Insights into the Sources and Tectonic Setting of Magmatism in a Complex Arc Setting: Major and Trace Element Variations in the ~1.2 Ga Barby Formation in SW Namibia

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ABSTRACT

The ~1.2 billion-year-old-Barby Formation is located in SW Namibia and has been argued to represent a continental volcanic arc. Previous studies on these rocks primarily relied on mobile-element data, which can be altered by secondary processes and therefore is unreliable for constraining petrologic processes. In an effort to establish the Barby Formation's petrotectonic history, 20 samples were analyzed using XRF and ICP-MS to determine whole-rock major and trace element concentrations. These data were used to answer two questions: (1) Do the samples represent one unique magma series that came from a single source? (2) If the Barby Formation is indeed a volcanic arc, did it form from normal, flat-slab, or oblique subduction? These questions were answered using a combination of geostatistical analyses (distribution, cluster, and outlier analyses), trace-element tectonic discrimination diagrams, and geospatial analyses (see other poster by Lehman et al.). This study supports previous interpretations that the Barby Formation formed in a continental arc setting, with rock samples displaying steeply dipping, light-rare-earth-element enriched patterns, negative Nb/Ta anomalies, and calc-alkaline andesitic to shoshonitic compositions. Major and trace element data indicate at least two magma series from two distinct mantle sources. These two groups are controlled by enrichment differences and variations in the high-field-strength element ratios. The presence of shoshonitic rocks is consistent with flat-slab or oblique subduction.

BACKGROUND

KONKIEP TERRANE

Located in south-west Namibia, the Konkiep Terrane has played an important role in reconstructing the formation of the Namaqua-Natal Orogenic Belt (NNOB) (Figure 1). The NNOB represents the ancient southern continental margin of the Kalahari Craton (e.g., Jacobs et al., 1993, 2008; Dalziel et al., 2000; Eglington and Armstrong, 2003). During the Mesoproterozoic, the NNOB acted as a major convergent margin, which underwent arc volcanism, arc/microcontinent collision, continent-continent collision and intraplate magmatism (e.g., Hanson et al., 2006; Miller, 2012; Cornell et al., 2015). This extensive orogenic belt formed during the large-scale accretionary event which ended in the formation of the supercontinent Rodinia at ~1 Ga, (e.g., Hanson, 2003; Becker et al., 2006; Jacobs et al., 2008).

The Konkiep Terrane may represent the oldest relatively unmetamorphosed Mesoproterozoic crust within the NNOB (Miller, 2008). The Konkiep Terrane is composed of amphibolitic basement termed the Gorrasis group (informal term), which is unconformably overlain by the relatively undeformed Konkiep Group comprises six volcanic formations with associated intrusive units, and two sedimentary formations (Miller, 2008) (Figure 2). Table 1, modified from Miller (2008), summarizes the lithology of the sedimentary and volcanic rocks. The Konkiep Group has undergone very low-grade metamorphism (zeolite and prehnite-pumpellyite facies) with depositional features, volcanic textures, and some primary mineralogy preserved (Miller, 2012). This lack of deformation, combined with the early time of accretion of at least part of the Konkiep Terrane (>1.33 Ga) and active magmatism until 1.1 Ga, provides a window into the tectonic and magmatic changes that occurred in this part of the NNOB (Panzik et al., 2015; Cornell et al., 2015).

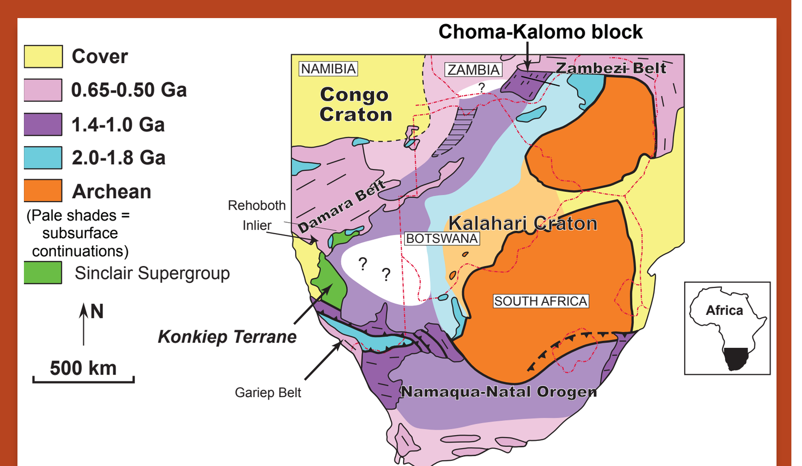


Figure 1: Simplified geologic map of southern Africa. Colors represent predominant rock ages in the region. Note the Sinclair Supergroup and Konkiep Terrane is highlighted in green and is considered to be a part of the NNOB. Map modified from Hanson (2003) and Panzik et al. (2006).

Table 1 (below): Lithological descriptions of the volcanic and sedimentary rock formations that make up the Konkiep Group. Ages and maximum thickness of each unit are noted. Table modified from Miller (2008). Colors correspond to Figure 2.

Konkiep Group			
Formation	**Lithology**	**Maximum Thickness (m)**	**Age (Ma)**
Aubures (Miller, 2008)	Dark rust red shales, rust red lithic to arkosic sandstones, polymictic conglomerates, Basal polymictic conglomerate	2590	1108 ± 9 (Kasbohm et al, 2016)
Guperas	Quartz porphyry lava, block and ash flows	1000	
	Basic lava		
	polymictic conglomerate, lithic sandstone		
	Green shale		
	Brown to grey polymictic conglomerate, purple-red lithic sandstone, quartzite	3700	
Barby (von Brunn, 1969; Watters, 1974)	Aruab Mountain: Cross-bedded orthoquartzite, feldspathic quartzite	400	1214 ± 5(Cornell et al., 2016) to 1217 ± 2 (Cornell et al., unpublished)
	volcaniclastic and lithic sandstone, conglomerate		
	Pyroxene trachyandesite lavas and tuffs;	400	
	Pyroxene trachybasalt lavas;	5800	
	Basaltic andesite lavas;	3150	
	Large-feldspar trachyandesite lavas;	1400	
	Small-feldspar trachyandesite lavas;	1300	
	Latite;	2000	
	Volcaniclastic sandstone	1550	
	Rhyolitic pyroclastic rocks	80	
Haiber Flats (Hoal, 1990)	Porphyritic rhyolite and ignimbrite, minor rhyodacite, interbedded volcaniclastic sandstone	120	
	Phyric and amygdaloidal basaltic andesite and andesite, occasionally pyroclastic, tuff, rhyolite and volcaniclastic sediment		
Kunjas	Lithic sandstone, polymict conglomerate;		1304 ± 1 (Cornell et al., unpublished data)- youngest detrital zircon grains
	Shale, minor rhyolitic and mafic volcanic layers, iron formation;		
	Basal conglomerate overlain by lithic sandstone (Watters, 1974)	300	
	Shale	1200	
	Pebbly lithic and arkosic sandstone, minor polymict conglomerate		
	siltstone, minor sandy limestone, red chert	100	
	Basal polymict conglomerate overlain by lithic sandstone, subarkose (Hoal, 1990)	800	
Welverdiend	Tholeiitic basalts, agglomerates, rhyolites and associated tuff, volcaniclastic and clastic sedimentary rocks		1327 ± 10 (Cornell et al., 2015)
Nagatis (von Brunn, 1967)	Pyroclastic quartz porphyry, ignimbrite layers at base, interbedded basic lava in middle of unit	1000	1363 ± 11 (Cornell et al., 2016)
	Polymict conglomerate, volcaniclastic grit and lithic sandstone, arkose, shale		
	Mafic lava, altered mafic lava		
	Block and Ash	1000	
	Felsic lavas, ignimbrite		
Kairab (Hoal, 1990)	Porphyritic mafic and felsic metavolcanic rocks; minor volcaniclastic metasediment	4000	1369 ± 10 (Cornell et al., 2016)
Gorrasis (Miller, 2008)	Basement		1372 ± 12 (Cornell et al., 2016)

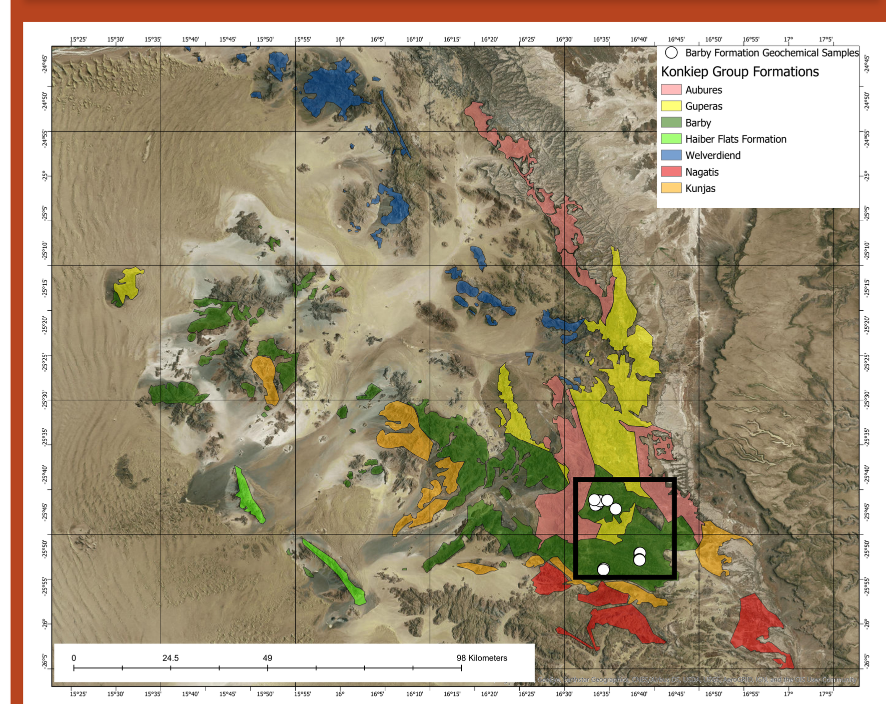


Figure 2: Simplified Map of Konkiep Terrane using Miller (2008) map and ArcGIS DigitalGlobe satellite data as an underlay. Unit colors are shown in both the key and Table 1. See Figure 1 for location reference for the Konkiep Terrane. Field Site is outlined in black and referred to in Figure 7-10.

BARBY FORMATION

The ~1.2 Ga Barby Formation has been the most researched formation of the Konkiep Group and is, arguably, the most complex volcanic unit within the group. The calc-alkaline to shoshonitic formation is preserved in extensional basins and is estimated to be <8500 m thick (Miller, 2008). Syndepositional faults, which indicate a lateral movement component, cut the formation (Watters, 1974; Brown and Wilson, 1986). Large feldspar-phyric intermediate lavas are characteristic of the Barby Formation and have been termed trachyandesites by previous researchers. Based on the high K_2O, high Zr, lack of iron enrichment, depletion in TiO_2 and Nb, and enrichment in light rare earth elements (LREE), the Barby Formation has been argued to consist of calc-alkaline to shoshonitic volcanic rocks that formed in a continental arc setting (Watters, 1974, 1977; Hoal, 1990, 1993; Brown and Wilson, 1996; Miller, 2008, 2012) (Figure 4). The presence of shoshonitic compositions could suggest that the Barby Formation formed in unusual arc settings, possibly related to oblique or flat-slab subduction (e.g., Becker et al., 2006; Kay and Mpdozis, 2002).

Previous studies heavily relied on mobile element data to makes these petrotectonic arguments (Watters, 1974; Brown and Wilson, 1986). The mobile element concentrations are likely to have been altered by secondary processes, making these data unreliable for constraining petrologic processes. This study utilizes major element and trace element data, particularly focusing on immobile element ratios from 25 samples collected in the 2016 field season. These samples were collected from the three main facies: (1) Hawaiian, Strombolian, and phreatomagmatic deposits; (2) lava flows; and (3) sill packages containing two to six lithologically distinct sills intruded into lacustrine deposits (Andrews et al., 2016, 2017; Lehman et al., 2016). Sample locations are shown in Figure 2.

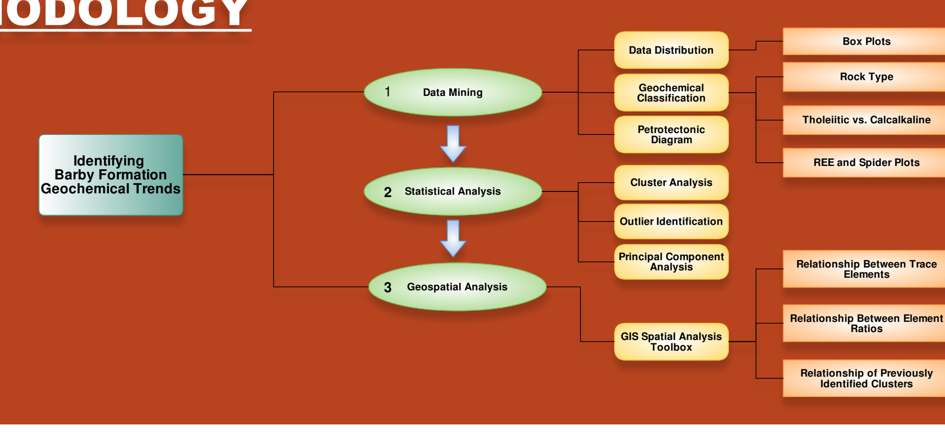
KEY QUESTIONS

1) Do the samples represent one unique magma series that came from a single source?

2) If the Barby Formation is indeed a volcanic arc, did it form from normal, flat-slab, or oblique subduction? Is there evidence of backarc-volcanism?

METHODOLOGY

Samples were collected from Namibia during the Summer 2016. The samples were analyzed using ICP-MS and XRF at Washington State University. This geochemical data was analyzed using a three stage process, which included a number of sub-steps shown in the flow chart to the right.



RESULTS

- All samples are high-K calc-alkaline andesites to basaltic andesites, or shoshonitic andesites to basaltic andesites. All samples plot as forming in an arc setting (Figure 4).
- K-means and median cluster analysis based on High Field Strength Element ratios (HFSE) and Rare Earth Element (REE) ratios support 2 groups, with 2 outliers. Both outliers (MS1.1 and VA16118) have high La/Yb ratios, MS1.1 is adakitic in composition (La/Yb ratio>20, high Sr/Y, low Y).
- Principal component analysis revealed that the clusters primarily result from the Ti/(Hf*Sm), Zr/Hf, Nb/Ta, Zr/Y, and Nd/Hf ratios distributions. Each of these ratios have a p value <0.0001, showing that the null hypothesis (that there are no clusters) can be rejected.

Group 1	Group 2	Figure(s)
More Enriched in REE, LREE enriched = **thicker crust, greater subduction component** (i.e. shallower subduction component) (White, 2013)	Enriched in LREE, REE = formed in an **arc setting**	Figure 5
Depletion in Nb-Ta relative to chondrites or primitive mantle, Nb/Ta fractionated = **volcanic arc** (White, 2013)	Depletion in Nb-Ta relative to NMORB normalized immobile ellements, sub- and suprachondritic Nb/Ta ratios chondrites or primitive mantle, Nb-Ta fractionated = **island arc, back-arc, melts formed above slab tears, less residual amphibole/rutile** (eg., Pearce and Norry, 1979; Prouteau et al., 2000; Aulbach et al., 2008; Huang et al., 2012)	Figure 6
Predominantly in the south portion of the field area	Predominantly in the north central portion of the field site	Figure 7
Plots as Shoshonitic Continental Arc or Continental Crust	Plots between Island Arc and Continental Arc Fields; High K to Shoshonitic	Figure 10-13
Often plots on or near continental crust and sediment fields = more assimilated crust or incomporation of subducted eroded material, compressional/ shallower subduction	Plots between island arc and continental crust/sediment fields = incorporation of different amount of subducted material, crust thickness differences	Figure 10-13
Interpretations Volcanic arc volcanism during compressional subduction producing thickened crust or more subducted eroded material to be incorporated into the melt	**Interpretations** Arc volcanism that has a greater mantle contribution. Represents either back-arc volcanism, rifts formed during oblique subduction, or slab steepening leading to wet-spot melting	

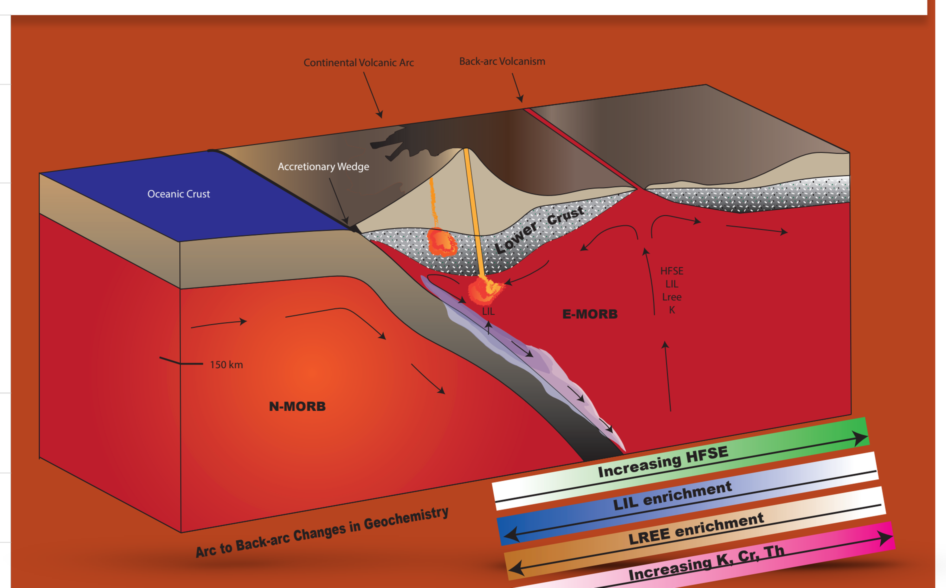


Figure 4: Schematic of the relationship between arc and back-arc volcanism in normal continental arcs (not to scale). To identify if the there is an arc-back-arc relationship these changes in geochemistry should be observable. The back-arc shows less of a subduction influence (lower oxygen fugacity, less LREE enrichment, LIL enrichment), and comes from a less depleted source (i.e. high HFSE and K) (e.g., Sanders and Tarney, 1984; Kay & Gordillio, 1994, Woodhead et al., 1993; Best, 2003; White, 2013).

Geospatial Trends

NW-SE Trends

- Nb/Ta increase to the NW
- Zr/Nb and V/Ti generally decrease to the NW

Group Trends

- Group 1 is in the S
- Group 2 is in the N
- 2 samples from each group do not follow these trends

No Geospatial Relationship

- High La/Yb = residual garnet in source
- High Ta/Yb = continental crust assimilation/ incorporation

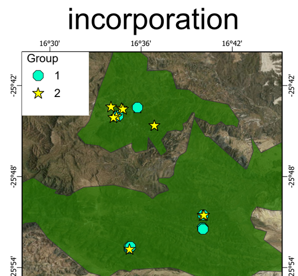
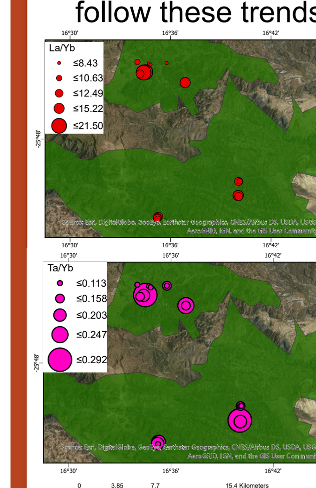


Figure 7: (above) Geochemical Group locations.Note the dominance of group 2 in the North and Group 1 in the South. There are 4 of the 25 samples, which do not follow this trend. Figure 9: (left) (A) La/Yb ratio geospatial relationships. Note the dispersed nature indicating differences in the amount of residual garnet in the source (White, 2013). (B) Ta/Yb ratios are used to determine mantle enrichment and/or oceanic or continental arc setting (Pearce & Norry, 1979).



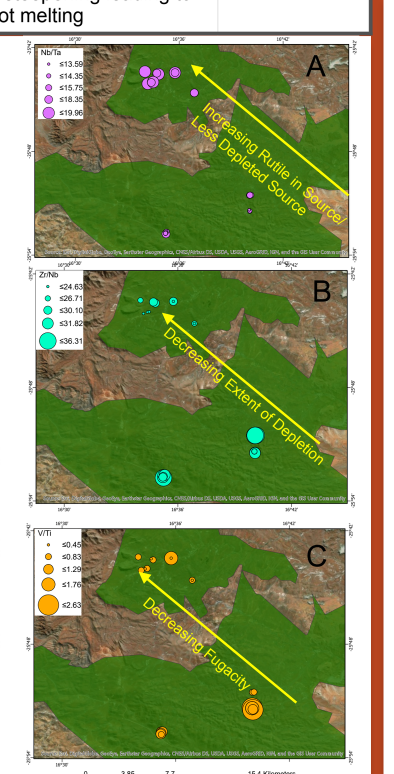


Figure 8: (above) N-S trending element ratio differences. A. Nb/Ta is an effective indicator of source enrichment and mantle source metasomatism (Pearce & Stern, 2006). B. Zr/Nb decreases in the transition from arc to back-arc and also decreases due to less depletion in the source (e.g., Weyer et al., 2003; Pearce & Stern, 2006) C. V/Ti are controlled, in part, by oxygen fugacity (Mallmann and O'neill, 2009). V/Ti decreases from arc to back-arc (Figure 4).

Immobile Element Group Differences

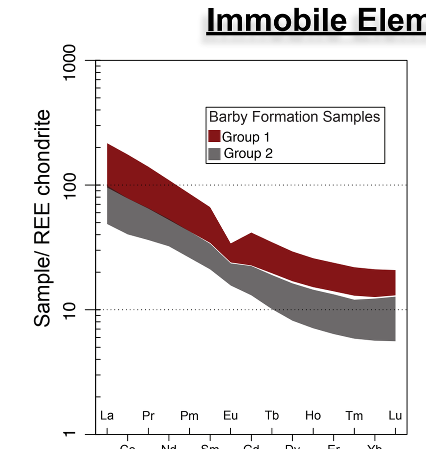


Figure 5: (to the left)REE plot of the Barby Formation samples. Fields represent two geochemical cluster. The two samples, which are anomalousMS1.1 and VA1618 are included into Group 1. The samples are normalized to the chondrite value from Nakamura (1974). Both groups are LREE enriched, supporting a volcanic arc origin (White, 2013). Group 1 is more enriched in REE, but shows a similar LREE enrichment (slope). Note that Group 1 has a more pronounced Eu anomaly, while Group 2 samples have little to no Eu anomaly. This could show that the melts that formed Group 2 samples did not have a large amount of residual plagioclase in the source (White, 2013). Eu anomalies are pronounced in lower crustal melts.

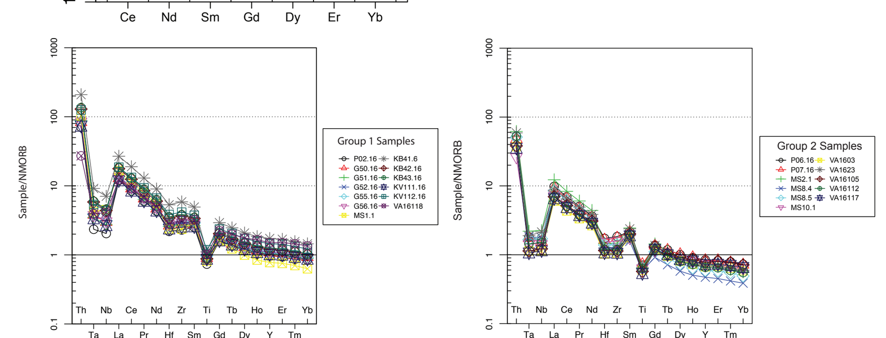


Figure 6: Immobile element spider diagram for Group 1 and Group 2 samples normalized to N-MORB from Sun and McDonough (1979). The two samples, which are anomalousMS1.1 and VA16118 are included into Group 1. Note the HFSE differences between each group. Zr is decoupled from Hf in the Group 1 samples. Group 1 and 2 also have different Nb/Ta relationships. Although samples here are plotted normalized using NMORB, it is important to note Nb/Ta$_N$ are subchondritic in Group 1 samples, and suprachondritic in Group 2 samples.

DIFFERENT MANTLE SOURCES?..... *Potentially*

DIFFERENT PETROGENETIC HISTORIES?..... *Definitely*

1) Do the samples represent one unique magma series that came from a single source?

- The variations in V/Ti, Zr/Nb, La/Yb, Nb/Ta, Zr/Sm, Ta/Yb, and Th/Yb cannot simply be explained by an evolving magma (i.e. fractional crystallization, partial melting, assimilation, etc.). There are at least two distinct petrogenetic groups (Group 1 and Group 2).
- Group 1 must be coming from a source that has more subduction input and/or crustal assimilation as it plots typically in the continental volcanic arc/continental crust field (Figure 10, 11). Group 1 is LREE enriched (Figure 5), more depleted (Figure 8B), has typical Nb/Ta subchondritic values (Figure 6), and has high oxygen fugacity (Figure 8C), which is all characteristic of a typical arc setting (e.g., Pearce & Stern, 2006; White, 2013). Group 1 does plot in both the Shoshonitic oceanic arc and continental arc field in Figure 12. This must be explored in more detail. Group 2 plots in both island arc fields and continental arc fields, has suprachondritic Nb/Ta values (Figures 6 and 8A), is LREE enriched (Figure 5),has indicator of higher degrees of carbonated metasomatism in the source (Figures 12 and 12), formed in an environment with lower oxygen fugacity (Figure 8C), less subduction input (Figure 5), but likely has lithospheric input based on high Ta/Yb (Figure 12), high Nb/Ta, high La/Yb, and since it plots in the PAP field (Figure 13) in some samples. The conditions which led to the formation of Group 2, must be explored in more detail.

2) If the Barby Formation is indeed a volcanic arc, did it form from normal, flat-slab, or oblique subduction? Is there evidence of backarc-volcanism?

- The Barby Formation is a volcanic arc based on the LREE enrichment, Nb/Ta ratios and calc-alkaline compositions (e.g., Best, 2003).
- Arc shoshonites form in unusual subduction geometries, either flat-slab or oblique subduction and usually form after a major tectonic change (slab steepening, slab-breakoff, or ridge subduction) (Müller, 2002). The dominance of shoshonitic compositions in both groups indicate that the Barby Formation must have had one of these geometries.
- Both flat-slab and oblique subduction can lead to increased thickening of the crust, which explains the high La/Yb values in some of the samples (e.g., Kay and Mpdozsis, 2002). In a typical arc to back-arc setting La/Yb would decrease towards the back-arc. The geospatial distribution of the La/Yb values paired with the N-S trends in Nb/Ta, V/Ti, and Zr/Nb, would support different amount of lithosphere from subduction erosion being incorporated into the melts or melts from a slab window created during ridge subduction. Ta/Yb, which also can be used as indicator for lithosphere incorporation, also shows a similar geospatial distribution- further supporting this argument.
- Based on the evidence that the Northern samples were emplaced in thinner lithosphere and had less of a subduction component, but showed evidence of carbonatitic metasomatism the Northern samples could represent a flat-slab back-arc setting, that formed when the slab steepened. In turn, the Southern samples represent the main portion of the arc.
- The Northern and Southern samples may simply represent flat-slab/oblique subduction volcanic arcs formed in different time periods and the Northern sample formed above a less depleted source.

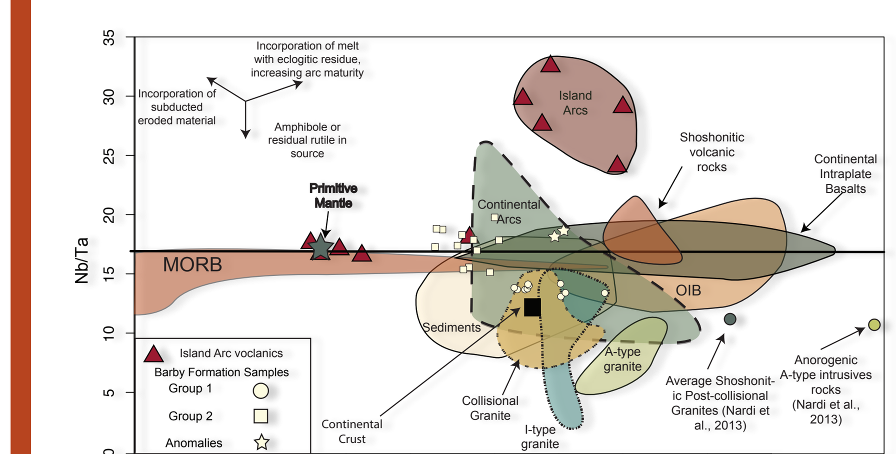


Figure 10: Nb vs Nb/Ta discrimination diagram. Nb/Ta vs Nb. Nb/Ta can help highlight processes including incorporation of subducted eroded material, melting of a source with residual amphibole or a source with residual eclogite. Note that the Barby Formation samples plot in a few different fields, but show a general trend of incorporation of subducted eroded material. Fields from Green (1995), Stolz et al. (1996),Turner et al. (1996), Shomer et al. (2008), Nardi et al. (2013).

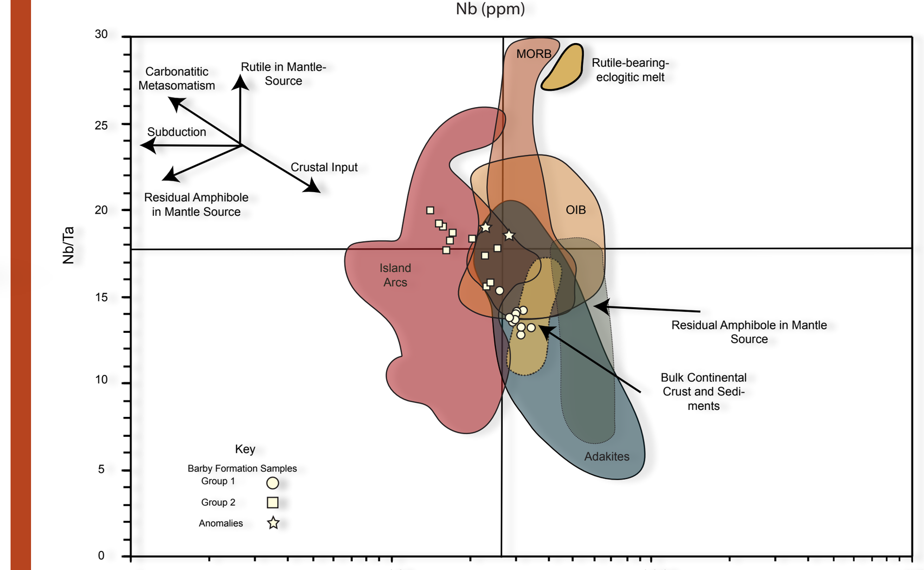


Figure 11: Nb/Ta and Zr/Sm tectonic discrimination diagrams fields from Foley et al. (2002) and Zhang et al. (2014). Shape distinguishes between the 2 groups and the anomalies. Group 2 has much more spread and plots in almost all of the fields. Group 1 sits between the Adakite and Continental Crust fields.

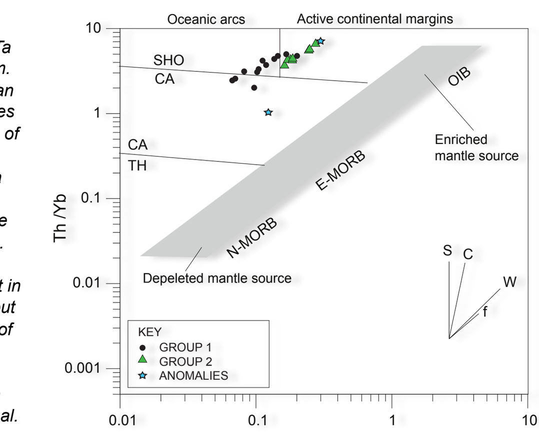


Figure 12: Ta/Yb vs Th/Yb discrimination diagram. S represent the subduction component, C represents a carbonatitic metasomatism, W represents metasomatism, and f stands for fractional crystallization. Diagram after Pearce et al. (1990) and Hari et al. (2013).

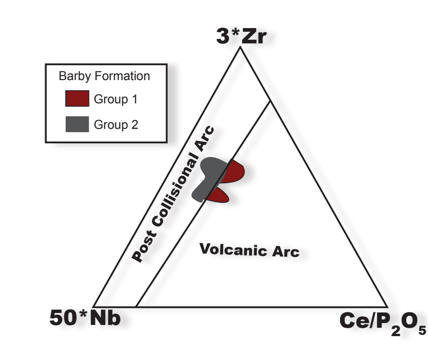


Figure 13: Group 1 plots in the Volcanic Arc field and Group 2 plots in the Post-Collisional Arc field. The diagram is from Müller (2002).

Conclusions

The Barby Formation formed above an unusual subduction geometry. The northern samples formed in a setting with thinner lithosphere. This could have been due to rifts formed from oblique subduction, or because this area was in a back-arc setting relative to the southern samples.

Future Work

1. Distinguish key residual source minerals
2. Determine fractionation, assimilation, and mixing from immobile trace element diagrams
3. Select samples with the most primitive compositions that represent each magma series.
4. Model the evolution of each magma series using melts.
5. Based on petrology determine likely magma/mantle source conditions (i.e. fugacity, mantle enrichment, amount of assimilated crust)
6. Use Sm-Nd and Lu-Hf isotope systems to clarify source differences and the potential for lithospheric/subducted-eroded material in the mantle source

References