RIDGE 2000 Integrated Study Site Proposal for Hotspot-Influenced Oceanic Spreading Centers: Iceland and the Reykjanes and Kolbeinsey Ridges

Summary

We propose that the Reykjanes Ridge, Iceland, and the Kolbeinsey Ridge be the integrated study site for hotspot-influenced spreading centers. Whereas previous RIDGE efforts have focused on spreading rate as the primary variable, the Iceland-MAR system offers an opportunity to examine how mantle temperature and source compositions influence processes in the mantle and crust, and how such processes influence and are affected by hydrothermal venting and biological communities along mid-ocean ridges. Because of the vastly different intrinsic length scales of processes from mantle to microbes at hotspot-influenced spreading centers, the comprehensive investigations outlined in the RIDGE Integrated Studies Program will have to be carried out in nested study areas, where regions of small-scale processes (e.g., vent) are encompassed by the study areas of large-scale processes (e.g., mantle flow). We envision that integrated studies in this area will first involve a characterization of long-wavelength variations in physical structure, chemistry, hydrothermal venting, and biological communities over the region of plume influence (~MAR 57º-71.5ºN). This characterization will fill in the gaps of an already extensive database. It will then be followed by studies focused on the linkages between the crust, hydrothermal circulation, and biological communities at an active volcanic and hydrothermal area (such as the Steinahóll vent site on the Reykjanes Ridge 63º06'N) to examine variations on length scales of tens of kilometers. A secondary submarine site at a different end of the spectrum of plume influence will provide a comparison for isolating the effects of plume influence from that of spreading rate and oblique plate-spreading if the primary site is on the Reykjanes Ridge. These integrated investigations, together with complementary studies of temporal (off-axis) variations, analog studies on Iceland, and theoretical and laboratory works, will provide a new understanding of the role of mantle temperature and source composition in mid-ocean ridge processes.

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> “Each (integrated study) site will become the focus of a comprehensive array of observations and experiments encompassing all the disciplines, becoming a reference against which variability at other parts of the system can be measured and understood.” -- RIDGE 2000 Report

1. Justification of Iceland and the Reykjanes and Kolbeinsey Ridges as a RIDGE 2000 Integrated Study Site

Hotspot-influenced spreading centers provide natural laboratories to study how mantle temperature and source composition affect the creation of the oceanic lithosphere and the associated hydrothermal circulation and biological communities. At least 18 hotspots have been identified to produce physical and chemical anomalies at mid-ocean ridges (http://triton.ori.u-tokyo.ac.jp/~intridge/hotspot.htm). Collectively they affect approximately 20% of the global mid-ocean ridge system. Hotspot-influenced spreading centers have been found to have systematic variations in along-axis seafloor depth, axial morphology, gravity, crustal thickness, and basalt chemistry. These systematic variations have been commonly interpreted as the result of along-axis flow of mantle plume material and mixing of the plume and normal mid-ocean ridge basalt (MORB) sources. However, how these variations in the crust and mantle affect and are affected by hydrothermal and biological activities remain largely unexplored, and a detailed understanding of the solid-earth processes at hotspot-influenced spreading centers has been elusive. To date, the RIDGE program has focused primarily on comparative studies of spreading centers with different spreading rates (fast-, intermediate-, or slow-spreading). Numerous studies have found, however, that mantle temperature and source composition are two major factors, other than spreading rate, that control ridge crest processes. For example, the global systermatics of ridge axial depths and major elements in MORB and mantle peridotites have been attributed to along-axis variations in mantle temperature and source composition [e.g., *Dick*, 1984; *Klein and Langmuir*, 1987; *Shen and Forsyth*, 1994]. Hotspot-influenced spreading centers, usually with fairly constant spreading rates, offer a natural setting to separate the control of mantle temperature and source composition on ridge processes from that of spreading rate. Given the large proportion of hotspot-influenced spreading centers and the demonstrated importance of mantle temperature and source composition, integrated studies at a hotspot-influenced spreading center, from mantle to microbes, is essential to our understanding of the global mid-ocean ridge system.

The Iceland hotspot and the Reykjanes and Kolbeinsey Ridges (RR and KR) is a relatively well studied, classic example of a hotspot interacting with a spreading center. The broad bathymetric swell and V-shaped topographic and gravity anomalies on the RR have been attributed to along-axis passage of anomalously hot mantle from the Iceland mantle plume [e.g., *Vogt*, 1971; *White et al.*, 1995]. Along-axis gradients in trace-element and isotope compositions in basalts suggest mixing of the plume and MORB sources [e.g., *Schilling*, 1973b]. Crustal thickness increases from 8-10 km on the RR and KR to 40 km beneath central Iceland [*Ritzert and Jacoby*, 1985; *Bjarnason et al.*, 1993; *Smallwood et al.*, 1995; *Kodaira et al.*, 1997; *Darbyshire et al.*, 1998; *Weir et al.*, 2000], reflecting progressively greater decompressional melting due to higher mantle temperatures and/or upwelling flux than beneath normal mid-ocean ridges. In spite of their slow-spreading rates (~18 mm/yr full rate), the northern RR and southern KR display axial high, ridge morphology usually found at fast-spreading centers. Furthermore, there is evidence for a magma chamber 2.5 km below the RR at 57.75ºN [*Navin et al.*, 1998; *Gill et al.*, 2000]. The RR has no major, first order segmentation, a fact that has been ascribed to the presumably especially high crustal temperatures and thus weak lithosphere that fails to develop large faults [*Francis*, 1969; *Bell and Buck*, 1992]. Recent broadband seismic experiments on Iceland reveal clearly a low-velocity anomaly down to at least 400-km depth [*Wolfe et al.*, 1997; *Allen et al.*, 1999; *Foulger et al.*, 2000; *Allen* 2001] and an anomalously thin and hot mantle transition zone beneath Iceland [*Shen et al.*, 1998], making Iceland so far the only spreading-center-related hotspot having *in situ* observations linking surface and shallow anomalies to a deep-rooted mantle plume. The seismological estimates of the excess temperature of the plume are 150-300 K [*Wolfe et al.*, 1997; *Shen et al.*, 1998; *Allen* 2001], consistent with the estimates based on basalt chemistry and other measures of shallow plume influences [e.g., *Schilling*, 1991; *White et al*., 1995]. No other hotspot has such seismological constraints on mantle temperature.

Its existence as a classic example of plume-ridge interaction is, however, not the foremost reason as a candidate for a RIDGE 2000 Integrated Study Site. The primary importance of Iceland-Mid-Atlantic Ridge (MAR) system as an integrated study site is that it is ideally suited to address fundamental questions of the mantle-temperature and source-composition controls on the global mid-ocean ridge system. For basalt samples from the RR and KR, $Na_{8.0}$ (Na_2O normalized to 8 wt% MgO) decreases and $Fe_{8.0}$ (FeO normalized to 8 wt% MgO) increases as the water depth shallows [e.g., *Langmuir et al*., 1992], consistent with the correlations among these parameters from the global mid-ocean ridge system [*Klein and Langmuir*, 1987]. Thus, an integrated study at Iceland and the adjacent MAR will have direct implications for the dominant effects of mantle temperature and source composition on the global mid-ocean ridge system and will provide a reference against which variability in the global mid-ocean ridge system in general and other Integrated Study Sites in particular can be measured and understood. In contrast, for data from the ridge segments adjacent to Galápagos and Azores, $Na_{8.0}$ increases and $Fe_{8.0}$ decreases towards the shallowest segment of the ridge near the hotspots and their relationship with depth is opposite to that observed globally [e.g., *Schilling*, 1986; *Schilling et al*., 1982; *Langmuir et al*., 1992]. While this anomalous correlation is intriguing, the implications of the geochemical systermatics observed at Galápagos and Azores for the global mid-ocean ridge system are not as straight forward as for Iceland.

Iceland and the RR and KR have the following other attributes that are desirable as a RIDGE 2000 Integrated Study Site:

- The proposed site has biologically-relevant characteristics unavailable at other ridge sites: A range of water depths from intertidal to normal mid-ocean ridge depth, and a terrestrial break in the marine habitat continuity along the ridge. Seasonal ice cover over parts of the system contributes to the unique opportunities available at this site. These three features make this site especially compelling for pursuit of biogeographical questions that link overlying water column characteristics (circulation and productivity) with vent-specific biology.
- The transition from subaerial to submarine eruption provides an ideal natural laboratory to study volatile degassing as a function of depth. The extent of volatile outgassing from magmas affects the morphology of magmatic eruptions, constructional volcanic features and magnetic properties. Decreasing solubility of H_2O, as eruption depths shallow to less than ~500 m depth along the RR has been shown to strongly influence degassing of other volatiles including He, CO_2, Cl, and Br [e.g., *Schilling*, 1986; *Poreda et al*., 1986; *Michael and Schilling*, 1989; *Dixon et al*., 1988, 1995a,b].
- The Iceland Seismic Network (SIL) provides long-term, real-time monitoring of seismic and magmatic activities on Iceland and the adjacent submarine portions of the MAR, allowing rapid-response expeditions that can gather data while the eruption is still in progress or shortly after the event [*Nishimura et al*., 1989; *Ólafsson et al*., 1991; *Crane et al*., 1997]. SIL earthquake catalogs show that magnitude M_L 2 events can be detected at the RR 60º-61ºN and M_L 1-2 events at 62ºN. For comparison, the minimum magnitude threshold for events in the northeast Pacific on the omni-directional SOSUS hydrophones, which detected the 1993 magmatic event on the northern Juan de Fuca Ridge [e.g., *Schreiner et al*., 1995], is about M_L=2.5 [*Fox*, 1994]. A combination of the SIL, Norwegian seismic array (including a station on Jan Mayen), and SOSUS hydrophones [*Blackman et al*., 2000] can be used to monitor seismicity at the entire Nordic mid-ocean ridges.
- Both the RR and KR display a wide range of ridge morphologies: axial valley, transitional morphology, and axial high. The axial high at these slow-spreading ridge segments represents a clean case of the effect of excess magma supply on ridge morphology without the ambiguity of the spreading-rate effects at intermediate-spreading ridges (axial morphology is sensitive to changes in spreading rate at intermediate-spreading centers) [*Chen and Phipps Morgan*, 1990; *Phipps Morgan and Chen*, 1993]. The RR has minimal

variation in spreading rate and degree of axial segmentation and therefore provides an opportunity to best isolate the effects of magma production, whereas large transform offsets along the KR allow us to examine the effects of transform faults.

- Over Iceland, there is a well-documented history of ridge segment jumps from west to east toward the current Iceland plume center [e.g., *Hardarson et al*., 1997]. These observations will allow us to study how rift relocations occur and in particular, how mantle flow and volcanism influences the location and geometry of plate spreading.
- The proposed site is ideally suited to examine how plume material is transported specifically along a ridge axis. The system is not subject to the complication introduced by the component of transport perpendicular to the ridge axis like the case for off-axis hotspots. Furthermore, because the ridge transects the center of the Iceland plume, it allows direct and continuous geochemical sampling of the plume-ridge system with minimal influence of the lithosphere or off-axis volcanism.
- As represented by the V-shaped ridges on the RR, plume anomalies at the proposed site are spatially and thus temporally separated. The different along-axis wavelengths of geophysical and geochemical anomalies [e.g., *Schilling*, 1986] provide information about the melting processes, the mixing of the plume and MORB sources, or the internal chemical layering of the plume. The spatial separation of plume anomalies is also important for resolving their mantle seismic structure with minimum lateral smearing. The imaging of the mantle structure over a broad region for any major plume-ridge system requires the use of surface waves having wavelengths of 80-500 km. Long-period (20-120 s) surface waves are necessary to resolve velocity structures at the depths of the onset of melting and plume material (100-200 km or deeper) because fundamental Rayleigh waves, for example, are most sensitive to the shear wave structure at a depth (in km) of about 4/3 times the dominant wave period (in sec) [*Forsyth*, 1992]. The proximity of the Greenland and European coasts makes it possible to use land-based, truly broadband seismometers [compared to the current short-period (1 Hz) and wide-band (0.02 - 30 s) OBS sensors] to record long-period teleseismic and regional surface waves that traverse the proposed site.
- Understanding plume-ridge interaction requires that manifestations of this interaction be understood not only as a function of distance along a ridge, but also as a function of time. The V-shaped ridges along the RR are among the most prominent evidence for temporal variation in magma production along a mid-ocean ridge. Longer period variations are also evident [*Hanan and Schilling*, 1997] and a considerable body of work on the rifted margins both east and west of the RR provides the framework for understanding the earliest evolution of plume-ridge interaction [e.g., *Dahl-Jensen et al*., 1997].
- Subaerial exposure of the MAR on Iceland offers unique opportunities to examine tectonic and volcanic processes along a mid-ocean ridge. It offers many logistical advantages to experiments. In certain cases (geodetic measurements, for example), the subaerial exposure of the MAR may provide the sites for analog studies of fundamental processes of mid-ocean ridges that are not physically accessible or difficult in the seafloor environment.
- Collaborations with Icelandic scientists and other Europeans, who actively study the region, help defray cost, facilitate logistics, and enhance science.

2. Scientific Questions to be Addressed

The overarching goal of the integrated study is to understand the interactions and linkages among mantle flow, melt generation and migration, crustal accretion, ridge segmentation, axial morphology, hydrothermal circulation and biological communities. The following is a list of the major scientific questions that can be addressed, each of which pertain to one or more of the fundamental questions defined in the RIDGE 2000 Science Plan (a more extensive list of questions can be found at http://espo.gso.uri.edu/~yang/RIDGE-IS.html).

How is plume material supplied to nearby submarine mid-ocean ridges? The presence of well-developed bathymetric and geochemical gradients away from Iceland suggests that plume material is somehow transported away from the plume. However, whether this flow is restricted to narrow channels or is broader and radially symmetric remains unclear. Furthermore, the asymmetry in apparent plume dispersal to the north and south of Iceland remains enigmatic.

What are the lithosphere-asthenosphere interactive processes that influence ridge geometry? Rift relocations have been documented on Iceland, however, the mechanism of rift relocation remains poorly understood. Do variations in plume flux cause rift relocations? In addition, the current co-existence of the overlapping west and east neovolcanic zones on Iceland provides an opportunity to study a case of active ridge propagation.

What is the ultimate "origin" of the geochemical anomalies and gradients? What are the causes behind the different wavelengths of variation observed for trace elements and isotopes with varying degrees of volatility and compatibility in melt generation? Are all the V-shaped ridges correlated isotopically and in time to variations in plume flux recorded in the Iceland Tertiary basalts [*Vogt*, 1971; *Watkins and Walker*, 1977*; McDougall et al*., 1977 and 1984; *White et al*., 1995; *Hanan and Schilling*, 1997]? Although mixing of the plume and ambient MORB mantle have been called upon to explain the geochemical gradients, the relative contributions of various mantle source components to the erupted magmas depends on the details of the melting process as well as the relative abundance of the components. Two comprehensive geochemical, petrological, and isotopic studies in progress of closely spaced (at 2-5 km intervals) samples from the RR and KR acquired recently under the BRIDGE program and by scientists from the University of Kiel should help considerably to address these questions.

What is the coupling between magma supply, ridge morphology, magma lens properties, and hydrothermal flux? Is the Iceland crust hot or “cool” [*Menke and Sparks*, 1995; *Allen*, 2001]? How does hydrothermal circulation affect the structure, composition, and morphology of the oceanic crust? How does degassing contribute to hydrothermal vent fluids and biologic activity? The large crustal thickness variation along the MAR near Iceland provides a natural setting to examine the effects of a maximal range of the magma supply variable.

How does a hotspot influenced ridge dissipate the excess heat associated with excess magma supply? The RR exhibits the morphology of a fast-spreading ridge from Iceland to 59ºN, and is decorated by 42 axial volcanic ridges (AVR) [*Searle and Laughton*, 1981; *Parson et al*., 1993; *Keeton et al*., 1997], one of which is known to be underlain by a magma chamber [*Sinha et al*., 1998]. On Iceland, there are huge geothermal fields. Given these facts, one might expect the RR and KR to be more hydrothermally-active than most of the MAR. Yet, only four unequivocal sites of focused hydrothermal venting have been located, all of which are in shallow water near Iceland (see Background section). The presence or lack of vents at greater depths provides information about the geologic controls on vent distribution. Is the failure to locate vents so far mainly due to the water column search strategy, as suggested by *German and Parsons* [1998]? Or, is there some fundamental difference in the nature of hydrothermal heat loss in this oblique- and slow-spreading environment that makes detection of vents difficult (e.g., pervasive low temperature dissipation of heat that is difficult to detect, or focused venting in unexpected places, such as along deep faults well off-axis)? The AVR underlain by a magma chamber [*Sinha et al*., 1997] lies south of the region where *German et al*. [1994] used hydrocasts to search for hydrothermal activity, so it is not known whether plumes are present in the water column there; however, by analogy with fast-spreading ridges one would expect hydrothermal activity along this AVR.

How do biological communities at the spreading centers vary as a function of depth? What is the relationship between chemosynthetic and photosynthetic carbon sources to the seafloor? Before vent biogeographic patterns can be analyzed on a global scale, we must know whether, and how, depth influences vent-species distributions. The depth at which a vent-specific fauna appears or dominates the community can only be discovered from a site with the full range of depths potentially available. Of broad relevance is the basic ecological question on benthic-pelagic coupling – at what depth does food become a limiting factor in the deep sea? This fundamental control on community mechanics can be elegantly investigated at the proposed site, where chemosynthetically- and photosynthetically-derived productivity zones overlap and faunal dependence on each can be isotopically traced. The seasonal cycles of ice-covered (dark) and ice-free (light) might allow the effect of these carbon sources to be isolated and differentiated. This, coupled with the shallow depth of these systems, might allow for the first time a measure of the chemosynthetic flux from submarine vents into the overlying water column.

How does the hotspot interruption of the submarine ridge system influence faunal dispersal dynamics? In addition to the physiological or competitive interactions that may limit species distributions, current patterns that may impact dispersal dynamics differ with depth. The circulation around Iceland suggests good surface connectivity from the Kolbeinsey to the Reykjanes Ridge, but not visa versa and not at depth (*R. Bourke*, pers. comm.). The several hundred km separation imposed by the Iceland hot spot is within the scale of some known vent species distributions (e.g. East Pacific Rise to North East Pacific) but will certainly pose a barrier to other species (i.e. those with crawl-away larvae). Occasional seasonal ice cover over Kolbeinsey Ridge will impact hydrothermal plume dynamics especially at shallow depths; this may alter dispersal pathways available to vent fauna via larval entrainment into the buoyant plume. The dispersal strategies inferred for any vent-species can be refined by research in this system with depth-dependent barriers.

What are the consequences of plume-ridge interaction in the overlying water column? The Neogene mantle plume activity and the associated Greenland-Scotland Ridge (GSR) have been found to be correlated with the deepwater circulation patterns in the north Atlantic [*Wright and Miller*, 1996; *Wright*, 1998]. However, the details of the control of the GSR on the overflow water and the role of the Northern Component Water production in long-term climate change during the Neogene are not clear.

3. Investigative Strategy

The investigative strategy at a hotspot-influenced spreading center must reflect the vastly different intrinsic length-scales of processes from mantle to microbes. Mantle flow, melt generation, ridge morphology, and ridge segmentation vary on the scales of hundreds of km; ridge segmentation changes over tens to hundreds kilometers, whereas individual hydrothermal vents and associated biological communities are controlled by conditions within few to tens of kilometers. For this reason, a comprehensive suite of integrated experiments envisioned in the RIDGE Integrated Studies Program will have to be carried out in nested study areas, where regions of small-scale processes (e.g., vents) are encompassed by the study areas of large-scale processes (e.g., mantle flow). A detailed design of an Integrated Study requires careful planning including workshops and inputs from a broader RIDGE community than represented by the proponents in this site proposal. The example given below serves to outline how a suite of integrated studies might be carried out at Iceland and the RR and KR and to stimulate discussions of coordinated experiments, if the site is selected:

We envision that the investigations will include a regional-scale characterization of hydrothermal and biological activities, morphology, geochemistry, and the upper mantle over the region of plume influence (~57º-71.5ºN). This regional characterization will build on the existing extensive mapping (multibeam bathymetry, side scan sonar, gravity, magnetics, and seismics) and closely-spaced (at 2-5 km intervals) rock sampling over a significant portion of the region along the ridge axis (see Background section). This work will be followed by selection of a primary site where comprehensive geophysical, geochemical/petrological, hydrothermal, and biological investigations will be conducted to examine variations on length scales of tens of kilometers. Ideally the selected site would be locate in an active volcanic and hydrothermal area along the spreading center, such as the Steinahóll vent site on the RR at 63º 06'N. We recommend that a secondary site at a different end of the spectrum of plume influence be studied to provide a comparison for isolating the effects of plume influence from that of spreading rate and oblique plate spreading. Complementary studies of temporal (off-axis) features by various methods including drilling into the oceanic crust, analog studies on Iceland, and numerical and laboratory works will also be conducted.

Appendix A - Site Selection Criteria

The following paragraphs summarize how the proposed site satisfies the “selection criteria” listed in the RIDGE 2000 Integrated Studies Workshop Report:

Encompass a representative variety of:

Micro- and macrofauna There has been little concerted effort to discover vent biology at this site. However, microbial taxa are similar to those found at other vent sites [Kurr et al. 1991, Pley et al. 1991, Burggraf et al. 1990], so there is no a priori reason to think that vent-specific macrobiota does not also exist here. The two explored vent sites were in shallow water (100 m at the KR, 400 m at Grimsey) and the fauna was dominated by species that were also found in the surrounding communities [Fricke et al 1989]. Abundances near the vents were much higher than in non-vent areas and individuals were observed exploiting vent productivity. The dominant species (sponges and hydroids) are not taxa that are typically found at hydrothermal vents, yet they must have characteristics that allow them to invade vent habitat. With directed searches, it is likely that vent sites over a full range of depths will be found. Regardless of whether vent-specific fauna is found, the characteristics of this site offer unique opportunities to pursue biological questions; indeed, the lack of an endemic community may be more telling than the presence of one. The Iceland area encompasses a full range of ridge crest depths, allowing depth be investigated as a controlling factor in species distributions. Interactions with the pelagic food web and plume dynamics in an ice-covered sea can define unusual community ecology and larval dispersal patterns. As a seasonally ice-covered system, it offers a prime site for testing of exobiological probes that will likely encounter similar ice conditions on other planets, and excellent background information on the existing community will be vital in determining the efficacy of such probes.

Hydrothermal venting styles, fluid and particulate compositions Four submarine vent areas have been identified thus far within the designated study area:

1) The Steinahóll vent site in <250 m water depth off the south coast of Iceland at 63º06'N [Ólafsson et al., 1991; German et al., 1994];

2) The Kolbeinsey Hydrothermal Field in 100-110 m water depth northwest of Iceland on the southern KR at 67°06’N, 18°43’W [Stoffers et al., 1997];

3) Another (un-named) site on the KR at 66°58'N, 18°43'N; this site is apparently underlain by a magma chamber [Scholten et al., 1999];

4) The Grimsey Hydrothermal Field in 400 m water depth northwest of Iceland at 66°36.4'N, 17° 39.3'W; this field is sited in an intratransform spreading basin within the Tjornes Transform [Stoffers et al., 1997; Scholten et al., 1999].

The temperatures of the vents in the Kolbeinsey field range up to 131°C. Vent fluids are emanating from fissures and crater-like pits [Fricke et al. 1989], and are boiling. Iron-rich muds and staining of basalt surfaces are described here [Scholten et al., 1999].

The Grimsey vent fluids also are boiling at temperatures up to 250°C. These fluids are precipitating anhydrite mounds topped with small (3m-high) chimneys of anhydrite and talc plus minor pyrite. The field covers a 300 m x 1000 m area, and the northern part of the field is most active. The hydrothermal fluids are significantly enriched in methane and higher hydrocarbons [Botz et al., 1999]. No macrofauna were found in the Grimsey field.

The variety of hydrothermal vent sites on the ridges within the proposed study area are unknown; but, the extreme range in the depths of this ridge system, the southward change in the structure of the RR from an axial high to a rift valley, and the variety of volcanic and tectonic environments where hydrothermal activity may be manifested, create a great potential for large variability in the hydrothermal vent systems.

Rock types and compositions The Iceland province is the most petrologically and geochemically diverse of any mid-ocean ridge on Earth. The Iceland crust is structurally complex due to rift jumping and rift propagation of the MAR-axis as it extends through Iceland.

The active rift system consists of parallel zones along the westward migrating MAR that have periodically relocated eastward presumably to where the hotspot is located [Aronson and Saemundsson, 1975; Helgason, 1984; Vink, 1984]. The petrologic type varies from olivine tholeiites in the mature rifts to Fe-Ti rich transitional basalts, associated with the SE zone propagating rift, and to alkali basalts in Surtsey and the Vestmann Islands [Jakobsson, 1979a,b]. Highly silicic volcanics are primarily associated with central volcanoes. Radiogenic isotopic data also indicate a wide diversity in Sr, Nd, Hf, Pb and He, form depleted MORB-like values to enriched OIB signatures. Incompatible element ratios such as La/Sm and Zr/Nb also show a wide variation that in general correlate with radiogenic isotope compositions. For the most part unradiogenic and incompatible element-depleted samples are olivine tholeiites and picritic lavas from the more mature neovolcanic zones, with values that overlap those of some north Atlantic MORB. The most "enriched" samples include alkalic lavas from central volcanoes along the propagating SE neovolcanic zone, Surtsey and Vestmann islands, and from the Snafellsness flank zone . Although variable partial melting processes undoubtedly play a role in the diversity of Icelandic lava compositions, moderate to good correlations between incompatible element ratios and isotopic compositions indicate that the mantle beneath Iceland is chemically and isotopically heterogeneous. The correlation suggests at least two component source mixing for the neo-volcanic zones and the KR and RR. However, when the basalts from the Iceland Tertiary paleo-rift zones are considered, it becomes evident that at least three components are required [Hanan and Schilling, 1997; 2000]. There is considerable debate concerning the nature of the "depleted" component in the Icelandic mantle, and whether it represents ambient MORB mantle or rather a distinct component entrained within the Iceland plume. Arguments for a chemical signature of recycled crust in the Iceland plume, and for melting of altered crustal materials in the origin of silicic lavas are widely accepted. However, the role of crustal assimilation is controversial [e.g. Oskasrron et al., 1982; Condomines et al. 1983; Sigmarsson et al., 1992, Hemond et al., 1993, Furman et al., 1995].

The submarine ridges to the north and south of Iceland show striking topographic and geochemical gradients away from Iceland. Along the RR to the south there is a generally smooth gradient in isotopic values and incompatible element abundances for ~250 km that level off at regional MORB values near 61°N. Published data suggests that the $^{3}He/^{4}He$ ratio goes through a maximum along the RR at about 60°N while La/Sm, $^{87}Sr/^{86}Sr$, and $^{206}Pb/^{204}Pb$ progressively increase from 61°N toward Iceland [Schilling, 1973b; Hart et al., 1973; Sun et al., 1975; Schilling et al., 1980; Poreda et al., 1986; Hilton et al., 2000]. The He isotopic anomaly extends the entire length of the RR and to 70°N on the KR. Existing geochemical data, including Nd, Sr, Pb isotopes, show that the Iceland plume has apparently had a more subdued geochemical influence northward on the KR (Schilling et al., 1983; Mertz at al., 1991; Schilling et al., 1999), The contrast between the ridges to the north and south of Iceland has important implications for mantle flow and the dispersal of plume material in the Iceland region.

Display a significant hydrothermal signature in the water column and sediments Phase separation in the Kolbeinsey and Grimsey Hydrothermal Fields are creating bubble-rich plumes that are detectable by sonar [Scholten et al., 1999; Botz et al., 1999]. These plumes are enriched in methane and helium. A search for hydrothermal plumes on the RR by German et al. [1996], from north of 57º45'N to 63º10'N, identified only one hydrothermal plume at the previously-discovered Steinahóll site at 63º 06'N [Ólafsson et al., 1991]. German and Parsons [1998] have suggested that the strategy of the survey may have resulted in failure to detect plumes that were present. Additional surveys are needed to address the mystery of why plumes were not found along the thermally-robust northern RR. The submarine volcanism associated with the shallow ridge sites provides unique sedimentary markers of glacial/interglacial changes in sea level. Fluctuating sea level has a distinct (pressure) effect on the mode of fragmentation of volcanic material ejected upon the seafloor. This has been well documented within sediments of the KR, along with clear geochemical signals of hydrothermal/volcanic activities [Lackshewitz and Wallrabe-Adams, 1991; Lackshewitz et al., 1994a,b].

Encompass a representative range of ridge offsets

While much of the northern MAR is characterized by a quasi-regular stair-step pattern of spreading segments oriented orthogonal to the direction of plate spreading, the RR (57°47'-64°N) is anomalous. The RR as a whole trends with an azimuth of 36° and with the spreading direction of 99° represents a spreading obliquity of 27°. Over almost 1000 km, the RR lacks significant offsets [e.g. Vogt et al., 1971; Fleischer, 1974; Keeton et al., 1997], but is instead composed of individual axial volcanic ridges (AVR), sinuous in plan view and having an en echelon arrangement [Parson et al., 1993; Appelgate and Shor, 1994; Keeton et al., 1997]. The separations between the AVRs form non-transform offsets, of lengths 3-10 km. In a few instances, these gaps are large enough that a small but distinct basin is formed.

By contrast, the KR spreads orthogonally to its overall trend, is bounded by two major transform faults, Tjornes FZ just north of Iceland and the Jan Mayen FZ near 71°30' N, and is segmented by non-transform offsets at ~69°N (Spar Offset) and at 70°40'N [Appelgate, 1997]. The Spar offset at 69°N is marked by overlapped ridges which are separated by ~30 km; it has migrated northwards for the past ~2 Myr. A smaller magnitude offset near 68.7°N has migrated northward over a longer period of time. The Tjornes FZ is a "leaky" transform with several active strands and intervening basins; it offsets the NE volcanic zone of Iceland from the KR by about 50 km. The minimal segmentation along RR and contrasting first and second-order segmentation on Iceland and along KR represent a range of ridge segment offsets that is representative of the global mid-ocean ridge system.

Encompass a variety of morphological expressions

Together, the RR and KR encompass a wide range of morphological expressions observed along the global mid-ocean ridge system. South of ~59°N along RR and north of ~69°N along KR, where geochemical influence of the hotspot is minimal [*Schilling,* 1986] and the axis is deepest (>1.5 km at RR and >1.0 km at KR), the ridge axis forms a prominent axial valley, ~40 km wide and ~1 km deep [Laughton et al., 1979; *Parsons et al. 1993*]. Large inward-facing normal faults form the flanks of the axial valley. Such axial morphology is typical of slow spreading ridges not influenced by hotspots. More proximal to Iceland (i.e. 59°-69·°N), the geochemical signatures of the hotspot strengthen, the ridge axis shallows, and the axial valley is replaced by a robust axial high. The transition between axial valley and axial high occurs abruptly between 58°50'-59°00'N on RR and at the Spar offset on KR. These axial changes combine with the subaerial exposure of the ridge axis on Iceland to represent a bathymetric variation larger than any other present-day spreading center.

Sufficiency of background data and logistical feasibility

A demonstration of the sufficiency of background data for the Iceland/MAR system and a description of the logistical feasibility of working in this region are linked. From the discussion of this site so far, and in the review of previous work in Appendix B below as well the extensive reference list, it is clear that this region has hosted an impressive suite of geologic and geophysical investigations. These studies encompass some of the most comprehensive existing data sets on the geochemistry of a particular plume, the geochemical trends along a plume-affected ridge, the crustal structure above a ridge-centered plume, and the deep seismic character of a plume. In brief, we believe that the sufficiency of background data for this region is easily demonstrated in the reviews that follow.

The volume of existing data for this system underscores not only the region's logistical feasibility but also its unique logistical benefits. The benefits of a subaerially exposed divergent plate boundary directly above a mantle plume to the study of plume/ridge interaction can not be overstated. Although the winter season is dark and less than ideal for field studies, the summer months are pleasant with long days for many hours of productive investigation. These generally welcoming conditions are coupled with a particularly robust Icelandic earth science community with intimate knowledge of locales and infrastructural support (see Appendix C). Similarly, numerous marine investigations of the KR and RR demonstrate the logistical feasibility of working in these locales. Offshore conditions are most favorable during the spring, summer and early fall months. Frequent storms during the late fall and winter months make these times less than ideal for marine work. Ice is generally not an issue along the mid-ocean ridges, but glacial ice becomes a factor for work near the Greenland coast. Ambient noise levels, important for long-term deployments of passive seismic instruments, are surprisingly low during the summer months, generally lower than in the Pacific [*Dozorov and Soloviev*, 1991; *Webb*, 1998]. Surface wind speeds at the Reykjanes Ridge (U.S. Navy Marine Climatic Atlas of the World) are less than 5.4 m/s 34% of the time during July and August and 24% of the time during May, June, September and October. The wind speeds are less than 10 m/s about 75% of the time in this 6-month period. Excellent port facilities in Reykjavik and an active Icelandic marine research community round out the logistical advantages of this region.

Display significant potential for magmatic or tectonic events Approximately 250 eruptions have occurred in Iceland in historic time (last 1100 years). The 1989 event on the RR [Nishimura et al., 1989] and the 1990 event near the RR 63ºN [Ólafsson et al., 1991] are two documented magmatic/tectonic events along the RR. The Steinahóll vent site coincides with the focus of the 1990 swarm [Ólafsson et al., 1991]. A response mission to the 1989 earthquake swarm near 60ºN on the RR found that the eruptive style of the axial volcanic ridges, which includes earthquakes swarms and lateral diking, seems quite similar to what occurs in Iceland [Crane et al., 1997].

Incorporate appropriate drilling targets The shallow water near Iceland and high sedimentation rates on the Reykjanes and Kolbeinsey Ridges make it feasible to drill on very young crust as well as off-axis (e.g., DSDP 407-409 [Luyendyk et al., 1979]). There are numerous DSDP and ODP sites near Iceland (see a site map at http://www-odp.tamu.edu/sitemap/sitemap.html).

Allow for active liaison with other programs and infrastructure The proposed investigation is strongly supported by Icelandic scientists and institutions (see Appendix C). Seismological aspects of the proposed studies tie in closely with the permanent Iceland Seismic Network and with the Global Seismic Network. Data would be archived at the IRIS Data Management Center. Although not yet funded, studies of mantle flow and melting beneath hotspots and slow-spreading ridges are primary objectives of the proposed Oceanic Mantle Dynamics Initiative (an interdisciplinary initiative to study the dynamics of the oceanic upper mantle). Off-axis, subsurface sampling to look at temporal and spatial variations in ridge and hotspot activity would require drilling; such a project would be consistent with several of the goals identified at the COMPLEX meeting (Vancouver, 1999) for the post-2003 scientific drilling program that will succeed the current Ocean Drilling Program (ODP). As indicated by the currently funded projects on Iceland (Appendix B.2), many research projects relevant to the Integrated Studies are supported by the NSF Earth Sciences Program.

Appendix B - Background Information

B.1 Previous Results, Data and Samples

Multibeam bathymetry, side-scan sonar, axial morphology, gravity, and magnetics Multibeam bathymetry and sidescan sonar imagery are presently available along nearly the entire length of the RR, in most cases extending 30-100 km off-axis (57°30'-62°00N, see summary in Keeton et al. [1997]). These data have been used to define detailed characteristic of the neo-volcanic zone [*Applegate and Shor* 1994; *Searle et al.*, 1998], fault characteristics and morphology adjacent to the neo-volcanic zone [*Searle et al.*, 1998], and distributions of axial seamounts [*Magde and Smith*, 1995]. These surveys also include shipboard gravity [*Searle et* *al.*, 1998] and magnetic measurements [*Lee and Searle*, 2000]. The KR has seen fewer detailed geophysical studies. Ridge segmentation and evolution is described by [*Applegate*, 1997], the morphology is characterized by *Vogt et al.*, [1980], *Meyer et al.* [1972], and *McMaster et al.* [1977], and magnetic data are in *Vogt et al.*, [1980] and *Vogt* [1986].

The RR and KR are the most outstanding examples of very slow spreading ridges with axial high axial relief. There is strong evidence that the ridge axis morphology and faulting are controlled by the axial thermal structure, which is linked closely to strength of the axial lithosphere [e.g. *Chen and Morgan*, 1990, *Phipps Morgan and Chen*, 1993]. Where the cold, strong axial lithosphere is thick (>5km) there are valleys and where lithosphere is thin (<3 km) there are highs. The thermal structure of the axis results mainly from the competition between advection of hot material (i.e. mantle and magma) to the ridge axis and the extraction of heat by hydrothermal circulation. The proximity of axial high relief to Iceland indicates the hotspot is perturbing this heat balance. One possibility is that heat loss is reduced by anomalously low hydrothermal circulation near Iceland. An alternative possibility is that the high heat flux from anomalously high magma flux is the dominant control on ridge thermal structure. Constraining the flux of magma (i.e. crustal thickness) and hydrothermally transported heat along the RR and KR would help us understand what makes this plume influenced ridge unique.

Geochemistry and Basalt Samples Lavas from Iceland and the adjacent Kolbeinsey and Reykjanes Ridge systems provide a continuous geochemical record of plume-ridge interaction over an age span of greater than 16 m.y. Petrological, geochemical and isotopic data on MORB erupted along the MAR around Iceland provide the constraints for deciphering the mixing and thermal conditions associated with the large scale dispersal of the Iceland mantle plume into the asthenosphere [Schilling, 1973a,b; Hart et al., 1973; Sun et al., 1975; Hémond et al., 1993; Devey et al., 1994; Mertz et al., 1991; Schilling et al., 1999; Hanan et al., 2000], for constraining the location, depth and orientation of the plume conduit in conjunction with seismic imaging [Chase, 1979; Hager and O'Connell, 1979; Wolfe et al. , 1997; Shen et al., 1998, 2000; Breddam et al., 2000], and numerical fluid-dynamic models of plume dispersion [Ribe et al 1995; Ito et al., 1996, 1999]. From the existing data, it would appear that the Iceland plume has had a more subdued geochemical influence northward on the KR but has significantly contributed to the mantle source of basalts beneath the RR, suggesting an asymmetry in the dispersion of the Iceland plume. MORB major element modeling also suggests some thermal asymmetry about Iceland [Schilling and Sigudsson 1978; Klein and Langmuir 1987; Schilling et al. 1999]. But surprisingly, and possibly at odds with the inferred dispersal pattern based on the current isotopic tracers limited to the MAR, the highest mean degree and the deepest depth of melting conditions of the entire mid-ocean ridge system are found on the KR [Klein and Langmuir 1987], whereas more intermediate conditions are found south of Iceland on the RR. Clearly, without a fully comparable petrological, geochemical and isotopic data set on Iceland and the adjacent MAR, the ambiguities on the real thermal, mixing and dynamic dispersion of the Iceland plume cannot be resolved. The different wavelengths of such geophysical and geochemical parameters, as proxies for constraining the actual thermal and dynamical dispersion of the Iceland plume, need to be firmly established along the Iceland neo-volcanic zones and the KR and RR. However, these spatial variations provide only a "zero-age" snapshot of the Iceland-MAR plume-ridge interaction. Basalts from the Faeroes islands, East –Greenland and from DSDP holes drilled into the oceanic crust provide the means of tracing the plume activity from the time it interacted with the continental lithosphere at 40-60 Ma at the onset of opening of the North Atlantic, in the last 16 m.y. as it interacted with drifting or jumping rift zones, to its present ridge-centered configuration and thermal regime [Schilling and Noe-Nygaard, 1974; Schilling et al 1982, Hanan and Schilling, 1997; 2000; Graham et al., 1998; Thirlwall et al., 1994; Kempton et al., 2000]. Temporal isotopic variations have great potential in providing additional important constraints, such as understanding variations in mantle source components at the D" core/mantle or mesosphere/asthenosphere boundary layers, and on the nature and extent of mantle entrainment and mixing during plume ascent.

The Reykjanes Peninsula-Ridge transition from sub-aerial to submarine eruption provides an ideal natural laboratory to study pre-eruptive magmatic volatile degassing as a function of depth/pressure. Volatiles play an important role in magma generation and can significantly affect mantle melting conditions and rheology. H_2O lowers mantle melting temperatures while allowing for increased degree of partial melting and extended range of fractional crystallization at a given temperature and pressure. The extent of volatile outgassing from magmas affects the morphology of magmatic eruptions, constructional volcanic features and magnetic properties. Decreasing solubility of H_2O, as eruption depths shallow to less than the ~500m depth, along the Reykjanes Ridge and the flank of Hawaii, has been shown to strongly influence degassing of other volatiles including He, CO_2, Cl, Br, [Moore and Schilling, 1973; Unni and Schilling 1977, Rowe and Schilling 1978; Schilling, 1986; Poreda et al., 1986; Michael and Schilling, 1989; Dixon et al., 1988, 1991, 1995a,b]. CO_2 solubility in basaltic melts inversely correlates to water content. Since CO_2 is the major gas phase in basaltic glasses and the carrier of magmatic He, low-pressure, pre-eruptive magmatic degassing results in degassed magmas being susceptible to addition of radiogenic ^{4}He and alteration of primary ^{3}He/^{4}He isotope ratios [Hilton et al., 2000]. Is the apparent decoupling between He isotopes, trace elements and radiogenic isotopes along the RR the result of volatile degassing or mantle source heterogeneity? In spite of the importance of water in modeling the mantle flow, melt generation, and magma evolution [e.g., Michael and Chase, 1987; Ito et al.,1999], very little data exist on the primary volatile contents of Icelandic magmas. Work on submarine basalts collected along the MAR between 29ºN and 73ºN [Moore and Schilling, 1973b; Schilling et al.,1980; Schilling et al., 1983; Poreda et al., 1986; Kingsley, 1989; Nihcols, 2000] suggest that hotspots, such as the Azores, (~3X greater) Jan Mayen and Iceland (~2X greater), have higher H_2O and halogen contents than surrounding MAR basalts, prompting the comment that hotspots should also be thought of as "wetspots" [Schilling et al., 1983]. Confirmation of the elevated H_2O in plume sources has not been realized due to the complication of subaerial degassing.. However, recent data from Iceland basalt glasses erupted beneath 1 to 2 Km of glacial ice, that have retained their pre-eruptive H_2O content, suggest even higher H_2O contents than previously estimated from the mantle source from below the Reykjanes Ridge [Nichols, 2000; Nichols et al., submitted]. Besides their recent work, preliminary data suggest that Icelandic magmas have water concentrations consistent with other North Atlantic basalts [Michael, 1995; Dixon et al., 1996] and that the mantle water content is ~600-900 ppm in the Icelandic plume. Sampling of submarine basaltic glass, either as pillows, tephra, or melt inclusions in phenocrysts will allow us to characterize spatial heterogeneity of volatiles in the Icelandic plume and to determine the relationship of plume flux to factors such as H_2O and thermal effects.

Recent studies of the Iceland Plume province have sparked controversy over the “fundamental axiom" that all mantle plumes are enriched and led to the idea that plumes may also have a substantial depleted component which is not readily distinguishable from the depleted MORB source usually observed in regions remote from mantle plumes [Thirlwall et al., 1994; Anderson, 1994; Thirlwall, 1995; Furman et al., 1995; Hards et al., 1995; Kerr, 1995; Kerr et al., 1995; Fitton et al., 1996; Fitton et al., 1997; Hardarson and Fitton, 1997; Hardarson et al., 1997; Graham et al., 1998; Schilling et al., 1999; Stecher et al., 1999; Kempton et al., 2000; Chauvel and Hémond, 2000; Hanan et al., 2000]. The implication is that basalts generated over the area of dispersal of the Iceland plume do not contain a substantial depleted MORB asthenosphere source component. In this model, the along-ridge isotopic and geochemical gradient observed about the Iceland plume, such as along the Reykjanes Ridge [i.e. Schilling 1973b; Hart et al. 1973;Sun et al. 1975], would simply reflect the zoning of the mantle plume conduit from entrainment in deeper mantle levels than the asthenosphere. It further implies that the non-radiogenic Pb and Sr isotope and incompatible element depleted restite part of the dispersing mantle plume may be the major influx of depleted mantle material into the asthenosphere from which so called N-MORB are derived [e.g. Saunders, 1997; Phipps Morgan and Morgan, 1999; Phipps Morgan, 1999]. In contrast, a temporal Pb isotope study of the east and west Tertiary plateau basalt sections of Iceland and spatial variations of MORB along the

MAR from 50-79°N, suggest that the apparent distinction between Iceland basalts and MORB can readily be accounted for by a three-component mixing model involving two incompatible trace element enriched components, one with relatively high, the other with low $^{206}Pb/^{204}Pb$ ratios, and the usual surrounding depleted MORB mantle source as the third component [Hanan and Schilling, 1997; Schilling et al., 1999; Hanan et al., 2000]. In this model the radiogenic ^{206}Pb-rich component represents the hot Iceland mantle plume source, while the enriched, but low-$^{206}Pb/^{204}Pb$ EM I-like component most likely represents entrained sub-continental lithospheric material embedded in the N-Atlantic depleted MORB source. Prior to the temporal perspective provided by the Iceland Tertiary Pb isotope data, the Pb-Sr-Nd isotope data from the Iceland neovolcanic zones and adjacent ridges were interpreted as binary mixing arrays between the Iceland plume and depleted mantle. Explanations for the scatter observed for the so-called binary trends were explained away by end-member isotope heterogeneity and/or variance in elemental ratios. We cannot expect to understand the Iceland plume – MOR system from a spatial perspective only. Temporal variations are another fundamental requirement [e.g. Schilling and Noe-Nygaard, 1974; Schilling et al 1982, Hanan and Schilling, 1997; Hanan et al., 2000].

The fundamental data base required to study Iceland plume-ridge interaction includes uniform petrologic, geochemical and isotopic basalt data from the adjacent MOR and on Iceland itself. Such a comprehensive data base is required for mapping spatial and temporal variations of the Iceland magmatic products along the neo- and recognized paleo-rift zones, dated Tertiary plateau basalt stratigraphic sections, and adjacent RR and KR for the purpose of understanding better the spatial and temporal evolution of mixing and melting conditions over Iceland, as well as resolving questions on the possible direction of bending the Iceland mantle plume and the geometric nature of its outward dispersal.

Hydrothermal and Biological Studies Active hydrothermal vents have been found at a site off the southern coast of Iceland [Steinahóll site, 63º06'N on the RR; Ólafsson et al., 1991; German et al., 1994]; and, at three sites north of Iceland: 67°06'N, 18°43'W on the southern KR (the Kolbeinsey Hydrothermal Fields); 66°58'N, 18°43'N on the southern KR (un-named site); and, at 66°36.4'N, 17°39.3'W in an intratransform spreading basin within the Tjornes Transform (Grimsey Hydrothermal Field) [Fricke et al. 1989; Stoffers et al., 1997; Scholten et al., 1999; Botz et al. 1999]. The water depths of these vent sites are all shallow (100-110 m at the Kolbeinsey Hydrothermal Fields, <250 m at the Steinahóll Site, and 400 m at the Grimsey site). The temperatures of these vents are on the boiling curve, and increase with water depth, from 131ºC in the Kolbeinsey Field to 250°C in the Grimsey Hydrothermal Field. A magma chamber was detected beneath the un-named vent at 66°36.4'N, 17°39.3'W [Scholten et al., 1999].

The Grimsey Hydrothermal Field was explored seismically and sampled by hydrocasts and submersible dives [Scholten et al., 1999]. The field extends over a 1000 m x 300 m area. In the northern portion of the Grimsey Field, venting chimneys made of anhydrite, talc and pyrite are growing on top of anhydrite mounds. The southern portion hosts less-active and extinct vents. Images of the Grimsey Field and other information about the sites north of Iceland are posted at `http://www.geophysik.uni-kiel.de/criedel/HOMEPAGE/abstrakt.htm#interridge` and http://www.icenews.is//05jun97.html#new).

The Kolbeinsey Hydrothermal vents issue from fissures, chimneys and craters [Fricke et al. 1989]. When last observed, Beggiatoa-like bacterial mats covered the bottom, and macrofauna was dominated by 2 species of sponges (Scypha quadrangulatum and Tethya aurantium at one site) and a hydroid (Corymorpha groenlandica at another site). These species are also found in the surrounding non-vent community, but abundances were much higher within the hydrothermally influenced zone. Other species, including several meiofaunal groups, were also found near the vents, however, species diversity was much lower than further away, suggesting that only a few species were capable of invading the hydrothermal zone. Direct observations revealed all three dominant species were suspension feeding within hydrothermal fluid. Lab cultures from hydrothermal fluid have resulted in unique (Methanococcus igneus, Burggraf et al.

1990) and unusual (Methaopyrus kandleri, Kurr et al. 1991; Pyrodictium abyssi, Pley et al. 1991, both also found in Guaymas) microbial isolates.

A water column survey of the Reykjanes Ridge from north of 57º45'N to 63º10'N found no evidence of hydrothermal plumes except at the previously-discovered Steinahóll site. However, Murton and German [1992] report side–scan sonar images of mounds on the Reykjanes Ridge that are comparable in morphology to hydrothermal mounds on the Mid-Atlantic Ridge.

The Reykjanes mounds near 58°N 33°W are ~180 m high, ~150 m wide, approximately twice as large as Mid-Atlantic mounds, but similarly steep sided. No visits have been made to this specific area to confirm hydrothermal activity or possible vent biota, but a general survey of the RR contains excellent background information on faunal distributions across the range of ridge depths (225 – 2600 m, Copley et al. 1996).

The Kolbeinsey Ridge-Iceland-Reykjanes Ridge system remains relatively unexplored for hydrothermal venting signatures and associated biology. Nevertheless, shallow water sites and the morphology of the ridge system suggests active venting is occurring elsewhere, and it would be very unusual, and informative, if vent-endemic biota were not also present. Though the background information presented here is sparse, the potential offered by this site is huge and worth research efforts.

Seismological Studies The overall character of the RR is strongly influenced by the Iceland Plume. The plume itself was first imaged in the early 1980's by Trygvasson et al. [1983], who used short period teleseismic delay times to trace it to several hundred kilometers depth in the mantle. Subsequent seismic imaging by Wolfe et al. [1997] showed that the plume is quite narrow (~100 km radius, centered in southeastern Iceland) and extends to at least 400 km depth. They quantified the compressional and shear wave velocity anomalies to be 2% and 4% respectively, corresponding to a temperature anomaly of at least 300K above the surrounding mantle. Shen et al. [1998] argue that the plume extends at least through the transition zone, because its perturbing effect on the depth of 410 and 670 km discontinuities is detected by receiver function analysis.

Tomographic images of the upper part plume have been further improved by Allen [2001], who supplemented teleseismic traveltimes with surface wave measurements in order to image top 100 km, the area in which melting is most intense. He shows that the plume widens in the very uppermost mantle. This plume head extends laterally under all of Iceland (and perhaps further). The thermal anomaly beneath the RR seems, on the basis of fairly low-resolution surface wave tomography, to be limited to above 200-250 km, with a shear velocity minimum of about 2-3% occurring at about 150 km depth [Zhang and Tanimoto, 1993]. The transition from a plume-dominated upper mantle beneath Iceland to a presumably narrower normal ridge anomaly to the south has not been adequately imaged.

Regional dispersion of seismic surface waves propagating along the Reykjanes Ridge from earthquakes on fracture zones of the MAR to Iceland show that velocity increases with age out at least 40 Ma seafloor and that velocities along the ridge are roughly comparable to the East Pacific Rise in the period range 15 to 40 s [Girardin and Jacoby, 1979; Keen et al., 1979; Evans and Sacks, 1980]. Gaherty [1999] showed that upper mantle SV-SH anisotropy was different along the RR from beneath the East Pacific Rise, perhaps indicative of a more vertical alignment of olivine a-axes. In all of these studies, the paths were roughly parallel to the ridge, so that they were not able to resolve lateral variations along the ridge or azimuthal anisotropy.

The high melt production from the Iceland plume has lead to the formation of the Faero-Iceland-Greenland ridge, a band of extremely thick crust that crosses the north Atlantic. Crustal thickness generally increases from 8-10 km on the RR [Ritzert and Jacoby, 1985], to 14 km at the southern tip of the Reykjanes Pennisula [Weir et. al. 2000], to 20-25 km in south Iceland [Bjarnason et al. 1993] to 40 km beneath the center of the plume [Darbyshire et al. 1998]. The crust appears to be in isostatic balance, with long-wavelength topography correlating with Moho depth [Menke, 1999]. The seismic structure of the crust south of Iceland is normal. Most of the northward thickening occurs in the cumulative section of the lower crust (e.g. Layer 3) [Zehnder and Mutter, 1990].

Each of the Icelandic volcanic systems is composed of a central volcano and an associated fissure swarm. The upper crust of Iceland is formed when magma from the shallow (3-4 km) crustal magma chambers [Brandsdottir et al. 1997] of these volcanoes intrudes into the fissure swarms during lateral diking events (which are accompanied by numerous earthquakes in the upper 5 km) [Einarsson and Brandsdottir, 1980]. The origin of the lower crust is less well understood. Palmason [1980], citing ridgeward dipping lava flows, has argues for a large component of lower crustal flow driven by primarily shallow accretion of crust in the neovolcanic zones. Further thermal modeling by Menke and Sparks [1995] indicates that shallow cooling of lower crustal material is needed to account for the relatively low lower-crustal temperatures inferred from the relatively high (Qs=1000) shear wave attenuation [Menke et al. 1995] and the relatively deep maximum depth of earthquakes (6 km below the neovolcanic zone, deepening to 14 km in 5 Ma crust) [Stefansson et al., 1993]. This cool "lithosphere" may explain the observation that uppermost mantle compressional and shear velocities (i.e. from Pn and Sn) are somewhat higher in central Iceland than at the northern and southern coasts [Menke et al. 1998]. Magmatic enrichment of the upper mantle in olivine cumulates (i.e. dunite bodies) may provide an alternate explanation for these higher velocities [Allen 2001]. Whether all of Icelandic neovolcanic zones are fed from mantle sources located directly beneath them, or whether some are fed by lateral, near-Moho transport from the region just above the plume is not known. A band of relatively low shear velocity that extends from the plume center along the northern neovolcanic zone is arguably suggestive of the later [Allen, 2001].

Shallow crustal magma chambers have been tomographically imaged below several of volcanoes on Iceland [Gudmundsson et al. 1994, Brandsdottir et al. 1997] and are believed, on the basis of physiography (e.g. calderas) to occur below many more. Those that have been imaged occur in the shallow (2-4 km) crust, have lateral dimensions of 3-8 km and contain several tens of cubic kilometers of melt. These magma chambers appear to be distinctly different than the one observed 2.5 km below an AVR on the RR at 57.75ºN [Navin et al. 1998; Gill et al. 2000]. That feature is quite similar to the axial magma chambers observed on the East Pacific Rise, and consists of a thin (100 m) melt lens that is fairly continuous along axis, atop of a broader mush zone. Notwithstanding this difference, the eruptive style of the AVR's, which include earthquakes swarms and lateral diking, seems quite similar to what occurs in Iceland [Crane et al., 1997].

Ocean bottom seismometer (OBS) deployments along the northern Reykjanes Ridge (near 62.5ºN) [Mochizuki et al., 2000] have detected numerous, mostly normal faulting events that occur on the flanks between the AVS's (implying that they are probably not associated with magmatism). Their depths are concentrated between 3 and 7 km, with some as deep as 11 km. Thus, most events are observed to occur in the mid-crust, with possibly a few extending as deep as the uppermost mantle. This relatively deep depth probably implies that vigorous hydrothermal cooling is taking place between the AVS's.

Seismicity along the Tjornes and Husavik-Flatley transform faults have been investigated by using OBSs [Mochizuki et al. 1995] and terrestrial stations on Iceland [Angelier et al. 1999]. Earthquakes are generally shallow (<10 km) and have mostly strike-slip mechanisms. The two faults differ, however, in that the Tjornes fault seems to be a mature fault with left right-lateral motion, while the Husavik-Flatley fault seems to consist of numerous en echelon segments that have left-lateral motion (i.e. bookshelf tectonics). The Husavik-Flatley is therefore interpreted as a transform in its initial stages of formation.

Crustal structure on the KR at has been investigated by Kodiara et al. [1997] who perform an OBS-based refraction experiment at 70ºN. Crustal thickness, constrained by PmP traveltimes, is about 10 km on an off-axis line. More variability is seen on an on-axis line, with thickness varying between about 8 and 12 km over a horizontal scale length of 50 km. No magma chambers are detected, but lower crustal velocities are generally slower on-axis than off-axis

(6.6-7.0 compared to 6.9-7.2), a fact that is attributed to elevated temperatures beneath the ridge axis.

Geodesy Because Iceland exposes a ridge on land, it allows measurements that have not yet been done on submarine spreading centers. Geodetic measurements are one example. Geodetic measurements on Iceland have led to a clearer picture of strain partitioning and the general tectonic setting there [e.g. *Sigmundsson et al*, 1995; *Jonsson et al.*, 1997], including the role of magma in accommodating extension [e.g. *Hofton and Folger*, 1996.]. In fact, Iceland is the only place where the response of the surface to the intrusion of magma at depth has been used to constrain the viscosity structure of the region around a ridge. This was done using geodetic measurements before, during and after the Krafla fissure swarm, that was active from 1975-1985 [e.g. *Foulger et al.*, 1993; *Heki*, 1993]. Basically, a wave of primarily horizontal displacement moves away from the zone of dike intrusion at a rate that depends on the thickness of the strong, elastic lithosphere and on the viscosity structure below the lithosphere. This is one of the only ways to constrain this viscosity of the axial region. If we could better constrain the viscosity structure of the ridge then we could determine whether some models for axial topography are potentially valid. For example, the lack of large variations in relief along the axis of the Reykjanes Ridge may indicate that the lower oceanic crust flows easily in response to topographically induced pressure gradients [*Lin and Phipps Morgan*, 1992; *Bell and Buck*, 1992]. If the viscosity of the axial region were determined to be greater than about 10^{18} Pas then this model would not be a good explanation for the smooth along-axis relief. More measurements, including interferometric radar data, would improve the constraints on axial viscosity structure, as would the development to 3D numerical models of visco-elastic responses to intrusion events.

Electromagnetic Studies Electromagnetic (EM) studies, including telluric, magnetotelluric, and controlled source EM experiments, have been important in delineating the distribution of melt beneath Iceland and the RR. EM studies have revealed very conductive zones [*Hermance and Grillot*, 1970; *Beblo et al.*, 1983; *Thayer et al.*, 1983; *Eysteinsson and Hermance*, 1985]. Combined analyses of both the seismic and EM data from Iceland [*Schmeling*, 1985] help to distinguish the roles of temperature and melt distribution in creating geophysical anomalies in the neovolcanic zone and support the notion [e.g. *Gudmundsson*, 1994] that crustal accretion in Iceland is in many ways a scaled-up version of what occurs at mid-ocean ridges such as the East Pacific Rise. Similar results have been found much farther south on the RR. The RAMESSES experiment [*Sinha et al.*, 1998], conducted near 57°45'N, involved coincident EM and active-source crustal seismic studies centered on an axial volcanic ridge of the spreading center. As in Iceland, the seismic results provide clear indication for the accumulation of melt beneath the spreading center [*Navin et al.*, 1998], including ponding in a shallow melt lens. The EM results, using the seismic observations as constraints, reveal a distribution of melt that is again similar to the EPR within the ~9-km-thick crust, with a shallow melt lens and a more pervasive underlying crystal mush zone, as well as an upper-mantle region of interconnected melt constrained to exist between ~50 to 120 km depth [*MacGregor et al.*, 1998; *Sinha et al.*, 1998]. This is the only such evidence for accumulated melt at a slow spreading ridge, and this evidence, in combination with the particularly thick oceanic crust, attest to the far-reaching influence of the Iceland plume along the RR.

B.2 Currently Funded Projects at the Proposed Site

The following is a list of currently NSF-funded relevant projects at Iceland and the Reykjanes and Kolbeinsey Ridges. A list of projects dated back to 1989 can be found at http://espo.gso.uri.edu/~yang/RIDGE/background.frame.html

Collaborative Research: Spatial and temporal geochemical evolution of the Iceland mantle plume and its dispersion along the Mid-Atlantic Ridge, Barry B. Hanan and Jean-Guy Schilling, OCE, 2001-2003.

This is a project to provide a consistent and comprehensive data set consisting of Hf, Pb, Nd and Sr isotope, related parent/daughter and diagnostic trace element data for Iceland basalts from the URI collection which have already been documented for petrology and REE abundances and also studied for paleo-magneto-stratigraphy, and K/Ar age dating. The goal is to provide a uniform mapping of the spatial and temporal geochemical variations over the Iceland paleo- and neo-rift zones for the purpose of further testing and refining current models for the origin, evolution and interaction of the Iceland mantle plume with the Mid-Atlantic Ridge.

US-Iceland cooperative research:Study of geothermal systems (pending). D.Kadko (8/01-8/04) OCE-0115651.

This project will allow the PI to collaborate with Dr. Karl Gronvold of the Nordic Volcanic Institute (Iceland) in the investigation of the crustal residence time of fluids circulating through geothermal systems of Iceland, utilizing isotopic tools developed by the PI for submarine hydrothermal systems in mid-ocean ridges. In addition, the PI will utilize an in-situ gamma detector within well waters of Iceland to perform remote, time-series measurements of radon gas. Previous work by Icelandic investigators (Dr. Pall Einarsson and others) has shown that radon measurements have great potential as an earthquake prediction tool.

An integrated approach to monitoring and interpreting ground deformation at the currently active Hengill volcanic system in southwest Iceland, using GIS to analyze GPS, seismic data, Amy Clifton, EAR, 2000-2003

This is a project to understand ground deformation due to faulting and volcanic activities on Iceland. Since 1994, the area around Hengill has experienced episodic swarms of enhanced seismicity attributed to magma moving within the system. GPS and InSAR data detected uplift about a point source of pressure under one of the volcanoes in the system. In June of 1998 there was a $M = 5.1$ earthquake in the area which then triggered slip on another fault in November, 1998. A number of faults in the area generated small-scale surface breaks. The PI has been comparing the number, size and spatial distribution of active and inactive fractures to that of earthquake epicenters and will be using GPS and InSAR measurements to help define the deformation fields of specific fractures, to better constrain the slip distribution on the faults and to understand the relationship between the faulting and the uplift. GIS is being used to integrate field and geophysical data to determine how the crust breaks in response to volcano inflation, and to see how much of the current activity is focused on existing weaknesses in the crust. A major goal of this research is to develop an assessment of seismic hazard at Hengill and the towns surrounding it. While the activity at Hengill has ended, similar methods will be applied to other volcanic areas in south Iceland.

Investigation of high precision Os measurements on laves from Iceland and the Austral Islands, Alan Brandon, EAR, 2000-2002

Recent work has shown that coupled enrichments in 186Os/188Os and ^{187}Os/^{188}Os for some Hawaiian lavas is consistent with the hypothesis of core-mantle interaction within the Hawaiian plume source. If this is correct, then these are perhaps the most robust geochemical data to date, that show some plumes originate in the D" region of the deepest part of the mantle. Alternatively, these data could instead be consistent with entrainment of ancient recycled crust provided certain conditions hold. As a further test of these hypotheses, high precision ^{186}Os/^{188}Os and ^{187}Os/^{188}Os data for lavas from Iceland and the Austral Islands will be obtained. These two suites are ideal for subsequent testing of the roles of core-mantle interaction and ancient crustal recycling in generating radiogenic Os compositions in plumes because of the following. Seismic evidence suggests that Iceland plume originates from D" just above the core-mantle boundary. It is a high ^{3}He hotspot with active volcanism in a relatively fixed position for at least 60 million years. Taken together, these observations support a deep mantle origin for the Iceland plume where core-mantle interaction may occur. Some Austral Islands lavas have ^{187}Os/^{188}Os that are too high to be produced by reasonable models for entrainment of outer core into plume sources. Therefore, the these lavas can be used to make a rigorous test of the role of ancient crustal recycling for potentially producing radiogenic ^{186}Os/^{188}Os in plume-derived lavas. The ultimate result of this study will be to provide a greater understanding of the significance of chemical exchange between the outer core and plume sources, the role of crustal recycling to produce Os isotopic signatures in plumes, and the use of coupled enrichments of $^{186}Os/^{188}Os$ and $^{187}Os/^{188}Os$ to constrain the depths of origin of plumes.

Plume-ridge interaction to the north of the Iceland plume: Kolbeinsey Ridge Iceland seismic experiment (KRISE), Emilie Hooft Toomey, OCE, 2000-2002

This is a cooperative project among US, Icelandic, Norwegian, and Japanese scientists. The purpose of the project is to constrain crustal thickness variations to the north of Iceland, along the Kolbeinsey Ridge. Crustal thickness will be measured along two seismic refraction profiles - one along 215 km of the southern Kolbeinsey Ridge from the Tjornes fracture zone northward to the 68 degree offset, and another cross-axis profile extending east from the northern end of the along-axis profile to 10 Ma-old crust. These two profiles will allow the determination of the distance dependence of melt flux at the ridge in the critical range of 200-400 km from the plume center, the asymmetry of the plume influence on the spreading centers to the north and south, and the temporal variability of the plume influence on the ridge over the past 10 Ma.

High-resolution mantle discontinuity structure beneath Iceland and Hawaii, Yang Shen, OCE, 2000-2002

This project will combine all available broadband teleseismic data from Iceland and Hawaii to obtain high-resolution mantle discontinuity structures beneath the two oceanic hotspots. The primary questions that will be addressed are the nature of the discontinuities near 200- and 300-km depths and the magnitudes and sharpness of the upper mantle discontinuities. Preliminary results show that the transition-zone thickness anomaly beneath Iceland is shifted to the south compared to the shallow measures of plume influence, indicating a tilted plume conduit in the upper mantle and a large-scale north-south mantle flow beneath north Atlantic.

U.S.- Iceland cooperative research: Study of hydrogeologic systems, David Kadko, INT, 2000-2001

This is a project to make preliminary investigations into the crustal residence times of fluids circulating through the geothermal systems on Iceland. The objectives of the investigations are to understand the hydrogeologic sampling sites and facilities available, obtain documents and maps available only in Iceland, and work out the unique contributions to be provided by each side. The overall results of the research will make it possible to study the ocean ridge system in entirely new ways, test sampling and analysis methods, and provide for an exchange of information and analytical techniques between experts in Iceland and the U.S.

International fellow awards: Modeling the spatial and temporal evolution of Vatnajokull hydrology, Gwen Flowers, INT, 2000-2001

The objective of this project is to understand the dynamics of ice cap hydrology that influence stable and unstable modes of water flow beneath Vatnajokull, Iceland's largest ice cap, and to test, improve and refine a numerical model in preparation for larger-scale investigations. Dr. Flowers will use a numerical model of glacier hydrology that she developed as the core of her doctoral research. She will use information available through the Science Institute of the University on Vatnajokull surface and bed geometry and hydraulic characteristics to evaluate how well the modeled drainage structure honors that which is presently observed. This project represents a first attempt to describe a complete computational picture of glacier hydrology. The results will benefit the field of glacier hydraulics and its impact on glacier dynamics.

Comprehensive study of the Lu-Hf Radiogenic isotope systematics of normal and hotspot affected mid-ocean ridge basalts, Jean-Guy Schilling, OCE, 1999-2002

A comprehensive documentation and study of 176Hf/177Hf isotope ratio variation of mid-ocean ridge basalt glasses from the URI dredge rock collection will be conducted. The collection focuses on unusually elevated mid-ocean ridge segments affected by nearby hotspots and underlying mantle plumes. About 300-400 samples from some 300 different sampling localities will be studied. Possible correlations, or decoupling, will be sought between radiogenic Lu-Hf isotope system with that of Pb, Sr., Nd, and He isotope systems, and other geochemical parameters previously established on the vary same basalt glasses. The study should provide new constraints on the depth and mode of melting and extent of garnet involvement beneath mid-ocean ridge segments affected by hotspots such as Jan Mayen, Iceland, Azores, Sierra Leone, St Helena and Tristan da Cuhna in the Atlantic, the Galapagos and Easter in the Pacific, and the Afar in the Gulf of Aden-Red Sea region. Greater insights should also be gained on suboceanic mantle geochemistry, length scales of heterogeneities, and mantle dynamics. The study will be done in collaboration with Dr. Janne Blichert-Toft and Dr. Francis Albarede, from the Ecole Superieure de Lyon, France, where the 176Hf/177Hf ratio measurements will be made by plasma source multi-collector mass spectrometry, after Hf has been separated at URI.

The timing, duration and correlation of north Atlantic igneous province magmatism, Robert Duncan, EAR, 1999-2001

This is an international collaborative investigation of the timing, genesis and evolution of the North Atlantic Igneous Province (NAIP), a classic volcanic rifted margin. It has been proposed that this large igneous province was constructed at the initiation of Iceland mantle plume activity, remnants of which include the West and East Greenland margin basalts, the Faeroe Islands, the British Tertiary Province, and extensive sequences of lava flows and sills that form most of the continental margins of the North Atlantic (seaward-dipping reflectors). We will contribute radiometric age determinations by the ^{40}Ar-^{39}Ar incremental heating method, for whole rock and mineral separates to define the timing and duration of volcanism, and in support of correlating volcanic stratigraphy across the province. Precise age determinations are required to establish the timeframe of widely separated volcanic and intrusive remnants, determine magma production rates through the volcanic history, describe the sequence and duration of magmatic phases in different tectonic settings, and correlate peak volcanic phases with the sedimentary record of environmental response to this large igneous province. The first order goal of the program is to use the record of magmatism and tectonism throughout the province to assess "active" (plume head) vs "passive" (plume incubation) models of continental rifting in the presence of a mantle plume.

Mechanics and termodynamics of crustal dike propagation, Allan Rubin, OCE, 1997-2001.

By analogy with volcanic rift zones in Iceland and Hawaii, most shallow magma transport along ridges lacking a continuous magma chamber occurs in vertical cracks (dikes), that are typically a few kilometers tall and a meter or so wide, and that can propagate laterally for several tens of kilometers. Through a combination of numerical models and laboratory experiments, the PI will study the mechanical and thermal behavior of laterally-propagating dikes along mid-ocean ridges. The study will focus on two aspects that are not addressed by existing models: The role of the topographic slope in driving magma flow, and the role of heat flow in limiting the distance the dikes propagate.

US-Iceland cooperative research:Study of hydrogeologic systems. D.Kadko (5/1/00-5/1/01). INT-0002162.

This grant supports the PI to visit Iceland and consult with investigators there for the purpose of planning a cooperative research project. The research entails investigation of the crustal residence time of fluids circulating through geothermal systems of Iceland, utilizing isotopic tools developed by the PI in submarine hydrothermal systems of the mid-ocean ridge system. The objectives are to: 1) hold crucial discussions with Icelandic investigators to learn about the hydrogeology and associated sampling sites for the project, and sampling and analytical facilities that will be available for the work. 2) Obtain documents and maps necessary for fieldwork planning. 3) Delineate the respective responsibilities within this cooperative project of the PI and the Icelandic investigators.

Eruptive History of the Western Volcanic Zone, Iceland, John Sinton, NSF OCE 98-11276, 1998-2001

This project involves the determination of the complete post-glacial eruptive record for the 170 km long Western Volcanic Zone of Iceland. Individual eruptive units are being identified and mapped, their areas calculated and their volumes estimated. Multiple samples from each unit are being analyzed for whole rock major element, trace element and isotopic ratios. New age constraints are being provided from 14C dating of charcoals and tephrachronology. The goal of this project is to constrain the eruptive history and composition of lavas in time and space. Chemical compositions and chemical heterogeneity of individual eruptions will provide insight into the subaxial magma chambers that feed mid-ocean ridge eruptions. This is a collaborative study with Karl Gronvold of the Nordic Volcanological Institute and Kristjan Saemundsson of the Iceland National Energy Authority.

B.3 Plan for Making Background Data Available to the RIDGE Community If the Iceland-MAR region is selected as a RIDGE 2000 Integrated Study Site, a web site will be created to point scientists to available background data. Several existing on-line databases already exist, which will facilitate this process. Multibean bathymetry data are available through the RIDGE Multibeam Database, published basalt petrology/geochemistry data are accessible through the RIDGE Petrology Database, GPS data are available through UNAVCO, and seismic data are available through the IRIS Data Management Center. In addition, local Iceland SIL earthquake locations are available (`http://hraun.vedur.is/ja/englishweb/earthquakes.html`).

The web site will contain an up-to-date compilation of projects in the Iceland region and a full bibliography of published work. There will be links to web pages of investigators who have conducted relevant work. The required Iceland-MAR Integrated Site Study Workshop will also be an important tool to educate the interested community about background work and provide a multidisciplinary forum for planning future studies.

Appendix C – Scientific Support and Facilities on Iceland

- a document from Bryndis and other Icelandic scientists.

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