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#### **Key Points:**

- Oceanic plagiogranite results from protracted fractional crystallization of parental ocean ridge basaltic magmas
- Fractional crystallization of Fe-Ti oxides results in felsic melts solidified to form plagiogranite in ocean crust
- Multiple small melt batch intrusion and differentiation are primary mechanism of ocean crust accretion at slow-spreading ridges

#### **Supporting Information:**

- Supporting Information S1
- Table S1
- Table S2
- Table S3
- Table S4
- Table S5
- Table S6

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# Petrogenesis of ODP Hole 735B (Leg 176) Oceanic Plagiogranite: Partial Melting of Gabbros or Advanced Extent of Fractional Crystallization?

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Abstract Oceanic plagiogranite was first defined by Coleman in 1975 as an assemblage of felsic rocks in the ocean crust and is the sole rock type in ophiolites for age dating. However, the petrogenesis of these felsic rocks remains controversial. Some consider them as partial melting products of gabbros, while others interpret them as representing highly evolved residual melt of ocean ridge magmatism. To resolve this debate, we focus our study on felsic veins from Ocean Drilling Program Hole 735B (Leg 176) in the Southwest Indian Ridge. We carried out detailed petrography, mineral compositional analysis, bulk-rock trace element, and Sr-Nd-Pb-Hf isotope analysis and petrological modeling. These data and observations lead to the conclusion that these felsic vein lithologies (i.e., oceanic plagiogranite) are solidified residual melts after advanced extents of fractional crystallization of ocean ridge basaltic magmas, rather than partial melting products of gabbros. At the late stage of mid-ocean ridge basaltic magma evolution, Fe-Ti oxides appear on the liquidus to crystallize, resulting in the residual melts rapidly enriched in SiO<sub>2</sub>. Such silicic melts are buoyant and can transport through "cracking" within the lithologies of the gabbroic sections of the ocean crust in the form of felsic dykes, veins, and veinlets. The volumetrically small ( $\sim 0.5\%$ ) but widespread plagiogranite veins and veinlets throughout the gabbroic sections provide evidence that multiple small melt batch intrusion and differentiation are primary mechanism and mode of ocean crust accretion at slow-spreading ridges.

# 1. Introduction

Oceanic plagiogranite refers to felsic rocks such as diorite, quartz diorite, tonalite, and trondhjemite found in the gabbroic sections of the ocean crust. These felsic rocks are dominated by plagioclase and quartz with minor ferromagnesian minerals and accessory phases. They are chemically characterized by high SiO<sub>2</sub>, Na<sub>2</sub>O, and CaO and low K<sub>2</sub>O and FeO<sup>T</sup> (Coleman & Donato, 1979; Coleman & Peterman, 1975). They have been well documented in the present-day ocean crust (e.g., Bortnikov et al., 2005; Dick et al., 2000; Nakamura et al., 2007; Nguyen et al., 2018; Silantyev et al., 2010) and many ophiolites (e.g., Amri et al., 1996; Coleman & Peterman, 1975). Though oceanic plagiogranites are volumetrically minor, accessory minerals such as zircon, apatite, and titanite they contained allow for dating the emplacement ages of the ocean crust and ophiolite complexes (e.g., Mukasa & Ludden, 1987; Schwartz et al., 2005). However, their origin remains under debate. Several models have been proposed, such as (1) partial melting of hydrated gabbros (Flagler & Spray, 1991; Koepke et al., 2004, 2007), (2) silicate liquid immiscibility (Charlier & Grove, 2012; Dixon & Rutherford, 1979; Holness et al., 2011; Natland et al., 1991), and (3) fractional crystallization at a late stage of basaltic magma evolution (Coleman & Donato, 1979; Coleman & Peterman, 1975; Niu et al., 2002). Experimental studies suggest that all these processes could produce high SiO<sub>2</sub> melts (e.g., Berndt et al., 2005; Dixon & Rutherford, 1979; France et al., 2010; Koepke et al., 2004; Koepke et al., 2018; Spulber & Rutherford, 1983), but it is important to correctly understand which one of these scenarios is actually at work to the ocean ridge magmatism, especially the ways of melt supply and differentiation that built the ocean crust.

The Ocean Drilling Program (ODP) Hole 735B in the Southwest Indian Ridge (SWIR) is one of the few boreholes that have recovered in situ oceanic plagiogranites (Casey, 1997; Dick et al., 2000; Hébert et al., 1991).





Table 1

Comparison of "Partial Melting Model" and "Silicate Liquid Immiscibility Model" With "Fractional Crystallization Model" for the Petrogenesis of Felsic Veins in Leg 176

Observation		Hydrous gabbro partial melting model	Silicate liquid immiscibility model	Fractional crystallization model
[1]	Magma source	Hydrous gabbros	Differentiated basaltic magma	Differentiated basaltic magma
[2]	Experimentally produced SiO <sub>2</sub> -rich melt	Yes	Yes, but the liquid immiscibility does not occur in "wet" experiments	Yes
[3]	Explanation for the close association with oxide gabbro	No	Yes	Yes
[4]	Explanation for the existence of euhedral Fe-Ti oxides	No	Yes	Yes
[5]	Explanation for the existence of albite	No	N/A	Yes
[6]	Explanation for the existence of zircon, apatite, and other accessory minerals	No, unless diminishingly small degree of melting in theory	Yes	Yes
[7]	Explanation for the correlation between bulk-rock MgO and Sc, V, Co, and Ni of gabbro and felsic vein in ODP Hole 735B	N/A	N/A	Yes
[8]	Explanation for the anomalies of Zr, P, and Ti of felsic vein in ODP Hole 735B	No	N/A	Yes
[9]	Explanation for the wide distribution of felsic veins in ODP Hole 735B	No	Yes	Yes
[10]	Mantle isotope signature	Yes, but Sr isotope is expected to show significant seawater signature	Yes	Yes

*Note*. ODP = Ocean Drilling Program.

Though oceanic plagiogranites from ophiolites can provide better outcrop scale relationships within the ophiolite sequences, the drill core samples with known in situ lithostratigraphic context offer prime opportunity to understand their petrogenesis. Hence, we choose to study the present-day plagiogranites (felsic veins/veinlets) from ODP Hole 735B (Leg 176). These felsic veins/veinlets together with gabbros have been documented by Niu et al. (2002) during the drilling. In this paper, we present new data on mineral compositions, bulk-rock trace element, and Sr-Nd-Pb-Hf isotope compositions and use these data, together with the literature data, to discuss the petrogenesis of these felsic vein lithologies through illustrations and demonstrations.

For clarity, we summarized our result in Table 1 by comparing the efficacies of the three scenarios in explaining all the observations. We conclude that the Hole 735B felsic veins are most consistent with being products of advanced extents of fractional crystallization from their parental ocean ridge basaltic magmas. In the following sections, we show the data and discuss why and how we have reached the conclusions in Table 1.

# 2. Geological Background and Petrology of the Felsic Veins

## 2.1. Geological Background

The ODP Hole 735B ( $32^{\circ}43'S$ ,  $57^{\circ}17'E$ ) was drilled at the SWIR during Leg 118 (Robinson et al., 1989) and Leg 176 (Dick et al., 1999). It is located on the Atlantis Bank, which is a wave-cut platform on the east side of the Atlantis II Fracture Zone, ~ 93 km south of the present-day SWIR axis (Figure 1). The SWIR separates the African and Antarctic plates with a half spreading rate of ~8 mm/year (Robinson et al., 2000), which is classified as a slow- and ultraslow-spreading ridge (Dick et al., 2003). The Hole 735B drilled into the ~11 Ma old lower ocean crust was dated using zircon U-Pb and biotite  ${}^{40}$ Ar/ ${}^{39}$ Ar methods (John et al., 2004; Schwartz et al., 2005). It was first drilled to 504.8 m below the sea floor (mbsf) during ODP Leg 118 in 1987 and then





**Figure 1.** Bathymetric map of the Atlantis Bank showing the location of Ocean Drilling Program Hole 735B. CIR, SWIR, and SEIR refer to Central, Southwest, and Southeast Indian Ridges; NER, Ninety East Ridge. The topography data are from Smith and Sandwell (1997).

deepened to the depth of 1,508 mbsf during Leg 176 in 1997 (Dick et al., 1999; Robinson et al., 1989). This hole provides a long in situ section of the lower ocean crust (Dick et al., 2000).

#### 2.2. Petrology of the Felsic Veins

The entire Hole 735B is dominated by gabbroic rocks with numerous volumetrically small (~0.5 vol%) felsic veins occurring throughout the hole. They intruded the host gabbroic rocks with varying thickness from a few millimeters to several centimeters (Niu et al., 2002). The detailed borehole stratigraphy was discussed by Dick et al. (1991, 1999, 2000). The gabbroic rocks, including gabbro, olivine gabbro, oxide gabbro, and minor troctolite, are mineralogically dominated by plagioclase and clinopyroxene with varying abundances of olivine and oxide (Figure 2a). Most of the felsic veins are quartz diorite with minor diorite, trondhjemite, and tonalite (Niu et al., 2002). They can be classified compositionally as quartz diorite, diorite, trondhjemite, and tonalite (Figure 3). Plagioclase is the principal mineral in the felsic veins and gabbros with varying compositions (Figure 4a; Niu et al., 2002). Albite twinning is common in plagioclase of gabbros and felsic veins (Figure 2). The plagioclase in the felsic veins can coexist with quartz as intergrowth showing myrmekite texture (Figure 2d), which may be formed by exsolution of plagioclase resulting from silica pumping during cooling (Castle & Lindsley, 1993). Amphibole in the felsic veins are either euhedral to subhedral, indicating their crystallization from magma (Figures 2b-2d), or anhedral, indicating their metasomatic origin (Figure 2e). Olivine and clinopyroxene are rare in the felsic veins and locally present at the contacts between felsic veins and the host gabbros (Figures 2e and 2f) with lower Fo and Mg# values than those in the gabbros (Niu et al., 2002). Accessory minerals such as zircon, apatite, and titanite are common in the felsic veins (Figure 2b). Clays and chlorites are the common alteration products after plagioclase and some mafic minerals (Figure 2). Deformation (both brittle and plastic) is observed in some samples. At the contacts of felsic veins with the host gabbros, clinopyroxene are locally reacted to form amphibole (Figure 2e).





**Figure 2.** Representative photomicrographs of gabbros and felsic veins of Hole 735B (Ocean Drilling Program Leg 176). (a) Sample FV61-14: subhedral olivine (Ol), clinopyroxene (Cpx), and plagioclase (Pl) in gabbro (crossed polarized light). (b) Sample FV13-3: anhedral quartz (Qtz) between Pl grains in felsic veins (crossed polarized light) with zircon (Zrn) locally observed. (c) Sample FV62-15: euhedral to subhedral titanomagnetite oxides in felsic veins (plane polarized light). (d) Sample 13-3: myrmekite texture of wormy Qtz inside Pl in felsic veins (crossed polarized light). (e) Sample FV21-4: contact of a felsic vein intruding the host gabbro (plane polarized light); Cpx in the gabbro have been partially transformed into amphibole (Amp) after reaction with felsic vein melt. (f) Sample FV50-11: contact of a felsic vein intruding the host troctolite (crossed polarized light); Ol in the troctolite along the contact were altered to talc. Orthopyroxene (Opx) coronas around Ol in the troctolite can be ascribed to an increase of silica activity during fractional crystallization following the reaction: Ol + SiO<sub>2</sub>  $\rightarrow$  Opx (Nishiyama, 1983; Turner & Stüewe, 1992). Information of these samples is given in supporting information Table S1.

# 3. Analytical Methods

During Leg 176, 21 felsic vein samples were selected from the drill cores (Niu et al., 2002). Information of these samples is given in Table S1 in the supporting information. Analytical methods, standards, and results for major elements were described in detail by Niu et al. (2002) and are only briefly mentioned here. All suspicious surface contaminants such as pen marks, saw marks, and sticker residues were thoroughly removed. The samples were then reduced to 1- to 2-cm size fragments and ultrasonically washed in Milli-Q water before being dried and grinded into powder using agate mill in a clean environment. Bulk-rock major



**Figure 3.** (a) Normative bulk rock anorthite (An)-albite (Ab)-orthoclase (Or) ternary plot (Barker, 1979) for felsic vein samples from Hole 735B (Ocean Drilling Program Leg 176); (b) Classification of the plutonic igneous rocks using CIPW norms (Le Bas & Streckeisen, 1991). Data are from Niu et al. (2002).

elements were analyzed on a Perkin Elmer Optima 3300 DV inductively coupled plasma (ICP)-optical emission spectrometer at the University of Queensland (Niu et al., 2002). Bulk-rock trace element analysis was done in the Laboratory of Ocean Lithosphere and Mantle Dynamics, Institute of Oceanology, Chinese Academy of Sciences by using an Agilent 7900 ICP-mass spectrometer (MS). United States Geological Survey rock reference standards W-2a, BHVO-2, AGV-2, and GSP-2 were used to monitor the analytical accuracy and precision. Analytical accuracy is better than 8%, with many elements agreeing to within 5% of the reference values, except for Ni, Co, Cu, and Ce ranging between 8% and 10% and Li, Be, Cr, and Pb ranging between 10% and 19% (see Chen et al., 2017, for analytical details).



Figure 4. (a) Feldspar (anorthite [An]-albite [Ab]-orthoclase [Or]) compositional diagram for felsic vein and gabbro samples from Hole 735B (Ocean Drilling Program Leg 176; Niu et al., 2002). For comparison, we also plot (b) compositions of plagioclase experimentally produced by hydrous partial melting of Leg 176 and 153 gabbros at 0.2 GPa, T = 900-1060 °C with Ni-NiO oxygen fugacity buffer (Koepke et al., 2004); (c) compositions of plagioclase calculated as resulting from increasing extent of fractional crystallization (An decrease and Ab increase) from average primitive midocean ridge basalt (MORB) compositions (Mg# > 0.637 according to Niu et al., 2002,  $49.0 > SiO_2 > 47.5$  wt%, MgO > 9.5 wt% according to Leuthold et al., 2018) from the Southwest Indian Ridge (25 to 42°S) database of PetDB (Lehnert et al., 2000; see supporting information Table S2) using Rhyolite-MELTS (Gualda et al., 2012) under conditions of 0.2 GPa, T = 1270-857 °C, and quartz-fayalite-magnetite oxygen fugacity buffer with 0.2 wt% water (average water concentration of natural MORB; Clog et al., 2013, and references therein).

Major and trace elements of clinopyroxene in gabbro domain and amphibole in felsic veins domain in FV thin sections were analyzed (see Table S1 for sample description) using a Photon Machines Excite 193-nm excimer Ar-F laser system attached to an Agilent 7900 ICP-MS in the Laboratory of Ocean Lithosphere and Mantle Dynamics. Amphibole and clinopyroxene were analyzed using 65- and 85- $\mu$ m spot sizes, respectively, and 3.94-J/cm<sup>2</sup> energy density at a repetition rate of 6 Hz. Each analysis includes 25-s background acquisition (gas blank) followed by 50-s data acquisition. United States Geological Survey glasses (BCR-2G, BHVO-2G, and BIR-1G) were used as external standards for calibration following Liu et al. (2008). The raw data were processed using ICPMSDataCal\_ver11.0 (Chen et al., 2011; Liu et al., 2008). Data quality was assessed by repeated analyses of GSE-1G over the analytical session. The precision and accuracy are generally better than 5% for major elements except for P<sub>2</sub>O<sub>5</sub> and better than 10% for trace elements.

Bulk-rock Sr-Nd-Pb-Hf isotope analysis was also done in the Laboratory of Ocean Lithosphere and Mantle Dynamics. About 100 mg of each sample powder was dissolved in HNO<sub>3</sub> + HCl + HF mixture in a Teflon beaker at 190 °C for Sr, Nd, Pb, and Hf analysis. Sr and Pb were first separated by running through Sr-Spec resin. AG resin was then used to separate high field strength elements and rare earth elements (REEs). Nd was separated using Ln (Nd) resin, and Hf was separated using Ln (Hf) resin, respectively. The purified Sr, Pb, and Hf were diluted in 2% HNO<sub>3</sub>, and Nd was diluted in Milli-Q H<sub>2</sub>O for analysis with Nu multicollector (MC)-ICP-MS. <sup>203</sup>Tl-<sup>205</sup>Tl isotopes were used as internal standard to correct for mass-dependent Pb isotopic fractionation. The Sr, Nd, Pb, and Hf isotope ratios were, respectively, normalized to <sup>86</sup>Sr/<sup>88</sup>Sr = 0.1194, <sup>146</sup>Nd/<sup>144</sup>Nd = 0.7219, <sup>205</sup>Tl/<sup>203</sup>Tl = 2.3875, and <sup>179</sup>Hf/<sup>177</sup>Hf = 0.7325. The NBS-987 Sr standard, Jndi-1 Nd standard, and Alfa Hf standard



**Figure 5.** MgO variation diagrams of bulk-rock major element oxides of Hole 735B (Ocean Drilling Program Leg 176) gabbros and felsic veins (Niu et al., 2002). The cumulation of Fe-Ti oxides will increase the bulk-rock  $\text{FeO}^{T}$  and  $\text{TiO}_{2}$  contents in the sample. The varying compositions imply that they are actually mixtures. With increasing SiO<sub>2</sub> in the residual melt, crystal separation becomes ineffective because of the high viscosity, resulting in the observed signature of varying extent of "crystal + melt" mixing. Thus, most of the felsic veins in Hole 735B are liquid-rich mixtures (felsic melt with the presence of cumulate crystals), whereas gabbros are crystal-rich mixtures (crystals with trapped melt). Because gabbros are dominated by clinopyroxene (Cpx) and plagioclase (Pl) with varying amounts of olivine (OI; reduced SiO<sub>2</sub>) and Fe-Ti oxides (elevated TiO<sub>2</sub> and FeO<sup>T</sup>), most gabbroic samples compositionally lie between Cpx and Pl, whose average compositions of Cpx and Pl in Hole 735B gabbros are from Niu et al. (2002). Experimental melts produced by hydrous partial melting of Leg 176 and 153 gabbros (Koepke et al., 2004) and fractional crystallization trends for the melt (MgO decrease in the melt with increasing extent of fractional crystallization) calculated using Rhyolite-MELTS (see Figure 4 for experimental conditions and calculation parameters) are also plotted for comparison. As most of the felsic vein samples are mixtures of residual liquid with incompletely segregated crystals, simple arbitrary modeling will be misleading.

yielded <sup>87</sup>Sr/<sup>86</sup>Sr = 0.710257  $\pm$  0.000019 (2 $\sigma$ , *n* = 10), <sup>143</sup>Nd/<sup>144</sup>Nd = 0.512105  $\pm$  0.000018 (2 $\sigma$ , *n* = 10), and <sup>176</sup>Hf/<sup>177</sup>Hf = 0.282180  $\pm$  0.000006 (2 $\sigma$ , *n* = 8). Repeated analyses of NBS-981 Pb standard gave <sup>208</sup>Pb/<sup>204</sup>Pb = 36.6690  $\pm$  0.0457, <sup>207</sup>Pb/<sup>204</sup>Pb = 15.4805  $\pm$  0.0117, <sup>206</sup>Pb/<sup>204</sup>Pb = 16.9283  $\pm$  0.0094, and <sup>207</sup>Pb/<sup>206</sup>Pb = 0.9145  $\pm$  0.0003 (2 $\sigma$ , *n* = 24). The <sup>87</sup>Rb/<sup>86</sup>Sr, <sup>147</sup>Sm/<sup>144</sup>Nd, and <sup>176</sup>Lu/<sup>177</sup>Hf ratios were calculated using their bulk-rock Rb, Sr, Sm, Nd, Lu, and Hf compositions. Detailed methods for Sr-Nd-Pb-Hf elemental separation and isotope analysis are given by Sun et al. (2018).

#### 4. Results

#### 4.1. Bulk-Rock Major and Trace Elements

In terms of bulk-rock major element compositions (see Niu et al., 2002), the felsic veins are leucocratic rocks with varying SiO<sub>2</sub> (50.53–74.79 wt%). Most of them have higher SiO<sub>2</sub> and Na<sub>2</sub>O (3.88–9.22 wt%), lower CaO (12.15–1.73 wt%), and relatively lower MgO (7.36–0.42 wt%) than the host gabbros of Leg 176 cores. They have a wide range of FeO<sup>T</sup> (0.96–15.61 wt%) and TiO<sub>2</sub> (0.13–2.71 wt%), and low K<sub>2</sub>O (0.03–0.57 wt%) in contrast to continental leucocratic rocks. Their SiO<sub>2</sub> and Na<sub>2</sub>O increase, whereas FeO<sup>T</sup> decreases, with decreasing MgO (Figure 5).

Trace element compositions of the felsic veins are given in supporting information Table S3. Most of these felsic vein samples show slightly light rare earth element (LREE) enriched patterns relative to model ocean crust (Niu & O'Hara, 2003) with  $[La/Yb]_{OCN}$  ratios (OCN refers to ocean crust normalized) of ~1.02–6.82, and a few samples are slightly depleted in LREE with  $[La/Yb]_{OCN}$  ratios of ~0.72–0.76 (Figure 6a). Most



**Figure 6.** Ocean crust (Niu & O'Hara, 2003) normalized REE (a, c) and multi-element (b, d) patterns of felsic veins, gabbros, and minerals therein from the Ocean Drilling Program Leg 176. The "messy" trace element variation of felsic veins in (b) reflect the fact that they are not simple melts, but melts with incompletely separated cumulate crystals. Average composition of gabbros is from Niu and O'Hara (2003). Amp = amphibole, Cpx = clinopyroxene.

of the samples show varying negative Eu anomalies ( $Eu/Eu^* = 2Eu_{OCN}/(Sm_{OCN} + Gd_{OCN}) = 0.28-1.02$ ) as a result of prior plagioclase crystallization/removal, but one sample has a high positive Eu anomaly ( $Eu/Eu^* = 2.12$ ) due to excess plagioclase accumulation.

In the ocean crust-normalized multi-element diagram (Figure 6b), most of the felsic vein samples show negative anomalies of Rb, K, Sr, P, and Ti, which differ from those of the gabbros. Negative Sr (Sr/Sr\* =  $2Sr_{OCN}/(Pr_{OCN} + Nd_{OCN}) = 0.04-0.80$ ) and Eu anomalies (Figure 6a) result from prior plagioclase removal.

#### 4.2. Mineral Geochemistry

Major and trace element data of clinopyroxene in the gabbros and amphibole in the felsic veins are given in supporting information Table S4. Clinopyroxene in the wall rock gabbros of felsic veins show LREE-depleted REE patterns (Figure 6c) with  $[La/Yb]_{OCN}$  of ~0.19–0.50 and slightly negative Eu anomalies (~0.62–0.82). Amphiboles in the felsic veins show elevated abundances of REEs, but LREE depleted REE patterns with  $[La/Yb]_{OCN}$  of ~0.18–0.51 and pronounced negative Eu anomalies (~0.15–0.26). They show similar negative anomalies of elements Rb, K, Sr, P, and Ti to those of their host rocks (Figure 6b, d). The negative anomaly of Zr in amphibole also occurs in some felsic vein samples (Figures 6b and 6d).

#### 4.3. Bulk-Rock Sr-Nd-Pb-Hf Isotopes

Bulk-rock Sr-Nd-Pb-Hf isotopic compositions are given in supporting information Table S5, and their variation with the borehole depth is shown in Figure 7.

The felsic vein samples have varying Sr isotope compositions ( ${}^{87}\text{Sr}/{}^{86}\text{Sr} = 0.702871-0.703794$ ), slightly higher than those of the host gabbros (average  $0.70287 \pm 0.00005$ ; Holm, 2002). The ( ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ )<sub>*i*</sub> values calculated using bulk-rock Rb and Sr abundances at 11.93 Ma (zircon U-Pb age of Leg 176 felsic vein dated using SHRIMP; John et al., 2004) range from 0.702864 to 0.703792, which is essentially the same as the present-day Sr isotopic ratios because of the low Rb/Sr of these samples and the younger age (Figure 6). Most of the high  ${}^{87}\text{Sr}/{}^{86}\text{Sr}$  ratio samples correspond to the fault zone at ~500 mbsf (Dick et al., 2000; Niu et al., 2002), implying the potential effect of seawater alteration (Figure 7a). The  ${}^{87}\text{Sr}/{}^{86}\text{Sr}$  ratios of felsic veins show similar characteristics to those of the host gabbros at depths deeper than 800 mbsf (Figure 7a). All the felsic vein samples have relatively uniform  ${}^{143}\text{Nd}/{}^{144}\text{Nd}$  (0.513097–0.513123) and  ${}^{176}\text{Hf}/{}^{177}\text{Hf}$  (0.283174–0.283204) ratios with  $\varepsilon_{\text{Nd}}(t)$  and  $\varepsilon_{\text{Hf}}(t)$  values ranging from +8.84 to +9.30 and



**Figure 7.** Radiogenic isotope compositions of Ocean Drilling Program Leg 176 felsic veins vs. borehole depth. For comparison, the downhole gabbro data from Leg 176 (unleached samples, Holm, 2002) and 118 (Kempton et al., 1991) are also plotted. The high  ${}^{87}$ Sr/ ${}^{86}$ Sr samples of felsic veins may be caused by alteration of seawater that infiltrated along a fault-zone at the borehole depth of ~500 m (Dick et al., 2000). The error bars of felsic veins in (a–c) are smaller than the symbols.

+14.34 to +14.98, respectively. The <sup>143</sup>Nd/<sup>144</sup>Nd ratios of felsic veins are even higher than those of some host gabbro samples (Figure 7b). The felsic vein samples have lower <sup>206</sup>Pb/<sup>204</sup>Pb (16.877–17.508) and higher  $\mu$ (<sup>238</sup>U/<sup>204</sup>Pb) ratios (1.36–42.07) than the gabbros (Holm, 2002). All these Sr-Nd-Pb-Hf isotopic compositions of felsic veins show mantle isotope signature as do the host gabbros in Hole 735B (Figure 7) and are similar to those of mid-ocean ridge basalt (MORB) from the SWIR (Hamelin & Allègre, 1985; Meyzen et al., 2005).

# 5. Discussion

#### 5.1. Debate on the Genesis of Oceanic Plagiogranites

As introduced above, several models have been proposed to explain the petrogenesis of oceanic plagiogranites. The three main views are as follows: (1) partial melting of hydrous gabbros; (2) silicate liquid immiscibility; and (3) fractional crystallization of basaltic magmas. We have summarized the pros and cons of the three models against observations in Table 1. In the following discussion, we elaborate in detail why and how we have reached the conclusions on the petrogenesis of the Hole 735B felsic veins.



#### 5.1.1. Partial Melting

Partial melting of amphibolite (i.e., anatexis) was first proposed to explain the origin of Archean trondhjemites and tonalites (Arth & Hanson, 1972). This model was later introduced to explain oceanic plagiogranites as many of them were found spatially associating with high temperature shear zones in ophiolites (Amri et al., 1996; Flagler & Spray, 1991; Pedersen & Malpas, 1984). These authors suggested that the oceanic plagiogranites were formed by partial melting of hydrous basaltic rocks such as gabbros ([1] in Table 1). This process is advocated by Koepke et al. (2004) who did an experimental study confirming that SiO<sub>2</sub>-rich melts with compositions similar to oceanic plagiogranites can be formed by hydrous partial melting of cumulate gabbros at low pressure (0.2 GPa; [2] in Table 1). The melts produced by hydrous partial melting would have very low TiO<sub>2</sub>, because the compositionally refractory gabbroic rocks are depleted in this element (Koepke et al., 2004, 2007).

However, the felsic vein samples differ from the products of hydrous partial melting of gabbros. Most of the felsic vein samples from Hole 735B have high TiO<sub>2</sub>, which is rather low in the melts by hydrous gabbroic melting (Figure 5d). Such low-Ti melts cannot explain the abundant Fe-Ti oxides in many felsic vein samples ([4] in Table 1). In addition, the compositions of plagioclase in equilibrium with the melts produced by hydrous gabbroic melting have too high An (Ca-rich plagioclase) and too low Ab (Na-rich plagioclase; Figure 4b; Koepke et al., 2004) to explain the variably high Ab and low An plagioclase in the felsic veins (Figure 4a; [5] in Table 1). Indeed, experimental melts by hydrous gabbroic melting have too low Na<sub>2</sub>O compared to the felsic veins (Figure 5c). Likewise, zircon and apatite are common in the felsic veins, but it is petrologically difficult that the SiO<sub>2</sub>-rich melts produced by hydrous gabbroic melting with low Zr and P (and other incompatible elements) due to gabbro source depletion would be saturated in zircon and apatite. Very low degree of partial melting could produce melt with elevated Zr abundances. For example, 1% melting of the gabbro with 21 ppm Zr (Niu & O'Hara, 2003) can produce felsic melt with 196 ppm Zr (see supporting information Table S6 for detailed calculation parameters), which is inadequate to reach the required zircon saturation levels of Zr > 350 ppm (Boehnke et al., 2013; Lee & Bachmann, 2014), let alone to produce abundant zircons in the felsic veins ([6] in Table 1).

For better assessing the viability of this model in explaining the petrogenesis of felsic veins in Hole 735B, we compare the observed felsic vein compositions with calculated compositions of model partial melts. Trace element compositions are modeled using modal equilibrium melting (Shaw, 1970; Zou, 1998) with the parameters given in Table S6 (for comparison, results of fractional melting are also given in Table S6). For hydrous partial melting model, gabbroic rock is the source of felsic vein melts. If the felsic veins were partial melting products, they would inherit the gabbroic "source" characteristics, but this is not the case as modeled (Figures 8a and 8b). It is hard to explain the strong negative Ti and both positive and negative Zr and P anomalies in felsic veins (Figures 6a and 6b) by using hydrous partial melting of gabbros (Figures 8a and 8b; [8] in Table 1). Melts produced by hydrous melting of gabbros could give negative Ti anomaly only if there were Ti rich residual phases, but this is unknown nor has been observed experimentally.

According to the hydrous partial melting model, transportation of seawater via high-temperature shear zones triggers the partial melting of preexisting gabbros, which form the oceanic plagiogranites (e.g., Koepke et al., 2004, 2007). This would require melting conditions met throughout the gabbroic sections on highly localized scales so as to explain the volumetrically small but widespread occurrence of the felsic veins ([9] in Table 1), but this is physically unlikely. Alternatively, such melting produced felsic melts would need widespread redistribution throughout the gabbroic sections, which is also unlikely because the temperature and viscosity of felsic melt prevent the melt from long distance transport before solidification. Besides, the Sr isotope of oceanic plagiogranites formed by hydrous partial melting is expected to show strong seawater signature, but it is absent for the felsic vein samples deeper than 800 m (Figure 7a; [10] in Table 1).

With all the above considered, we suggest that the felsic veins in Hole 735B were not produced by partial melting of hydrous gabbros.

#### 5.1.2. Silicate Liquid Immiscibility

Dixon and Rutherford (1979) performed a fractional crystallization experiment on a primitive basaltic melt at low pressure under an anhydrous condition. They found the immiscibility between a Fe-enriched basaltic liquid and a granitic liquid after 95% crystallization. They believed that the immiscibility in late-stage differentiation of basaltic melt formed the plagiogranites in the ocean crust and ophiolites ([1] and [2] in Table 1).





**Figure 8.** Ocean crust (Niu & O'Hara, 2003) normalized rare earth element (a, c) and multi-element patterns (b, d) of calculated results. The partial melt composition (at degree of melting F = 1%, 5%, 10%) of modal equilibrium melting is calculated using experimentally determined mineral modes of  $Pl_{0.69} + Cpx_{0.18} + Opx_{0.09} + Am_{0.04}$  (Brophy, 2009; Koepke et al., 2004) from average Ocean Drilling Program Leg 176 gabbros (Niu & O'Hara, 2003; detailed calculation parameters are given in supporting information Table S6). Southwest Indian Ridge (SWIR) mid-ocean ridge basalt (MORB) data are from Gao et al. (2016). The partition coefficients used to calculate melt compositions in equilibrium with amphibole (Amp) in the felsic veins and clinopyroxene (Cpx) in the gabbros are given in Table S6.

Some authors considered that high degrees of crystallization of parental MORB magma may lead to the segregation of siliceous and Fe-rich liquids in Hole 735B (Dick et al., 2000; Natland et al., 1991; Natland & Dick, 2001), because felsic veins are sometimes in close association with oxide-rich (such as ilmenite and magnetite) ferrogabbros ([3] in Table 1).

According to this model, if the felsic veins in Hole 735B were formed by oxide-silicate immiscibility, the immiscible textures must exist, but this is not observed. In contrast, oxide minerals in the felsic veins are commonly euhedral to subhedral (Figure 2) rather than supposed anhedral or globules of immiscibility origin (Dixon & Rutherford, 1979; Charlier & Grove, 2012; [4] in Table 1). Recently, Koepke et al. (2018) conducted crystallization experiments in a range of temperatures from 850 to 1050 °C with water activities from 0.1 to 1 under redox conditions from quartz-fayalite-magnetite (QFM) – 1.1 to QFM + 3.2, but they did not obtain liquid immiscibility. The existence of water inhibited the immiscibility process (Charlier & Grove, 2012; [2] in Table 1). As amphibole is common in the felsic veins, wetter experiments (Koepke et al., 2018) more closely approximate the conditions of crystallization of oxide gabbros in Hole 735B than the "dry" experiments (Charlier & Grove, 2012; Dixon & Rutherford, 1979). Hence, the oxide-silicate immiscibility scenario is possible, but there is no textural evidence, or the rock textures do not support this possibility. In fact, the simple fractional crystallization process can explain all the observations adequately and effectively (see Table 1 and below).

#### 5.1.3. Fractional Crystallization

The common occurrence of small-volume plagiogranites in the upper sections of cumulate gabbros in many ophiolites have convinced many that the oceanic plagiogranites are formed by fractional crystallization of basaltic magmas (Coleman & Peterman, 1975; Coleman & Donato, 1979; Niu et al., 2002; [1] in Table 1). This process is supported by many experimental studies in tholeiitic systems that show that high SiO<sub>2</sub> liquids (SiO<sub>2</sub> contents can reach higher than 73 wt%) can be produced by fractional crystallization of Fe-Ti oxides during its late stage differentiation (e.g., Perfit & Fornari, 1983; Juster et al., 1989; Thy & Lofgren, 1994;



**Figure 9.** Bulk-rock MgO-variation diagrams with (a) Sc, (b) V, (c) Co, (d) Ni, (e) Zr, and (f) Y. Sc, V, Co, and Ni are compatible or less incompatible elements in gabbroic mineral assemblages (Sc and V in preference to clinopyroxene [Cpx], while Co and Ni in preference to olivine [OI]). With fractional crystallization proceeding, these elements will decrease in the residual melt. The abundances of elements in gabbros are mainly controlled by modal proportions of clinopyroxene and plagioclase. Zr and Y are incompatible elements in the gabbroic mineral assemblages and will be progressively enriched in residual melt until saturation of zircon, apatite, and other minerals. The abundances of these elements in gabbros are largely controlled by the trapped melt between cumulate crystals. For felsic vein, they are residual liquid with incompletely segregated crystals. Their compositions are mainly controlled by the compositions of melt and influenced by the proportion and compositions of plagioclase and Sc, V, and Co compositions of olivine are summarized from those in gabbro and basalt samples in database GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/Start.asp). Ni and MgO compositions of olivine are from Niu et al. (2002). Black lines with arrows are hypothetical trends for fractional crystallization of basaltic melt.

Toplis & Carroll, 1995; Regelous et al., 1999; Berndt et al., 2005; Koepke et al., 2018; [2] in Table 1). This is simply because Fe-Ti oxides contain no  $SiO_2$  and their crystallization will cause rapid  $SiO_2$  increase in the residual melt, thus producing  $SiO_2$ -rich liquids and plagiogranites.

According to Robinson et al. (2000), Fe-Ti oxide gabbro and Fe-Ti oxide gabbronorite with Fe-Ti oxide contents varying from <1% to 50% (modal percent) make up ~15% of the recovered core, which suggest that Fe-Ti oxides have largely crystallized during SWIR magma differentiation. Most of these oxides occur as interstitial minerals with euhedral to subhedral shapes between plagioclase and clinopyroxene (Figure 2), which is most consistent with their resulting from fractional crystallization. Since large amounts of Fe-Ti oxide have been proved to be crystallized from differentiated MORB in Hole 735B (Koepke et al., 2018), SiO<sub>2</sub>enriched residual melts thus must be the complementary products ([3] in Table 1).





**Figure 10.** Liquid line of descent (SiO<sub>2</sub> wt% shown at right axis) and phase proportions (left axis) of primitive Southwest Indian Ridge mid-ocean ridge basalt melt fractionation in response to cooling (*x* axis) using Rhyolite-MELTS at 0.2 GPa, quartz-fayalite-magnetite oxygen buffer, and 0.2 wt% H<sub>2</sub>O (see Figure 4 for experimental conditions and calculation parameters). With decreasing temperature, olivine crystallizes first, followed by plagio-clase, clinopyroxene, oxide, and finally apatite. The corresponding cumulate rocks are dunite, troctolite, olivine gabbro, gabbro, and oxide gabbro. The red dash lines indicate SiO<sub>2</sub> contents in the residual melt, which does not increase until oxides begin to crystallize.

It is important to note that crystal-liquid separation is likely incomplete because of high viscosity, which result in varying compositions of felsic veins in Hole 735B (Figures 5, 6a, and 6b). Most of the felsic vein samples are mixtures of residual liquid with incompletely segregated crystals. In contrast, the gabbro samples are mixtures of cumulate with trapped melt. The bulk compositions of felsic veins are mainly controlled by the composition of high-SiO<sub>2</sub> melt with the influence of cumulate crystals of varying proportion and composition. Hence, simple fractional crystallization modeling will not fit well (Figure 5). The transition metals like Sc, V, Co, and Ni are compatible in mafic minerals like olivine and clinopyroxene. Their abundances in the residual melts will decrease during basaltic magma evolution, and the gabbro mineral assemblages crystallizing from such cooling/evolving melt also decrease with cooling (decreasing MgO; Figures 9a-9d; [7] in Table 1). The elements like Na, Zr, Y, and REE that are incompatible in the crystallizing gabbroic mineral assemblages will be progressively more enriched in the residual melt and also in the crystallizing gabbroic mineral assemblages with cooling (decreasing MgO). For example, the plagioclase in the progressively more evolved melt is progressively Ab rich and An poor (Figure 4c; [5] in Table 1), which is consistent with their bulk-rock compositions (Figure 5c). The preference of these incompatible elements in the residual melts readily explain why Zr and Y continue to increase with cooling (decreasing MgO) with highest abundances in samples

with lowest MgO and thus highest  $SiO_2$  (Figures 9e–9f). Further enrichment in incompatible elements will lead to zircon saturation and crystallization from the felsic melt as observed in the felsic veins (Figure 2b; [6] in Table 1).

The compositions of melts in equilibrium with clinopyroxene in the gabbros and amphibole in the felsic veins were calculated using the partition coefficients given in Table S6 and showed in Figures 8c and 8d. The prominent negative anomalies of Zr, P, and Ti in reconstructed melts in equilibrium with amphibole from the felsic veins (Figure 8d) result from highly evolved melt with fractional crystallization and removal of zircon, apatite, and Fe-Ti oxides prior to amphibole crystallization. The negative anomalies of Zr and Ti are absent in reconstructed melts in equilibrium with clinopyroxene from the gabbros (Figure 8d), suggesting that zircon and Fe-Ti oxides crystallized and removed after crystallization of clinopyroxene. Retention or incomplete separation of crystals like Fe-Ti oxides, zircon, and apatite from the residual felsic melts can effectively elevate  $\text{FeO}^{T}$ , especially TiO<sub>2</sub> and Zr in bulk composition of the felsic veins, which explain the wide range of TiO<sub>2</sub> and Zr in the felsic vein samples (Figure 5d and 9e) and positive anomalies of Zr in some felsic vein samples (Figure 6b; [8] in Table 1).

The widespread distribution of felsic veins in Hole 735B is in accord with multiple melt injection and differentiation mode of ocean crust accretion at slow-spreading ridges (Dick et al., 2000; Niu et al., 2002; Stone & Niu, 2009; [9] in Table 1). Cooling and crystallization of these small magma pockets result in the extremely small-scale chemical and textural variability with products of highly evolved melt throughout the hole (Niu et al., 2002; also see in Figures 5, 7, and 9).

All these observations are most consistent with protracted fractional crystallization from basaltic parental magmas with the felsic veins representing most evolved melts after significant Fe-Ti oxide, zircon, and apatite crystallization although incomplete crystal-melt separation can still retain these minerals in the felsic veins. In brief, our data and interpretation are consistent with the observations in Hole 735B.

#### 5.2. Petrogenesis of the Felsic Veins

We have evaluated the three principal models on the petrogenesis of oceanic plagiogranite against petrographic and geochemical observations of the Hole 735B felsic veins, which allow us to conclude, as summarized in Table 1, that highly advanced extents of fractional crystallization from MORB is the most likely mechanism for the origin of the felsic veins in the SWIR. According to the stratigraphy of Hole 735B (Dick et al., 1991, 1999, 2000; Niu et al., 2002), the primitive MORB melts derived from the SWIR mantle have undergone continuous fractional crystallization of olivine-plagioclase-clinopyroxene-oxide (Figure 10), which explains why the felsic veins have similar Sr-Nd-Pb isotopic compositions to the gabbros (Figure 7) and MORB from the SWIR (Hamelin & Allègre, 1985; Meyzen et al., 2005). The occurrence of troctolite in the Hole 735B (Dick et al., 1991, 1999, 2000; Niu et al., 2002) is consistent with MORB, including SWIR basalts, being dry or water-unsaturated. This is because if the parental magma is hydrous, clinopyroxene will crystallize prior to plagioclase to form wehrlite (Niu, 2005, and references therein). During the gabbroic crystallization (dominated by clinopyroxene and plagioclase), Fe-Ti increases in the residual melt, while SiO<sub>2</sub> remains constant (Figure 10). With the increasing Fe-Ti, Fe-Ti oxides appear on the liquidus to crystallize, which leads to rapid SiO<sub>2</sub> increase in the residual/fractionating melt (Niu et al., 2002; Niu, 2005; Figure 10). It is physically straightforward that the buoyant felsic melts rise wherever possible (through "cracking"), whereas the dense solid aggregates of Fe-Ti will not, and physical separation between the two in response to crystal deformation is a natural consequence. Incompatible elements such as Zr, Y, and REEs will be progressively and highly enriched in the felsic vein melts, leading to the saturation and crystallization of zircon, apatite, and other accessory minerals (Figures 2, 6, 9e, and 9f). Meanwhile, H<sub>2</sub>O, an incompatible "element," will also be concentrated in this late-stage SiO<sub>2</sub>-rich melt, resulting in the crystallization of amphiboles in the felsic veins (Figure 2). The varied isotopic compositions of felsic vein samples (Figure 7) may imply that they are coming from isotopically varying mantle source, which is consistent with the model of "multiple injections and thin melt lenses" of SWIR (Dick et al., 2000, 2002; Niu et al., 2002; Stone & Niu, 2009). These widespread felsic veins in Hole 735B are highly differentiated products of multiple small melt batch injections at SWIR ocean crust.

## 6. Conclusions

Petrography, major element data, trace element data, and Sr-Nd-Pb-Hf isotope compositions for the felsic veins in the ODP Hole 735B are most consistent with these felsic veins resulting from advanced extents of fractional crystallization from MORB melts. Specifically, crystallization of Fe-Ti oxides at the late stage of MORB melt evolution elevates the  $SiO_2$  content in the residual melt, which becomes  $SiO_2$  rich melt, whose solidification gives rise to the felsic veins in the gabbroic section of the Hole 735B in particular and oceanic plagiogranites in general. The widespread distribution of plagiogranite veins and veinlets with varying isotope compositions throughout the gabbroic sections is evidence that multiple small melt batch intrusion and differentiation are primary mechanism and mode of ocean crust accretion at slow-spreading ridges.

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