New geochemical constraints for the origin of ridge-subduction-related plutonic and volcanic suites from the Chile Triple Junction (Taitao Peninsula and Site 862, LEG ODP141 on the Taitao Ridge)

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Abstract

Several features of Neogene and Quaternary magmatism in the region south of the present-day Chile Triple Junction (CTJ) at 46°12'S are directly related to the migration of the triple junction. Due to the obliquity of the ridge orientation with respect to the subduction front, the triple junction migrated from South to North during the last 14 Ma. The Taitao Peninsula — the westernmost promontory of the Chile coast — and the Taitao Ridge — a submarine promontory north of the Taitao Peninsula — provide the most complete collection of ridge subduction-related magmatic products in the region. The emplacement of near-trench volcanics, the intrusion of a variety of plutonic rocks and the related hydrothermal activity at these two sites have been interpreted as resulting from magma interactions between subducted ridge segments of the Chile spreading centre and the continental crust. We present new field observations and geochemical data that help to better constrain the problem of the sources and evolution of the Taitao magmas. The new geochemical data were obtained on samples collected from the Taitao Peninsula during a field expedition in 1995, and from samples of the Taitao Ridge during Leg ODP141, Site 862, which have been re-sampled in 1996 by one of us. Selected major- and trace-element compositions of 20 volcanic rocks from the Taitao Ridge are discussed together with 53 analyses from different rock types from the Taitao Peninsula including 24 unpublished analyses. Nd and Sr isotopic compositions were obtained from 5 whole rocks and separated minerals of the Taitao Peninsula together with the oxygen isotope composition of four separated clinopyroxenes. Six main magmatic types are identified: (1) N-type MORB; (2) E-type MORB; (3) LREE-depleted MORB showing some trace-element features typical of arc basalts; (4) moderately Nb-depleted E-MORB; (5) calc-alkaline andesites, dacites and rhyolites; and (6) andesites and dacites with adakitic signature. Chemical similarities exist between some forearc magmas of the Taitao Ridge and the Taitao Peninsula and magmas emplaced at the Chile active spreading ridge. One important result, based on isotope data, is that the lavas emplaced over the continental crust (Taitao Peninsula) did not originate from melting of continental crust nor from extensive assimilation of such a crust by mantle-derived...
magmas. The likely source of these basalts could be the hot convective oceanic mantle of the southern Chile spreading ridge buried at moderate depth (10–30 km). © 1999 Elsevier Science B.V. All rights reserved.

Keywords: triple junction; ridge subduction; forearc magmatism; geochemistry

1. Introduction

The Chile Triple Junction, located at 46°12’S (CTJ; Fig. 1) is the site where the Antarctic, the Nazca and the South America plates meet; it is presently a ridge–trench–trench triple junction.

During the last ten years, investigations in the CTJ region have shown that subduction of the Chile ridge beneath the South American margin was coeval with the emplacement of magmatic suites and possibly with ophiolite obduction close to the trench axis. Young magmatic products with highly vari-
able chemical characteristics were described in this region, especially on the Taitao Peninsula, 50 km south of the present-day triple junction (Mpodozis et al., 1985; Bourgois et al., 1993; Le Moigne et al., 1996), and on the Taitao Ridge which protrudes into the trench, north of the Taitao Peninsula (Forsythe et al., 1995a). The chemical characteristics of plutonic and volcanic rocks from these two areas suggest that magmas originated either from mantle sources (Kaeding et al., 1990), from slab melting (Bourgois et al., 1996), or directly from the subducted spreading centre interacting with the overlying continental crust of the Chile margin (Lagabrielle et al., 1994).

In the vicinity of the triple junction, the southern Chile spreading ridge consists of three first-order segments (Fig. 1), 40–225 km long, separated by fracture zones (FZ), namely from north to south: the Guafo, Guamblin, Darwin and Taitao FZ. Lavas from the active ridge axis have heterogeneous compositions ranging from typical Mid-Ocean Ridge Basalts (MORB) to basalts and dacites with trace-element characteristics (e.g., high La/Nb or equivalent ratios) usually considered as typical of arc-related volcanics or continental crust. These compositions support the hypothesis of sub-ridge contamination associated with ridge subduction (Klein and Karsten, 1995).

Therefore, one of the basic problems of the CTJ region is to understand how the magmatism related to a currently subducting spreading ridge may interact with the continental crust of the upper plate. In this paper, we present new field observations and geochemical data which are used to better constrain this problem. The new geochemical data were obtained on samples collected in the Taitao Peninsula during a field expedition done by two of us (JB and YL) in 1995, and from the Taitao Ridge during Leg ODP141, Site 862 (Fig. 2), the cores of which have been re-sampled in 1996 by one of us (CG).

2. Regional setting and kinematics

North of the triple junction, the Nazca plate is currently subducting beneath the South America plate at a rate of 9 cm/yr, whereas to the South, the Antarctica plate is being subducted at a rate of only 2 cm/yr (Cande et al., 1987). Segment 1 of the southern Chile ridge (Fig. 1), located between the Taitao and the Darwin fracture zones, entered the trench ca. 0.3 Ma ago. Previously, two short ridge segments were subducted after 6 Ma and 3 Ma, respectively: one between the Esmeralda and the Tres Montes fracture zones and the second one between the Tres Montes and the Taitao fracture zones, west of the Taitao Peninsula.

The Chile Triple Junction has migrated rapidly northwards during subduction of ridge segments for the past 14 Ma. It is now located beneath the northern part of the volcanic gap that exists between the southermmost volcano of the Southern South Volcanic Zone (SSVZ, Mount Hudson at latitude 46°00'S) and the northernmost volcano of the Austral Volcanic Zone (AVZ, Mount Lautaro at latitude 49°00'S) (Fig. 1). Between 42°S and 46°S, the SSVZ is characterized by basalts and basaltic andesites with typical calc-alkaline affinities. South of the volcanic gap, the five active stratovolcanoes of the AVZ (Lautaro, Viedma, Aguilera, Burney and Cook) have a spacing of 100 to 170 km. These magmas display adakitic (slab melt) signatures (Stern and Kilian, 1996; Sigmarsson et al., 1998).

The geometry of the slab beneath the Taitao Peninsula is poorly known because of the lack of seismicity, but its dip is estimated to be ca. 15° (Bangs et al., 1992). The continental crust thickness is ca. 30 km (Cande and Leslie, 1986).

3. Regional geology and previous geochemical data on young volcanic–plutonic suites in the CTJ area

3.1. The Taitao Peninsula: geological units and previous geochemical results

Numerous geological, radiometric and geochemical data have been collected on the magmatic suites and related rocks exposed on the Taitao Peninsula (Mpodozis et al., 1985; Forsythe et al., 1986; Kaeding et al., 1990; Lagabrielle et al., 1994; Le Moigne et al., 1996; Bourgois et al., 1996). Two field investigations conducted in 1992 and 1995 (Fig. 3a) allowed us to produce an updated geological map (Fig. 3b).

Five main rock units have been recognized (Fig. 3b): (1) the Bahia Barrientos ophiolite; (2) a late Cenozoic volcano–sedimentary sequence of
Fig. 2. Detailed bathymetric map of the CTJ area (250 m contour interval) showing segment 1 of the active Chile spreading ridge currently being subducted, the Taitao Ridge and the locations of ODP Leg 141 borehole site 862 and the Taitao Peninsula. BBO: Bahía Barrientos Ophiolite, GP: Golfo de Penas.
the Chile Margin Unit (CMU) and the Main Volcanic Unit (MVU); (3) the Bimodal Dike Complex (BDC); (4) the Taitao plutonic intrusions; and (5) the Pliocene volcanoes.

3.1.1. The Bahia Barrientos ophiolite

The Bahia Barrientos ophiolite (Bourgois et al., 1993) includes mantle peridotites, gabbros and doleritic dikes. The gabbros are Light Rare Earth Element (LREE)-depleted and, according to Le Moigne et al. (1996), the peridotites and gabbros show petrological, geochemical and mineralogical characteristics consistent with an oceanic origin. Pieces of the ophiolitic complex are also found as xenoliths of various sizes (10 to 100 m) in the later intrusions. Gabbric and doleritic lenses are found within the Seno Hoppner pluton. Doleritic xenoliths are found in granodiorite magmatic breccias exposed along the western coast of the Tres Montes Peninsula. Several pluriometric fragments of gabbro and dolerite occur within the acidic dike complex exposed in the central part of the Taitao Peninsula (Fig. 3b). Con
dent geochronological dating of the ophiolitic rocks is not available yet; K/Ar ages of about 13 and 6 Ma have been obtained on a hornblende vein and a doleritic dike, respectively (Bourgois et al., 1992, 1993; Le Moigne, 1994). Therefore, the timing of obduction and the processes that led to ophiolite emplacement are still under debate. There is no clear evidence for an emplacement linked to recent obduction of the Nazca or the Antarctic oceanic lithosphere due to triple junction tectonics, but, in turn, there are no arguments for an age clearly older than that of the triple junction migration.

3.1.2. The volcano–sedimentary units (CMU–MVU)

The Pliocene Chile Margin Unit (CMU) (Fig. 3b), 4–6 km thick, consists of interbedded sedimentary and volcanic material deposited in a shallow-water environment. It unconformably overlies the pre-Jurassic metamorphic basement of the Chile margin. The Main Volcanic Unit (MVU) consists of pillow-lavas and associated sediments that also accumulated in shallow water environments. It differs from the CMU by a well developed green schist metamorphic overprint, a lack of evolved lavas such as rhyolites, a greater amount of intermediate lavas and a lack of pyroclastic deposits. MVU and CMU lava flows show a large range of compositions including Normal-MORB (N-MORB), Enriched-MORB (E-MORB), and calc-alkaline lavas. The abundance of pyroclastic material in CMU and the evidence for deposition in subaerial to shallow water conditions in the MVU and CMU demonstrate that these units do not belong to a recently obducted deep-oceanic section created at the Chile spreading ridge (Le Moigne et al., 1996). According to Lagabrielle et al. (1994), the MVU and CMU volcanic rocks were emplaced in or close to their present-day location by MORB-derived magmas erupting through the Chilean continental basement. Thus, the lavas likely originated from the buried active spreading centre as it was subducted at shallow depth. The variety of chemical compositions of the magmas have been interpreted as the results of various degrees of upper crustal contamination coupled with fractional crystallization (AFC) during their ascent and possible storage within the Chilean continental crust (Lagabrielle et al., 1994).

3.1.3. The Bimodal Dike Complex (BDC)

Nelson et al. (1993) mentioned that a central sheeted dike unit is exposed within the ophiolitic plutonic suite, in the centre of the peninsula and along the western shore. They also mapped a ‘central’ pluton near the centre of the sheeted dike unit. This is confirmed by our own field observations and helicopter sampling conducted in 1995 (Guivel et al., 1996). Basaltic dikes are spatially associated with dacitic to rhyolitic intrusive rocks and volcanic breccias exposed near the central pluton (Fig. 3b). Genetic relationships between the basaltic and acidic dikes are not always clear, but locally, silicic sheeted dikes intrude gabbros and green schist facies dolerites, which are probably part of a former ophiolitic dike complex (Guivel et al., 1996). For this reason, the sheeted dike unit is referred hereafter to as the Bimodal Dike Complex. The basic dikes show both diabasic and porphyritic textures. They are fine- to medium-grained rocks showing evidence of green schist-facies metamorphism (saussuritized plagioclase and uralitized pyroxene). The lavas contain secondary chlorite, amphibole and quartz. Their SiO2 contents vary from 50.8 to 53.8 wt%. These dikes show E-MORB affinities. Silicic dikes intruding the ophiolitic dolerites are amphibole-bearing dacites and rhyolites with SiO2 contents varying
from 65.8 to 76 wt%. Dacites contain dominant subhedral phenocrysts of plagioclase together with clinopyroxene phenocrysts replaced by chlorite, amphiboles and ilmenite; apatite is present as accessory mineral. The groundmass mainly consists of plagioclase grains. Rhyolites contain quartz and plagioclase phenocrysts, and epidotes and chlorite replace primary Fe–Mg minerals. Radiometric ages are lacking for these rocks. There are no intermediate compositions between the two groups of dykes (basaltic and silicic) which display different rare earth element (REE) patterns. In addition, polymict volcanic breccias with glassy rhyolitic matrix are exposed in the central part of the dike complex, at the site where Nelson et al. (1993) described the central pluton. Likely, these breccias were subsequently emplaced above previously eroded basaltic and acidic dikes. They include angular fragments of granite and subordinate coarse-grained ophiolitic dolerites.

3.1.4. The Taitao plutons

The Taitao Peninsula includes six plutons labelled P1 to P6 hereafter. The two largest and best studied are the Cabo Raper (P1) and the Seno Hoppner (P2) plutons.

The Cabo Raper pluton (P1), located only 17 km east of the trench axis, is a biotite–hornblende-bearing granodiorite or tonalite (Fig. 4). New $^{40}$Ar/$^{39}$Ar data obtained recently by one of us (NA; see Arnaud et al., 1993, for analytical conditions) on separated biotite from two samples, yielded ages of 5.1 ± 0.6 and 4.8 ± 0.3 Ma, in contrast with previous data from
Mpodozis et al. (1985) which gave younger K/Ar ages (3.6 ± 0.6 and 3.3 ± 0.3 Ma on biotite). The Cabo Raper and Tres Montes plutons have chemical characteristics similar to those of the adakitic or trondhjemite–tonalite–dacite suites (Bourgois et al., 1996) which are believed to derive from partial melting of metabasalts under amphibolite–eclogite transition conditions (Defant and Drummond, 1990; Drummond and Defant, 1990; Kay et al., 1993; Martin, 1993).

The Seno Hoppner pluton (P2) is a fine- to medium-grained biotite and hornblende-bearing granite with SiO₂ contents ranging from 68 to 75 wt%. Its composition is granitic to trondhjemitic (Fig. 4) and unlike the Cabo Raper pluton, it displays characteristics of typical calc-alkaline series. New ⁴⁰Ar/³⁹Ar ages obtained from biotite and feldspar by one of us (NA) are 5.9 ± 0.5 Ma and 6.9 ± 1 Ma, respectively, and are consistent with previous K/Ar ages from Mpodozis et al. (1985) (5.5 ± 0.4 and 5.2 ± 0.3 Ma on biotite).

The remaining plutons are smaller or have been poorly explored. The Bahia Barrientos pluton (P3) has been described in Mpodozis et al. (1985) and the Estero Cono pluton (P4) in Nelson et al. (1993). The Tres Montes pluton (P5) has been sampled during our field expedition in 1995. It shows tonalitic to granodioritic compositions (Fig. 4). Along the seashore, north of Cabo Helena (Fig. 3b), this pluton consists of magmatic breccias, showing evidence of hydraulic fracturing, and locally includes clasts of greenschist facies dolerites. Granite fragments (P6) observed within the rhyolite breccias associated with the bimodal dike complex as well as the cen-
The Taitao Ridge

The Taitao Ridge is located immediately south of the Chile Triple Junction at the boundary between two segments of the active margin that exhibit strong differences in their tectonic regime: a linear trench to the North, suggesting active subduction-erosion, and a wider forearc domain to the South with development of an accretionary prism (Behrmann et al., 1994; Bourgois et al., 1997). The Taitao Ridge has been defined as an anomalous bathymetric ridge in the trench region (Fig. 2). According to Behrmann et al. (1994), the volcanic pile of the Taitao Ridge was probably formed at a ridge-transform intersection and represents a possible candidate to become an ophiolite body emplaced into the South American forearc. However, a recent bathymetry and geophysical survey of the triple junction region in 1997 by R/V L’Atalante has revealed that the basement of the Taitao Ridge is not only volcanic but also con-
sists of tectonic units made up of continent-derived sediments (Bourgois et al., 1997).

At ODP Site 862, the Taitao Ridge crest is composed of a 20-m-thick sedimentary layer overlying mafic and silicic volcanic rocks (Fig. 5). The volcanic rocks have been drilled down to 42.9 m at hole 862B and 102.1 m at hole 862C. The sediments and sedimentary rocks are composed of silty clay to clayey silt and fine silty sand. Microfossils recovered from the sediments indicate a Late Pliocene age consistent with $^{40}$Ar/$^{39}$Ar ages of 1.54 ± 0.08 and 2.2 ± 0.4 Ma obtained on hornblende separated from the rhyolitic samples (Forsythe et al., 1995b).

The cores contain sedimentary rocks in depositional contact with the glassy rims of pillow basalts flows. Volcanogenic material within the cores is found as isolated clasts or glass shards within the sediments, which is consistent with a Late Pliocene magmatic activity (Forsythe et al., 1995a).

The underlying volcanic units are bimodal and consist of an alternation of plagioclase–clinopyroxene–olivine phric basalts and plagioclase–hornblende phric dacites/rhyolites (Fig. 5) among which Forsythe et al. (1995a) have distinguished three main groups: two groups of basalts (Group 1 and Group 2) and one group of dacites/rhyolites. Group 1 basalts differs from Group 2 by having lower SiO$_2$, Na$_2$O and K$_2$O with higher FeO*, MgO and CaO, and lower Sr and Ba contents. The REE patterns of Group 1 basalts are characterized by strong LREE depletion, whereas Group 2 basalts exhibit LREE-enriched patterns. The Sr–Nd isotopic composition of one Group 1 basalt is similar to those of common MORB but its $^{207}$Pb/$^{204}$Pb ratio is higher. Group 2 basalts have distinctly different Sr–Nd compositions ($^{87}$Sr/$^{86}$Sr = 0.7033, $e_{Nd} = +8.0$). Group 2 basalts, and rhyolites, have similar Pb isotopic ratios, which are higher in $^{207}$Pb/$^{204}$Pb and $^{208}$Pb/$^{204}$Pb than the Northern Hemisphere Reference Line or the Nazca Plate Basalts.

Distinct sources are required to account for the differences in major, trace elements and isotopic compositions of Group 1 and Group 2 basalts. Group 1 basalts most resemble N-type MORB in their major, trace elements and isotopic geochemistry, except for their Rb enrichment, high Pb contents and isotopic ratios which are consistent with small amounts of subducted sediments in their source. Group 2 basalts are calc-alkaline with higher K$_2$O, incompatible trace-element contents and LREE-enrichments. Their Nb depletion and low Ce/Pb and K/Pb ratios are consistent with a subducted-sediment component in their mantle source. The available data suggest that there is a continuum from N-type MORB to arc basalts among the samples recovered from the Taitao Ridge.

Rhyolites and dacites are presumably melts of metamafic sources. Trace-element patterns and Pb isotopic compositions indicate that their sources were chemically similar to those of the Group 2 calc-alkaline basalts. The higher $^{87}$Sr/$^{86}$Sr ratios of the rhyolites might result from incorporation of seawater-derived fluids in these sources (Forsythe et al., 1995a).

4. A summary of geochemical data from the southern Chile spreading ridge

Samples have been collected from four ridge segments (segment 4 to segment 1, from N to S) of the southern Chile ridge between the Chiloé F. Z. and the Chile Margin Triple Junction including the segment currently being subducted at the Chile Trench (segment 1) (Klein and Karsten, 1995). Their analysis reveals that the sub-ridge mantle appears to be highly heterogeneous at the scale of each of these segments as evidenced by the occurrence of N-MORB and two types of E-MORB. Segment 4 lavas have many trace-element similarities with E-MORB and ocean island basalt (OIB). Segments 1 and 3 show trace-element patterns rather similar to those of convergent margin magmas (Klein and Karsten, 1995).

The most enriched samples from segments 1 and 3 are similar to arc lavas regarding their high abundances in the most incompatible trace elements, their enrichment in Pb (relative to Ce and Sr) and their depletion in Nb and Ta (relative to U and K), although all segment 1 samples are LREE-depleted. In contrast, enriched samples from segment 4 display little or no depletion in Nb and Ta and exhibit enrichments that are often regarded as typical of OIB.

The corresponding trace-element variations have been modeled by bulk mixing of a depleted MORB source mantle with a mantle contaminated by various amounts of oceanic sediments and altered oceanic crust or melts/fluids derived therefrom (Klein and Karsten, 1995). To explain the presence of the sub-
ducted component contaminant beneath the ridge axis, Klein and Karsten (1995) propose two different models: (a) slab fragments reintroduced by the shallow asthenospheric flow and entrained in the upwelling and melting regime beneath the ridge due to slab breaking, or (b) the presence of a slab window providing a major connection between the metasomatized sub-arc mantle and the adjacent sub-oceanic mantle.

5. New geochemical data on young volcanic suites from Taitao Ridge and Taitao Peninsula

5.1. Sampling and analytical methods

5.1.1. Major- and trace-element data

New major- and trace-element whole-rock analyses of 24 magmatic rocks from the Taitao Peninsula (field expedition Taitao 1995) and 20 volcanic rocks
from the Taitao Ridge (Site 862, Leg ODP 141) have been performed for this study. They are presented here together with 29 analyses from the Taitao Peninsula previously published by Le Moigne (1994).

Whole-rock analyses (major, trace and rare earth elements) were obtained by inductively coupled plasma-atomic emission spectrometry (except Rb which was obtained by atomic absorption spectroscopy). Calibrations were made using our own standards and controlled with international reference samples: PM-S; WS-E; BE-N; AC-E; JB-2 and SY-4 (Université de Bretagne Occidentale). Relative standard deviation for major elements is 2% except for MnO and P₂O₅. That for trace elements is 5%.

Analysed samples include 2 greenschist facies dolerites from the Bahia Barrientos ophiolite, 12 dolerites and 6 dacites and rhyolites from the Bimodal Dike Complex, and 2 fresh basalts and 2 rhyolites from the CMU. The 20 analysed rocks of the Taitao Ridge drill hole include 8 samples from ODP hole 862B and 12 from hole ODP 862C. Selected geochemical analyses are listed in Tables 1 and 2, with detection limits for the trace elements. Site locations are shown in Fig. 3a.

5.1.2. Strontium, neodymium and oxygen isotopic data on Taitao Peninsula samples

New analyses were conducted on both whole rocks and separated clinopyroxenes, to avoid the effects of alteration on the isotopic data. Clinopyroxenes were separated by rock crushing followed by heavy liquid separation and finally handpicking.

Nd and Sr compositions have been obtained from one gabbro of the Bahia Barrientos ophiolite (TA65), one ophitic dolerite, one dacite and one rhyolite of the Bimodal Dike Complex, and 2 fresh basalts and 2 rhyolites from the CMU. The 20 analysed rocks of the Taitao Ridge drill hole include 8 samples from ODP hole 862B and 12 from hole ODP 862C. Selected geochemical analyses are listed in Tables 1 and 2, with detection limits for the trace elements. Site locations are shown in Fig. 3a.

5.2. Rock classification and geochemical characteristics

5.2.1. Major- and trace-element geochemistry

Taitao Ridge and Peninsula lavas display in the alkali–silica diagram (Fig. 6a) a wide compositional range from basalts to intermediate and acidic lavas with SiO₂ contents ranging from 47 to 72.5%. This diagram also shows the wide range of variation of alkalis (up to 8%) in the basaltic lavas of the Taitao Peninsula, reflecting their high degree of alteration or metamorphism. In an AFM triangle (Fig. 6b) most of the lavas emplaced at the Chile Triple Junction area plot within the calc-alkaline trend rather than within the tholeiitic one.

In the Harker diagrams shown in Fig. 7a, most major elements are negatively correlated with SiO₂ (MgO, Fe₂O₃, CaO and TiO₂) except for Na₂O and K₂O. Cr and Ni decrease from near primitive contents to very low concentrations in the most evolved lavas (Fig. 7b). But differences at equivalent SiO₂ contents are observed among the basalts. The Taitao Ridge basalts have higher Ni contents than basalts from the Taitao Peninsula consistent with the occurrence of olivine crystals in the former.

The rock classification used in this study is not based on major-element variations as the rocks have suffered various degrees of alteration especially on the Taitao Peninsula. The magma types shown in Table 4 are distinguished using some key trace-element ratios [(La/Nb)N, (La/Yb)N and (Sr/Y)] and multi-element patterns of incompatible trace elements normalized to N-MORB (Sun and McDonough, 1989).

When considering the available whole-rock analyses on both the volcanic and plutonic rocks found on the Taitao Ridge and on the Taitao Peninsula, six main magma types can be recognized. They include four types of basalts and two types of intermediate to evolved lavas and their plutonic equivalents: (Type 1) N-type MORB; (Type 2) E-type MORB;
### Table 1
Selected whole-rock analyses of Taitao Peninsula Bimodal Dike Complex magmatic rocks

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<td><strong>P₂O₅</strong></td>
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<td>58.95</td>
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<td>99.68</td>
<td>99.90</td>
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<tr>
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<td>63.55</td>
<td>53.96</td>
<td>53.09</td>
<td>53.09</td>
<td>58.95</td>
<td>56.37</td>
<td>56.74</td>
<td>51.36</td>
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</tbody>
</table>

* Sampling sites are shown in Fig. 3.

b | Major elements in wt%, Fe₂O₃ as total iron. Trace elements in ppm. ICP-AES analyses: J. Cotten, Brest (France). Analytical methods discussed in the text.

Mg# = 100(Mg/Mg + Fe²⁺).

(La/Nb)N: chondrite-normalization from Sun and McDonough (1989).

---

(Type 3) LREE-depleted N-MORB with trace element characteristics of arc basalts; (Type 4) Nb-depleted E-MORB; (Type 5) calc-alkaline andesites, dacites and rhyolites; and (Type 6) andesites and dacites with adakitic affinities. The spatial distribution of these types throughout the Taitao Ridge, the Taitao Peninsula and the southern Chile ridge is presented in Table 4.

5.2.2. Basalts

The distinctions among the basalt types are based on their chondrite-normalized (La/Nb)N and...
Table 2
Selected whole-rock analyses of Taitao Ridge lavas, Leg ODP141, Site 862

<table>
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<tr>
<th>Sample: Detection limit</th>
<th>B1W01-1</th>
<th>B2XCC-1</th>
<th>B3X01-5</th>
<th>B4X01-4</th>
<th>B4X01-7</th>
<th>C1W01-3</th>
<th>C3R01-2</th>
<th>C5R01-2</th>
<th>C6R01-9</th>
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<td>Interval (cm)</td>
<td>1-5</td>
<td>33-38</td>
<td>28-35</td>
<td>28-41</td>
<td>60-66</td>
<td>41-46</td>
<td>9-13</td>
<td>10-18</td>
<td>61-69</td>
</tr>
<tr>
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<td>Taitao</td>
<td>Taitao</td>
<td>Taitao</td>
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<td>Taitao</td>
<td>Taitao</td>
<td>Taitao</td>
</tr>
<tr>
<td>Nature: Nature:</td>
<td>rhyolite</td>
<td>basalt</td>
<td>basalt</td>
<td>basalt</td>
<td>basalt</td>
<td>basalt</td>
<td>dacite</td>
<td>basalt</td>
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<tr>
<td>SiO₂</td>
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<td>51.20</td>
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<td>68.90</td>
<td>51.90</td>
<td>64.90</td>
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<td>17.70</td>
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<td>16.50</td>
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<td>Fe₂O₃</td>
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<td>8.22</td>
<td>8.12</td>
<td>2.76</td>
<td>6.92</td>
<td>3.89</td>
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<td>2.00</td>
<td>10.24</td>
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<td>2.89</td>
<td>2.93</td>
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<td>0.09</td>
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<td>0.14</td>
<td>0.09</td>
<td>0.12</td>
<td>0.13</td>
<td>0.11</td>
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<td>L.O.I.</td>
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<td>3.41</td>
<td>1.09</td>
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</tr>
<tr>
<td>Sum</td>
<td>100.12</td>
<td>99.71</td>
<td>100.15</td>
<td>99.90</td>
<td>99.56</td>
<td>99.67</td>
<td>99.52</td>
<td>99.51</td>
<td>99.57</td>
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<tr>
<td>Mg#</td>
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<td>69.28</td>
<td>69.52</td>
<td>68.91</td>
<td>69.11</td>
<td>65.88</td>
<td>69.65</td>
<td>72.62</td>
</tr>
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</table>

a Major elements in wt%, Fe₂O₃ as total iron. Trace elements in ppm. ICP-AES analyses: J. Cotten, Brest (France). Analytical methods discussed in the text.

(Mg/Nb)₀ = 100(Mg/Mg + Fe²⁺). (La/Nb)₀ chondrite-normalization from Sun and McDonough (1989).

(La/Yb)₀ ratios (Fig. 8). Magmas of Type 1 and 3 are N-type MORBs with respect to their LREE depletion [(La/Yb)₀ < 1; Fig. 8]. Type 2 and 4 are E-type MORBs which display enriched light rare earth elements patterns (Fig. 9) with (La/Yb)₀ ratios ranging from 1.3 to 3.4 (Fig. 8).

5.2.3. Type 1 and Type 3 basalts
Type 1 and Type 3 basalts can be distinguished one from another using the spidergram pattern of the incompatible trace elements normalized to N-MORB. Compared to Type 1, Type 3 N-MORB show enrichments in large ion lithophile elements...
Table 3
Isotopic and chemical data for Taitao Peninsula magmatic rocks

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO$_2$ (wt%)</th>
<th>LOI (wt%)</th>
<th>K$_2$O (wt%)</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
<th>$^{143}$Nd/$^{144}$Nd</th>
<th>$\varepsilon_{Nd}$ (‰ vs. V-SMOW)</th>
<th>$\delta^{18}$O (‰ vs. V-SMOW)</th>
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<tbody>
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<td>CMU</td>
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</tr>
<tr>
<td>T18a</td>
<td>64.25</td>
<td>1.5</td>
<td>1.28</td>
<td>0.704390 ± 11</td>
<td>0.512793 ± 5</td>
<td>+3.02</td>
<td>+6.06 ± 0.06</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>0.704039 ± 15</td>
<td>0.512839 ± 5</td>
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<td>+6.36</td>
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<td>1.57</td>
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<td>+5.9 ± 0.07</td>
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<td></td>
<td>0.704394 ± 14</td>
<td>0.512889 ± 8</td>
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<tr>
<td>TA55</td>
<td>48.6</td>
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<td>+5.9 ± 0.26</td>
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<td></td>
<td>0.704303 ± 17</td>
<td>0.513017 ± 10</td>
<td>+7.39</td>
<td>+6.2</td>
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<tr>
<td>TA65</td>
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<td>0.01</td>
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<td>+6.29</td>
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<td></td>
<td>0.702650 ± 10</td>
<td>0.513151 ± 34</td>
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<td>0.512801 ± 5</td>
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<td>0.512686 ± 7</td>
<td>+0.93</td>
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</table>

WR: whole rocks; Cpx: separated clinopyroxenes; and magma: $\delta^{18}$O-magmatic values obtained from $\delta^{18}$O-clinopyroxenes +0.03‰ (Sheppard and Harris, 1985).

(Type 1) basalts are found in the Taitao Peninsula, mainly in the Bahia Barrientos ophiolite. These basalts display LILE variations as illustrated by their K/Ti ratios, ranging from 0.03 in a dolerite from the Bahia Barrientos ophiolite to 0.6. However, due to the LILE mobility during alteration and metamorphism, these features may be secondary. Type 3 magmas are N-MORB with selective trace element enrichments usually interpreted as tracing a continental and/or subduction-related component. They are found in the Taitao Ridge (Group 1 basalts of Forsythe et al., 1995a). Uncommon N-type MORB found on the Taitao Peninsula display similar patterns (Fig. 9), together with rather variable Sr and P contents.

5.2.4. Type 2 and Type 4 basalts

Distinction between Type 2 and 4 is based on the ratios between LILE and HFSE, especially the behaviour of Nb compared to La. Type 2 basalts show (La/Nb)$_N$ ratios lower than 1.2, whereas Type 4 basalts display (La/Nb)$_N$ ratios ranging from 1.2 to 2.35 (Fig. 8). These ratios emphasize the HFSE depletion of Type 4 magmas relative to LILE and LREE, which is a characteristic feature of arc magmas. Type 2 is unknown in the Taitao Ridge but we found some E-MORB in the Taitao Peninsula in CMU and MVU. Some of the greenschist facies dolerites of the BDC may also be classified as Type 2. In Fig. 9, they display REE-enriched but Nb- and K-depleted patterns possibly due to alteration or metamorphism. In the AFM plot (Fig. 6b) they define a tholeiitic trend with Fe and Ti enrichment in the early stages of crystallization. They also have the highest Nb and Yb contents (Fig. 7b) of our set, and, compared to other magma types, rather constant trace element ratios, e.g. (La/Nb)$_N$ (Fig. 8). Type 4 magmas are enriched mid-ocean-ridge basalts with trace element features usually considered as typical of subduction-related magmas. This type is typical of most basalts drilled on the Taitao Ridge and is equiv-
Fig. 6. (a) TAS diagram (Le Maitre, 1989) Na$_2$O + K$_2$O (wt%) vs. SiO$_2$ (wt%) from the Taitao Peninsula, Taitao Ridge and Southern Chile Ridge (SCR). Our new data for the Taitao Peninsula and the Taitao Ridge are compared with Taitao Peninsula data published by Le Moigne (1994). Southern Chile ridge data are from Klein and Karsten (1995). Symbols as in Table 4. (b) AFM diagram showing the boundary between the calc-alkaline field and the tholeiitic field after Irvine and Baragar (1971); FeO$^*$ calculated assuming Fe$_2$O$_3$ = 0.9 FeO$^*$. 
Fig. 7. Harker diagrams showing (a) major, and (b) trace element variations of magmatic rocks from the Taitao Peninsula, Taitao Ridge and Southern Chile ridge (shaded field). Data sources as in Fig. 6. We convert FeO* of the Southern Chile ridge basalts (Klein and Karsten, 1995) assuming $\text{Fe}_2\text{O}_3 = 0.9 \text{ FeO}^*$. 
Fig. 7 (continued).
Table 4
Magma types and their geographic distribution

<table>
<thead>
<tr>
<th>Table 4 Magma types and their geographic distribution</th>
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</thead>
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<td><strong>Southern Chile Ridge</strong></td>
</tr>
<tr>
<td>Seg. 1</td>
</tr>
<tr>
<td>N-type MORB</td>
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<td>E-type MORB</td>
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<tr>
<td>N-type MORB</td>
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<tr>
<td>E-type MORB</td>
</tr>
<tr>
<td>Intermediate to evolved lavas</td>
</tr>
<tr>
<td>Subduction imprint</td>
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</tbody>
</table>

*This distribution is based on our new data from the Taitao Peninsula and the Taitao Ridge, on the Taitao Peninsula data published by Le Moigne (1994) and on the Southern Chile ridge data published by Klein and Karsten (1995). Symbols as in Figs. 6–8 and 11.

alent to the Group 2 of Forsythe et al. (1995a). On the Taitao Peninsula, they occur in the CMU, MVU and BDC. In the N-MORB-normalized plot, they display LILE and LREE enrichments (Fig. 9) and clear negative Nb anomalies relative to neighbouring incompatible elements.

Fig. 8. (La/Yb)N vs. (La/Nb)N showing the differences between three types of basalts. Chondrite-normalization values are from Sun and McDonough (1989).
Fig. 9. Multi-element plots of the Taitao Ridge and Taitao Peninsula basaltic lavas normalized to the N-MORB of Sun and McDonough (1989). Trace-element patterns of the basalts from the Southern Chile ridge (Klein and Karsten, 1995) are shown for comparison (bold-face curves).
5.2.5. Evolved lavas: Type 5 and Type 6

All of the intermediate and evolved lavas (SiO$_2$ > 53\%) show chemical characteristics of arc magmas, i.e. depletion in HFSE relative to LILE and LREE (Fig. 10). They have low TiO$_2$ contents (<1\%) and high LILE/HFSE and HREE/HFSE ratios compared with other mantle-derived magmas. Their N-MORB-normalized trace-element plots display Nb and Ti negative anomalies with respect to adjacent elements (Fig. 10). Fig. 11 is a Sr/Y vs. Y plot for all of the intermediate and evolved lavas showing the expected fields for slab melts (solid envelop) and mantle-derived magmas (dashed envelop). It allows us to discriminate between Type 5 and Type 6 magmas. The distinction between Type 5 (calc-alkaline or mantle-derived magmas) and Type 6 (adakites or slab melts) is based on the higher contents of Sr and lower Y and lower heavy REE contents in Type 6 lavas (Fig. 10), characteristic of adakitic compositions (Drummond and Defant, 1990). Lavas from the Austral Volcanic Zone and from the Southern South Volcanic Zone have been plotted for comparison in Fig. 11. Austral Volcanic Zone lavas display adakitic compositions (Stern and Kilian, 1996; Sigmarsson et al., 1998). The Southern South Volcanic Zone volcanoes are typically mantle derived and calc-alkaline (Lopez-Escobar et al., 1993).

Type 5 magmas (andesites, dacites and rhyolites) occur in the MVU, CMU and BDC of the Taitao Peninsula and also include all the evolved lavas drilled on the Taitao Ridge. Their chemical features are typically calc-alkaline. Finally, Type 6 magmas, which display adakitic characteristics, are represented by the Pliocene volcanic edifices of Chaicayan Islands, Pan de Azucar and Fjordo San Pedro, as well as the Cabo Raper pluton.

5.2.6. Isotope geochemistry

The $^{87}$Sr/$^{86}$Sr values vary from 0.702650 in one gabbro of Type 1 from the Bahia Barrientos to 0.704394 in Type 5 magmas and the $\epsilon_{Nd}$ from +10.01 in Type 1 to +3.92 in one dacite from Type 5. The $\delta^{18}$O magma values deduced from $\delta^{18}$O-values measured on clinopyroxenes vary from +6.2 to +6.6\% which is slightly higher than typical mantle values (+5.7 ± 0.3\%) and than those measured on the Chile ridge basalts (+5.6 to +6.0\%, Sherman et al., 1997b).

A positive correlation between whole-rock $^{87}$Sr/$^{86}$Sr isotopic ratios and loss on ignition (LOI) is ob-
Fig. 11. Sr/Y vs. Y diagram showing fields expected for slab melts (solid curve) and mantle-derived magmas (dashed curve) (Maury et al., 1996). Dacites from the Chaicayan Islands plot within the slab melt field while all the andesites, dacites and rhyolites from the Taitao Peninsula and Taitao Ridge plot within the mantle-derived field. The Austral Volcanic Zone (AVZ) lavas classified as adakites (Stern and Kilian, 1996) and the Southern Volcanic Zone (SVZ) lavas that include ‘normal’ dacites (Lopez-Escobar et al., 1993) are also shown for comparison.

served in Fig. 12a, whereas $^{143}\text{Nd}/^{144}\text{Nd}$ ratios and LOI appear uncorrelated (not shown). This may be attributed to interaction of the studied rocks with seawater, which results in an increase of their $^{87}\text{Sr}/^{86}\text{Sr}$ ratios whereas their $^{143}\text{Nd}/^{144}\text{Nd}$ ratios remain unchanged. This is well illustrated by sample T16d for which the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the whole rock is clearly higher than that of the separated clinopyroxenes at equivalent $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (Table 3). If, in a conservative way, we only consider the behaviour of $\delta^{18}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios measured on handpicked clinopyroxenes, no correlation appears between oxygen isotopic ratios, which remain approximately constant, and strontium and neodymium ratios which vary significantly (e.g. Fig. 12b).

5.2.7. Comparison between the Taitao Peninsula and Taitao Ridge lavas

The similarities between the Taitao Ridge and some of the Taitao Peninsula units (BDC, CMU and MVU) reside in the nature of magmatic products erupted in these two areas, and their association with sediments. Spatially associated basaltic as well as dacitic and rhyolitic flows occur on both structures. The mafic–felsic sequence recovered from the Taitao Ridge recalls the volcano–sedimentary sequences found in the Taitao Peninsula. In both cases, they may represent a volcano–sedimentary blanket of a forearc region in the vicinity of the Chile Triple Junction. However, Taitao Ridge and Taitao Peninsula lavas display distinct alteration/metamorphic features. The degree of alteration of basalts from Site 862 on the Taitao Ridge is low, with smectites as the main secondary minerals (Kurnosov et al., 1995). In contrast, the Taitao Peninsula volcanic units have experienced moderate to strong development of greenschist facies minerals. Available ages of these magmatic units are rather similar: in the Taitao Peninsula, Cabo Raper and Seno Hoppner plutons are dated between 6 and 3.5 Ma (Mpodozis et al., 1985) and the volcano–sedimentary units between 4.6 and 1.5 Ma (Mpodozis et al., 1985; Bourgois et al., 1992). On the Taitao Ridge, sediments yield Late Pliocene ages and a radiogenic date available on a rhyolitic flow is 1.5 Ma (Forsythe et al., 1995b).
5.2.8. Comparison with the southern Chile spreading ridge basalts

The four kinds of basalts discussed also occur among the southern Chile ridge lavas. Type 1 magmas have been sampled along all four segments of the southern Chile ridge (Klein and Karsten, 1995; Karsten et al., 1996; Sherman et al., 1997a). Sherman et al. (1997a) characterized these basalts by their K/Ti ratios lower than 0.15. Type 2 magmas are only found on segment 4 and have trace-element affinities with ocean island basalts (OIB) (Klein and Karsten, 1995). Type 3 magmas are only represented by sample D20-1 from segment 1 (Klein and Karsten, 1995) which is characterized by its K/Ti ratio higher than 0.15. In addition, Type 4 magmas have been sampled on segment 3 of the southern Chile ridge (Klein and Karsten, 1995). Finally, Sherman et al. (1997a) mentioned that some samples (station 12, segment 1) are dacitic (SiO₂ = 65%) and that they show calc-alkaline affinity. They could represent equivalents of our Type 5.

5.2.9. Isotopic composition of the Chile Triple Junction area magmas

A similar range of Sr, Nd isotopic variations is observed for the Taitao Peninsula (our data on clinopyroxenes plus those on whole rocks from Kaeding et al., 1990), the Taitao Ridge (data on whole rocks from Forsythe et al., 1995a) and the southern Chile ridge (data on whole rocks from Klein and Karsten, 1995). The observed patterns range from the field of typical MORB to Nd and Sr ratios close to 0.5127 and 0.705, respectively, and have been considered by former authors as indicative of continental crust or subduction-related imprint (Fig. 12c).

6. Discussion

6.1. Magma emplacement in the forearc domain during active ridge subduction

There is an ongoing discussion on the origin of magmas emplaced in the near-forearc in the situation of active spreading ridge subduction. This debate mainly concerns peripacific geologic history, punctuated by collisions between spreading ridges and trenches. In central Hokkaido, the Hidaka magmatic suite include plutons of N-MORB affinity as
well as granitic plutons which have been emplaced within the accretionary prism during the subduction of the Kula–Pacific ridge in Late Paleocene to Early Eocene time. The diversity of the magma is interpreted as interaction of mantle-derived N-MORB magma of the spreading ridge and the accretionary prism through AFC (assimilation and fractional crystallization) processes. Partial melting of forearc accreted material is supposed to have generated the granitic magma (Maeda and Kagami, 1996). Middle Tertiary bimodal volcanism in the Santa Maria Province of west-central California, including basalts and basaltic andesites with rhyolites and dacites, has been interpreted as the result of interactions between subducting segments of the East Pacific Rise and the North American continental crust (Cole and Basu, 1992). In most examples, MORB magmas (often referred as in situ basalts, Kinimani et al., 1994) are supposed to derive directly from the subducted mid-ocean ridge with variable interaction with the continental crust (Johnson and O’Neil, 1984; Hibbard and Karig, 1990; Sharma et al., 1991; Harris et al., 1996; Osozawa and Yoshida, 1997).

In the case of the Taitao region, the recent age and the present-day location of the intrusions, 17 to 30 km away from the trench axis, are not easy to explain according to current models of magma genesis and emplacement in typical subduction zones. Age constraints indicate that the studied volcano–plutonic suites have been emplaced in the Triple Junction region during its migration along the Chile margin. Kinematic reconstructions show that the triple junction migrated northward in front of the Golfo de Penas between 6 and 3 Ma and was located at the latitude of the Peninsula around 3 Ma ago. The triple junction migrated along the trench toward the present-day location of the Taitao Ridge between 3 and 2 Ma. This kinematic evolution is in good agreement with the age pattern of the magmatic rocks from south to north: 6–2 Ma on the Taitao Peninsula and 2–1.5 Ma on the Taitao Ridge.

6.2. Constraints on magma genesis in the Taitao area

6.2.1. Origin of basaltic magmas

The problem of the emplacement of basaltic magmas in the Taitao Peninsula, only some kilometres away from the trench axis, has been already discussed by Kaeding et al. (1990) and Lagabrielle et al. (1994) who pointed out that where basalts were generated is not far enough inland to expect a sub-continental mantle wedge as a source. Assuming a slab dip of 15° (Bangs et al., 1992), the Chile continental lithosphere should not be thicker than 15 km at a distance of ca. 40 km from the trench (Fig. 13) and consequently there is no subcontinental mantle wedge overlying the subducting slab. In these conditions, the only possible source for the Taitao basalts appears to be the hot convective oceanic mantle of the subducted Chile spreading ridge. The diversity of basaltic magma types erupted in the Chile Triple Junction, both on the Taitao Ridge and on the Taitao Peninsula, should thus reflect (a) the small-scale chemical diversity of the sub-oceanic mantle, already evidenced by Klein and Karsten (1995), and (b) additional heterogeneities resulting from interactions between the ascending basaltic magmas and the continental crust.

Former studies of Taitao Peninsula lavas led to the recognition of crustal contamination as an important process likely responsible for Sr–Nd isotopic variations (Kaeding et al., 1990) and random variations of La/Nb ratios in basalts (Lagabrielle et al., 1994). However, these studies were published prior to the discovery of the important chemical variability of basalts from the Chile ridge axis (Klein and Karsten, 1995; Karsten et al., 1996; Sherman et al., 1997a). Our data on clinopyroxenes from gabbroic samples (TA65 and TA55) fall within the range of Sr and Nd isotopic compositions found at the Chile ridge axis (Fig. 14) but corresponding δ¹⁸O magma values (+6.2 and +6.6‰) are slightly higher than those measured on the Chile ridge basalts (+5.6 to +6.0‰, Sherman et al., 1997b).

The geochemical characteristics of the basaltic lavas erupted in the Chile Triple Junction region may be the result of processes linked to the present-day ridge–trench configuration by direct emission of the sub-oceanic mantle magmas contaminated by recent reflux of subduction-related material into the mantle source. Klein and Karsten (1995) proposed that the sub-oceanic Chile ridge mantle was contaminated either by slab fragments re-injected into the asthenospheric convection or, alternatively, by passage through a slab window of the metasoma-
tized sub-continental mantle wedge. In all the areas investigated, a model involving direct emission of magmas from the buried active spreading centre as it was subducted at shallow depth is still acceptable (Lagabrielle et al., 1994), as similar chemical diversity is found along the Chile ridge and the South American margin.

6.2.2. Origin of the intermediate/evolved calc-alkaline magmas

The main difference between the magmatic rocks from the Taitao Peninsula and the Taitao Ridge and those from the Chile ridge resides in the occurrence of abundant intermediate or evolved rocks in the former areas. They include basaltic andesites, andesites, dacites and rhyolites from CMU, MVU, BDC (Kaeding et al., 1990; Lagabrielle et al., 1994; Guivel et al., 1996; Le Moigne et al., 1996) and dacites and rhyolites from the Taitao Ridge (Forsythe et al., 1995a).

The high diversity of the chemical characteristics of the lavas (trace-element patterns, isotopic data) precludes a simple closed-system fractionation of a single primitive magma source to generate the silicic lavas from the Taitao Peninsula or the Taitao Ridge. The decrease of Yb with SiO$_2$ contents in Fig. 7b precludes fractional crystallization as the main process. The correlations between Sr, Nd isotopic ratios and SiO$_2$ contents (Kaeding et al., 1990), and between La/Nb ratios and SiO$_2$ (Lagabrielle et al., 1994) led these authors to propose assimilation of continental crust or assimilation coupled with fractional crystallization (AFC) as a mechanism accounting for the origin and abundance of the intermediate/evolved lavas. For instance, Kaeding et al. (1990) concluded that their isotopic data were consistent with assimilation of 5–10% of pre-Jurassic metasedimentary rocks by tholeiitic magmas.

A very different explanation was proposed by Forsythe et al. (1995a) to account for the geochemi-
Fig. 14. O–Sr–Nd isotopic variations for the Taitao Peninsula magmas compared to calculated mixing models for: (a) crustal contamination of mafic magma (N-MORB type) by various amounts of Andean continental crust (And CC) or ODP Leg 141 sediments (ODP sed.; bold curve); and (b) source contamination of a depleted mantle (DM) by Andean continental crust (And CC) or ODP Leg 141 sediments (ODP sed.; bold curve). Numbers on the curves indicate the mass fraction of crustal or sediment component. See Table 5 for parameters.
Table 5
Chemical and isotopic parameters used in the calculation of mixing models

<table>
<thead>
<tr>
<th>Component</th>
<th>Sr (ppm)</th>
<th>Nd (ppm)</th>
<th>( ^{87}\text{Sr}/^{86}\text{Sr} )</th>
<th>( ^{143}\text{Nd}/^{144}\text{Nd} )</th>
<th>( ^{18}\text{O} ) (‰ vs. V-SMOW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM</td>
<td>8.8</td>
<td>0.857</td>
<td>0.702674</td>
<td>0.513162</td>
<td>+6.0</td>
</tr>
<tr>
<td>N-MORB</td>
<td>88</td>
<td>8.57</td>
<td>0.702674</td>
<td>0.513162</td>
<td>+6.0</td>
</tr>
<tr>
<td>Andean continental basement</td>
<td>220</td>
<td>23.6</td>
<td>0.715</td>
<td>0.5123</td>
<td>+12</td>
</tr>
<tr>
<td>ODP sediments</td>
<td>305</td>
<td>21</td>
<td>0.708</td>
<td>0.5124</td>
<td>+10</td>
</tr>
</tbody>
</table>

DM: depleted mantle [sample D34-1 from segment 2 of the Southern Chile ridge (Klein and Karsten, 1995)].
N-MORB: normal oceanic crust [sample D34-1 from segment 2 of the Southern Chile ridge (Klein and Karsten, 1995)].
And. CC: Andean continental basement (see Stern and Kilian (1996) and references therein).
ODP sed.: ODP Leg141 sediments [see Stern and Kilian (1996) and references therein].

Indeed, these authors regarded the Taitao Ridge as built on an oceanic substratum and, therefore, did not consider continental crust contamination. Two rhyolites were analysed for Sr, Nd and Pb isotopes (Forsythe et al., 1995a). The sample displaying the strongest continental (or subduction-related) imprint has Nd and Pb isotopic ratios similar to those of calc-alkaline basalts from the Taitao Ridge but a slightly higher \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratio. On the basis of trace elements patterns, these authors proposed that the rhyolites were formed by 10% melting of hydrothermally altered gabbroic equivalents of the calc-alkaline basalts (Type 4), leaving a residue of hornblende and plagioclase at 800°C and 1.5 GPa. Thermal anomaly due to the subduction of a spreading ridge segment may lead to such a high temperature peak (DeLong et al., 1979). The latter pressure, however, seems inconsistent with the estimated depth of the Chile ridge ocean crust below the Taitao Ridge (less than 10 km).

In order to discuss the origin of the geochemical signatures of the Taitao Peninsula magmatic rocks, we have plotted their \( ^{87}\text{Sr}/^{86}\text{Sr} \), \( ^{143}\text{Nd}/^{144}\text{Nd} \), and \( ^{18}\text{O} \) ratios deduced from measurements on primary clinopyroxene phenocrysts in Fig. 14 together with literature data on the Chile ridge basalts. In addition to the two N-MORB gabbros discussed here-above, data on clinopyroxenes have been obtained on a basaltic andesite (T16d) showing a typical trace element calc-alkaline imprint (Type 4) and on a dacite (T18a) also typically calc-alkaline. The mixing curves in Fig. 14 correspond to bulk mixing between:

(a) One of the least Sr radiogenic N-MORB from the Chile ridge (D34-1 from Klein and Karsten, 1995), and Andean continental crust or ODP Leg 141 detrital sediments (see Table 5 for calculation parameters), and

(b) A theoretical depleted sub-oceanic mantle (DM) isotopically similar to N-MORB D34-1 but having Sr and Nd concentrations ten times lower, and Andean continental crust or ODP Leg 141 detrital sediments.

Mixing curves in Fig. 14a and b approximate crustal contamination of mafic magmas and mantle source contamination processes, respectively (Taylor, 1980; James, 1981; Davidson, 1985; Davidson and Harmon, 1989; Fourcade et al., 1994). Although we have taken for the MORB/DM pole a \( ^{18}\text{O} \) of +6.0‰, corresponding to the upper bracket of the data on the Chile ridge basalts, none of the mixing curves fits closely with our analytical data. It seems thus impossible to decipher between the two models (source contamination of DM by less than 5% sediments or assimilation of less than 10% continental crust or derived sediments by N-MORB magmas). Of course, the predominantly mantle-like signature of the studied clinopyroxenes precludes the hypothesis that their host rocks derived either from anatectic melting of continental crust/sediments or from contamination/AFC processes involving large amounts of a continental component. The fact that the dacite and the basaltic andesite clinopyroxenes are slightly less radiogenic in Nd than the gabbros could give some support to the crustal contamination hypothesis but corresponding Sr isotopic ratios are nearly identical (Fig. 14a). The hypothesis of dacite–rhyolite production through partial melting of hydrothermally altered oceanic crust can also account
for the available isotopic data. Indeed, hydrothermal alteration of the upper part of the hole 504B basaltic sequence resulted in an overall increase of $\delta^{18}O$ values by +1 to +2 units (Alt et al., 1996). Such a process may explain the $\delta^{18}O$ differences between Taitao Peninsula lavas and Chile ridge basalts.

7. Conclusions

The Taitao Peninsula and the adjacent Taitao Ridge are characterized by a remarkably variable Pliocene–Quaternary magmatic activity whichemplaced over a Benioff zone less than 10 km (Taitao Ridge) to 20 km (Taitao Peninsula) deep: (1) N-type MORB; (2) E-type MORB; (3) LREE-depleted N-MORB showing trace element features typical of arc basalts; (4) moderately Nb-depleted E-MORB; (5) calc-alkaline andesites, dacites and rhyolites; (6) andesites and dacites with adakitic signature (Bourgois et al., 1996).

The chemical variability of the studied basalts is similar to that of the Chile spreading ridge basalts regarding trace elements and Sr–Nd isotopes. This observation suggests that their most likely origin is the actively subducting Chile ridge. There is no need for important assimilation or melting of continental material during the ascent of ridge-generated MORB through the Chile crust (Lagabrielle et al., 1994). The slightly higher $\delta^{18}O$ of Taitao Peninsula magmas (with respect to Chile spreading ridge basalts) deduced from the analysis of their primary clinopyroxenes could result from (a) minor amounts of mantle source contamination by continental components, (b) minor assimilation of Chilean continental crust by basaltic to dacitic magmas, and, for the acidic rocks, (c) remelting of previously hydrothermally altered oceanic crust (Forsythe et al., 1995a). The origin of the continental imprint of the Chile ridge basalts (and consequently of their Taitao Peninsula and Taitao Ridge equivalents) remains highly conjectural. Klein and Karsten (1995) already envisioned:

(1) The reintroduction of slab fragments beneath the ridge due to slab breaking and entrainment by shallow asthenospheric flow, or
(2) The presence of a slab window providing a major connection between the metasomatized sub-arc mantle and the adjacent sub-oceanic mantle.

Bourgois et al. (1996) suggested a high rate of subduction-erosion below Taitao. Such a process necessarily results in the dissemination of fragments of continental crust within the Chilean mantle wedge. If a slab window exists beneath Taitao, as suggested by recent seismic data (Russo and Murdie, 1997), it may provide a way of access to the sub-ridge mantle for these continental materials.

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