PETROLOGICAL AND GEOCHEMICAL STUDY OF CRUSTAL XENOLITHS FROM 1961 ERUPTION OF CALBUCO VOLCANO, CHILE (LATITUDE 41 20 S)

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Abstract

Twenty four samples of xenoliths and country rocks from the 1961 lava flow of Calbuco volcano have been studied. Fourteen samples have been analyzed for major elements and P, Ni, Ba, Cr, V, Zr, Sc, Y, and Sr. Five of these samples were further analyzed for Sm, Nd, Sr, and Pb isotope ratios. Seventeen samples were analyzed under the microscope and three samples were analyzed by microprobe for their pyroxene composition. Based on petrograghic studies xenoliths were divided into three groups. Fine grained xenoliths (groups I and II) probably formed from metamorphosed MORB-like basalts , whereas coarse grained xenoliths (group III) were apparently derived from cumulate minerals that crystallized from the Calbuco magma. The fine grained xenoliths were probably entrained in magma at intermediate levels of the crust, near the stability limit of amphibole to form pyroxene and plagioclase. In the coarse grained xenoliths amphibole that form at depth dehydrated as the xenoliths were brought to the surface. The country rocks are apparently unrelated to the xenoliths.

Introduction

Calbuco volcano is an active volcanic center within the Southern Volcanic Zone (SVZ) of the Chilian Southern Andes. There are more than twenty-five other active volcanic centers in the SVZ (33- 46 S). However, Calbuco volcano is unique in the large number and diverse nature of crustal xenoliths that were erupted in lavas.

The study of crustal xenoliths is important for a number of reasons. First, the contamination of lavas by crustal country rocks is one of many factors that can cause chemical variations in the lavas. Both along-strike and intra-volcano chemical variation have been observed in the SVZ [7,9, 24]. The study of crustal xenoliths in

lavas aids in the assessment of possible crustal contaminants especially the role of lower crustal rocks because of their lack of accessibility. Second, crustal xenoliths also provide a window into the structure and composition of the lower and middle crust.

These samples can give information about petrology and geochemical characteristics of lower crustal rocks.

Numerous xenoliths have been brought up to the earth's surface by andesitic lavas from Calbuco volcanic center. The goals of the present study are therefore:1. to describe the petrology and geochemistry of basaltic xenoliths from Calbuco volcanic center; 2. to determine the nature of the xenoliths prior to incorporation in the magmas; and 3. to draw some conclusions concerning the crust beneath Calbuco volcano and its origin.

Geological Setting

The SVZ is one of the four Quaternary-recent zones of Andean volcanism [23]. The Northern Volcanic Zone (NVZ) is located between latitudes 5 N and 2 S (Fig. 1). The Central Volcanic Zone (CVZ) starts from latitude 16 S to 28 S, and followed by the Southern Volcanic Zone (SVZ) from 33 S to 46 S. The southernmost Andean volcanos are also aligned in a linear volcanic zone between latitudes 49 S and 56 S. This zone is called the Austral Volcanic Zone (AVZ).
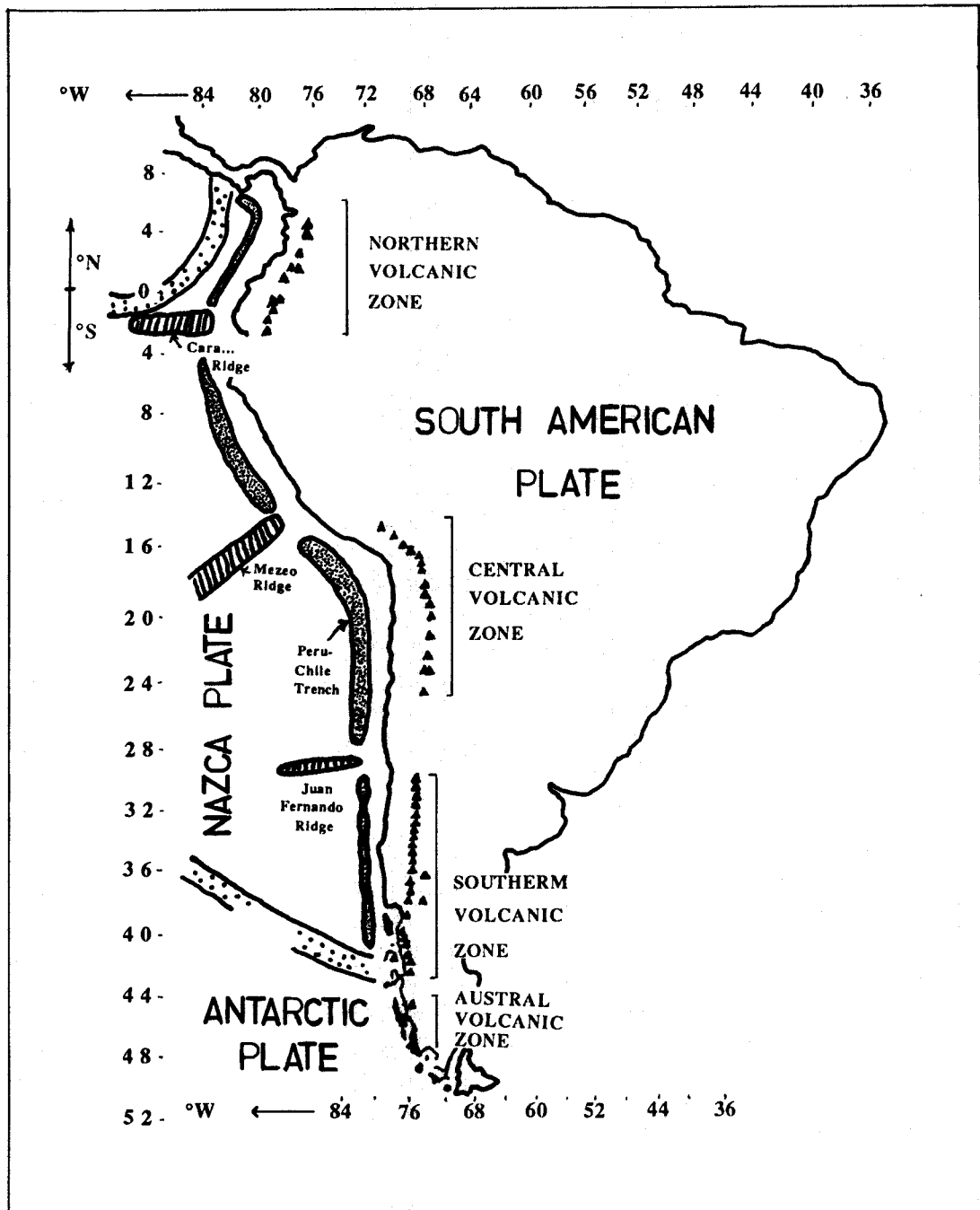

Figure 1. Outline map of South America showing the major tectonic features associated with orogenic magmatism in Andean Cordillera, the boundaries of the volcanic provinces, and the locations of Late Cenozoic volcanic centers (triangles), (After Lopez-Escobar, 1984).

The SVZ is produced by an oceanic-continental subduction zone with an active volcanic arc which extends from 33 S to 46 S. The thickness of the continental crust varies from about 65 km. at the 33 S, to 25-30 km. at 41 S [24]. The dip of Nazca plate is approximately 25-30 along the SVZ [1]. North of 37 S, SVZ volcanics range in composition from basalts to rhyolites. However, andesites are predominant and frequently contain hydrous minerals [8, 11, 13, 25].

South of 37 S, basalts and basaltic andesites are the most abundant rocks, followed by dacite and andesite, whereas rhyolith is rare in this region [11]. The common mafic minerals in this area are olivine, clinopyroxene, and orthopyroxene. Hornblende occurs only in dacitic and more silicic volcanics and is frequently absent.

South of 33 S, it has been suggested that the Andes consists of two main geosyncline belts; west and east. The west Andean geosyncline is Jurassic-Cretaceous in age and probably developed on an older continental basement. The basement consists of late Palaeozoic sediments or more commonly of foliated metamorphic rocks of probably Palaeozoic age [20, 25]. For Jurassic and younger rocks, the geosyncline can be divided into a eugeosynclinal volcanic zone and miogeosynclinal sedimentary zone. These two north-south oriented tectonic units are called the Coast Range and the Longitudinal Depression which is also known as the Central Valley. The Peru-Chile Trench on the western side and the Andean Cordillera on the eastern side are two other tectonic units in central Chile [10, 20].

Between latitudes 39 S and 42 S, in the Andean Lake region, Palaeozoic granitoid batholithe occur within the Cordillera and to the east in Argentina. High grade gneisses of probable Palaeozoic age are associated with these intrusives in scattered areas [14, 18]. There is an oblique plutonic belt of Jurassic age and a NNW plutonic belt of Cretaceous age in this region. This Cretaceous aged belt developed mainly in Argentina, but continues into Chile at 39.5 S [14]. Jurassic plutons in this region intrude into the late Palaeozoic Panguipulli Formation, which is Carboniferous to Permian in age. The Panguipulli Formation consists of epimetamorphic clastic sedimentary rocks, which contain plant fossils of late Palaeozoic and detritus of metamorphic and intrusive sources [4, 14, 17].

A north-south trending belt of Miocene batholiths and stocks also occur in this area. These granitoid

batholiths appear to be the most extensive unit beneath the volcanoes in SVZ.

Calbuco, which is an active volcano located between latitudes 41 13 S and 41 26 S, and longitudes 72 30 W and 72 45 W, on the east side of Puerto-Montt and Puerto-Varas.

The oldest rocks in this region are Palaeozoic and the youngest are Quaternary. Palcozoic granitoids and metamorphic basement occur along the Coast Ranges and eastern Andes [2,3,14]. The metamorphic basement at the Coast Range consists of mica schists, serpentinites, greenschists, metacherts and gneisses [5,14,16]. These rocks have been interpreted as late Palaeozoic subduction complex [18]. Small Cretaceous granitoid stocks intrude into this basement [25].

Calbuco has been an active volcano since the Pleistocene period and is characterized by a typical stratovolcano evolution [13]. Different stages in this volcano are separated by glacial erosion and its final stage is marked by an active central cone, lava flows, and large amounts of laharic deposits. Eruptions of this volcano have been recorded in 1837-1838, 1906, 1909, 1912, 1917, 1929, and 1961 [13]

Volcanic materials of Calbuco volcano are mainly basalts, andesites, and to a smaller extent dacites. The volcanic flows unconformably overlie the granitic Miocene bedrock. The basalts are composed of augite, hypersthene, labradorite and olivine as phenocrysts. The phenocryst in andesitic rocks are hypersthene, augite, and labradorite [13].

An unusual feature of the 1961 lava flows from Calbuco is that they contain an exceptionally high number of crustal xenoliths. The xenoliths of this eruption are mainly medium grained gabbros and fine grained hornfelsic metabasalts with minor amounts of pyroxenite, quartzite and granite [6].

Twenty-four mafic xenoliths and country rocks were selected for the present study from the collection made by Dr. Hickey. These xenoliths were classified into three groups on the basis of their mineralogy and texture. Two metamorphic country rocks which are representative of the only nearby metamorphic rocks have also been studied (Table 1).

Group I (fine grained amphibole free):

Mineral constituents: plagioclase 30-44%, clino-pyroxene 25 - 38%, magnetite 7 - 18%, glass 2.5 - 25%, orthopyroxene 0-7% and hematite up to 0.10%.

Samples from this group are fine grained amphibole

Group No.	Characteristics	Sample No.
I	Fine grained amphibole free pl+ px+mt+gl±hem	12-18-6, 12-18-13 12-18-14, 12-19-5 12-19-8b, 12-19-13 12-19-14, 12-19-16 12-21-1, 12-21-4 and 12-21-6
II	Fine grained amphibole bearing pl+px+mt+gl+amph±hem	12-18-7, 12-18-12 12-19-7, 12-19-10 12-19-12, 12-20-5 and 32822-F
III	Coarse grained gabbros pl+px+mt+gl+amph±hem	12-18-1 12-19-3 12-19-18, 12-20-2
Metamorphic Country rocks	Coarse grained Amphibolites pl+amph+mt±px	12-29-2, 12-29-3

Table 1: Classification of Calbuco xenoliths and country rocks. In this Table pl stands for plagioclase, px for pyroxene, mt for magnetite, gl for glass, amph for amphibole and hem for hematite.

free xenoliths. In general, they show granulitic textures. Polygonal texture occurs among the plagioclase grains. Foliation in this group is defined mainly by magnetite. pyroxene, and plagioclase. Sample 12-19-5 is a granoblastic porphyritic rock. There is a variation in size among the plagioclase and pyroxene in this rock giving porphyritic texture to the xenolith. Foliation in this rock is not as clear as in the other xenoliths, but still it can be seen from plagioclase and pyroxene grains.

Samples of group I plot with the gabbroic field on the Pl-Px-Hbl diagram, recommended by IUGS.

Group II (fine grained amphibole bearing):

Mineral constituents: plagioclase 33-53%, clinopyroxene 19-43%, magnetite 14-26%, glass 0.5-10%, orthopyroxene 0-8%, amphibole 0.09-0.49%, and hematite 0.16-2.52%.

Group II of the xenoliths are fine grained. Medium to strong foliation is observed in this group and is usually defined by pyroxene, plagioclase and magnetite (32822F), or by plagioclase and pyroxene [12-19-7]. Sample 32822F in this group is equant grained and

contains very few amphiboles, but sample 12-19-7 contains amphiboles that are either large crystals or very fine grained. Plagioclase grains also occur as large tabular or fine grained. Coarse grained amphiboles in these rocks show symplectite textures. Polygonal texture occurs among the plagioclase minerals in this group. On the IUGS Pl-Px-Hbl diagram these xenoliths are grouped as gabbro. On the ACF diagram they are hypersthene granulites. Clinopyroxene are in different sizes from fine grains to large (about 1 mm). Some of clinopyroxenes occur as a rim on opaque minerals which may be due to reaction: opaque + glass------>cpx. Also some of the clinopyroxenes contain small minerals of orthopyroxene which may have exsolved.

Group III (coarse grained gabbros):

Mineral constituents: plagioclase 36-49%, clinopyroxene 6-15%, magnetite 7-12%, glass 2-16%, orthopyroxene 8-20%, amphibole 1-27%, and trace amounts of hematite.
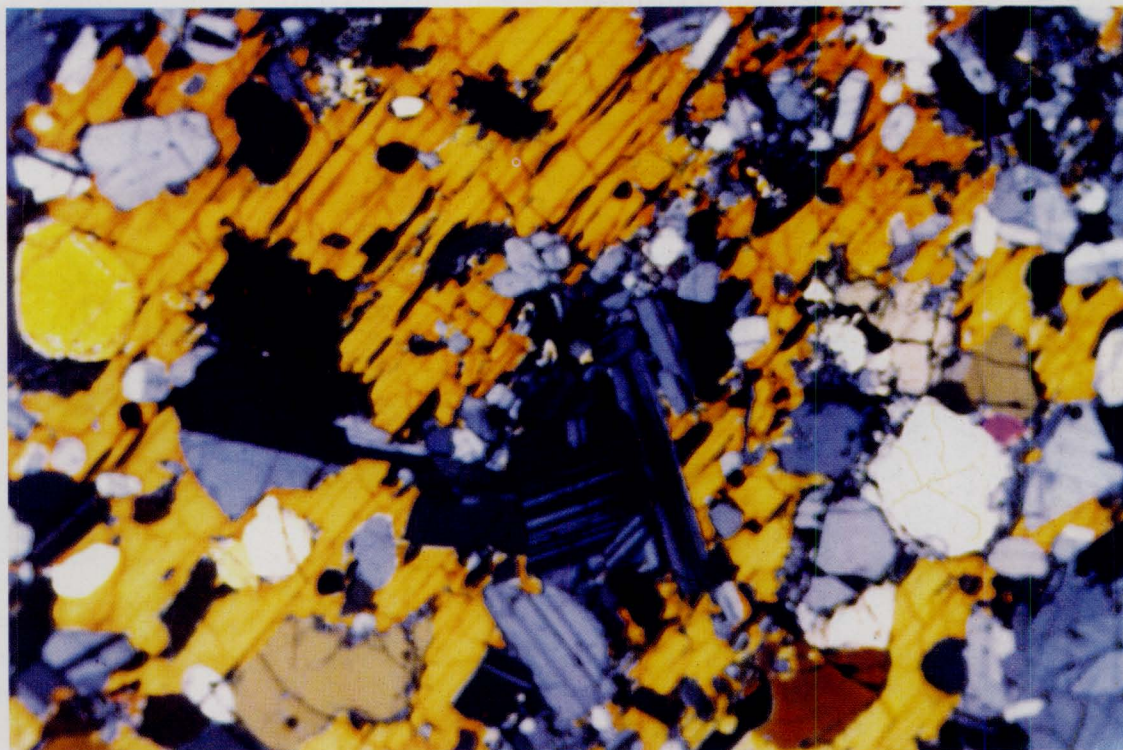
Xenoliths of this group are coarse

Figure 2. Photomicrograph of sample 12-19-18 under crossed nicols, showing grain size and poikiloblastic texture.

grained and heterogranular. Poikiloblastic and porphyroblastic textures have been distinguished for these xenoliths (Fig. 2). These xenoliths contain lower clinopyroxene and higher orthopyroxene than the fine grained xenoliths. Among the xenoliths of group III, polygonal texture is the most abundant in sample 12-20-2, less abundant in 12-19-18, and least abundant in sample 12-19-3. Symplectite textures and twinning are very common in sample 12-19-18 and 12-19-3, but these texture are less in sample 12-20-2. Classification of these rocks indicate that samples 12-19-18, and 12-20-2 are pyroxene-hornblende gabbronorite and sample 12-19-3 is gabbronorite.

Country Rocks (coarse grained):

Mineral constituents: plagioclase 59-78%, clinopyroxene 1-1.4%, magnetite 0.5-2%, green amphibole 18-39%, and hematite less than 1%,

These rocks are coarse grained and contain a very high percentage of plagioclase and amphibole, but a very low percentage of pyroxene. About 96% of the mineral constituents in sample 12-29-2 and about 98% in sample 12-29-3 are plagioclase and amphibole. Porphyroblastic

and hypidiomorphic granular textures occur in these rocks. Twinning and triple junction textures are clear among the plagioclase grains. On the P1-Px-Hb1 diagram these rocks are hornblende-gabbro. In the classification of Williams *et al.*, (1982) and Moorhouse (1959) they are amphibolites.

Mineral Chemistry

Pyroxene grains in sample 12-18-1, 12-18-6, and 12-18-7 were analyzed by energy dispersive spectrometery with a partially automated electron microprobe (ARL model EMX). The microprobe analytical methods were similar to those in Sen (1988). The results of pyroxene analyses of these three rocks are given in Table 2.

Mineral constituents of sample 12-18-1 include clinopyroxene, orthopyroxene, plagioclase, amphibole, magnetite, and hematite. The texture of this rock varies from fine grained (0. 1mm) to coarse (4 mm) grained. grained.

Amphiboles in this rock are mostly coarse grained. Other minerals, however, vary in size. This rock is categorized with the group III of xenoliths. The orthopyroxene and clinopyroxene analyses, for this rock

Samples 12-18-1 & 12-18-7

Mineral	Sample 12-18-1 cpx (4)		opx (2)		Sample 12-18-7 opx (1)
SiO_2	51.02	(0.67)	52.47	(0.57)	51.07
TiO_2	0.4	(0.14)	0.18	(0.15)	n.d.
Al_2O_3	n.d.		n.d.		n.d.
FeO	8.46	(0.19)	17.01	(1.4)	15.09
MnO	0.41	(0.14)	0.64	(0.05)	2.16
MgO	14.82	(0.37)	24.83	(0.89)	23.78
CaO	20.50	(0.26)	1.66	(0.13)	0.90
Na_2O	**n.d.**		**n.d.**		**n.d.**
Total	95.61		96.79		93.00

Number of cations for 6 oxygens			
Si	1.991	1.982	2.003
Ti	0.012	0.005	-
Al	-	-	-
Fe	0.276	0.536	0.495
Mn	0.0328	0.020	0.07
Mg	0.847	1.390	1.388
Ca	0.8576	0.067	0.037
Na	-		
Sum	4.01	4.00	4.00

Sample 12-18-6

Mineral	cpx (5)	Sample 12-18-6
SiO_2	51.54	(0.58)
TiO_2	0.51(0.07)	
Al_2O_3	n.d.	
FeO	9.63(0.33)	
MnO	0.56(0.24)	
MgO	13.00	(0.16)
CaO	22.07	(0.16)
Na_2O	**n.d.**	
Total	97.28	

Number of cations for 6 oxygens	
Si	1.99
Ti	0.0147
Al	-
Fe	0.311
Mn	0.0185
Mg	0.752
Ca	0.913
Na	-
Sum	4.00

Table 2. Microprobe analysis of pyroxenes from Calbuco xenoliths . Numbers in parentheses are the numbers of analyses averaged and the standard deviations of those analyses

are averaged analyses however, they closely represent the composition in physical contact with each other, since no zoning was observed in these pyroxenes. It is probable that values shown are those of two pyroxenes in chemical and textural equilibrium. The temperature of such equilibrium is estimated to be 917 degrees C according to the Wells (1977) two - pyroxene thermometer. Note that the computer program THERMOBAR Prabhakaran and Sen, (1988) was used to do this calculation.

The clinopyroxene in sample 12-18-1 is lower in CaO than those in 12-18-6 and 12-18-7 (Table 2). This is to be expected since the clinopyroxene in sample 12-18-1 equilibrated with a Ca-poor orthopyroxene, whereas the other two xenoliths are nearly devoid of orthopyroxene. Plotting these three samples on the pyroxene quadrilateral indicates that clinopyroxenes are diopsidic augites and orthopyroxenes are bronzitic hypersthene.

Geochemistry of the Xenoliths

Thirteen samples were chosen for chemical analysis. Samples were analyzed using an Iductively Coupled Plasma Emisson Spectrometer (ICP) Jobin Yvon JY70 Type III. Six of these samples were also analyzed for isotopes. Ten samples of fine grained xenoliths (groups I and II) were selected for major and trace element chemical analysis. Two country rocks and sample 12-19-18 of group III have also been analyzed. To evaluate the precision of the techniques sample 12-19-10 of group II was analyzed twice, also the results of chemical analysis of sample 32822F were compared with pre-existing data of this rock which had been done by XRF, INAA, and ID.

Major and Trace Element Data

Major, minor, and trace element abundances of xenoliths and two country rocks of Calbuco volcano are given in Table 3. SiO2 contents in the xenoliths and

Table 3, Major, minor, and trace element abundances of three groups of xenoliths and two country rocks

Group No.	I	I	I	I
oxides (%)	12-19-5	12-21-1	12-18-6	12-18-14
SiO_2	51.21	44.33	47.84	49.13
TiO_2	0.81	1.95	1.36	1.38
Al_2O_3	18.43	14.68	15.45	14.15
Fe_2O_3	10.19	17.07	13.27	14.14
MnO	0.15	0.19	0.19	0.22
MgO	5.71	6.46	7.07	8.61
CaO	10.42	13.53	12.64	10
K_2O	0.29	0.16	0.20	0.20
P_2O_5	0.15	0.20	0.14	0.15
P(ppm)	681	877	606	666
Ni	24	46	53.5	55
Ba	84.5	60.5	60.5	64.5
Cr	89	176	287	280
V	267	423	358	328
Ti	4865	11684	8199	8309
Zr	87	88	98	103
Sc	33.26	54.28	46.28	44.96
Y	20.25	29.74	26.47	22.10
Sr	329	242	285	257

Table 3. continued

Group No. oxides (%)	I 12-21-4	I 12-19-13	I 12-19-14	I 12-19-16
SiO_2	49.90	49.61	45.20	48.99
TiO_2	1.69	1.66	1.61	1.60
Al_2O_3	14.10	13.26	13.69	13.88
Fe_2O_3	15.03	14.54	16.38	14.70
MnO	0.25	0.22	0.20	0.22
MgO	8.27	8.15	6.49	8.31
CaO	8.06	10.08	14.68	9.88
Na_2O	2.45	2.04	1.45	1.99
K_2O	0.09	0.23	0.15	0.26
P_2O_5	0.16	0.20	0.17	0.16
P(ppm)	731	871	748	723
Ni	50	37	78	42
Ba	26	64	47	73
Cr	176.5	119	143	152
V	432	403	424	400
Ti	10154	9956	9639	9616
Zr	91	98	68	97
Sc	51	47.92	49.73	46.66
Y	40.66	36.70	27.65	29.44
Sr	123	210	239	240

Group No. oxides (%)	II 12-19-10	II 12-19-10 X	II 32822F
SiO_2	44.29	44.61	49.38
TiO_2	2.13	2.10	1.82
Al_2O_3	16.06	16.05	13.64
Fe_2O_3	18.67	18.43	15.35
MnO	0.26	0.26	0.24
MgO	9.36	9.39	9.26
CaO	7.60	7.59	7.99
Na_2O	1.33	1.31	2.00
K_2O	0.09	0.06	0.15
P_2O_5	0.21	0.20	0.19
P(ppm)	901	888	828
Ni	76	64	25.5
Ba	67	68	37
Cr	152	135	121
V	418	431	437
Ti	12772	12600	10937

Table 3, continued

Zr	187	155	105
Sc	53	53	51.89
Y	30	31	47.50
Sr	237	234	107

Group No. oxides (%)	III 12-19-18	C.R.* 12-29-3	C.R. 12-29-2
SiO_2	45.54	48.50	46.02
TiO_2	0.83	0.17	0.36
Al_2O_3	21.96	25.92	27.81
Fe_2O_3	8.49	3.73	4.95
MnO	0.11	0.06	0.07
MgO	8.40	4.38	1.89
CaO	13.10	14.64	16.94
Na_2O	1.36	2.40	1.62
K_2O	0.12	0.13	0.23
P_2O_5	0.10	0.09	0.12
P(ppm)	438	413.5	535
Ni	408	89	39.5
Ba	38	23.5	37
Cr	145	29	69
V	257	68	88
Ti	5011	1025	2165
Zr	24	12	38
Sc	40.85	18.58	12.15
Y	14.40	5.33	9.25
Sr	341	223	30

* country rock

Table 4,

Group No. Sample No.	I 12-19-5	I 12-21-1	I 12-21-4	II 32822F	III 12-19-18	C.R. 12-29-2
143Nd/144Nd	0.512908	0.512900	0.513149	0.513170	0.512707	0.513128
87Sr/86Sr	0.70436	-	0.70421	0.70401	0.70458	-
206Pb/204Pb	18.629	-	18.384	18.462	18.667	18.630
207Pb/204Pb	15.603	-	15.568	15.564	15.624	15.593
208Pb/204Pb	38.496	-	38.192	38.251	38.579	38.521
Sm	2.35	3.26	3.51	3.90	1.68	0.788
Nd	7.75	8.96	8.81	10.02	4.60	2.34
Sr	339.2	-	114.7	105.00	347.5	-

country rocks vary from 44% to 51% and MgO content vary from 2%-9%, therefore they are roughly basaltic or gabbroic in composition.

Based on the classification of Taylor et al., (1981), by using the K_2O and SiO_2 diagram, the Calbuco xenoliths plot as low-potassium tholeiitic basalts. Metabasalts and greenschist from the metamorphic basement of the Coastal Cordillera also plot in this diagram and show a wide range which might be due to redistribution of potassium during metamorphism. The data also were plotted on SiO2 versus Alk., Fe2O3/MgO versus SiO_2/Fe_2O_3/ MgO versus Fe_2O_3, A-F-M,

TiO_2- K_2O_5, $TiO_2$2 MnO- P_2O_5,, Ti-Zr-Y, Ti-Zr-Sr, Ti versus Zr, Zr/Y versus Zr, and Ti/Cr versus Ni diagrams and indicate that the protolith rocks for the xenoliths, with the exception of 12-29-5, are tholeiitic basalts, low-K tholeiite, ocean floor basalts, and MORB'S.

Isotope Geochemistry

Samples 32822F, 12-19-5, 12-19-18, 12-21-1, 12-21-4 and 12-29-2 were also analyzed for Nd, Sr, and Pb isotopes and Sm, Nd, and Sr abundances by isotope dilution. The techniques that have been used are the same as those described in Hickey et al., (1986). Data are given in Table 4. The results of 143Nd 144Nd vs 87Sr/86Sr where plotted on the Nd-Sr diagram in Hickey et al., (1986). It appears that samples 32822F and 12-21-4 xenoliths have affinities with the altered MORB and island arc basalts. They do not have Sr and Nd isotope ratios like modern SVZ lavas. Sample 12-19-5 plots in range of Pacific ocean, Atlantic and Indian ocean crust, and OIB. This xenolith has Sr, and Nd isotopic ratios like some SVZ basalts [9]. Three Calbuco lavas and one xenolith sample 12-19-18 plot together with the field of Pacific ocean crust and Atlantic and Indian ocean crust.

Xenoliths 12-21-4, and 32822F with high 143Nd/144Nd, have 206Pb/204Pb=18.38-18.46, 207Pb/204Pb= 15.56-15.57, and 208Pb/204 Pb =38.19-38.25. These values are unlike modern SVZ lavas but are similar to MORB. Xenoliths 12-19-5 and 12-19-18 have Pb-isotope ratios that are indistinguishable from the SVZ lavas, therefore in these samples Sr, Nd, and Pb isotope ratios are like SVZ lavas. Country rock 12-29-2 also has Pb-isotope ratios like SVZ lavas, but 143Nd /144Nd is significantly higher.

Samarium and neodymium are two rare earth elements which have been analyzed in six rocks from three different groups of Calbuco xenoliths and the country rocks. The results indicate that sample 12-19-5 of group I and Calbuco lavas have lower Sm/Nd ratios relative to chondrites and are LREE-enriched. Xenoliths 12-21-1, 12-21-4, 32822F, and 12-19-18, and country rock 12-29-2 are depleted in LREE. Compared to MORB, xenolith 12-19-5 and country rock 12-29-2 are LREE-enriched and four other xenoliths are LREE-depleted.

Discussion
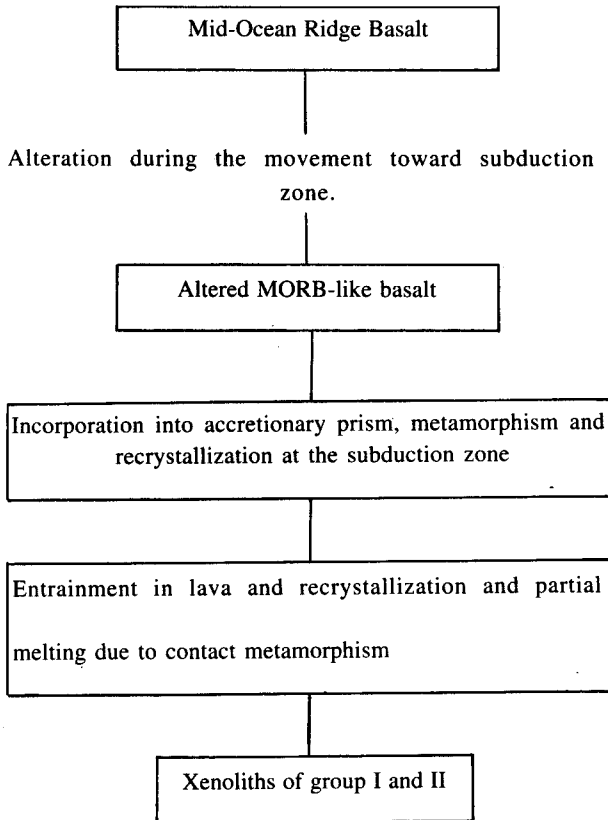
SiO2 content of samples range from 44.5 to 51.5%, which classifies them as low silica rocks. Low K and Na in the xenoliths may indicate that either these elements have been moved out during metamorphism or originally the parent rocks had low potassium and sodium contents. If the parent rocks were sedimentary, the low K and Na found in the xenoliths may indicate that these elements have moved out during metamorphism. However, there are at least two lines of evidence that the xenoliths are not metasedimentary. First, the isotopic values are unlike sediments but similar to igneous rocks. Second, all the groups I, II and III of the xenoliths except 12-19-5 are LREE-depleted which is also uncharacteristic of sediments. In general, abundances of major and trace elements and isotope ratios in the xenoliths resemble those of mafic igneous rocks.

By using different diagrams it was indicated that the xenoliths with the exception of 12-19-5 have affinities with tholeiitic basalts, low-K tholeiite, ocean floor basalts, and MORB's. Two samples analyzed for isotopic ratios have Pb, and Nd isotope ratios characteristic of MORB and they are LREE-depleted, also characteristic of MORB's. Based on these features, it is probable that the group I and II xenoliths were altered-MORB-like basalts. Such a metabasalts are found in the ophiolites of Coastal Ranges and may underlie the magmatic arc. The fact that these xenoliths overlap with the metabasalt and greenschist fields supports this interpretation. Table 5 is a flow chart which shows different stages that these xenoliths probably have undergone.

Sample 12-19-5 consistently plots with lavas from Puyehue and other SVZ volcanoes and close to Calbuco lavas. It has Nd and Pb isotope ratios similar to SVZ basalts. Based on these features, this xenolith was probably a subduction-related basalt, possibly a young lava associated with the recent volcanism. This interpretation is consistent with the poorly developed

foliation and porphyritic texture in this sample. Different stages of this rock is shown by a flow chart in Table 5.

Table 5

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        ┌─────────────────────────────┐
        │    Mid-Ocean Ridge Basalt   │
        └─────────────────────────────┘
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Alteration during the movement toward subduction zone.

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        ┌─────────────────────────────┐
        │    Altered MORB-like basalt │
        └─────────────────────────────┘
                      │
┌───────────────────────────────────────────┐
│ Incorporation into accretionary prism,     │
│ metamorphism and recrystallization at the  │
│ subduction zone                            │
└───────────────────────────────────────────┘
                      │
┌───────────────────────────────────────────┐
│ Entrainment in lava and recrystallization  │
│ and partial melting due to contact         │
│ metamorphism                               │
└───────────────────────────────────────────┘
                      │
        ┌─────────────────────────────┐
        │  Xenoliths of group I and II│
        └─────────────────────────────┘
```

Xenolith 12-19-18, a group III xenolith is isotopically identical to Calbuco lavas. Major and trace element features differ from Calbuco lavas, specifically, Cao, and Al2O3 contents are higher and TiO2 and incompatible element abundances are lower. This xenolith group probably formed from cumulate plagioclase and amphibole that crystallized from Calbuco magmas at depth. This interpretation is consistent with the temperature of 917 degrees C obtained from pyroxenes in group III xenolith, which is appropriate for andesite magma like the Calbuco magmas. Table 7 shows a flow chart that summarizes these processes.

Country rock 12-29-2 and 12-29-3 may also have been cumulate rocks based on their high Al2O3, and CaO abundances and low incompatible element abundances. Isotopically they are unlike any of the xenoliths and probably represent a different protolith.
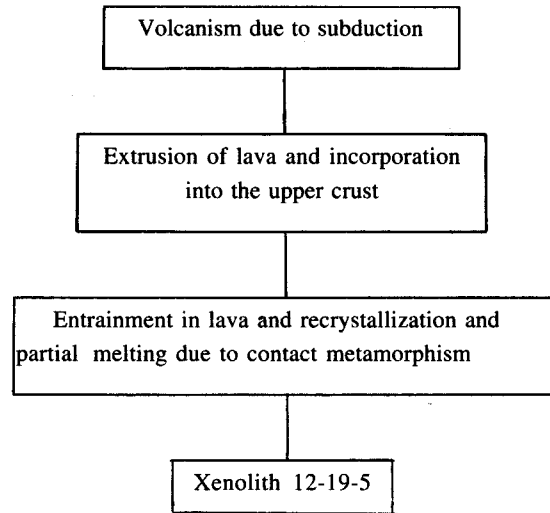
```
        ┌─────────────────────────────┐
        │   Volcanism due to subduction│
        └─────────────────────────────┘
                      │
        ┌─────────────────────────────┐
        │ Extrusion of lava and        │
        │ incorporation into the upper │
        │ crust                        │
        └─────────────────────────────┘
                      │
┌───────────────────────────────────────────┐
│ Entrainment in lava and recrystallization  │
│ and partial melting due to contact         │
│ metamorphism                               │
└───────────────────────────────────────────┘
                      │
        ┌─────────────────────────────┐
        │      Xenolith  12-19-5       │
        └─────────────────────────────┘
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Table 6

```
        ┌─────────────────────────────┐
        │  Accumulation in the magma   │
        │  chamber feeding Calbuco     │
        │  volcano                     │
        └─────────────────────────────┘
                      │
┌───────────────────────────────────────────┐
│ Segregation from Calbuco magma of          │
│ accumulative minerals such as amphibole    │
│ and plagioclase at 12.5-15 kbar pressure   │
│ (37-45 km depth). The minerals collect on  │
│ the floor and/or walls of the magma        │
│ chamber.                                   │
└───────────────────────────────────────────┘
                      │
┌───────────────────────────────────────────┐
│ Entrainment in magma and eruption at the   │
│ surface resulting in dehydration of        │
│ amphibole and partial melting due to       │
│ decompression.                             │
└───────────────────────────────────────────┘
                      │
        ┌─────────────────────────────┐
        │    Xenoliths of group III    │
        └─────────────────────────────┘
```
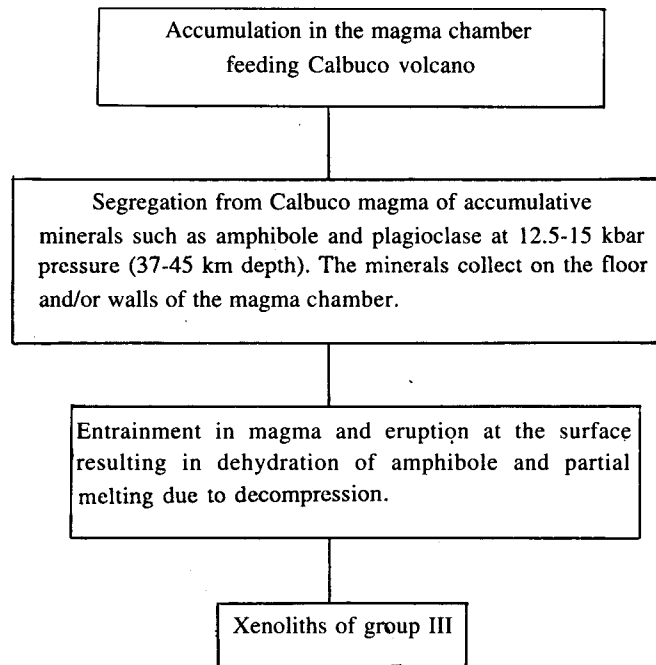
Table 7

Pressure and Temperature of Origin of the Xenoliths

A temperature of 917 degrees C was obtained from pyroxenes in sample 12-18-1, a group III xenolith that contain amphibole. In order to estimate pressure for the xenoliths, the P-T synthesis diagram for ferritschermakit Oba (1987) was used. The starting material in his experiment was anorthite, clinopyroxene, orthopyroxene, and hematite.
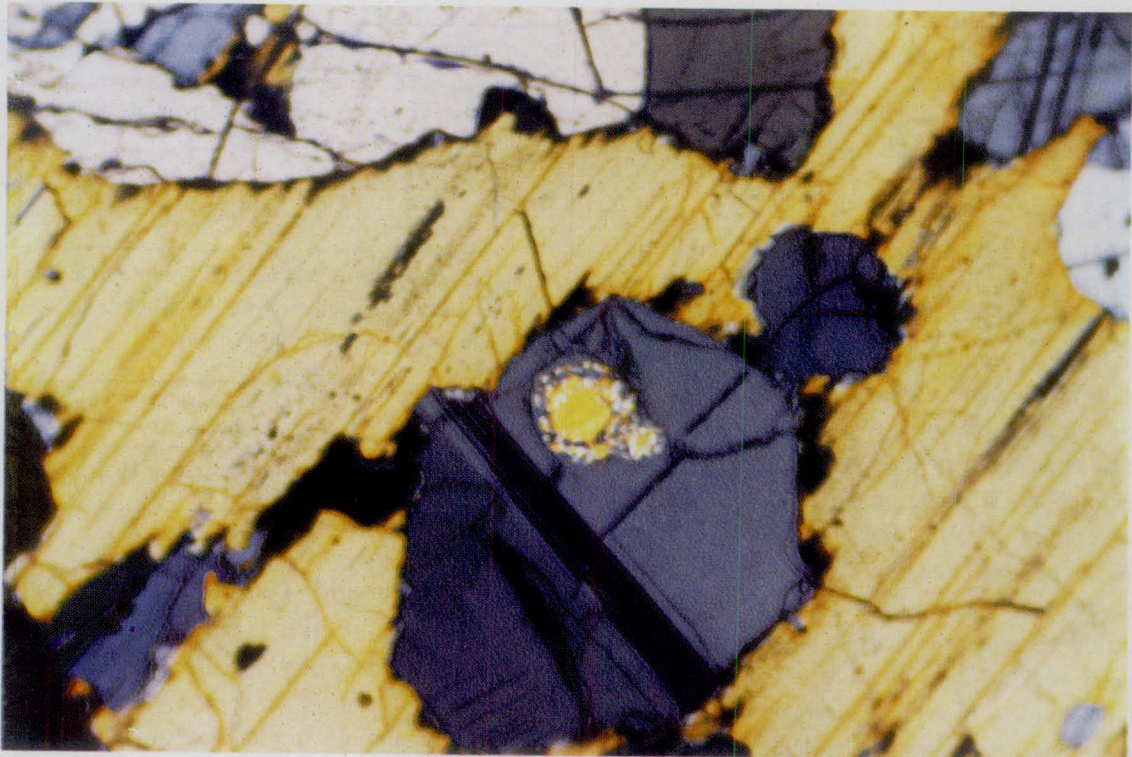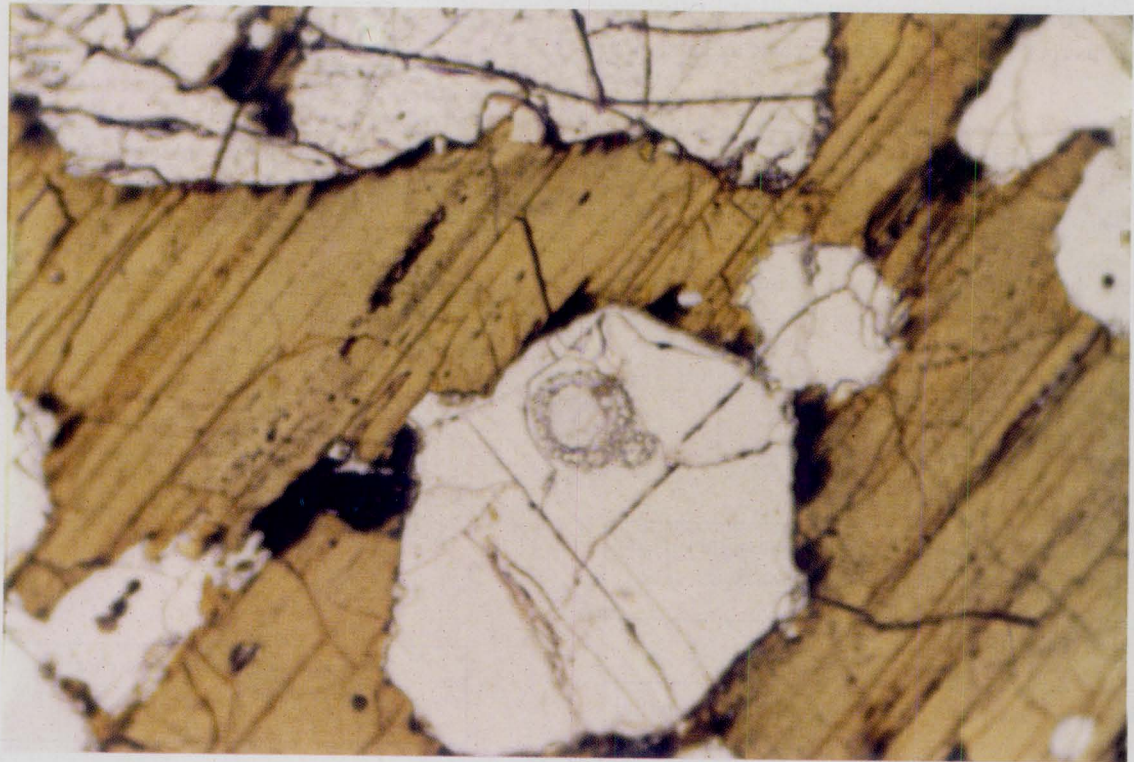
Figure 3. Photomicrographs of sample 12-19-18 displaying poikiloblastic texture of one euhedral plagioclase in a largegrain of amphibole. One round grain clinopyroxene which is surrounded by many tiny pyroxenes can be seen in this Figure.

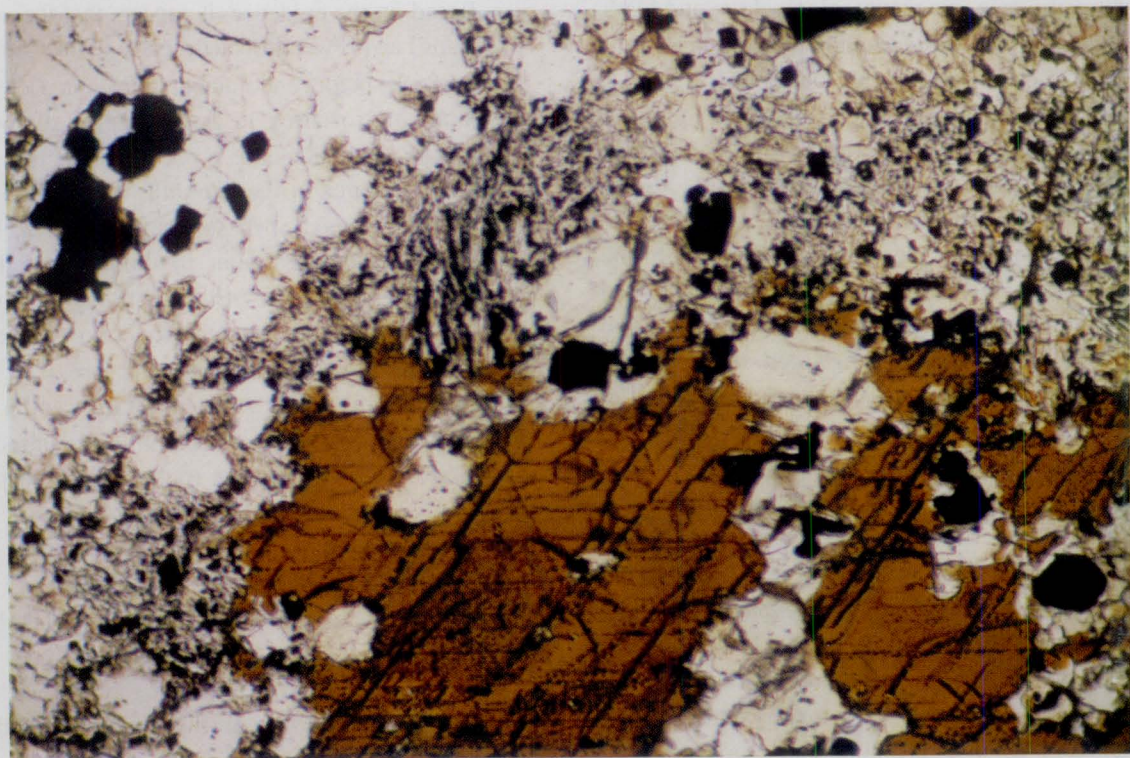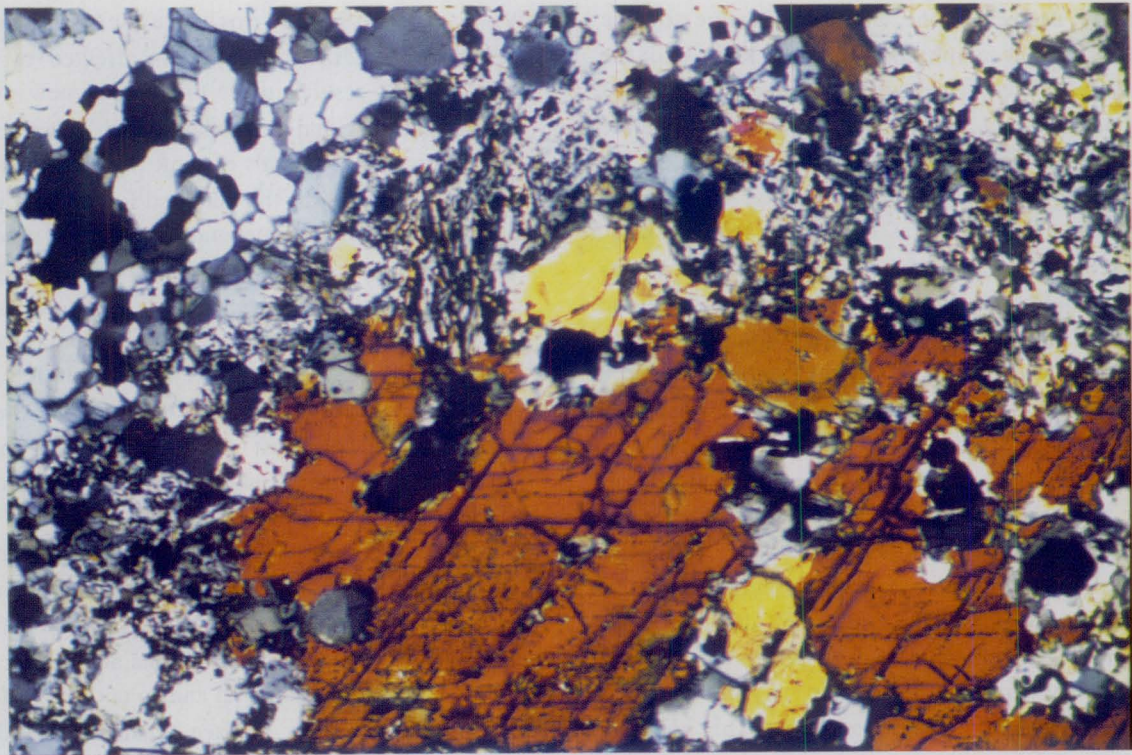A: Under plane polarized light. B: Under crossed nicols.

Figure 4. Photomicrographs of xenolith 12-20-2 _illustrating polygonal and symplectite textures. A: under plane polarized light, B: under crossed nicols.

At 917 degrees C, the minimum pressure for the stability field of amphibole is 12.5 kbar and the maximum estimated value is around 15 kbar (Fig.5). At this temperature and above 15 kbar pressure amphibole is no longer stable, but garnet (and/or olivine) enters. None of the xenoliths contain garnet or olivine, indicating that pressure was not higher than 15 kbar. Based on the minimum and maximum pressure that was obtained from Oba's diagram, it can be concluded that the xenoliths of group III originated at the minimum depth of around 37 to 45 km. The present estimate make the crust about 10 km thicker than the previous estimate for this area (Fig.6).

A lack of olivine and garnet in groups I and II can indicate that pressure and temperature for these two groups were not higher than those obtained for group III.

Group II xenoliths also contain amphibole showing symplectite texture. Xenoliths of group I do not contain amphibole. However, some of the pyroxene, magnetite, and plagioclase grains in this group may have formed from amphiboles which no longer exist. This idea has been confirmed from the xenoliths of group II. In the xenoliths of group II, amphibole grains have almost changed to pyroxene, magnetite, plagioclase, and glass. Still in this group, traces of amphibole that remain from partial melting can be seen giving symplectite texture to the xenoliths. In group III, the change of amphibole to the other minerals is in the early stage. The new minerals have formed within amphibole grains displaying poikiloblastic textures in these xenoliths.

Isotopic data indicate that the protolith rocks of the xenoliths of group III are amphibolite that segregated from Calbuco magma in the magma chamber. The amphibole have dehydrated during ascent to the surface by the host lava. In this group foliation is absent, but in groups I and II foliation is one of their characteristic features. Even though foliation occurs in different stages of development in these two groups, the differences among these xenoliths and group III are easily distinguishable. Foliation in groups I and II may have formed because of two metamorphic events. As shown in Table 5, the protolith rocks of the xenoliths originated from the mid-ocean basalts. These rocks have undergone a fist metamorphism and recrystallization at the subduction zone. Palaeozoic metamorphic rocks exposed at the Coastal Ranges are probably formed in this way. The foliation in these metamorphic rocks is defined by mica, chlorite, and other platy minerals.

When the foliated rocks undergo a second metamorphism, their foliation is affected by partial melting. This results in the creation of new minerals such as pyroxene and plagioclase which give the second orientation to the minerals of some xenoliths. It is noted that in some xenoliths the inherited foliation indicates a higher pressure during metamorphism at the subduction zone. Pyroxene and plagioclase grains that have crystallized during the ascent of xenoliths to the surface, as a result of amphibole dehydration, define foliation in some xenoliths (e.g. 32822F). This foliation follows the same orientation as foliation due to the first metamorphism in most of the xenoliths. In other xenoliths, foliation is found in domains and does not follow one specific direction (e.g. 12-19-14).

Granulite texture in the xenoliths groups I and II is formed due to contact metamorphism. In some samples, a few anhedral minerals are changing to form other minerals. These new minerals are mainly smaller in size and are subhedral or euhedral and do not show alteration or oxidation in their surface when seen under the microscope. In minerals however, alteration, oxidation, and melting occur frequently.

Based on the evidence, it appears that the xenoliths of groups I and II were foliated, coarse grained amphibole-bearing rocks before entrainment in magma. Dehydration of amphibole resulting in crystallization of pyroxene, plagioclase, and magnetite is one of the factors causing granulitic textures in the xenoliths of groups I and II. The protolith rocks for these xenoliths are likely to be metamorphic rocks, similar to those exposed in the Coastal Ranges. In Fig.4, these Palaeozoic metamorphic rocks are extended to the east in the deeper part of the continental crust and are overlain by Quaternary and Tertiary sediments at the Central Valley. Farther to the east, granitoid batholiths are intruded into the Palaeozoic metamorphic rocks and outcrop at the surface.

Conclusion

On the basis of petrology, microprobe, and chemical data it has been concluded that:

1. Group I and II xenoliths are gabbros on the P1-P x-Hb1 diagram, and they are hypersthene granulites on the ACF diagram. These xenoliths probably formed from altered-MORB-like basalts. Sample 12-19-5 of group II has different characteristics and is more similar to subduction-related basalts.
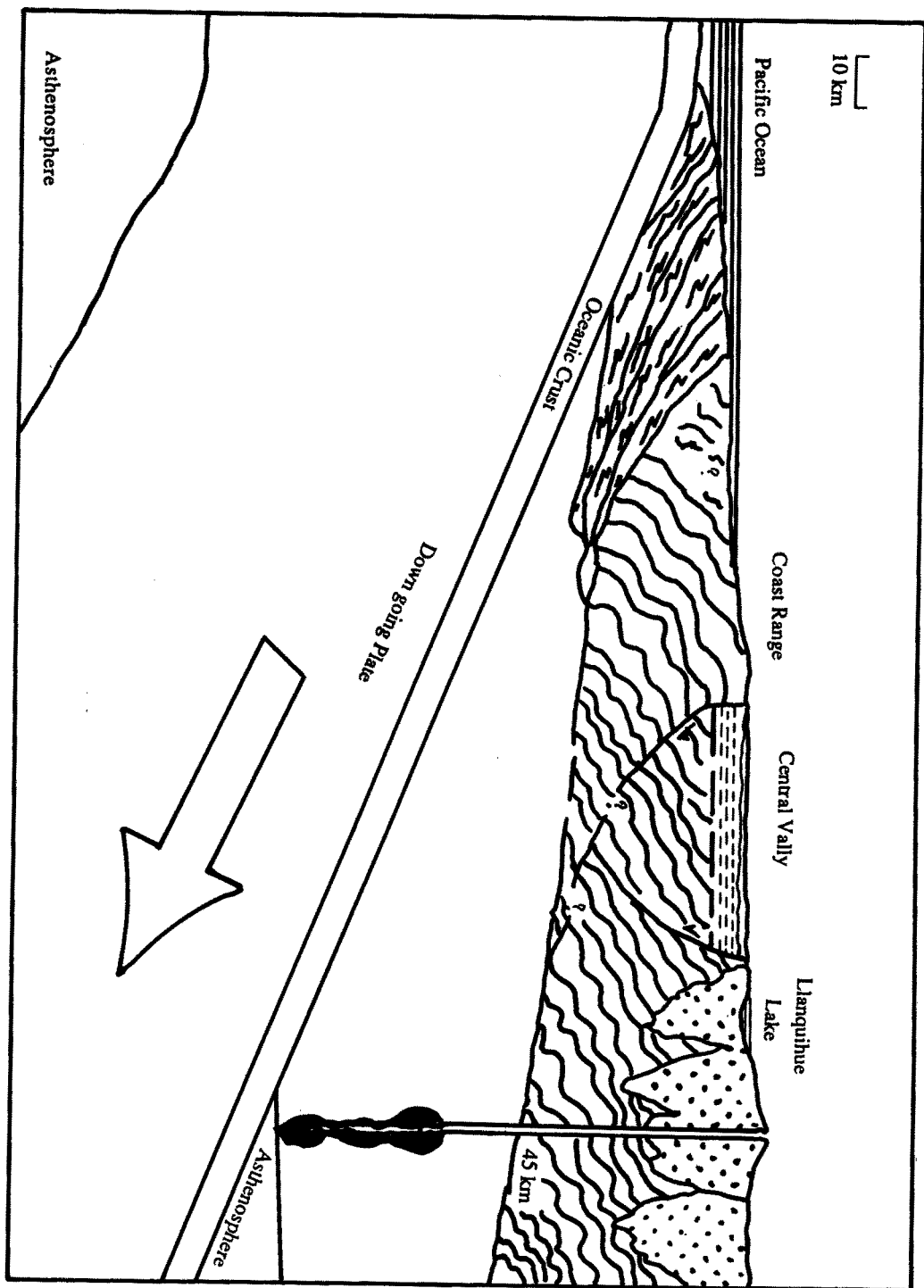
Figure 6, Cross-section of Chilean Southern Andes at latitude 41°20' showing Calbuco volcano and proposed structure of underlying rocks. In this Figure the top of the subducting oceanic plate is situated approximately 100 km beneath the Calbuco volcano.
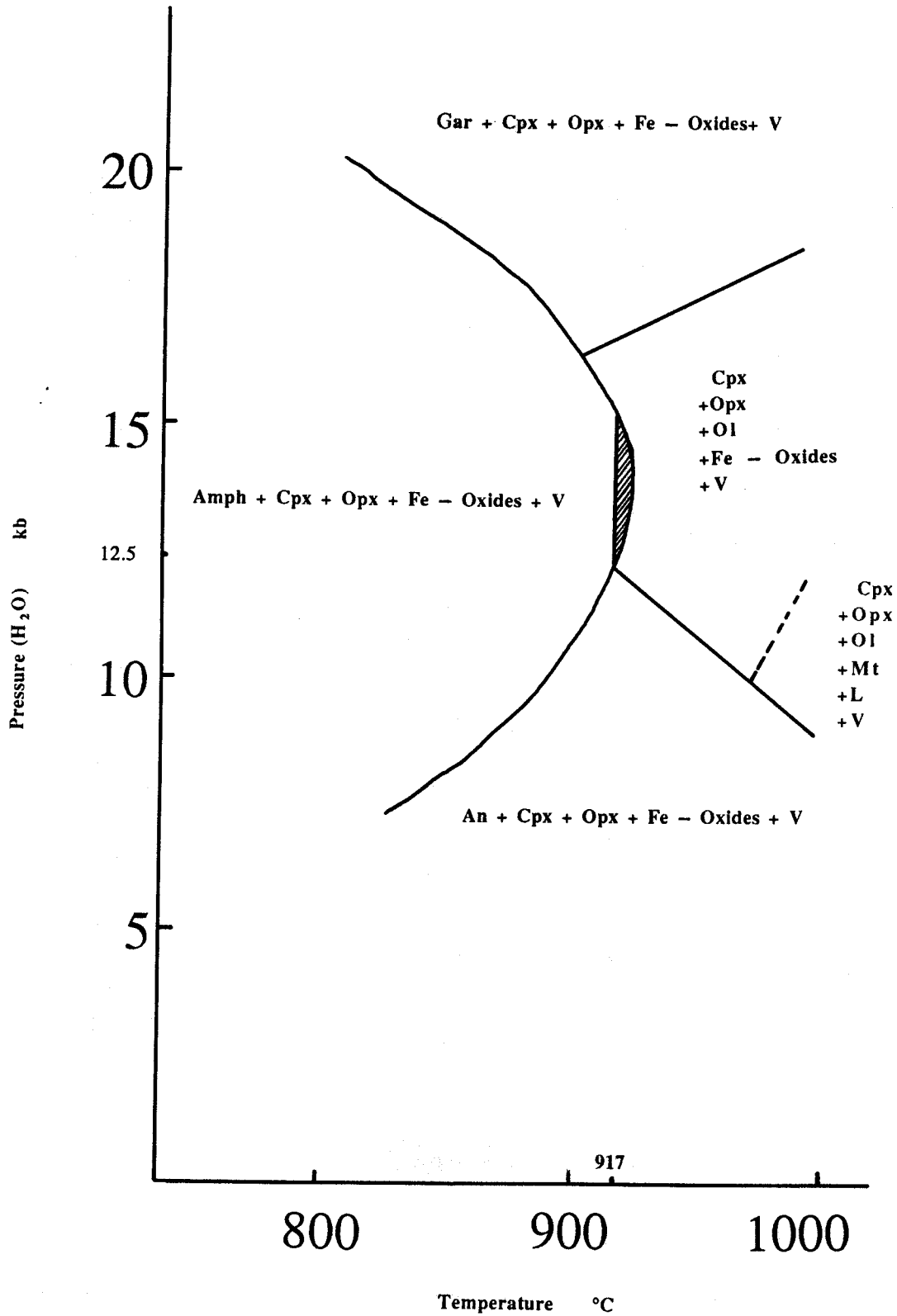
Figure 5.P-T synthesis diagram for ferritschermakite. Starting material was anorthite, clinopyroxene, orthopyroxene, and hematite (after Oba 1978).

2. Group III xenoliths are Px-Hbl-gabbronorite and gabbronorite. Based on the similarities between isotopic ratios of these xenoliths and Calbuco lavas and differences in their major and trace element abundances, it has been concluded that these xenoliths may be formed from the cumulate minerals that crystallized from the Calbuco magmas at depths.

3. Two metamorphic country rocks are Hbl-gabbro on the P1-Px-Hbl diagram, and they are amphibolite on the classification of Winkler (1979). These rocks may also have been cumulate rocks based on their high CaO and A1203 and low incompatible element abundances. The results show that the protolith rocks of these country rocks were not the same as xenolith protoliths.

4. A temperature of 917 degrees C obtained from pyroxenes in group III xenolith and the lack of garnet and olivine indicate a pressure 12.5-15 kbar for xenoliths of group III. The xenoliths originated at the depth of around 37 to 45 km. This depth is about 10 km. thicker than the previous estimate for the earth's crust for SVZ at this latitude. Groups I and II also originated at the same depth or less.

5. In groups I and II, foliation probably formed because of two metamorphic events: one at the subduction zone and another during dehydration in magma.

6. Palaeozoic metamorphic rocks exposed in the Coastal Ranges which have been interpreted as subduction accretionary complex, may extend to the east in the deeper part of the continental crust and be the source of group I and II xenoliths.

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