Are the Taitao granites formed due to subduction of the Chile ridge?

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Abstract

The Taitao granites are distributed around the Late Miocene Taitao ophiolite (5.66 ± 0.33 Ma to 5.22 ± 0.18 Ma) exposed at the western tip of the Taitao peninsula, southern Chile, approximately 50 km southeast from the present day Chile triple junction. In this paper, we report sensitive high mass-resolution ion microprobe (SHRIMP) U-Pb ages for the Taitao granites to elucidate the temporal relationship between the ophiolite and granites, and discuss the origin of the granitic melts. Five intrusive bodies of the Taitao granites have U-Pb ages ranging from 5.70 ± 0.25 Ma (Tres Montes pluton in southeast) to 3.92 ± 0.07 Ma (Cabo Raper pluton in southwest). The Estero Cono, Seno Hoppner and Bahia Barrientos intrusions that fringe eastern margin of the ophiolite have U-Pb ages ranging from 5.17 ± 0.09 Ma to 4.88 ± 0.3 Ma. Recycled zircon cores are common only in the Tres Montes pluton. Our data indicates that the generation of the granitic melts started in the Tres Montes area when a short segment of the Chile ridge system started to subduct ca. 6 Ma ago. This magmatism involved contamination with sediments/basement rocks. A part of the subducting ridge center was emplaced to form the present Taitao ophiolite at ~ 5.6 Ma. Generation of granitic melts continued as the spreading center of the same ridge segment subducted, due perhaps to partial melting of the ophiolite and/or oceanic crust enhanced by heat from upwelling mantle beneath the ridge. Granitic magmas with various compositions developed during subduction of the ridge. Emplacement of the ophiolite and formation of continental crust took place almost simultaneously.

1. Introduction

"There may be granites and granites." Earth scientists after Read (1957) repeatedly confirmed the complexity involved in the genesis of granites. In this paper, we provide evidence for the generation of granitic magmas during ridge subduction.

The presence of young granite stocks at the tip of the Taitao peninsula (Fig. 1), the westernmost promontory of the Chilean coast, was first reported by Mpodoziz et al. (1985). Five intrusive bodies of tonalite, granodiorite and granite, collectively referred in this paper as the Taitao granites, are distributed around the Taitao ophiolite (Forsythe et al., 1986) exposed approximately 50 km southwest from the present day Chile triple junction. The five bodies of the Taitao granites are: the Estero Cono pluton (EC in Fig. 2), the Seno Hoppner pluton (SH), the Bahia Barrientos pluton (BB), the Cabo Raper pluton (CR) and the Tres Montes pluton (TM) from north to south (Fig. 2).

Figure 1 shows that two oceanic plates, the Nazca plate in the north, and Antarctic plate in the south, separated by spreading ridges of the Chile ridge system, subduct beneath the South American plate with convergent rates of 9 cm/yr and 2 cm/yr, respectively (Cande *et al*. 1982; Cande & Leslie 1986). Because NNW-trending central axis of the Chile ridge is oblique to the NS-trending continental margin, three short spreading centers subducted repeatedly almost at the same latitude offshore the Taitao peninsula at around 6 Ma, 3 Ma and present (Cande and Leslie, 1986; Forsythe et al., 1986, Guivel et al., 1999). The Taitao ophiolite and granites are exposed where these ridge subduction events had taken place (Fig. 1). They emplaced into Pre-Jurassic meta-sedimentary rocks of the Los Chonos complex (Fig. 2).

The Taitao ophiolite consists of a complete sequence expected for oceanic lithosphere (Forsythe et al., 1986; Nelson et al., 1993; Bourgois et al., 1993; Guivel et al., 1999; Veloso et al., 2005; Anma et al., 2006; Shibuya et al., 2007): pillow lavas, pillow breccias and sheet flows, sheeted dike complexes, gabbros and ultramafic rocks from the top to the bottom of the sequence (Fig. 2). However, no metamorphic sole has been reported. Although there are discrepancies in petrology between the lower plutonic rocks with N-MORB compositions and upper volcanic rocks with enriched compositions (Kaeding *et al*. 1990; Lagabrielle *et al*. 1994; Le Moigne *et al*. 1996; Guivel *et al*. 1999), current petrological models favor a mid-ocean ridge (MOR)-origin for the Taitao ophiolite (Guivel et al., 1999; Lagabrielle et al. 2000). Shibuya et al. (2007) demonstrated the pattern of ocean-floor metamorphism of the ophiolite and compared it with other ophiolites and the oceanic crusts, and concluded that the Taitao ophiolite has many hydrothermal alteration features similar to those of MOR crusts.

The internal structure of the Taitao ophiolite, however, is not simple. The ultramafic rocks and gabbros are intensely folded and thrusted, and appear repeatedly as tectonic slices in the southeastern part of the ophiolite (Fig. 2). Sheeted dike complexes are exposed in two separate bodies that have contrasting dike trends: the one exposed along the Pacific coast trends NW-SE, and the other exposed in Estero Cono trends NNE-SSW. Volcanic sequences are exposed in two separate bodies (Fig. 2): the Main Volcanic Unit (MVU in Fig. 2) in the northern part and the Chile Margin Unit (CMU in Fig. 2) in the eastern part of the ophiolite (Guivel et al., 1999).

Veloso et al. (2005) reconstructed original orientations of internal structures in the

Taitao ophiolite using paleomagnetic data to argue emplacement processes. Veloso et al. (2005) demonstrated that layered gabbros originally dipping eastward underwent folding, whereas the sheeted dike complexes and volcanic sequences underwent block rotation during the ridge subduction. They attributed the orthogonal trend of sheeted dike complexes to the block rotation; both originally trend NNE-SSW. Veloso et al. (2009) further discussed change in stress field during the block rotation. Anma et al. (2006) used sensitive high mass-resolution ion microprobe (SHRIMP) U-Pb and fission-track (FT) data of zircon separated from gabbros and a sheeted dike of the ophiolite (Fig. 2) to discuss rapid emplacement and northward migration of magmatic activity during the ridge subduction that took place ~ 6 Ma ago. Veloso et al. (2005) and Anma et al. (2006) concluded that it was an eastern part of the ridge segment that was emplaced to form the Taitao ophiolite. Anma et al. (2006) attributed ductile deformation of the ultramafic rocks and gabbros to basal shearing during subsequent subduction of the western part of the ridge just after the ophiolite emplacement. Obliquity between the current trend of the Chile ridge axis (NNW-SSE) and the original trend of the sheeted dike complexes (NNE-SSW) was attributed to ridge magmatism under influence of a transform fault nearby (Anma at al., 2006).

We use SHRIMP U-Pb data in this paper to demonstrate the temporal correlation between the emplacement of the Taitao ophiolite and Taitao granites. These radiometric ages are incorporated in geological observations and petrochemical data to assess the origin of the Taitao granites.

2. Previous age constraints

Radiometric age data of the Taitao ophiolite and the Taitao granites reported by previous workers are compiled in figure 2 (data based on Mpodozis *et al*. 1985; Guivel *et al*. 1999 and reference therein; Herve et al., 2003; Anma et al., 2006).

The radiometric ages for the Taitao granites were first determined by Mpodozis et al. (1985). They applied the K-Ar method on biotite separated from the Seno Hoppner, Cabo Raper and Bahia Barrientos plutons. Bourgois et al. (1992, 1993), and Guivel et al. (1999) applied the Ar-Ar dating technique on biotite, hornblende and feldspar separated from the Seno Hoppner and Cabo Raper pluton. The K-Ar and Ar-Ar data show the ages of the Seno Hoppner pluton range from 5.9 Ma to 5.2 Ma with error of less than ± 0.5 Ma (except a feldspar Ar-Ar age with larger error), and those of the Cabo Raper pluton from 5.1 Ma to 3.3 Ma with error of less than ± 0.8 Ma (except one data with larger error due to low concentration of K in hornblende). The biotite K-Ar age for the Bahia Barrientos pluton was determined to be 3.2 ± 1.2 Ma by Mpodozis et al. (1985).

Recently, Herve et al. (2003) applied SHRIMP U-Pb and FT techniques on zircon (plus apatite for FT) separated from Cabo Raper, Bahia Barrientos and Estero Cono plutons. The SHRIMP U-Pb age for the Cabo Raper pluton was reported to be 3.97 Ma to 3.84 Ma in an error range smaller than 0.14 Ma. Herve et al. (2003) also reported existence of few inherited zircon of Cretaceous ages from the Cabo Raper pluton. Zircon FT ages (closing temperature of the zircon FT system ~ 300^{o}C) for the Cabo Raper pluton overlap the U-Pb ages within error range, whereas apatite FT ages (closure temperature of the apatite FT system ~ 100^{o}C) indicate slightly younger ages. Zircon FT ages for the Estero Cono and Bahia Barrientos plutons were 3.49 ± 0.27 Ma and 3.47 ± 0.22 Ma, respectively (Herve et al., 2003).

The SHRIMP U-Pb ages of zircon separated from the rocks of the Taitao ophiolite were reported by Anma et al. (2006): 5.66 ± 0.33 Ma and 5.61 ± 0.09 Ma for gabbros and 5.22 ± 0.18 Ma for a NW-SE trending dacite dike. Mpodozis et al. (1985) reported a whole-rock K-Ar age from the Main Volcanic Unit to be 4.6 Ma and six whole-rock K-Ar ages ranging from 4.4 Ma to 2.5 Ma from the Chile Margin Unit (Fig. 2). No other geochronological data is available for the volcanic rocks of the Taitao ophiolite.

Nelson et al. (1993) reported that the lowermost Main Volcanic Unit underwent lower greenschist metamorphism. Shibuya et al. (2007) reported the presence of contact metamorphic aureole in the volcanic rocks of the Main Volcanic Unit (4.6 Ma old) and Chile Margin Unit (4.4 Ma to 2.5 Ma old) around the Seno Hoppner pluton (6.9 Ma to 5.2 Ma old). There is contradiction between field observation and the previous age constraints. This is partly because most previously applied methods provided cooling ages with different closure temperatures. We therefore applied SHRIMP U-Pb dating technique to magmatic zircons separated from the Taitao granites, to discuss the age of crystallization. The U-Pb ages of clastic zircons from volcaniclastic sandstone in the Main Volcanic Unit were also obtained to constrain age and source area of the deposition. To test the precision of the previous measurements, we also obtained a U-Pb age for a gabbro sample (TPG107) collected from the Taitao ophiolite.

3. Methodology

Field observation and sample collection were performed during the 2000-2001 and 2002-2003 Japanese Taitao expedition. Major and trace element concentrations were determined on glass beads using an XRF at the Earthquake Research Institute of the University of Tokyo. We followed sample preparation and experimental procedure described in Tani et al. (2002) and Orihashi and Hirata (2003).

Zircon crystals were separated using conventional heavy liquid and magnetic separation methods at the Tokyo Institute of Technology and Kyoto Fission-Track Co. LTD. Zircon samples were mounted in EPOFIX resin with 416.8 Ma (± 0.4 Ma) TEMORA 2 (Black et al. 2003a, 2003b, 2004) standard for monitoring and calibration. The sample piece was then polished and Au coated. Cathodoluminescence (CL) images of zircon grains were obtained before U-Pb measurement to visualize zoning patterns and presence of recycled zircon cores. We used a SHRIMP II for single-grain zircon U-Pb measurement at the Australian National University. Details of SHRIMP U-Pb dating technique and experimental conditions used for this study are described in Claue-Long et al. (1995) and Williams (1998), and Anma et al. (2006), respectively. During the measurement, ages of standard samples coincided with recommended values within the errors in standard calibration less than 0.7 % (Tables 1 to 3). We used ISOPLOT/EX and SQUID programs developed by Ludwig (1999, 2002) for the data analyses. We assumed two-stage model (Stacey and Kramers, 1975) to calculate intercept ages.

4. Sample description and results

The results of U-Pb dating of the Taitao granites are listed in Table 1 and shown in the Tera-Wasserbourg diagrams in Figure 3. Results for zircons separated from gabbro and sandstone of the Main Volcanic Unit are shown in Tables 2 and 3, respectively. Major and trace element abundances for the dated Taitao granites are listed in Table 4.

4.1 The Tres Montes pluton

The Tres Montes pluton is classified as tonalite to granodiorite with major mineral assemblage of plagioclase – quartz > biotite > hornblende. K-feldspar is rare but present in places. Plagioclase underwent saussuritization. Myrmekite texture was observed in places. Colorless minerals (up to 80 modal %) are 2 mm to 0.2 mm across. Hornblende was observed to replace clinopyroxene in places. Opaque minerals, zircon and apatite are common accessory minerals. Chlorite and epidote were observed as secondary minerals, along with thin veins of prehnite. We found no field evidence to indicate a contact relationship between the pluton and the ophiolite.

The Tres Montes pluton is characterized by the presence of numerous mafic dikes trending NNE-SSW. The intrusion of the mafic dikes melted the host tonalite extensively to form hybrid rocks. Leucocratic veins continuous from the host tonalite were commonly observed in the mafic dikes, and mafic blobs with chilled margins are developed in places. These features reflect syn-plutonic nature of the mafic dikes. Sample TPA14 was collected for analyses from tonalitic part of an outcrop intruded by the syn-plutonic dike intrusion. The sample TPA14 has approximately 66 wt % SiO_2

(Table 4).

Zircon grains from the Tres Montes pluton (TPA14) are pink to colorless, contain numerous inclusions, but show no evidence for inherited cores under transmitted light. Some are strongly zoned or exhibit sector zoning under CL image. Crystals that develop {100} prism faces (Pupin, 1980) are predominant, implying that they were crystallized at high temperatures.

TPA14 zircons show wide variation in age; recycled zircons of Cretaceous to Late Proterozoic ages were commonly observed (Table 1). Eight out of 15 measured grain spots yielded Late Miocene to Pliocene ages ranging from 6.25 Ma to 5.06 Ma with standard error less than 0.41 Ma. Only grain spot 6.1 (shaded in Fig. 3) has slightly younger discordant age (5.06 ± 0.24 Ma). The younger age may reflect the time of zircon overgrowth due to the intrusion of the syn-plutonic mafic dike. Thus, we excluded grain spot 6.1 from the calculation and obtained a weighted mean age of 5.70 ± 0.25 Ma (Fig. 3).

4.2 The Seno Hoppner pluton

The rocks of the Seno Hoppner pluton have granite compositions and mineral assemblages of plagioclase – quartz > K-feldspar > biotite - hornblende. Colorless minerals are 0.5 mm to 2 mm across. Some plagioclase exhibit oscillatory zoning and underwent saussuritization. Myrmekite texture was observed in places. Zircon, apatite and titanite were observed as accessory minerals and actinolite, chlorite, zoisite and epidote as secondary minerals. Shibuya et al. (2007) reported contact aureole in the host

Main Volcanic Unit and Chile Margin Unit around the Seno Hoppner pluton. This pluton also accompanies mafic dike intrusion in the northern part. However, there is no visible reaction between the mafic dike and the host granite unlike the Tres Montes pluton.

We separated zircon crystals from two localities: the northern part (TPD172) and the southern part (TPD110) of the pluton (Fig. 2). Both samples have approximately 74 wt % SiO_2 (Table 4). Zircon crystals from the Seno Hoppner pluton are pink in color and contain numerous inclusions. Crystals with {100} prisms are predominant and most crystals are zoned. Sector zoning is less common in TPD110 than TPD172.

We found only one recycled zircon core (grain spot 14.2 of TPD172) with Paleozoic age out of total 31 measured grain spots from the Seno Hoppner pluton. The Mio-Pliocene fraction of spot ages range from 5.61 Ma to 4.93 Ma for TPD110 and from 5.31 Ma to 4.79 Ma for TPD172 (except for grain spot 4.1 with anomalously high common lead content and larger standard error) within standard errors less than 0.26 Ma. One grain (grain spot 7.1) from TPD110 is metamict with anomalous U contents (Table 1). It yielded the oldest, yet similar age (5.61 Ma) to the other TPD110 zircons. We rejected this grain spot and calculated a weighted mean age for TPD110 to be 5.17 ± 0.09 Ma (Fig. 3). For TPD172, we used all data except for the recycled zircon core (grain spot 14.2) and obtained the weighted mean age of 5.09 ± 0.09 Ma (Fig. 3). Influence of common lead was observed in TPD 172 zircon and we also calculated a model age (Fig. 3: Watson et al., 1997).

4.3 The Estero Cono pluton

The Estero Cono pluton is separated from the ophiolite by the embayment of Estero Cono and there is no outcrop that exhibits contact relationship between them. The rocks of the Estero Cono pluton are granodiorite with mineral assemblages of plagioclase – quartz > K-feldspar > biotite > hornblende. Some are hornblende-free. Colorless minerals are 0.5 mm to 2 mm across. Plagioclase grains are subhedral with clear compositional zoning. K-feldspar is anhedral. Myrmekite texture was conspicuous in places. Zircon and apatite are common accessory minerals. Actinolite, chlorite + magnetite, and epidote are often observed as secondary minerals. Phengite and calcite were also observed in places.

We separated zircon crystals from sample TPD169 (Fig. 2) that has SiO_2 contents of ~ 68 wt % (Table 4). Zircon crystals from the Estero Cono pluton are colorless and contain fewer inclusions than those from the other plutons. Crystals with {100} prisms are predominant, but {110} prisms were also observed. All crystals are compositionally zoned. However, sector zoning was rarely developed.

All data from TPD169 were plot near the concordia line except for the grain spot 10.1 that has large error and anomalously high concentration of common lead. Thus, we omitted this spot from the age calculation. The rest of the spot ages range from 5.41 Ma to 4.83 Ma within standard errors less than 0.24 Ma. The calculated mean age for the TPD169 was 5.12 ± 0.09 Ma (Fig. 3).

4.4 The Bahia Barrientos intrusion

The Bahia Barrientos intrusion is an isolated minor body (perhaps a thick dike) exposed in small outcrops. Again, we found no field evidence to support a contact relationship with ophiolite. The rocks of the Bahia Barrientos intrusion possess tonalite to trondhjemite compositions and mineral assemblages of plagioclase – quartz > K-feldspar - biotite. Colorless minerals are 0.2 mm to 1.5 mm across. Porphyritic plagioclase is up to 3 mm across. Zircon and apatite are common accessory minerals. Plagioclase has undergone saussuritization and biotite is commonly replaced by chlorite. The sample TPB246 has SiO_2 contents of ~ 69 wt % (Table 4).

Zircon crystals separated from TPB246 (Fig. 2) have similar characteristic to those from the Estero Cono pluton. All data from TPB246 plot near the concordia in the Tera-Wasserbourg diagram (Fig. 3). There was no recycled zircon among the measured spots. Spot ages range from 5.19 Ma to 4.56 Ma with standard errors less than 0.20 Ma. The calculated mean age for the TPB246 was 4.88 ± 0.07 Ma (Fig. 3).

4.5 The Cabo Raper pluton

The Cabo Raper pluton is fault-bounded against the ultramafic rocks of the ophiolite. Large scale pressure ridges (~ 1 km across) were developed in the ultramafic rocks along the fault. There is no clear evidence for thermal aureole in the ophiolite. The Cabo Raper pluton is granodioritic to tonalitic in composition with mineral assemblages of plagioclase >> quartz > biotite > hornblende – K-feldspar. Typical grain size is 0.4 mm to 2 mm across. Hornblende is euhedral and plagioclase is euhedral to subhedral. Shape of biotite and quartz was constrained by plagioclase. K-feldspar is anhedral. Zircon, apatite and titanite were observed as accessory minerals, and actinolite, chlorite, epidote and muscovite as secondary minerals.

Zircon crystals were separated from TPB236 (Fig. 2). The sample TPB236 has SiO_2 contents of ~ 68 wt % (Table 4). TPB236 zircons are pink to colorless. They developed both {100} and {110} prisms and contain numerous inclusions. All crystals exhibit compositional zoning. Sector zoning was rarely seen. Most U-Pb data for TPB236 plot near the concordia in the Tera-Wasserbourg diagram (Fig. 3) except for grain spots 13.1 and 14.1. Spot ages range from 4.20 Ma to 3.66 Ma with standard errors less than 0.20 Ma, except grain spot 13.1 with slightly older age and larger error. There was no recycled zircon among the measured spot. Thus, we used all grain spots to calculate a weighted mean age. The calculated mean age for the TPB236 was 3.92 ± 0.07 Ma (Fig. 3).

4.6 Gabbro of the Taitao ophiolite

Zircon crystals were also separated from a gabbroic rock (TPG107) of the Taitao ophiolite, near the boundary with the Cabo Raper pluton (Fig. 2). TPG107 outcrop exhibits blobs of melanocratic gabbros mixed up with leucocratic gabbros. Nevertheless, U and Th contents in the TPG107 zircon were rather homogeneous (Table 2). Colorless zircon crystals developed {100} prisms, but some had irregular shapes. They exhibit weak compositional zoning and sector zoning. Spot ages range from 6.86 Ma to 4.36 Ma with standard errors less than 1.10 Ma (Table 2). The standard error is larger than those from the granite plutons reflecting less concentration of U in zircon. We used all

16 grain spots to calculate weighted mean age for the TPG107. The obtained age was 5.59 ± 0.23 Ma.

4.7 Detrital zircons from the Main Volcanic Unit of the Taitao ophiolite

Zircon crystals were separated from sample TPB338, a fine-grained volcaniclastic sandstone interbedded within thick pile of pillow lavas and sheet flows of the Main Volcanic Unit (Fig. 2). The clasts of TPB338 sandstone comprise angular grains of albitized plagioclase, quartz, clinopyroxene, biotite and lithic fragments of basalts. The typical grain size of clasts is less than 2 mm across. Calcite cementation was observed in the clayey matrix.

Zircon crystals in TPB338 are smaller than those from the igneous rocks. Many have euhedral shapes with {100} prisms, but grains with rounded or irregular shape were also observed. Euhedral grains were weakly zoned and sector zoning was also observed. Measurement on randomly chosen 24 grain spots showed that 19 out of 24 clastic zircon crystals have Miocene to Pliocene ages ranging from 5.57 Ma to 4.89 Ma with standard errors less than 0.26 Ma. U contents of zircon of the TPB338 sandstone are higher than those of TPG107 gabbros, but comparable to those of the granite plutons. Three grains have Late Oligocene to Early Miocene ages and two grains have Mesozoic ages. The weighted mean age of the Mio-Pliocene fraction was 5.28 ± 0.09 Ma.

5. Discussion

5.1 Age constraints and their tectonic implication

Anma et al. (2006) reported two SHRIMP U-Pb ages for gabbros of the Taitao ophiolite; one is 5.66 ± 0.33 Ma (TPB268 in Fig. 4: U contents less than 90 ppm and spot ages range from 6.6 Ma to 4.8 Ma) and the other 5.61 ± 0.09 Ma (TPG244: U contents as high as 5000 ppm and spot ages range from 5.9 Ma to 5.1 Ma). A newly obtained SHRIMP U-Pb age for the TPG107 gabbro (5.59 ± 0.23 Ma) coincides within the error range with the previous measurements. Thus, the age of crystallization of the gabbros was confined to 5.66 ~ 5.59 Ma, and the precision of the measurement was proven to be smaller than the errors of the calculated ages.

Figure 4 summarizes the SHRIMP U-Pb data for the Taitao granites and the Taitao ophiolite. The crystallization age of the Tres Montes pluton (5.70 ± 0.25 Ma) is slightly older, but coincides within the error range with the ages of the gabbros of the Taitao ophiolite. The Tres Montes pluton includes many recycled zircon. This implies that the origin and development of the magmas that formed the Tres Montes pluton was different from those for the other plutons with less, if any, sediment/basement contamination.

Anma et al. (2006) reported the age of a sheeted dike of the Taitao ophiolite to be 5.22 ± 0.18 Ma (TPG262: U contents as high as 3600 ppm, and spot ages ranging from 5.4 Ma to 4.9 Ma). The obtained average ages of the Seno Hoppner and Estero Cono plutons (5.17 ~ 5.09 Ma ± 0.09 Ma) are slightly younger than that of the sheeted dike. This result agrees with the presence of thermal aureole in the Main Volcanic Unit (and in the sheeted dike complex exposed in the Estero Cono area) around the Seno Hoppner pluton (Shibuya et al., 2007). The Bahia Barrientos pluton (4.88 ± 0.07 Ma) and the

Cabo Raper pluton (3.97 ~ 3.84 Ma with error less than 0.17 Ma) have younger ages than the ophiolite.

Our data indicates that the generation of the granitic melts started in the Tres Montes area at ~ 6.25 Ma (the oldest spot age from the Tres Montes pluton) during the inception of subduction of a short segment of the Chile ridge system (Fig. 5A to B). This magmatism involved partial melting and/or contamination by incorporation of the trench-fill sediments/basement rocks. Behrmann et al. (1994) used seismic reflection data to show the presence of the accreted sediments in the north of the present Chile triple junction, where subduction of the Chile ridge system has not taken place yet. Bourgois et al. (2000) demonstrated the lack of accretionary complex off shore of the Taitao peninsula. Bourgois et al. (1996) argued significant amount of subduction erosion took place in between 4.2 ~ 3 Ma and 1.6 ~ 1.5 Ma ridge subduction events. Such subduction erosion must have taken place during and prior to the 6 Ma ridge subduction events (Fig. 5A, B and D). The eroded sediments in turn might have incorporated in magmas of the Tres Montes tonalite-granodiorite during the subsequent subduction of the hot ridge center (Fig. 5 B to C and Fig.5D to E). The NNE-SSW trending syn-plutonic dikes observed in the Tres Montes pluton might be related to the subduction of a transform fault (Fig. 5B).

A part of the subducting ridge center emplaced to form the present Taitao ophiolite at approximately 5.6 Ma (Fig. 5C and E; Anma et al., 2006). Generation of granitic melts continued as the spreading center of the same ridge segment subducted beneath the ophiolite, due perhaps to partial melting of the ophiolite and/or oceanic crust enhanced by heat from upwelling mantle beneath the ridge (Fig. 5E; De Long et al., 1979). Subduction erosion of the accreted sediments may have occurred at this stage. Thus, there was only negligible influence of sediment contamination in the generation of granitic magmas that formed the Seno Hoppner, Estero Cono, Bahia Barrientos and Cabo Raper intrusions, unlike arc magmas in the Andean Austral Volcanic Zone (Kilian and Behrmann, 2003). Slightly higher $^{87}Sr/^{86}Sr$ ratios (0.70440 to 0.70497) and lower $^{143}Nd/^{144}Nd$ ratios (0.51270 to 0.51288) of these granitic rocks, compared to the $^{87}Sr/^{86}Sr$ ratios (0.70271 to 0.70405) and $^{143}Nd/^{144}Nd$ ratios (0.51287 to 0.51313) of basaltic and dacitic rocks of the Taitao ophiolite (Kaeding et al., 1990), support this idea.

An important implication of these results is that granitic melts formed prior to the ridge subduction intrude into the overriding continental crust/accretionary complex and are more contaminated by subducted sediments or continental materials. Conversely, granitic melts formed during or after the ridge subduction retain information about their primary source region.

5.2 Implications of age distribution of the detrital zircon of the Main Volcanic Unit

Age distribution of the TPB338 detrital zircons from the Main Volcanic Unit provides information about generation of granitic magmas of the Cabo Raper pluton and the emplacement processes of the Taitao ophiolite. Nineteen out of 24 clastic zircon grains have Miocene to Pliocene spot ages ranging from 5.57 Ma to 4.89 Ma. The youngest age of clastic zircon implies that the volcaniclastic sequence was deposited after 4.89 Ma. The age distribution range coincides with the crystallization ages for the Taitao ophiolite and the Taitao granites, except for the Cabo Raper pluton. Nelson et al. (1993) and Veloso et al. (2007) showed that the interbedded sediments in the Main Volcanic Unit were derived from SE ~ ESE and deposited on a westward-facing slope on the basis of sedimentary structures and anisotropy of magnetic susceptibility fabrics. These results, together with age distribution of detrital zircons, support the idea that the clasts were derived from the Taitao ophiolite and granites. Another possibility is that the clasts were derived from age-equivalent volcanic rocks. However, considering the scarcity of zircons in volcanic (both felsic and mafic) rocks, this possibility is unlikely.

This paucity of the clastic zircons with pre-Jurrasic basement ages implies that a trench-slope break, that separated the depositional basin from the pre-Jurassic basement, had formed at the time of deposition of the volcaniclastic sequence. During our field study, we observed a subaerial pyroclastic deposit at the westernmost part of the Main Volcanic Unit. A part of the Taitao ophiolite must have been exposed and formed the trench-slope break (Fig. 5E). This conclusion is supported by rapid emplacement and exhumation of the ophiolite suggested by Anma et al. (2006).

If the trench-slope break had been formed just after the ophiolite emplacement, then detrital zircons in sediments deposited in newly formed trench basin (Fig. 5C and E) must have the similar age distribution to those of the TPB338 detrital zircons. Spot ages of the Cabo Raper pluton ranging from 4.20 Ma to 3.66 Ma do not overlap with those of TPB338 detrital zircons, and there are only few recycled zircons with pre-Miocene ages in the Cabo Raper pluton (Herve et al., 2003). Thus, there is no evidence for incorporation of the trench-fill sediments newly deposited after the ophiolite emplacement in the Cabo Raper pluton. Consequently, two source regions are possible for granitic magmas of the Cabo Raper pluton. One is in the western part of the same ridge segment in front of the trench basin (possible source region (1) in Fig. 5C), and the other is in eastern part of the ridge segment subducted at ~ 3 Ma (possible source region (2) in Fig. 5C) where subducted sediments might have been scraped off during the subduction of a transform fault that accompanied southward migration of the Chile triple junction. We prefer the former possibility because the Cabo Raper pluton is located in the south of the ophiolite. Thus, we conclude that the generation of magmas of the Cabo Raper pluton must be related to the 6 Ma ridge subduction event, and not to the later subduction event that started ~ 3 Ma.

5.3 Granitic melts formed due to ridge subduction

Figure 6 shows a possibility that granitic melts with various compositions may have formed due to the partial melting of subducted oceanic crust. We calculated normative An-Ab-Or compositions for the Taitao granites from the chemical data listed in Table 4 and compared them with experimental data of the melts produced by partial fusion of basalts, gabbros and amphibolites (Beard and Lofgren, 1990; Rapp et al., 1991; Patino Douce, 1995; Rapp and Watson, 1995; Springer and Seck, 1997; Sisson et al., 2005) and sediments (Patino Douce and Johnston, 1991; Vielzeuf and Montel, 1994; Patino Douce and Harris, 1998; Spicer et al., 2004) under pressure conditions less than 1 GPa.

The previous experimental studies suggest that granitic melts with compositions of the Tres Montes, Bahia Barrientos, Estero Cono and Cabo Raper plutons could be developed due to partial melting of amphibolites under pressure conditions less than 1 GPa. Granitic melts with the Seno Hoppner composition (with ~74 wt % SiO_2 contents), however, requires more complicated processes (Fig. 6). Our preliminary study implies that the Seno Hoppner granite alone exhibits a large negative Eu anomaly when compared to the other Taitao granites. This suggests that fractional crystallization modified the composition of primary melts of the Seno Hoppner granite.

The compositions of the subducting oceanic crust formed in the Chile ridge (Klein and Karsten, 1995; Karsten et al., 1996; Sherman et al., 1997) and of the mafic rocks of the Taitao ophiolite are diverse (Kaeding et al., 1990; Le Moigne et al., 1996; Guivel et al., 1999; Lagabrielle et al., 1994, 2000; Guivel et al., 2003). Thus, we expect that granitic melts with wide compositional variation could be formed due to partial melting of oceanic materials at shallow crustal levels (less than 1 GPa) during subduction of the Chile ridge.

6. Conclusion

We have demonstrated that the origin of granitic magmas that formed the Taitao granites was temporally related to the subduction of a short segment of the Chile ridge spreading center that started ~ 6 Ma ago; a part of the subducted spreading center is now preserved as the Taitao ophiolite.

The SHRIMP U-Pb ages for the Taitao ophiolite range from 5.66 ± 0.33 Ma to 5.22 ± 0.18 Ma, whereas those for the Taitao granites range from 5.70 ± 0.25 Ma to 3.92 ±

0.07 Ma. Our data indicates that the generation of the granitic melts started in the Tres Montes area during the inception of the ridge subduction. Generation of granitic melts continued as the spreading center of the ridge segment subducted, due perhaps to partial melting of the ophiolite and/or oceanic crust. Emplacement of the ophiolite and formation of continental crust took place almost simultaneously. Granitic magmas with various compositions were developed during the ridge subduction.

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