Contrasting rift and subduction-related plagiogranites in the Jinshajiang ophiolitic mélange, southwest China, and implications for the Paleo-Tethys

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The Jinshajiang ophiolitic mélange zone in southwest China represents a remnant of the eastern Paleo-Tethys Ocean. Field, geochronological and geochemical studies have identified two distinct suites of plagiogranites within the mélangé, the Dongzhulin trondhjemite and Jiyidu tonalite, which represent rift and subduction settings, respectively, related to opening and closing of the ocean. SHRIMP U-Pb analysis on zircons extracted from the Dongzhulin trondhjemite yields a mean 206Pb/238U age of 347 ± 7 Ma. REE and isotopic characteristics suggest an origin from low pressure partial melting of an amphibolitic protolith. Highly variable Hf isotopic compositions for zircons from this body may indicate a heterogeneous source involving both depleted mantle and enriched continental components. This, together with geologic relations, suggests formation near an embryonic spreading center in a continent-ocean transition setting. The Jiyidu tonalite has a U-Pb zircon age of 283 ± 3 Ma, and geochemical data indicates high Sr/Y, (La/Yb)N, Nb/Ta and low Y, and marked heavy REE depletion. These signatures suggest derivation from low degree partial melting of subducted slab at pressure high enough to stabilize garnet and rutile. A slab-melt origin is also supported by in situ Hf and O data for zircon that show isotopic compositions comparable with typical altered oceanic crust. Thus, the crystallization age of the Jiyidu high Sr/Y tonalite provides a constraint for the subduction of the Jinshajiang ocean floor. The rift-related Dongzhulin trondhjemite and subduction-related Jiyidu high Sr/Y tonalite constrain the timing and setting of opening and closing of this segment of the Paleo-Tethys Ocean.


1. Introduction

The recognition of ophiolites as fossil slices of oceanic lithosphere has played a major role in reconstructing ancient plate boundaries [Dilek and Robinson, 2003; Dilek and Furnes, 2011]. Plagiogranite is commonly present in the plutonic section of most ophiolites, forming a volumetrically minor part of a compositionally diverse ophiolite sequence. Plagiogranite magma can form by various processes including fractionation from a basaltic source [e.g., Aldiss, 1981; Floyd et al., 1998], and partial melting of metabasaltic and amphibolitic sources [Barker and Arth, 1976; Pedersen and Malpas, 1984; Koepke et al., 2004]. The generation of plagiogranite occurs in a variety of tectonic settings including high temperature shear zones close to a spreading ridge or in supra-subduction zones [Floyd et al., 1998; Li and Li, 2003; Koepke et al., 2007; Bonev and Stampflil, 2009]. Plagiogranite commonly contains zircon as a primary accessory mineral and is useful in constraining age and source through U-Pb, hafnium and oxygen isotopic analysis [e.g., Samson et al., 2004; Jiang et al., 2008].

Dismembered ophiolites associated with the Paleo-Tethyan ocean occur in N-S trending suture zones as part of the Sanjiang Orogen of southwest China (Figure 1) [Zhang et al., 1994; Zhong, 2000]. The suture zones (Lancangjiang-Changning-Menglian, Jinshajiang-Ailaoshan and Garze-Litang sutures) and adjoining magmatic belts constitute the dominant geological features of the region. Although the original ophiolite stratigraphy has been disrupted, slices displaying complete ophiolitic sequences [Dilek and Furnes, 2011] have been identified within the Jinshajiang suture zone [Mo et al., 1993; Zhang et al., 1994; Sun and Jian, 2004]. U-Pb geochronological data from the Jinshajiang ophiolites has revealed a wide age range spanning from Early Carboniferous to Permian (i.e., ~343 Ma to ~294 Ma) [Wang et al., 2000; Jian et al., 2008, 2009b]. Together with the apparent geochemical ambiguity of these rocks, this
Figure 1. Sketch map highlighting principal Paleo-Tethys suture zones (ophiolitic belts) and major litho-
tectonic units of the Sanjiang Orogen, southwest China. Suture zones concerned in this study: I. Garze-
Litang, II. Jinshajiang, III. Ailaoshan, IV. Changning-Menglian. Inset shows regional location of map area.
extends over the western Yangtze is restricted to the area [2009a, 2009b]. The Emeishan large igneous province that are also found in the serpentinite-matrix mélange [6]. shear, particularly in the serpentinized ultramafic rocks [2000a], and locally a [1995, 2000]. Strongly foliated amphibolite blocks occur within a N-S striking tectonic mélange [2000]. Basement of this terrane is represented by high-grade metamorphic rocks (the Damenglong, Diancangshan and Shigu complexes) in this terrane is represented by high-grade metamorphic rocks (the Damenglong, Diancangshan and Shigu complexes) in which amphibolites have Mesoproterozoic Sm-Nd whole-rock isochron ages [Zhong, 2000; Li et al., 2002]. The oldest exposed sedimentary rocks are Lower Ordovician metasedimentary rocks that are unconformably overlain by Middle Devonian conglomerates and shallow-marine sediments followed by Carboniferous to Permian shallow-marine, paralic and continental sediments with coal measures in places, and Lower-Middle Triassic shallow-marine clastics and carbonates [Bureau of Geology and Mineral Resources of Yunnan Province (BGMRYP), 1990].

The Jinshajiang ophiolites consist of a number of blocks that occur within a N-S striking tectonic mélangé zone along the Jinsha River over a distance of hundreds of kilometers (Figure 1). The ophiolite sequence shows an overall steep westerly dip. It is composed of serpentinized peridotite, deformed gabbros, mafic volcanic rocks including pillow basalts with intercalated limestone, and radiolarian cherts [Zhang et al., 1994] in a greenschist-facies matrix that comprises Permo-Carboniferous metasedimentary rocks (Gajinxueshan Group) [Wang et al., 2000], and locally a middle to late Triassic volcano-sedimentary succession [BGMRYP, 1990]. These rocks form slivers separated by cataclastic zones that show normal and right-lateral senses of shear, particularly in the serpentinized ultramafic rocks [Leloup et al., 1995]. Strongly foliated amphibolite blocks are also found in the serpentinite-matrix mélangé [Jian et al., 2009a, 2009b]. The Emeishan large igneous province that extends over the western Yangtze is restricted to the area east of the Jinshajiang suture, and its major eruption pulses occurred at ca. 260 Ma (Figure 1) [He et al., 2007; Zi et al., 2008, 2010].

The Jinshajiang ophiolite-bearing suture zone (and its southern extension) constitutes the eastern part of the so-called Sanjiang (Three Rivers) Orogen in southwest China, and marks the boundary between the Qamdo-Simao Terrane and the Yangtze Block (including the Songpan-Garze and Zhongga blocks) (Figure 1). The Qamdo-Simao Terrane is thought to have an affinity to the Yangtze Block (BGMRYP, 2000) or to represent the northern continuation of the Indochina Block [Metcalfe, 1996b, 2006]. To the west, this terrane is bounded by the Lancingang-Changling-Menglian suture zone which is generally considered to represent the main Paleo-Tethys seaway, and beyond which lie the Qiange-Sibumasu blocks of Gondwanan affinity (Figure 1) [Wu et al., 1995; Fang et al., 1998]. Basement of this terrane is represented by high-grade metamorphic rocks (the Damenglong, Diancangshan and Shigu complexes) in which amphibolites have Mesoproterozoic Sm-Nd whole-rock isochron ages [Zhong, 2000; Li et al., 2002]. The oldest exposed sedimentary rocks are Lower Ordovician metasedimentary rocks that are unconformably overlain by Middle Devonian conglomerates and shallow-marine sediments followed by Carboniferous to Permian shallow-marine, paralic and continental sediments with coal measures in places, and Lower-Middle Triassic shallow-marine clastics and carbonates [Bureau of Geology and Mineral Resources of Yunnan Province (BGMRYP), 1990].

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Figure 2
Trondhjemite samples were collected from a roadcut near Dongzhulin (28°18.151′N, 99°08.966′E), where the rock occurs as a leucocratic dike intruding layered gabbro. Plagioclase and quartz are the principal modal components withapatite, titanite and zircon as accessory phases. Plagioclase consisting of oligoclase (An11–16) is euhedral or subhedral and shows fine and compact polysynthetic twinning. Quartz forms a granophyric mosaic enclosing tabular plagioclase feldspar, and shows irregular intergrowth. Chlorite and epidote-group minerals have developed at the expense of plagioclase, but are mainly localized to cracks or mineral edges.

3.2. Jiyidu Intrusion

A well-developed cumulate complex, consisting of metamorphosed lherzolite (serpentinite), gabbro and tonalite intrusion, is located near the Jiyidu village (27°46.290′N, 99°15.278′E), which represents the southern segment of the Jinshajiang ophiolitic mélange zone (Figure 2a) [Zhang et al., 1992]. The Jiyidu tonalite body, about 20 m wide, intrudes serpentinized lherzolite. The rock is medium-grained with a granular or granophyric texture and is composed mainly of plagioclase (An16–28) and quartz. Plagioclase is euhedral and shows weakly positive compositional zoning. Hypidiomorphic granular quartz occurs as interstitial sub-grain filling among plagioclase crystals and shows undulatory extinction. Secondary chlorite and epidote are present in minor but variable amounts. Zircon and apatite are typical accessory minerals.

4. Zircon U-Pb Geochronology

4.1. Analytical Technique

Zircon U-Pb isotopic ratios were measured on the sensitive high-resolution ion microprobe (SHRIMP II) at Curtin University following procedures outlined by Williams [1998]. Details of sample preparation and analytical procedure can be found in the auxiliary material (Text S1). Zircon fragments of BR266 with an age of 559 Ma and U content of ~903 ppm [Stern, 2001], were used as the calibration standard. Errors for individual analyses are reported at 1σ level. Unless otherwise stated, all ages reported in the text are weighted mean 206Pb/238U ages and uncertainties are quoted at the 95% confidence level. Data processing was carried out using the Isoplot and Squid programs of Ludwig [2001a, 2001b].

4.2. Zircon U-Pb Data and Interpretation

4.2.1. Dongzhulin Trondhjemite

Zircons in sample SJ-151 from the Dongzhulin trondhjemite are generally subhedral grains or crystal fragments.
fragments up to ~70 μm in length. Most zircon grains exhibit oscillatory zoning in CL images (Figure 3a). SHRIMP U-Pb results for this sample are listed in Table 1 and plotted on a concordia diagram in Figure 4a. In situ zircon analysis reveals significant variation in Th and U concentrations (180–2340 ppm and 252–2683 ppm, respectively) with high and variable Th/U ratios ranging from 0.23 to 2.15, indicating a magmatic origin. The concordia plot for the 12 analytical spots shows mainly concordant analyses (Figure 3a). One spot, SJ151.12, is discordant with an obviously younger age (Table 1). Excluding this analysis, the 12 analytical spots shows mainly concordant analyses with high and variable Th/U ratios ranging from 0.23 to 2.15, indicating a magmatic origin. The concordia plot for the sample. Two analytical spots are discordant consisting of 10 concordant analyses yields a weighted mean 206Pb/238U age of 283 ± 3 Ma (MSWD = 1.03, 95% confidence level). This age is slightly older than the weighted mean for all fourteen concordant analyses, which in view of the bimodal distribution, is considered a more reliable estimate of the formation age of host plagiogranite. The other four analyses ranging in 206Pb/238U age from 271 Ma to 274 Ma, with a weighted mean of 273 ± 4 Ma (MSWD = 0.13), may reflect post-crystallization hydrothermal perturbation on zircon U-Pb systematics (e.g., lead loss).

5. Geochemical and Isotopic Characteristics

[14] Whole-rock major and trace element abundances and Sr-Nd isotopic ratios were determined at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS). In situ zircon Lu-Hf isotope analyses were performed at the Hong Kong University by an ArF excimer laser.
laser ablation system, attached to a Neptune Plasma multicollector ICP-MS. Zircon oxygen isotope data were obtained using a Cameca IMS 1280 multicollector ion microprobe located at the Centre for Microscopy, Characterization and Analysis (CMCA) at the University of Western Australia. The pits generated by SHRIMP analysis were targeted when analyzing oxygen isotopes. Refer to Text S1 for detailed analytical techniques and parameters applied in analyses of major and trace elements, Sr-Nd isotopes and zircon in situ hafnium and oxygen isotopes.

5.1. Whole-Rock Geochemistry

Data of major and trace elements of the plagiogranites are listed in Table 2. The well-preserved igneous texture and the relatively low loss on ignition (LOI) of the samples suggest that effects of alteration and/or metamorphism are minor, with the obtained chemical data largely reflecting the primary composition of the rocks.

The Dongzhulin trondhjemite has high SiO$_2$ (~75.8 wt%) and Na$_2$O (~5 wt%), and low Al$_2$O$_3$ (<13 wt %), MgO (~0.69 wt%), Fe$_2$O$_3$ (~1.14 wt%) and CaO (~1.75 wt%) with metaluminous character (A/NCNK = 0.96–0.98) and are classified as high silica-low alumina trondhjemites [Barker and Arth, 1976]. In terms of trace elements, they exhibit low Rb and Sr concentrations. Chondrite-normalized REE patterns show fractionated light REE ((La/Sm)$_N$ = 4.9–5.1) and flat heavy REE ((Gd/Yb)$_N$ = 0.9–1.2) profiles, with apparent negative europium anomaly (Eu/Eu$^*$ = 0.59) (Figure 5a). On a multielement spider diagram (Figure 5b) the samples normalized to primitive mantle display large-ion lithophile element (LILE) enrichment relative to high-field strength elements (HFSE). The trondhjemites are characterized by notable Nb-Ta, and Ti depletions and variable Sr anomalies, but at higher abundances relative to primitive mantle (Figure 5b).

The Jiyidu samples are mildly peraluminous (A/NCNK = 1.05–1.13) with high Al$_2$O$_3$ (16.19–16.48 wt.%), Na$_2$O (5.03–5.82 wt.%) and Mg# (68–72), but are low in K$_2$O (0.89–1.63 wt.%), Fe$_2$O$_3$ (1.74–1.99 wt.%), TiO$_2$ (0.29–0.31 wt%) and P$_2$O$_5$ (~0.1%) at SiO$_2$ contents of 69.75–70.30 wt.% (Table 2). They have low REE abundances (total REE = 40–52 ppm), and resemble those of the other ophiolitic rocks in the suture zone [Zhang et al., 1994; Jian et al., 2009a]. When normalized to chondritic values, the samples display strongly fractionated REE patterns (Figure 5c), with significant LREE enrichment relative to HREE.
Table 2. Whole-Rock Chemical and Sr-Nd Isotopic Compositions of the Dongzhulin and Jiyidu Plagiogranites

<table>
<thead>
<tr>
<th>Sample</th>
<th>SJ-98</th>
<th>SJ-100</th>
<th>SJ-101</th>
<th>SJ-151</th>
<th>SJ-152</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ (wt %)</td>
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<td>68.73</td>
<td>68.34</td>
<td>75.80</td>
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</tr>
<tr>
<td>TiO₂ (wt %)</td>
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<td>0.29</td>
<td>0.30</td>
<td>0.30</td>
<td>0.31</td>
</tr>
<tr>
<td>Al₂O₃ (wt %)</td>
<td>15.93</td>
<td>15.82</td>
<td>16.14</td>
<td>12.98</td>
<td>12.58</td>
</tr>
<tr>
<td>Fe₂O₃ (wt %)</td>
<td>1.69</td>
<td>1.90</td>
<td>1.95</td>
<td>1.18</td>
<td>1.08</td>
</tr>
<tr>
<td>MgO (wt %)</td>
<td>1.91</td>
<td>2.05</td>
<td>1.87</td>
<td>0.55</td>
<td>0.81</td>
</tr>
<tr>
<td>MnO (wt %)</td>
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<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>CaO (wt %)</td>
<td>2.32</td>
<td>1.89</td>
<td>3.40</td>
<td>1.93</td>
<td>1.53</td>
</tr>
<tr>
<td>Na₂O (wt %)</td>
<td>5.66</td>
<td>5.36</td>
<td>4.92</td>
<td>5.59</td>
<td>5.55</td>
</tr>
<tr>
<td>K₂O (wt %)</td>
<td>1.51</td>
<td>1.59</td>
<td>0.87</td>
<td>0.52</td>
<td>1.16</td>
</tr>
<tr>
<td>P₂O₅ (wt %)</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>LOI (wt %)</td>
<td>2.37</td>
<td>1.86</td>
<td>1.65</td>
<td>0.72</td>
<td>0.65</td>
</tr>
<tr>
<td>Total (wt %)</td>
<td>99.64</td>
<td>99.62</td>
<td>99.57</td>
<td>99.65</td>
<td>99.54</td>
</tr>
</tbody>
</table>

6. Discussion

6.1. Genesis of the Dongzhulin Trondhjemite

[22] The Dongzhulin trondhjemites have initial Sr and Nd isotopic ratios analogous to that of the Paleo-Tethys mantle [Zhong, 2000; Wei et al., 2003]. The presence of high initial Hf isotopic ratios (εHf(t) up to 18, Table 3 and Figure 6a) for zircons from this intrusion also suggests they are derived from a depleted mantle source. Geochemical characteristics combined with field occurrence intimately associated with the Jinhajiang ophiolite complex, indicate oceanic plagiogranite affinities for the Dongzhulin body. Several models for the petrogenesis of oceanic plagiogranite have been put forth.
forward, including (a) extreme fractionation of mid-ocean ridge basaltic melts [e.g., Aldiss, 1981; Floyd et al., 1998], (b) partial melting of hydrated basaltic/gabbroic protoliths [e.g., Barker and Arth, 1976; Pedersen and Malpas, 1984; Koepke et al., 2004], and (c) silicate immiscibility of an evolved tholeiitic liquid [Dixon and Rutherford, 1979]. The high Mg# but low TiO2 of the Dongzhulin trondhjemites present a striking contrast to the majority of plagiogranites that formed through MORB differentiation or immiscibility (Mg# < 40, TiO2 > 1%) [Barker and Arth, 1976; Dixon and Rutherford, 1979; Koepke et al., 2007]. However, these features are compatible with a genesis by anatexis of basaltic sources, as experimentally demonstrated by Koepke et al. [2004]. On the other hand, LREE enrichment relative to HREE and a negative europium anomaly observed in the Dongzhulin samples (Figures 5a and 5b) also favor an origin from partial melting of gabbroic/basaltic rocks [e.g., Flagler and Spray, 1991; Floyd et al., 1998; Bonev and Stampfli, 2009]. This is in contrast to plagiogranites produced by low-pressure crystal fractionation of a MORB source which generally show flat/unfractionated REE patterns, subparallel to those of MORB-type parents [e.g., Pallister and Knight, 1981; Pedersen and Malpas, 1984; Floyd et al., 1998; Dilek and Thy, 2006].

Undepleted/flat heavy REE profiles suggest that the trondhjemite liquid were generated in a low-pressure (garnet-absent) field. Residues from partial melting containing plagioclase, hornblende (and/or pyroxene) and accessory minerals may be responsible for the high silica, low Al2O3, TiO2 and P2O5 and negative europium anomaly observed in the Dongzhulin samples. Gabbro and amphibolite were tested, respectively, as possible parents of the trondhjemite by REE-modeling partial melting. Gabbros from the Jinshajiang ophiolitic assemblage show slight depletion of light REEs (Figure 5a) [Jian et al., 2009a]. Following the batch melting equation of Shaw [1970], partial melting of the Jinshajiang gabbro with residual plagioclase and clinopyroxene can generate the negative Eu anomalies in the resulting melts, but fails to account for the enrichment of light REEs of the Dongzhulin trondhjemite, because of the relatively flat REE patterns (except for the Eu anomaly) for both plagioclase and clinopyroxene [Arth, 1976]. Assuming the amphibolite xenolith [Jian et al., 2009a] as a starting material and using the partition coefficients of Arth [1976], the resulting melts of 30–40% batch melting leaving behind...
85% plagioclase and 15% hornblende yield the REE distribution patterns matching well with that of the Dongzhulin trondhjemite (Figure 5a).

[34] The well-known resilience of zircon to Hf isotopic disturbance during post-crystallization processes makes Hf composition of zircon a reliable geochemical tracer to elucidate the origin of a host rock [Kinny and Maas, 2003]. Zircons from the Early Carboniferous trondhjemite show a broad range up to ∼30 ε units for a single sample, with maximum εHf(t) equivalent to depleted mantle value (Table 3 and Figure 6a). This is consistent with a mantle-derived amphibolite as its precursor. The negative shift of the εHf(t) values might have been enhanced by incorporation of inclusions or possible xenocrysts zircons during analysis, in view of the small grain size and complicated morphology of the Dongzhulin zircons (Figure 3a). If the considerable variability (probably to a less extent) is genuine, this indicates that magmas forming the trondhjemite intrusions were heterogeneous in Lu/Hf ratios during periods of zircon saturation (Figure 6b). The highly negative εHf(t) values require an additional component of nonradiogenic Hf to be present, which is likely to be a continental contaminant [Griffin et al., 2000]. Zircons crystallizing from magmas formed by variable degrees of interaction of the depleted source with the extra low Lu/Hf component tend to show within-sample Hf isotope variations in excess of analytical error [Griffin et al., 2002; Hawkesworth and Kemp, 2006]. We therefore suggest that the magmas from which the trondhjemite zircons crystalized were derived from depleted mantle-type sources, and developed negative εHf(t) through reaction with ancient continental materials, which also accounts for the LIL enrichment and negative Nb and Ti anomalies (Figure 5c) and the presence of the Proterozoic Hf model ages (TDM = 1.42–2.53 Ga; Table 3 and Figure 6a).

6.2. Genesis of the Jiyidu High-Sr/Y Tonalite

[25] The Jiyidu tonalite samples share some similarities with the Dongzhulin trondhjemite in terms of geochemical characteristics such as high Na2O-low K2O, HSFE-depletion and presence of MORB-like Sr-Nd isotopic compositions. However, they are distinguished by high Al2O3, Sr (374–480 ppm, positive Sr anomaly in spidergram) and Sr/Y ratios
(42–61), and depletion of heavy REEs (Table 2 and Figure 5c). Moreover, they have elevated SiO$_2$ (67.85–68.73%) and Na$_2$O/K$_2$O (3.36–5.63), but low MgO (1.87–2.05%) and TiO$_2$ (0.29–0.31%). All these characteristics are reminiscent of those of the adakites (*sensu stricto*) of Defant and Drummond [1990] or the high-silica adakites of Martin et al. [2005].

[26] Primitive mantle normalized multielement diagrams for the Jiyidu high Sr/Y tonalites show LILE-enrichment and HFSE-depletion profiles and consequential high LILE/HFSE ratios, characteristic of island arc-related petrogenesis (Figure 5d). The Jiyidu samples have relatively high Hf contents and (Hf/Nd)$_N$ ratio, both pertinent to proto-arc magma genesis [Pearce et al., 1999]. Their moderately high Sr abundance, as shown by the Sr spike, and absence of negative Eu anomaly in the spidergram, preclude substantial plagioclase in the residual phase. The negative Nb and Ta anomalies, and the elevated Nb/Ta ratios (11–14) likely reflect the presence of rutile as a high pressure phase [Green, 1995].

[27] Elevation of Sr/Y and depletion of the heavy REEs, can be achieved via different processes including deep fractionation of a garnet-dominated assemblage, partial melting of subducted oceanic slab or mafic lower crust with abundant residual garnet or interaction of felsic melts with the mantle [e.g., Petford and Gallagher, 2001; Garrison and Davidson, 2003; Wang et al., 2005; Macpherson et al., 2006; Richards and Kerrich, 2007]. High pressure fractional crystallization of garnet may account for the depletion of heavy REEs and high Sr/Y, but fails to explain the enrichment of light REEs. Melting of mafic lower crust may be the source for high-Sr/Y rocks in some intracontinental or arc settings in response to significant thickening of crusts [e.g., Wang et al., 2005; Schwartz et al., 2011], but this is generally restricted to the late stages of a collisional orogenesis, and such a source is inconsistent with the high Mg# and Na$_2$O/K$_2$O of the Jiyidu high Sr/Y tonalite. Geochemical modeling has revealed that the classic slab melting model provides the most plausible explanation for genesis of high-silica adakites [Martin et al., 2005; Moyen, 2009], which reinforces the prevailing views relating generation of *sensu* adakite to the subduction of oceanic lithosphere [Defant and Drummond, 1990; Peacock et al., 1994; Drummond et al., 1996; Stern and Kilian, 1996; Smithies and Champion, 2000; Bourdon et al., 2002]. Striking geochemical similarities between the Jiyidu high-Sr/Y tonalite and the high-silica adakites, make a slab-melting model also applicable for genesis of the former. Moreover, the studied samples from Jiyidu display uniformly low ISr of $/C24$0.7045 and positive $\varepsilon^{Nd}(t)$ of 2.18 (Table 2) similar to the Sr-Nd isotopic values.

Table 4. Oxygen Isotopic Composition of the Dongzhulin and Jiyidu Plagiogranites

<table>
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<th>Analysis Number</th>
<th>Zircon $\delta^{18}O$ (‰)</th>
<th>$\pm 2\sigma$</th>
<th>Calculated Melt $\delta^{18}O$ (‰)</th>
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<td><strong>Jiyidu Tonalite (SJ-101)</strong></td>
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<td>01</td>
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Figure 6. Hf isotope composition of the ophiolitic plagiogranites from the Jinshajiang zone showing highly heterogenous Hf compositions for the Early Carboniferous Dongzhulin trondhjemite (diamonds) and predominantly positive $\varepsilon^{Hf}(t)$ values for the Early Permian Jiyidu high Sr/Y tonalite (squares).
for the Jinshajiang MORBs [Xu and Castillo, 2004], consistent with a slab-melt origin.

Further compelling evidence in favor of a slab-melt origin derive from zircon Hf and O isotopic systematics. The predominantly positive $\varepsilon_{\text{Hf}}(t)$ values (4.9–11, except for one spot –4.5; Table 3 and Figure 6) for zircons from Jiyidu high-Sr/Y tonalite indicate a variably depleted precursor, compatible with a derivation from partial melting of subducted oceanic slab. The mantle-like $\varepsilon_{\text{Hf}}(t)$ together with the relatively low ISr values rule out appreciable involvement of subducted sediments into the adakitic melts, consistent with trace element modeling which shows that low-degree (≈20%) partial melting of an eclogitic MORB (see Stern and Kilian [1996] for parameters and distribution coefficients used in the partial melting modeling) with little contribution from sediments can produce the Sr-Y signature observed in the Jiyidu tonalite (Figures 8a and 8b). High Mg# and Ni and Cr contents are similar to those of high-silica adakites [Martin et al., 2005], but clearly higher than in experimental liquids obtained by basalt or amphibolite melting [Rapp and Watson, 1995]. These differences are generally interpreted to result from interaction of the slab derived melts with mantle peridotite as they rise through the overlying mantle wedge [Yogodzinski et al., 1995; Stern and Kilian, 1996; Rapp et al., 1999; Smithies and Champion, 2000].

The measured zircon $\delta^{18}$O values for the Jiyidu high-Sr/Y tonalite range from 6.06 to 6.80‰ with a weighted mean of 6.37 ± 0.13‰. The calculated $\delta^{18}$O values for the silicate melts in equilibrium with these zircons vary between 7.72‰ and 8.46‰ (Table 4 and Figure 7), higher than the normal mantle value of ~5.5‰ [Eiler et al., 2000; Valley, 2003]. This is consistent with the observation that slab-melt derived adakitic magmas as a group are $^{18}$O enriched compared to fresh MORBs and typical arc basalts, as documented by modern adakites in Fiji and Kamchatka [Bindeman et al., 2005]. Such a deviation can be interpreted as inheritance from high-$^{18}$O altered basaltic upper oceanic crust with or without contribution of sediments [McCulloch et al., 1981; Stakes et al., 1984; Staudigel et al., 1995; Bindeman et al., 2005]. The whole-rock $\delta^{18}$O values for the Jiyidu high-Sr/Y tonalite fall within the range typically observed for the basaltic sections of ophiolites [Gregory and Taylor, 1981; Cocker et al., 1982; Putlitz et al., 2000; Eiler, 2001; Stakes and Taylor, 2003], and in the range for MORB-type eclogites from the Raspas Complex, Ecuador (Figure 7) [Halama et al., 2011]. Furthermore, these values overlap with those of the altered (lower greenschist facies) upper oceanic crust ($\delta^{18}$O = 7.1–8.8‰) recorded for the Macquarie Island ophiolite (Figure 7) [Cocker et al., 1982], in accordance with the above contention suggesting such rocks as magma source.

6.3. Geodynamic Significances and Implications for the Paleo-Tethys at Jinshajiang Segment

6.3.1. Geodynamic Significances Inferred From Geochemical and Geochronologic Data
sources. But the differences between the two bodies in REE distribution patterns along with multiple isotopic features indicate distinct tectonic settings.

[31] The Dongzhulin body probably originated from hydrous partial melting of an altered gabbroic/amphibolitic protolith. The Sr-Nd isotopic data (1 parameter = 0.70448, $\varepsilon_{Nd}(t) = 3.34$) are permissive of mantle-derived protoliths. The ca. 443–401 Ma amphibolites with low-Ti tholeiitic composition [Jian et al., 2009a, 2009b] that are entrapped within the Jinshajiang ophiolite are a plausible candidate for such a source. Anatectic amphibolite in high-temperature shear zones in proximity to a spreading center has been demonstrated to be a feasible mechanism generating plagiogranite liquid [e.g., Flagler and Spray, 1991]. This is consistent with the in situ zircon oxygen isotopic data which show low $\delta^{18}$O values (3.49–4.57‰, Table 4) for the Dongzhulin trondhjemite relative to normal mantle ($\delta^{18}$O/C24 = 5.3‰ [Valley, 2003]) and suggests that the rocks or the amphibolite precursors might have experienced high-temperature hydrothermal alteration [Gregory and Taylor, 1981; Cocker et al., 1982], in response to heat input from a spreading center. The significant zircon Hf isotopic variant exhibited by the Dongzhulin trondhjemite (Table 3 and Figures 6a and 6b) suggests a highly heterogenous source, which may reflect involvement of an enriched source (i.e., continental materials) into depleted melts. Together, the above observations imply that the oceanic crust preserved in the Dongzhulin ophiolite was generated in the ocean-continent transition setting in which both enriched continental materials and depleted mantle source were readily involved. Some basalt and diabase samples from the Jinshajiang ophiolite exhibit an overall EMORB affinity [Mo et al., 1994], compatible with the above scenarios. If this inference is correct, the ca. 347 Ma igneous age obtained from the Dongzhulin trondhjemite provides an older age for the onset of Jinshajiang seafloor spreading.

[32] Identification of high Sr/Y and MORB-like Sr-Hf-O isotopic signatures (highly resemble those of the classic adakites, [Defant and Drummond, 1990; Moyen, 2009]) on the Jiyidu tonalite body suggests an oceanic subduction setting. The 283 ± 3 Ma SHRIMP zircon U-Pb age yielded from the high Sr/Y tonalite provides a minimum estimate for the age of the oceanic crust produced by the intraoceanic subduction within the Jinshajiang branch. This age is comparable with an Alaska-type zoned mafic-ultramafic complex occurring in the southern Lancangjiang zone, which is believed to represent a plutonic arc produced by the early stage westward subduction of the branch ocean beneath the Qamdo-Simao Terrane [Zhang et al., 1994], and yields U-Pb zircon age of ca. 286 Ma [Jian et al., 2009b], representing the oldest arc related magmatism recorded in the zone.

[33] Our new zircon ages of the plagiogranite samples from Dongzhulin and Jiyidu show a ~60 Ma age difference. No single ophiolite with a single tectonic pathway for its igneous evolution displays such a large age gap [Dilek and Robinson, 2003]. Therefore, the plagiogranites and the ultramafic-mafic associations within the Jinshajiang tectonic zone likely represent different geodynamic settings. In light of the recent ophiolite classification scheme of Dilek and Furnes [2011], the 347 ± 7 Ma trondhjemite and associated ultramafic-mafic rocks formed part of a continental margin ophiolite at an Ocean-Continent Transition (OCT) during the rift-drift tectonics of the Jinshajiang ocean basin, whereas the 283 ± 3 Ma high Sr/Y tonalite and associated
ultramafic-mafic rocks may have formed part of a volcanic arc ophiolite after the inception of an intraoceanic subduction zone within the Jinshajiang ocean basin. These contrasting environments were tectonically telescoped during orogeny as the Jinshajiang ocean basin closed and the bounding continents collided resulting in the formation of an ophiolitic mélange zone \cite{Dilek and Flower, 2003; Festa et al., 2010}.

6.3.2. Implications for the Paleo-Tethys

Paleogeographic reconstruction suggests that the late Paleozoic to early Mesozoic Paleo-Tethys in Southeast Asia was characterized by an archipelago of arcs or continental ribbons separating multiple seaways (Figures 9a and 9b), a configuration analogous to the present-day southwest Pacific \cite[e.g., Metcalfe, 1996a; Pan et al., 1997; Zhong, 2000; Pan et al., 2003; Metcalfe, 2006].

Figure 9. Paleogeographic reconstructions of the Tethyan region placing the study area in a regional context in (a) Early Carboniferous and (b) Early Permian \cite[after Metcalfe, 2006]. YZ = Yangtze; T = Tarim; IC = Indochina; NC = North China; QS = Qamdo-Simao; S = Sibumasu; Q = Qiangtang; L = Lhasa; ZZ = Zhongza. Cartoons (not to scale) illustrating opening and subduction scenarios of the Paleo-Tethyan Jinshajiang Ocean with respect to formations of the two types of oceanic plagiogranites. (c) Formation of the ca. 347 Ma Dongzhulin trondhjemite during opening of the Jinshajiang oceanic basin in the Early Carboniferous, was preceded by lithospheric extension and rift magmatism over the western Yangtze; (d) Formation of the ca. 283 Ma Jiyidu high-Sr/Y tonalite indicates an ongoing subduction of the Jinshajiang oceanic lithosphere in the Early Permian, and birth of an intraoceanic island arc. Positions of transects are marked as red line in Figures 9a and 9b.
Paleozoic extension-related magmatism [Mo et al., 1993; Jian et al., 2009a] in the Jinshajiang suture zone suggests that opening and spreading of the Jinshajiang branch ocean was preceded by intracontinental extension and rifting over the western Yangtze margin, probably in the middle to late Devonian [Feng et al., 1999], with the rift succession comprising Late Devonian conodont and radiolarian-bearing limestone and turbidite sequences [Sun and Jian, 2004]. The presence of zircon grains yielding apparently older ages (ca. 375 Ma, [Jian et al., 2008]) against the predominant Permo-Carboniferous age obtained from gabbro-anorthosite components of the Jinshajiang ophiolite may also be attributed to an early phase of continental rift-related magmatism in the Late Devonian. Our new SHRIMP U-Pb age (347 ± 7 Ma) from the Dongzhulin trondhjemite, along with an age of ca. 343 Ma for a cumulate gabbro [Jian et al., 2009b] are the oldest precise igneous ages for the Jinshajiang ophiolite. This constrains the onset of spreading of the Paleo-Tethyan Jinshajiang branch to be of Early Carboniferous age or earlier (Figures 9a and 9c).

Given that the Jinshajiang and Ailaoshan belts (see Figure 1) have comparable lithological assemblages and deformation-metamorphic history, it is suggested that ophiolites occurred in both belts are contiguous and represent the same ocean basin (Figure 9a) [Metcalfe, 1996a; Zhang et al., 1996; Pan et al., 1997; Wang et al., 2000]. However, as previously demonstrated by Wang et al. [2000] and Jian et al. [2008, 2009b], and affirmed by the present study, the earliest age of the Jinshajiang ophiolites (ca. 347–343 Ma) is apparently younger than that of the Ailaoshan ophiolites (ca. 383–376 Ma, [Jian et al., 2009b]), which indicates a significant difference between timing of initial spreading of the two segments. This may indicate diachronous opening of the branch ocean [e.g., Zhang et al., 1996; Pan et al., 1997; Zhong, 2000].

Despite considerable debate over nature and scale of the Jinshajiang-Ailaoshan ocean [e.g., Mo et al., 1993; Wu et al., 2000; Zhong, 2000; Fan et al., 2010], it is generally believed that this branch of the Paleo-Tethys attained its widest expanse in the Late Carboniferous to Early Permian [Sun and Jian, 2004] and began the process of closure through westward subduction (present-day coordinates), while the main ocean floor was being consumed beneath the Qamdo-Simao Terrane at a east-dipping subduction zone [Wu et al., 2000; Zhong, 2000; Wang et al., 2010] (Figures 8b and 8d). Radiometric dating of hornblende from an andesite in the arc created by subduction of the Jinshajiang oceanic slab yielded K/Ar ages of 269–257 Ma [Wang et al., 1999]. The ca. 283 Ma Jiyidu high-Sr/Y tonalite in this study may record an early episode of magmatism triggered by deep-seated partial anatexis of the oceanic slab in the Early Permian, and thus demonstrate that subduction of the Jinshajiang ocean was in operation at that time. Subduction of the Jinshajiang oceanic lithosphere likely facilitated separation of a micro-continental sliver, the Zhongza terrane (Figure 1), from the Yangtze block through opening a smaller Paleo-Tethys branch (the Garze-Litang ocean) along the western Yangtze since the Early Permian time (Figures 9b and 9d), as evidenced by recognition of the Garze-Litang ophiolitic belt (Figure 1) [Zhang et al., 1994; Pan et al., 2003], in which a gabbro yielded a SHRIMP zircon U-Pb age of ca. 292 Ma [Yan et al., 2005].

## 7. Conclusions

Two suites of plagiogranites sampled from the Jinshajiang ophiolitic mélangé zone show divergent ages, trace element and isotopic features indicative of distinct geodynamic settings within the Paleo-Tethys.

 Petrology and geochemistry of the Dongzhulin trondhjemite suggest a derivation from partial melting of an amphibolitic protolith in response to heat input from an upwelling asthenospheric mantle near the newly formed spreading center. The low-Ti tholeiitic rocks (metamorphosed to amphibolites) that were emplaced during a preceding rift magmatic episode occur as xenoliths within the ophiolitic assemblage and represent a plausible source for the trondhjemite. The Early Carboniferous (ca. 347 Ma) SHRIMP U-Pb age for this trondhjemite intrusion provides a minimum estimate for the onset of seafloor spreading.

The Jiyidu high-Sr/Y tonalite demonstrates geochemical and isotopic signatures in common with slab melt-derived adakites. We propose an origin from melting of the subducted Paleo-Tethys Oceanic crust within the garnet-bearing source region for this intrusion. Therefore, its crystallization age (ca. 283 Ma) indicates ongoing subduction of ocean floor in the Early Permian. This is compatible with a scenario where the Jinshajiang oceanic basin achieved its maximum width in the Late Carboniferous to Early Permian, and then began to shrink by the west-dipping subduction of its oceanic lithosphere, an event possibly accompanied by the opening of a smaller Garze-Litang ocean in its wake.

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## References


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