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A LA-ICMPS Sr Isotope and Trace Element Study of Plagioclase and Clinopyroxene of the Higganum Dike, Connecticut: Determining the Magma Source of the Central Atlantic Magmatic Province

Caprise Steadman Harper

A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

A LA-ICMPS Sr Isotope and Trace Element Study of Plagioclase and Clinopyroxene of the Higganum Dike, Connecticut: Determining the Magma Source of the Central Atlantic Magmatic Province

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The Higganum dike of Connecticut is one of the earliest basaltic dikes of the Central Atlantic Magmatic province and is geochemically representative of the widespread low-Ti basaltic lavas (~1 wt % TiO_2) that make up the majority of the province in North America. Liquid compositions calculated from Cr-rich clinopyroxene cores from the Higganum dike are significantly more primitive than the bulk rock with average Mg# s of 0.63 compared to the Higganum dike which has Mg #'s ~ 0.55. However, the negative Nb and positive Pb anomalies that are seen in trace element patterns of the low-Ti group are also found in the liquids calculated from the Cr-rich clinopyroxene cores.

Ca-rich plagioclase cores that probably come up from depth with the Cr-rich clinopyroxenes were found to be more radiogenic than bulk Earth with $^{87}Sr/^{86}Sr_i$ ratios ranging from 0.7057 to 0.7064. We conclude that this enriched isotopic signature and the trace element signatures of primitive liquids calculated from clinopyroxene are inherited from the source. This source is identified as a subduction-enriched metasomatized lithospheric mantle.

High-Ti magmas (~2-5 wt % TiO_2) that are limited to a small geographic area of the Central Atlantic Magmatic Province were found to be unrelated to the low-Ti magmas. These two groups probably originated from different degrees of partial melting of different sources and follow distinctive differentiation paths.

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Table of Contents

List of Tables

List of Figures

Introduction

The origin of continental flood basalts present a unique geologic problem as they are comprised of large volumes of magma that are typically erupted in a short amount of time. The origin for such voluminous flows has been explained by invoking a variety of sources and mechanisms such as mantle plumes, subduction-enriched lithospheric mantle, delamination of the lithosphere, or even meteorite impacts (Saunders, 2005; Garfunkel, 2008). The key to determining the most suitable model of petrogenesis is identifying a primary magma (Baker et al., 2000). However, as continental flood basalt magmas move from their sources in the mantle up through the crust, they can fractionate and become contaminated before eventually erupting. This magma evolution makes primary compositions difficult to determine because the erupted lavas can show variations in chemical composition due to fractionation, variable contamination by continental crust, and/or mantle heterogeneities (Pe-Piper et al., 1992). If it is possible to “see through” these effects of fractionation and contamination, then perhaps a primary source can be identified.

The focus of this study is to try to see through effects of lithospheric contamination and identify a primitive source for the magmas of the Central Atlantic Magmatic Province. This province is comprised of tholeiites related to the breakup of Pangea, specifically, the fragmentation of Gondwana and the inception of the Atlantic Ocean basin and is dated at ~199 Ma (Dunning and Hodych, 1990; Marzoli et al., 1999; Hames et al., 2003; Knight et al., 2004; Merle et al., 2007; Verarti et al., 2007). Mesozoic tholeiites from the Central Atlantic Magmatic Province are located on four continents (fig. 1): West Africa (from Morocco to the Ivory Coast), western Europe (Iberian Peninsula and France), northern South America (French Guyana, Surinam and Brazil), and eastern North America (from Nova Scotia to Florida) (Puffer, 1992;

McHone, 1992; Deckart et al., 2005; Verati et al., 2005; De Min et al., 2003; Fodor et al.,1990; Marzoli et al., 1999; Jourdan et al., 2003; Youbi et al., 2003; Cebriá et al., 2003; Martins et al., 2007).

There are two lava types found in the Central Atlantic Magmatic Province: widespread low-Ti lavas and narrowly distributed high-Ti lavas. The division of these groups is based on SiO_2 and TiO_2 concentrations and illustrated on fig. 2. Both the low-Ti and high-Ti groups have enriched trace element patterns as they differ from mid-ocean ridge basalts (MORB) by higher concentrations of light rare earth elements (REE), K, Ba, Rb and Th (Marzoli et al., 1999; Puffer, 2001; Cebriá et al., 2003; Deckart et al., 2005). However, the low-Ti group has evidence of either crustal contamination or incorporation of a subduction zone component in the form of negative Nb-Ta anomalies and large positive Pb anomalies. On the other hand, the high-Ti group lacks Nb-Ta anomalies, has negligible Pb anomalies, and typically has slightly positive Ti anomalies (Deckart et al., 2005). On an εNd vs. $^{87}Sr/^{86}Sr_i$ diagram, high-Ti rocks plot in the depleted quadrant, while low-Ti rocks plot in the enriched quadrant. There is a distinct gap between the Sr-Nd isotopic compositions of the two groups. And this gap led previous researchers to conclude that the two groups had different and distinct mantle sources (Deckart et al., 2005).

However, as the focus of this study is to determine a primitive source composition, we focused on the relationship between the low-Ti and high-Ti groups of the Central Atlantic Magmatic Province. The high-Ti group appears to be “more primitive,” in the sense that it plots in a more primitive field on an εNd vs. $^{87}Sr/^{86}Sr_i$ diagram making this magma type a candidate for revealing the nature of the primitive source composition.

To determine if the groups are related, we examined the possibility that the two magmas were derived from the same source and the high-Ti magma is parental to the low-Ti tholeiites through assimilation and fractionation (fig. 2). Our method was to analyze the most primitive component found in the low-Ti group to see if it shows an isotopic relationship to the high-Ti group. As the low-Ti group has chemical and field evidence of an evolved or “crustal component” (Philpotts and Asher, 1993; Asher and Philpotts, 1995; Dorais and Tubrett, 2008), determining the most primitive composition will require us to “see through” this contamination. Thus, our method requires variation from traditional bulk-rock geochemical analysis. Instead, we chose to target primitive chromium-rich clinopyroxene cores and calcium-rich plagioclase cores from the Higganum dike in Connecticut. The electron microprobe was used to select the best plagioclase grains for laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). Using LA-ICPMS allowed us to determine the ^{86}Sr/^{87}Sr ratios of individual plagioclase grains and was also used to determine the trace element concentrations in the clinopyroxene (Dorais and Tubrett, 2008).

Our first approach was to measure the Sr ratios of primitive Ca-rich plagioclase cores to see if the resulting ratios bridge the gap between the enriched low-Ti magmas and the depleted high-Ti magmas on an εNd vs. ^{87}Sr/^{86}Sr diagram. Our second approach was to compare the trace element composition of a liquid calculated from the composition of chromium-rich clinopyroxene cores (Dorais and Tubbert, 2008), to observed trace element concentrations of rocks in the high-Ti group. We also compared Cr and Ni concentrations along with Mg numbers of this liquid calculated from clinopyroxene core compositions to the low-Ti and high-Ti groups.

Geologic Setting

The Central Atlantic Magmatic Province is possibly the largest flood basalt province in the world spanning four continents, with remnants of lava flows and dikes outcropping in an area of seven million km^2 (Salters et al., 2003; Marzoli et al., 1999; De Min, 2003) to ten million km^2 (Marzoli et al., 2006; Hames et al., 2003). The volcanism has been tentatively linked to the Triassic-Jurrassic extinction when an estimated 80% of all species disappeared (Hames et al., 2003; Courtillot et al., 1996; Marzoli et al., 1999; Knight et al., 2004; Jourdan et al., 2009).

The mean age and the peak of the Central Atlantic Magmatic Province volcanism is ~ 199 Ma (Marzoli et al., 1999; Knight et al., 2004; Verati et al., 2007; Nomade et al., 2007; Merle et al., 2007; Jourdan et al., 2009). This average age is representative of the low-Ti group and is corroborated by $^{40}Ar/^{39}Ar$ plateau ages done on sericites from the Hartford basin which yielded ages of 198.6 ± 20 and 199.8 ± 1.1 (Jourdan et al., 2009). U-Pb zircon ages also confirm this age range with ages of 201.7 + 1.4/–1.1 Ma (North Mountain Basalt), 200.9 ± 1.0 Ma (Palisades sill) and 201.3 ± 1.0 Ma (Gettysburg sill) (Dunning and Hodych, 1990; Hodych and Dunning, 1992). The ages of High-Ti lavas are indistinguishable from the rest of the Central Atlantic Magmatic Province (Nomande et al., 2007). According to Nomande et al., (2007) and Jourdan et al., (2009), the magmatism for the Central Atlantic Magmatic Province spans < 3 million years. However, the main part of the volcanism occurred over a shorter period of time—less than 1 million year duration in northwestern Africa (Knight et al., 2004) and in eastern North America (Olsen et al., 2003).

The earliest and most widespread intrusions of the Central Atlantic Magmatic Province in eastern North America were originally classified as high-Ti quartz-normative tholeiites, by Weigand and Ragland (1970); however, as these basalts have an average TiO_2 of ~1 wt % they are now commonly classified as low-Ti quartz normative tholeiites, or in this paper the low-Ti group. The eastern North American low-Ti group outcrops as scattered, large dikes whose remnant flows are found in Mesozoic rift basins (McHone, 1992). Our study focuses on one member of this group, the Higganum dike, an eastern North American dolerite, found adjacent to the Hartford basin of Connecticut (Puffer, 1992).

The Higganum dike is the longest dike in New England; it is as much as 70 m wide and it extends 200 km from beneath the Long Island Sound, through Connecticut and Massachusetts. A fourth dike, the Fairhaven, is compositionally similar to the Higganum dike and is interpreted to be the upper part of the Higganum dike that has been down-faulted into the Hartford basin (Philpotts and Martello, 1986).

During the Mesozoic Era, there were three short-lived episodes of volcanism in the Hartford basin. According to Philpotts (1992), the first eruption came from the most eastern dike, the Higganum dike, which erupted the Talcott basalt. The eruptions then progressed westward with the second eruption of the Holyoke basalt from the Buttress dike 138,000 years later. The third eruption was the Hampden basalt from the Bridgeport dike 345,000 years after the Holyoke basalt (Puffer et al., 1981; Philpotts and Martello, 1986). Age differences were estimated from Milankovitch-type cycles in lake sediments between the flows (Philpotts, 1992). Melting experiments show successively lower liquidus temperature with decreasing age of these basalts (Philpotts and Reichenbach, 1985). As eruption age changed, so did the chemical characteristics.

The Talcott basalt is the most primitive of the three flows, with the highest magnesium and calcium contents and the lowest iron and phosphorous contents (Philpotts and Reichenbach, 1985). The Holyoke basalt contains smaller amounts of incompatible elements than the Talcott and has less MgO and TiO_2 (Philpotts, 1992). The Hampden rocks have the least MgO of the three groups, and have the most TiO_2 and FeO resulting in their classification as high-Fe quartz normative (HFQ) (Weigand and Ragland 1970; Philpotts, 1992; Philpotts and Reichenbach, 1985).

Similar tripartite volcanism is seen in other areas of the Eastern North American area of the Central Atlantic Magmatic Province. For example, in the Newark Basin the Orange Mountain Basalt is chemically equivalent to the Talcott, the Preakeness basalt with the Holyoke, and the Hook Mountain with the Hampden (Olsen, 1980). These secondary flows that erupted after Talcott-type basalts probably represent second and third magma batches that quickly followed initial magmatism (Puffer and Philpotts, 1988; Gottfried and Tollo, 1989; Puffer, 2003). Melting experiments and mass-balance calculations indicate that the Holyoke and Hampden basalts could have been derived from Talcott magma (Philpotts and Reichenbach, 1985). Furthermore, shallow in situ fractionation of Talcott-type magma involving pyroxene and plagioclase has commonly generated highly evolved, Fe and Ti-enriched intrusive rocks equivalent to the Hampden basalt (Puffer and Lechler 1979; Ragland and Arther, 1985).

The Talcott basalt and the Higganum Dike have the same composition (Philpotts and Martello, 1986) and can only be distinguished from other lavas from the low-Ti quartz normative group by their higher Cr concentrations (Cummins et al. 1992). Other low-Ti quartz normative volcanic rocks with broadly similar compositions are located throughout the eastern North American province such as the Onway dike of southeastern New Hampshire (Sundeen and Huff, 1992; Dorais et al., 2005); the Orange Mt. basalt in New Jersey (Puffer et al., 1981; Puffer, 1992; Puffer, 2000); the York Haven basalt in Pennsylvania (Smith et al., 1975); Hardee and Highlands rocks from Florida (Heatherington and Mueller, 1991); and lavas from South Carolina and Virginia (Ragland et al., 1992). In Atlantic Canada, rift-related low-Ti quartz normative mafic rocks include Novia Scotian North Mountain basalts of the Fundy Basin (Dostal and Greenough, 1992), the Shelburne dike (Papezik and Barr, 1981; Dostal and Greenough, 1992), the New Brunswick Caraquet dike (Dostal and Durning, 1998); and the Newfoundland Avalon dike (Papezik and Hodych, 1980; Dostal and Greenough, 1992; Pe-Piper et al., 1992).

Similar low-Ti basaltic dikes, sills and lavas that are also found elsewhere throughout the Central Atlantic Magmatic Province in Guinea (Deckart et al., 2005), Morocco, (Youbi et al., 2003), Mali (Verati et al., 2005), Liberia (Dupuy et al., 1988), Brazil (Fodor et al., 1990; Marzoli et al., 1999; De Min et al., 2003), France (Alibert, 1985; Jourdan et al., 2003), and Portugal and Spain (Youbi et al., 2003; Cebriá et al., 2003; Martins et al., 2008). Typically all low-Ti lavas have major element concentrations of TiO_2 (0.59-1.72 wt %, 1.09 aver. wt %), MgO (3.33-10.74 wt %, 7.07 aver. wt %), SiO_2 (49.26-56.09 wt %, 51.79 aver. wt %), and Fe_2O_3 (7.54-14.14 wt % 11.34 aver. wt %) (fig. 2, 4-7).

In contrast, Central Atlantic Magmatic Provice high-Ti tholeiitic dikes, sills, and lavas have only been documented in the Liberia and Ivory Coast regions of western Africa (Dupuy et al., 1988; Mauche et al., 1989; Nomade et al., 2002a), and in two areas of northernmost South America: French Guyana/Surinam and Cassiporé Brazil (Oliveira et al., 1990; Nomade et al., 2002a; DeMin et al., 2003; Deckart, 2005; Merle et al., 2007). This is a narrow band compared to the large extent of the low-Ti group as they are constrained to a zone that corresponds with the Rokelides suture (Nomade et al., 2002a; Deckart et al., 2005). This suture resulted from the Braziliano ocean closure (Nomade et al., 2002a). The main field difference between representative African low-Ti and South American high-Ti formations is the much larger volume of the low-Ti rocks (Deckart et al., 2005). Geochemically, major element ranges and averages of the high-Ti group tholeiites are typically SiO_2 : (46.12-53.50 wt%, 49.20 aver. wt %), Fe_2O_3:

(14.07-19.23 wt %, 16.38 aver. wt%), TiO_2: (2.15-5.20 wt %, aver. 3.05 wt %), MgO: (2.15-6.88 wt %; 5.240 aver. wt %) (fig. 2, 4-7)

Petrochemistry of the Higganum Dike

Asher and Philpotts (1995) classified the Higganum dike as a porphyritic diabase, containing up to 30% phenocrysts of augite, plagioclase, orthopyroxene and olivine. These phenocrysts range from 1-1.5 mm in diameter, and are enclosed in a groundmass of augite, pigeonite, plagioclase, illmenite, magnetite, and accessory biotite, apatite, and granophyre. Granophyric patches are composed of potassium feldspar and quartz, and are up to about 250 µm in length. Augite and plagioclase are recognized in all exposures of the dike; however, orthopyroxene and olivine have limited abundances. For example, chilled margins contain euhedral orthopyroxene phenocrysts, but in the central slower cooled part of the dike, orthopyroxene phenocrysts are rimmed by pigeonite. In the shallower exposures of the dike, orthopyroxene grains are never euhedral and only occur as rounded and resorbed phenocrysts. Boundaries between augite and orthopyroxene indicate that augite replaced orthopyroxene; in contrast, boundaries between olivine and orthopyroxene indicate that olivine grew around euhedral orthopyroxene (Philpott and Reichenbach, 1985). This description is similar to published descriptions of comparable dikes of the low-Ti group located in Portugal, Africa, and South America (Deckart et al., 2005; Youbi et al., 2003; Cebriá et al., 2003; Martins et al., 2008).

Instrumental Methods

Samples of the Higganum dike were collected at a large road cut along Exit 9 off Route 9 in Haddam, Connecticut. These cuts were studied and described by Philpotts and Asher (1993). Electron microprobe analyses and imaging were conducted at Brigham Young University with a Cameca SX50 using 15kV excitation voltage for plagioclase and pyroxene analyses.

Clinopyroxene grains were analyzed using the smallest beam size (approximately 1-2 µm) and a 20 nA current. Plagioclase grains were analyzed using a 10 µm beam and a 10 nA current. Thick sections were used in order to conduct LA-ICPMS analyses on the same grains analyzed by the electron probe.

Bulk-rock major and selected trace elements were analyzed by X-ray fluorescence (XRF) and by ICP-MS in ALS Chemex at Reno, NV. Isotopic compositions of Nd and Sr were obtained at Memorial University of Newfoundland. Approximately 0.1 g of rock power are dissolved in Savilex Teflon beakers using a mixture of concentrated HF – HNO_3 acids. A mixed ^{150}Nd/^{149}Sm spike was added to each sample prior to acid digestion. Both sample and spike were weighed on a high-precision balance. After five days of digestion, the solution was evaporated to dryness and then taken up in 6N HCl acid for two days. The solution was then dried and taken up in 2.5NHCl and loaded on cationic exchange columns using AG50W – X8 resin to collect the REE fractions on one hand and Sr on the other hand (this chemistry is done twice to purify the Sr). The REE fractions were then purified and Sm and Nd were isolated using a secondary column loaded with Eichrom Ln resin. Sr was separated with the resin Spec Sr. All reagents are purified in order to insure a low contamination level. The measured total chemical blanks ranged between 40 and 90 pg and are considered negligible. Sm and Nd concentrations and Sr and Nd isotopic compositions were analyzed using a multicollector Finnigan Mat 262 mass spectrometer in static mode. Nd isotopic ratios are normalized to ^{146}Nd/^{144}Nd = 0.7219. The reported values were adjusted to the La Jolla Nd standard (^{143}Nd/^{144}Nd = 0.51186). During the course of data acquisition, replicates of the standard gave a mean value of ^{143}Nd/^{144}Nd = 0.51189 ± 15 (2 sigma, n=25). The in-run precisions on Nd isotopic ratios are given at 95% confidence level. Errors on Nd isotopic compositions are <0.002% and errors on the ^{147}Sm/^{144}Nd ratio are estimated to be lower than 0.1%. Sr isotopic ratios are normalized to 88/86=8.375209. Reported Sr values are adjusted to the NBS987 Standard (87/86=0.7103). Replicates of the standard gave a mean value of 87/86=0.7103 ± 13 (2 sigma, N=7). Epsilon Nd values were calculated using ^{147}Sm/^{144}Nd = 0.1967 and ^{143}Nd/^{144}Nd = 0.512638 values for the present day chondrite uniform reservoir (CHUR). ^{147}Sm decay constant is 6.54 x 10^{-12} y-1 (Steiger and Jäger 1977), T_{DM} is calculated both with respect to a D.M. with an epsilon Nd_0 value of +10 isolated from the CHUR since 4.55 Ga following a linear evolution and with respect to the De Paolo mantle model.

Sr isotopic micro-analyses were obtained at Washington State University using a New Wave™ UP213 nm Nd:YAG Laser Ablation System coupled with a double focusing ThermoFinnigan Neptune™ multicollector-inductively coupled plasma-mass spectrometer (MC-ICP-MS) equipped with 9 Faraday collectors and 10^{-11} Ω resistors. MC-ICP-MS operating parameters are given in Ramos et al. (2004). Plagioclase cores and rims were sampled by ablating "troughs" with dimensions varying from 80 × 400μm to 80 × 600 μm and ranging fro m 40-80 μm deep, depending on the grain. Each set of analyses measured ^{83}Kr, ^{85}Rb, and all four natural Sr isotopes concentrations. Once the raw data were obtained, it was corrected for mass fractionation and interference of Kr and ^{87}Rb with ^{86}Sr and ^{87}Sr, respectively following Davidson et al. (2001). Mass bias corrections were made following the method of Albarède et al. (2004). Once the 100 analyses were measured and corrected, the corrected values then passed through three iterations of removing outliers beyond 2 σ. The reported ^{87}Sr/^{86}Sr values reported are the average of the remaining analyses along with the calculated 2 σ.

Results

A database of more than 300 major and trace element analyses and more than 170 isotopes of individual samples were compiled for the Central Atlantic Magmatic Province from published data (authors noted in table 1). This data set comes from all four continents that comprise the Central Atlantic Magmatic Province. Best attempts were made to include nearly all of the samples identified to be part of the Central Atlantic Magmatic Province. However, as the goal of this study was to identify a primitive source for the low-Ti group, we have chosen to exclude samples identified as HFQ as they are differentiates of the low-Ti lavas. Furthermore, samples were excluded if described as heavily altered, and/or had > 2 L.O.I. or <96% total wt %. Results from this study of the Higganum dike were added to this Central Atlantic Magmatic Province database. These results include major element compositions (table 2), Nd and Sr isotopic compositions (table 3), and $^{87}Sr/^{86}Sr$ isotopic compositions of plagioclase (table 4). The rocks from the database were divided into two groups; high-Ti and low-Ti based on the natural break seen between these groups on a TiO_2 vs. SiO_2 diagram (figure 2). These groups fit the fields of low-Ti and high-Ti continental flood basalts of Albarède (1992).

Major Elements

The high-Ti group differs from the low-Ti group generally by lower SiO_2, and higher Fe_2O_3 and TiO_2 concentrations. On a TiO_2 vs. SiO_2 diagram (fig. 2) the low-Ti group forms a definite cluster; however, there appears to be a continuum linking to the high-Ti group. This apparent continuum is labeled as three groups, the “outliers,” the “Portugal/Spain outliers,” and “HFQ”. The “outliers” group has similar TiO_2 concentrations as the low-Ti group but is not part of the main cluster of the low-Ti group. These “Outliers” are only found in the small geographic area of the high-Ti group. This separate distinction is also plotted on figures 4-7, 10-12, and 15. Although we have already discussed the rationale of excluding the HFQ group, they are included in this diagram because of the similarities they show with the “Portugal/Spain” outlier group. Coupling this diagram to figure 3, a mafic-index vs. TiO_2 diagram, we have concluded that the

"Portugal/Spain" outlier group is alike enough to the HFQ group to be similarly eliminated from this study. Additionally plotted on figure 2 is a group of "contaminated high-Ti." These samples appear to be isotopically enriched and will be discussed later.

On a total-alkali vs. silica plot (fig. 4), the high-Ti group and "Outliers" have lower silica contents and almost all plot as true basalts, while the low-Ti group has a greater range and includes basalts, basaltic andesites, trachy-basalts, and basaltic trachy-andesites. A FeO_t/ (FeO_t+MgO) vs. SiO_2 plot (fig. 5) shows that most of the Central Atlantic Magmatic Province rocks are ferroan with a Fe-enrichment trend. The high-Ti group follows a strong Fe-enrichment trend, with SiO_2 declining in the more differentiated rocks (fig 2). Fe-enrichment is also accompanied by strong TiO_2 enrichment (figure 6). The "outlier" group follows the same differentiation paths as the high-Ti group. The differentiation path for the low-Ti group has less Fe_2O_3 and TiO_2 enrichment and SiO_2 increases with differentiation (Fig. 2, 5, and 6). A TiO_2 vs. P_2O_5 diagram (figure 7) further illustrates titanium enrichment by differentiation for the high-Ti group. This pattern is less extreme for the low-Ti group.

Trace Elements

Figure 8 shows a trace element spider diagram of mafic rocks from the Central Atlantic Magmatic Province (Sun and McDonough, 1989). In general, the lavas are enriched in incompatible elements and have positive slopes. Samples classified in the high-Ti group appear to be enriched in heavy REE elements, lack Nb-Ta anomalies, and have negligible Pb anomalies relative to the low-Ti group which uniformly has negative Nb and Ta anomalies and large positive Pb anomalies. Both groups have negative Sr anomalies. In addition, the high-Ti group has positive Ti anomalies while the low-Ti group has slight negative Ti anomalies. The two

“Contaminated high-Ti” samples follow the patterns of the high-Ti group. The erratic variability of Rb, Ba, and K in the province is probably due to slight alteration (Deckart et al., 2005).

Figure 9 shows a rock/bulk silicate earth normalized trace element diagram (McDonough and Sun, 1995) that includes the average low-Ti and high-Ti groups, an ocean island basalt (Sun and McDonough, 1989), a typical continental arc basalt (Hickey et al., 1986), the plume continental flood basalt field (P-CFB) and arc continental flood basalt (A-CFB) field of Puffer, (2001). P-CFB include the provinces of Lebombo (Sweeney et al., 1994), Ethiopia (Barbieri et al., 1995), Columbia River Basalts (main sequence; Hoper and Hawkesworth 1993), Keweenawan basalts (Nicholson et al., 1997), East Greenland (Hogg et al., 1989), Paraná-Etendeka (Peate, 1997), and Deccan Traps (Lightfoot et al., 1990b). The A-CFB field includes mafic rocks from eastern North American Central Atlantic Magmatic Province (Orange Mountain, Preakness, and Hook Mountain; Puffer, 1992), Lesotho, (Marsh et al., 1997), and Siberia (Lightfoot et al., 1990a). Although Puffer’s (2001) A-CFB was partially developed by using compositions from eastern North America Central Atlantic Magmatic Province, it is significant that the average of the entire low-Ti group from four continents falls within this range. The average high-Ti group plots within the P-CFB field. There is a well-defined gap separating the data into two groups in the high field strength elements of Nd-Lu.

Figure 10 shows a TiO_2 (wt %) vs. Ba/Nb (ppm) diagram. High-Ti and low-Ti groups are plotted as well as the Higganum dikes, the “contaminated high-Ti” group and the “outliers” identified on figure 2. The high-Ti, the “contaminated high-Ti” group, and most of the “outliers” group have similar low vales of Ba/Nb, while the majority of the low-Ti group has larger Ba/Nb ratios.

Figure 11 shows the spread of Mg #s as they are plotted relative to TiO_2. This diagram further illustrates possible fractionation trend differences between the low-Ti and high-Ti group. The high-Ti group increases in TiO_2 much more drastically than the low-Ti group with decreasing Mg #s. The "Outliers" appear to be more primitive members of the high-Ti group with higher Mg #'s. This is also seen on figure 12, a TiO_2 vs. Cr diagram. The Higganum Dike has some of the highest concentrations of Cr in the Central Atlantic Magmatic Province. The "Outliers" have mostly higher Cr contents than the high-Ti group. As with the other diagrams, the "contaminated high-Ti" samples plot within the field of the high-Ti group on figures 11 and 12. Liquids compositions calculated from the Cr-rich clinopyroxene cores using a partition coefficient of 8.4 (Henderson, 1984) are also shown on figure 12, and plot near the primary basalt field (Wilson, 1989). Only calculated liquids with >600 ppm Cr are shown.

Cr-rich Clinopyroxene Cores

The clinopyroxene from the Higganum dike are chemically identified as augites (Dorais et al., 2005). Figure 13 shows the trace element patterns for rocks from the Central Atlantic Magmatic Province compared to liquid compositions from representative Cr-rich clinopyroxene cores calculated using partition coefficients of Hauri et al. (1994). Only the most primitive compositions were included, all low-Ti samples have greater than 7.0 MgO concentrations while high-Ti samples are all greater than 6.0 MgO. As the "outlier" group has higher MgO concentrations, these samples were grouped with the high-Ti. Overall, the liquids calculated from the clinopyroxene show strong similarities to the low-Ti group. They mimic the patterns of the low-Ti group with a large Pb anomaly negative Nb and Sr anomalies. However, they are less enriched in LREE and heavy REE compared to the high-Ti and low-Ti groups but REE partition coefficients are influenced by pressure and temperature controls (Wood and Blundy, 1997). A discussion about the chosen partition coefficients can be found in Dorais and Tubrett, (2008). Only calculated liquid compositions from cores with greater than 6000 ppm Cr are plotted to target the most primitive liquids in the Higganum dike (Dorais and Tubrett, 2008). The calculated La_N liquid concentrations for the cores of these six grains range from 13-37 times chondrites while the rims range from 53-681 (Dorais and Tubrett, 2008). Significantly, the cores lack negative Eu anomalies that become more prominent with increasing REE contents toward the rim of the grains (Dorais and Tubrett, 2008).

An-rich plagioclase cores

The compositions of plagioclase feldspars of the Higganum dike from the electron microprobe are given in table 5. Of the six feldspars analyzed, the greatest core to rim change is seen in HI-205Plagioclase 4 with the rim at 49 An (wt %) and the core at 78 An (wt %). Core to rim profiles of the feldspars are shown in figure 14. The same plagioclase grains that were analyzed with the electron microprobe were used for LA-ICPMS. The resulting $^{87}Sr/^{86}Sr_i$ isotopic compositions of the plagioclase cores range from 0.7057 to 0.7064 while the rims range from 0.7058 to 0.7071 (fig. 14, table 4). The rims and the cores fall well within the analytical error of the Higganum whole rock which yielded a $^{87}Sr/^{86}Sr_i$ ratio of 0.7057 and 0.7058 (table 4, fig. 15 and 16). Figure 17 shows an image of grain HI-205 Plagioclase 3 with the LA-ICMPS troughs. Attempts were made to use LA-ICPMS for similar analysis of $^{87}Sr/^{86}Sr$ ratios of the clinopyroxene cores. However, the concentration or Sr was too low to produce any usable results.

Isotopes

Bulk-rock isotope data are presented on an εNd vs. $^{87}Sr/^{86}Sr_i$ diagram (Fig. 15). These data were calculated to 199 Ma. In general, low-Ti samples show a large isotopic range and generally plot in the enriched quadrant (εNd $_{(199\ \mathrm{Ma})}$ -3.66 to 3.16 and ^{87}Sr/^{86}Sr$_i$ of 0.705 to 0.708), while the high-Ti samples plot in the depleted quadrant and are characterized by unradiogenic Sr compositions and low εNd values (εNd $_{(199\ \mathrm{Ma})}$ 2.95 to 5.80 and ^{87}Sr/^{86}Sr$_i$ of 0.703 to 0.705). Higganum dike bulk-rock isotopic compositions fall within the low-Ti field with εNd of 0.2 and -0.2 ^{87}Sr/^{86}Sr $_{(199\ \mathrm{Ma})}$ values of 0.7057 and 0.7058 respectively. The ^{87}Sr/^{86}Sr isotope compositions of plagioclase of the Higganum dike are plotted below the other points on figure 15 as the concentration of Nd was too low to allow measurement of Nd isotope ratios. However, the Sr isotope data appear to extrapolate to the low-Ti field and the gap between the low-Ti group and high-Ti group is not bridged by the Ca-rich plagioclase cores (fig. 15).

There are two exceptions to the general pattern of an enriched low-Ti group and a depleted high-Ti group seen on figure 15: Samples C/8019 from Liberia (De Min et al., 2003) and 6916 from Brazil (Dupuy et al., 1988) have sufficient wt% TiO_2 to be classified as high-Ti, but plot in the low-Ti field. These samples are also marked on figures 2, 4-8, and 10-12 and are labeled as "contaminated high-Ti."

An ^{87}Sr/^{86}Sr histogram (fig. 16) shows that LA-ICPMS analyses of plagioclase cores and rims plot within error with the peak of the low-Ti group. Additionally, they are nearly identical to the Higganum Dike which also plots with the majority of samples from the low-Ti group.

Discussion

Before discussing the implications of the results of this study for determining possible sources for the igneous rocks of the Central Atlantic Magmatic Province, we need to justify our decisions in studying the Higganum dike, and our interpretation that the Cr-rich pyroxene cores and Ca-rich plagioclase cores represent the most primitive composition from the low-Ti group.

The chemical composition of the Higganum dike is typical of the low-Ti group as seen in figures 2-16 (Philpotts and Martello, 1986). As part of the low-Ti group, the Higganum dike and corresponding Talcott basalt represent the most widespread and common composition of Central Atlantic Magmatic Province and erupted in a very short amount of time—possibly less than 1 million years (Salters et. al 2003; Marzoli et al., 1999; Olsen et al., 1996). In searching for a primitive composition in the low-Ti group, the Higganum is a reasonable target as it is the earliest extensive tholeiitic flow of the Central Atlantic Magmatic Province in eastern North America (Philpotts and Reichenbach, 1985). It is not a differentiation product and has been determined to be the possible parental magma for the Holyoke and Hampden basalts (Puffer and Lechler, 1979; Philpotts and Reichenbach, 1985; Ragland and Arther, 1985; L.E. Cummins et al., 1992; Ragland et al., 1992; Puffer, 1992). The Higganum is a very wide dike connected to a surface flow. As a result, the buoyant rise of magma was rapid enough to possibly retain phenocrystic information about the intratelluric history (Asher and Philpotts, 1995). Evidence for this is indicated in the Cr-rich clinopyroxenes that have euhedral zoning with no compositional gaps from core to rim (Dorais and Tubrett, 2008) and the zoned calcic plagioclase crystals.

Although the low-Ti Higganum dike and Talcott basalt do not have primary compositions in terms of Mg #s at 0.58 and 0.59, they have some of the highest Cr contents in the low-Ti group (fig 12). Furthermore, liquid compositions calculated from the clinopyroxene cores have Cr concentrations are near primary (fig. 12), and slightly higher Mg #s that the bulk rock (~63) (Dorais and Tubrett, 2008). These Mg #s approach those of primary basalts which are between 65 and 75 (Basaltic Volcanism Study Project, 1981). There is evidence that the slightly lower Mg number of the Cr-rich clinopyroxene cores was probably caused by olivine fractionation, which would have lowered the Mg/Fe ratio but would not have appreciably changed the incompatible trace element relationships; therefore, spider diagrams created using liquids of these cores would still retain information about near primary magma characteristics (Dorais and Tubrett, 2008).

Based on experiments, the Cr-rich clinopyroxene cores (some >6000 ppm) appear to have crystallized from a more primitive magma than the bulk rock at high pressures of 5.8-7.9 kbars (Philpotts and Reichenbach, 1985; Asher and Philpotts, 1995; Dorais and Tubrett, 2008). In melting experiments of the Talcott basalt, compositionally the same as the Higganum dike, Philpotts and Reichenbach (1985) concluded that plagioclase probably began to crystallize before the clinopyroxene. So in the Higganum dike the most primitive clinopyroxene and plagioclase were probably brought up from depth together where they were possibly in equilibrium. We interpret the high Cr contents of the pyroxene and the high An contents of the plagioclase to establish that these minerals crystallized early, perhaps before crustal contamination. The plagioclase cores used for isotopic data in this study are assumed to be those that came up from depth. Only the most calcic plagioclase with cores ~An_{70} were targeted for LA-ICPMS.

Contamination

Chemical evidence for a crustal component in the Higganum dike and greater eastern North America province is evidenced by depletion of Nb-Ta, and Ti, enrichment of K, Rb, Ba, light rare earth elements and Th compared to MORB, as well as an overall enriched isotopic composition (figs. 7, 8, and 12) (Dostal and Greenough, 1992; Pe-Piper et al., 1992; Dostal and During, 1998; Dorais et al., 2005). Field evidence of the Higganum dike also shows evidence of crustal assimilation by melting of wall rocks and xenoliths (Philpotts and Asher, 1993; Asher and Philpotts, 1995). This characteristic crustal component is found in all the low-Ti group of the

Central Atlantic Magmatic Province (figs. 8, 9, and 13) (Marzoli et al., 1999; Puffer, 2001; Cebriá et al., 2003; Youbi et al., 2003; Deckart et al., 2005).

Even though Nb, Ta, and Ti depletions and enrichment of K, Rb, Ba, and light REE and Th, may not indisputably distinguish between crustal contamination and source contamination (Deckart et al., 2005) many researchers have concluded that there is identifiable source contamination (Dostal and Greenough, 1992; Youbi et al., 2003; Deckart et al., 2003; Martins, 2008). This conclusion is based on various lines of evidence: (1) The negative Nb-Ta, and Ti anomalies seen throughout the Central Atlantic Province, but specifically in Nova Scotia they are not easily related to any liquidus phases as Fe-T oxides are late-stage crystallization minerals (Dostal and Greenough, 1992). Thus, these geochemical characteristics resulted from process other than shallow level crystallization, and probably reflect mantle source characteristics (Youbi et al., 2003). (2) ^{187}Os/^{188}Os ratios measured on the least differentiated low-Ti tholeiites from Iberia rule out significant contamination for those samples, which shows the importance of source contamination to produce the geochemical characteristics found in the low-Ti lavas (Rapaille et al., 2003). (3) Modeling of AFC processes of Moroccan and Portuguese lavas require further involvement of an enriched source besides crustal contamination (Youbi et al., 2003). (4) The presence of the LILE and REE enrichments and negative Nb anomalies found in both the low-Ti lavas and in ultramafic cumulates from Guinea magmas led Deckart et al., (2005) to conclude that these geochemical signatures were representative of the source. Because these cumulates are thought to represent the early fractionation products of these lavas, a signature of a crustal component was interpreted to represent source contamination.

Our plagioclase isotopic study revealed that even the most primitive plagioclase in the most primitive magma from eastern North America provide evidence for contamination prior to crystallization. The results of our study show that the $^{87}Sr/^{86}Sr_i$ ratios are very similar to the Higganum bulk rock (fig. 15 and 16). As these An-rich cores were the most primitive we found, and probably were brought up from depth with the Cr-rich primitive clinopyroxenes which were concluded above to represent crystallization from near primary liquids, we conclude that these isotopic compositions are also representative of the source. This conclusion is supported by a similar plagioclase core study from Central Atlantic Magmatic Province done in France where Marzoli et al. (2006) likewise concluded that plagioclase core $^{87}Sr/^{86}Sr$ ratios also reflected mantle source characteristics. Furthermore, Deckart et al. (2005) and Jourdan et al. (2003) have concluded the magma-crust interactions have not modified Sr and Nd isotope signatures enough to prevent their use as tracers of mantle source compositions in similar Central Atlantic Magmatic Province magmas from South America and France. Therefore, we conclude that little crustal contamination occurred before the plagioclase cores crystallized and both the core and bulk-rock isotopic compositions are close to primary. Any crustal component in the Higganum would therefore appear to reflect source contamination.

Low-Ti Source

This enriched source contamination has been identified in the Central Atlantic Magmatic Province research literature as a subduction-enriched metasomatized lithospheric mantle (De Min, 2003; Jourdan et al., 2003; Puffer, 2003; Salters et al., 2003; Youb et al., 2003; Verati et al., 2005; Merle et al., 2007; Dorais and Tubrett, 2008; Martins et al., 2008). Trace elements diagrams from this study confirm this conclusion as the low-Ti group on figure 9 plots in the Arc Continental Flood Basalt field of Puffer (2001), and figures 8 and 9 illustrate the negative Nb-Ta and Ti anomalies and positive Pb anomalies of the low-Ti group which is typical of subduction-enriched magmas. In eastern North America, this source contamination may have occurred during any of the multiple Paleozoic arc accretion events (Puffer, 2003). The orogenies of the northern Appalachians include the Taconic, Salinic, Acadian, Neoacadian and Alleghanian which involved the collision of island arcs, microcontinents, and Gondwana to the Laurentian margin prior to 200 Ma (van Staal et al., in press).

Our technique of looking at the most primitive components in the Higganum dike similarly validates the conclusion that the source contamination of low-Ti Central Atlantic Magmatic Province is a subduction component (Dorais and Tubrett (2008). Trace element liquid compositions calculated from from the pyroxene cores outlined in an earlier study indicate the influence of subduction-zone fluids as illustrated by negative Nb and positive Pb anomalies, Ba/La values ranging from 3-30, and overall arc-like trace element patterns.

High-Ti as a parent?

The idea that the high-Ti group is derived from a more depleted source than the low-Ti group originated from the εNd vs. $^{87}Sr/^{86}Sr_i$ (fig. 15) diagram, as the high-Ti group plots in a more depleted field at lower $^{87}Sr/^{86}Sr_i$ and higher εNd than the low-Ti group. The TiO_2 vs. SiO_2 diagram shows a continuum linking the two groups (fig. 2). Furthermore, the low-Ti group and primitive Cr-rich clinopyroxene calculated liquids have positive Pb anomalies (figs. 8, 13) which typically indicates crustal contamination. Therefore, it was speculated that the low-Ti group was a contaminated version derived from a primitive high-Ti parent.

Determining the most primitive high-Ti parent requires an examination of the “outliers” group. All of the data points that comprise this “outliers” group are located in the geographically narrow ribbon of the high-Ti magmas (fig 1). Furthermore on figure 2 and all of the other major element diagrams (figs. 4-7) they appear to link and fill in the gaps between the low-Ti and high-Ti group. This group generally has higher MgO and Cr concentrations than the majority of the high-Ti group, and appears to be at the beginning of the differentiation trends of the high-Ti group. Thus, we interpret this "outliers" group to be a more primitive representation of the high-Ti group.

Our study shows that the most primitive "outlier" members of the high-Ti group cannot be parental to the low-Ti group. Figures 11 and 12 reveal that the "outliers" group generally has lower Cr contents and Mg#'s than most of the low-Ti group. Generating the low-Ti group from an "outlier" parent requires significant assimilation and/or fractionation, but these processes cannot explain higher Cr contents and Mg#s in the daughter product than found in the parent. This argument also eliminates the liquid compositions calculated from clinopyroxene Cr-rich cores from linking the low-Ti and outlier/high-Ti groups as they have even higher Cr contents than the all of the low-Ti group (fig. 12). Furthermore, the high Mg numbers of these calculated liquids indicate that they had not experienced significant fractionation—possibly just some olivine and/or orthopyroxene (Dorais and Tubrett, 2008). Additionally, the TiO_2 vs. P_2O_5 diagram (fig. 7) shows that the outlier/high-Ti group increase in P concentrations as they differentiate. To be parental to the low-Ti group, they would have to decline in P concentrations with differentiation. In addition, the trace element diagram of the liquids in equilibrium of these Cr-rich cores (fig. 13) reveals little similarities to the high-Ti group. The cores, instead, have the features of the low-Ti group such as large negative Nb anomalies and less enrichment in the more compatible trace elements of Sr through Lu. The plagioclase core $^{87}Sr/^{86}$ Sr ratios further negate a link between the outlier/high-Ti and low-Ti groups. Figure 15 shows that the composition of the calcic cores is more similar to the low-Ti magmas and therefore does not bridge the Sr-isotope gap between the low-Ti and outliers/high-Ti Central Atlantic Magmatic Province groups.

The two points labeled “contaminated high-Ti” identified on figure 15 also show there is no compositional link between the low-Ti and high-Ti groups. These are isotopically enriched high-Ti rocks from Liberia and Brazil. In spite of their high Sr_i and low εNd these samples plot solidly with the high-Ti group on element variation diagrams (figs. 2, 4-7) and suggest that “crustal” contamination of high-Ti magmas does not make low-Ti magmas. Similarly, the incompatible trace element patterns (fig. 8) of the two samples plot clearly within the field of the high-Ti group. Furthermore, these “contaminated” samples lack the major negative Nb-Ta, and Ti anomalies and positive Pb anomaly that characterize the low-Ti group (figs. 8, 9). These contaminated high-Ti rocks have MgO and Cr concentrations which are lower than the majority of the low-Ti group (figs. 11, 12). These samples, are therefore considered to be isotopically enriched, but in all other respects best classified with the high-Ti group. This group does not show any relation to the low-Ti group and does not bridge the gap between the two Central Atlantic Magmatic Province magma types.

High-Ti Source

A clue to the source of the high-Ti magmas is seen in the differentiation path labeled on figures 2 and 6. In these diagrams, the high-Ti group evolves to increase in TiO_2 and Fe_2O_3 as SiO_2 decreases. This is the classic tholeiitic differentiation trend. Similar differentiation paths are found of basalts from Iceland, (Carmichael, 1964) and the Snake River Plain (Christiansen and McCurry, 2008). The differentiation paths of these olivine tholeiites is explained by their low fO_2 and fH_2O, which can impede Fe-Ti oxide crystallization, and thus differentiating magmas are enriched in TiO_2 and Fe_2O_3 and silica becomes lower as olivine and plagioclase fractionate (Christiansen and McCurry, 2008). Relatively low oxygen fugacities are characteristic of the sources of the Snake River Plain and Iceland basalts and mantle plumes. Therefore, based on major element trends, it is possible that the source for the high-Ti group is similarly plume related. Trace elements also appear to support the suggestion of the association with a plume because, as shown if figure 9, the high-Ti group plots in the Plume Continental Flood Basalt Field of Puffer (2001). We concur with the model offered by Nomade et al., (2002a), which suggests that the topography resulting from the Rokelides suture induced a preferential plume ascent at the base of the narrow zone of the high-Ti group. The high-Ti lavas from French Guyana, Surinam, Liberia and Cassioporé resulted when an asthenospheric upwelling in this zone (fig. 18).

Conclusions

We conclude that the source of the widespread low-Ti tholieiites of the Central Atlantic Magmatic Province is a subduction-enriched metasomatized lithospheric mantle. This conclusion is based in part on Sr isotopic composition of the cores of An-rich plagioclase feldspar phenocrysts in typical low-Ti dike. The Sr_i of the cores (and rims) is indistinguishable from the isotopic composition of the Higganum dike or from the rest of the low-Ti group. Liquids re-calculated from the trace element composition of Cr-rich clinopyroxene also reveal evidence of subduction-related contamination in the source of the low-Ti Central Atlantic Magmatic Province.

In addition, it is unlikely that the high-Ti Central Atlantic Magmatic Province tholeiites were the parental magmas of the low-Ti group. The outlier/high-Ti group was found to generally have lower MgO, Cr, and Ni concentrations, and there is not an assimilation and/or fractionation process that could produce that relationship. Thus, we have identified a possible subduction contaminated lithospheric mantle suite (low-Ti group) and a source that lacks a subduction signature for the outliers/high-Ti groups of the Central Atlantic Magmatic Province.

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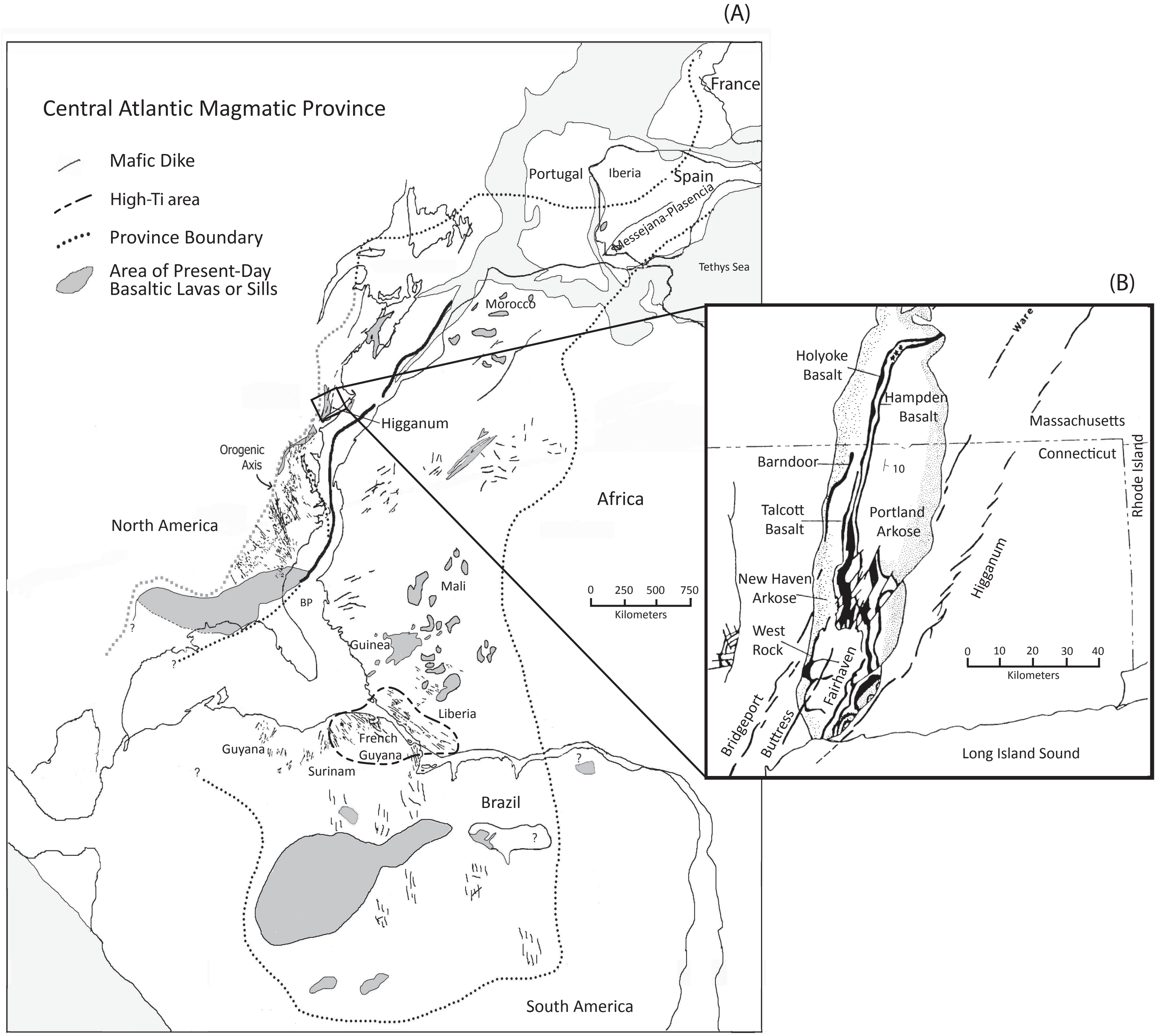

Figure 1. (A) Extent of the Central Atlantic Magmatic Province. Modified from McHone (2000). The low-Ti group of the Central Atlantic Magmatic Province is widespread and constitutes all of the dikes and flows shown except those in the outlined area of the high-Ti group. The high-Ti group is clustered on the margin of South America and Africa (Nomade et al., 2002a). (B) Map of the Higganum dike and Hartford Basin of Connecticut. Dark black lines indicate dikes and lava flows, and shaded stippled areas indicate arkose. Modified from Philpotts and Martello (1986).

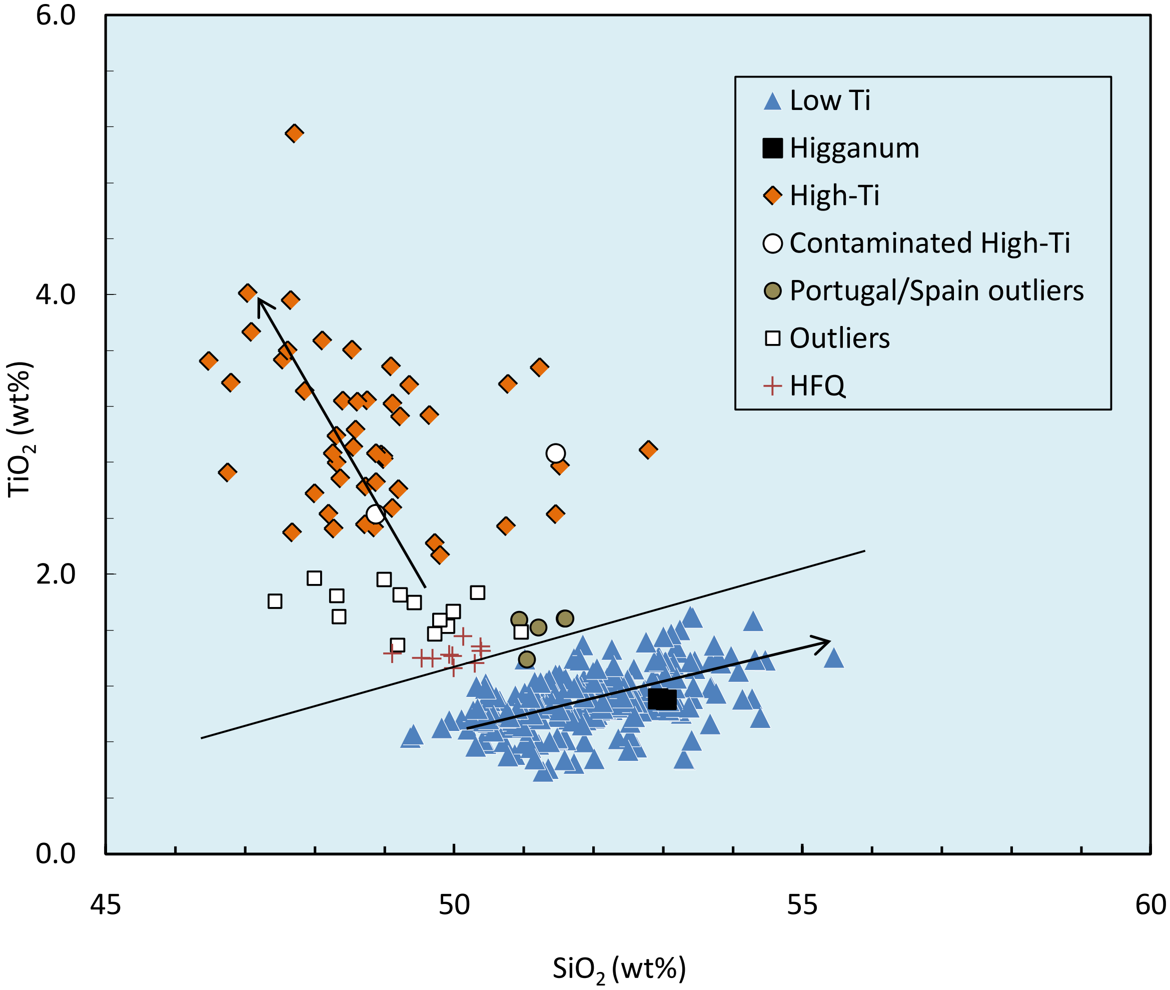

Figure 2. SiO_2 vs. TiO_2 variation diagram. The line separates the high-Ti group from low-Ti group as used in this paper. Outliers have lower TiO_2 concentrations than the high-Ti group but are found in small geographical area of the high-Ti group. This outlier group appears as a continuum between the high-Ti and low-Ti group. This relationship is also seen on figures 4-7 and 10-13. The Portugal/Spain and HFQ groups were determined to be differentiates of low-Ti magmas and are only shown on this diagram to illustrate their similarities. Possible differentiation paths for the two groups are delineated by arrowed lines and based on linear trend lines. The low-Ti group shows TiO_2 enrichment as silica increases while the High-Ti group shows the inverse.

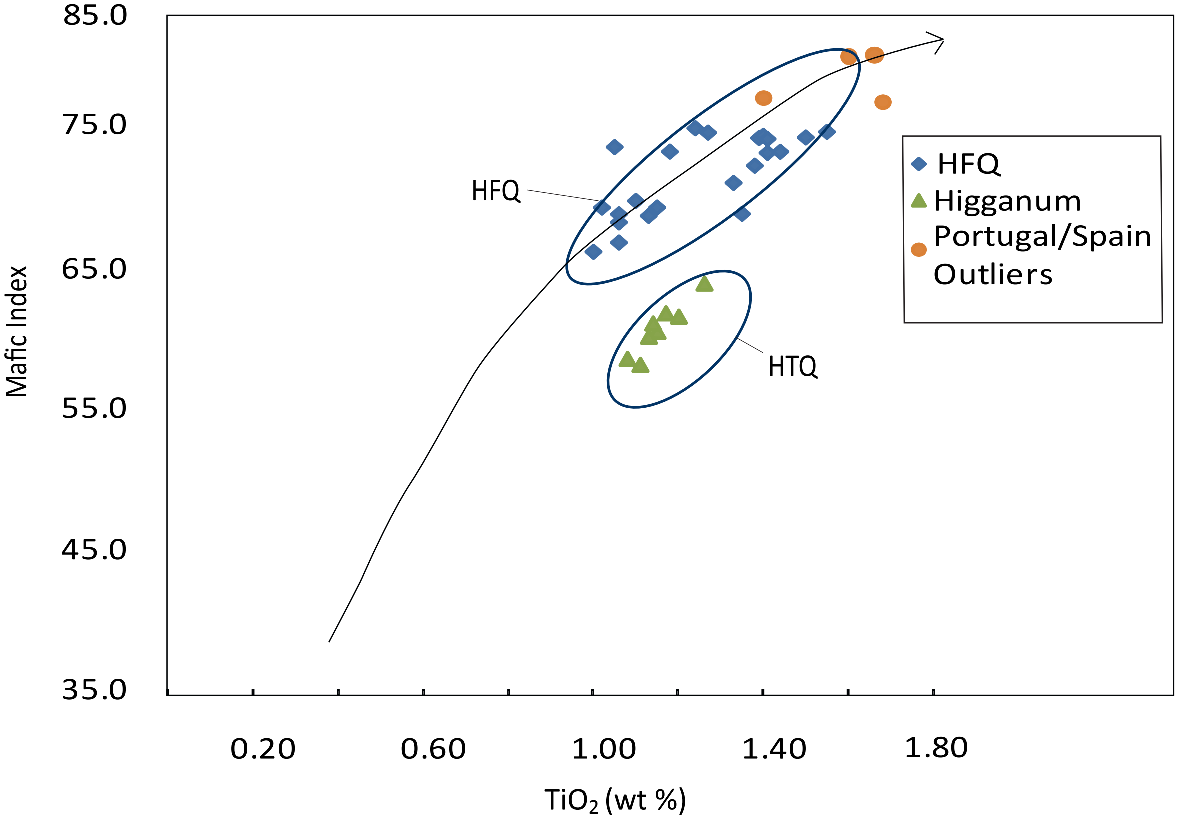

Figure 3. Mafic Index vs. TiO_2 variation diagram based on Puffer, (1992). HFQ stands for high-Ti iron normative while HTQ stands for high-Ti quartz normative. Note that the Portugal/Spain outliers plot within or near the HFQ field along with the HFQ samples collected from the Central Atlantic Magmatic Province. Only Higganum Dike samples are shown to represent the HTQ basalts of the Central Atlantic Magmatic Province. Mafic Index calculated as $\frac{FeO + Fe_2O_3 \; *100}{MgO + FeO + Fe_2O_3}$.

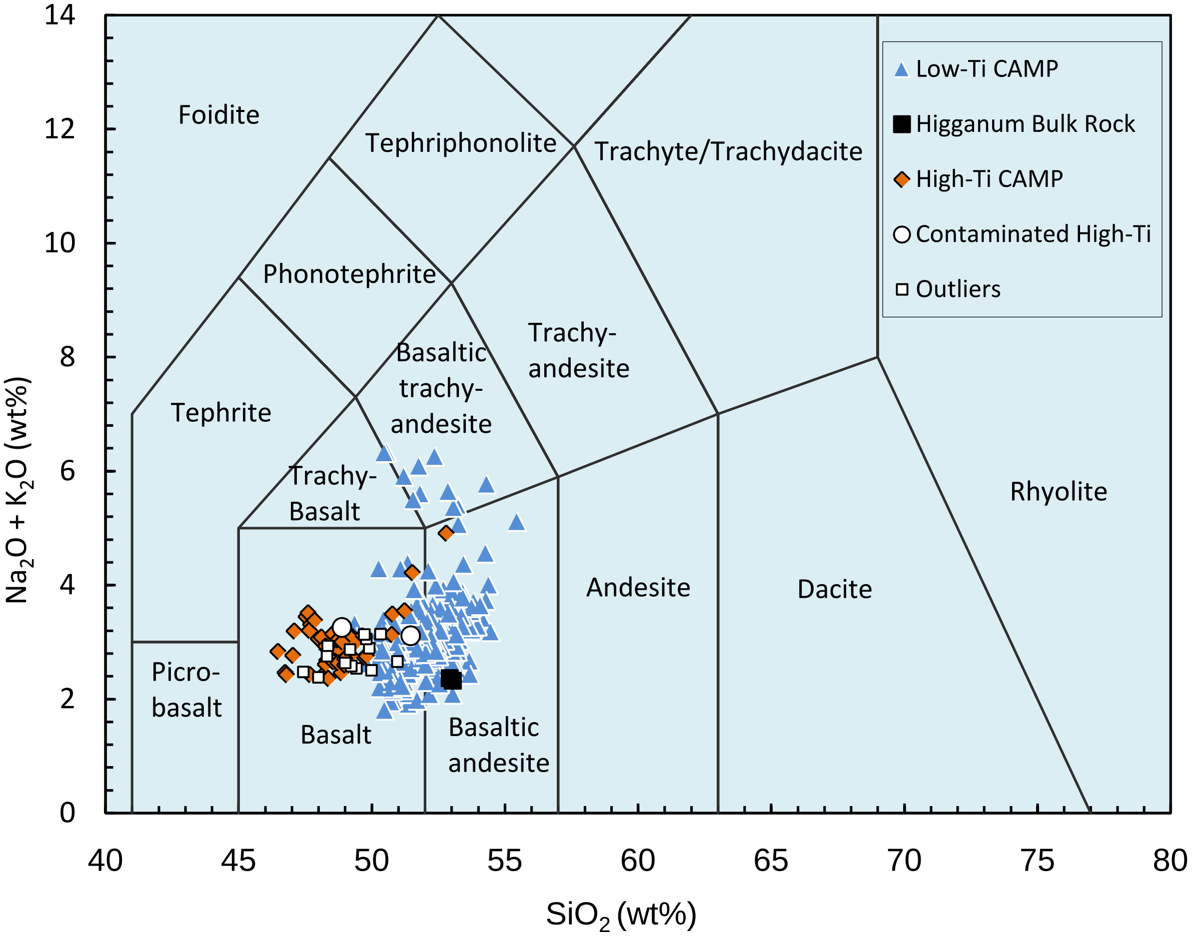

Figure 4. Total alkalies vs. silica diagram (after Le Maitre, 1989)

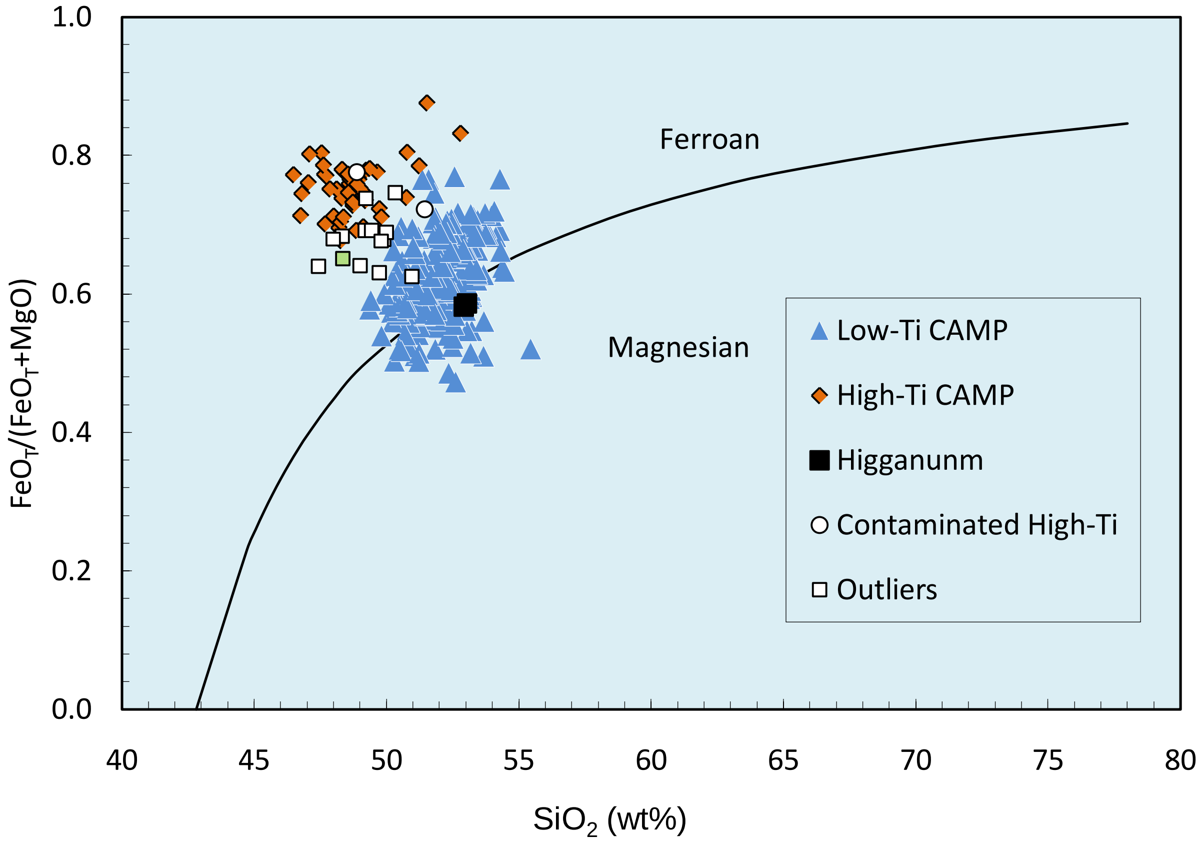

Figure 5. FeO$_T$/(FeO$_T$+MgO) vs. SiO$_2$ diagram (boundary line from Miyashiro, 1974).

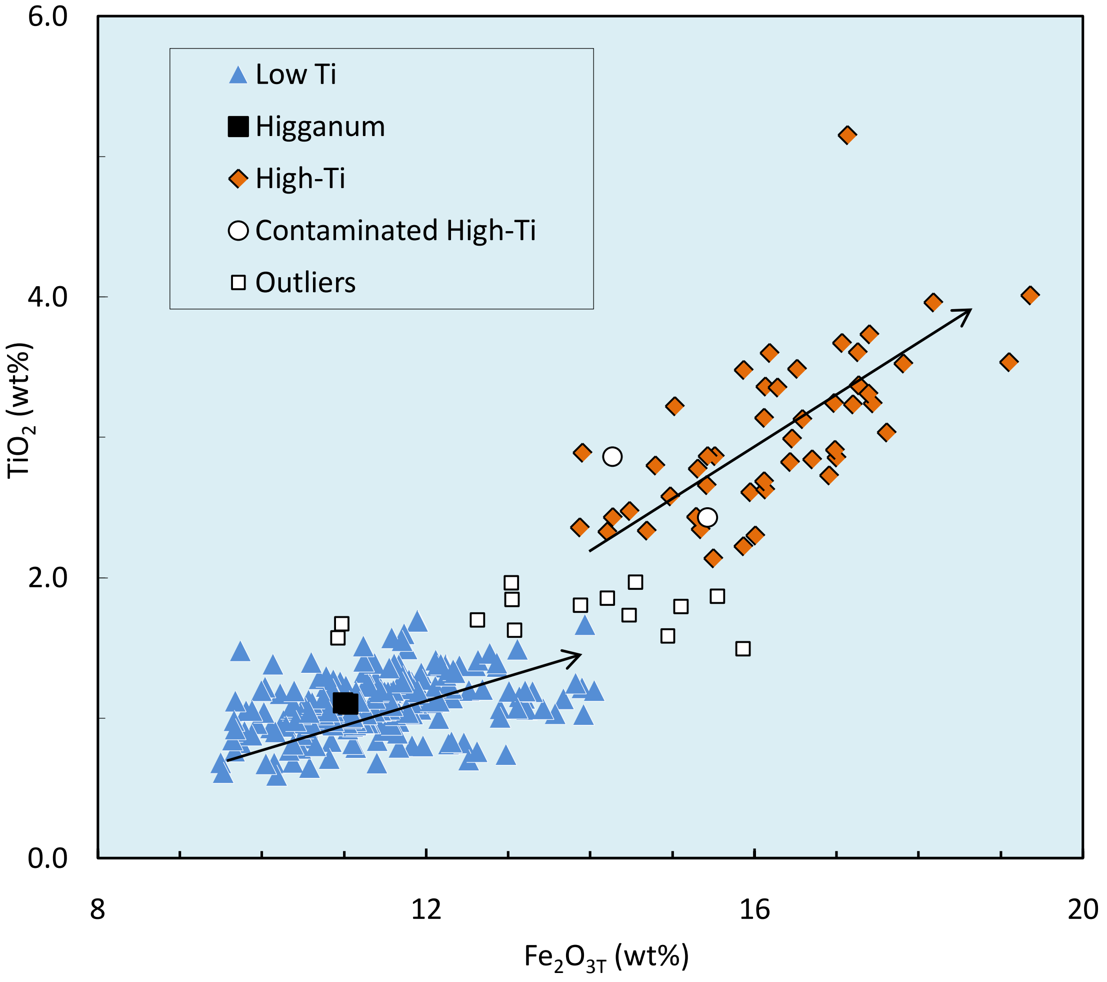

Figure 6. Fe_2O_3 vs. TiO_2 variation diagram based on normalized weight percents. Lines are linear trend line showcasing differentiation paths of the low-Ti and high-Ti groups. There is greater Fe_2O_3 enrichment of the high-Ti group.

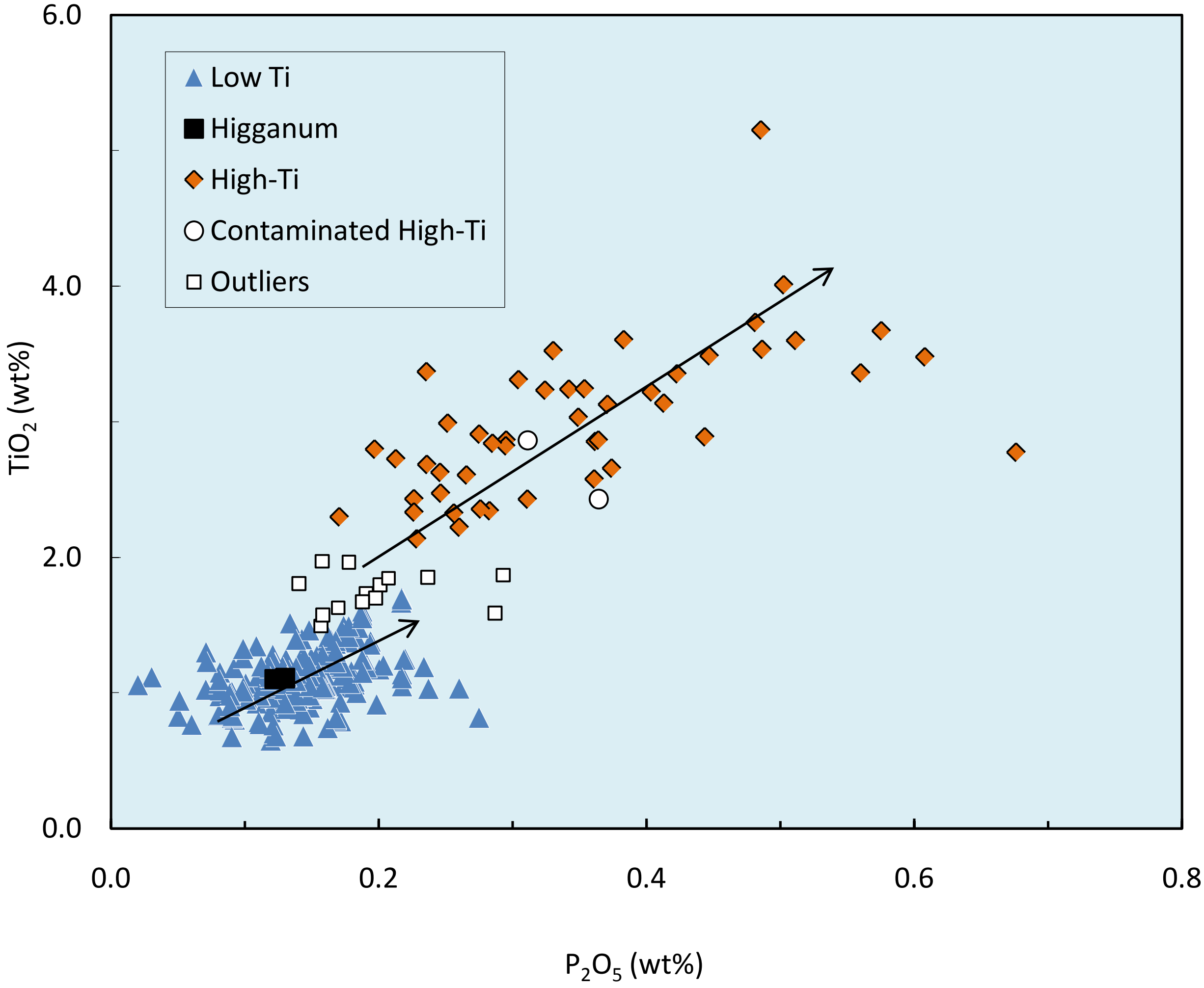

Figure 7. P_2O_5 vs. TiO_2 variation diagram. Lines are based on linear trend lines and reflect the differentiation paths of the two groups showing P_2O_5 enrichment as TiO_2 increases. This relationship is not as strong in the low-Ti group.

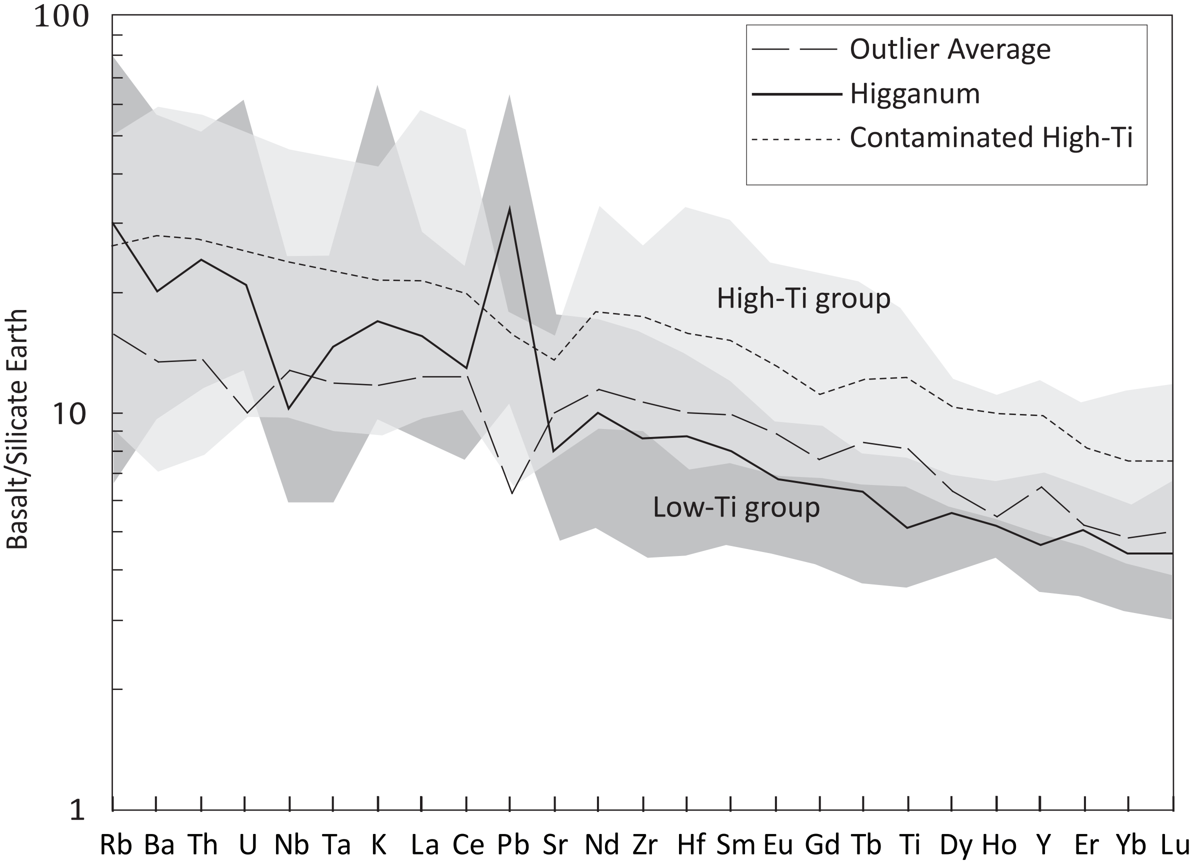

Figure 8. Primitive mantle normalized multi-element diagram (Sun and McDonough, 1989) of the Central Atlantic Magmatic Province. The outliers group was plotted as an average of the 14 available samples. The "Contaminated high-Ti" group is also plotted as an average of 2 samples. Data points of Th, Ta, Pb, and Ho were extrapolated from surrounding points. Higganum data is from this study. High-Ti and Low-Ti fields were created from the authors listed in table 1.

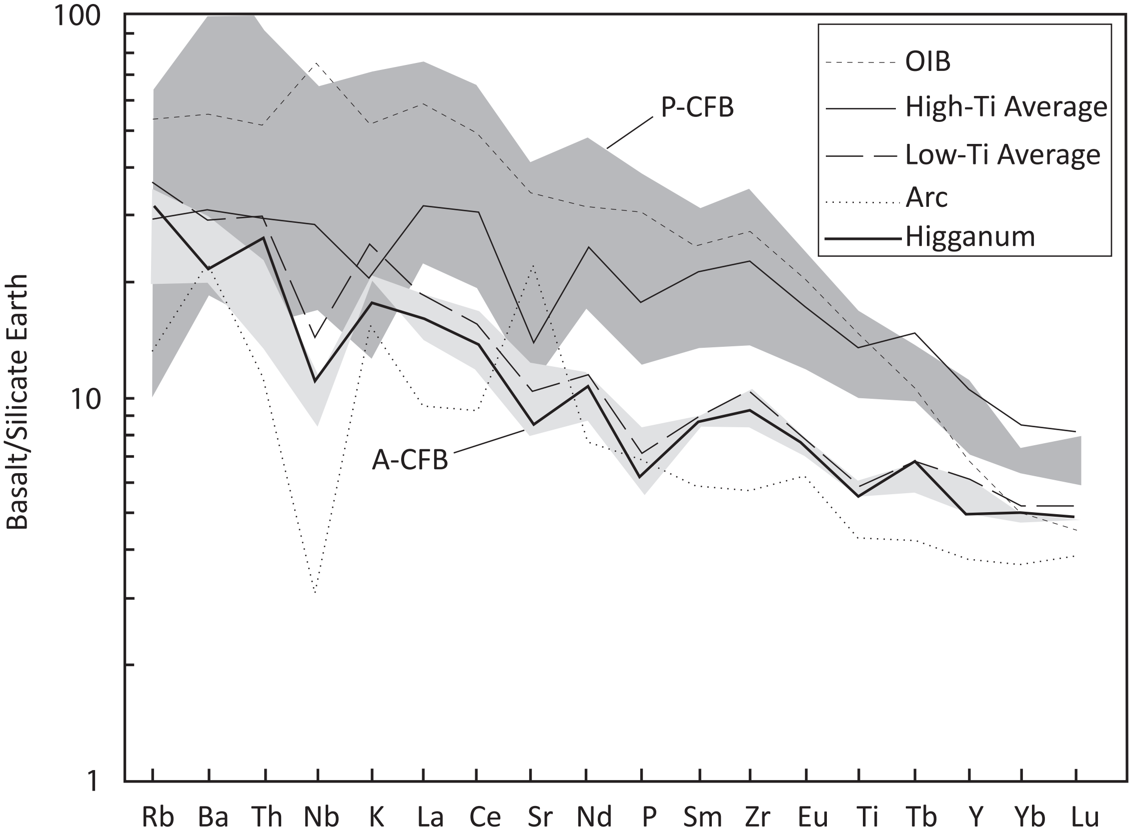

Figure 9. Basalt compositions normalized to silicate Earth of McDonough and Sun (1995). Plume continental flood basalt (P-CFB) field (Puffer, 2001) comprises data from Lebombo (Sweeney et al., 1994), Ethiopia (Barbieri et al., 1995), Columbia River Basalts (main sequence; Hoper and Hawkesworth 1993), Keweenawan basalts (Nicholson et al., 1997), East Greenland (Hogg et al., 1989), Paraná-Etendeka (Peate, 1997), and Deccan Traps (Lightfoot et al., 1990b). Arc continental flood basalts (A-CFB) field comprises data from eastern North American Central Atlantic Magmatic Province (Puffer, 1992), Lesotho, (Marsh et al., 1997), and Siberia (Lightfoot et al., 1990a). Ocean Island Basalt (OIB) from Sun and McDonough (1989), Arc from sample 272825 (Hickey et al., 1986), Higganum (this study), and High-Ti and Low-Ti averages derived from the compositions found in the database (Authors listed in table 1).

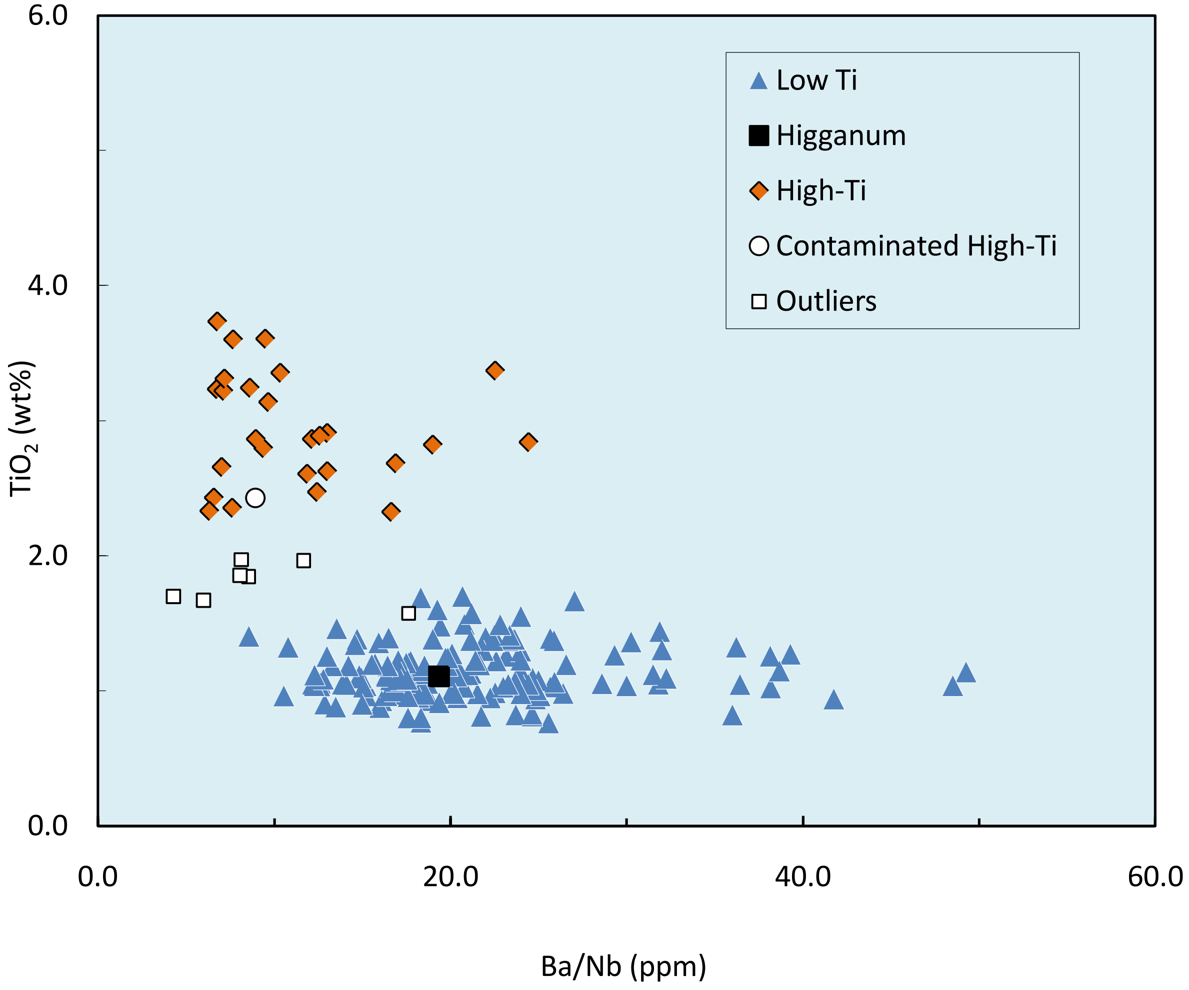

Figure 10. Ba/Nb vs. SiO_2 variation diagram. The low-Ti group has with few exceptions a much larger Ba/Nb ratios as compared to the high-Ti group and outliers.

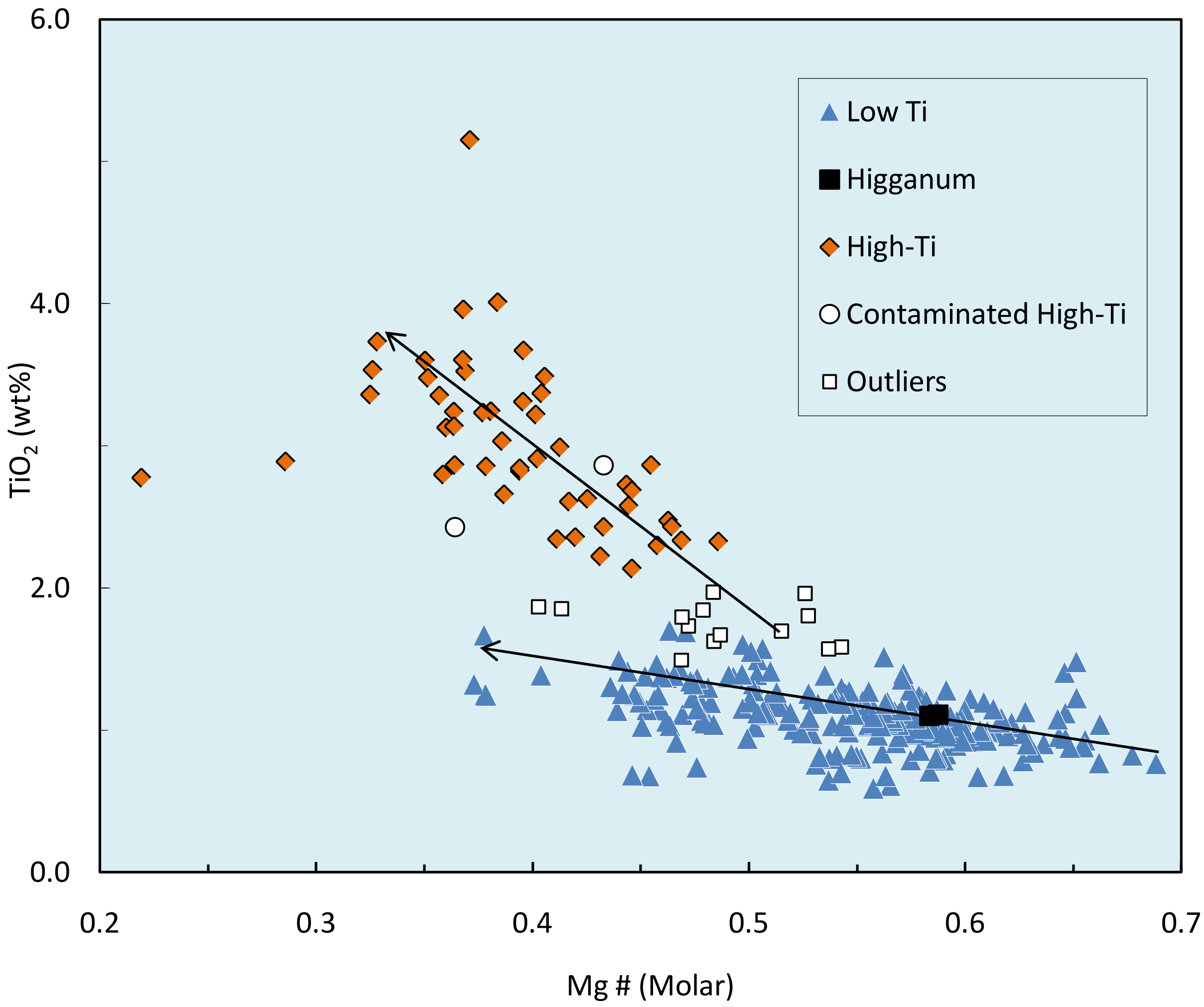

Figure 11. Mg# vs.TiO$_2$ variation diagram. Lines are reflect the possible differentiation paths of the two groups.

$$\frac{\text{MgO (molar)}}{\text{MgO (molar)} + \text{FeO}_T\text{(molar)}} \qquad \text{FeO}_T = (\text{Fe}_2\text{O}_{3*}\ 0.8898)$$

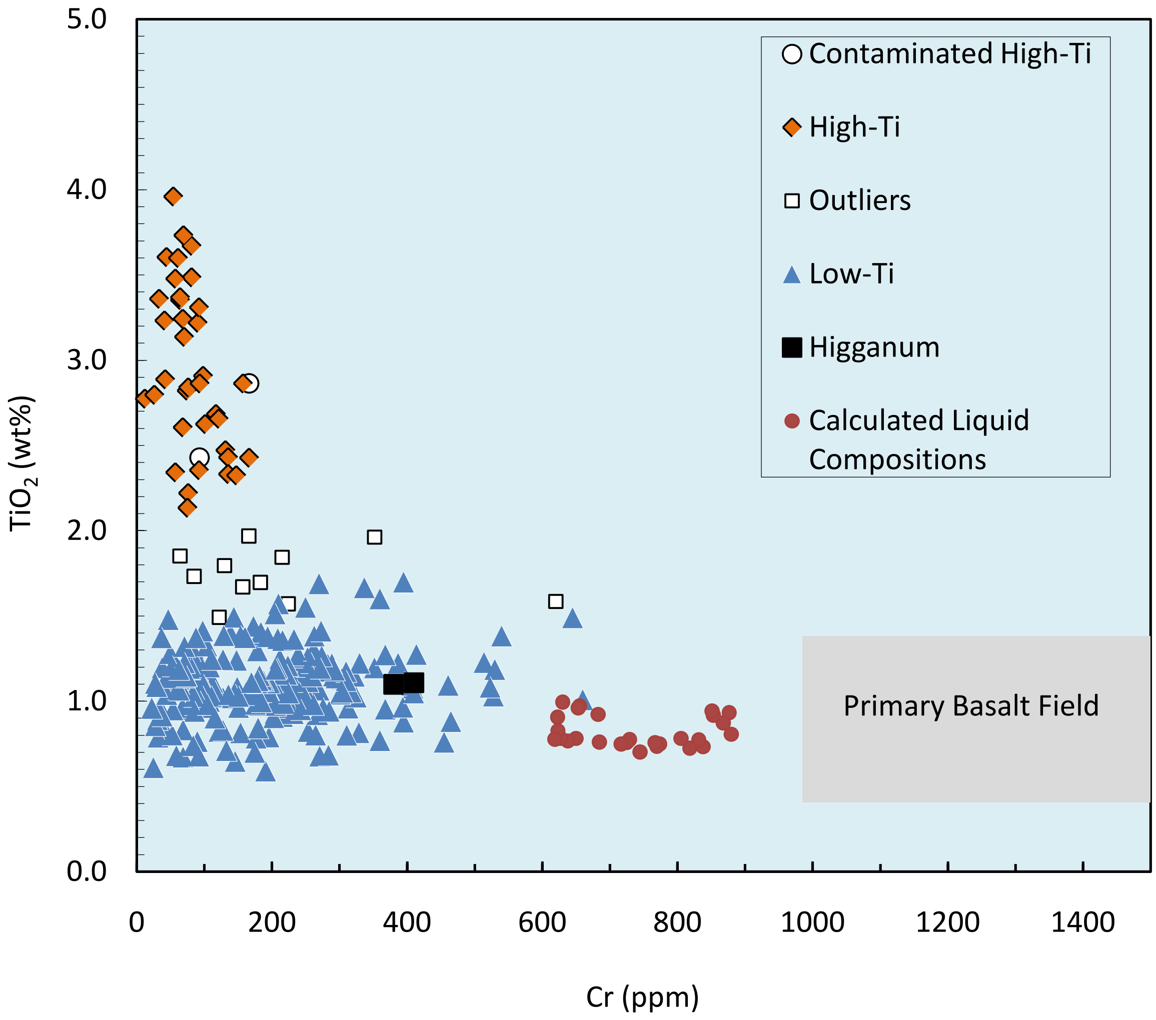

Figure 12. Cr vs. TiO_2 variation diagram. Liquid compositions calculated from Cr-rich clinopyroxene cores are shown using partition coefficients from Henderson (1984). The primary basalt field is based on primary basalt compositions from Wilson (1989).

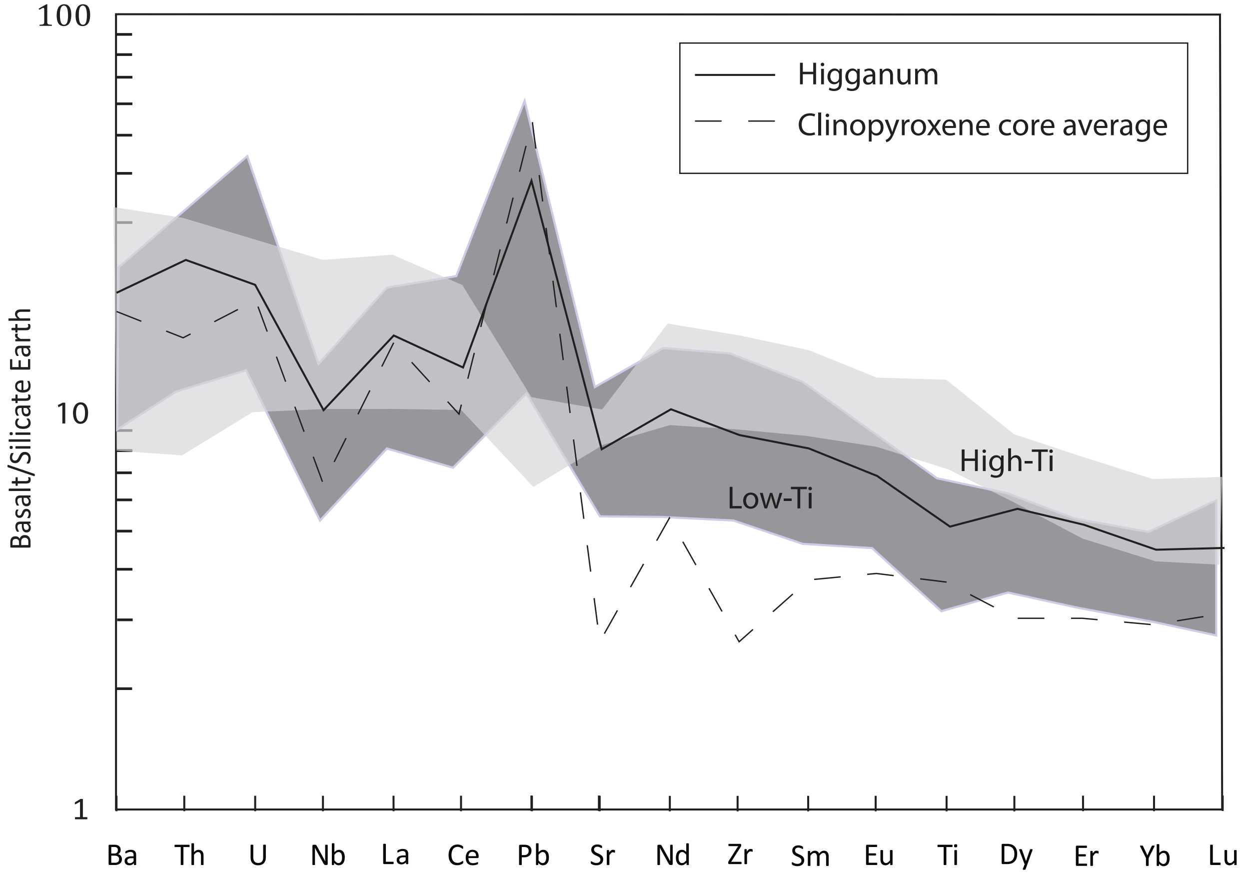

Figure 13. Primitive mantle normalized multi-element diagram (Sun and McDonough, 1989). Solid black line is the average Higganum dike, and stippled line is the average of liquids compositions calculated from six Cr-rich clinopyroxene cores (Hauri et al., 1994; Dorais and Tubrett, 2008). Low-Ti field was created from samples with > 7.0 MgO. High-Ti field includes the "outlier" group and all samples have >6.0 MgO.

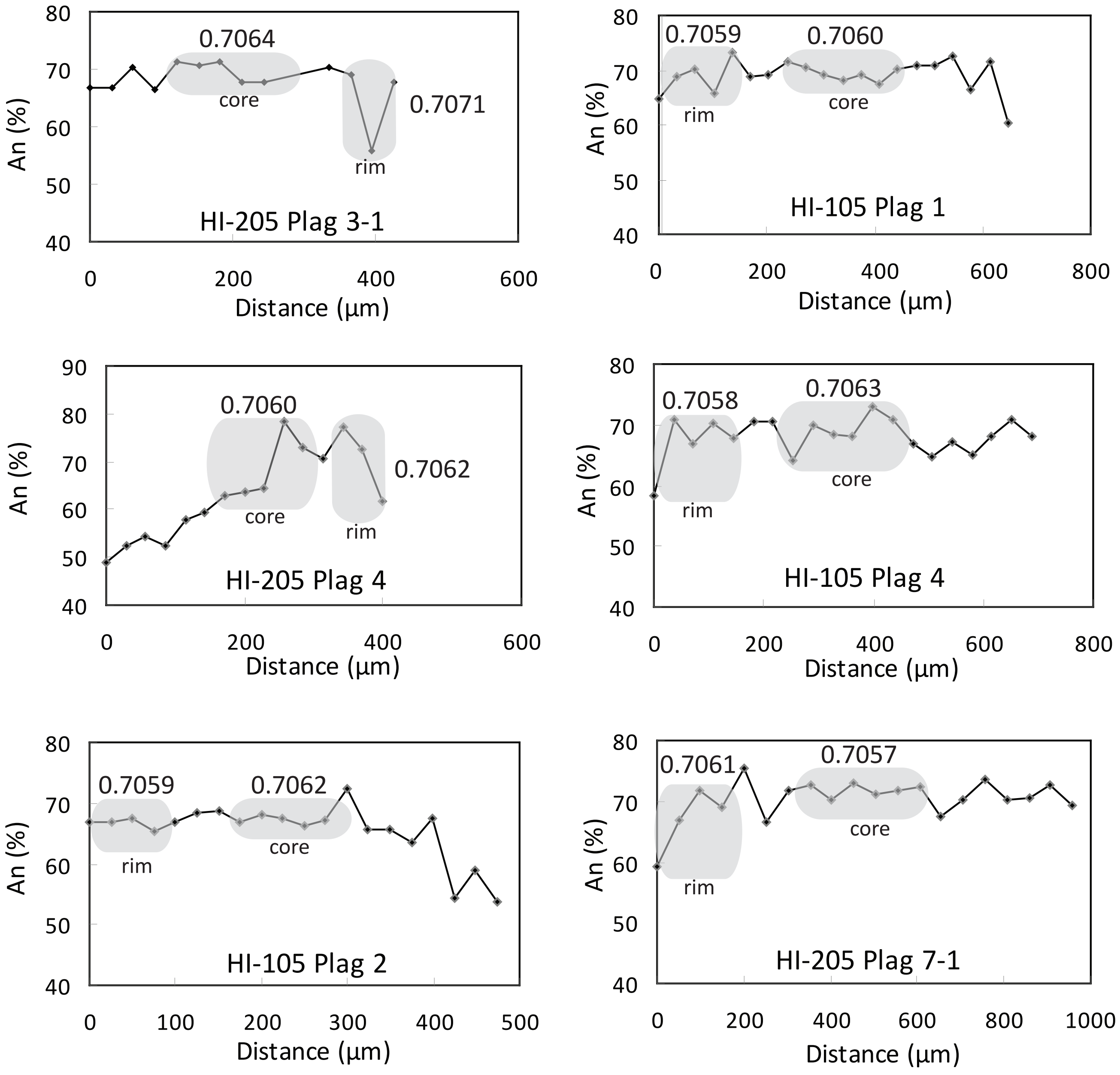

Figure 14. Traverses across plagioclase grains obtained with microprobe analysis. Locations of LA-ICPMS troughs and $^{87}Sr/^{86}Sr$ ratios are labeled for the cores and rims.

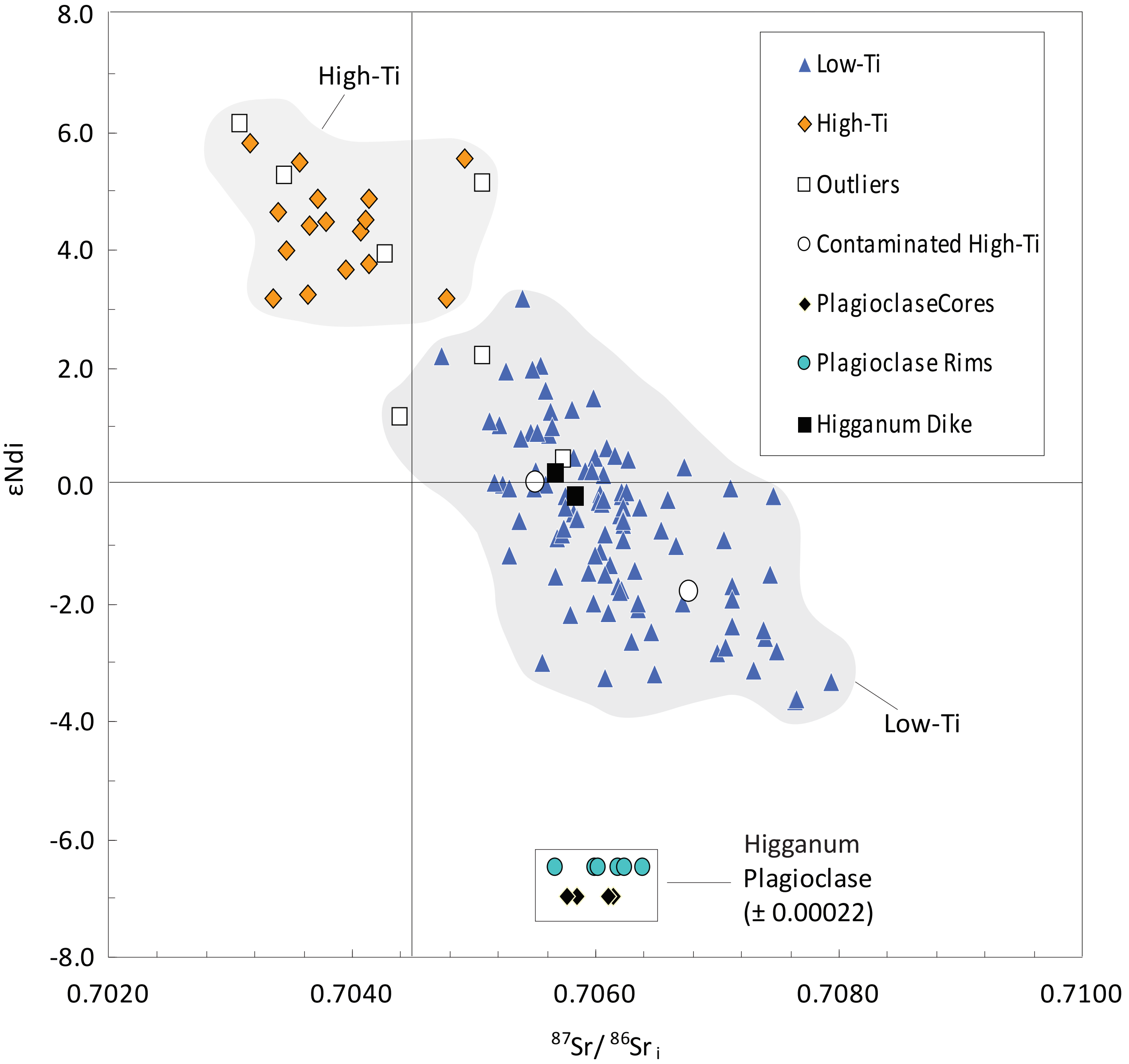

Figure 15. ε Nd vs. $^{87}Sr/8^{6}Sr_i$ diagram. Values were calculated at 199 Ma. The two fields of the low-Ti and high-Ti group are shaded. References in table 1.

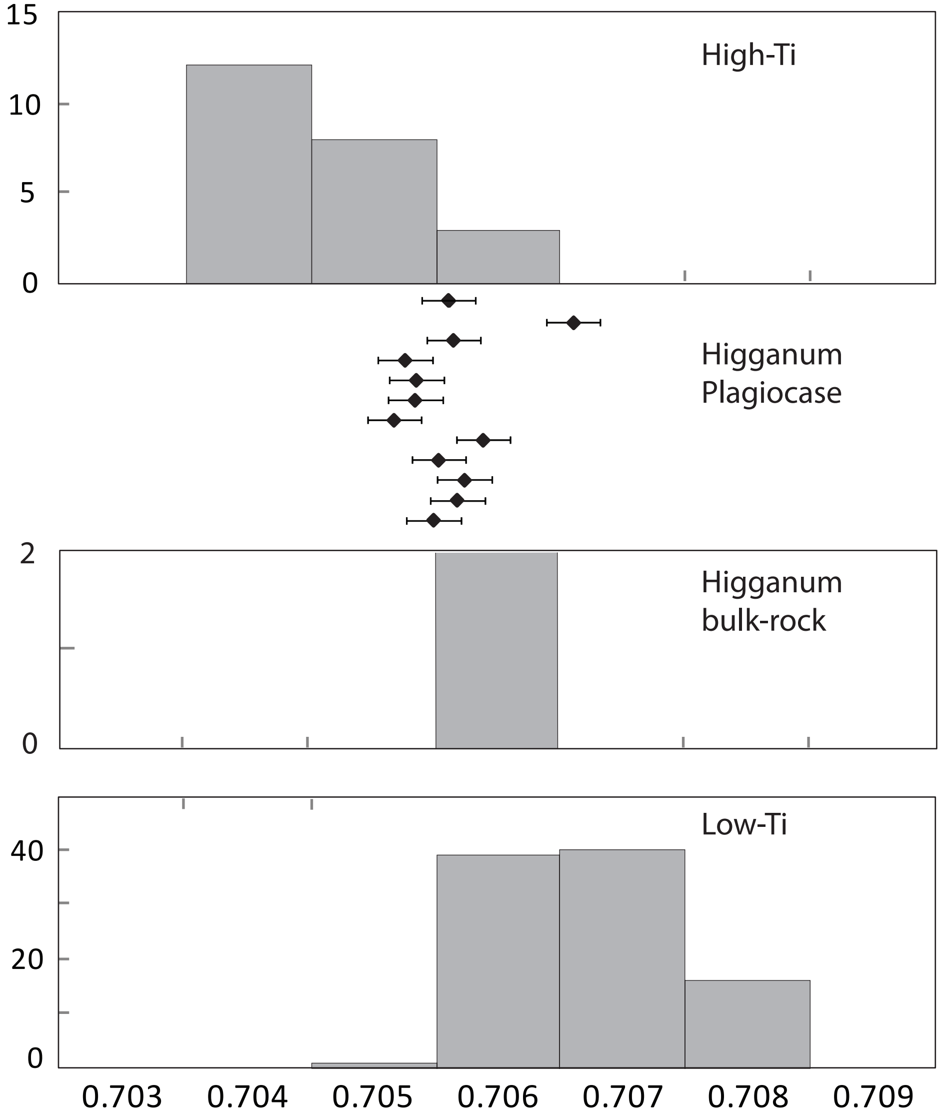

Figure 16. Histogram $^{87}Sr/^{86}Sr_{(199\ Ma)}$ of the low-Ti group, the high-Ti group, the Higganum dike and plagioclase cores and rims from the Higganum Dike. Error bars for plagioclase grains are one standard deviation (± 0.0011). $^{87}Sr/^{86}Sr$ ratios for the plagioclase grains are almost indistinguishable from the low-Ti group and the Higganum dike.

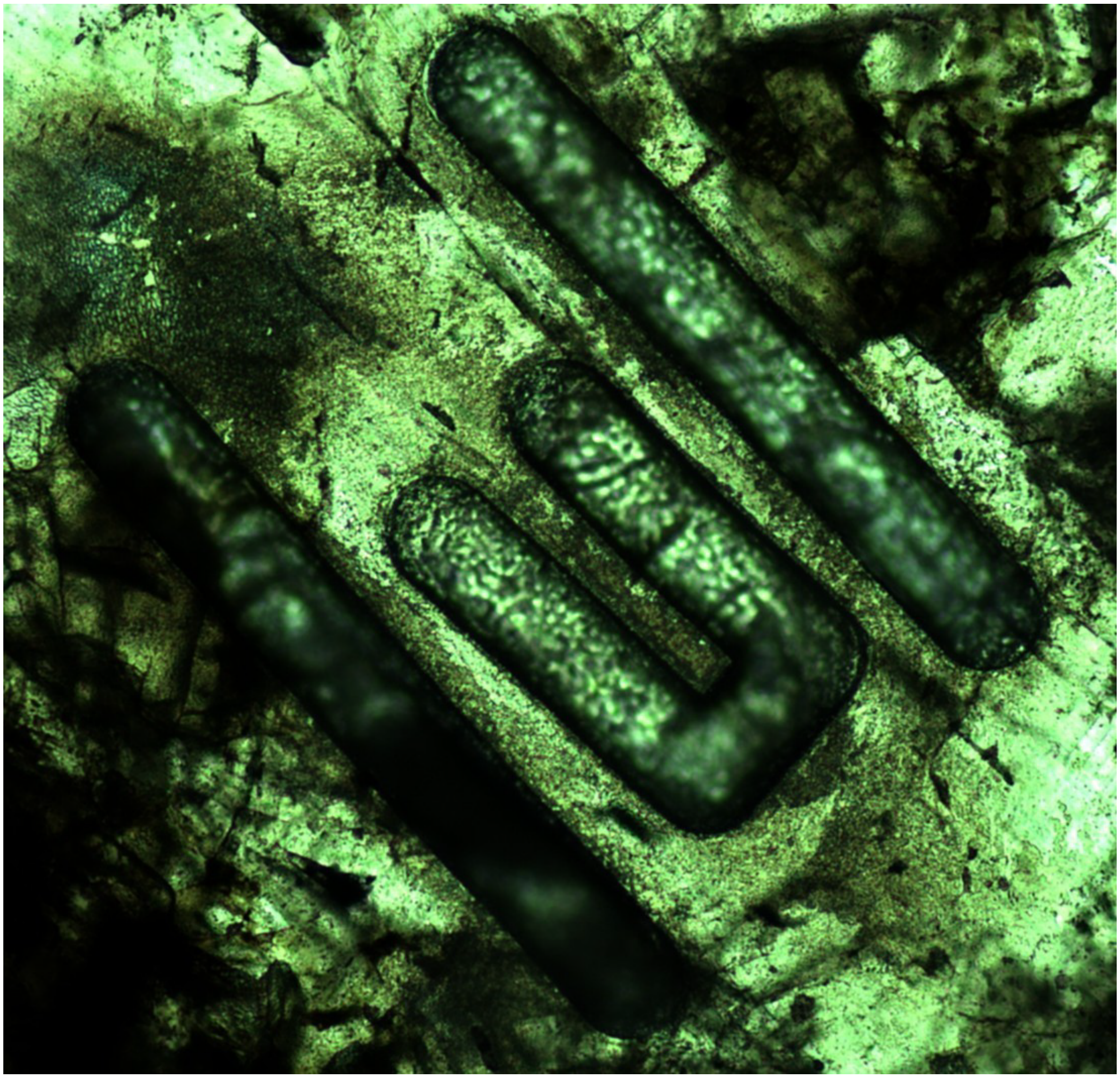

Figure 17. Image of grain HI-205 Plagioclase 3 following LA-ICPMS. In this image there is a “U” shaped trough in the center of the grain where the core was ablated and two parallel troughs on either side of the grain where rim samples were taken.

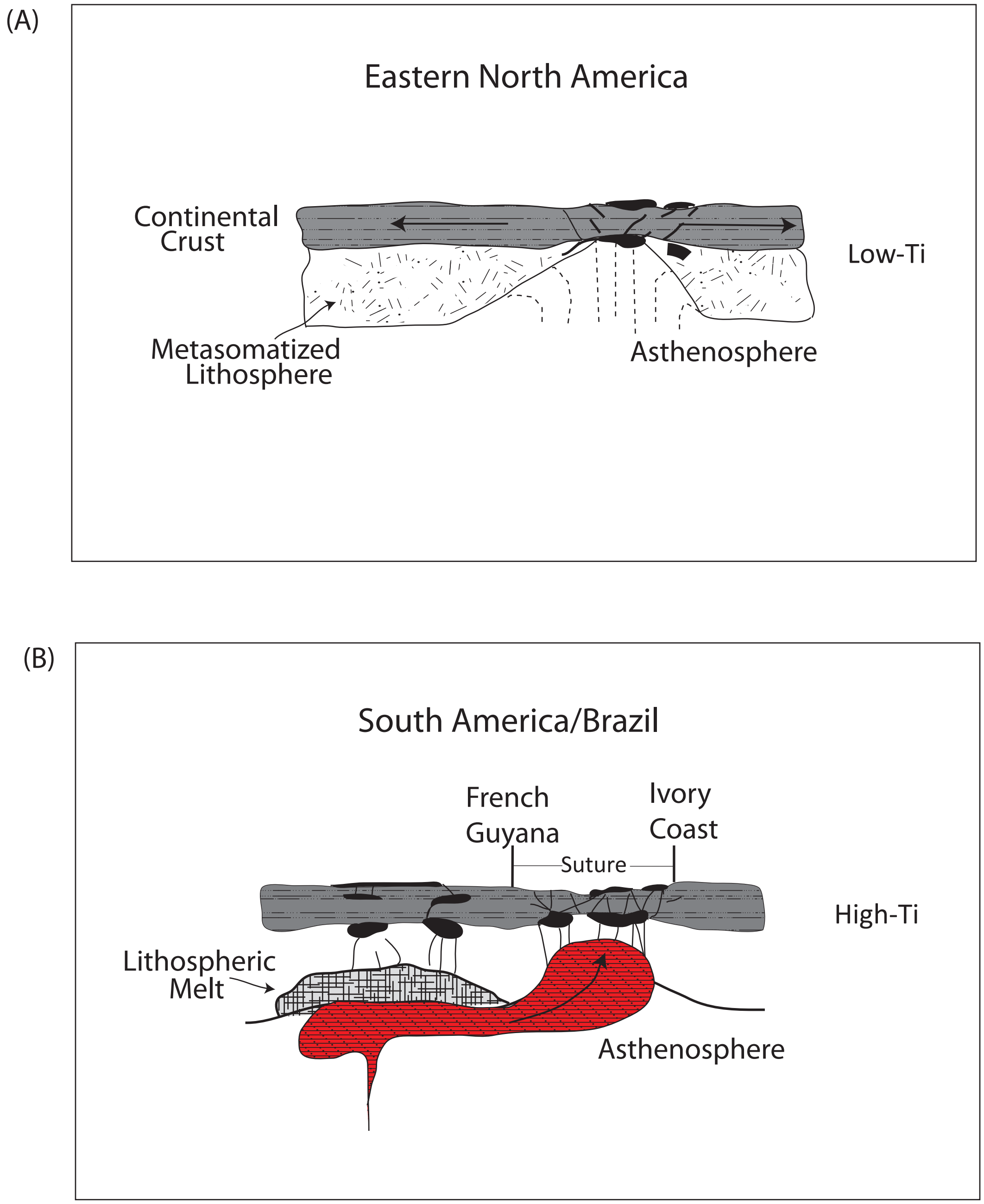

Figure 18. Hypothetical cross section of eastern North America and Africa/South America ~200 Ma. (A)The North American cross section shows extension causing decompression melting of the lithospheric mantle that has been enriched by metasomatism. (B)The South American/Brazil cross section shows a preferential asthenospheric upwelling due to the Rokelides suture located between French Guyana and Ivory Coast (Nomade et al., 2002a). This suture zone is related to the closing of a Neoproterozoic to Early Cambrian ocean basin during the Pan-African orogeny and final assembly of Gondwana (Lytwyn et al., 2006).

Table 1. Database of references sorted by area. The number of samples used for each author is sorted by number of major and trace elements and isotopes. Major elements are graphed in figures as normalized percentages.

		Maj. & Trace	Isotopes
Area	Reference	N	N
ENA, Higganum, Plagioclase core and rim	This Study		12
ENA, Conneticut, Hartford basin	This Study	2	2
ENA, New Hampshire	Dorais et al., 2005	6	4
ENA, Conneticut, Hartford basin	Philpotts and Asher, 1993	4	
ENA, Conneticut, Hartford basin	Philpotts and Reichenbach, 1985	2	
ENA, Conneticut, Hartford basin	Asher and Philpotts, 1995	2 (31)	
ENA, Conneticut, Hartford basin	Philpotts, 1992	3	
ENA, Conneticut, Hartford basin	Puffer et al., 1981	2 (19)	
ENA,New Jersey, Newark Basin	Puffer et al., 1981	2	1
ENA,New Jersey, Newark Basin	Puffer, 1992	29	
ENA, Nova Scotia, North Mt. Basalt	Dostal and Greenough, 1992	9	
ENA, Nova Scotia	Dostal and Durning, 1998	6	
ENA, Nova Scotia	Pe-Piper et al., 1992	10	
ENA, New Brunswick	Pe-Piper et al., 1992	1	
ENA, New Brunswick	Dostal and Durning, 1998	3	6
ENA, Newfoundland	Pe-Piper et al., 1992	1	
ENA, Appalachian	McHone, 1992	1 (41)	
ENA, N. and S. Carolina Dikes	Beutel et al., 2005	4	
ENA, PA, N.J., CN, S.C.	Pegram, 1990		12
ENA, S.C. and Virginia	Cummins, 1987	6	
ENA, S.C. and Virginia	Weigand and Ragland, 1970	2	
ENA, S.C. and Virginia	Bell, 1988	1	
ENA, S.C. and Virginia	Steele, 1971	1	
ENA, Florida	Mueller and Porch, 1983	2	
ENA, Florida	Heatherington and Mueller, 1991		3
Portugal	Youbi et al., 2003	5	
Portugal/Spain, Messejana-Plasencia Dyke	Cebriá et al., 2003	21	21
Portugal/Spain, Messejana Dyke	Alibert, 1985	12	12
Portugal, (Southern) Algarve Basin	Martins et al., 2008	17	
France, Kerforne	Jourdan et al., 2003	9	5
Africa, Morocco	Youbi et al., 2003	9	
Africa, Guinea, French Guyana, Surinam	Deckart et al. 2005	25	10
Africa, Mali Taoudenni basin	Verati et al., 2005	23	4

Table 2. Major and trace element composition of the Higganum dike.

Sample	HI-105	HI-205
SIO_2	52.10	53.00
TIO_2	1.08	1.11
Al_2O_3	13.30	13.55
Fe_2O_3t	10.85	11.00
MnO	0.17	0.17
MgO	7.67	7.91
CaO	10.65	10.90
Na_2O	1.79	1.86
K_2O	0.49	0.51
P_2O_5	0.12	0.13
LOI	0.55	-0.10
Total	98.77	100.04

Sample	HI-105	HI-205
Rb	19	19
Ba	140	141
Th	2	2
Nb	7	7
U	0	0
La	10	11
Ce	23	23
Pb	5	7
Nd	13	14
Sr	167	170
Sm	3	4
Zr	98	97
Eu	1	1
Gd	4	4
Dy	4	4
Y	21	21
Er	2	2
Yb	2	2
Lu	0	0
Cs	1	1
V	266	285
Cr	380	410
Co	104	75
Ni	88	96
Hf	3	3
Ta	1	1
Pr	3	3
Tb	1	1
Ho	1	1
Tm	1	0
Ga	18	18
Zn	90	91
Cu	107	110

Table 3. Composition of Higganum dike Nd and Sr isotope ratios.

Sample	Nd (ppm	Sm (ppm)	^{147}Sm/^{144}N	^{143}Sm/^{144}Nd	2 σ	Epsilon (0	εNd$_{(199Ma}$	T$_{DM}$ (Ma)	TDM2 (Ma)
HI-105	12.59	3.223	0.1548	0.5126	0.000005	-0.9	0.2	1165	1444
HI-205	12.52	3.206	0.1548	0.5126	0.000005	-1.3	-0.2	1217	1496

Sample	Rb (ppm)	Sr (ppm)	(^{87}Sr/^{86}Sr)$_m$	(^{87}Sr/^{86}Sr)$_{(199Ma}$	2 σ
HI-105	18.6	166.5	0.7066	0.7057	0.000009
HI-205	18.5	169.5	0.7067	0.7058	0.000014

Table 4. Plagioclase core/rim $^{87}Sr/^{86}Sr$ isotope ratios.

Grain	core/rim	$^{87}Sr/^{86}Sr$	2σ
HI-105 Plagioclase 1.1	core	0.7060	0.00022
HI-105 Plagioclase 1.2	rim	0.7059	0.00022
HI-105 Plagioclase 2.1	core	0.7062	0.00022
HI-105 Plagioclase 2.2	rim	0.7059	0.00022
HI-105 Plagioclase 4.1	core	0.7063	0.00022
HI-105 Plagioclase 4.2	rim	0.7058	0.00022
HI-205 Plagioclase 4.1	core	0.7060	0.00022
HI-205 Plagioclase 4.2	rim	0.7062	0.00022
HI-205 Plagioclase 3.1	core	0.7064	0.00022
HI-205 Plagioclase 3.3	rim?	0.7071	0.00022
HI-205 Plagioclase 7.1	core	0.7057	0.00022
HI-205 Plagioclase 7.2	rim	0.7061	0.00022

Table 5: Compositions of plagioclase feldspars of the Higganum Dike given in wt%.

Sample	HI-105 Plagioclase 1		HI-105 Plagioclase 2		HI-105 Plagioclase 4	
	rim	core	rim	core	rim	core
SiO_2	53.46	50.49	54.66	50.23	52.86	50.79
Al_2O_3	29.55	31.59	28.43	31.22	29.12	31.52
FeO	1.15	0.53	0.57	0.69	0.78	0.58
CaO	12.19	14.71	10.81	14.36	11.83	14.54
Na_2O	4.28	2.90	4.92	2.98	4.52	2.91
K_2O	0.19	0.11	0.30	0.09	0.21	0.13
Total	100.82	100.33	99.69	99.56	99.31	100.46
Ab	38.41	26.15	44.39	27.18	40.36	26.40
Or	1.12	0.63	1.76	0.54	1.21	0.75
An	60.48	73.22	53.85	72.28	58.43	72.85

Sample	HI-205 Plagioclase 3		HI-205 Plagioclase 4		HI-205 Plagioclase 7	
	rim	core	rim	core	rim	core
SiO_2	53.90	49.61	56.15	48.17	52.85	49.97
Al_2O_3	28.74	31.36	27.85	32.22	29.22	31.72
FeO	0.55	0.65	0.59	0.63	0.85	0.66
CaO	11.38	14.77	10.00	15.87	12.10	14.97
Na_2O	4.88	3.17	5.52	2.33	4.40	2.90
K_2O	0.14	0.14	0.37	0.12	0.29	0.12
Total	99.59	99.70	100.48	99.34	99.70	100.34
Ab	43.33	27.74	48.92	20.88	39.00	25.77
Or	0.84	0.81	2.15	0.70	1.68	0.67
An	55.83	71.45	48.93	78.43	59.32	73.56