PROCEEDINGS OF THE TWENTY-EIGHTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2015
Union College, Schenectady, NY

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ISSN# 1528-7491

The Consortium Colleges   The National Science Foundation   ExxonMobil Corporation

KECK GEOLOGY CONSORTIUM
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Keck Geology Consortium: Projects 2014-2015
Short Contributions— Paleoclimate Reconstruction From Weddell Sea ODP Cores Project

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PROVENANCE OF WEDDELL SEA DROPSTONES: PETROGRAPHIC AND GEOCHEMICAL EVIDENCE
HALI ENGLERT, Macalester College
Research Advisors: Karl Wirth and Suzanne O'Connell

Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1358987
ExxonMobil Corporation

KECK Geology Consortium
Learning Science Through Research
Published by Keck Geology Consortium

ShortContributions
28th Annual Symposium Volume
25th April, 2015
ISBN: 1528-7491

PROVENANCE OF WEDDELL SEA DROPSTONES: PETROGRAPHIC AND GEOCHEMICAL EVIDENCE

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Research Advisors: Karl Wirth and Suzanne O'Connell

INTRODUCTION

In Antarctica, flowing ice transports rock and sediments plucked from bedrock in the interior regions. When the ice reaches the coast, it calves and floats icebergs offshore. Then, as the ice melts, ice rafted detritus (IRD) is deposited on the seafloor and on the continental rise (Whitehead et al., 2006). The purpose of this study is to incorporate evidence from IRD's collected from Ocean Drilling Program (ODP) Sites 692 and 693 in the Weddell Sea into models of ice flow and the terrestrial geology of Antarctica.

The east Antarctic craton hosts the complex history of a former suture zone separating the Gondwanan supercontinent into West and East counterparts (Mieth and Jokat, 2014). Dronning Maud Land (DML) outcrops display Pan African (~650-490 Ma) metamorphic affinities, and are the hypothesized provenance of IRD collected in ODP Sites 692 and 693. A chief goal of this research is to compare dropstone compositions with those of bedrock exposures in the interior regions (Barker and Kennett, 1988; Mieth and Jokat, 2014) for the purpose of enhancing our understanding of DML geology along the ice sheet drainage paths into the Weddell Sea (Figure 1). On the basis of new geochemical data from this study, we conclude that the compositions of the mafic volcanic dropstones from ODP Sites 692 and 693 correlate with those of known bedrock exposures along the ice flow trajectories in the DML. Dropstones also correlate with bedrock sources that would not drain into the Weddell Sea following ice flow models, requiring additional sub-glacial sources of mafic volcanic rocks to explain the dropstone origins.

Geology of the Dronning Maud Land and Nearby Rock Affinities

The primary goal in this research is to better understand the provenance and the geologic setting of the dropstones that were ice rafted to ODP Sites 692 and 693 in the Weddell Sea. Basalt, gneiss, and crystalline rock are disproportionately represented within the cores due to their resistance to erosion. For this same reason, crystalline rocks are more commonly represented in exposures of bedrock Antarctica (Juckes, 1972). At the time the dropstones were collected, Barker and Kennet (1998) proposed on the basis of previously examined sediments that the dropstones and other detrital material were likely derived from the Dronning Maud Land. This study further tests that hypothesis by examining the petrography and elemental compositions of crystalline rocks, and especially mafic volcanics to further constrain the origins of the dropstones deposited in the Weddell Sea.

METHODOLOGY

Ocean Drilling Program and Expedition 113

Dropstones were recovered in sediment cores collected during Expedition 113 of the Ocean Drilling Program (now International Ocean Discovery Program) during the austral summer of 1987 (Barker and Kennett, 1988). Three ODP Sites (691, 692, and 693) were drilled in this region (Figure 1). Sites 691 and 692 were located near the edges of Wegener Canyon and the cores were drilled through turbidite deposits. No sediment was recovered from Site 691, but the cores from Site 692 yielded a ~40% Neogene sediment

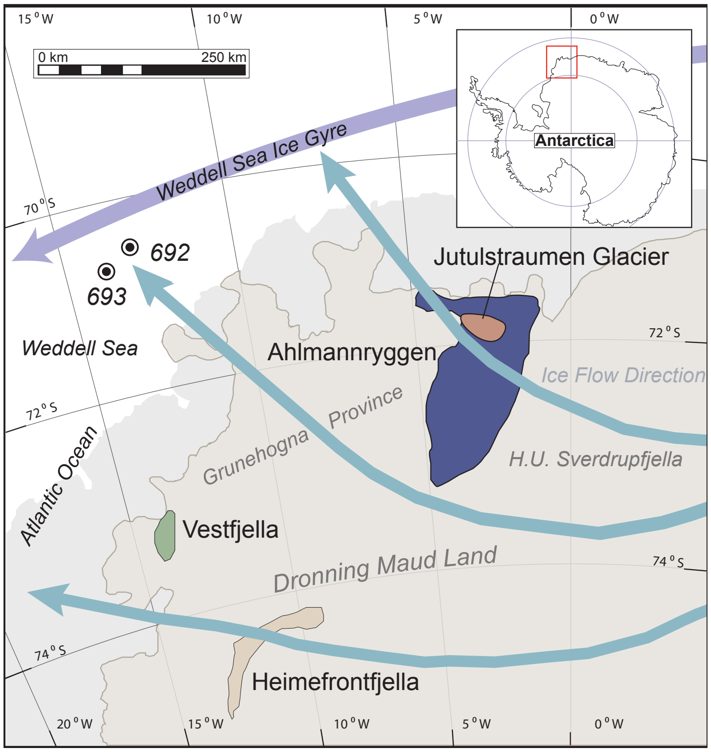

Figure 1. Map of Eastern Antarctica showing Sites 692 and 693 and the current ice flow conditions and lateral flow off coast by the Weddell Ice Gyre. Regions correlate to literary sources and their respective geochemical data in the accompanying figures. (Modified from Veevers et al., 2013; Fahrbach et al., 1994; Grosch et al., 2007)

recovery before reaching Cretaceous sediments at 53 meters below the seafloor. Drilling processes flushed out the unconsolidated sediment from the sediment cores and often collect dropstones near the tops of the cores (Barker and Kennett, 1988). Site 693 is located on a mid-slope bench in slightly shallower water and across a submarine canyon. Sediment recovery for Site 693 was about 44% and although many dropstones were found in their original stratigraphic location, some were found at the tops of the cores due to recovery methods. The dropstones collected for this study are not representative of the entire suite of recovered dropstones. Some dropstones have been misplaced or analyzed destructively over the past 28 years. No sedimentary dropstones were analyzed in this study.

Dropstone Sample Preparation

In total, 46 dropstones were collected from drill cores from ODP Sites 692 and 693, but not all of these dropstones were analyzed. Each dropstone was weighed to determine the most profitable analytical methods given the limited size of many dropstones. For this study we used 15- 20 g of rock for bead preparation to create glass beads for X-Ray Fluorescence (XRF). Dropstones weighing 10-25 g were selected solely for petrographic analyses and cut to show representative textures of the whole rock. Dropstones greater than 25 g were petrographically and geochemically analyzed.

Ohio Polar Rock Repository

In addition to the ODP dropstones, we examined rocks sampled from bedrock exposures in DML from the Ohio Polar Rock Repository. The samples we used were from the Straumsnutane Volcanic Formation from the Jutulstraumen Glacier region of DML (Figure 1). Four of the igneous rock samples were large enough for geochemical analyses and later compared to the dropstones collected from Expedition 113.

Instrumental Techniques and Analytical Methods

All 16 samples were analyzed using a Phillips PW 2400 X-Ray Fluorescence (XRF) Spectrometer at Macalester College (Vervoort *et al.* 2007). Due to the limited sizes of most dropstones we analyzed both the major and trace elements on the fused glass beads that were prepared with a 5:1 flux: sample ratio.

RESULTS

With a goal of constraining the bedrock sources of ice-rafted detritus from the Weddell Sea, we focused our study on the petrography and geochemistry of mafic volcanic dropstones. Of the forty-six dropstone samples available from ODP sites 692, and 693, only thirty-six were large enough for thin sectioning and petrographic analysis.

The dropstones identified as basalt in hand sample show similar textures and alteration. In thin section, the samples are aphanitic and some are porphyritic. Of the porphyritic basalts, plagioclase (0.05 mm to 1.5 mm long) is extensively altered and comprises 55-65% of the modal abundance. Many of the samples contain irregularly shaped amygdules that are filled with secondary minerals including chlorite, quartz, and zeolites. Extensive saussuritization is also commonly associated with porphyritic samples containing amygdules. Nine dropstones are identified as basalts based on their low modal quartz percentage and porphyritic to aphanitic textures. Two dropstones from Site 693A-21R exhibit gneissic banding in hand specimen. These rocks classify as metadiorite and are interpreted to be a result of high-grade metamorphism of plutonic rocks.

After characterizing the mafic volcanic rocks in thin section, we determined that eleven of the dropstones were large enough for chemical analysis by XRF. The chemical compositions of the Weddell dropstones are listed in Table 1. In order to ascertain the effects of alteration on the whole rock chemistry, I compared the major (SiO_2, Na_2O, K_2O) and immobile trace element (e.g., Zr, Ti, Y) compositions using classification diagrams. The eleven analyzed dropstones are classified as alkaline or sub-alkaline basalt on a total alkali versus silica (TAS) diagram (Le Maitre *et al.*, 1989) (Figure 2a). All of the dropstones have consistently low total silica contents (48 – 51 wt. %), but appear to define separate high and low total alkali ($Na_2O + K_2O$) groups. The samples can be further sub-classified as tholeiitic to calc-alkaline on an AFM diagram (Irvine and Baragar, 1971).

Table 1. Major and trace element data for mafic volcanic dropstones and select Dronning Maud Land samples(from Ohio Polar Rock Repos.).

Sample	5R1	5R	7R1	5R1	21R2	21R2	4R5	8R4	1W4	8R	WCC	10265	10266	10268	10269
Location	692B	692B	692B	692B	693A	693A	693A	693A	693B	693B	693B	PRR	PRR	PRR	PRR
Core Depth	6	13	11	35	110	113	43	129.5	24	14	10				
Major Elements (Wt. %)															
SiO2	50.71	48.45	48.80	51.17	60.24	61.48	50.91	49.84	51.38	48.63	47.90	51.55	51.60	51.68	52.78
TiO2	0.66	1.93	1.00	0.67	0.38	0.43	1.39	1.77	1.11	2.10	2.28	0.84	1.00	2.07	1.04
Al2O3	14.44	14.32	19.34	14.44	13.69	14.08	15.48	12.39	14.56	14.31	13.69	14.38	13.92	12.92	13.29
Fe2O3	9.11	14.34	8.14	9.56	4.88	4.55	11.92	13.33	9.13	13.26	13.64	10.53	11.51	14.40	11.52
MnO	0.15	0.19	0.12	0.16	0.17	0.12	0.18	0.18	0.11	0.19	0.21	0.16	0.17	0.19	0.18
MgO	8.05	4.28	3.39	8.38	4.08	3.43	4.87	6.76	8.71	6.53	6.93	6.61	5.14	3.80	5.45
CaO	10.96	8.10	9.42	11.15	9.27	7.34	8.80	7.50	6.98	10.58	10.78	7.89	7.26	6.77	7.40
Na2O	2.05	4.01	4.16	2.03	2.91	2.99	3.78	3.44	2.85	2.44	2.45	3.11	2.99	4.24	3.48
K2O	0.65	0.39	0.83	0.66	1.54	2.10	0.73	1.31	2.82	0.54	0.34	1.43	2.94	1.36	1.35
P2O5	0.07	0.24	0.10	0.08	0.11	0.20	0.32	0.15	0.40	0.28	0.21	0.10	0.13	0.26	0.13
LOI	2.45	2.81	3.76	0.76	1.84	1.64	0.46	2.11	0.81	0.31	0.58	2.76	2.33	1.66	1.98
Total	99.30	99.06	99.06	99.06	99.11	98.36	98.84	98.78	98.86	99.17	99.01	99.36	98.99	99.35	98.60
Mg_Num	0.67	0.40	0.49	0.67	0.66	0.63	0.48	0.54	0.68	0.53	0.54	0.59	0.50	0.38	0.52
CIPW Norm Compositions (Wt. %)															
Q	1.49			1.03	14.99	17.43									1.72
Ne			1.92												
Ol		8.15	9.14				3.92	8.74	12.68	1.62	3.85	1.51	5.92	1.79	
Trace Elements (ppm)															
Ba	197	235	94	214	650	793	208	323	1808	179	100	405	867	365	374
Ce	30.9	26.9	17.0	17.5	26.2	26.5	38.8	28.7	170.3	29.9	17.2	25.9	35.5	80.6	39.2
Co	42.6	42.1	26.0	43.7	9.5	9.2	32.2	52.8	38.0	45.9	51.0	43.8	45.2	45.9	42.5
Cr	354	71	72	352	36	58	145	312	471	154	226	149	62	79	36
Ga	12.0	20.1	18.6	11.9	10.1	10.5	18.6	18.6	15.5	15.0	15.6	11.7	14.3	16.1	11.1
Hf	4.2	7.4	5.1	5.0	2.3	1.6	4.6	4.2	6.9	6.0	5.3	5.8	4.2	6.9	4.2
La	7.2	6.5	0.3	-	7.5	4.9	20.6	3.6	80.0	17.9	9.9	7.8	9.8	33.1	14.4
Nb	5.2	9.1	5.5	4.3	5.2	6.9	14.3	5.2	10.9	13.6	10.6	5.5	7.5	14.1	6.9
Nd	14.3	22.3	17.0	15.9	11.1	8.2	26.9	16.6	56.2	22.9	18.2	13.9	18.6	34.4	13.1
Ni	84	62	48	88	34	25	36	138	111	78	86	89	76	57	49
Pb	5.5	4.9	2.6	4.0	7.2	6.6	4.0	4.2	47.3	7.3	3.6	7.8	8.5	13.1	9.5
Rb	21.1	0.3	12.8	20.2	24.2	30.2	14.9	24.1	89.3	6.3	8.0	82.3	107.7	38.3	46.7
Sc	34.8	27.9	22.8	33.1	13.4	15.7	27.2	24.1	22.8	33.9	36.8	34.4	33.5	24.3	30.7
Sr	182	133	417	182	242	256	321	607	821	271	211	175	126	150	178
Th	3.3	2.6	7.1	5.3	5.9	3.6	4.6	5.2	30.1	4.3	5.6	5.2	11.7	13.8	9.1
U	3.9	5.8	8.0	6.9	4.6	1.6	7.6	8.5	15.5	6.3	6.6	2.6	4.6	6.6	4.2
V	194	328	181	205	71	80	174	324	170	312	372	255	252	306	251
Y	15.6	37.9	18.6	16.2	15.4	18.0	37.2	26.4	26.8	32.6	30.2	23.3	28.6	46.9	26.1
Yb	12.7	12.3	9.0	14.2	6.9	2.9	10.9	19.2	13.2	13.6	12.6	13.9	11.1	9.8	11.1
Zn	63	123	64	64	46	47	106	110	91	107	106	74	90	130	93
Zr	66	142	74	65	53	72	166	102	256	146	121	89	124	229	118

Table 1. Major and trace element data for mafic volcanic dropstones from Sites 692 and 693 and Dronning Maud Land rock samples from Ohio Polar Rock Repository.

Given the evidence of alteration in many of the samples, I also classified the dropstones using the Nb/Y - Zr/TiO2 discrimination diagram (Figure 2b). These trace elements are generally regarded as being less mobile during alteration and metamorphism (Winchester and Floyd, 1977). This diagram classifies the dropstones mostly as subalkaline basalt, with a few of the dropstones plotting along the andesite-basalt field boundary. Interestingly, the dropstones do not show the same clustering on the Nb/Y versus Zr/TiO_2 diagram as is seen in the TAS diagram. Instead, the

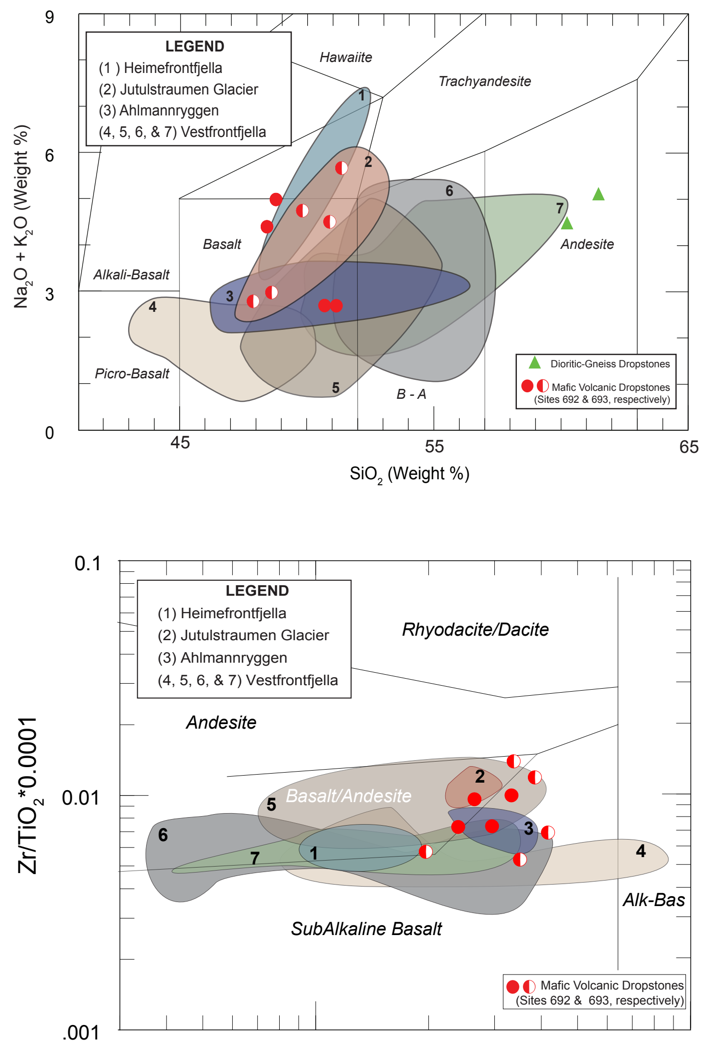

Figure 2. (a) Dropstones from Sites 692 and 693. Plot of total Alkali vs. Silica concentrations (after Le Maitre et al. 1989). Dropstone sources are also shown in the compositions of ranges of rocks; Heimefrontfjella Range (1), Jutulstraumen Glacier region (2), Ahlmannryggen Range (3), and Vestfjella Range (4, 5, 6, & 7). Region geochemical data based on the following sources; Bauer et al., 2003 (1), OPRR samples (2), Riley et al., 2005 (3), Heinonen et al., 2010 (4), and Luttinen and Furnes, 2000 (5, 6, & 7); (b) Dropstones from Sites 692 and 693 subdivided on the basis of their Nb/Y - Zr/TiO2 concentrations (Winchester and Floyd, 1977).

samples plot in a single, relatively tight cluster (Figure 2b).

DISCUSSION

In this section, we explore the relationships among the dropstones from the Weddell Sea. Next, we consider potential rock sources based on the geology upstream of the East Antarctic Ice Sheet and the cyclonic Weddell Ice Gyre to determine the most likely sources to Sites 692 and 693 dropstones. Lastly, we determine possible source regions by comparing the geochemical compositions of the dropstones to the geochemical compositions of mafic volcanic rocks from Dronning Maud Land.

We first consider whether the dropstones could have originated from a single source within the Dronning Maud Land region. Based on the total alkalis versus silica (TAS) diagram, the dropstones seem to cluster into three distinct groups within the fields of basalt (Figure 2a). We see more variance between the dropstones where they plot along a tholeiitic to calc-alkaline trend on a $Na_2O + K_2O$, versus $FeO + Fe_2O_3$, versus MgO diagram. This trend could reflect derivation from multiple sources, or more likely reflects some alteration and possibly some mixing between a mantle plume source and continental crust. These same dropstones form a single cluster that straddles the boundary from basalt to basalt/andesite on the Nb/Y versus Zr/TiO_2 classification diagram. Similarly, the samples tend to form as a single cluster when plotted on other diagrams that involve trace elements. We explored these trends more on a Zr v. TiO_2*0.0001 v. Nb/Y ternary diagram. There dropstones classifications range between calc-alkaline basalts to within plate basalts (Figure 3). These trends are consistent with a hypothesis that the dropstones originated from source rock derived from a mantle sources that intruded continental crust. The ranges in alkali elements between the dropstones may be reflective of crustal contamination rather than multiple sources and we would expect that they likely originate from a single source within the Dronning Maud Land. Given their basalt to within plate basalt compositions, we expect to find multiple sources similar compositions for the dropstones within Karroo-Dronning Maud Land flood basalt province but can further narrow down possible sources using modern ice flow models in eastern Antarctica (Luttinen *et al.*, 1998).

In order to narrow down possible sources within the basalt province, we refer to ice flow patterns in the Dronning Maud Land that most likely drain into the Sites 692 and 693 in the Weddell Sea. Ice flow patterns of the terrestrial Eastern Antarctic Ice Sheet are driven by elevation changes while the cyclonic Weddell Gyre controls detached oceanic iceberg flow (Figure 1) (Orsi *et al.*, 1993; Fahrbach *et al.*, 1994). Following ice flow paths as seen in Figure 1, we hypothesize that the upstream sources would most likely be from the Ahlmannryggen Range (AR), the Jutulstraumen Glacier within the AR, and from ranges directly to the southeast of Sites 692 and 693 in the Grunehogna province. Continental ice sheet flow trajectories directly drain to sites 692 and 693 from the Grunehogna Province where there are not many exposed volcanics. Exposed bedrock regions of the Vestfjella and Heimefrontfjella Ranges 100 km south of the Grunehogna Province. Their downstream output regions are 250-400 km south of Sites 692 and 693, making them unlikely dropstone sources, but comparing their bedrock compositions may help account for dropstone compositions that show variation from known bedrock exposures within the Ahlmannryggen Range. It is possible that the dropstones come from a sub-glacial bedrock source between the Vestfjella and Ahlmannryggen Range within the Grunehogna Province.

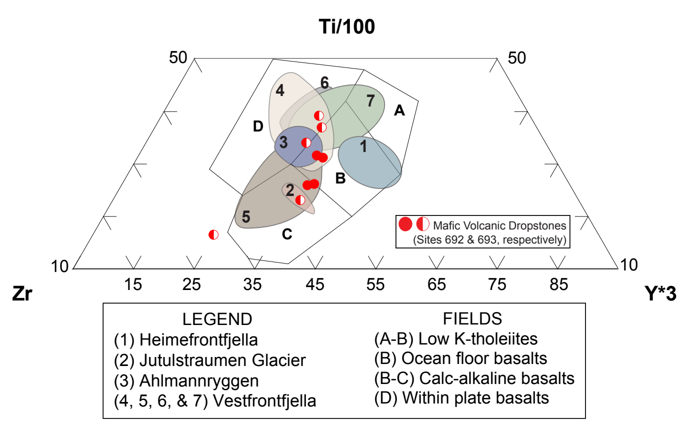

*Figure 3. Dropstones from Sites 692 and 693 subdivided on the basis of Zr v. TiO2*0.0001 v. Nb/Y (Pearce and Cann, 1973). Fields as in Figure 2.*

Potential Bedrock Volcanics

We explored potential dropstone sources within the Ahlmannryggen, Vestfjella and Heimefrontfjella Ranges using published analyses of exposed mafic volcanics. I compared Site 692 and 693 dropstone geochemical data with geochemical data from the mentioned regions using discrimination diagrams. On each diagram I ranked the compositional similarity of each group of published analyses with the dropstones (Figures 2 and 3; Table 2). In the following sections, we will discuss the potential bedrock volcanics that closely correlate geochemically with the Weddell dropstones and are upstream of Sites 692 and 693. We will also discuss potential previously unrecognized sub-glacial bedrock sources.

Table 2. Comparison scheme used to analyze geochemical compositions of dropstones and of volcanic source regions. Bold indicates greatest rel

Source Region	Jutulstraumen Glacier			Heimefrontfjella Range					Ahlmannryggen Range				Vestfro
Group No. from Literature	1	2	3	1	2	3	4	5	1	2	3	4	1
Si vs Na+K	2	1	1	1	1	0	1	1	2	2	0	1	2
Hf vs Nb vs Th	3	3	3	0	0	3	3	3	3	0	1	0	2
MnO*10 vs P2O5*10 vs Ti	3	3	3	1	1	3	1	3	2	3	0	0	3
FeO2 vs MgO vs Al2O3	3	3	1	1	1	1	0	2	1	2	0	1	2
Ba/Y vs Ti/Y	3	3	3	-	-	-	-	-	3	2	1	0	3
Ba/Nb vs Ti/Y	3	3	3	-	-	-	-	-	3	3	1	1	2
Ce/Nb vs Zr/Y	3	3	3	-	-	-	-	-	2	1	0	0	0
K/Nb vs Ti/Y	3	3	3	-	-	-	-	-	3	2	1	0	2
K/Y vs Nb/Y	3	3	3	-	-	-	-	-	3	3	1	0	1
K2O vs P2O5 vs TiO2	3	3	3	3	1	1	1	3	2	1	1	1	2
Na2O vs K2O vs SiO2	2	2	2	0	0	0	0	1	2	1	0	0	1
Ti/100 vs Zr vs Y*3	1	1	1	0	0	0	0	1	1	1	0	0	2
Zr/TiO2*.0001 vs Nb/Y	1	1	1	0	0	0	0	1	1	0	0	0	2
Relative Score	**85%**	**82%**	**77%**	25%	17%	33%	25%	**63%**	**72%**	**54%**	15%	10%	**62%**

Legend: Overlap of compositions between source regions and dropstones of various geochemical diagrams; 0 = no overlap complete overlap. A score of 75% means that the compositions of the analyzed rocks form a source region mostly overlap w geochemical diagrams. Note that diagrams with more mobile elements (e.g. Si, Na, K, Ba, Fe) may show more variance due dropstone and source region compositions may not be representative of the true geochemical trends.

Table 2. Scheme used to compare geochemical compositions of dropstones and of volcanic source regions using different discrimination diagrams.

Geochemical data for the mafic volcanics from the Ahlmannryggen Range most closely correlated with the Weddell dropstones and it is located upstream of Sites 692 and 693, making it a likely source of the dropstones. The rocks collected in the Ahlmannryggen Range that correlated geochemically and petrographically with the dropstones were collected from early Jurassic (~191 Ma.) intrusive dikes and sills of tholeiitic composition (Group One from Riley et al., 2005). The dropstones plot with compositions that indicate crustal contamination and follow within plate basalt trend, which are consistent with the intrusive volcanics across western Dronning Maud Land (Figures 1). The trace element trends of the Ahlmannryggen rocks overlap more with the Weddell dropstones than with the other intrusive volcanics from the DML we analyzed. Ahlmannryggen rocks show similar low Ti abundances to the dropstone compositions, negative Th-Nb anomalies, and both consist of low Mg-numbers. Petrographically, both the mafic dropstones and the Ahlmannryggen volcanics are typically show fractured and weathered olivines with plagioclase laths as the predominant mineral phase and groundmass phase. The dropstones are seemingly less abundant in olivine, but show ophitic clinopyroxene growth. Riley *et al.* (2005) was also able to collect more fresh samples from the Ahlmannryggen whereas the dropstones all showed low temperature alteration i.e. secondary zeolite crystallization and saussuritized. Given their upstream location, similar geochemistry, and petrography, the Ahlmannryggen is the most likely bedrock source of the dropstones collected at Sites 692 and 693.

Dropstone samples also consistently show compositions that overlap with rocks from the Jutulstraumen Glacier region in the Ahlmannryggen Range (Ohio Polar Rock Repository). The greatest differences between the two groups are illustrated in the relative abundance of trace elements but the dropstones still show similar enrichment with the Jutulstraumen Glacier rock samples. The Jutulstraumen Glacier samples in this had not been previously analyzed but previous studies describe massive tholeiitic sill and dike intrusions similar to the southern Ahlmannryggen. As we have discussed through discrimination diagrams such as the Zr v. TiO2*0.0001 v. Nb/Y diagram (Figure 3), the dropstones look enriched in LILE elements which could be a product of crustal contamination (Pearce and Cann, 1973). As such, the Jutulstraumen Glacier is a potential bedrock source of the dropstones.

Potential Subglacial Volcanic Sources

The dropstones did not match exclusively with exposed volcanic sources that were upstream of Sites 692 and 693. We compared geochemical compositions, formational ages of nearby source regions, and upstream locations to identify possible unrecognized sources. The dropstones also matched with rocks from the Vestfjella and Heimefrontfjella Ranges. Many of the dropstones have compositions that overlap with mafic metavolcanic rocks from the Vestfjella Range. The CT1 group from Luttinen and Furnes (2000), show similar geochemical compositions to the dropstones, Jutulstraumen Glacier rocks, and to Group One from Riley et al. (2005) in the Ahlmannryggen Range. The Vestfjella rocks are between 160 and 170 Ma, and rocks analyzed from the Ahlmannryggen Range are ~191 Ma, and were erupted about the same time 300 km apart. If this is true, it is possible that the Jurassic flood basalts extend laterally through the Grunehogna Province and the range of similar geochemical trends we see are resultant of the variation in rock formation between the Vestfjella Range and Ahlmannryggen Range. The Grunehogna Province extends between the Vestfjella Range and the Ahlmannryggen Range, and shows the most direct ice flow path to Sites 692 and 693. Ice flow patterns through the Grunehogna Province could imply a potential bedrock source of similar but different compositions than the potential exposed volcanic sources. We argue that if the upstream location, geochemical similarity, and ages of exposed volcanics surrounding the Grunehogna Province are true, it may be a previously unrecognized sub-glacial bedrock source for the dropstones collected at Sites 692 and 693 (Figure 1).

CONCLUSIONS

The following conclusions can be drawn from this research on the mafic dropstones collected in sites 692 and 693 from the Weddell Sea; 1) The dropstone rock types range from mid ocean ridge basalt to within plate basalt compositions consistent with low pressure melts we may find on ocean island systems or in crustal contaminated mid ocean ridge basalts (Luttinen and Furnes, 2000). The dropstones show more variation on mobile element diagrams than trace element diagrams. Variations seen between the dropstones are likely due to crustal contamination rather than multiple sources; and 2) the basaltic dropstones likely originate from the same rock source based on geochemical data and petrography.

After comparing the dropstone geochemical compositions to rocks from various regions of the Dronning Maud Land, we offer the following as a more constrained provenance of the dropstones deposited in the Weddell Sea; 1) Ahlmannryggen and the Jutulstraumen Glacier Range are the most likely sources of the dropstones based on ice flow trajectory to Sites 692 and 693 in the Weddell Sea; 2) The dropstones were most similar compositionally and petrographically to rocks from the Ahlmannryggen Range and the Jutulstraumen Glacier Range (Riley et al., 2005; Ohio Polar Rock Repository samples); 3) Vestfjella and Heimefrontfjella show similar geochemical compositions, but are not likely bedrock sources of the dropstones in the Weddell Sea (Luttinen and Furnes, 2000; Heinonen et al., 2010); 4) ice flow trajectories across the Grunehogna Province make it possible that the dropstones come from a previously unrecognized subglacial bedrock source between the Vestfjella and Ahlmannryggen Range.

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