**Isotope geochemistry of basaltic glasses from the Vance Seamounts, a
near-ridge seamount chain adjacent to the Juan de Fuca Ridge**

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B.Sc.H. Geology

A thesis submitted to the School of Graduate Studies in partial fulfillment of
the degree of Master of Science

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Abstract

Volcanic glass from 24 grab-samples from the Vance Seamounts, a chain of seven near-ridge seamounts (NRS) located adjacent to the southern Juan de Fuca Ridge (SJdF), was analysed for Sr, Nd, and Pb isotopic composition. The selected samples show a relatively large range of isotopic compositions ($^{87}\text{Sr}/^{86}\text{Sr}$ from 0.702473 to 0.702755, $^{143}\text{Nd}/^{144}\text{Nd}$ from 0.513048 to 0.513182, and $^{206}\text{Pb}/^{204}\text{Pb}$ from 18.12 to 18.82).

The isotopic diversity, seen both within and among seamounts of the chain, is consistent with melt-induced mixing of a heterogeneous mantle source comprised of a depleted mantle (DM) matrix with 'plums' of HIMU(high μ)-like material. The observed isotopic compositions fall outside of previously observed compositional ranges from SJdF and neighbouring NRS lavas, but are consistent with compositions previously observed in lavas from the greater northeast Pacific. The data also support previous, recent melting events of the seamount source components beneath the adjacent SJdF.

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I will be forever grateful to the Monterey Bay Aquarium Research Institute for funding the Vance 2006 research cruise and to Dr. David Clague (MBARI) who led the scientific party. It was an opportunity of a lifetime. I would like to thank the other members of the scientific party, especially Prof. Mike Perfit and his student Rachel Wendt (both of the University of Florida) who provided me with unpublished data that greatly added to the interpretation of isotopic data.

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Original Work by the Author

The author was an active team member participating in sample collection, description, and processing while aboard the Vance 2006 research cruise led by the Monterey Bay Aquarium Research Institute (MBARI). The author, Brian Cousens (supervisor), and R. Wendt (University of Florida, M.Sc. candidate) were responsible for sub-sampling the volcanic glass component for subsequent geochemical analyses. All sample preparation, geochemical separation, and mass spectrometry methods used in the collection of isotopic data were done by the author with helpful technical assistance from members of the Isotope Geochemistry and Geochronology Research Center at Carleton University. All petrography, mineral chemistry data, and related interpretations are those of the author. Major element data for volcanic glasses were provided by MBARI, but all interpretations are those of the author. Trace element data for volcanic glasses were collected and interpreted by R. Wendt; however interpretation of the combined trace element and isotopic data are those of the author.

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Note to the Reader

The author has attempted to write a manuscript that is both technically accurate and yet still accessible to those not well versed in isotope notation and terminology. Appendix I is a brief overview of the three radiogenic isotope systems used in this thesis (Rb-Sr, Sm-Nd, and U-Th-Pb). The author recommends *Isotopes: principles and applications* (Faure and Mensing, 2005) for a complete discussion of radiogenic isotope theory. Isotopic ratios used in this thesis include:

$^{87}\text{Sr}/^{86}\text{Sr}$, often referred to in this manuscript as the Sr isotopic ratio

$^{143}\text{Nd}/^{144}\text{Nd}$, often referred to as the Nd ratio. Epsilon Nd (ϵ_{Nd}), a notation common to many studies involving crustal rocks, is not used here.

$^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$, often referred to as the Pb isotopic ratios

All of the isotopic data presented in this thesis represent present-day ratios that have not been age-corrected. The seamount lavas used in this thesis have not yet been age-dated, but cannot be older than the underlying oceanic crust (< 2.55 Ma). The half-lives of the Sr, Nd, and Pb isotopes are too long to have a measurable effect on isotopic ratios of these lavas.

Higher values of a given isotopic ratio are termed 'more radiogenic' and lower values are termed 'less radiogenic'. Enriched mantle sources are characterized by higher (more radiogenic) Sr and Pb ratios, and by lower (less radiogenic) Nd ratios, relative to depleted mantle. Progressive mixing between depleted and enriched mantle sources can result in lava

compositions trending between more 'enriched' and more 'depleted' mantle signatures (relative to one another). Hence, a more 'enriched' composition in lavas derived from mantle sources is defined by higher Sr and Pb, and lower Nd isotopic ratios, relative to a more 'depleted' composition. Trace element abundances can also be described as enriched or depleted, but the two systems are not directly related (i.e. it is possible for a lava to be characterized by a highly depleted trace element signature but with an isotopic signature characteristic of, or trending toward, an enriched mantle source composition).

Every attempt has been made to be clear and consistent with the various ratios, notations, etc., but isotope geochemistry is a complex subject and the author apologizes for any remaining lack of clarity in the following chapters.

CHAPTER 1: INTRODUCTION

Oceanic volcanic lavas, produced through the partial melting of the mantle, have long been used to study the chemical and physical structure and processes of the Earth's mantle. Although magmatic processes such as fractionation, magma mixing, and contamination may act to modify them, oceanic basalts still offer the best 'window' into the mantle.

Studies of oceanic basalts have traditionally been focused on mid-ocean ridge basalt (MORB) or ocean-island basalt (OIB); this study, however, is focused on near-ridge seamount (NRS) basalt. Bathymetric mapping of the seafloor in the 1980s revealed the NR seamounts, although typically much smaller than hotspot-type volcanoes, are the most abundant volcanic edifices on Earth (e.g. Fornari *et al.*, 1987). They commonly occur in linear chains or as more dispersed zones across the seafloor adjacent to slow, intermediate, and fast spreading centers (e.g. Fornari *et al.*, 1987; Batiza *et al.*, 1989).

What controls the location and formation of NR seamounts is still unresolved, but it has been proposed that they are related to offset ridges, overlapping spreading centers, and/or topographically high areas of mid-ocean ridges (Batiza and Vanko, 1984; Lonsdale, 1985; Fornari *et al.*, 1987, 1988b). Linear chains of NR seamounts are common along

Pacific spreading centers and it has been shown that they form parallel to subaxial asthenospheric motion rather than to absolute or relative plate motion (Schouten *et al.*, 1987; Lonsdale, 1991; Clague *et al.*, 2000b).

NRS lavas have been studied extensively since the 1980s because their chemical compositions can provide insight into mantle heterogeneity, mantle upwelling, and magma genesis at and near ridges (e.g. Barr, 1974; Batiza and Vanko, 1984; Davis and Karsten, 1986; Allan *et al.*, 1987, 1989; Batiza *et al.*, 1990; Smith *et al.*, 1994; Shen *et al.*, 1993, 1995; Niu *et al.*, 2002). Although NRS and mid-ocean ridge lavas appear to share a common heterogeneous upper mantle source, the increased chemical diversity and more primitive nature (higher MgO) typical of NRS lavas, as well as the observation that NR seamounts can reach shallower waters than the adjacent ridge segments, are evidence of an independent magmatic plumbing system and different degrees of melting and storage of those melts (Batiza and Vanko, 1983, 1984; Zindler *et al.*, 1984; Allen *et al.*, 1987, 1989; Fornari *et al.*, 1988a; Cousens, 1996a; Davis and Clague, 2000).

Additionally, NRS lavas are likely produced from smaller melt volumes that did not reside in a steady-state magma chamber, at least not for long periods of time (Batiza and Vanko, 1984; Zindler *et al.*, 1984; Clague *et al.*, 2000b; Davis and Clague, 2000). Therefore, their commonly primitive and unmixed nature (a contrast to axial MORB), has proven NRS

lavas to be a good material for studying heterogeneity in the underlying mantle source(s) (e.g. Batiza and Vanko, 1984; Zindler *et al.*, 1984; Graham *et al.*, 1988; Allen *et al.*, 1994; Cousens, 1996a).

A wide variety of basalt compositions, primarily normal MORB (NMORB) but also including enriched MORB (EMORB) and alkalic basalt, have been recovered from NR seamounts (e.g. Batiza and Vanko, 1984; Allan *et al.*, 1987; Batiza *et al.*, 1989; Desonie and Duncan, 1990; Leybourne and Van Wagoner, 1991; Niu and Batiza, 1997; Davis and Clague, 2000). These lavas have also been characterized by mantle isotopic signatures that are similar to, more enriched (i.e. higher $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and lower $^{143}\text{Nd}/^{144}\text{Nd}$), or more depleted (i.e. lower $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and higher $^{143}\text{Nd}/^{144}\text{Nd}$) than those of the nearby ridge lavas. While ranging in $\text{La}/\text{Sm}_{\text{cn}}$ values from 0.3 to 4.0 (i.e. very depleted to significantly enriched in trace elements) the wide range of basalt compositions (alkalic to tholeiitic) recovered from the Northeast Pacific, for example, all have MORB-like (never OIB-like) isotopic signatures, indicating a source (or sources) in common with the regional tholeiites (Cousens, 1996a; Cousens *et al.*, 1984, 1985; Eaby *et al.*, 1984; Zindler and Hart, 1986; Davis and Clague, 1987; Cousens, 1988; Hegner and Tatsumoto, 1989; Desonie and Duncan, 1990; Allan *et al.*, 1993).

While heterogeneity in the upper mantle is well accepted, the nature and scale of the heterogeneity is still a subject of ongoing

research. The compositional range from enriched alkalic basalts to depleted tholeiites requires different mantle sources and different melting histories, and the fact that these compositions can be found on the same seamount requires that the mantle be heterogeneous on a relatively small scale. As more data are collected from NRS lavas, it is becoming clear that no single model or statement can be universally applied to the composition of NRS lavas or their relationship to the adjacent ridge; however, the chemistry of these seamounts continues to be useful in the study of the underlying mantle.

The Vance Seamount Chain is one of several seamount chains in the Northeast Pacific region adjacent to the Juan de Fuca-Gorda spreading center system (Figure 1). The petrology, morphology, and geochemistry of some NRS chains on the western flanks of the Juan de Fuca Ridge have been fairly well studied, including the Heck and Heckle Seamounts and the Cobb-Eickelberg Seamounts to the north of the Vance Seamounts, as well as the President Jackson Seamounts adjacent to the Gorda Ridge to the south of the Vance Seamounts.

The Vance Seamounts, a roughly linear array of seven seamounts (Figure 2), are located on the Pacific plate adjacent to the Vance segment of the southern Juan de Fuca Ridge (Clague *et al.*, 2000b). The Juan de Fuca Ridge, a spreading center with average spreading rates of

Figure 1: Near-ridge seamount chains of the Northeast Pacific (Davis and Clague, 2000)

Figure 2: A northward-looking perspective view (2x vertical exaggeration) of the Vance near-ridge seamount chain, a roughly linear chain of seven seamounts (Vance A through Vance G). The strike length of the chain (and length of seafloor imaged) is approximately 57 km. (MBARI Mapping Team, 2001)

anywhere between 4 to 6 cm/yr since 6 Ma (Riddihough and Hyndman, 1992), extends between the Blanco and Sovanco fracture zones and has been divided into as many as nine segments, with up to seven located south of the Cobb-Offset (Delaney *et al.*, 1986; Karsten *et al.*, 1990; Hey and Wilson, 1982). The seven seamounts, Vance A through Vance G, appear approximately 19 km west of the Juan de Fuca Ridge and extend at an azimuth of 324-331° for approximately 57 km to the northwest on ocean crust ranging in age from 0.78 Ma in the southeast to 2.55 Ma in the northwest (Clague *et al.*, 2000b).

This thesis is part of a larger study encompassing many aspects of the physical volcanology and geochemistry of the Vance Seamounts, a chain that has not been well studied. In particular, this project is a detailed study of the Sr, Pb, and Nd radiogenic isotope geochemistry of the Vance seamount lavas, with the primary purpose of describing and examining the scale and source of isotopic variations, their relationship to other NRS lava compositions, and their relationship to lavas from the adjacent Juan de Fuca Ridge segments.

Direct sampling of the mantle is not available to scientists; therefore, one needs to search for a reasonable alternative, for example, that of melts of the mantle that have been minimally modified/alterd from the original mantle composition. Partial melting of the mantle produces basaltic lavas that may be modified by a variety of processes (such as

fractionation, mixing, and contamination) while *en route* to the Earth's surface. Partial melting and fractional crystallization, processes very important to the study of major and trace elements, do not affect radiogenic isotope ratios; thus the isotopic character of a mantle source is preserved in lavas produced from that source.

In general terms, magma contamination can be limited by avoiding lavas that have passed through the continental crust, which is easily melted and chemically very dissimilar from a basaltic melt. Oceanic crust, on the other hand, does not have a significant contamination effect on basaltic magmas because its melting temperature is too high to allow it to be re-melted. Additionally, lavas quenched by seawater produce substantial amounts of volcanic glass (the quenched form of the liquid phase of a lava)—arguably the most representative material for geochemical studies of lavas.

Previous research cruises typically recovered seamount samples by dredging, a technique with limited control on the sample type or precise location. Therefore, the extent to which fine-scale geochemical and especially isotopic variability is present within an individual seamount could not be well established. Recent advances in seafloor exploration distinguish this study from many others in two ways: (1) the field-work and sample collection (described in Chapter 4) for the project is the most extensive and detailed work yet done on any of the seamount chains in

the Northeast Pacific region. This research cruise employed a sophisticated remotely operated vehicle (ROV) that was able to collect grab-samples along with detailed video-recorded descriptions of the outcrop environments; and (2) the ROV was able to collect samples quickly, therefore enabling the research party to collect an exceptionally complete suite of rocks from each seamount, given the time constraints that are typical of such research cruises. Previous isotope studies of seamount chains were often based on only one analysis per seamount.

As a result of the advances mentioned above, this study was able to analyze multiple glass samples for each seamount. The control on sample type and location has provided the opportunity to (1) investigate potential relationships between isotopic ratios and sample type or location within the volcanic sequence, and (2) further the study of geochemical heterogeneities in the mantle and how they may or may not be expressed within individual seamounts and/or among the seven seamounts of the chain.

CHAPTER 2: REGIONAL GEOCHEMICAL FRAMEWORK

2.1 Melting and Mantle Heterogeneity in the Northeast Pacific

Isotopic compositions of basalt samples from various tectonic environments throughout the Northeast Pacific typically plot along a broad mixing array between the DM (depleted mantle) and HIMU (high $^{238}\text{U}/^{204}\text{Pb}$, or μ) components of Zindler and Hart (1986) (e.g. Cousens, 1988, 1996a; Cousens and Ludden, 1991; Michael *et al.*, 1994). Mixing arrays between distinct mantle end-members in isotope-isotope plots can be used to account for the variety of isotopic compositions from basalts found on individual volcanoes and also among volcanoes of a seamount chain (White and Hofmann, 1982; Zindler and Hart, 1986).

The DM mantle component is characterized by high $\text{CaO}/\text{Al}_2\text{O}_3$, low $\text{K}_2\text{O}/\text{Na}_2\text{O}_3$, low $\text{La}/\text{Sm}_{\text{cn}}$, low $^{87}\text{Sr}/^{86}\text{Sr}$ and Pb isotope ratios and high $^{143}\text{Nd}/^{144}\text{Nd}$ and $^3\text{He}/^4\text{He}$. Melting and removal of magma in the ancient geologic past is needed to explain this source's depletion in Rb relative to Sr and enrichment in Sm relative to Nd. To explain isotopic ratios, the DM component is generally interpreted as the residual upper mantle left after repeated episodes of partial melting and the formation of the Earth's oceanic and continental crust (Faure and Mensing, 2005). DM is the dominant component in many MORBs and is typified by the composition of lavas recovered from the Heck and Heckle Seamounts.

The high U/Pb component of the mantle, HIMU, by comparison, is characterized by higher K_2O/Na_2O_3 and La/Sm_{cn} , higher $^{87}Sr/^{86}Sr$ and Pb ratios, and lower $^{143}Nd/^{144}Nd$ and $^3He/^4He$ ratios. An ancient event (1.5-2.0 Ga ago), thought to be recycling of oceanic crust and a preferential loss of Pb relative to U during fluid loss as the crust was subducted, resulted in a higher U/Pb ratio relative to DM (Hofmann and White, 1982; Weaver, 1991). The HIMU component is typified by the lavas of the island of St. Helena, and is commonly found in alkalic basalts and EMORBs. The HIMU-like component in the Northeast Pacific is not fully understood, but is likely sourced from hydrated, subducted oceanic crust, which is now stored in the mantle transition zone. Isotopic variations limit the age of the enriched source to 0.5 to 2.0 Ga. Mantle plumes or rising partial melts of the enriched source could transport this material into the upper mantle. (Cousens 1996a)

The distribution, scale, and volume of these two mantle components in the Northeast Pacific are still matters of debate. Cousens (1996a) and Cousens *et al.* (1995) proposed that the Northeast Pacific upper mantle be comprised of a depleted peridotite matrix with veins or 'plums' of enriched lherzolite/clinopyroxenite (Figure 3), a model that has similarities to earlier discussions on the formation of young Pacific seamounts (e.g. Batiza and Vanko, 1984; Zindler *et al.*, 1984). A veined architecture, rather than a point source such as a mantle plume, is better

able to explain the ubiquity of the enriched component in the Northeast Pacific basalts. Melts of the enriched plums could result in the alkaline lavas while the variety of MORBs could result from variable melting and mixing proportions of the enriched plums and the DM matrix (Cousens, 1996a). Cousens (1996a) also proposed that thermal anomalies in the mantle and fractures in the oceanic crust likely control the formation and location of NR seamounts.

Veins or plums of enriched material (if present) would be the first to melt, resulting in an increase of K, Sr, and Rb in the melt (e.g. Pertermann and Hirschmann, 2003). More clinopyroxene is involved as the degree of melting increases, resulting in higher Ca, Na, and a further increase in Sr. Continued melting will begin to exhaust the limited budget of incompatible elements and will eventually begin to melt the residual enriched component as well as the depleted matrix component. These melts may begin to mix during transport or in a subvolcanic magma chamber, and can then produce the entire range of mixing compositions between the two end-member components. The relative proportion of the two components in a given melt is thus dependent on the extent of melting and the presence/volume of each component.

Mid-ocean ridges and their adjacent NR seamounts may share a common heterogeneous upper mantle source; however, the individual style of volcanism associated with each differs in such a way that NRS

lavas have been proposed to be more discriminating samplers of the underlying mantle source(s) (e.g. Batiza and Vanko, 1984; Allen *et al.*, 1989; Fornari *et al.*, 1988a, 1988b).

Magma mixing (and the subsequent homogenization of isotopic ratios) is an important process to consider when studying mantle heterogeneity. Although the Vance Seamounts and some other NR seamounts have caldera structures, indicating the presence of a subvolcanic magma chamber and the possibility of magma mixing, Clague *et al.* (2000b) have proposed that individual melts neither reside in these chambers for long periods of time nor mix with subsequent melts.

Magma mixing and chemical homogenization at mid-ocean ridges, particularly those with fast spreading rates, can significantly obscure the range of compositional heterogeneity present. NR seamount lavas, therefore, present a better material for studying the extremes in melt source characteristics and the nature mantle heterogeneity.

Figure 3: Cartoon model demonstrating the distribution of enriched and depleted sources for MORB and near-ridge seamount lavas in the upper mantle; dark grey 'plums' represent untapped enriched mantle, lighter grey 'plums' have been partially melted (from Cousens, 1996a).

For example, the degree of melting can be significant or very limited. If both depleted and enriched components are present, and the depleted component is volumetrically dominant, and a sufficiently hot thermal regime exists, then the melt composition will be controlled by the depleted component. If the same sources are melted under a cooler thermal regime, the enriched component, although still volumetrically subordinate, may dominate the melt composition.

Since NR seamounts share a common mantle source with the spreading centers, but do not use the same magmatic plumbing system, the melt compositions will be determined by what directly underlies the seamount at the time of melting. The NRS style of volcanism appears to be better at revealing the degree of heterogeneity in the underlying mantle heterogeneity (at least when compared to fast spreading centers with a robust magma supply); however, the direction of regional mantle flow will also have a profound effect on the seamount source composition (Figure 3).

If the mantle first passes under the ridge, melt generation there will act to 'deplete' the enriched component, leaving only depleted components to pass under the seamount. If, however, the enriched plums first reach an active seamount, there may be a significant enriched signature to the seamount lavas. An example of this model may be seen in the off-axis eruptions both west and west of the East Pacific Rise at

9°31'N; most lavas to the west are EMORB, while both NMORB and EMORB lavas are common on the east side (Perfit *et al.*, 1994). In this manner, the difference in heterogeneity between the seamounts and the ridge is, in part, a function of the magma supply at the ridge, the regional flow direction, and the distribution of the enriched plums in the upper mantle.

2.2 NR seamounts adjacent to the Juan de Fuca and Gorda Ridge spreading centers of the Northeast Pacific

The Vance Seamounts are similar in size, shape, volume, and length to three other neighbouring NRS chains in the NE Pacific; the Heck and Heckle Seamounts both adjacent to the West Valley segment of the Juan de Fuca Ridge (i.e. north of the Cobb-Offset), and the President Jackson Seamounts adjacent to the Gorda Ridge (Figure 1). All are composed of seven or eight seamounts forming short linear chains, and are commonly characterized by circular, truncated cones with steep flanks and relatively flat summit plateaus, many of which also share the distinctive off-set caldera collapse features very prominent in Vance Seamounts (Hammond, 1997; Davis and Clague, 2000).

Lavas dredged from the Heck and Heckle Seamounts are compositionally very 'primitive', have restricted incompatible element ranges, and show isotopic ratios equivalent to highly depleted MORB (Leybourne and Van Wagoner, 1991). In comparison to samples from the adjacent West Valley ridge segment, the seamount lavas are more

restricted and are characterized by a more depleted mantle isotopic signature (Leybourne and Van Wagoner, 1991; Cousens *et al.*, 1995). The formation of these seamounts is consistent with the model where a heterogeneous mantle first passes below a spreading center (where enriched components melt first and become depleted) and is then left with depleted sources for the seamounts to tap or a situation where no enriched plums were present at that time.

All samples from the President Jackson Seamounts and the adjacent Gorda Ridge have NMORB signatures, but the seamount lavas are generally more primitive (higher MgO), lack evidence for magma mixing, have trace element patterns that range from highly depleted to moderately enriched, and have isotopic compositions that range from more depleted to more enriched mantle signatures, with Pb ratios clearly trending toward values more typical of EMORB (Davis and Clague, 2000).

While sharing many physical characteristics, the Heck & Heckle Seamount lava compositions are overall more depleted in trace elements and are characterized by a more depleted (i.e. lower $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and higher $^{143}\text{Nd}/^{144}\text{Nd}$) mantle isotopic signature than lavas from the President Jackson Seamounts. Additionally, the seamount lavas have an inverse relationship with lavas from the adjacent ridge; the Heck & Heckle lavas are more restricted and 'depleted' whereas the President Jackson lavas are more heterogeneous and 'enriched' than the ridge samples.

However, lavas from all three seamount chains have more primitive (i.e. higher MgO) compositions than the adjacent ridge, do not show evidence for magma mixing, and support a quick passage through crustal magma chambers (Leybourne and Van Wagoner, 1991; Davis and Clague, 2000).

The Cobb-Eickelberg NRS chain is the closest neighbouring chain to the Vance Seamounts, and the only other chain adjacent to the southern Juan de Fuca Ridge (Figure 1). Despite their close proximity, the physical characteristics of the two chains are quite different; the Cobb-Eickelberg chain is much longer and more voluminous and has some physical similarities with a typical OIB hotspot chain. The Cobb-Eickelberg lavas, however, have isotopic signatures very similar to the adjacent Juan de Fuca MORB. And so, what resembles a hotspot chain morphologically actually has MORB-like chemistry, and may be forming from a stationary upper mantle melting anomaly rather than a traditional plume from the lower mantle (Desonie and Duncan, 1990). There are slight heterogeneities in the isotopic ratios, which Desonie and Duncan (1990) explain by partial melting and magma mixing from a heterogeneous upper mantle.

Karsten *et al.* (1990) proposed that the Cobb-Offset in the Juan de Fuca Ridge marks a division in the mantle beneath the Explorer-JdF spreading center system; one that separates a northern 'enriched'

province and a southern 'depleted' province. At the time of Karsten *et al.*'s (1990) proposal, lava samples from ridge segments and adjacent NR seamounts located north of the Cobb Offset showed ranges from depleted to enriched MORB (e.g. Barr and Chase, 1974; Cousens *et al.*, 1984, 1985; Michael and Chase, 1985; Michael *et al.*, 1989; Karsten *et al.*, 1990; Leybourne and Van Wagoner, 1991; Van Wagoner and Leybourne, 1991; Allen *et al.*, 1993). Data for lavas south of the Cobb Offset were less abundant, especially from NRS, but clearly lacked the EMORB seen to the north (Schilling *et al.*, 1983; Eaby *et al.*, 1984; Rhodes *et al.*, 1990).

Davis and Karsten (1986) proposed that melting of low-temperature, enriched mantle heterogeneities in advance of a migrating ridge axis was the process responsible for the formation and asymmetric distribution of near-ridge seamounts adjacent to the JdF. Their model predicted a progression from enriched to depleted compositions toward the ridge; however more recent data from the Heck and Heckle Seamounts, Lamont Seamounts, and President Jackson Seamounts do not show such a progression and thus do not support the model (Allen *et al.*, 1989; Karsten *et al.*, 1990; Leybourne and Van Wagoner, 1991; Davis and Clague, 2000). The Cousens (1996a) model differs from that of Davis and Karsten (1986) in that ridge migration is not required nor do NR seamounts form as the direct result of the presence of an enriched plum.

CHAPTER 3: THE VANCE SEAMOUNTS

Previous work on the Vance Seamounts has been primarily based on bathymetric mapping from SeaBeam and more recent high-resolution data. The most recent high-resolution bathymetry and side-scan data were collected by the Monterey Bay Aquarium Research Institute (MBARI) in 1998 with a hull-mounted 30 kHz Simrad EM300 multibeam sonar and analyzed by Clague *et al.* (2000b).

Mapping has led to the creation of a conceptual volcanic genetic model and to various estimates of nature and duration of magmatic activity. A small number of geochemical analyses have been published for some dredge-haul samples that were collected during a cruise to the southern Juan de Fuca Ridge (Smith *et al.*, 1994). To date, no radiogenic isotope analyses have been published for any of the Vance Seamount lavas.

3.1 Physical Characteristics

The characteristic morphology (seen in Vance A, C, D/E, and F) is that of a steep-sided, flat-topped, cone-shaped volcano with nested calderas progressively offset toward the ridge axis (Figure 2). Vance B and Vance G are less organized volcanic structures that consist of multiple small cones and pillow ridges. Clague *et al.* (2000b) measured and calculated many of the key physical characteristics of the Vance

Seamounts, some of which are mentioned here and presented in Table 1. The volcanic structures have volumes ranging from 15 to 67 km³ and heights of 440 to 1140 m above the seafloor (Clague *et al.*, 2000b). The collapse calderas range from 1 to 4 km across and up to 400 m deep.

Table 1: Physical Characteristics of the Vance Seamounts (Clague *et al.* 2000b)

Seamount	Base (m bls*)	Height (m)	Summit (m bsl)	Volume (km ³)	Calderas/ Craters
Vance A	2700	1050	1652	35	1
Vance B	2700	770	1932	67	0
Vance C	2650	830	1820	36	2
Vance D	2600	1140	1460	25	3
Vance E	2600	1040	1560	23	3
Vance F	2725	850	1876	34	2
Vance G	2725	440	2281	15	0

* meters below sea-level

3.2 Morphology and Modeling

Near-ridge seamounts typically have the form of nearly flat-topped truncated cones, and the Vance Seamounts are no exception (Batiza, 1982, 1989; Searle, 1983; Lonsdale, 1983; Smith, 1988; Hammond, 1997; Rappaport *et al.*, 1997; Clague *et al.*, 2000b).

The flat-tops were, up until recently, thought to have formed from eruptions along circumferential faults (e.g. Batiza and Vanko, 1983; Fornari *et al.*, 1988), similar to a process observed in the Galapagos Islands (Simkin, 1972). However, high-resolution bathymetric mapping of the Vance, President Jackson, and Taney Seamounts shows no evidence of the presence of such circumferential faults, and therefore, could not

provide support for the model. Clague *et al.* (2000b) found evidence for central volcanism on the summit plateaus and proposed that the flat tops formed by filling and overflowing of earlier calderas. Some recently described flat-topped volcanic cones in Hawaii may be subaerial analogs to flat-topped NR seamounts (Clague *et al.*, 2000a).

Hammond (1997) selected 43 NR seamounts adjacent to the Juan de Fuca in order to study the relationship between seamount morphology and the magmatic processes that resulted in their formation. The sample set included only Vance seamounts C to F, as the northwest portion of the chain had not been imaged at that time.

Through the analysis of the bathymetry, it became clear that nearly all the seamounts shared remarkably similar morphologies, suggesting a common mode of formation from a similar sequence of volcanic events. The common morphology, "exemplified by the Vance Seamounts", consisted of circular, truncated cones with steep sides and large, relatively flat summit plateaus (Hammond, 1997).

Many were also characterized by calderas or craters offset toward the Juan de Fuca axis, which indicated to Hammond that the seamount morphology had been influenced by plate motion. These morphological observations were echoed by Clague *et al.* (2000b) in a more recent and detailed bathymetric analysis of the Vance, President Jackson, and Taney Seamounts. Hammond recognized that his model, or any model, of the

evolution of the JdF NRS had to account for (1) the circular shape of the edifices in map view, (2) the tendency for only one crater or caldera to be present, and (3) the displacement of the crater or caldera from the center of the cone, consistently toward the ridge axis.

Hammond's (1997) conceptual model (Figure 4) relates a seamount's lifecycle to plate motion away from the spreading ridge. In the model, NR seamounts are built by pulses of magma erupting from a stationary source onto a plate that is moving away from the nearby ridge. Initial pulses of relatively fluid and/or voluminous magmas (**Stage A**) begin to create the basal slopes and/or platforms that are present beneath the seamounts. By **Stage B**, sustained cone-building volcanic activity has progressed to a point where steeper slopes are being formed. Eventually though, volcanic activity becomes less intense, and collapse from magma withdrawal begins to dominate over construction (**Stage C**). The collapse features are located over the most recently active magma conduit (i.e. on the side of the seamount closest to the ridge). As plate motion carries the seamount farther from the magma source, the magma conduits are eventually abandoned and the volcano becomes extinct. Any new magma pulses would then find a new, more direct route to the surface, creating a new volcanic center (**Stage D**).

Figure 4: Conceptual model for the formation of the Vance and other NR seamounts (Hammond, 1997)

Considering that the seamounts tend to be circular in map view, and assuming they formed from a stationary magma source, the main cone-building volcanic activity must have taken place relatively quickly (i.e. while the seamount was still directly over the principal magma conduit). The simplified time frame for the model can then be divided into two principal stages: a relatively quick, voluminous constructional phase, followed by a collapse phase as the magma supply is diminished.

Large, unfilled calderas support the idea of a rather abrupt end to peak magmatic activity (Clague *et al.*, 2000b).

Hammond (1997) recognized the possibility that a seamount may not always proceed beyond Stage A. The disorganized volcanic region of Vance B, later mapped by Clague *et al.* (2000b), may represent such a case. However, the cumulative volume of erupted lava at Vance B is roughly twice the average volume for a Vance, Taney, and President Jackson seamount (Clague *et al.*, 2000b), suggesting the morphology of Vance B formed *in lieu* of (rather than as a precursor to) a large circular cone. Clague *et al.* (2000b) proposed that Vance B formed from more frequent, smaller eruptions possibly in response to increased permeability of the underlying oceanic crust (i.e. more ridge-parallel faulting).

3.3 Age and Lifecycle

No absolute age data are available for any of the Vance Seamounts; however, Clague *et al.* (2000b) used magnetic anomalies to calculate the age of the underlying oceanic crust. The crust at the southeast end of the seamount chain (i.e. closest to the ridge) was determined to be 0.78 Ma years of age, and the crust at the northwest end of the chain (i.e. farthest from the ridge) was determined to be 2.55 Ma years of age.

A common interpretation is that the seamounts in NR chains are built sequentially, with a younging direction toward the ridge axis (e.g. Barr, 1974; Barone and Ryan, 1990; Lonsdale, 1991; Hammond, 1997). While crosscutting relationships within individual Vance seamounts clearly indicate that the south-eastern calderas are younger than those to the northwest, there is very limited evidence for a definitive age sequence in the chain. Bathymetric data indicate that the summit shield on Vance E has partially filled the calderas on Vance D and that the Vance E shield was subsequently modified by additional caldera collapses on the SE flank, supporting a younging trend toward the SE end of the chain (Clague *et al.*, 2000b).

The tendency for NR seamounts to form in linear chains, begs the question, what do they parallel? Various workers have proposed absolute or relative plate motion vectors (Davis and Karsten, 1986; Batiza *et al.*, 1990; Mukhopadhyay and Batiza, 1994), migrating nontransform offsets (Lonsdale, 1985), and plate motion relative to subaxial asthenospheric flow (Schouten *et al.*, 1987; Lonsdale, 1991).

The idea that the migration of a volcanic center is related to motion over melting anomalies upwelling in the shallow subaxial asthenosphere (SAA) was originally proposed by Schouten *et al.* (1987) and successfully tested on NRS chains along the East Pacific Rise by Lonsdale (1991). A correlation between the migration rate of the volcanic center along axis

and the along-axis component of the absolute migration of the ridge forms the basis of this theory. Clague *et al.* (2000b) applied the Schouten *et al.* (1987) model to the Vance, President Jackson, and Taney seamount chains, and found that they all formed parallel to Pacific-SAA vectors rather than absolute or relative plate motion vectors.

Hammond (1997) used his model to estimate the lifespan of individual seamounts, from the onset of the cone building stage to the final cessation of magmatism withdrawal and caldera collapse. Measuring the distance of caldera offset from the central cone and using the half spreading rate for the ridge, Hammond (1997) calculated the average lifespan of a JdF NR seamount to be about 50,000 yrs. Clague *et al.* (2000b) modified the calculation after determining that the seamount chain's propagation rate is actually related to flow in the subaxial asthenosphere, not the seafloor spreading rate, as was used by Hammond. The re-calculated average lifespan of the volcanic cycle in the Vance chain is approximately 75,000 yrs (Clague *et al.*, 2000b).

3.4 Magmas and Calderas

Experimental studies on caldera formation (Marti *et al.*, 1994; Roche *et al.*, 2000) were able to produce structures similar to those observed on the Vance Seamounts. Marti *et al.* (1994), using inflatable balloons in a medium of fused alumina powder, concluded that multiple overlapping

calderas are associated with magma chamber migration from the volcanic edifice (or plate migration over a stable magma source), and nested calderas can form from repetitive withdrawal of magma from a single chamber.

Based on the experimental results, Clague *et al.* (2000b) proposed that most of the Vance calderas likely formed from a succession of infrequent, voluminous magma withdrawals, while others likely formed from smaller, episodic withdrawals from the same magma chamber. Many of the calderas may have become offset and overlapping as the seamount edifice was rafted further away from the magma. Clague *et al.* (2000b) incorporated bathymetric mapping and the experimental results to estimate that the magma chambers of the Vance, President Jackson, and Taney Seamounts probably had volumes of around 3 km³, with diameters of 3-5 km, and summits located between 0.8 and 3 km below the surface (Clague *et al.*, 2000b).

As there is no evidence of large-volume flanking lava flows to account for the large volume of magma once present in the magma chambers, the withdrawn magma may have intruded as multiple dykes into ridge-parallel faults. Ridge-parallel faults are visible on the seafloor as well as on the tops of some of the seamounts, indicating the seamounts likely formed within 30-40 km of the ridge axis where such faulting is still active (Clague *et al.*, 2000b). Magmas likely used these faults for

transport to and from the magma chambers, as the spacing is similar in scale to the spacing of the offset calderas (Clague *et al.*, 2000b).

Working with data from the Lamont NR seamount chain off the East Pacific Rise, Fornari *et al.* (1988b) argued that the primitive, unfractionated lavas of NRS could not support the presence of large crustal magma chambers. Previously published geochemical work on the Vance Seamounts is limited, but indicates that the lavas are relatively primitive (i.e. high MgO) (Smith *et al.*, 1994).

In light of the overwhelming structural evidence for crustal magma chambers under the Vance Seamounts, Clague *et al.* (2000b) proposed a solution to the apparent paradox: the lavas do reside in large, shallow crustal magma chambers, but only for relatively short periods of time. By passing quickly through a magma chamber, lavas do not have sufficient time to extensively cool and fractionate; this could be accomplished with high volumes of rapidly-moving magma traveling from source region to eruptive setting.

To explain the structural and limited geochemical data from the Vance Seamounts, Clague *et al.* (2000b) proposed episodic pulses of magmas, between which, any remaining magma either solidified or intruded into ridge-parallel fractures (triggering caldera collapse). Taking into account the size of the seamounts (15 to 67 km³), the size of the calderas (up to 3 km³), and the calculated interval of volcanic activity

(75-95 kyr), Clague *et al.* (2000b) estimated individual magma batches for the Vance, President Jackson, and Taney Seamounts to have volumes of 1-5 km³, and recurrence times of 1000 to 10,000 years.

3.5 Geochemistry

As mentioned previously, there are very few published (or even unpublished) data available for the Vance lavas. Reconnaissance-type dredge sampling was done by Smith *et al.* (1994), who focused more on the trace element geochemistry of lavas from the southern Juan de Fuca Ridge segments than from the seamount chain.

The few published analyses of major and trace elements indicate that the easternmost Vance seamounts (only Vance E and F were sampled) are constructed of relatively primitive lavas with a depleted NMORB signature (Smith *et al.*, 1994). Smith *et al.* (1994) determined that lavas from the neovolcanic zone of the Cleft segment of the southern JdF (adjacent to the Vance seamounts) were crystallized from relatively primitive, but not primary, depleted (N-type) melts. Published La/Sm_{cn} values for the Cleft segment are intermediate between those of the Vance and Cobb-Eickelberg Seamounts (Desonie and Duncan, 1990; Smith *et al.*, 1994). Smith *et al.* also proposed that scatter in the trace element data is likely a result of magma mixing generated from a mantle

with small-scale heterogeneities with both very depleted and more enriched signatures.

CHAPTER 4: VANCE 2006 RESEARCH CRUISE

4.1 Cruise Details

The author was a member of the scientific party aboard the Monterey Bay Aquarium Research Institute (MBARI)-led Vance 2006 Research Cruise. MBARI is a private, non-profit research center located in Moss Landing, California whose mission is to advance ocean science research.

The cruise departed from Moss Landing, California on July 24th and arrived in Newport, Oregon on August 6th. The cruise was led by Dr. David Clague, who also serves as the project leader of the submarine volcanism unit at MBARI. Much of the information in this chapter is summarized from the cruise logbook, available on the MBARI website: <http://www.mbari.org/expeditions/vance/>

4.1a The scientific party

The scientific party was comprised of 11 geologists, biologists, and students from MBARI, the host institution, and three invited universities. The MBARI team included Dr. David Clague (chief scientist), Jennifer Paduan, Joe Jones, and Gillian Clague (student). Professor Mike Perfit and Rachel Wendt (student) came from the University of Florida; Professor John Stix and Christoph Helo (student) came from McGill University; and Professor

Brian Cousens, Kristen Choquette (student), and the author came from Carleton University.

4.1b The plan

The original cruise plan consisted of three parts: (1) to collect sediment and video footage from the Northern Escanaba Trough (NESCA) along the Gorda Ridge; (2) to collect long vibracore sediment samples from the flanks of Axial Seamount on the Juan de Fuca Ridge; and (3) to collect rocks, sediments, and video footage of the Vance Seamount Chain west of the Juan de Fuca Ridge. This study includes only rock samples from the third location, the Vance Seamount Chain.

No samples were collected from NESCA, as poor weather conditions forced the cancellation of the dives at this site. *Tiburon* dives T1009 and T1010 were to Axial Seamount and are not included in the study. Glass sub-samples from the Vance rocks were split between the author for isotope analysis (at Carleton University) and Rachel Wendt for trace element analysis (at the University of Florida). Small chips of fresh glass from the same samples remained with MBARI and were later analyzed for major element contents at the USGS facility in Menlo Park, California by A. Davis of MBARI.

4.1c The equipment

Research was conducted aboard the R/V *Western Flyer*, a 117-ft small water-plane area twin hull (SWATH) vessel owned and operated by MBARI (Figure 5). The R/V *Western Flyer* is outfitted with wet and dry laboratories and also provides a stable platform for the operation of a tethered, remotely operated vehicle (ROV) to a depth of 4,000 meters. The ROV *Tiburon*, developed at MBARI, is equipped with forward-looking and downward-looking high-resolution video cameras, and a sophisticated manipulator arm with a vibration feature (Figure 6).

The ROV was operated from a control room on the *Western Flyer* equipped with high-definition screens, a video annotation and screen capture system, a computer with ArcView GIS software and live GPS data from the ROV, and an audio recording system for live scientific descriptions of the incoming video. All samples, images, and observations were located with respect to the EM300 bathymetric base map using the real-time ArcView-based navigation and GIS systems. Members of the scientific team rotated through the various operational stations.

Figure 5: R/V *Western Flyer* (photo courtesy MBARI)

Figure 6: ROV *Tiburon* (photo courtesy Brian Cousens)

4.2 Dive Summaries

Below are descriptions of individual dives by the ROV *Tiburon*. Dive transects were designed to study the morphology and history of each seamount. Bathymetric maps with 30 m resolution were used as base maps. Each dive represents a day of sea-time. Samples collected included rocks, sediments, and biota; only the rock samples are discussed here. The dive descriptions are based on dive log entries by David Clague, comments by other members of the scientific party, and the author's own observations. Complete dive logs are available at: <http://www.mbari.org/expeditions/vance/July24.htm>.

Caldera walls and fault scarps provided the scientific party with excellent access to information on the sequence of events and history of the seamounts. A large variety of lava types were observed and collected wherever possible. Massive lava flows were often difficult to sample, but video and screen captures were able to document thick, commonly columnar-jointed, sections. Manganese-oxide precipitate proved to be ubiquitous and thick, and the thick coating often obscured lava morphology and at times cemented outcrops together to the point that the manipulator arm could not break a sample free. One benefit to the thick Mn-oxide coating was that it held together the fractured volcanic glass rinds during sampling.

4.2a T1007 – Vance F

Tiburon dive T1007 was designed to study the Vance F seamount (Figure 7). The dive began on the large caldera floor truncating the southeast corner of the main volcanic edifice and proceeded to the northwest. The *Tiburon* climbed up and over the caldera wall, down the backside into the central caldera, across the caldera floor, and then finally up the central caldera wall to the flat-topped summit. The ROV landed on lava flows dusted with post-caldera sediments. The ridge separating the two calderas was composed of a talus-covered basal slope, interbedded massive and pillowed flows up the wall, and a relatively thin cap of fine-grained volcanoclastite. The central (older) caldera floor was covered in rippled pelagic sediments; some protruding post-caldera lava flows and hyaloclastites were also seen (Figure 8). The far northwest wall of the central caldera was similarly composed of interbedded massive and pillowed flows with a volcanoclastite cap (Figure 9).

Figure 7: Map of Vance F (T1007). Sample label categories: R = rock; PC/SB = sediment; A = biological. ROV dive transect marked by small dots. Location of samples used in this thesis marked by large star. Map created by Jennifer Paduan of MBARI. Base map (~30 meter resolution) produced by the MBARI mapping team (2001).

Figure 8: Hyaloclastite on Vance F caldera floor

Figure 9: Interbedded pillow and massive flows on Vance F caldera wall

4.2b T1008 – Vance A

Tiburon dive T1008 was designed to study the Vance A seamount (Figure 11). The dive began at the base of the circular seamount and proceeded up a steep slope to a nearly flat summit; no large caldera feature was observed. The outer slope was largely covered in talus and the summit consisted of small constructional volcanic features (Figure 10). Small ridge-parallel faults were seen on the summit, as well as a thin layer of volcanoclastite. Coarser gravel-sized lava fragments were included in the sediment. Manganese-oxide coating of these outcrops and samples was especially evident, making descriptions difficult.

Figure 10: Constructional pillow mound on Vance A shield

Figure 11: Map of Vance A (T1008). Sample label categories: R = rock; PC/SB = sediment; A = biological. ROV dive transect marked by small dots. Location of samples used in this thesis marked by large star. Map created by Jennifer Paduan of MBARI. Base map (~30 meter resolution) produced by the MBARI mapping team (2001).

4.2c T1011 – Vance E

Tiburon dive T1011 was designed to study the Vance E seamount, which is the southeast portion of a larger coalesced structure built by both Vance E and D (Figure 12). The dive began on the deep floor of the southeast caldera and proceeded northwest up three nested caldera walls toward the summit of Vance E. Pelagic sediments and post-caldera lavas were seen on the caldera floor (Figure 13). The first wall began with a large talus slope that then became a vertical section of interbedded massive and pillowed basalts. The top of the wall (or floor of the next caldera) was composed of a few meters of layered volcanoclastite buried by pelagic sediment (Figure 14). The next wall also consisted of interbedded lava flows with a volcanoclastite cap. The final traverse toward the oldest wall found older pillow lavas partially hidden by the volcanoclastite unit. The oldest caldera wall was an ambiguous mix of talus, lava flows and/or dykes capped by a thin layer of coarse-grained volcanoclastite.

Figure 12: Map of Vance E (T1011). Sample label categories: R = rock; PC/SB = sediment; A = biological. ROV dive transect marked by small dots. Location of samples used in this thesis marked by large star. Map created by Jennifer Paduan of MBARI. Base map (~30 meter resolution) produced by the MBARI mapping team (2001).

Figure 13: Rippled sediment on the Vance E caldera floor

Figure 14: Layered volcaniclastite on Vance E caldera rim

4.2d T1012 – Vance B

Tiburon dive T1012 was designed to study the Vance B field of volcanic cones, ridges and mounds (Figure 16). The dive began on a small cone in the northwest and proceeded SE over many features too small to be seen clearly identified on the existing bathymetric map. Though there is no single large seamount structure here, the total volume of lava exceeds that of neighbouring seamounts. Multiple steep-sided constructional volcanic mounds of pillow lavas and talus were seen throughout the dive (Figure 15), although no volcaniclastite was observed.

Figure 15: Extensive pillow formation at Vance B

Figure 16: Map of Vance B (T1012). Sample label categories: R = rock; PC/SB = sediment; A = biological. ROV dive transect marked by small dots. Location of samples used in this thesis marked by large star. Map created by Jennifer Paduan of MBARI. Base map (~30 meter resolution) produced by the MBARI mapping team (2001).

4.2e T1013 – Vance C

Tiburon dive T1013 was designed to study the Vance C seamount (Figure 17). The dive began near the base of the deep southeast caldera and proceeded northwest up the caldera wall and along its rim, across and up a less prominent caldera floor and wall, and finished by exploring the summit shield area. Rock types and morphology were often unclear due to a thick manganese-oxide coating on all outcrops. The first caldera wall consisted of a talus slope, massive flows, and pillowed flows near the top. Volcaniclastite appeared to coat both the lava flows and talus. Sheet flows and sediments were seen on the upper caldera floor (Figure 18), while the wall was again composed of talus and lava flows (Figure 19). The summit area consisted of a series of small constructional pillow ridges.

Figure 17: Map of Vance C (T1013). Sample label categories: R = rock; PC/SB = sediment; A = biological. ROV dive transect marked by small dots. Location of samples used in this thesis marked by large star. Map created by Jennifer Paduan of MBARI. Base map (~30 meter resolution) produced by the MBARI mapping team (2001).

Figure 18: Sedimented sheet flow on upper caldera floor of Vance C

Figure 19: Columnar joints in massive flow of Vance C upper caldera wall

4.2f T1014 – Vance G

Tiburon dive T1014 was designed to study the Vance G seamount (Figure 21). The dive began on a low ridge of young sheet flows and proceeded northwest across older terrain cut by multiple small and large normal faults. The older pillow lava and sheet flow outcrops were covered with volcanoclastite and pelagic sediments (Figure 20). The fault scarps revealed sections of interbedded pillow and sheet flows. Vance G is a small, broad shield without a large caldera; therefore, the volcanoclastite may have come from the collapse at the adjacent Vance F seamount.

Figure 20: Large pillows draped by hyaloclastite, Vance G

Figure 21: Map of Vance G (T1014). Sample label categories: R = rock; PC/SB = sediment; A = biological. ROV dive transect marked by small dots. Location of samples used in this thesis marked by large star. Map created by Jennifer Paduan of MBARI. Base map (~30 meter resolution) produced by the MBARI mapping team (2001).

4.3 Field Findings

In general, flat-lying volcanoclastite with variable amounts of overlying pelagic sediment covered each caldera floor. The caldera walls began with a talus slope that broke into a vertical wall of truncated lava flows. The caldera rims were blanketed by layered volcanoclastite. These observations support the idea that the caldera floors collapsed in piston-cylinder like events (D. Clague, personal communication).

Based on their morphologic analysis of the Vance Seamounts, Clague *et al.* (2000b) proposed that many of the caldera collapse structures had been filled or partially filled by post-caldera lava ponds. This idea was confirmed by the ROV dives, as video footage clearly showed truncated thick lava flows in the caldera wall sequences where one caldera cut another. Some of the lava flows even displayed columnar jointing and diabasic textures.

Volcaniclastic sandstones and mudstones, produced from the caldera collapse events, were found on caldera rims and caldera floors, and none were seen within the caldera wall sequences. Small mounds of pillow lavas were occasionally seen poking through the caldera floor hyaloclastite deposits, evidence of post-caldera volcanism. In addition to angular glass fragments, the volcanoclastite samples commonly contained

limo o Pele, or bubble wall fragments, indicating a submarine pyroclastic eruption during the caldera collapse.

The matrix for many of the volcanoclastite samples is a green to tan hydrothermal clay, while the cement is often a hydrothermal Mn-oxide. Hydrothermal Mn-oxide also universally coats the lava outcrops and talus piles. The clays and Mn-oxide likely precipitated from warm hydrothermal fluids that were discharged during caldera collapse and pyroclastic explosions.

4.4 Rock Samples

4.4a Rock sampling methods

Multiple grab samples were collected during each ROV dive. Samples were chosen based on changes in morphology and/or location within each volcanic structure. Sample size was limited to what the ROV manipulator arm could grab and remove from an outcrop. Samples were photographed before placing them in a compartmentalized drawer on the ROV.

Once on board the ship, each sample was carefully rinsed and cleaned of any organic matter before being photographed and described. When dry, volcanic glass was sub-sampled from each rock (where possible). A few small glass chips were collected for grain mounts and electron microprobe analysis; all remaining glass was collected and

stored in whirl-pak™ bags. It is this glass pick that was used for isotopic and trace element analysis.

4.4b Sample summary

Rocks recovered with the ROV *Tiburon* manipulator arm included 101 lava samples, 37 volcanoclastite samples, and 9 samples that turned out to be either erratics or pieces composed entirely of Mn-oxide crust. Many of the lava samples were parts of pillows, but a large number of massive flow and glassy sheet flow pieces were also collected. A nicely preserved glassy rind was often found on the pillow bud and lip pieces beneath the outer coating of Mn-oxide. Massive samples were often holocrystalline and rarely contained glass; where they did, it was typically a very thin layer on one surface only. Sheet flow samples often contained a significant portion of glass. Volcanoclastite samples ranged from volcanic mudstones to sandstones, typically exhibit bedding, and contain variable amounts of volcanic glass particles.

Photographs of representative rock samples are included from Figure 22 to Figure 25. Table 2 summarizes basic geological information for the 24 samples used in this study.

Figure 22: Representative pillow bud sample with glassy rind beneath the Mn-oxide coating (T1007-R2). (photo courtesy MBARI)

Figure 23: Representative slab from a sheet flow, variable amount of glass beneath the Mn-oxide coating (T1014-R13). (photo courtesy MBARI)

Figure 24: Representative block of massive lava, minimal glass beneath the Mn-oxide coating (T1011-R12). (photo courtesy MBARI)

Figure 25: Representative cross-section of a bedded volcanoclastite sample (T1011-R8). (photo courtesy MBARI)

Table 2: Rock Sample Descriptions

Sample Number	Sample Type	General Location	Sampling Notes	Latitude (°N)	Longitude (°W)
Vance A T1008-R05a	lava-talus-pillow	outer seamount wall	From pillow lava in area that looked to be hyaloclastite. Recovered several pieces that may in fact be different rocks. Sufficient glass collected from the glassy rind on the largest piece (5a). Aphyric, non-vesicular core with radial fractures.	45.66	130.84
Vance A T1008-R20	lava-lobate flow	near summit	Crust of a lobate flow on top of a pillow ridge. Minor fine vesicles. Sufficient glassy collected from 5-mm thick glassy rim.	45.67	130.83
Vance A T1008-R23	lava-sheet flow	near summit	From area of truncated, stacked sheet flows. Very glassy, rare vesicle. Ample glass collected.	45.68	130.84
Vance B T1012-R01	lava-pillow	pillow mound	Piece of pillow from a mound that appears to head into a crater. Small, holocrystalline sample; very small amount of waxy glass collected.	45.64	130.69
Vance B T1012-R08	lava-pillow	pillow mound	Large pillow sample from area with many pillow tubes heading down a slope into a small sediment covered valley. Ample glass was collected from glassy bud on tube.	45.64	130.68
Vance B T1012-R14a	lava-pillow	pillow mound	Two samples (a and b), both from a hollowed out pillow near the peak of a constructional pillow mound. Holohyaline, minor small vesicles. Ample, very fresh glass.	45.64	130.67
Vance B T1012-R21	lava-pillow	pillow ridge	Piece of pillow tube from an elongate, but near-vertical, pillow ridge. Ample glass collected from thick (1 cm) glassy rind.	45.63	130.66
Vance C T1013-R02	lava-talus	talus pile at youngest caldera wall	Piece taken from the top of the talus pile at base of caldera wall. Trace amount of glass collected, difficult to separate thin glassy layer from more massive sample.	45.45	130.51
Vance C T1013-R17	lava-pillow	broad middle caldera floor	Broken slab from the lip of a pillow on flat caldera plateau. Holohyaline, rare vesicle. Sub-sampled entire piece except Mn crust.	45.45	130.52
Vance C T1013-R18	volcaniclastite	broad middle caldera floor	Layered volcanic sandstone (glassy fragment rich) slab poking through sedimented plateau. Glass pick is a collection of glassy particles separated from the sample.	45.45	130.52

Vance C T1013-R21	lava-sheet flow	broad middle caldera floor	From a folded sheet flow on a sediment covered linear feature in the caldera floor (possible fault). Abundant glass collected from the 5 mm glassy rind.	45.45	130.52
Vance C T1013-R30	lava-pillow	pillow mound above upper wall	Piece of pillow from a large pillow mound near the summit (above the older caldera wall). Abundant glass collected from the thick 7-mm glassy rind. Aphyric, tiny vesicles.	45.46	130.53
Vance E T1011-R01	lava-pillow	youngest caldera floor	Piece of pillow tube from a lightly sedimented pillow mound in the caldera floor. Sufficient fresh glass sample from ball-like end of the large sample.	45.39	130.44
Vance E T1011-R07	lava-sheet flow	youngest caldera wall	Folded glassy sheet atop massive flow. Sufficient glass, mostly waxy, collected from the upper surface.	45.40	130.44
Vance E T1011-R12	lava-pillow	middle caldera wall	Massive flow fragment with thin sliver of glass on one side. Very limited amount of glass collected. From caldera wall of interbedded sequence of pillow and massive flows.	45.40	130.44
Vance E T1011-R20	lava-sheet flow	oldest caldera floor	From a scrambled sheet flow on the upper/older caldera floor. Vapor pockets on bottom surface. Very little fresh glass available for sub-sampling.	45.41	130.45
Vance E T1011-R27	lava-sheet flow	oldest caldera wall	Glassy, aphyric piece of small sheet flow at top of the upper most caldera wall. Ample glass for analysis collected.	45.41	130.45
Vance F T1007-R02	lava-pillow	oldest caldera floor	From pillow 'tube' in area of more fluid-looking pillow flows at the top of a lava shield. Glassy exterior rind and finely holocrystalline core. Ample glass was collected from the 1-cm thick glassy rind.	45.32	130.38
Vance F T1007-R16	lava-pillow	youngest caldera floor	Elongate pillow bud/log on sediment covered caldera floor. Glassy rind (0.5 cm) and finely crystalline core. Sufficient glass taken from smaller fragment in order to preserve the larger specimen.	45.34	130.39
Vance F T1007-R17	lava-pillow	youngest caldera floor	Pillow bud from small ridge of pillow lava on caldera floor. Waxy, aphyric texture. Ample glass for analysis was collected from thick glassy rind.	45.34	130.40
Vance G T1014-R04	lava-sheet flow	sedimented flat below talus slope	From folded sheet flow poking through sediment. Abundant volcanic glass, rare vesicles.	45.29	130.33

Vance G T1014-R13	lava-sheet flow	fault scarp	From fault scarp with thin slabby flows. Bottom of sample is vesicular with cusped/droopy features. Abundant glass collected from thin glassy selvage.	45.29	130.34
Vance G T1014-R18	lava-pillow	pillow mound	Piece of lip from a drained pillow. Low, sedimented pillow mound en route to fault scarp. Holohyaline. Abundant glass collected for analysis.	45.29	130.35
Vance G T1014-R22	lava-talus- pillow	fault scarp	One of the seven samples taken in the last few minutes of the dive. From fault scarp. Nearly <i>in situ</i> piece of holocrystalline, radially jointed pillow. Small amount of glass for analysis collected from top edge.	45.29	130.35

CHAPTER 5: MAJOR ELEMENT AND MINERAL CHEMISTRY DATA FOR THE VANCE SEAMOUNT LAVAS

5.1 Major Element Geochemistry

5.1a Data sources

Major element data for the Vance seamount lavas come from three sources. The primary data set (Vance GLS in Figure 26 and Figure 27) includes electron microprobe analyses of the 71 volcanic glass picks (hand-picked at sea by B. Cousens, the author, and R. Wendt) from the glass-bearing lava samples collected on the Vance 2006 Research Cruise. Alicé Davis of MBARI performed the electron microprobe analysis of the glass chips at the USGS, Menlo Park. Each value is an average of multiple glass chips from the same glass fraction used for trace element analysis by R. Wendt and isotope analysis by the author. Values for the 24 samples chosen for this thesis are marked individually (Thesis Samples in Figure 26) within the comprehensive Vance GLS data field, and are also used for the variation diagrams of Figure 28. Whole-rock (WR) major element data were also provided by MBARI and have been included in Figure 26 (Vance WR). The Vance WR data set includes Vance lava samples that did not have a glassy rind and are presented as a reference field with the purpose of showing the full variety of Vance lava compositions collected. The two data sets include a large amount of overlap; however, the

petrologic discussion will focus solely on the glass data because they better reflect magmatic liquid compositions upon eruption (Melson *et al.*, 1976). The third data set (Appendix III) is from the author's own electron microprobe work on glass chips from the 24 samples chosen for the thesis. While the glass chips are not the identical ones used by A. Davis for the Vance GLS data set, they are from the same glass fraction. The analyses were performed in order to provide a link between the MBARI data set and the author's mineral chemistry work on the microphenocrysts found in the volcanic glass chips (discussed in Section 5.2).

5.1b General data observations

Major element data for the lavas show the Vance Seamounts were built by subalkaline MOR-basalt (Figure 26). Mg-numbers ($\text{Mg \#} = \text{Mg}/(\text{Mg} + \text{Fe}^{2+}) * 100$ where $\text{Fe}^{2+} = 0.9 \text{ Fe total}$) range from 56 to 70, with an average of 62.5 (N=71). The glass compositions are relatively primitive for typical MORB with MgO contents averaging 8.2 wt. %, but ranging from 6.9 to 9.5 wt. %. Vance G is the only seamount without at least some primitive (i.e. MgO > 8 wt. %) lavas. The most primitive samples (MgO > 9 wt. %) were recovered from Vance B, C, and F where compositions (Mg# to 70, Cr to 510 ppm, Ni to 314 ppm) could approximate primary mantle melts in equilibrium with mantle peridotite (e.g. Green, 1971; Sato, 1977; Cr and Ni data provided by R. Wendt, personal communication). All of the

samples recovered are NMORB (except four EMORB samples from Vance A) with major element variations that reflect a typical tholeiitic differentiation trend (Figure 27).

Samples from the Vance GLS data set (Figure 26) have been grouped by seamount and are presented again in Figure 28 in a series of plots showing the variation in oxide weight percent (wt. %) versus MgO wt.%. It is evident from these plots that the Vance seamount lavas have small compositional variations both between seamounts as well as within individual seamounts. Major element data from the Vance seamount lavas follow the typical correlation trends of NMORB, but there is a fairly large amount of scatter and also large variation in oxide contents at a given MgO content. While some of the data for individual seamounts have fairly strong linear correlations, many do not. The variety of lava compositions seen from some of the seamounts cannot be accounted for by simple fractionation of a single magma composition.

Figure 26: Alkali-silica plot (modified after Le Bas et al., 1986) for Vance NRS lava samples collected on the Vance 2006 Research Cruise. GLS = glass; WR = whole rock. Data provided by MBARI (Dave Clague, personal communication), as discussed in Section 5.1a. The southern Juan de Fuca field represents data from Smith et al. (1994) and Stakes et al. (2006), discussed in Section 5.1e.

Figure 27: Ternary AFM diagram (after Irvine and Baragar, 1971) showing Vance seamount glasses (Vance GLS) all plot within the tholeiitic field. Seamount data provided by MBARI (Dave Clague, personal communication), as discussed in Section 5.1a. The southern Juan de Fuca field represents data from Smith *et al.* (1994) and Stakes *et al.* (2006), discussed in Section 5.1e.

Figure 28: Variation in major element oxides (wt. %) with MgO for the Vance seamount glasses. Data provided by MBARI (Dave Clague, personal communication), as discussed in Section 5.1a. Arrows indicate fractionation trends of olivine (Ol), plagioclase (Pl), and clinopyroxene (Cpx).

Figure 28 (cont.)

In general, the incompatible element concentrations of TiO_2 , FeO^t (total iron), Na_2O , and K_2O tend to correlate negatively with the MgO content, while the compatible element Al_2O_3 shows a positive correlation with MgO content, indicating at least a small amount of fractionation has occurred in many of the seamount lavas. CaO shows a great deal more scatter than do the other major elements, but does tend to correlate positively with MgO content, at least within some lavas from an individual seamount suite. The data also show evidence for both very depleted and slightly enriched sources (0.02-0.31 wt. % K_2O , at $\text{MgO} > 7$ wt. %), with only Vance A reaching K_2O values typical of EMORB. The K_2O content of four of the Vance A lavas is anomalously high for lavas recovered from the Vance Seamounts and other seamounts adjacent to the southern Juan de Fuca Ridge.

5.1c Data observations for individual seamounts

Lava samples from Vance A, as mentioned previously, are distinct from the other seamount lavas in that they have significantly higher K_2O values, reaching the lower levels of EMORB composition (very unusual for NRS and southern Juan de Fuca lavas). They also show the highest TiO_2 values at a given MgO content. Other oxide concentrations are relatively moderate, and the Vance A lavas represent a relatively large range of $\text{Mg\#s}$ (56 to 65).

Vance B lavas typically plot as a distinct group from the rest of the Vance lavas on all the variation diagrams in Figure 28. Concentrations of SiO_2 and CaO are relatively low, and concentrations of Al_2O_3 , Na_2O , and FeO^t are relatively high. The Vance B data plot very low in the diagram of $\text{CaO}/\text{Al}_2\text{O}_3$ versus MgO . Like many of the seamount suites, the Vance B lavas also span a relatively large range of Mg#s (57 to 64).

Vance C lavas often plot within the general trends shown in Figure 3, and show one of the largest ranges of Mg#s (58 to 68). As a group, the Vance C lavas are characterized by very high CaO , MgO , and low TiO_2 contents. Two of the most primitive of all the Vance seamount lavas were recovered from Vance C (MgO wt. % of 9.45 and 9.38).

Samples from Vance E are distinct only in the fact that they tend to show the least amount of scatter about a trend line on the variation diagrams in Figure 3 and tend to follow a more consistent fractionation trend over the entire range of compositions. The Mg#s range from 56 to 64, and including some of the most evolved lavas recovered from the Vance Seamounts.

Vance F lavas are similar to those of Vance E in that they also span a wide range of compositions (Mg# 60 to 70) and tend to fall within the general trends of all the Vance data.

Lavas from Vance G are distinct in that they are the only ones to cluster in a tight group on the diagrams of Figure 28, as Mg#s

range only from 59 to 62. Beyond that observation, the Vance G lavas also fall within the general range and trends of the other Vance lavas.

5.1d Data correlation with sample location

Given the relatively high density of sampling and the strong control on sample location within the seamount edifice, an attempt was made at finding a correlation between the oxide data and the relative location of the sample in the volcanic stratigraphy of a given seamount. However, no simple or systematic relationship was evident in the data.

A similar attempt was made with data for the Lamont Seamounts (Allan *et al.*, 1989), where use of the ALVIN submersible allowed for good control of the sample location. That attempt was also unsuccessful. A more comprehensive analysis of the geochemical data and sample location information may reveal some subtle correlations.

5.1e Comparison with southern Juan de Fuca Ridge lavas

Many lava samples have been recovered from the Vance, Northern Cleft, and Southern Cleft segments of the southern Juan de Fuca Ridge. Analyses of glass from these samples, from Smith *et al.* (1994), and Stakes *et al.* (2006), have been compiled to show the range of lava compositions found at the ridge segments adjacent to the Vance Seamounts.

As a general statement, the Vance seamount lavas are more primitive and more diverse at given MgO values than on-axis lava samples from the adjacent Vance, Northern Cleft, and Southern Cleft segments of the southern Juan de Fuca Ridge (SJdF) (Smith *et al.*, 1994; Stakes *et al.*, 2006). The TAS and AFM diagrams in Figure 26 and Figure 27, respectively, indicate that lavas from the adjacent ridge segments reach much more evolved compositions (i.e. basaltic andesite) than anything recovered from the seamounts.

While many of the seamount samples have major element concentrations that overlap with those of the ridge lavas (or follow the same trend line in variation plots), some of the seamount compositions are distinct from the general trends of the ridge lava compositions. This occurs for many of the Vance B samples, but also for some Vance A, C, E, and F (all but Vance G) samples.

The variable major element concentrations at a given MgO content is an indication of different geologic processes operating at the seamounts than at the ridge (e.g. different depths or degrees of melting, magma transport and storage, and possibly even different source compositions). This concept will be further developed after the presentation of isotopic and trace element data in Chapter 6.

5.2 Mineral Chemistry

5.2a Introduction

The author did not perform a complete or extensive investigation into the mineral chemistry of the Vance seamount lavas. This is in part due to the original focus of the thesis (isotope geochemistry), and also to the scientific collaboration with the Monterey Bay Aquarium Research Institute (MBARI), who is the principle investigator of the general petrology/petrography and physical volcanology of the Vance Seamount Chain. That being said, the author described and analyzed 23 glass chips from the seamount lavas in order to confirm certain assumptions of their petrography and mineral chemistry.

5.2b Sample preparation

Polished sections were produced from small (av. 3 mm²) chips of fresh glass for 23 of the 24 samples comprising the thesis suite. Sample T1011-R20 did not contain enough glassy material for both petrography and geochemical analysis, and was therefore not analyzed. The glass chips were hand-picked under a binocular microscope, mounted on a thin section slide and ground to ~ 30 µm thickness. Analytical methods for the electron microprobe analyses are described in Appendix II.

5.2c Petrography

The glass chips show very little variation in texture and commonly contain a small percentage of olivine and plagioclase microphenocrysts. These crystals appear to be in chemical equilibrium with their hosts (e.g. no strong reaction rims or corroded margins), but show some disequilibrium textures likely due to the quenching process. Photos of three representative glass chips (under plane-polarized light and low magnification) are shown in Figure 29. The volcanic glass appears brown and typically very clean (i.e. free of microlites, microphenocrysts, etc.). A common, but highly variable (0-25%) component appears as opaque 'blobs' that were later determined to have the same composition as the host glass and may represent very fine crystallization. Small microphenocrysts (av. 1%) of both olivine and plagioclase were observed in many, but not all, of the glass chips and are described in more detail below. Tiny microvesicles were a very minor component in some of the samples.

Figure 29: Typical Glass Chips from the Vance seamount lava samples. Glass chips photographed under low magnification and plane polarized light with a field of view (FOV) of 5 mm. (a) T1007-R16 (Vance F); (b) T1008-R5a (Vance A); (c) T1013-R30 (Vance C).

Figure 30: Back-scatter electron images of typical olivine and plagioclase crystals, hosted by volcanic glass. (a) T1007-R16 (Vance F); (b) T1008-R05a (Vance A); (c) T1012-R02 (Vance B); (d) T1013-R30 (Vance C).

5.2d Plagioclase

Nine plagioclase microphenocrysts and microlites from eight different samples were analyzed. Small microlites (100-300 μm long) were common and often surrounded by a 'halo' of finely crystalline material (Figure 30b). Some blockier subhedral microphenocryst rhombs were also seen (Figure 30d), and were typically <100 μm with some reaching 200 μm . Some larger plagioclase phenocrysts and/or glomerocrysts were observed in the original glass separate picked from the lava samples, but none of these samples were observed in thin section. Plagioclase compositions were calculated from the microprobe data, where $An = [Ca/(Ca+Na+K)]$. An contents from the analyzed plagioclase crystals vary from 70.44 to 83.98, with the two most calcic samples coming from Vance C (Table 3). All analyses fall within the very calcic Bytownite (An_{70-90}) variety of plagioclase feldspar (Figure 31). No compositional zoning was observed.

5.2e Olivine

Twelve olivine microphenocrysts from nine different samples were analyzed. The crystals varied in size between small ~100 μm subhedral, blocky microphenocrysts (Figure 30c) and larger 500-800 μm euhedral (but often skeletal) microphenocrysts (Figure 30a). Olivine compositions were calculated from the microprobe data, where $Fo = [Mg/(Mg+Fe^{2+}) \cdot 100]$.

Overall, compositions are very Mg-rich and similar to one another. One of the larger microphenocrysts showed weak normal zonation (T1011-R01), while all other analyzed olivines showed no obvious signs of compositional zoning or chemical disequilibrium. Fo contents from the analyzed olivine crystals range from 83.90 to 88.99, with the vast majority of samples having compositions between 87.24 and 88.99 (Table 4).

Only two samples have Fo < 85, one from Vance A (T1008-R20) and one from Vance B (T1012-R01). Figure 32 shows the strong correlation between the Mg# of the host glass with the Fo content of the olivine microphenocrysts. The weakly zoned olivine from Vance E (T1011-R01) has a Fo_{87.41} core and a Fo_{86.16} rim (i.e. normal compositional zoning), consistent with magma fractionation during crystal growth. The most primitive olivines (Fo > 88.0) all come from Vance F. No olivine was found in the four glass chips from Vance G.

Figure 31: Stacked feldspar composition ternary plots for the plagioclase microphenocryst data listed in Appendix III.

Table 3: Summary of Plagioclase Composition

Seamount	Sample	An content
Vance A	T1008-R05a	73.20
Vance A	T1008-R05a	74.12
Vance A	T1008-R20	72.43
Vance B	T1012-R01	76.02
Vance C	T1013-R02	83.98
Vance C	T1013-R18	81.65
Vance C	T1013-R21	73.96
Vance E	T1011-R12	70.44
Vance G	T1014-R18	70.75

*data and calculations shown in Appendix III

Figure 32: Olivine composition versus Mg# of host glass. Data and calculations shown in Appendix III

Table 4: Summary of Olivine Composition

Seamount	Sample	Fo content
Vance A	T1008-R20	83.90
Vance B	T1012-R01	84.53
Vance B	T1012-R08	87.61
Vance B	T1012-R21	87.37
Vance C	T1013-R21	87.24
Vance E	T1011-R01	87.41 (core)
Vance E	T1011-R01	86.16 (rim)
Vance F	T1007-R02	88.99
Vance F	T1007-R16	88.02
Vance F	T1007-R16	88.21
Vance F	T1007-R17	88.60
Vance F	T1007-R17	88.49

*data and calculations shown in Appendix III

5.3 Comments on Major Element and Mineral Chemistry Data

Fractional crystallization likely occurred in the Vance seamount lavas, as indicated by Mg#s as low as 56. This is also consistent with the physical evidence for crustal magma chambers (i.e. the caldera structures). However, most of the seamount lavas are very primitive, which supports the Clague *et al.* (2000b) proposal that many NRS magmas do not reside, cool, or fractionate in magma chambers for extended periods of time. The lack of reverse zoning patterns in the observed olivine and plagioclase microphenocrysts also supports the Clague *et al.* (2000b) proposal that the NRS magmas do not mix with successive batches of magma.

The trends seen in $\text{CaO}/\text{Al}_2\text{O}_3$ versus MgO (Figure 28) indicate the dominance of olivine and plagioclase + olivine fractionation over fractionation of clinopyroxene. This is consistent with the observation of only plagioclase and olivine microphenocrysts in the mounted glass chips from the glassy rinds of the Vance lava samples.

The pattern in the Vance B samples is consistent with olivine fractionation at higher MgO values and the addition of plagioclase fractionation at lower (more evolved) MgO values. However, the relatively low $\text{CaO}/\text{Al}_2\text{O}_3$ ratio of all the Vance B samples (due to the combined effect of low CaO and high Al_2O_3 values relative to the other Vance seamount lavas) may be an indication of clinopyroxene or

amphibole in the lava source (Allan *et al.*, 1993; Allan *et al.*, 1994; Cousens, 1996a). Clinopyroxene fraction may have occurred at depth, however the high Mg#s of the lavas do not support this idea.

The question of whether the geochemical differences in the Vance seamount lavas reflect different geologic processes (i.e. depth and degree of melting, magma storage and transport) or compositional heterogeneity of the mantle source will be further investigated with the addition of trace element and isotope data in the following chapters. These data provide the best indication of magma source characteristics.

CHAPTER 6 ISOTOPE GEOCHEMISTRY RESULTS

6.1 Introductory Notes

Volcanic glass was recovered from 71 of the samples collected on the Vance 2006 Research Cruise (Chapter 4). All samples were analyzed first for major element geochemistry (Chapter 5), but not all were chosen for subsequent isotopic (and trace element) analysis. This is in part due to the lengthy and resource intensive nature of a single isotope analysis (relative to a microprobe analysis), but also in consideration of what constitutes a representative sample set for a seamount or a chain of seamounts.

Previous isotopic studies of NRS lavas were typically based on data from a single sample or dredge haul, with little to no spatial or temporal resolution, for each seamount of a chain. This allowed for characterization of the chain as a whole, but not of the evolution of each seamount in the chain. Variation in isotopic ratios had been observed in neighbouring NRS chains (e.g. the President Jackson Seamounts), but it was unknown if the observed variations also existed within an individual seamount.

To investigate this possibility, three to five samples were selected from each of the six seamounts in the study. The samples were chosen based on (1) the availability of a glass sample large enough for analysis of

major and trace elements as well as isotopic ratios (a total of at least a few grams of crushed rock powder was needed), (2) the major element composition (representative and extreme values were targeted), and (3) the relative location within the volcanic edifice (maximum sample spacing and outcrop variety was attempted).

Selected samples were then crushed, acid washed, and dissolved in preparation for ion-exchange column chromatography. Lead, Sr, and Nd were isolated and their isotopic ratios later analyzed on a ThermoFinnigan Triton TI thermal ionization mass spectrometer at the Isotope Geochemistry and Geochronology Center at Carleton University, Ottawa, Canada. Details of the analytical method can be found in Appendix II. Reference information on radiogenic isotope systems and mantle components can be found in Appendix I.

6.2 Results

6.2a Summary of entire data set

New Pb, Sr, and Nd isotope data for the 24 analyzed seamount glass samples are presented in Table 5 and plotted in Figure 33 to Figure 36. The ranges in $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ are 0.702473 to 0.702755* and 0.513048 to 0.513182, respectively. The Pb isotope ratios show relatively larger variations: $^{206}\text{Pb}/^{204}\text{Pb}$ from 18.12 to 18.82, $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.46 to 15.58, and $^{208}\text{Pb}/^{204}\text{Pb}$ from 37.48 to 38.56. The observed ranges are well outside of analytical error.

* Glass samples were acid washed prior to dissolution in order to remove seawater Sr contamination. Modern seawater has an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70918, much higher than the average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for mid-ocean ridge basalts. A minor amount of residual seawater Sr in the sample can lead to elevated Sr ratios, essentially 'pulling' data points to artificially high values and affecting correlations with other isotopic ratios. As seen in the $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ plot (Figure 33), the seamount data, despite acid washing, still show some amount of seawater contamination. Most values plot within a realistic range, but a few samples (those greater than 0.7028) have been excluded from the data plots and interpretations. More work must be done in order to fully understand the extent of seawater contamination still present in the samples, as well as how to best eliminate (through modified acid washing techniques) or correct for (through further data analysis) seawater contamination in NRS glass samples. For this study, the data analysis and interpretations are focused on Nd and Pb isotope ratio data, which are unaffected by seawater contamination. Sr isotope ratio data are used, but with caution.

Table 3: Isotopic compositions of the Vance seamount lavas

Seamount Sample	$^{87}\text{Sr}/^{86}\text{Sr}^1$	2σ	$^{143}\text{Nd}/^{144}\text{Nd}$	2σ	$^{208}\text{Pb}/^{204}\text{Pb}$	2σ	$^{207}\text{Pb}/^{204}\text{Pb}$	2σ	$^{206}\text{Pb}/^{204}\text{Pb}$	2σ
Vance A T1008-R05a	0.702617	0.000006	0.513111	0.000012	37.920	0.005	15.492	0.002	18.499	0.002
Vance A T1008-R20	0.702759	0.000011	0.513107	0.000008	38.106	0.007	15.543	0.002	18.562	0.002
Vance A T1008-R23	0.702755	0.000012	0.513132	0.000009	38.214	0.005	15.538	0.002	18.580	0.003
Vance B T1012-R01	0.702667	0.000011	0.513082	0.000007	38.557	0.002	15.576	0.001	18.816	0.001
Vance B T1012-R08	0.702574	0.000009	0.513048	0.000009	38.077	0.006	15.511	0.002	18.699	0.002
Vance B T1012-R14a	0.702600	0.000012	-	-	38.138	0.009	15.527	0.003	18.631	0.003
Vance B T1012-R21	0.702629	0.000013	0.513065	0.000012	38.119	0.008	15.540	0.003	18.636	0.003
Vance C T1013-R02	0.702612	0.000008	0.513156	0.000011	37.157 ²	0.007	15.409 ²	0.003	17.728 ²	0.003
Vance C T1013-R17	0.702577	0.000009	0.513156	0.000007	37.877	0.009	15.491	0.004	18.389	0.005
Vance C T1013-R18 ³	0.702791	0.000008	0.513142	0.000011	37.894	0.009	15.500	0.003	18.451	0.002
Vance C T1013-R21	0.703117 ¹	0.000008	0.513146	0.000013	38.129	0.015	15.536	0.005	18.531	0.006
Vance C T1013-R30	0.704789 ¹	0.000009	0.513139	0.000007	37.904	0.016	15.482	0.006	18.471	0.007
Vance E T1011-R01	0.702612	0.000012	0.513156	0.000010	38.044	0.011	15.510	0.004	18.507	0.004
Vance E T1011-R07	0.702552	0.000011	0.513149	0.000010	37.850	0.010	15.498	0.004	18.409	0.005
Vance E T1011-R12	0.702584	0.000011	0.513150	0.000007	37.803	0.003	15.489	0.001	18.395	0.001
Vance E T1011-R20	0.702572	0.000012	0.513147	0.000015	-	-	-	-	-	-
Vance E T1011-R27	0.702670	0.000010	0.513157	0.000007	37.823	0.011	15.496	0.004	18.373	0.004
Vance F T1007-R02	0.702520	0.000010	0.513182	0.000012	37.479	0.010	15.456	0.003	18.119	0.004
Vance F T1007-R16	0.702473	0.000010	0.513167	0.000009	37.734	0.010	15.482	0.004	18.311	0.004
Vance F T1007-R17	0.702485	0.000010	0.513174	0.000009	37.744	0.015	15.485	0.005	18.314	0.006
Vance G T1014-R04	0.702573	0.000010	0.513146	0.000009	37.788	0.009	15.490	0.003	18.341	0.003
Vance G T1014-R13	0.703153 ¹	0.000009	0.513134	0.000013	37.844	0.008	15.500	0.002	18.365	0.002
Vance G T1014-R18	0.702594	0.000009	0.513144	0.000013	37.827	0.018	15.491	0.005	18.387	0.005
Vance G T1014-R22	0.702682	0.000012	0.513145	0.000007	37.695	0.008	15.460	0.003	18.325	0.003

Notes for Table 5:

¹ Samples with $^{87}\text{Sr}/^{86}\text{Sr}$ values > 0.7028 have likely been contaminated by seawater strontium; these data have been excluded from plots and interpretations.

² These anomalously low Pb isotopic values indicate that sample T1013-R02 has been contaminated by metallic material during sample processing; these data have been excluded from plots and interpretations.

³ Sample T1013-R18 is a hyaloclastite, not a lava sample, and may not be representative of lava compositions; these data have been excluded from plots and interpretations.

Those values in bold font are included in data plots and interpretations; those values not in bold font have been excluded (see above notes). See Appendix II for details on analytical methods, standards, and fractionation corrections.

Figure 33: $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ for lavas from the Vance Seamounts. The southern Juan de Fuca (SJdF) reference field (solid grey) is based on data from this study and M.R. Perfit (personal communication); Hegner and Tatsumoto, 1987; Ito *et al.*, 1987; Eaby *et al.*, 1984; and White *et al.*, 1987. See Section 6.2a for a note on possible contamination by seawater Sr in the data.

Figure 34: $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for the Vance seamount lavas. The southern Juan de Fuca (SJDf) reference field (solid grey) is based on data from this study and M.R. Perfit (personal communication); Hegner and Tatsumoto, 1987; Ito *et al.*, 1987; Eaby *et al.*, 1984; and White *et al.*, 1987.

Figure 35: $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for the Vance seamount lavas. The southern Juan de Fuca (SJdF) reference field (solid grey) is based on data from this study and M.R. Perfit (personal communication); Hegner and Tatsumoto, 1987; Ito *et al.*, 1987; Eaby *et al.*, 1984; and White *et al.*, 1987.

Figure 36: $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for the Vance seamount lavas. The southern Juan de Fuca (SJdF) reference field (solid grey) is based on data from this study and M.R. Perfit (personal communication); Hegner and Tatsumoto, 1987; Ito *et al.*, 1987; Eaby *et al.*, 1984; and White *et al.*, 1987.

6.2b Summary of data for individual seamounts

Vance A

Three samples from Vance A were analyzed. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the three samples ranges from 0.702617 to 0.702759, with two of the samples (T1008-R20 and R23) falling within error of each other and have more radiogenic values than T1008-R05a. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratio for the three samples ranges from 0.513107 to 0.513132, with very little statistical difference among the three. The Pb ratios for the three samples show variations generally just outside of error, but show a general trend of increasing radiogenic character from T1008-R05a to R20 to R23, with T1008-R05a being the least radiogenic of the three.

Vance B

Four samples from Vance B were analyzed. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the four samples ranges from 0.702574 to 0.702667, with all values falling just outside of error of one another. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratio for three of the samples ranges from 0.513048 to 0.513082; no successful analysis was completed for sample T1012-R14a. The two extreme Nd ratios both fall within error of the middle value. The Pb ratios for these four samples show variations just outside of error, with values for

sample T1012-R01 consistently and significantly higher than the values from the other Vance B samples.

Vance C

Five samples from Vance C were analyzed. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the five samples ranges from 0.702577 to 0.704789. Samples T1013-R21 and R30 both have Sr ratios >0.7028 and likely contain some residual seawater Sr contamination. These two analyses have been included in Table 5, but will be disregarded in further discussion of the Vance C results. Of the remaining three $^{87}\text{Sr}/^{86}\text{Sr}$ results, T1013-R18 has a value significantly higher than the other two, which are more similar, but just outside of error, from one another. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratio for the five samples ranges from 0.513139 to 0.513156, all falling within error of each other, showing no statistical difference in the $^{143}\text{Nd}/^{144}\text{Nd}$ character of each lava. The Pb ratios for the Vance C samples show a range much larger than any of the other seamounts. Sample T1013-R02 shows the least radiogenic values, while R21 shows the most radiogenic values. The other three samples tend to cluster within an intermediate range, usually just outside of error from one another. Further analysis of the anomalously low Pb isotope ratios from sample T1013-R02 has determined that contamination, possibly by steel tools used in the crushing process, has occurred. These data have been included in

Table 5, but will be disregarded in further discussion of the Vance C results.

Vance E

Five samples from Vance E were analyzed. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the five samples ranges from 0.702552 to 0.702670, with each value either within or just beyond error from the next higher value. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratio for the five samples ranges from 0.513147 to 0.513156. All Nd ratios fall within error of one another, showing no statistically significant variation. The Pb ratios for the five samples show a very restricted range of values, with only T1011-R01 having a slightly more radiogenic signature. No successful Pb analysis was completed on sample T1011-R20 before the very limited amount of glass was exhausted.

Vance F

Three samples from Vance F were analyzed. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the three samples ranges from 0.702473 to 0.702520, with T1007-R16 and R17 falling within error of one another; R02 has a slightly more radiogenic value. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratio for the three samples ranges from 0.513167 to 0.513182 and shows no statistically significant variation. The Pb ratios for T1007-R16 and -R17 are nearly identical, while ratios for R02 are lower and well outside of error of the others.

Vance G

Four samples from Vance G were analyzed. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the four samples ranges from 0.702573 to 0.703153. Sample T1014-R13 has a Sr ratio >0.7028 and likely contains some residual seawater Sr contamination. This analysis has been included in Table 5, but will be disregarded in further discussion of the Vance G results. Of the remaining three Sr analyses, samples T1014-R04 and R18 fall just outside of error from one another, while R22 has more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ value. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratio for the three samples ranges from 0.513134 to 0.513146, with all values falling within error of one another. The Pb ratios for three of the four samples show very little variation and cluster tighter than those from the other seamounts. Sample T1014-R22 has slightly lower Pb ratios than the other four samples.

6.3 Correlation with Sample Location/Type

6.3a Comparing seamount suites

The variation in isotopic ratios does not correlate with the order of seamount within the chain (e.g. $^{87}\text{Sr}/^{86}\text{Sr}$ does not increase from Vance A to B to C, etc.). Additionally, the range of compositions observed in one seamount often overlaps with the range of compositions seen in other

seamounts. The data do tend to cluster in discrete groups based on seamount affiliation.

In a few cases, however, some statements can be made. For example, on a plot of $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 33), Vance F samples are characterized by high $^{143}\text{Nd}/^{144}\text{Nd}$ and low $^{87}\text{Sr}/^{86}\text{Sr}$, while Vance B samples are characterized by low $^{143}\text{Nd}/^{144}\text{Nd}$ and intermediate $^{87}\text{Sr}/^{86}\text{Sr}$. Samples from Vance F and Vance B often have extreme compositions distinct from those of the other seamounts on isotope-isotope plots, while samples from Vance C, E, and G often overlap and have intermediate values. Samples from Vance A typically fall somewhere between the cluster of Vance C, E, and G values and the more enriched values of Vance B.

In a very generalized sense, the isotopic signature of the various seamount suites becomes more enriched (i.e. higher Sr and Pb, and lower Nd) from Vance F (i.e. the most depleted) to Vance C/E/G to Vance E to Vance B (i.e. the most enriched).

6.3b Comparing samples within individual seamounts

Although many samples were collected from each seamount, and each sample location was described with great detail, there may not be a sufficient number of isotope analyses to provide a clear correlation with volcanic stratigraphy. Volcanic glass was not present on all rock samples,

nor were all glassy samples analyzed for isotope geochemistry. That being said, there is now a greater abundance of isotope data for the Vance seamount lavas than for lavas from any other NRS chain along the Juan de Fuca Ridge, and information in Table 2 can be used to provide a few observations on the relationship between isotope data and sample location:

Vance A

T1008-R20 and R23 are both from the summit area of Vance A and within a kilometer of each other, while T1008-R05a was collected a couple of kilometers away on the outer flanks for the edifice. The similarity of the summit samples may indicate they were produced from the same melt batch, while R05a was produced from a different melting event that can be identified by a different source composition.

Vance B

Samples T1012-R14a and R21 show the closest isotopic similarities (either within error or very close to being within error of each other) and are also both located along the topographic ridge running NW-SE through the region mapped in Figure 16. No other correlations are evident, other than different sample locations are characterized by subtly different isotopic signatures.

Vance C

Sample T1013-R18 is distinct in that it was not a lava sample, but rather a collection of glass fragments from a volcaniclastite sample. Its relatively indistinct isotopic composition suggests that the glass fragments shared a similar source but a different eruptive history as the Vance C lavas. Nevertheless, sample T1013-R18 may not be representative of Vance C lavas, and has been excluded from further discussion of the Vance C results.

Vance E

The samples show only small or statistically insignificant variations in their isotopic signatures, despite being from very different outcrop locations in the volcanic sequence. Only T1013-R01, collected from the youngest caldera floor, shows significantly more radiogenic Pb ratios.

Vance F

Samples T1007-R16 and -R17 were collected nearly half a kilometer apart, but both outcrops are located on the same caldera floor, and show very similar isotopic signatures. Sample T1007-R02 was collected from the outer, younger caldera floor and has a slightly different isotopic signature.

Vance G

The four samples are well spaced across the ~2 km dive track but show no significant variation in isotopic character.

6.4 Correlation with Major Element Geochemistry

An attempt was made to correlate elemental data with isotopic data. No strong correlations were expected, as variations in major element concentrations are more reflective of magmatic processes (such as partial melting or crystal fractionation) rather than source characteristics, although certain anomalies in elemental data set may be related to isotopic (i.e. source) anomalies.

The isotopic variations in the Vance seamount samples, however, do not correlate with major or minor element variations. For example, the anomalously high K₂O content in Vance C samples T1008-R05a and R20, consistent with EMORB major element geochemistry, does not always correspond to an anomalous or strongly enriched isotopic signature.

6.5 Trace Element Geochemistry

6.5a Data source

Trace element geochemical analyses on the same glass separate used for isotopic analyses were performed by R. Wendt of the University of Florida as part of a M.Sc. thesis that is near completion. The samples were

analyzed at the University of Florida using an Element II Inductively Coupled Plasma Mass Spectrometer (ICP-MS).

Results of the analyses (normalized to primitive mantle and chondrite values) are presented in Figure 37 and Figure 38. Precision for the data is about $\pm 1\%$ for the concentrations in parts per million. The trace element and isotopic data sets include a great deal of sample overlap; however a few of the samples selected for isotopic analysis were not selected for trace element analysis, and vice versa.

Complete results and a full discussion of the trace element analyses can be found in the thesis by R. Wendt (University of Florida), but a few comments will be made here in order to address certain ideas with respect to the isotopic results.

6.5b Trace element results

The Vance seamount samples are generally very depleted in the most incompatible elements and tend to group together by seamount. Compositions from Vance A are anomalous in that they are slightly enriched in the most incompatible elements. Samples from Vance B, C, E, F, and G have $\text{La}/\text{Sm}_{\text{cn}}$ ratios of 0.35 to 0.68, while samples from Vance A have $\text{La}/\text{Sm}_{\text{cn}}$ ratios of 0.60 to 1.06.

The degree of trace element enrichment is best exemplified by the $\text{La}/\text{Sm}_{\text{cn}}$ ratio; NMORB is characterized by unfractionated heavy rare earth

element (REE) abundances, a strong depletion in light REEs, and La/Sm_{cn} values < 1 . Trace element abundances and ratios for the Vance seamount samples, with the exception of some of the values from Vance A samples, are all typical of NMORB. Some of the Vance A samples have values characteristic of EMORB.

Figure 37: Primitive mantle (Sun and McDonough, 1989) normalized incompatible element patterns for Vance seamount lavas (R. Wendt, personal communication). Analyses were completed using acid-dissolution inductively coupled plasma – mass spectrometry (ICP-MS) by R. Wendt at the University of Florida. Further information can be found in the M.Sc. thesis by R. Wendt (in progress) and in Section 6.5. The southern Juan de Fuca reference field (solid gray) is based on data provided by M.R. Perfit (personal communication) and Smith *et al.* (1994).

Figure 38: Chondrite (Sun and McDonough, 1989) normalized rare earth element patterns for Vance seamount lavas (R. Wendt, personal communication). Analyses were completed using acid-dissolution inductively coupled plasma – mass spectrometry (ICP-MS) by R. Wendt at the University of Florida. Further information can be found in the M.Sc. thesis by R. Wendt (in progress) and in Section 6.5. The southern Juan de Fuca reference field (solid gray) is based on data provided by M.R. Perfit (personal communication) and Smith *et al.* (1994).

6.5c Correlation of trace element and isotope data

Figure 39, a plot of isotopic ratios versus $\text{La}/\text{Sm}_{\text{cn}}$, can be used to determine whether enriched isotopic signatures (i.e. high $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and low $^{143}\text{Nd}/^{144}\text{Nd}$) correspond to enriched trace element patterns (i.e. high $\text{La}/\text{Sm}_{\text{cn}}$). Correlations are not strong, but in general show that enriched isotopic signatures do correspond to higher $\text{La}/\text{Sm}_{\text{cn}}$.

As in previous plots of seamount geochemistry data, samples from Vance A and Vance B tend to plot distinct from the general cluster of samples of Vance C, E, F, and G. The Vance B lavas are characterized by a relatively enriched isotope signature without a corresponding high $\text{La}/\text{Sm}_{\text{cn}}$ ratio, while some of the Vance A lavas are characterized by a relatively enriched isotopic signature and a relatively high $\text{La}/\text{Sm}_{\text{cn}}$ ratio.

Figure 39: (a) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\text{La}/\text{Sm}_{\text{cn}}$, (b) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $\text{La}/\text{Sm}_{\text{cn}}$, (c) $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $\text{La}/\text{Sm}_{\text{cn}}$ for the Vance seamount lavas. $\text{La}/\text{Sm}_{\text{cn}}$ data were provided by R. Wendt (personal communication). The southern Juan de Fuca (SJdF) reference field (solid gray) is based on data this study and that provided by M.R. Perfit (personal communication) and Smith *et al.* (1994).

6.6 Comparison with southern Juan de Fuca Geochemistry

6.6a Data sources

A large geochemical data set ($n = 339$) for samples collected from the southern Juan de Fuca ridge (including the Vance, northern Cleft, and southern Cleft segments) has been compiled and used as a reference field to represent the adjacent MORB composition. The data set is a compilation of many sources, largely from Stakes *et al.*, 2006; M.R. Perfit, personal communication; and Smith *et al.*, 1994. Other data come from Hegner and Tatsumoto, 1987; Ito *et al.*, 1987; Eaby *et al.*, 1984; and White *et al.*, 1987. The author has contributed new isotopic data for some of the Vance Segment samples (Table 6).

It is important to note that many of the samples lack a complete set of major, trace, and isotope analyses, and that major element data are more abundant than trace element data which are more abundant than Sr and Nd isotopic data which are more abundant than Pb isotopic data. That being said, the southern Juan de Fuca reference field is always based on *at least* 10 samples, including *at least* one sample from each of the three adjacent ridge segments. Based on the available data, the author has made some general comparisons between the Vance seamount data and that of the adjacent southern Juan de Fuca ridge.

Table 6: New isotope data for lavas dredged from the Vance segment of the Juan de Fuca Ridge

Sample	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
DR17-2	0.702514 + 11	0.513179 + 39	18.465 + 4	15.470 + 4	37.818 + 9
DR17-1	-	-	18.462 + 6	15.464 + 5	37.804 + 13
DR12A-8	0.702660 + 11	0.513146 + 9	18.450 + 13	15.479 + 11	37.806 + 27
DR12A-7	-	-	18.431 + 14	15.459 + 12	37.745 + 28
DR12-2	0.702539 + 11	0.513090 + 8	18.436 + 10	15.470 + 8	37.781 + 19
DR12-1	0.702582 + 12	0.513146 + 10	18.442 + 9	15.470 + 8	37.776 + 18

Analyses were performed using the methods described in Appendix II. Crushed glass powders were provided by M.R. Perfit (University of Florida). Location and sampling information described in Smith *et al.* (1994).

6.6b General observations

Like the seamount samples, lavas from the southern Juan de Fuca (SJdF) Ridge do not show a strong correlation between $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$, and many of the Vance seamount compositions overlap with samples from the SJdF Ridge on the Nd-Sr plot (Figure 33). Some of the seamount lavas from Vance A and Vance B, however, have significantly more radiogenic Sr and less radiogenic Nd (i.e. a more enriched signature) than the vast majority of the ridge lavas. One of the SJdF Ridge lavas has a composition similar to those of the samples from Vance B, indicating that the more enriched signature appears to be less common (for both seamount and especially ridge samples) but present in both settings.

Overall, the Vance seamount lavas have Sr and Nd ratios similar to those of the SJdF, but samples from Vance A and Vance B have a more enriched mantle signature (i.e. higher $^{87}\text{Sr}/^{86}\text{Sr}$ with lower $^{143}\text{Nd}/^{144}\text{Nd}$) than

what is typical of the SJdF lavas and samples from Vance F have the most 'depleted' mantle Nd-Sr signature but one that is typical of the most depleted SJdF lavas.

Lead isotopic ratios for the SJdF ridge lavas overlap with the values from the Vance seamount lavas, but have a much more restricted range that is typically in the low to intermediate range of the seamount sample values (Figure 34 and Figure 35). One of the SJdF samples falls outside of the tight cluster of the other ridge samples. That single, anomalous sample has Pb isotopic ratios very similar to the anomalously enriched (i.e. high) Pb signature of Vance B T1012-R01. Overall, the seamount lavas show a greater range of Pb isotopic values, both more radiogenic and less radiogenic, than the tightly clustered SJdF lavas.

Trace elements, as analyzed by R. Wendt (personal communication) are overall less abundant in the seamount samples than in the ridge samples (Figure 37 and Figure 38). Both are generally characterized by the depleted signature typical of NMORB, although the seamount samples show a stronger depletion in the light REEs. The difference in light REE depletion is evident in the non-overlapping La/Sm_{cn} values shown in Figure 39.

CHAPTER 7: DISCUSSION

7.1 Summary of Geochemical Results

Major element data indicate that all lava samples recovered from the Vance Seamounts are subalkaline MORB. On average, the Vance seamount lavas are more primitive (higher MgO) and exhibit greater geochemical diversity than lavas from the adjacent segments of the southern Juan de Fuca Ridge. Subtle variations do exist (e.g. K₂O from 0.02-0.31 wt. %), indicating a range from very depleted to slightly enriched MORB varieties. Trace element data (R. Wendt, personal communication) for selected samples vary in the amount of LREE depletion, ranging from very depleted N-MORB (La/Sm_{cn} as low as 0.345) to slightly enriched values with La/Sm_{cn} as high as 1.07. Isotopic ratios for selected samples vary well outside of analytical error and have mantle source signatures ranging from very 'depleted' (low ⁸⁷Sr/⁸⁶Sr, low ²⁰⁶Pb/²⁰⁴Pb, high ¹⁴³Nd/¹⁴⁴Nd) to more 'enriched' (higher ⁸⁷Sr/⁸⁶Sr, higher ²⁰⁶Pb/²⁰⁴Pb, lower ¹⁴³Nd/¹⁴⁴Nd).

Variations in major, trace, and isotope geochemistry are seen both within individual seamounts and also between seamounts of the Vance chain, with values tending to cluster by seamount. Some of variations in major and trace element geochemistry may have been controlled by differences in the extent of partial melting. Figure 40, a variation plot of

La/Sm_{cn} versus TiO₂ wt. %, shows a clear difference between the Southern Juan de Fuca data (which follow a fractionation trend typical of MORB) and the Vance seamount data (which show a positive correlation and follow a partial melting trend).

The relatively primitive nature of all the Vance seamount lavas (6.9-9.5 wt. % MgO, with an average of 8.2 wt. % MgO) argues against fractionation as the dominant process controlling geochemical diversity in the Vance seamount lavas. The relatively large variations in isotopic ratios in the Vance seamount lavas cannot be produced by partial melting of a homogeneous mantle source, thus a heterogeneous source (of at least two compositions) is required. Variable source compositions may also help explain some of the major and trace element variations (i.e. variable oxide abundances at similar MgO values, and crossing trace element patterns) not entirely explained by variations in magmatic processes.

Figure 40: La/Sm_{cn} versus TiO₂ (wt. %) for Vance seamount lavas. Arrows indicate trends defined by magmatic processes: FC, increasing fractional crystallization; PM, increasing partial melting. Note that source depletion from a recent, previous melting event would parallel the increasing partial melting trend. La/Sm_{cn} data were provided by R. Wendt (personal communication); TiO₂ data were provided by MBARI (D. Clague, personal communication). Southern Juan de Fuca (SJdF) based on data from Stakes *et al.*, 2006; M.R. Perfit (personal communication); and Smith *et al.* (1994).

7.2 Isotopic Signatures of the Vance Seamount Lavas as Evidence for Mantle Heterogeneity

7.2a Compositional end-members

Lavas recovered from the Vance Seamount Chain have isotopic compositions ranging from very depleted to slightly more enriched mantle isotopic signatures (i.e. less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and more radiogenic $^{143}\text{Nd}/^{144}\text{Nd}$ trending toward more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and less radiogenic $^{143}\text{Nd}/^{144}\text{Nd}$), and which can be explained by melt-induced mixing of multiple parental magmas with slightly different compositions that have been developed independently and resulting from ancient differences in the Rb/Sr, U/Pb, Th/Pb, and Sm/Nd ratios in each of the sources.

In order to produce the spectrum of lavas recovered from the Vance Seamounts, at least one of the seamount sources must be characterized by a mantle signature equally or more enriched (higher $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and lower $^{143}\text{Nd}/^{144}\text{Nd}$) than the most 'enriched' seamount lava, and a second seamount source must be characterized by a mantle signature equally or more depleted (lower $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and higher $^{143}\text{Nd}/^{144}\text{Nd}$) than the most 'depleted' seamount lava.

The Vance seamount lavas, excluding those from Vance B, plot along a general mixing trend between the relatively 'depleted' Vance F

compositions (lowest $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and highest $^{143}\text{Nd}/^{144}\text{Nd}$) and the relatively 'enriched' Vance A compositions (highest $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and lowest $^{143}\text{Nd}/^{144}\text{Nd}$), thus the seamount sources can be discussed in terms of a 'depleted' end-member characterized by the Vance F samples, and an 'enriched' end-member characterized by the Vance A samples. The source(s) of Vance B will be discussed separately, as the samples do not fall along the general mixing trend defined by samples from Vance A, C, E, F, and G.

The 'depleted' compositional end-member for the Vance seamount lavas is characterized by samples from Vance F which have Sr, Nd, and Pb isotopic ratios varying from 0.702476 to 0.702570, 0.513167 to 0.513182, and 18.12 to 18.31, respectively. The 'enriched' compositional end-member for the Vance seamount lavas is characterized by samples from Vance A which have Sr, Nd, and Pb isotopic ratios varying from 0.702617-0.702759, 0.513107-0.513132, and 18.50-18.58, respectively.

The Vance B lavas fall along the general Vance seamount mixing trend in Pb-Pb isotope plots, but the relatively low $^{143}\text{Nd}/^{144}\text{Nd}$ values (0.513048-0.513082) do not have the same relationship with the Sr and Pb isotopic ratios as do the rest of the Vance seamount lavas. Thus, the Vance B lavas plot off the general Vance seamount mixing trend in isotope-isotope plots involving $^{143}\text{Nd}/^{144}\text{Nd}$.

7.2b Melt-induced mixing of depleted mantle (DM) and HIMU-like mantle components

The HIMU (high $^{238}\text{U}/^{204}\text{Pb}$, or μ) mantle component of Zindler and Hart (1986) is characterized by slightly higher $^{87}\text{Sr}/^{86}\text{Sr}$, lower $^{143}\text{Nd}/^{144}\text{Nd}$, and higher Pb isotope ratios than those of DM, the depleted mantle source of most MORB. Mixing between the two components predicts that lavas with the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ and highest $^{143}\text{Nd}/^{144}\text{Nd}$ will also have the lowest $^{206}\text{Pb}/^{204}\text{Pb}$, and vice versa. Isotopic compositions for Vance Seamount lavas are consistent with the DM-HIMU mixing trend (Figure 41).

The ubiquity of the enriched HIMU-like component in basalts from the northeast Pacific led to the proposal that the enriched material is dispersed as plums or veins throughout the northeast Pacific upper mantle rather than being concentrated in a point source such as a mantle plume (e.g. Cousens, 1996a). The cartoon in Figure 3 was used by Cousens (1996a) to explain how melts of the enriched plums could result in the alkaline lavas of the northeast Pacific while the variety of MORBs could result from variable melting and mixing proportions of the enriched plums with a depleted mantle matrix. Through this model, Cousens also proposed that differences in the regional direction of mantle flow can explain the variable differences between near-ridge seamount and mid-ocean ridge geochemistry. The key factor is whether the mantle passes

Figure 41: $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$ (a); $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (b); $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (c) showing the Vance Seamount lava compositions (x) in reference to the mantle components of Zindler and Hart (1986) (lined boxes), modified from Rollinson (1993). BSE, bulk silicate earth; DM, depleted mantle; EM, enriched mantle; MORB, mid-ocean ridge basalt (as compiled by Saunders *et al.*, 1988); NHRL, northern hemisphere reference line (Hart, 1984).

beneath the ridge (a region of melt extraction) before or after it passes beneath an active near-ridge seamount.

If the mantle is heterogeneous, the enriched trace element signature of the enriched plums or veins will be observed in the seamount lavas only if they have not been affected by melting at the ridge where they would be preferentially melted (and therefore stripped of their most incompatible trace elements). The enriched mantle isotopic signatures, however, would be preserved in the residual enriched mantle material.

The great isotopic diversity (on such a short length-scale) of the Vance seamount lavas is consistent with an upper mantle source composed dominantly of depleted mantle (DM) with plums or veins of variable trace-element depleted, isotopically enriched HIMU-like mantle material. Figure 42 is a modified (i.e. Vance seamount and southern Juan de Fuca specific) version of the Cousens (1996a) model from Figure 2. The Vance Seamount lavas typically have highly to moderately depleted trace element signatures and overall lower trace element abundances than the adjacent ridge lavas (R. Wendt, personal communication), but also have heterogeneous isotopic signatures best explained by mixing between depleted (DM) and enriched (HIMU-like) mantle sources.

In the scenario depicted in Figure 42, the heterogeneous mantle (dominantly DM, but containing plums of HIMU-like enriched material) first passes beneath the southern Juan de Fuca Ridge, where both

components may be melted. The residual mantle sources, now modified from a recent melting event, will be variably depleted of trace elements (depending on the presence of enriched mantle as well as the melting regime) but will still retain the original isotopic signature of each source component. This model will now be used to further the discussion and interpretation of the Vance seamount geochemistry results.

Figure 42: Cartoon model showing the distribution and variable composition of mantle sources beneath the Vance Seamounts and the southern Juan de Fuca Ridge. See text for discussion. Modified from Cousens (1996a).

7.3 Vance Seamount Lava Compositions in a Regional Context

7.3a Relation to isotopic compositions from lavas of neighboring seamounts

Data Sources

Lead, Sr, and Nd isotopic data from five neighbouring studies have been plotted along with the Vance Seamount data in the isotope-isotope plots of Figure 43. These data include: (1) the Heck Seamount 'depleted' source (H/H) for the West Valley lavas from Cousens *et al.* (1995), including lavas from the Heck and Heckle seamounts and also one sample from Endeavour Seamount which are all located adjacent to the Endeavour Segment of the Juan de Fuca Ridge north of the Cobb-Offset; (2) lavas from Southwest Seamount and South West Valley (SWS/SWV) representing the 'enriched' source for the West Valley lavas from Cousens *et al.* (1995) which are also located adjacent to the Endeavour Segment of the Juan de Fuca Ridge north of the Cobb-Offset; (3) lavas from the Cobb-Eickelberg (C-E) seamount chain located directly north of the Vance Seamounts and adjacent to the southern Juan de Fuca Ridge and south of the Cobb-Offset (Desonie and Duncan, 1990); (4) lavas from the President Jackson seamount chain (PJ) located to the south of the Vance Seamounts and adjacent to the Gorda Ridge (Davis and Clague, 2000); and (5) lavas from Axial Seamount located on the Juan de Fuca Ridge at

the intersection with the Cobb 'hotspot' (Rhodes *et al.*, 1990). Data for the southern Juan de Fuca Ridge (discussed in Section 6.6a) have also been included.

$^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$

It is evident from Figure 43a that the SWS/SWV, PJ, and C-E lavas all have similar ranges of Sr and Nd isotopic ratios, while the H/H samples have a significantly more 'depleted' (i.e. low Sr, high Nd ratios) values, and lavas from Axial Seamount overlap with the H/H lavas but also trend toward the more 'enriched' SWS/SWV lavas. Lavas from the Southern Juan de Fuca Ridge are intermediate to, but also overlap with, all lava suites. The Vance Seamount lavas have Sr and Nd ratios that span a larger range of values than any of the comparison fields. Looking at individual seamount data, lavas from Vance F plot with a similar 'depleted' signature as the H/H lavas (but with slightly higher $^{87}\text{Sr}/^{86}\text{Sr}$), while lavas from Vance A have Sr and Nd ratios very similar to the most 'enriched' lavas from the President Jackson seamounts (PJ). Lavas from Vance C, E, and G have Sr-Nd signatures very similar to the PJ lava suite (but with slightly higher $^{143}\text{Nd}/^{144}\text{Nd}$).

As a group, the Vance Seamount lavas, excluding those from Vance B, appear to follow a Sr-Nd mixing trend very similar to a mixing trend between the 'depleted' H/H lavas and the most 'enriched' lavas of the President Jackson seamounts. Lavas from Vance B do not overlap

with any of the comparison fields, but do appear to extend the Sr-Nd mixing trend through the 'depleted' H/H lavas, the Axial Seamount lavas, and the more 'enriched' SWS/SWV lavas. A couple of SJdF lavas with anomalous (or rarely observed) Sr-Nd signatures also plot along this trend line toward the Vance B lavas. The two trend lines appear to be controlled by similar 'depleted' end-member compositions, but by 'enriched' end-members with different Sr-Nd signatures.

$^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$

Many of the Vance Seamount lavas, more than in the previous plots, show significant overlap with the 'depleted' (or less radiogenic) Pb-Pb isotopic signature of the H/H lavas (Figure 43b). Lavas from Vance A and Vance B, on the other hand, show more 'enriched' signatures, similar to the PJ and SWS/SWV lavas. As in other isotope-isotope plots, the Vance Seamount data span a greater range of values than any of the other individual suites, but fall within the combined range of all the comparison data fields. Lavas from Vance B, aside from having more radiogenic Pb ratios than many of the other Vance lavas, do not plot off the general trend line and show similar values to other 'enriched' (higher Pb) data fields.

$^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$

As in Figure 43a, the Nd and Pb ratios for the Vance Seamount lavas overlap with values from the other data sets, and show a range of

values larger than any of the individual data sets (Figure 43c). The combined data show a negative linear correlation from the 'depleted' (low Pb, high Nd ratios) H/H end-member to the more 'enriched' (higher Pb, lower Nd ratios) SWS/SWV end-member.

Samples from Vance F once again overlap with the H/H field, while samples from Vance A overlap with the President Jackson lavas. All Vance Seamount data, excluding samples from Vance B, fall along the trend line between Vance F and Vance A (i.e. between the H/H and PJ fields). The SWS/SWV and C-E fields extend the trend line to more 'enriched' ratios, not seen in the Vance Seamount data. One sample from Vance F plots at lower $^{206}\text{Pb}/^{204}\text{Pb}$ than the H/H field, but along the same trend line.

Data for all of the Vance samples, excluding those from Vance B, as well as all of the various comparison fields, appear to be controlled by similar 'enriched' and 'depleted' end-members; lavas from Vance B, as well as two samples from the southern Juan de Fuca data set, have significantly lower $^{143}\text{Nd}/^{144}\text{Nd}$, and do not fall along the same trend line as the other data.

Summary

In all the isotope-isotope plots of Figure 43, lavas from the Southern Juan de Fuca typically overlap with the depleted H/H field and trend toward the more enriched values of the other data fields. Also seen in all

the plots is that the Vance Seamount lavas span the entire compositional range of the other data sets combined.

Lavas from both Vance A and Vance B show relatively 'enriched' isotopic signatures relative to the other Vance seamount lavas. However, the Vance B compositions do not plot along the same mixing line as lavas from Vance A and the other Vance seamounts, and therefore cannot be attributed to mixing between the same set of mantle components. The Vance A and Vance B lavas have similar Sr and Pb isotopic ratios, but the Vance B lavas have significantly lower $^{143}\text{Nd}/^{144}\text{Nd}$. The 'enriched' Vance A lavas plot very similar to the President Jackson lavas, thus the Vance F – Vance A trend is very similar to a hypothetical H/H – President Jackson mixing trend. The Vance B 'enriched' signature is either rare and/or rarely sampled in this region, and is not associated with any of the compositions observed in the regional data suites.

Figure 43: (a) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$, (b) $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$, (c) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ for the Vance seamount lavas compared to data from neighboring seamount lavas. Data for comparison fields discussed in Section 7.3a: SWS/SWV = Southwest Seamount and South West Valley (Cousens *et al.*, 1995); C-E = Cobb-Eickelberg Seamounts (Desonie and Duncan, 1990); PJ = President Jackson Seamounts (Davis and Clague, 2000); H/H = Heck & Heckle and Endeavour Seamounts (Cousens *et al.*, 1995); SJdF = southern Juan de Fuca Ridge (this study; M.R. Perfit, personal communication; Hegner and Tatsumoto, 1987; Ito *et al.*, 1987; Eaby *et al.*, 1984; and White *et al.*, 1987); Axial Seamount (Rhodes *et al.*, 1990). The SJdF data set does not consist of an equal number of Sr, Nd, Pb analyses: $n = 50$ for $^{87}\text{Sr}/^{86}\text{Sr}$; $n = 50$ for $^{143}\text{Nd}/^{144}\text{Nd}$; $n = 19$ for Pb ratios. NHRL, Northern Hemisphere Reference Line (Hart, 1984).

7.3b Relation to isotopic compositions from lavas of the greater northeast Pacific region

Data Sources

Building on what was observed in Section 7.3a, it is possible to broaden the comparison data sets to include Sr, Nd, and Pb isotopic ratios for lavas from seamounts (both near-ridge and intra-plate) adjacent to and including lavas from northern Juan de Fuca ridge segments and Explorer Ridge (Figure 44). The H/H, P/J, SWS/SWV, and C-E data fields from Figure 43 have been combined and labelled as *Juan de Fuca, Gorda NRS*; the data for lavas from the southern Juan de Fuca are included in the larger *Juan de Fuca, Explorer MORB* field. Two other data fields have been added: (1) *Explorer, Pratt Welker NRS*, and (2) *Pratt-Welker, Tuzo Wilson Intraplate Alkaline Basalts*. The four comparison fields include, or are representative of most, if not all, of the lavas collected from the various tectonic environments of the northeast Pacific.

Relationships on Isotope-Isotope Plots

It is evident from Figure 44 that the addition of data from seamounts and ridge segments north of the Vance Seamounts greatly expands the regional isotopic space. Isotopic compositions observed in the Vance Seamount lavas, even including those from Vance B, now plot within previously observed isotopic compositional ranges observed in lavas from the greater northeast Pacific.

In a plot of $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$, the varieties of Vance Seamount compositions are largely encompassed by the *Pratt-Welker, Tuzo Wilson Intraplate Alkaline Basalts (PWTWIAB)* field. While still very similar in Sr-Nd isotopic space to lavas from the President Jackson seamounts, the slightly higher $^{143}\text{Nd}/^{144}\text{Nd}$ values of Vance C, E, and G lavas are better associated with PWTWIAB field. The same PWTWIAB field is also able to accommodate the higher $^{87}\text{Sr}/^{86}\text{Sr}$ values of Vance A lavas and the low $^{143}\text{Nd}/^{144}\text{Nd}$ values of the Vance B lavas. The two lavas suites (Vance seamount and PWTWIAB) are not, however, associated in Pb-Pb isotopic space.

The previously 'odd' composition of the Vance B lavas consistently overlaps here with the *Explorer, Pratt-Welker NRS* compositional field. Specifically, the Vance B lava compositions are very similar to the isotopic compositions observed in lavas from Oshawa Seamount, located at the southern terminus of the Pratt-Welker Seamount Chain (Cousens *et al.*, 1999). This relationship will be discussed further in Section 7.3f.

The range of compositions seen in the Vance Seamount lavas appears to be relatively large, even when compared to the spatially expansive fields of the *Explorer, Pratt-Welker NRS* and the *Pratt-Welker, Tuzo Wilson Intraplate Alkaline Basalts* fields, emphasizing the degree of compositional heterogeneity observed in the relatively restricted spatial range covered by the Vance Seamount lavas.

Figure 44: (a) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$, (b) $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$, (c) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ for the Vance seamount lavas compared with mid-ocean ridge (MORB), near-ridge seamount (NRS), and alkaline intraplate seamount (IP) lavas from the greater northeast Pacific region (this study; Cousens *et al.*, 1985, 1995, 1999; Hegner and Tatsumoto, 1987, 1989; White *et al.*, 1987; Cousens, 1988; Allan *et al.*, 1993; M.R. Perfit, personal communication; Ito *et al.*, 1987; Eaby *et al.*, 1984; and White *et al.*, 1987). Juan de Fuca, Gorda NRS field represents the combined reference data fields used in Figure 43 (Cousens *et al.*, 1995; Desonie and Duncan, 1990; Davis and Clague, 2000). NHRL, Northern Hemisphere Reference Line (Hart, 1984).

7.3c The 'depleted' Vance Seamount end-member, as represented by the Vance F lava compositions

The 'depleted' (low $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and high $^{143}\text{Nd}/^{144}\text{Nd}$) lavas from Vance F have Sr, Nd, and Pb isotopic compositions very similar to those of lavas forming the Heck Seamount 'depleted' source (plotted as the H/H field in Figure 43) proposed as the depleted end-member component for the West Valley floor lavas by Cousens *et al.* (1995).

The Heck Seamount 'depleted' source is defined by lavas from the Heck and Heckle seamounts along with Endeavour Seamount and the West Ridge flow, and is characterized by low $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$, combined with low La/Ce, La/Sm, and Nb/Zr. The trace element patterns of the Heck and Heckle lavas, as interpreted by Leybourne and Van Wagoner (1991), are indicative of a mantle source that has undergone a previous, recent melting event that resulted in trace element depletion of the source. This melting event was likely that of the melting and formation of the adjacent Juan de Fuca MORB. The isotopic data, as interpreted by Cousens *et al.* (1995), indicate that this source has had low Rb/Sr, U/Pb, Th/Pb, and high Sm/Nd for a period of time greater than 1.5 Ga.

To explain the isotopic heterogeneity of the Heck Seamount 'depleted' basalts and assuming they were sourced from the residue of a

recent melting event to produce the adjacent Juan de Fuca MORB, Cousens *et al.* (1995) proposed that the degree of partial melting of the MORB source was sufficient to exhaust only the enriched component of the regionally heterogeneous mantle. Furthermore, Cousens *et al.* (1995) argue that in order for this scenario to be reasonable, the mantle source must have retained a fraction (10%-20%) of the original melt produced beneath the ridge due to incomplete melt extraction at the ridge. Subsequent re-melting beneath the seamounts would produce compositions trending between a highly depleted mantle component and a Juan de Fuca MORB-like component of variable trace element and isotopic composition.

Like the Heck Seamount 'depleted' source, the Vance F lavas are characterized by similarly low $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and high $^{143}\text{Nd}/^{144}\text{Nd}$, combined with very depleted trace element patterns (e.g. $\text{La}/\text{Sm}_{\text{cn}}$ 0.35-0.52). These values now characterize the proposed Vance Seamount 'depleted' source. Since the two 'depleted' sources share very similar geochemical characteristics, the author proposes that the two lava suites share a similar heterogeneous and highly depleted mantle source, such as that proposed by Cousens *et al.* (1995). If the mantle source never contained an enriched component, the seamount lavas would be characterized by homogeneous isotopic ratios. Neither the Heck & Heckle seamount lavas nor the Vance seamount lavas have

homogeneous isotopic ratios, supporting the presence of some amount of enriched component in their mantle source.

The mixing scenario of a previously melted heterogeneous source, as proposed by Cousens *et al.* (1995), is consistent with very trace element (especially LREE) depleted patterns and slightly heterogeneous isotopic ratios of the Vance F lavas. The isotopic data indicate that this source, like Heck 'depleted' source, has had low Rb/Sr, U/Pb, Th/Pb, and high Sm/Nd for a long period of time. The previous melting event proposed for the Heck 'depleted' source with respect to the Vance seamount geochemistry will be discussed in the following section.

7.3d The 'enriched' Vance Seamount end-member, as represented by the Vance A lavas

The 'enriched' lavas from Vance A have Sr, Nd, and Pb isotopic compositions very similar to those of lavas from the President Jackson Seamounts adjacent to the Gorda Ridge. Lavas from both seamount chains have overlapping isotopic compositions in all isotope-isotope plots, indicating they were influenced by a similar 'enriched' heterogeneous mantle source.

The Vance A and Vance B lava compositions, while not identical, both trend toward an enriched HIMU-like component with higher $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and lower $^{143}\text{Nd}/^{144}\text{Nd}$ than depleted mantle (DM). The HIMU-like component contributing to the Vance B lavas must be characterized

by a lower $^{143}\text{Nd}/^{144}\text{Nd}$ ratio than the HIMU-component contributing to the Vance A lavas in order to account for the significantly lower $^{143}\text{Nd}/^{144}\text{Nd}$ at similar $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$ values.

Studies of intraplate and near-ridge seamount lavas adjacent to the northernmost part of the Juan de Fuca Ridge and Explorer Ridge have recognized the importance of a HIMU-like enriched component that variably contributes to the chemistry of these lavas (e.g. Cousens, 1996a). Melts of this enriched source, represented by alkaline intraplate lavas of the Tuzo Wilson and Pratt-Welker seamounts, are characterized by higher $\text{K}_2\text{O}/\text{Na}_2\text{O}$, $\text{La}/\text{Sm}_{\text{cn}}$, $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$, and lower $^{143}\text{Nd}/^{144}\text{Nd}$ and $^3\text{He}/^4\text{He}$ than melts from depleted mantle (Cousens, 1996a).

7.3e Evidence supporting a recent melting event affecting the mantle components contributing to the Vance Seamount lavas

Partial melting of the mantle results in a decrease of the Rb/Sr ratio in the source rocks due to the different geochemical properties of Rb and Sr (Rb behaves more incompatibly during partial melting of the mantle and prefers the liquid phase). A re-melt of the same source rocks at a relatively similar time (i.e. within a few million years) will result in a magma with a lower Rb/Sr ratio than that of the original melt but characterized by a similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratio.

Figure 45 is a plot of Rb/Sr versus $^{87}\text{Sr}/^{86}\text{Sr}$ for lavas from both the Vance Seamounts and the adjacent southern Juan de Fuca Ridge. It has been proposed that the underlying mantle was first tapped (or depleted) by the adjacent ridge before it was tapped again by the seamounts (refer to the model in Figure 42). The Vance Seamount data plot with lower Rb/Sr at similar $^{87}\text{Sr}/^{86}\text{Sr}$, consistent with re-melting of the mantle source that produced the southern JdF MORB (i.e. a melting event in the recent past). It is also apparent from Figure 45 that the seamount lavas follow a mixing trend between a low Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ composition toward a higher Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ composition. This trend is consistent with melt-induced mixing between isotopically enriched and depleted mantle components. A depleted mantle component is characterized by a lower Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than those of an enriched mantle component. Again, the lavas from Vance F are characterized by the most depleted mantle signature from the recovered lavas, while the lavas from Vance A are characterized by the most enriched mantle signature. Also, the 'depleted' end-member, with similar $^{87}\text{Sr}/^{86}\text{Sr}$ but lower Rb/Sr than the ridge lavas, appears to be a recently re-melted version of the same mantle source.

An inverse relationship is expected in a plot of Sm/Nd versus $^{143}\text{Nd}/^{144}\text{Nd}$ due to the fact that a basaltic melt will have a lower Sm/Nd ratio than its mantle source rocks (both Sm and Nd are light rare earth

elements, but Nd has a slightly larger and therefore more incompatible ionic radius than Sm). The seamount lavas do tend to show higher Sm/Nd values at similar $^{143}\text{Nd}/^{144}\text{Nd}$ values than do the ridge lavas, and also show a general mixing trend from more enriched (lower Sm/Nd and lower $^{143}\text{Nd}/^{144}\text{Nd}$) to more depleted mantle source signatures (Figure 46).

Figure 47 is a conceptual model showing the effects of the proposed recent, previous melting event at the southern Juan de Fuca Ridge affecting the compositions of the Vance seamount lavas. If the heterogeneous mantle is first melted at the ridge, then the ridge lavas would fall on a mixing line between the DM (depleted mantle) and EM (enriched mantle) components (shown as boxes) in the two plots of Figure 47, and the Vance seamount lavas (the proposed re-melt compositions) would fall on a mixing line between the re-melted DM and EM components. Re-melting a recently melted, residual mantle source would result in lavas with a lower Rb/Sr ratio and a higher Sm/Nd ratio than the first melt lavas (i.e. SJdF MORB) without changing the corresponding isotopic ratios, due to the fact that initial Sr isotope systematics differ from those of Sm/Nd.

The Vance seamount data are consistent with the effects of a recent, previous melting event at the adjacent ridge. The proposed model appears to better fit the data in Figure 47a (Rb/Sr vs. $^{87}\text{Sr}/^{86}\text{Sr}$) than in Figure 47b (Sm/Nd vs. $^{143}\text{Nd}/^{144}\text{Nd}$). This is likely related to the fact that

the Vance B lavas have a similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratio as the other Vance seamount lavas but a very different $^{143}\text{Nd}/^{144}\text{Nd}$ ratio (i.e. variable isotopic differences in source characteristics complicate the model). These plots (Figure 45 - Figure 47) also reveal some interesting characteristics of some of the lavas from Vance A and Vance B, discussed the next section.

Figure 45: Rb/Sr versus $^{87}\text{Sr}/^{86}\text{Sr}$ for the Vance seamount lavas compared to lavas from the southern Juan de Fuca Ridge (SJdF). Rb/Sr data for the Vance samples provided by R. Wendt (personal communication). SJdF data from this study, M.R. Perfit (personal communication) and Smith *et al.* (1994).

Figure 46: Sm/Nd versus $^{143}\text{Nd}/^{144}\text{Nd}$ for the Vance seamount lavas compared to lavas from the southern Juan de Fuca Ridge (SJDf). Sm/Nd data for the Vance samples provided by R. Wendt (personal communication). SJDf data from this study, M.R. Perfit (personal communication), and Smith *et al.* (1994).

Figure 47: Conceptual diagrams to explain the trends seen in the Vance seamount and southern Juan de Fuca data in Figures 45 and 46. See text for discussion.

7.3f Further analysis of the geochemistry of lavas from Vance A and Vance B

Two of the Vance A lavas are interesting in that they have Sm/Nd ratios similar to the relatively low ratios of the ridge lavas. It appears that these samples could represent original melts, not re-melts, of the mantle source rocks. The slightly less radiogenic $^{143}\text{Nd}/^{144}\text{Nd}$ value is consistent with a more enriched mantle source, one that may have been obscured in the ridge lavas (due to magma mixing and homogenization of the isotopic signatures of individual mantle components). The two Vance A samples also have Rb/Sr ratios similar to the ridge lava values, but the association is not quite as obvious.

To further the investigation into the geochemistry of the Vance A lava, $\text{K}_2\text{O}/\text{Na}_2\text{O}$ versus MgO has been plotted for both the seamount and ridge lavas in Figure 48. The two Vance A data points that plot well off the general trend line (i.e. higher $\text{K}_2\text{O}/\text{Na}_2\text{O}$ at similar MgO) are also those characterized by slightly enriched T-MORB trace element patterns (e.g. $\text{La}/\text{Sm}_{\text{cn}}$ 0.99-1.06).

These two samples (T1008-R05a and R20) do not, however, come from nearby locations on the Vance A edifice, nor do they plot with overlapping isotopic ratios. The third sample from Vance A (T1008-R23) is characterized by lower $\text{La}/\text{Sm}_{\text{cn}}$ and K_2O wt. % values typical of the

majority of the Vance seamount lavas, but also by the relatively enriched mantle isotopic signature of sample T1008-R20. Both T1008-R20 and R23 were recovered from the summit of Vance A, while T1008-R05a was recovered from the flanks.

It appears that T1008-R05a, marked by the more depleted mantle isotopic signature of the three samples, has been derived from a mantle source with a greater proportion of the depleted component (DM) yet somehow retained an enriched trace element signature than sample T1008-R23 which appears to have been derived from a mantle source with a greater proportion of the enriched HIMU-like mantle component. Differences in the degree of partial melting may be a critical factor controlling the Vance A lava geochemistry. The relatively high K_2O/Na_2O ratio in some of the Vance A lavas is consistent with a lower degree of melting (Figure 48). Further analysis, involving all aspects of the geochemistry, could improve the understanding of the Vance A lavas.

Figure 48: K_2O/Na_2O versus MgO (wt. %) for the Vance seamount lavas compared to lavas from the southern Juan de Fuca Ridge (SJdF). Vance seamount data provided by MBARI (Dave Clague, personal communication). SJdF includes data from Stakes *et al.*, 2006; M.R. Perfit (personal communication); and Smith *et al.*, 1994.

The Vance B lavas, while not distinct in Figure 45, have an interesting relationship to the other Vance Seamount and ridge lavas in Figure 46. While characterized by a Sm/Nd ratio similar to many of the other lavas (both seamount and ridge), the Vance B lavas have much lower $^{143}\text{Nd}/^{144}\text{Nd}$ than any of the lavas with similar Sm/Nd. The characteristically low $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of the Vance B lavas may be the result of an ancient event, not a recent melting event.

Additionally, it could be said that the relatively low $\text{Ca}/\text{Al}_2\text{O}_3$ ratios observed in most of the Vance B lavas (as well as in a few lavas from some of the other Vance seamounts) is consistent with a magma that has undergone clinopyroxene (cpx) fractionation (i.e. the $\text{Ca}/\text{Al}_2\text{O}_3$ ratio of a magma decreases with increasing cpx fractionation). However, the thinness of oceanic crust adjacent to an active spreading center argues against high-pressure fractionation, and the primitive nature of the seamount lavas (i.e. high MgO) argues against shallow, low-pressure fractionation.

Figure 49, a plot of $\text{CaO}/\text{Al}_2\text{O}_3$ versus MgO for both the seamount and ridge lavas, shows that the seamount lavas do not follow the same trend as the ridge lavas. The positive correlation trend displayed by the ridge lavas is consistent with shallow level fractionation of olivine, plagioclase, and finally clinopyroxene in the ridge magmas. The $\text{CaO}/\text{Al}_2\text{O}_3$ ratio of the Vance seamount lavas increases with a

Figure 49: $\text{CaO}/\text{Al}_2\text{O}_3$ versus MgO for the Vance seamount lavas compared with lavas from the southern Juan de Fuca Ridge (SJdF). Data for the Vance lavas provided by MBARI (Dave Clague, personal communication). SJdF data from Stakes *et al.* (2006), M.R. Perfit (personal communication), and Smith *et al.*, (1994).

corresponding slight decrease in the MgO content. The near-vertical trend of the Vance seamount lavas may be explained by re-melting a previously melted (and cpx fractionated) source. The CaO/Al₂O₃ ratio does not correlate well with variations in trace element or isotopic ratios, and has likely been affected by a number of magmatic processes both in the original melting event at the ridge, the proposed second melt event that produced the Vance seamount lavas, as well as by possible variations in the initial source composition(s).

The four analyzed lava samples from Vance B have a distinct and anomalous isotopic signature compared to those of the other Vance Seamount samples. Compared to the other Vance seamount samples, the Vance B samples are characterized by high, but not anomalous, ⁸⁷Sr/⁸⁶Sr values, anomalously low ¹⁴³Nd/¹⁴⁴Nd values, and very high, but not particularly anomalous, Pb isotopic ratios. Additionally, the Vance B samples show anomalous major element geochemistry characterized by low SiO₂, CaO, and CaO/Al₂O₃, and high Al₂O₃, FeO_(total), and Na₂O.

The Vance B lavas have trace element patterns (slightly depleted in LREE) typical of the majority of the other Vance Seamount lavas (R. Wendt, personal communication). The anomalous major element geochemistry therefore is likely related to a mantle source composition not present (or perhaps not dominant) in the other Vance seamount lavas. Furthermore, the Vance B isotopic signature is not common to any

of the seamount or ridge lavas. Only one (out of 50) of the samples from the southern Juan de Fuca data set has an isotopic signature similar to that of the Vance B lavas. The Vance B isotopic composition is not common to the seamount or adjacent ridge lava, or even to any of the other neighbouring seamounts (Figure 43), but has been observed in lavas of the Pratt-Welker near-ridge seamounts (Figure 44).

In particular, some of the lavas recovered from Oshawa Seamount (Cousens *et al.*, 1999) have a very similar isotopic signature to the Vance B lavas (Figure 50). With the exception of $^{207}\text{Pb}/^{204}\text{Pb}$, the Pb, Sr, and Nd isotopic ratios of the Vance B lavas overlap with some of the Oshawa Seamount lavas in all isotope-isotope plots, indicating a similar mantle component may have contributed to the lavas of both seamounts.

The relative relationships in isotope-isotope plots between the Vance B and Oshawa seamount compositions share some similarities to the relative relationships between the Vance Seamounts (excluding Vance B) and southern Juan de Fuca compositions (compare Figure 50 with Figure 33 through Figure 36. For example, $^{143}\text{Nd}/^{144}\text{Nd}$ values for the Oshawa Seamount and SJdF lavas are similar to or higher than the values for the Vance B and Vance Seamount (excluding Vance B) lavas, respectively. Also, both Oshawa Seamount and SJdF lavas have very restricted $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ values compared to those of the

Figure 50: (a) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$, (b) $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$, (c) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$, (d) $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ for the Vance seamount lavas compared with Oshawa Seamount lavas (Cousens *et al.*, 1999).

Vance B and Vance Seamount (excluding Vance B) lavas, respectively. The $^{207}\text{Pb}/^{204}\text{Pb}$ ratio shows more variation than the other Pb ratios in both the Oshawa and SJdF lavas, which also show a similar or less radiogenic $^{207}\text{Pb}/^{204}\text{Pb}$ ratios than the Vance B and Vance Seamount (excluding Vance B) lavas.

Given the similarity of these relationships and that it has been proposed that the Vance Seamount (excluding Vance B) lavas may represent re-melts of the southern Juan de Fuca MORB source(s), is it possible that the Vance B lavas could represent a re-melt of an Oshawa Seamount-type source(s)? The Oshawa Seamount lavas (proposed 'first melt' compositions), characterized by a less depleted to slightly enriched trace element pattern (i.e. $\text{La}/\text{Sm}_{\text{cn}}$ 0.83-1.06), similar to lower Sm/Nd ratio (0.28-0.35), and $\text{CaO}/\text{Al}_2\text{O}_3$ versus MgO consistent with cpx fractionation (0.76-0.82 and 5.62-7.77, respectively)(Cousens *et al.*, 1999) when compared to the Vance B lavas (proposed 're-melt' compositions) are consistent with the re-melting scenario. While a thorough analysis of this proposal is perhaps beyond the scope of this thesis, these relationships are similar to the relationships between the southern Juan de Fuca lavas (proposed 'first-melt' compositions) and the Vance Seamount (excluding Vance B) lavas (proposed 're-melt' compositions).

The physical characteristics of Vance B, observed to be a region of disorganized but voluminous volcanism, are also very different than the

typical Vance seamount morphology of a distinct volcanic cone with progressively off-set, nested calderas. Does the physical expression of Vance B volcanism have a relationship to depth of melting and therefore a possible vertical heterogeneity of the underlying mantle that is different than the lateral heterogeneity presumed to be sampled by the Vance Seamounts?

Experimental studies into the effects of variable pressure on the partial melting of pyroxenites (i.e. an enriched mantle lithology) have shown how major element concentration will vary with increasing pressure (e.g. Kogiso *et al.*, 2003). Figure 51 shows that increasing pressure (within conditions relevant to basalt petrogenesis beneath oceanic ridges and islands) will act to increase the SiO_2 and CaO content and decrease the Al_2O_3 content of the MIX1G garnet pyroxenite without a considerable increase in MgO content.

Figure 51 also shows that partial melts of peridotite (i.e. depleted mantle) do not follow the same trends and become more enriched in MgO with increasing pressure. Variable mixing proportions of the two lithologies (or similar pyroxenite and peridotite lithologies) during melting would likely complicate the application of this study to data sets like that of the Vance seamounts. However, another experimental study into the partial melting of pyroxenite (Pertermann and Hirschmann, 2003) has shown that basaltic pyroxenite, if present in a heterogeneous mantle

source, will largely be melted before the peridotite solidus is reached. This finding supports the idea that melting at the ridge will first act to deplete the enriched heterogeneities and may not extensively melt the depleted matrix unless the degree of melting is sufficiently robust, thus affecting the available trace element budget during a proposed second melting event forming near-ridge seamount lavas (e.g. the Vance lavas).

Since the Vance B lavas have been proposed to have a heterogeneous mantle source different from the other Vance seamount lavas, it is hard to say whether the variable major element chemistry can be attributed to different depths of melting (i.e. different pressures). The work of Kogiso *et al.* (2003) has shown that the $\text{CaO}/\text{Al}_2\text{O}_3$ ratio in partial melts of the MIX1G pyroxenite will increase with increasing pressure (i.e. increasing depth of melting).

The results are seemingly contradictory to the idea that the Vance B melts (with a typically lower $\text{CaO}/\text{Al}_2\text{O}_3$ ratios compared to most of the Vance seamount lavas) may represent higher pressure (i.e. deeper) partial melts of the underlying mantle sources. However, the isotopic signature of the Vance B lavas (characterized by relatively low $^{143}\text{Nd}/^{144}\text{Nd}$) does not fall along the same mixing lines as the other Vance lavas in isotope-isotope plots, and therefore the lava suits cannot be compared as possible partial melts from similar sources but different pressures (depths of melting).

Additionally, the experimental studies were based on homogeneous compositions whereas the Vance seamount lavas are likely the result of melt-induced mixing of a heterogeneous mantle source. Further research into the combined effects of re-melting and melt-induced mixing of enriched and depleted mantle sources (e.g. lherzolite/clinopyroxenite and peridotite, the proposed mantle lithologies in the northeast Pacific upper mantle [Cousens et al., 1996a]) at variable pressures and the possibility of both vertical and lateral heterogeneity of mantle sources would certainly help to improve the understanding of the geochemical heterogeneities present in the Vance seamount lavas.

Figure 51: Change in composition of partial melts of MIX1G garnet pyroxenite and anhydrous peridotite with increasing pressure (from Kogiso *et al.*, 2003). Numbers indicate pressures in GPa.

7.3g Comments on the distribution of enriched mantle material

It has been proposed that both depleted and enriched mantle are present beneath the northern most part of the JdF (i.e. north of the Cobb-Offset) and Explorer Ridge while only depleted mantle is present beneath the southern (i.e. south of the Cobb-Offset) JdF Ridge (e.g. Michael *et al.*, 1989; Karsten *et al.*, 1990; Smith *et al.*, 1994; Cousens 1996a).

A recent study of the President Jackson Seamounts, a near-ridge seamount chain adjacent to the Gorda Ridge (i.e. south of the Cobb-Offset and the entire Juan de Fuca Ridge), revealed isotopic heterogeneities in the seamount lavas consistent with mixing between DM and HIMU-like mantle components (Davis and Clague, 2000). Enriched compositions in the Vance A and Vance B lavas, as well as in the President Jackson seamount lavas, are similar to those observed elsewhere in the northeast Pacific, suggesting the enriched mantle component is not exclusive to regions north of the Cobb-Offset. Trace element patterns in lavas from both the President Jackson and the Vance seamounts are typically depleted NMORB; however, the enriched pattern in some of the Vance A lavas ($\text{La}/\text{Sm}_{\text{cn}}$ up to 1.06), combined with the enriched mantle isotopic signature, strongly support the presence (albeit rare or rarely observed) of an enriched component in the underlying mantle south of the Cobb-Offset.

As mentioned previously, the relatively enriched mantle source signatures of the Vance A and Vance B lavas cannot be explained by mixing of DM with a similar HIMU-like component. The Vance A compositions are more consistent with some of the enriched compositions of the alkaline intraplate lavas of the northeast Pacific, whereas the Vance B compositions are more consistent with some of the enriched compositions of the Pratt-Welker near-ridge seamount lavas.

Cousens (1996a) noted that the enriched component was present only in the most recent lavas from the northern Juan de Fuca, suggesting that the enriched province is expanding southward. The EMORB identified in the Vance Seamount lavas is a first for the Southern Juan de Fuca Ridge and its adjacent seamounts (R. Wendt, personal communication). It is likely that the enriched mantle component contributing to the Vance A lavas was not completely stripped of its incompatible trace element budget (during the proposed recent, previous melting event at the ridge), thus explaining both the enriched trace element signature and the enriched mantle signature.

The Vance seamount lavas show a range of compositions reaching mantle signatures far more depleted than those seen in the President Jackson lavas. This may result from the fact that the President Jackson isotopic data set is composed of only five samples. Based on the variability of the Vance Seamount data, further testing of the President

Jackson seamounts could reveal greater isotopic heterogeneity in the lavas.

In comparison to the northeast Pacific, NR seamounts are more common and certainly better-studied along fast-spreading ridges, especially the East Pacific Rise (EPR) (e.g. Batiza and Vanko, 1983, 1984; Batiza *et al.*, 1984; Fornari *et al.*, 1984, 1985, 1988; Allan *et al.*, 1989; Niu and Batiza, 1991; Niu *et al.*, 2002). Located on both sides of the EPR, these NRS lavas typically have a greater compositional diversity (NMORB, EMORB, and alkali basalts) than those from the ridge (Batiza and Vanko, 1984; Batiza *et al.*, 1989; Allan *et al.*, 1987; Niu and Batiza, 1997; Perfit and Chadwick, 1998).

The Lamont Seamounts, a near-ridge chain adjacent to the East Pacific Rise, share the distinct off-set caldera morphology of the Vance and President Jackson near-ridge seamount chains. Lavas from the Lamont Seamounts show a very similar degree of heterogeneity as the Vance Seamount lavas from a data set of only nine samples. Isotope-isotope plots in

Figure **52** compare Vance and Lamont near-ridge seamount lavas with MORB from their adjacent ridge segments. The two seamount suites have very similar compositions, both in the degree of heterogeneity and source characteristics, and also share the same relationship with the adjacent MORB. The seamount lavas have both more and less

radiogenic Sr, Nd, and Pb isotopic ratios than ridge lavas which are more restricted (homogenized) and intermediate to the seamount end-members. Also similar to the Vance Seamount – southern Juan de Fuca relationship, the Lamont seamount lavas are generally more primitive and have lower trace element abundances than lavas from the East Pacific Rise (e.g. Fornari *et al.*, 1988).

Although the Lamont Seamounts formed adjacent to a ridge with a fast spreading rate and the Vance Seamounts formed adjacent to a ridge with an intermediate spreading rate, the underlying mantle source region for the seamount lavas appears to be heterogeneous on a similar length scale (i.e. equal or less than the diameter of an individual seamount, as significant isotopic heterogeneity is observed in samples from an individual seamount) and compositional scale. Given that the two seamount chains also share very similar physical characteristics, the petrogenetic processes responsible for the lavas seem to be particularly good at revealing compositional heterogeneities in the underlying mantle.

Figure 52: (a) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$, (b) $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$, and (c) $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ for the Vance and Lamont seamount lavas compared to lavas from their adjacent ridge segments. Lamont data from Fornari *et al.*, 1988; East Pacific Rise (EPR) data (including only on-axis samples recovered between 9.7° and 10.1°N) from Sims *et al.*, 2003; southern Juan de Fuca (JdF) data from M.R. Perfit (personal communication) and this study.

7.4 Concluding Remarks and Future Research

The Vance seamount lavas, similar to other near-ridge seamount lavas, display a large range of isotopic compositions ($^{87}\text{Sr}/^{86}\text{Sr}$ from 0.702473 to 0.702755, $^{143}\text{Nd}/^{144}\text{Nd}$ from 0.513048 to 0.513182, and $^{206}\text{Pb}/^{204}\text{Pb}$ from 18.12 to 18.82) best explained by melt-induced mixing of heterogeneous upper mantle source. The Vance seamount lava compositions are consistent with other isotopic data from northeast Pacific lavas, and support the presence of at least two components (with DM and HIMU-like characteristics) in the underlying mantle.

The origin and implications of the distinctive Vance A and Vance B lava compositions remain open to further investigation. Additional isotopic analyses as well as the full integration of trace element data will likely improve the understanding of these lavas. Further research into recent experimental petrology studies would also help to support (or discount) certain ideas put forth in this thesis. A better understanding of the Vance A and Vance B geochemical variations is necessary before improvements and details can be added to the proposed two-step melting process.

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APPENDIX I RADIOGENIC ISOTOPE SYSTEMS

Rubidium-Strontium (Rb-Sr)

Rubidium has two naturally occurring isotopes: ^{85}Rb (72.17%), and ^{87}Rb (27.83%), which is radioactive. Rubidium is geochemically similar to potassium, allowing for substitution of Rb^+ for K^+ in K-bearing minerals such as mica and alkali feldspar (Faure and Mensing, 2005). Radioactive ^{87}Rb decays to stable ^{87}Sr by the emission of a β particle, and is thus the isotope of interest. The rubidium half-life has been calculated to be 48.8 billion years (Byr) (Steiger and Jaeger, 1977).

Strontium has four naturally occurring, stable isotopes: ^{88}Sr (82.58%), ^{87}Sr (7.0%), ^{86}Sr (9.86%), and ^{84}Sr (0.56%). Strontium is geochemically similar to calcium, allowing for substitution of Sr^{2+} for Ca^{2+} in Ca-bearing minerals such as plagioclase feldspar and apatite (Faure and Mensing, 2005).

Fractional crystallization of a magma concentrates Sr in plagioclase while Rb prefers to remain in the melt. Therefore, the Rb/Sr ratio of a magma increases with increased fractional crystallization.

Samarium-Neodymium (Sm-Nd)

Neodymium has seven naturally occurring isotopes: ^{142}Nd (27.2%), ^{143}Nd (12.2%), ^{144}Nd (23.8%), ^{145}Nd (8.3%), ^{146}Nd (17.2%), ^{148}Nd (5.7%), and ^{150}Nd (5.6%). Samarium also has seven naturally occurring isotopes: ^{144}Sm

(3.1%), ^{147}Sm (15.0%), ^{148}Sm (11.2%), ^{149}Sm (13.8%), ^{150}Sm (7.4%), ^{152}Sm (26.7%), and ^{154}Sm (22.8%). The isotope of interest, ^{147}Sm , is radioactive and decays to stable ^{143}Nd by the emission of an α particle ($t_{1/2} = 106$ Byr).

Sm and Nd are both light rare earth elements and are found in trace amounts in common rock-forming minerals such as feldspar, biotite, and apatite (Faure and Mensing, 2005). The ionic radius of Nd is slightly larger than that of Sm; as a result, partial melting of the mantle preferentially concentrates Nd in the liquid phase. Basaltic magmas, therefore, have lower Sm/Nd ratios than their source rocks. Sm-Nd together with Rb-Sr provide complementary data, as depleted upper mantle evolves to higher $^{143}\text{Nd}/^{144}\text{Nd}$ but lower $^{87}\text{Sr}/^{86}\text{Sr}$ than oceanic or continental crust.

Uranium-Thorium-Lead (U-Th-Pb)

Lead has four main isotopes: ^{208}Pb (52.4%), ^{207}Pb (22.1%), ^{206}Pb (24.1%), and ^{204}Pb (1.4%). Uranium and Thorium follow a complex chain of decay paths all ending with a stable Pb isotope: $^{238}\text{U} \rightarrow ^{206}\text{Pb}$ ($t_{1/2} = 4.47$ Byr), $^{235}\text{U} \rightarrow ^{207}\text{Pb}$ ($t_{1/2} = 0.704$ Byr), $^{232}\text{Th} \rightarrow ^{208}\text{Pb}$ ($t_{1/2} = 14.01$ Byr); ^{204}Pb is the only stable Pb isotope, and is therefore used as a reference.

Uranium and Thorium are both members of the actinide series of elements and readily substitute for one another. Highest concentrations of U and Th are found in accessory minerals, rather than common rock-

forming minerals (Faure and Mensing, 2005). Partial melting of the mantle preferentially concentrates U and Th compared to Pb, resulting in crustal rocks with higher U/Pb and Th/Pb ratios than their mantle source.

APPENDIX II ANALYTICAL METHODS

Electron Microprobe Methods

The major element data reported in Appendix III were acquired with the use of a Camebax (Cameca) MBX electron microprobe equipped with four WDX (wavelength dispersive x-ray) spectrometers. The instrument is located in the Department of Earth Sciences at Carleton University.

The microprobe was operated with a 15 kV accelerating voltage and a 20 nA beam current over a raster area of 5x5 to 10x10 microns. Peak counting times of 15-60 seconds or 30,000 accumulated counts were used, depending on the element. A suite of well characterized natural and synthetic minerals and compounds were used as calibration standards.

Raw data were converted to elemental wt. % by the Cameca PAP matrix correction program and into mineral formulae using the MINREP program by G.J. Pringle (1995). Analyses are accurate to 1-2 % of the quoted values for major elements (> 10 wt. %), and 3-10 % for minor elements (0.5 to 10 wt. %).

Digital BSE (back-scatter electron) images were collected with an Electron Optic Services digital imaging system at 512 x 512 pixel resolution with a Lamont 4 element solid state BSE detector and BSE Quad Summing

Amplifier interfaced to a 4Pi Analysis Inc. digital imaging and EDX x-ray system and Power Macintosh computer.

Data for the microprobe analyses of olivine, plagioclase, and glass can be found in Appendix III. Olivine formulae are calculated on the basis of 4 oxygens and are expressed in terms of the end member composition Mg_2SiO_4 (forsterite; Fo). Feldspar analyses are recalculated on the basis of 16 oxygens and stated in terms of the molecular percentage of $\text{CaAl}_2\text{Si}_2\text{O}_8$ (anorthite, An).

Isotope Geochemistry and Mass Spectrometry Methods

Procedural steps for Sr, Nd, and Pb isotope analyses included crushing, acid washing, dissolution, column chromatography, filament loading, and mass spectrometry. All chemistry and mass spectrometry was performed at the Isotope Geochemistry and Geochronology Research Center (IGGRC) at Carleton University, Ottawa, Canada. The mass spectrometer used was a ThermoFinnigan Triton TI, operated in static mode. The chemical procedures, originally published by Cousens (1996b), are outlined below.

Sample Preparation: Clean glass samples (i.e. free of visible Mn-oxide crust) were handpicked using a binocular microscope. The samples were then hand-crushed in a two-step process using both a steel and an

agate mortar and pestle. The powders were weighed and split into two fractions: (1) 400 mg for Sr chemistry, (2) 300 mg for Pb and Nd chemistry.

Acid Washing: The acid washing step proved to be critical in the success of the analyses. The standard laboratory procedures were insufficient for some of the Sr samples (i.e. the seawater contamination was not entirely eliminated) and too harsh for some of the Pb samples (i.e. too much lead was leached from the sample prior to dissolution). Many samples were processed and analyzed multiple times in order to achieve a satisfactory analysis. The modifications resulted in improved data; however, further work could be done in order to perfect the acid washing methods for NRS glasses.

Sr Split: The Sr split was originally washed for four days in hot ($\sim 125^{\circ}\text{C}$) 6N HCl, rinsed with ultrapure H_2O , and washed for an additional four days in hot 2N HCl. The strong and lengthy washing was designed to eliminate contamination from seawater Sr. The glassy material, however, did not survive the acid wash, turning to a gel-like substance that could not be separated from the leachate. Many of the samples were re-processed with only four days of acid washing in hot 6N HCl. Enough material was preserved with the shorter wash, but minor to significant seawater contamination is still present in the data.

Pb/Nd Split: The original washing procedure used 200 mg of sample that was then washed in 1.5N HCl and put on a hot plate for 24 hours. This proved to be too strong for volcanic glass samples with low lead contents, since no lead signal could be detected or analyzed from the final sample. The sample size was increased to 300 mg, the HCl-washing procedure was shorted to 1 hour in 1.5 N HCl, and the beakers were placed in a room-temperature ultrasonic bath (with the water level below the cap) for agitation (rather than on a hot plate). The samples were then rinsed with ultrapure H_2O and ready for dissolution. The lead level was still often very low, but usually high enough for an acceptable analysis.

Dissolution: Rock powders were dissolved in three steps: (1) 50% HF + 16N HNO₃, (2) 7N HNO₃, and (3) 6N HCl. Following complete dissolution, the dried residue from the Sr split was taken up in 2.5N HCl and the dried residue from the Pb/Nd split was taken up in 1N HBr.

Separation: Ion-exchange column chromatography was used to isolate the various elements of interest. The dissolved Sr split was centrifuged and loaded into 14-mL Bio-Rad borosilicate glass chromatography columns with 3 mL of Dowex 50-X8 cation resin. Sr was eluted with 2.5N HCl.

Pb was separated from the Pb/Nd split using Bio-Rad 10-mL polyethylene columns and Dowex AG1-8X anion resin, using 1N HBr to elute other elements and 6N HCl to elute Pb. Samples were centrifuged prior to loading. The captured HBr solution (containing the rare earth elements) was dried and the residue taken up in 2.5N HCl.

The rare earth elements (REE) were separated with the Sr columns (as above), but using 6N HCl. The REE fraction, dried and dissolved in 0.26N HCl, was loaded into 14 mL Bio-Rad borosilicate glass chromatographic columns containing a 2 cm-high bed of Teflon powder coated with HDEHP [di(2-ethylhexyl) orthophosphoric acid, Richard *et al.* 1976]. Nd was then eluted using 0.26N HCl. The final batch of samples (4 from the Vance segment) was processed in similar fashion on a set of Eichrom 2ml pre-packed LN resin columns.

Mass Spectrometry:

Lead: Pb was loaded onto single Re filaments with phosphoric acid (H_3PO_4) and silica gel. While there are no stable Pb isotopes to provide a fractionation correction, the $^{208}\text{Pb}/^{206}\text{Pb}$ ratio was monitored during the runs and used to monitor fractionation effects. Measured ratios for NBS 981 averaged $^{206}\text{Pb}/^{204}\text{Pb} = 16.893 \pm 17$ (2σ), $^{207}\text{Pb}/^{204}\text{Pb} = 15.432 \pm 22$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.515 \pm 73$ ($n=39$). Two different loading gels were used (one for the seamount samples, and one for the ridge samples), and all analyses were appropriately corrected for fractionation based on the values of Todt *et al.* (1984).

Strontium: Sr was loaded onto single Ta filaments with H_3PO_4 . Isotope ratios are normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.11940$ to correct for fractionation. Two standards are run at the IGGRC, NBS987 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710258 \pm 22$, $n=16$) and the Eimer and Amend (E&A) SrCO_3 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.708027 \pm 15$, $n=9$).

Neodymium: Nd samples were loaded on one side of a Re double filament with H_3PO_4 . Isotope ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$ to correct for fractionation. Analyses of the Nd Std standard averaged $^{143}\text{Nd}/^{144}\text{Nd} = 0.511817 \pm 8$ ($n=28$). Analysis of the La Jolla standard averaged $^{143}\text{Nd}/^{144}\text{Nd} = 0.511847 \pm 6$ ($n=13$).

Isotope ratios for the various standards correspond closely to those obtained by other laboratories, and no correction to measured ratios in samples has been made. The ratios are averaged from all standards run at the IGGRC during the study period. The uncertainties quoted for the standards are 2 standard deviations of the mean over the entire dataset.

APPENDIX III SUPPLEMENTARY MICROPROBE DATA

Plagioclase Analyses

Seamount	Vance A	Vance A	Vance A	Vance B	Vance C	Vance C	Vance C	Vance C	Vance E	Vance G
Sample	T1008-R05a	T1008-R05a	T1008-R20	T1012-R01	T1013-R02	T1013-R18	T1013-R21	T1011-R12	T1014-R18	
Analysis	8-5a-2	8-5a-3	8-20-2	12-1-3	13-2-2	13-18-2	13-21-3	11-12-2	14-18-2	
SiO ₂	51.59	51.11	50.77	49.60	47.80	48.74	50.65	51.30	51.55	
Al ₂ O ₃	31.39	31.99	30.72	31.97	32.83	32.98	30.77	28.30	30.84	
Fe ₂ O ₃	1.00	0.76	0.71	0.64	0.59	0.68	0.82	1.62	0.81	
K ₂ O	0.07	0.06	0.07	0.02	0.01	0.01	0.04	0.03	0.06	
CaO	14.92	15.31	14.65	15.49	16.94	16.78	15.10	14.17	14.46	
Na ₂ O	3.02	2.95	3.08	2.70	1.79	2.08	2.94	3.29	3.30	
BAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
TOTAL	101.99	102.18	100.00	100.42	99.96	101.27	100.32	98.71	101.02	
Feldspar formulae calculated on the basis of 16 oxygen										
Si	4.618	4.570	4.632	4.517	4.391	4.417	4.613	4.748	4.652	
Al	3.312	3.371	3.303	3.432	3.554	3.522	3.303	3.087	3.281	
Fe ³⁺	0.067	0.051	0.049	0.044	0.040	0.047	0.056	0.113	0.055	
Total	7.997	7.992	7.984	7.993	7.985	7.986	7.972	7.948	7.988	
K	0.008	0.007	0.008	0.002	0.002	0.001	0.005	0.004	0.007	
Ca	1.431	1.466	1.432	1.512	1.667	1.629	1.474	1.406	1.398	
Na	0.524	0.512	0.545	0.477	0.318	0.366	0.519	0.590	0.578	
Ba	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Total	1.963	1.985	1.985	1.991	1.987	1.996	1.998	2.000	1.983	
An Content	72.90	73.85	72.14	75.94	83.90	81.61	73.77	70.30	70.50	

Uncertainty of $\pm 1\%$ for major elements, $\pm 3-10\%$ for minor elements.

An = $[Ca/(Ca+Na+K)*100]$

Olivine Analyses

Seamount Sample Analysis	Vance A T1008-R20 8-20-1	Vance B T1012-R01 12-1-2	Vance B T1012-R08 12/8/02	Vance B T1012-R21 12/21/02	Vance C T1013-R21 13-21-2	Vance E T1011-R01 11/1/02	Vance E T1011-R01 11/1/03	Vance F T1007-R02 7/2/02	Vance F T1007-R16 7/16/02	Vance F T1007-R16 7/16/04	Vance F T1007-R17 7-17-1	Vance F T1007-R17 7-17-2
						core	rim					
SiO ₂	39.88	40.46	41.07	41.40	40.79	41.19	40.72	41.30	40.77	41.11	41.13	40.72
Al ₂ O ₃	0.05	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.07	0.08
FeO ⁺	14.71	13.97	11.10	11.59	11.69	11.56	12.64	10.00	10.77	10.81	10.30	10.54
MgO	45.56	45.78	47.56	47.97	47.73	47.96	47.14	48.83	48.33	48.72	48.60	49.19
MnO	0.24	0.22	0.15	0.15	0.19	0.09	0.16	0.15	0.21	0.16	0.19	0.17
CaO	0.38	0.37	0.30	0.29	0.34	0.30	0.26	0.31	0.33	0.30	0.28	0.32
NiO	0.16	0.26	0.36	0.26	0.17	0.24	0.38	0.27	0.32	0.24	0.30	0.32
Total	100.98	101.06	100.54	101.66	100.99	101.34	101.30	100.86	100.73	101.34	100.87	101.34
Olivine formulae calculated on the basis of 4 oxygen												
Si	0.992	1.001	1.008	1.006	0.999	1.004	0.999	1.005	0.998	0.999	1.002	0.990
Al	0.001	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.002	0.002
Total	0.993	1.001	1.008	1.006	1.001	1.004	0.999	1.005	0.998	0.999	1.004	0.992
Fe ²⁺	0.306	0.289	0.228	0.235	0.239	0.236	0.259	0.203	0.221	0.220	0.210	0.214
Mg	1.689	1.689	1.739	1.737	1.743	1.742	1.724	1.771	1.764	1.766	1.765	1.783
Mn	0.005	0.005	0.003	0.003	0.004	0.002	0.003	0.003	0.004	0.003	0.004	0.004
Ca	0.010	0.010	0.008	0.008	0.009	0.008	0.007	0.008	0.009	0.008	0.007	0.008
Ni	0.003	0.005	0.007	0.005	0.003	0.005	0.008	0.005	0.006	0.005	0.006	0.006
	2.013	1.998	1.985	1.988	1.998	1.993	2.001	1.990	2.004	2.002	1.992	2.015
Fo content	83.90	84.53	87.61	87.37	87.24	87.41	86.16	88.99	88.02	88.21	88.60	88.49

Uncertainty of $\pm 1\%$ for major elements, $\pm 3-10\%$ for minor elements.

Fo = $[\text{Mg}/(\text{Mg}+\text{Fe}^{2+}) \times 100]$

Glass Analyses

Seamount Sample	Vance A T1008-R05a	Vance A T1008-R20	Vance A T1008-R23	Vance B T1012-R01	Vance B T1012-R08	Vance B T1012-R14a	Vance B T1012-R21	Vance B T1012-R21	Vance B T1012-R21	Vance C T1013-R02
Analysis	8-5a-1	8-20-3	8-23-1	12-1-1	12-8-1	12-14A-1	12-21-1	12-21-1	12-21-2	13-2-1
SiO ₂	50.02	49.73	50.13	48.06	47.89	47.46	48.03	48.23	48.23	49.82
Al ₂ O ₃	16.13	15.10	15.96	16.17	17.24	17.14	17.51	17.68	17.68	15.18
TiO ₂	1.39	1.68	1.18	1.41	1.28	1.18	1.21	1.21	1.21	0.96
CR ₂ O ₃	0.07	0.06	0.05	0.06	0.00	0.06	0.03	0.07	0.07	0.04
FeO [†]	8.77	9.89	9.12	10.86	9.90	9.72	9.38	9.56	9.56	9.44
MgO	8.36	7.38	8.69	8.03	9.28	9.27	8.92	9.03	9.03	8.93
MnO	0.17	0.14	0.12	0.23	0.16	0.26	0.15	0.14	0.14	0.18
K ₂ O	0.24	0.34	0.11	0.08	0.07	0.03	0.05	0.05	0.05	0.07
CaO	12.13	11.66	12.34	11.51	11.48	11.48	11.53	11.40	11.40	12.63
Na ₂ O	2.55	2.66	2.62	3.02	2.88	2.84	2.88	2.96	2.96	2.30
P ₂ O ₅	0.17	0.22	0.10	0.06	0.06	0.01	0.10	0.09	0.09	0.03
S	0.08	0.12	0.07	0.08	0.10	0.08	0.10	0.09	0.09	0.08
Cl	0.06	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.01
Total	100.14	98.98	100.50	99.57	100.34	99.53	99.91	100.51	100.51	99.67
Mg#	65.36	59.63	65.35	59.41	64.98	65.37	65.31	65.16	65.16	65.19

Uncertainty of $\pm 1\%$ for major elements, $\pm 3-10\%$ for minor elements.

FeO[†], all iron as FeO

Mg# = $\text{Mg}/(\text{Mg}+\text{Fe}^{2+}) \times 100$, where $\text{Fe}^{2+} = 0.9 \times \text{FeO}^{\dagger}$

Glass Analyses (cont.)

Seamount	Variance C	Variance C	Variance C	Variance E	Variance E	Variance E	Variance E	Variance E	Variance F	Variance F	Variance F
Sample	T1013-R17	T1013-R21	T1013-R30	T1011-R01	T1011-R07	T1011-R12	T1011-R27	T1007-R02	T1007-R02	T1007-R16	T1007-R16
Analysis	13-17-1	13-21-1	13-30	11-1-1	11-7-1	11-12-1	11-27-1	7-2-1	7-2-1b	7-16-1	7-16-1
SiO ₂	49.54	50.12	50.09	51.01	51.45	50.84	49.78	49.09	48.45	48.86	48.86
Al ₂ O ₃	17.05	15.09	15.06	15.59	14.47	14.69	15.14	18.02	17.99	16.70	16.70
TiO ₂	0.92	0.94	1.07	1.02	1.48	1.21	1.20	0.96	0.96	1.37	1.37
Cr ₂ O ₃	0.04	0.12	0.07	0.09	0.08	0.06	0.06	0.00	0.03	0.05	0.05
FeO [†]	8.64	8.72	9.18	9.61	10.20	10.38	9.67	7.92	8.15	8.67	8.67
MgO	9.61	8.79	8.46	9.16	7.49	7.95	8.69	9.53	9.30	8.95	8.95
MnO	0.16	0.17	0.14	0.12	0.19	0.24	0.18	0.13	0.11	0.13	0.13
K ₂ O	0.04	0.06	0.08	0.09	0.12	0.10	0.08	0.01	0.04	0.07	0.07
CaO	12.47	13.02	12.94	11.16	12.10	12.48	12.31	12.25	12.45	11.86	11.86
Na ₂ O	2.20	2.37	2.21	2.19	2.65	1.80	2.41	2.45	2.64	2.89	2.89
P ₂ O ₅	0.06	0.05	0.11	0.03	0.10	0.11	0.09	0.06	0.06	0.09	0.09
S	0.08	0.08	0.12	0.06	0.09	0.07	0.09	0.08	0.09	0.08	0.08
Cl	0.00	0.01	0.03	0.01	0.02	0.00	0.02	0.00	0.00	0.00	0.00
Total	100.83	99.54	99.56	100.14	100.44	99.93	99.72	100.50	100.27	99.72	99.72
Mg#	68.77	66.62	64.59	65.36	59.25	60.26	64.02	70.43	69.32	67.14	67.14

Glass Analyses (cont.)

Seamount	Vance F	Vance G	Vance G	Vance G	Vance G	Vance G
Sample	T1007-R17	T1014-R04	T1014-R13	T1014-R18	T1014-R22	
Analysis	7-17-1	14-4	14-13-1	14-18	14-22-1	
SiO ₂	48.71	51.23	50.29	50.77	50.66	
Al ₂ O ₃	16.50	14.39	14.87	14.89	14.17	
TiO ₂	1.33	1.41	1.32	1.40	1.39	
Cr ₂ O ₃	0.05	0.03	0.05	0.08	0.00	
FeO ¹	8.48	9.69	9.55	9.69	10.09	
MgO	9.13	7.48	8.06	7.87	7.51	
MnO	0.13	0.21	0.19	0.20	0.18	
K ₂ O	0.08	0.12	0.11	0.14	0.11	
CaO	11.72	12.36	12.18	12.38	12.22	
Na ₂ O	2.95	2.69	2.70	2.74	2.84	
P ₂ O ₅	0.08	0.13	0.10	0.09	0.13	
S	0.06	0.09	0.09	0.12	0.08	
Cl	0.00	0.01	0.03	0.03	0.00	
Total	99.22	99.84	99.54	100.40	99.38	
Mg#	68.07	60.45	62.56	61.65	59.57	