 1% subducted sediment, the Middle to Upper Miocene El Teniente Volcanic and Plutonic Complex rocks from mantle modified by the addition of 2% subducted sediment, and the younger lamprophyre dikes by 4% subducted sediment. The temporal variations observed for $^{206}Pb/^{204}Pb$ are also consistent with increased source region contamination by subducted sediment (Fig. 7).

The temporal isotopic trend continues such that the younger olivine-bearing basaltic andesite lavas in the Cachapoal River, west of El Teniente deposit (Figs. 6-8; Stern and Skewes, 1995), and volcanic rocks erupted from the active volcanoes in the northern SVZ (Fig. 1; Stern *et al.*, 1984, 2007a; Futa and Stern, 1988; Hildreth and Moorbath, 1988), have even higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$. The Upper Pliocene basaltic andesite lavas in the Cachapoal river valley contain olivine, and have relatively high Ni (~50 ppm) and Cr (~100 ppm; Stern and Skewes, 1995), as do mafic basaltic andesites in the northern SVZ (Fig. 6; Hickey *et al.*, 1986). We suggest that the isotopic compositions of all these volcanic rocks reflect that of the subarc mantle currently underlying the broad zone from west to east of El Teniente deposit at 34°S. The source region contamination model (Fig. 9) indicates that these isotopic compositions could be produced by contamination of the subarc mantle by 6% subducted sediment.

The crust also thickened below this latitude of the Andes between the Oligocene and Pliocene, and figure 9 also illustrates a model, presented previously by Kay *et al.* (2005), of assimilation of various amounts of continental crust, consisting of Paleozoic-Triassic granitic basement, by a primitive Coya-Machalí olivine basalt (Table 6). The model produces the same isotopic variations as does the source region contamination model, but with much higher proportions of assimilation: 15% to produce the Upper Miocene El Teniente Volcanic and Plutonic Complex rocks, 30% to produce the younger lamprophyre dikes and 40% to produce the Upper Pliocene Cachapoal lavas and northern SVZ volcanics. However, as also noted by Kay *et al.* (2005), these amounts of assimilation of granite are clearly inconsistent with the primitive mafic chemistry of the olivine-bearing basalts in El Teniente Mafic Complex and even less so for the younger mafic olivine-bearing lamprophyre dikes. Furthermore, the isotopic data indicate that mafic, intermediate and felsic igneous rocks of each of the different episode of igneous activity in the Andes at the latitude of El Teniente, are, for each age group, isotopically similar to each other (Figs. 6-8; Kay *et al.*, 2005; Stern *et al.*, 2010). This rules out significant intra-crustal contamination or melting of isotopically heterogeneous Paleozoic and Mesozoic Andean continental crust in the generation of the rocks of each age group.

We therefore conclude that source region contamination is a more viable model to produce the temporal isotopic changes observed between the Oligocene and the Pliocene in Andean mafic igneous rocks at this latitude. Increased contamination of the subarc mantle may have occurred due to either decreasing volume of the mantle wedge as both subduction angle decreases and the crust thickens, and/or increased subduction erosion of the continental margin. Subduction erosion along the central and northern Chilean continental margin has been demonstrated as the normal mode of transfer of fore-arc material since at least the Middle Miocene (Kukowski and Oncken, 2006), based on both geological (Rutland, 1971; Ziegler *et al.*, 1981; Stern, 1991), and marine geophysical data (Scholl *et al.*, 1980; Lallemand *et al.*, 1992; von Heune *et al.*, 1999, 2004). Rates of subduction erosion may change with time due to climate changes resulting in variations in sediment flux to the trench (Thornberg and Kulm, 1987; Lamb and Davis, 2003; Kukowski and Oncken, 2006), changes in subduction rate and angle (Shreve and Cloos, 1986) and/or subduction of buoyant features such as oceanic ridges (Lallemand *et al.*, 1992; von Huene *et al.*, 1997; Yáñez *et al.*, 2001, 2002; Clift *et al.*, 2003).

Kay *et al.* (2005) conclude, based on both geochemical arguments and structural grounds, that significant (~50 km) fore-arc truncation by subduction erosion occurred between 9 Ma and the present across the arc-trench gap west of El Teniente, and that an important part of the temporal isotopic changes observed in the igneous rocks generated through time at this latitude resulted from subduction erosion of the continental margin and increased contamination of the subarc mantle by continental components. They attribute increased rates of subduction erosion at the latitude of central Chile during the Miocene to non-steady-state convergent plate boundary processes, and they suggest that major episodes of subduction erosion, fore-arc loss and arc migration occurred in conjunction with episodes of back-arc shortening, deformation and crustal thickening.

Kukowski and Oncken (2006) suggest that the rates of subduction erosion west of central Chile have been higher than west of northern Chile since the Middle Miocene. They attribute this accelerated rate to the subduction of the Juan Fernández Ridge, which they speculate widened the subduction channel, enabling it also to effectively remove northwardly transported trench sediment originating from glaciation in southern Chile. Ridge subduction has been demonstrated to enhance rates of subduction erosion (Lallemand *et al.*, 1992; Bourgois *et al.*, 1996), by as much as 10-fold greater in the case of the Nazca Ridge off the coast of Peru (Clift *et al.*, 2003). Marine geophysical studies have also concluded that increased rates of subduction erosion along the central Chilean margin have resulted from the subduction of the Juan Fernández Ridge (von Huene *et al.*, 1997; Yánez *et al.*, 2001, 2002).

Stern (1989, 1991, 2004) and Stern and Skewes (1995, 2005) previously attributed increased rates of subduction erosion along the central Chile continental margin to decreasing subduction angle associated with the southward migration of the locus of subduction of the Juan Fernández Ridge. They demonstrated that the timing of both eastward arc migration and isotopic changes similar to those that occur at the latitude of El Teniente also occurred across the Andes at 32°S and 33°S, but at progressively younger ages as the locus of subduction of the ridge migrated southwards.

As detailed by Kay *et al.* (2005), the temporal isotopic changes, observed for the igneous rocks in central Chile at the latitude of El Teniente between the Miocene and Pliocene, are similar to changes that occur spatially from south-to-north in the currently active Southern Volcanic Zone (SVZ; Fig. 1; Stern *et al.*, 1984, 2007a; Futa and Stern, 1988; Hildreth and Moorbath, 1988; Stern, 2004). Upper Oligocene to Lower Miocene Coya-Machalí volcanic rocks have isotopic compositions similar to Southern SVZ volcanoes south of 36°S. Middle to Upper Miocene El Teniente Volcanic and Plutonic Complex rocks have isotopic compositions similar to magmas erupted in the transitional zone (34.5 to 36°S) between the Northern and Southern SVZ, and Pliocene basaltic andesites in the Cachapoal River valley have isotopic compositions similar to active Northern SVZ volcanoes north of 34.5°S. Since we interpret the temporal isotopic changes at the latitude of El Teniente to reflect progressive changes in the subarc mantle due to progressively greater amounts of subduction erosion and source region contamination, we also suggest that the south-to-north spatial changes observed in the isotopic composition of SVZ volcanic rocks is produced by these same processes (Stern *et al.*, 1984, 2007a; Stern, 1991, 2004; Stern and Skewes, 1995). These changes correlate spatially with the amount of post Middle Miocene fore-arc removal, as estimated by Kay *et al.* (2005), to have occurred progressively southward, from ~50 west of the El Teniente transect at 34°S, to ~35 km west of the transitional SVZ between 34.5 and 36°S, and to none west of the Southern SVZ south of 36°S.

4.6. Implications for El Teniente Cu deposit

As discussed above, the temporal change from the porphyritic, plagioclase-rich olivine-basalts (Fig. 3c) which formed the upper Miocene El Teniente Mafic Complex to the younger chemically and isotopically distinct olivine+hornblende lamprophyre dikes, with scarce or no plagioclase phenocrysts (Fig. 3a), implies progressively greater hydration of the subarc mantle source, below the 34°S transect, of the magmas that formed these rocks. There is thus a correlation between increasing water content of the Andean sub-arc mantle at this latitude and the increasing degree of contamination of this mantle by subducted components as indicated by the isotopic data. A similar correlation has been documented in magmas erupted from different regions of the subduction-related trans-Mexican volcanic arc (Cervantes and Wallace, 2003).

Althought the lamprophyre dikes within El Teniente mine are post-mineralization in age, Stern *et al.* (2010) have proposed that during the main period of mineralization, between >6.3 to ~4.4 Ma, similar magmas may have recharged the large magma chamber below El Teniente deposit, mixing with more differentiated magmas in this chamber. Only after this chamber cooled and solidified could mantle derived mafic magmas again intrude to near the surface in the region of the deposit underlain by this large chamber. However, the change to more hydrated lamprophyre magmas generated in the subarc mantle below El Teniente may have occurred as early as the Late Miocene as indicated by their isotopic similarity with felsic plutons belonging to the regionally defined Young Plutonic Complex (6.6 to ~5 Ma; Figs. 6-8; Kay *et al.*, 2005). This is the same time period during which breccias, mineralization and felsic plutons were being emplaced within the giant El Teniente Cu-deposit (Skewes *et al.*, 2002; Maksaev *et al.*, 2004; Stern *et al.*, 2010). The progressively more hydrated and oxidized magmas being generated in the mantle and recharging the large magma chamber below this deposit during this time period may have facilitated the transfer into the shallow crust of greater amount of oxidized sulfur and metals out of the roof of the magmatic system below El Teniente (Garrido *et al.*, 2002; Stern *et al.*, 2007b; Stern *et al.*, 2010), since in less oxidized and volatile poor systems, sulfur and metals are retained near the base of the system as immiscible sulfur and pyrrhotite.

Both the observed temporal isotopic changes (Figs. 6-8) and increasing hydration of the subarc mantle, as implied by the generation of the plagioclase-rich, but hornblende-free, porphyritic olivine basalts in the Late Miocene as contrasted with the younger lamprophyres with scarce or no plagioclase phenocrysts, may, as discussed above, reflect increased rates of subduction erosion, which has an important influence on the extent to which the subducted slab is hydrated (Lamb and Davis, 2003; Ranero and Sallarés, 2004), as well as the extent of subarc mantle source region contamination. In general, subduction of oceanic crust, pelagic and terrigenous sediments and continental crust tectonically eroded off the edge of the continent provide the large amounts of water, sulfur and copper involved in the generation of all Andean copper deposits (Macfarlane, 1999), but we suggest that the increased rates of subduction erosion and source region contamination below central Chile since the Middle Miocene have been key factors in creating the unique conditions for the generation of the giant Miocene and Pliocene Cu deposits in this region (Stern, 1989; Stern and Skewes, 1995, 2005; Stern *et al.*, 2010).

5. Conclusions

We conclude that between the Late Miocene and Pliocene there is a coherent trend of increasing degree of hydration and mantle-source region contamination below the Andes at latitude 34°S. This trend was caused by a combination of decreasing subduction angle, decreasing sub-arc mantle volume, and increasing subduction erosion and mantle source region contamination by subducted crustal components. This resulted in the generation within the mantle of a small volume of relatively water-rich lamprophyric magmas with higher $^{87}Sr/^{86}Sr$ and lower ϵ_{Nd} compared to the large volume of older Late Miocene olivine basalts that host the El Teniente deposit. Progressive hydration of the sub-arc mantle below El Teniente may have played an important role in producing the highly oxidized water-rich igneous rocks that produced this giant deposit.

We attribute these changes to the subduction of the Juan Fernández Ridge (Stern, 1989, 2004; Stern and Skewes, 1995, 2005). Ridge subduction has been shown to be an important factor in the generation of mineral deposits in the Andes of both Peru and Chile (Rosenbaum *et al.*, 2005). Geotectonic processes attributed to ridge subduction also include possibly melting of subducted oceanic lithosphere (Gutscher *et al.*, 2000; Mungall, 2002), but the progressively higher $^{87}Sr/^{86}Sr$ and lower ϵ_{Nd} of the plutonic rocks associated with El Teniente deposit and the younger lamprophyres rule out the involvement of melts of subducted MORB in their generation. Instead we suggest that the role of subduction of the Juan Fernández Ridge was to enhance the rates of subduction erosion along the continental margin and progressively increase both the amount of source region contamination by continental crust and the degree of hydration in the subarc mantle below the area of El Teniente.

Acknowledgements

We thank P. Zúñiga, Superintendent of Geology, for access to and logistic support within area of the El Teniente mine. Reviews by S. Kay, G. Wörner and D. Morata provided helpful comments incorporated in the preparation of the final manuscript.

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Manuscript received: August 18, 2009; revised/accepted: September 23, 2010.