



POLAR RIDGES MEETING AND WORKSHOP 2006

Sestri Levante, September 19-22

An interdisciplinary three-days meeting to discuss the state of the art on ultra-slow spreading ridges, and to promote interaction with studies on on-land analogues

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Ridge 2000 Program



Biogeography of deep-water Chemosynthetic Ecosystems

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ABSTRACTS

BIOGEOGRAPHY OF DEEP-WATER CHEMOSYNTHETIC ECOSYSTEMS - A CENSUS OF MARINE LIFE FIELD PROJECT THE POLAR FIELD PROGRAMME

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ChEss (www.noc.soton.ac.uk/chess) is one of the 14 pilot projects within the Census of Marine Life initiative (www.coml.org). The aim of ChEss is to determine the biogeography of deep-water chemosynthetically-driven ecosystems and to understand the processes driving them. The main objectives are to assess and explain the global diversity, distribution and abundance of species from chemosynthetic systems including hydrothermal vents, cold seeps, whale falls, sunken wood and oxygen minimum zones where they intersect the deep seafloor along certain ocean margins. ChEss follows two approaches: 1- development of a web-based relational database for all species from deep-water chemosynthetic ecosystems including taxonomical, biological, ecological and distributional data as well as information on specific samples and collections (ChEssBase – www.noc.soton.ac.uk/chess/database/database.html); 2- development of a long-term international field programme for the exploration for and investigation of novel chemosynthetically-driven communities at key locations. Finally, ChEss is also developing a strong outreach and education component.

One of the recently selected key target areas for ChEss investigations, and the subject of this meeting, are the Polar regions, both Arctic and Antarctic, in conjunction with the IPY. This region has been chosen to complement the target regions (Atlantic Equatorial Belt, SE Pacific off Chile and New Zealand; see map on poster) in order to address specific scientific questions pertinent to biogeographic and biodiversity issues. Determining the evolutionary and ecological relationships amongst the fauna of polar chemosynthetic environments is crucial to understanding the processes that shape the distribution of species from chemosynthetic ecosystems at the global scale. Several polar chemosynthetic ecosystems (both hydrothermal vents and cold seeps) have been discovered to date and projects are underway to explore them using the latest technology, including Autonomous Underwater Vehicles and ROVs. The discovery of chemosynthetic ecosystems in the Polar regions is of particular importance as ridge systems that are geographically, hydrographically and/or topographically isolated (e.g., the Eastern Arctic field area) are more likely to have developed distinctive endemic biota and ecosystems. Hypotheses relating to hydrographic, bathymetric and biogeographic barriers may be tested by studying the relationships between these and other biogeographic regions.

STRUCTURE AND DEVELOPMENT OF MAR 30°N OCEANIC CORE COMPLEX

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Oceanic core complexes (OCC) are documented at slow, ultraslow, and some intermediate spreading centers. Prior hypotheses suggest that periods of reduced magma supply are key to development of asymmetric detach-

ment faulting that controls OCC development along spreading centers. Here, we use new geophysical analysis, in combination with recent drilling/logging results at Atlantis Massif, Mid-Atlantic Ridge 30°N, as a basis for discussing how magma supply along a ridge segment might relate to the observed lithospheric structures. An updated model (Ildefonse et al., 2006) of the relationship between episodes of increased magma supply and the onset, evolution, and end of detachment-controlled tectonics is included. The emphasis of the new model changes from OCCs reflecting periods of low magma supply to their representing past periods of greater than normal supply in that portion of the segment. Most aspects of the updated model are in line with previous hypotheses. However, the implication that OCC might document greater than normal magmatism in a section of the ridge is an important conceptual difference.

Although a number of questions remain to be addressed before the updated hypothesis can be proven or ruled out, recent results that lend support to the model include IODP drilling at Site U1309, which recovered 1415 m of mainly gabbroic rocks from the central dome of Atlantis Massif (Blackman et al., 2006). Updated analysis of bathymetry and gravity data, using a quasi-3-D approach, rather than the typical 2-D interface approach for estimating mantle Bouguer anomaly, shows that observations can be modeled with a significant amount of gabbro in the core of the massif. Post-cruise analysis of checkshot data at the drillsite indicates that a regional strong seismic reflector ("D" of Canales et al, 2004) may be most strongly related to differences in alteration within the section. Re-analysis of prior seismic refraction data and more in-depth analysis of the reflectivity in the local region of the drill site are currently underway and we will summarize the results at this meeting.

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TRANSITION FROM A CONTINENTAL TO AN OCEANIC RIFT IN THE NORTHERN RED SEA

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The transition from a continental to an oceanic rift is a fundamental step in the Wilson cycle; it leads to the generation of a new ocean and to the formation of passive margins. This transition can be observed today nowhere better than in the Red Sea/Gulf of Aden system.

We have carried out during several years a number of expeditions in the axial portion of the Northern Red Sea, in the region where the northernmost nuclei of axial emplacement of oceanic crust can be observed, up to the Zabargad Fracture Zone, a feature that crosses the Red Sea from coast to coast in a roughly N-S direction between 24 and 25 N, displacing its axis in what appears to be the precursor of an oceanic transform system. We also carried out field work in the Island of Zabargad, an uplifted fragment of sub-Red Sea lithosphere.

The two northernmost axial troughs, Thetis and Nereus, have been explored with multibeam acoustic surveys, magnetometry, seismic reflection profiling and bottom rock sampling. The Thetis deep is made up of three en echelon fault-bounded axial basins that are joined together, with axial volcanic ridges (resembling neovolcanic zones of mature slow-spreading ridges), and a large number of scattered small central volcanoes. The three basins are separated by shallower transfer zones where the deformation is more diffuse. Nereus is a well formed miniature axial rift valley, with a well developed neo-volcanic zones.

The neo-volcanic zones of both Thetis and Nereus are made of fresh MORB-type rocks, including fresh glasses. We have started a petrographic-geochemical study of these samples, that will include also major and trace element chemistry as well as isotopic (Sr, Nd, Pb and He) chemistry, in order to characterize their affinity to MORB, and to check possible systematic variations in the composition of the Red Sea crust moving from south to north.

The hypothesis is that, if the opening of the Red Sea will continue, the sub-deeps will evolve into oceanic ridge segments, perpendicular to the relative plate motion direction, and the transfer zones will evolve in oceanic transforms, parallel to the motion. This segmentation could be derived either from the ongoing coalescence of regularly spaced diapirs of upwelling asthenosphere, or from an initial structural segmentation of the rift in the continental stage, exploiting pre-existing structural discontinuities as suggested by the correspondence between axial valley segmentation and heterogeneities observed onshore on the continental margins.

Observations in the islands of Zabargad and Brothers suggest that the Red Sea crust outside the axial troughs is made of thinned continental crust criss-crossed by basaltic dykes and underplated by gabbroic intrusions.

THE SUBSOLIDUS SPINEL TO PLAGIOCLASE TRANSITION IN MANTLE PERIDOTITES: NATURAL AND EXPERIMENTAL CONSTRAINTS

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Plagioclase-bearing peridotites are diffuse in passive continental margin and mid-ocean ridge settings and constitute an important geodynamic marker. Their origin can be related either to i) impregnation of melts produced by asthenosphere upwelling or ii) metamorphic recrystallization via subsolidus tectonic exhumation of the lithospheric mantle from spinel- to plagioclase-facies conditions. The two processes can be concomitant and sometimes difficult to distinguish because detailed petrologic criteria are not yet available to properly define the metamorphic origin. So far, few studies have documented the spinel-plagioclase transition in mantle peridotites from both on-land and oceanic settings and experimental data are available only on simplified chemical systems (CaO-MgO-Al₂O₃-SiO₂, CMAS, CMAS + NaO₂, CMAS + FeO), for fertile mantle compositions (pyrolite), and at near-solidus temperatures (T = 1100-1300°C). These studies have evidenced that the spinel-plagioclase transition is isobar and occurs at pressures between 0.8 and 1.1 GPa, but the transition behaviour at lower temperature (600-1100°C) is only defined by thermodynamic calculations. The aim of this study is to locate the spinel to plagioclase transition as a function of the compositional variability of mantle peridotites, thus providing insights on the subsolidus exhumation of the lithospheric mantle at passive margins and ultra-slow spreading oceanic settings.

The research is based on a combined methodological approach including studies on Ligurian ophiolitic peridotites (Northern Apennine, Italy) coupled to experimental investigations performed on dry peridotite compositions modelled in complex systems (e.g. CMAS + NaO₂ + FeO + Cr₂O₃ + TiO₂) at P from 0.5 to 1.0 GPa and T from 900 to 1200°C. High pressure experiments are carried out in a single stage piston cylinder at the Dipartimento di Scienze della Terra (Milan) using salt-pirex-MgO assemblies. Synthetic gels reproducing bulk compositions of natural peridotites from the Ligurian ophiolitic massifs are used as starting materials. In order to favour crystal growth, gels are added with 1% of seeds mixture made of 30% spinel s.s. and 70% anorthite. Selected peridotite compositions range from fertile lherzolite to depleted lherzolite to harzburgite. Gels are sealed in an inner graphite capsule used to minimize Fe loss to the noble metal (Pt or AgPd) outer welded capsule, and to constrain the *f*O₂ at the C-CO₂-CO equilibrium. Temperature is measured by S-type thermocouple and is considered accurate to ±5°C.

Preliminary experimental investigations have been performed at T=1100°C and P= 0.5-1.0 GPa on a fertile lherzolite (CaO=3.41%; Al₂O₃=3.79%), representative of the composition of the Suvero ophiolitic peridotites (External Liguride Units, Northern Apennines; Rampone et al., 1993, 1995). These latter are spinel lherzolites (cpx ≈ 14%) partially recrystallized at plagioclase-facies conditions. Previous studies have documented extremely depleted Sr and Nd isotope ratios in these peridotites (⁸⁷Sr/⁸⁶Sr = 0.701736; ¹⁴³Nd/¹⁴⁴Nd = 0.513543), which were considered to reflect old time (> 800 Ma) of lithospheric accretion. Preservation of such isotopic compositions indicate that plagioclase crystallization in the Suvero peridotites was likely unrelated to melt impregnation (as documented in other Tethyan ophiolitic peridotites, Rampone et al., 1997; Piccardo et al., 2004), rather it occurred in response to subsolidus exhumation. The plagioclase-facies recrystallization is testified by i) fine-grained granoblastic aggregates of plagioclase + olivine + new pyroxenes developed between porphyroclastic spinel-facies minerals, ii) plagioclase rims around brown Al-rich spinels, iii) orthopyroxene + plagioclase exsolutions in spinel-facies clinopyroxene.

Experimental results at T=1100°C show that spinel-bearing assemblage is stable at 1.0 GPa whereas plagioclase-bearing assemblage is stable at 0.5 GPa. Inspection of BSE images show that plagioclase occurs as thin rim around spinel seeds or as small anhedral crystals associated with olivine and pyroxenes (see Segata et al., this volume). Textural features in the plagioclase-bearing experiment are thus consistent with natural occurrence. Reasonable grain size (up to 50-70 μm), and coherent element partitioning, in particular X_{Mg} in olivine (X_{Mg}=88-90), clino- (X_{Mg}=89-90) and orthopyroxene (X_{Mg}=89-90), strongly support approach to equilibrium and reliability of the experiments. Systematic compositional variations in minerals at different P-T conditions (e.g. decrease of the Al₂O₃ content in spinel-facies to plagioclase-facies pyroxenes) are consistent with those documented in the Suvero peridotites (Rampone et al., 1993). Plagioclase compositions in the experiment at 0.5 GPa, 1100°C are An 65-70, within the compositional range of plagioclase in the Suvero lherzolites (An60-70). Preliminary estimates of plagioclase modal abundance, by mass-balance calculations and Rietveld method, have furnished values ranging 6-8 wt% in the plagioclase peridotite at 0.5 GPa, 1100°C.

The spinel to plagioclase transition is expected to shift towards lower pressure at increasing bulk peridotite depletion. Further experimental investigations, performed on variably depleted peridotites will have the specific aims i) to locate in the P-T subsolidus space the spinel to plagioclase reaction (pl+ol=sp+cpx+opx), as a function of peridotite composition, and ii) to define the reaction progress as a function of pressure through the determination of reaction coefficients.

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SNAPSHOTS OF THE MAGMA PLUMBING SYSTEM FROM MELT INCLUSION AND RESIDUAL PERIDOTITES OF THE VEMA LITHOSPHERIC SECTION (MAR 11N)

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An attempt to picture out the magma plumbing system beneath a mid-ocean ridge slow-spreading segment has been done by combining data from residual mantle peridotites and associated erupted MORBs sampled along the Vema Lithospheric Section of the Mid Atlantic Ridge (11°N). The degree of melting undergone by the upper mantle has been estimated from major and trace element mineral chemistry of residual peridotites. The degree of melting recorded by the mantle residua steadily increased during the last 20 My.

REE patterns of the residual clinopyroxenes suggest that melting started in a garnet-bearing source and continued in the spinel field. The degree of melting experienced in the garnet stability field and in the spinel stability field both increased through time.

Mantle peridotites show textural evidence of crystallization of melts percolating along grain boundaries and deformation-controlled microfractures. The partial reequilibration of the residual assemblages with such melts induced a weak refertilization of the mantle residua. This results in a slight enrichment of the most incompatible trace element content. Modelling such deviation from the expected pure residue of partial melting allowed us to identify the nature of the transient melts. Model percolating melts range from quasi-instantaneous to partially aggregated melts extracted from discrete portions of the melting regions rooted in the garnet-stability field, across the garnet-spinel transition or in the spinel-stability field. Their pressure distribution (estimated assuming a fixed grt-sp transition depth) reveals rapid/discontinuous percolation through the source.

Associated MORB major element systematics show they are equilibrated at 4-6 kbar. High equilibration pressures are due possibly to the cold edge effect control on crystallization.

A systematic study of plagioclase-hosted melt inclusions allows inferences on MORB parental melts. Primary melts equilibrate in a broad pressure range with a maximum between 7 to 10 kbar, well separated from the host lava pressure distribution. Equilibration results by separation of a troctolitic component followed by crystallization of an olivine-gabbro component. Preliminary data on trace elements in melt inclusions and host lavas suggest mixing of deep (garnet in the source) and shallow (depleted source in the spinel-stability field) components of partially aggregated melts to form the erupted MORBs.

WAY OF EMPLACEMENT AND COMPOSITIONAL VARIATIONS OF MAGMA AT THE MID-OCEANIC RIFT AXIS, KEYS FOR DECIPHERING MECHANISMS OF SLOW RATE SEA FLOOR SPREADING

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The mechanisms of slow to ultra-slow oceanic spreading along the rift axis are still misunderstood. Spreading is associated with tectonic exhumation on the sea floor of mantle and lenticular gabbro bodies, and from place to place with basaltic eruptions.

The volcanoes are small in size but very numerous. They cover by hundreds small reliefs (abyssal hills) which only form at the axial zone. The most puzzling is that the most recent eruptions always occur on the crest of

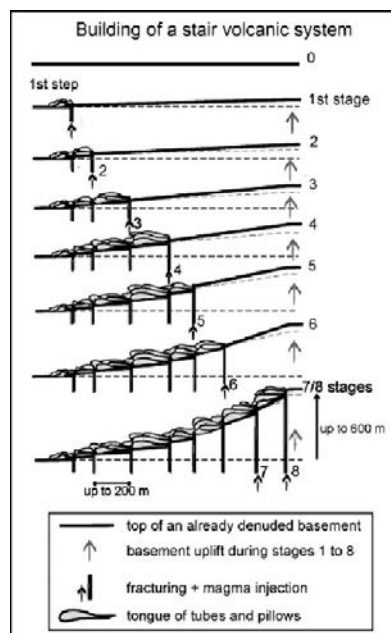


FIG. 1

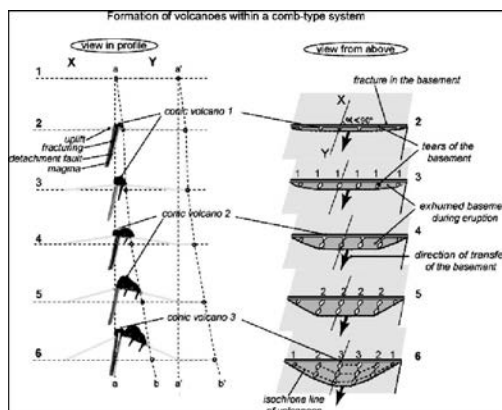
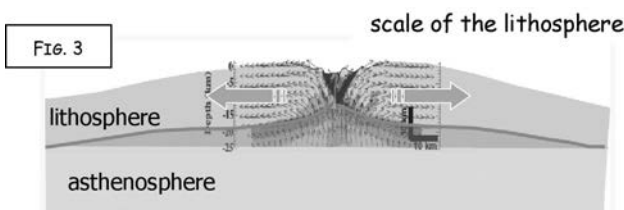


FIG. 2



mantle melting controlled by the relative motions
of asthenosphere and lithosphere

the hill, the previous ones being like dragged away and downward. Until now the published tectonic models do not integrate the building of such volcanic reliefs at the rift axis. They do not explain anymore the exhumation, only at the rift axis, of gabbro bodies, the shape of which remains also enigmatic. The last but not the least observation, which remains to integrate to the tectonic model, concern the rather primitive features of intrusive and extrusive magmas. That first suggests rapidly varying archeological behaviour of the sub-oceanic mantle as gabbros and basalts outcrop next to each other along the rift axis. It also means that fissure fed-dikes should be more or less rooted in the mantle source below the lithospheric mantle. Consequently mantle exhumation, magmatism and processes of enlargement of the ocean floor should be closely linked.

One of the keys for trying to solve these questions is to look both at the way of emplacement of magma and the recorded compositional variations. My study (Chalot-Prat, 2005; <http://francoise.cp.free.fr/geol/>), supported by a 1/25 000 geological map, related cross-sections and an exhaustive geochemical sampling of volcanics, mainly focused on the building of the volcanoes and the space-time relationships with their

mantle or gabbro basement on a fossil abyssal hill at the axial zone of a slow spreading ocean (Chenaillet ophiolite, Franco-Italian Alps).

A model is proposed whereby: (1) the volcanic reliefs forming at the axial rift are linked to the uplift of serpentinized mantle during eruptions, whatever its exhumation pre-dates or is synchronous with magma outpouring on the sea floor; (2) mantle melting is controlled by the relative motions of asthenosphere and lithosphere at divergent plate boundaries.

The main observations on volcanoes can be summarized and interpreted as follows:

Volcanoes formed on slopes, and the higher the edifice, the younger it is relative to the others. Two types of volcanic architecture, stairs and combs, exist.

Stairs are associated with tongue-like volcanoes cascading down the steps. Stairs emplaced by rifting of a basement in uplift and already denuded by detachment faulting (Fig.1).

Combs consist of strings of conical volcanoes or hummocks, sitting at the intersections of major fissures parallel to the spreading axis with oblique subsidiary fractures. Combs formed on a basement in uplift and in the process of denudation along detachment faults serving as magma conduits at depth and as a travelator for volcanoes on the sea floor to a limited extent (< 500m)(Fig.2).

In both types of architecture, the magma chamber remained located beneath the highest part of the relief.

In the stairs and combs, rhythmic compositional variations occurred with time. They attest to cyclic eruptions of primary and differentiated melts, or to extraction of melts as they formed successively. The magma conduits were rooted within ephemeral, small and frequently recharged, reservoirs, or even within the mantle source.

Lithospheric tectonics controlled not only magma ascent but also mantle melting by adiabatic decompression of asthenosphere during spreading of lithosphere (Fig.3, with numerical model from Poliakov & Buck 1998, AGU, Geophysical Monograph 106, 305-323).

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KNIPOVICH RIDGE: VOLCANISM, TECTONICS AND HYDROTHERMALISM

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Knipovich Ridge is the northern continuation of Mid-Atlantic Ridge (MAR) locating between the Greenland and Spitsbergen Archipelago. It orthogonally joins the Mohs Ridge on the south and is limited by the Molloy fracture zone on the north. In contrast to MAR, Knipovich Ridge occupies not a central position but is shifted towards the Spitsbergen Archipelago. Knipovich Ridge features ultra-slow spreading rates (1.4 cm/year, [1]) and oblique orientation of the rift valley in relation to the spreading direction [2]. Compared to other Atlantic ridges, the Knipovich Ridge is very poorly studied. The essential contribution to its research based on the results of side-scan sonar survey with SeaMarc in 1989-1990 has been provided by K. Crane et al (1995). The subsequent multi-disciplinary studies of different sections of the ridge have been carried out in the course of scientific cruises onboard RV "Professor Logachev" (1996) and RV "Akademik Mstislav Keldysh" (1998) [4, 5]. The last international expedition onboard RV "Professor Logachev" has been executed in 2000 [6, 7].

The conducted research revealed a number of new characteristic features of the Knipovich Ridge rift valley, particularly, the distinctions in volcanism and tectonics in its northern and southern parts [8]. Four volcanic

ridges were distinguished within its rift valley, the most studied one was called "Logachev" rift mountains. Ridge axes are associated with volcanic cones areas interpreted as neovolcanic zones. As ridges as a whole, neovolcanic zones are oriented north-eastward, obliquely to general submeridional orientation of the rift valley. Neovolcanic zones widen northward and ridge altitudes increase from 400 m to 1000 - 1350 m in the same direction.

Volcanic ridges can correspond to segment centers about 100 km in length. Lower-order segments of approximately 20 km long are also suggested. The chain of off-axis seamounts extends at both sides of each volcanic ridge in the rift valley. These ridges can be interpreted not only as a present segment centers but as a long-living volcanic centers. Orientation of the mountain chain corresponds to spreading direction. The faults located in the axial part of the rift valley are well-pronounced at the sonar records, most of them are orthogonal to the vector of Eurasian plate motion relative to the North American plate (306-307°, after [1]), but do not completely coincide with NUVEL-1 model of plate motion. Whereas the volcanism is more active in the northern part of the Knipovich Ridge rift valley, the faults are more abundant in its southern part. This difference in volcanic and tectonic activity can be evidence of different stages of the Knipovich Ridge evolution and/or suggest the difference in magma sources for its southern and northern parts. Data obtained with TV-grab profiling and dredging imply that neovolcanic zones in the southern part of the ridge are mostly covered by sediments and the basalts are more altered compared to its northern part. This give a reason to suggest a more ancient age for the neovolcanic zone of the southern part.

Unexpected results were obtained at dredging the western slope of the Knipovich Ridge rift valley at 77°50'N. The rocks collected by the dredge were represented by dark argillites, marbles and highly altered basalts. One sample has a hot contact between the basalts and argillite implying the younger age of the basalts. The age of argillite was determined by micropaleontological method as Oligocene. This data allow to reconsider the evolution of the Knipovich Ridge.

The following indicators of hydrothermal activity were detected in the water column and bottom sediments:

1. At least five temperature anomalies are revealed at the near-bottom profile along the ridge axis.
 2. The same profile demonstrates the highly anomalous particle concentration in the near-bottom waters of the southern part of the ridge. Repeat studies at the same place revealed anomalous methane content, pH, TDM and bacteria activity (PTA).
 3. Essential methane anomalies were also observed in the bottom waters in the northern part of the ridge.
 4. High concentrations of copper and zinc were detected in the sediments of central and northern part of the ridge.
- All this data have confirmed the perspectives of Knipovich ridge in terms of hydrothermal activity and associated sulfide mineralization.

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FROM MAGMA-ENGORGED TO MAGMA STARVED "CONSTIPATED" LITHOSPHERE: THE MID ATLANTIC RIDGE FROM 40°N TO THE EQUATOR

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The near zero-age Mantle Bouguer anomaly tends to grow in the Mid Atlantic Ridge from the Azores swell at ~40° to the equator, suggesting that crustal thickness decreases from north to south. The subridge mantle degree of melting estimated from the mineral chemistry of mantle equilibrated spinel, opx and cpx of peridotites, as well as from the Na8 content of basaltic glasses, decreases from north to south in parallel to the decrease of crustal thickness. This pattern can be explained if the mantle that upwells below the ridge becomes gradually cooler and/or less fertile moving from the Azores swell to the equator.

The temporal evolution of this portion of a slow-spreading mid ocean ridge can be studied along seafloor spreading flowlines normal to ridge segments. Mantle Bouguer anomalies obtained along 4 profiles normal to axial segments between 28° N to 31°30' N all indicate steady crustal thickening from ~10 my old crust to present. A lithospheric section exposed between 10° and 11° N, south of the Vema Fracture Zone (Vema Lithospheric Section or VLS) is giving us the opportunity to study how generation of lithosphere at a 80-km long ridge segment evolved from 25 my ago to present. Gravity data as well as mantle peridotite and crustal basalt chemistry converge in suggesting a steady increase in crustal thickness and in mantle degree of melting from 20 my ago to present. Superimposed on this trend are 2-4 my oscillations that were also observed in the 28° N to 31°30' N profiles. The mantle degree of melting and the crustal thickness are not directly proportional to spreading rate in this section, suggesting a non-purely passive model of formation of the lithosphere at ridge axis. The combination of the zero-age axial ridge trend with the 25 my to present trend could be explained by a subaxial hot mantle flow from the Azores swell toward an equatorial "cold" belt characterized by long offset transforms.

This equatorial belt is magma starved and nearly free of basaltic crust. Small quantities of basalt are generated by low (<5%) degrees of partial melting mostly in the garnet stability region of the upper mantle. The equatorial cold mantle belt is made of nearly undepleted peridotites containing small frozen melt pockets. This dispersed melt could not be expelled from the mantle, and froze to form a "constipated", crust free lithosphere.

SEGMENTATION OF THE GAKKEL RIDGE AS REVEALED IN POTENTIAL FIELDS DATA

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Gakkel Ridge segmentation has been recognized in the apparently abrupt change from magmatic to amagmatic seafloor spreading. Potential fields data, which reflect the integrated volumetric characteristics of magnetization and density, are influenced by the striking contrasts in rock properties associated with changing processes of seafloor spreading. Quantitative analysis of the co-variation of bathymetry with the co-registered gravity and magnetic anomalies provide another method to study segmentation and make predictions about as yet unvisited pieces of the seafloor.

AUTONOMOUS BATHYMETRIC DATA ACQUISITION IN THE EURASIAN BASIN – A ROLE FOR LANGRANGIAN SWATH MAPPING?

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While development and deployment of capable icebreakers has dramatically improved access to the deep Arctic Ocean over the last decade, much of the basin remains unmapped. The retreating sea ice and distance are the two primary obstacles to be overcome to access the slowest spreading portions of the Gakkel Ridge.

A tool under development (Anderson and Chayes, 2003), the Seafloor Sounding in Polar and Remote Regions (SSPARR) buoy, will utilize communications technology commonly employed on drifting oceanographic buoys to return bathymetric data via satellite in real time. Each battery-powered buoy will contain a simple single-beam echo sounder, a GPS receiver and a bi-directional satellite link. Design life is four years. Given sufficient production, the price of each buoy is predicted to be between USD 3,000 and 5,000.

An array of these buoys, deployed in the ice in the Laptev Sea could ride the drifting ice across the slope and the slowest spreading segments of the Gakkel Ridge, returning an incremental swath map over days, months and years. This could be accomplished with sixty buoys, on a two kilometer spacing, at relatively low cost compared to an icebreaker cruise.

Two options could make it possible to deploy these buoys. Over the last few years, the Nansen and Amundsen Basin Observational System (NABOS; <http://nabos.iarc.uaf.edu>) has had an annual cruise to the central Laptev Shelf to service a set of moorings on the slope. Until this year, these cruises sailed without a hull-mounted bottom sounder capable of measuring full ocean depths. Deploying these buoys during the annual NABOS cruises would provide bathymetric data to support the oceanographic objectives of this program.

The preferable option would be to link deployment to a planned repeat of the drift of the Fram. The Galileo Project (see; <http://polarfoundation.org/index.php?s=3&rs=home&uid=75&lg=en>) would freeze in an ice-capable vessel to ride the sea ice across the basin. A manned, drifting platform accompanying the buoys would make it possible to fix defective buoys and, if necessary, redeploy the array to ensure coverage of the ridge axis.

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DISTRIBUTION AND NATURE OF VOLCANISM AND FAULTING ALONG THE WESTERN GAKKEL RIDGE (6°W - 30°E)

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Plate separation at mid-ocean ridges involves both magmatic and mechanical extension. The balance and interplay of these two mechanisms varies as a function of spreading rate and melt availability to produce the differing ridge axis and flank morphology characteristic of fast- and slow-spreading ridges. Mantle melting models based on decompression melting predict that melt production and crustal thickness should decrease dramatically at spreading rates of less than < 15 mm/a. The extremely low spreading rate on the Gakkel Ridge may affect not only the crustal thickness, but also the form and along-axis distribution of volcanism and faulting, as well as the shape of abyssal hills and ridge segmentation.

We have undertaken a quantitative study of the distribution and nature of volcanism and faulting along the western and central Gakkel ridge axis and of the relationship between the two processes. The distribution of volcanism was determined using a numerical algorithm to identify isolated volcanic edifices by searching for closed concentric bathymetric contours. This technique allows the location of volcanic features to be determined, as well as estimated of their height and volume. Volcanic and tectonic features are initially distinguished by their aspect ratio. The distribution of faulting is investigated by analysis of the slopes of gridded bathymetric data.

There is a distinct and abrupt boundary along the Gakkel Ridge axis near 3°E. West of that longitude, the axis has a morphology that is superficially similar to the Mid-Atlantic Ridge, and the rift valley axis is marked by elongate axial volcanic ridges [Michael et al., 2003]. The bathymetric

analysis shows the presence of small, presumably volcanic seamounts scattered across the rift valley floor and within the rift mountains. However, both the number and height of seamounts is significantly less than observed at the Mid-Atlantic Ridge [e.g., *Smith and Cann, 1990, 1992, 1993*]. It appears that volcanism in the western magmatic portion of the Gakkel Ridge is characterized primarily by higher volume fissure eruptions rather than the small volume point source eruptions that characterize the Mid-Atlantic Ridge.

East of 3°E, the rift valley becomes much deeper (> 5000 m). In this region, the rift valley floor is basically devoid of volcanic features and a bathymetric low, rather than a volcanic ridge, marks the axis. The few seamounts observed in our analysis tend to be on the rift valley walls or in the rift mountains. It appears that plate separation occurs primarily by faulting with a small amount of minor secondary volcanism off of the axis. The rift valley walls consist of large throw faults. Within the resolution of our gridded data, rift valley walls with heights of > 1000 m appear to be single fault surfaces. The rift valley morphology west of 19°E is asymmetric, suggesting that plate separation occurs along a dipping detachment.

Seamounts are again observed within the rift valley at the 19°E magmatic center. However, they are small and are fewer in number than at the MAR. The volcanic activity in this region is characterized by constructional ridges. This could be the result of fewer, but higher volume eruptions than at the Mid-Atlantic Ridge, with the eruptions occurring along fissures.

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ULTRASLOW SPREADING RIDGES

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Ultraslow spreading ridges represent a newly recognized class of ocean ridge that constitute a major portion of the global ridge system. They are as different from slow spreading ridges as slow are from fast. They are characterized by extreme crustal heterogeneity and unique tectonic structures, but are most easily defined by their spreading rates <20 mm/yr full rate. While their unique features do not depend solely on spreading rate, this division is convenient as it is the point below which seismic crustal thickness becomes highly irregular, frequently anomalously thin or even zero in thickness over long sections of ridge. Where the effective spreading rate is less than 12 mm/yr, transform faults disappear, and the plate boundary may consist of linked amagmatic and magmatic accretionary segments.

Amagmatic segments are an entirely new class of stable plate boundary structure, equivalent in rank to transform faults, subduction zones, and accretionary magmatic segments. They were not previously recognized as they appear to occur principally only at ultraslow ridges, which have been little studied until recently. Amagmatic accretionary segments, unlike magmatic, may assume any orientation to the spreading direction, and extend the plate boundary both in the direction of spreading and perpendicular to it. Amagmatic accretionary segments expose abundant mantle peridotite, and basaltic crust is generally thin or even absent.

Where ultraslow spreading ridges consist of linked amagmatic and magmatic segments, the basalt chemistry is often highly enriched far from mantle hotspots, and may even erupt alkaline basalt magmas. This is taken to represent aggregation of low degree melts from large regions of the mantle beneath ridges where higher degree melts are not produced due to a thicker conductive lid and lithosphere limiting melting. Amagmatic accretionary segments also provide the first opportunity to look at the abyssal mantle

source where it has undergone very low degrees of mantle melting. Surprisingly, the mantle is far more depleted than would be anticipated for simple models for MORB generation that generally predict clinopyroxene contents >10%. In fact, over large regions, virtually clinopyroxene free harzburgite occurs, and may represent relict mantle from an earlier melting events. This suggests that mantle veins may be more important in the generation of MORB than previously thought, as these would largely melt out prior to melting of the host peridotite, and could account for the high apparent clinopyroxene contents predicted for the abyssal mantle by inverting MORB compositions.

Another anomaly associated with ultraslow spreading ridges is a far higher abundance of hydrothermal plumes than found at faster spreading ridges. Curiously, these plumes are largely restricted to magmatic accretionary segments at the Gakkel, while they are abundant at amagmatic segments on the SW Indian Ridge. The explanation for this may be that at the Gakkel, the amagmatic segments are largely oriented perpendicular to the plate spreading direction, and thus the low-angle faults on which mantle peridotites are emplaced to the seafloor there can accommodate most of the extension. With abundant fine-grained mylonites, serpentinization, talc metamorphism, these faults are likely relatively aseismic, slip smoothly and provide poor pathways for hydrothermal circulation. By contrast, at the highly oblique amagmatic segments on the SW Indian Ridge, strain is highly partitioned, with the low angle faults oriented at highly unfavorable angles for faulting, brittle faulting in the shallow crust is largely accommodated by innumerable small normal faults oriented perpendicular to the spreading direction that likely provide excellent pathways for hydrothermal circulation.

A COMBINED RAYLEIGH WAVE, LOVE WAVE, AND GRAVITY STUDY OF THE UPPER MANTLE BENEATH THE REYKJANES RIDGE

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Along the Reykjanes and Kolbeinsey ridges, geochemical, seismic, and seafloor morphological evidence for high mantle melt production is usually attributed to outward flow of Icelandic plume material beneath those ridges [e.g., *Schilling, 1973; Fitton et al., 1997; Smallwood et al., 1995; White et al., 1995; Searle et al., 1998; Murton et al. 2002; Pilidou et al., 2004*]. Although debate continues over the origin of such a plume [*Foulger and Pearson, 2001*], seismic tomographic images reveal a plume-like structure in the upper mantle beneath Iceland [*Wolfe et al., 1997; Foulger et al., 2000; Allen et al., 2002; Zhao, 2004*] and several plume-flow models have been developed to explain Icelandic volcanism and the observations along the adjacent ridges. Although the observations are most often attributed to sub-lithospheric spreading of plume material away from Iceland [*Vogt, 1976; Ribe et al., 1995; Ito et al., 1996; Ito et al., 1999; Albers and Christensen, 2001; Ito, 2001*], the exact manner of such spreading is not yet understood. At least two end-member models have been proposed: in one model buoyant plume material is narrowly channeled down a ridge within a lithospheric groove that is formed by the thin axial lithosphere [e.g., *Albers and Christensen, 2001*]. In an alternate model, plume material spreads out broadly beneath the lithosphere [e.g., *Hirth and Kohlstedt, 1996; Ito, 2001*]. To test such models, we used broadband records of fundamental mode Love and Rayleigh waves to study the seismic properties of the upper mantle beneath the Reykjanes Ridge. The seismic waves were generated by regional earthquakes occurring in the North Atlantic to the south of Iceland, and were recorded by the HOTSPOT and ICEMELT arrays and the GSN station BORG, located on Iceland. The phase, group, and amplitude information were measured for narrow-band wavelets over the period range of 12-100s. We used the multispectral finite-frequency tomography method of *Dunn and Forsyth [2003]* and over 12,000 such measurements to solve for mantle and crustal shear wave velocity structure and seismic anisotropy. In a vertical plane oriented normal to the ridge axis, the shear wave velocity structure contains a high-velocity lithospheric lid that thickens asymmetrically with distance from the ridge, and beneath that a broad (over 500 km wide) and deep (140+ km depth) low velocity zone in the upper mantle centered beneath the Reykjanes Ridge. A joint analysis of the seismic structure with gravity data reveals that the low velocities are consistent with elevated temperatures (<200°C) and only a very small amount of melt, if any (<0.1%). Our study indicates that plume material spreading outward beneath the Reykjanes Ridge from Iceland is not confined to a lithospheric channel beneath the ridge. Although seismic anisotropy that could con-

strain flow along the ridge is not determined by our experiment (i.e. azimuthal anisotropy), our results do reveal anisotropy in a vertical plane normal to the ridge (i.e., “transverse isotropy”) that is derived from the different polarizations of the Love and Rayleigh waves. This type of anisotropy may be used as an indicator of mantle flow within a vertical, ridge-normal plane. At lithospheric depths everywhere and at sub-lithospheric depths far from the ridge, the shear wave anisotropy indicates a predominant horizontal alignment of the fast-axes of anisotropic crystals in the spreading direction. However, at sub-lithospheric depths beneath the ridge, the anisotropy indicates a general vertical alignment of the fast axes. The anisotropy agrees with a general pattern of vertical flow and shear in the mantle beneath the ridge, with subsequent rotation to horizontal flow at shallow depths near the ridge and at deeper depths far from the ridge. Our presentation will include a comparison of the Reykjanes ridge upper mantle seismic structure with new results from a similar study located along the southern East Pacific Rise and, given time, early results from a new study of the upper mantle structure beneath the Arctic mid-ocean ridge system (Kolbeinsey, Mohns, and Gakkel ridges) that are also derived from a surface wave analysis.

THE GEOLOGICAL SETTING OF HYDROTHERMAL VENT SITES ON THE GAKKEL RIDGE

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Hydrothermal plume reconnaissance conducted during rock sampling operations on the Arctic Mid-Ocean Ridge Expedition (AMORE) in 2001 revealed evidence of abundant hydrothermal venting on the Gakkel Ridge [Edmonds et al., 2003]. Comparison of the plume distributions with multi-beam bathymetry data collected during AMORE showed that vent plumes were closely associated with topographic highs located inside the axial valley. Prior to the AMORE program, the 1998 and 1999 Science Ice Exercises (SCICEX) had mapped the finer scale textures of the axial valley, clearly depicting the locations and distribution of lightly sedimented volcanic flows and faults [Edwards et al., 2001]. Here we present the results of integrating the water column and broad-scale topographic information from the AMORE program with more detailed textural data from the SCICEX surveys to improve models for predicting where hydrothermal venting is likely to occur on ultra-slow spreading mid-ocean ridges.

The 1998 and 1999 SCICEX mapping was accomplished using a 12 kHz Sidescan Swath Bathymetric Sonar (SSBS) mounted on the hull of the U.S. Navy's nuclear-powered submarine *USS Hawkbill*. During a total twelve-day survey of the Gakkel Ridge (approximately six days in 1998 and six days in 1999) the SSBS simultaneously collected co-registered sidescan and phase-difference bathymetry for the ridge axis and flanks from ~4°E to 97.5°E. The sidescan data collected for the Gakkel Ridge have a sampled per-ping across-track resolution of 20m. The along-track resolution of the sidescan data is ~120m, a function of the ping rate (16 seconds) and the speed of the submarine (average = 16 knots). The sidescan data were processed to improve the signal-to-noise ratio, then navigated using raw and processed positional data collected by the *USS Hawkbill's* Submarine Inertial Navigation System (SINS). The enhanced, navigated sidescan values were gridded into 100 and 200m cells for integration into geographic information systems and charting.

Hydrothermal plume data (optical backscatter and temperature profiles) were collected during AMORE using Miniature Autonomous Plume Recorders (MAPRs) deployed 75 m above each dredge and 50 m above each rock core. A total of 145 deployments were made along 1100 km of the ridge from ~7°W to 85°E from the *USCGC HEALY* and *PFS Polarstern*. Eight of the hydrothermal plumes observed have been “tracked” to particular areas of the seafloor, with evidence for at least two additional plumes of less certain origin. Baker et al. [2004] postulated that the plume overlying one site identified by Edmonds et al. [2003], at 69°E, is in fact the plume emanating from the volcano at 85°E and advected >150 km along axis. Mueller and Jokat [2000] and Edwards et al. [2001] had identified the 85°E site as a potential 1999 volcanic eruption based on teleseismic data and SCICEX sidescan imagery for the area.

To create detailed predictions for the types of geological sites where hydrothermal activity might be expected to occur along ultra-slow spreading ridges, we have integrated the AMORE plume distributions with the SCI-

CEX sidescan and bathymetry data. Our preliminary efforts focus on five hydrothermal sites identified by Edmonds et al. [2003] and Baker et al. [2004] (7.5°E, 37°E, 43°E, 55°E and 85°E). We co-register the observed plume distributions with the locations of tectonic and volcanic features such as faults and reflective lava flows and generate three-dimensional interpretative maps of the hydrothermal sites. These results will be compared with similar interpretative products for the 69°E region and other sites where plume signals were observed but the hydrothermal activity could not be localized, based on the strength of the MAPR signals or the occurrence of “near-field” signatures such as distinct layering or temperature anomalies. Comparison of the two classes of vent sites will be used to produce an improved model for predicting where hydrothermal venting might be observed during future Gakkel Ridge expeditions.

SIMULATED DRILLING PROFILES FROM A MAGMA-POOR MARGIN ON LAND

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Several vertical profiles have been conducted over a paleo magma-poor margin on land in order to simulate drilling profiles providing comparative data with ODP/IODP drill holes. The Tasna ocean-continent transition (OCT), south-east Switzerland, was selected for this study as this OCT is considered a direct analogue of present-day magma-poor margins, e.g. west of Iberia. In analogy with the famous Hobby High in Iberia, a wedge of lower continental crust is bound by two detachment faults, the Lower (LTD) and upper (UTD) Tasna Detachments (Froitzheim and Rubatto 1998). The LTD (HD equivalent in Iberia) separates crustal rocks in the hanging wall from serpentinized mantle rocks in the footwall. The UTD (HHD equivalent in Iberia) cuts the LTD and exhumed the continental crust and the serpentinized mantle to the sea floor (Whitmarsh et al. 2001).

Profiles were constructed from the LTD contact (continental rocks/mantle) and the UTD contact between sediments and exhumed mantle and end at the base of the exposed mantle. A measuring tape was placed in a direction normal to the fault surface. The maximum vertical length of the profiles is 160 m, similar to 16 ODP/IODP drilling cores with full recovery. Along each profile continuous magnetic and structural data were collected with samples taken at regular intervals for geochemical and physical analysis. These data can be compared directly with the same data from the Newfoundland-Iberia margin. The main aim of this study was to recognize what geochemical, structural and geophysical signatures are characteristic for a magma-poor margin. Other objectives were to test how representative one “drilling profile” is for a larger (10¹ to 10³ m) area and how deformation and erosion affect the recovery of a profile.

We find that: i) stable isotopic data from the two margins and land-analogue generally show very different characteristics. This is mainly because isotopes are sensitive to overprinting fluids. Similar findings support the presence of a narrow “fault core” located directly beneath the detachment contact. In this zone fluids are either depleted or enriched in ¹⁸O. ii) Whole-rock geochemical data demonstrate some similarity and record differences in the degree of calcification, marine weathering and erosion between the sites. iii) Density data from the serpentinized rocks are similar. iv) Magnetic data demonstrate differences in reducing/oxidizing conditions subsequent to serpentinization.

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ISOTOPE GEOCHEMISTRY OF GAKKEL RIDGE BASALTS AND ORIGIN OF A "DUPAL" SIGNATURE

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The initial results of AMORE 2001 [1,2] showed that the Gakkel Ridge is composed of three tectonic segments: the magmatically robust Eastern and Western Volcanic Zones (EVZ and WVZ, respectively), and the magma-starved Sparsely Magmatic Zone (SMZ), where peridotite outcrops on the ridge axis. Here we use radiogenic (Pb-Sr-Nd) isotope data on axial lavas to characterize the composition of the sub-Arctic mantle. The results confirm distinct mantle compositions beneath the EVZ and WVZ, and a boundary in the SMZ. Thus upper mantle chemistry is reflected in the surface tectonics. Moreover, the pattern of isotopic variations in this small region of the Arctic mimics the global-scale variability of the oceanic mantle. Consideration of the regional tectonic history and volcanism constrains the processes that impart major heterogeneity to the upper mantle.

Results:

Lavas of the EVZ, closest to the continent and where the spreading rate is the slowest, sample normal depleted "Atlantic-Pacific" oceanic mantle. They display the lowest Sr and highest Nd isotope ratios among the ridges north of Iceland.

Lavas of the WVZ display isotope ratios reflecting greater (time-integrated) incompatible trace element enrichment, with strong affinities to the "DUPAL anomaly" of the Southern Hemisphere [3,4], including high $^{208}\text{Pb}/^{204}\text{Pb}$ and a steep negative correlation between Sr (y-axis) vs Pb isotope ratios.

The SMZ records an abrupt isotopic discontinuity, like the Australian-Antarctic Discordance (AAD) marking the boundary between the "DUPAL" and "Pacific" mantle isotopic provinces. Common features of the SMZ and AAD (great depths, low magma production, boundaries between chemically and isotopically distinct regions in the mantle) indicate close relationships between sea floor structure, bathymetry, melting regime, and upper mantle convective processes.

Within the SMZ there is no geographical overlap of WVZ and EVZ affinities. Near the SMZ midpoint at $\sim 14^\circ\text{E}$, lavas with affinities to the WVZ and EVZ were collected within 20 km of each other. Thus the discontinuity is sharp, with no apparent "leakage" across it.

Discussion:

The Gakkel WVZ the only spreading ridge outside of the "Indian Ocean isotopic province" clearly showing "special" isotopic compositions associated with the "DUPAL anomaly". Through its presence in the Northern Hemisphere, we infer that a DUPAL signature is neither an "anomaly", nor is it necessarily a Circum-Indian ocean phenomenon. The geographically constrained nature of the Eurasian Basin makes it possible to constrain the responsible processes, thus shedding light on the origin of the first order compositional distinctions of global MORB.

Recent volcanism in the Svalbard Archipelago, on the margins of the Eurasian Basin near the Gakkel WVZ, offers clues to the origin of the DUPAL-like isotopic signature. In all isotope ratio diagrams, Quaternary alkaline lavas of NW Spitsbergen [5,6] lie at the "enriched" end of the trend for WVZ lavas. Thus it is clear that WVZ isotopic trends reflect input into the western Arctic asthenospheric mantle of an end-member component present in Spitsbergen.

Many incompatible element ratios in Spitsbergen basalts (e.g. Th/La and U/La) also lie at the end of WVZ trends, further supporting its role as an end-member for the WVZ. However, elements with significant compatibility in amphibole and phlogopite such as Rb and Ba show significant depletions (reflected by low Rb/La and Ba/La), indicating that the source of the Spitsbergen lavas contains residual amphibole and/or phlogopite, phases that are characteristic constituents of the lithospheric mantle.

The generation of basaltic magmas in Spitsbergen requires a mantle source, and the Rb/La and Ba/La depletions strongly indicate melting of the sub-continental lithospheric mantle (SCLM). Since this end-member plays an important role in the WVZ, the data strongly suggest that the DUPAL signature is generated by a SCLM contribution to western Gakkel asthenospheric mantle.

The introduction of SCLM to the western Gakkel asthenosphere, and the presence of a compositional boundary in the middle of the Arctic, can be understood in the context of the regional tectonic history. Arctic and North At-

lantic seafloor spreading began at 55-60 Ma [7], however, the nascent Eurasian and Atlantic ocean basins remained separated by continental. Greenland and Norway-Svalbard began to separate at ~ 34 Ma, accompanied by the northward propagation of the N. Atlantic ridges. This caused North Atlantic mantle to flow primarily northeast, into the Arctic, accompanied by detachment and dispersal of Svalbard SCLM, with linkage of the Arctic and N. Atlantic occurring only at ~ 10 Ma. Considering the geologic history of the Arctic region and our new data, we interpret the SMZ as the surface manifestation of a physical boundary within the mantle where the linkage occurred. The origin of the "DUPAL signature" is an ongoing debate in mantle geochemistry. Studies have focused on the role of (1) ancient subduction of continental crust or altered oceanic crust and sediment, or (2) contamination of the asthenosphere by detachment of lower continental crust during continental breakup. These two models are not unique and neither can be rejected on purely geochemical grounds. The combination of the Gakkel data, the evidence from Spitsbergen volcanics, and the well-constrained tectonic history provides for the first time a genetic relationship where geochemistry and tectonics are understood and in accord.

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HELIUM-3, METHANE AND MANGANESE IN WATER COLUMN HYDROTHERMAL PLUMES ALONG THE ULTRA-SLOW SPREADING GAKKEL RIDGE, ARCTIC OCEAN

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The Gakkel Ridge is the slowest-spreading end-member of the global mid-ocean ridge system. During August and September 2001, the US Coast Guard icebreaker Healy, in collaboration with the German ice-breaker Polarstern, carried out a 63-day, high-resolution mapping and sampling expedition (AMORE - Arctic Mid-Ocean Ridge Expedition) to this region of the high Arctic, which had remained largely unsampled due to pervasive ice cover.

Discoveries of hydrothermal venting into the water column along the Gakkel Ridge were made during AMORE (Edmonds et al. 2003; Michael et al. 2003; Baker et al. 2004). These studies show the presence of plumes discharging from about 12 distinct vent localities between 8°W and 85°E . Six water column profiles of ^3He , CH_4 and Mn further attest to the vigorous nature of the venting. Five of our six hydrocasts targeted plumes in volcanically active areas where fresh basalt was recovered. These plumes are typically present at water depths of a few hundred meters above the summit of a nearby volcano. Two exceptions are a large plume at 85°E that is located >800 m above young volcanic features in the rift valley floor, and a plume near 24.7°E located above an amagmatic section of the rift valley where the seafloor exhibits abundant exposures of peridotite.

Significant ^3He , Mn and CH_4 anomalies occur at 37.0°E , 43.2°E and 84.9°E . Near 85°E , in a volcanic area marked by seismic activity in 1999 (Edwards et al. 2001; Tolstoy et al. 2001), we sampled an unusually thick near-field plume spanning ~ 1000 m in water depth. This plume has ^3He up to 40% and [Mn] up to 10 nmol/kg. The $^3\text{He}/\text{heat}$ ratio at 85°E is $0.65 \times 10^{-17} \text{ mol J}^{-1}$, similar to values observed in hydrothermal event plumes ('megaplumes') along the Juan de Fuca and Gorda Ridges. The largest ^3He of 85% occurs at 43.2°E , and this locality also has the largest [CH_4]

anomaly ($[\text{CH}_4]$ up to 110 nmol/kg and $\text{CH}_4/{}^3\text{He}=2\times 10^6$). The ${}^3\text{He}/\text{heat}$ ratio at 43.2°E is 6.7×10^{-17} mol J^{-1} , a factor of 4 larger than the theoretical ratio for the upper mantle. Such high ${}^3\text{He}/\text{heat}$ ratios are unusual, but have been observed in a few previous cases where hydrocasts were taken over fresh young lava flows (Lupton et al. 1999), or where phase separation produced vent fluids enriched in volatiles. At 24.7°E, a region where only peridotite was recovered from the seafloor, a Mn anomaly ($[\text{Mn}]$ up to 2.4 nmol/kg) is clearly detectable but ${}^3\text{He}$ is only 2% above background. This suggests that peridotite-hosted hydrothermal systems along the Gakkel Ridge may not produce significant water column ${}^3\text{He}$ anomalies.

Collectively, the ${}^3\text{He}/\text{heat}$ and $\text{Mn}/{}^3\text{He}$ ratios in water column plumes along the Gakkel Ridge vary by more than an order of magnitude. These results suggest that different hydrothermal end-member fluids, reflecting different stages of magmatic evolution as well as pressure-temperature conditions, are actively venting along the Gakkel Ridge.

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INHERITED DEPLETION IN THE OCEANIC MANTLE INFERRED FROM PERIDOTITE COMPOSITION AND DISTRIBUTION ALONG GAKKEL RIDGE

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Our knowledge about melting processes underneath ultraslow-spreading ridges has improved dramatically since the exploration of Gakkel Ridge by the joint US-German AMORE expedition in 2001. Particularly from a peridotite perspective, Gakkel Ridge changed from the most enigmatic to best studied mid-ocean ridge. This is the result of joint systematic petrological/geochemical investigations over the past five years conducted at the MPI and WHOI labs. We have collected *in-situ* major and trace element compositions of relict mantle minerals from over 300 peridotite hand specimens from 33 sampling stations. In addition, spinel fragments extracted from the matrix of carbonate-cemented peridotite breccias (29 breccias, 7 dredge hauls) serve as an additional source of information for estimating the extent of outcrop-scale heterogeneity. Although the study focussed on plagioclase- and vein-free (i.e. residual) peridotites to address the local-scale and regional-scale variations, we also performed highly detailed studies on the role of late melt stagnation. Those results are presented elsewhere (von der Handt *et al.*, this meeting).

The first-order petrologic segmentation Gakkel Ridge is straightforward. The western part is characterized by robust magmatism and a normal fault-dominated seafloor morphology. At 3°E, this morphology ends abruptly, accompanied by an increase in axial water depth from 4500 to 5500 m and exclusive occurrence abyssal peridotites for nearly 100 km along the axis. Between 10 and 30°E, there is a sparsely magmatic zone, with one pronounced long-lived volcanic center at 20°E. Eastwards, the remainder of Gakkel Ridge is again basalt-dominated with only sporadic peridotite occurrences. Based on the peridotite compositions, the magma-poor region between 3

and 20°E can be divided into 4 domains. Domains A and B are devoid of basalts. The spinel Cr# (=molar Cr/(Cr+Al), which increases with increasing degree of partial melting), in modally fertile lherzolites varies between 0.14 and 0.21 (n=23, 70 km along axis). In the easternmost B dredge haul, dunites were sampled (spinel Cr# 0.41-0.43), as yet the only evidence for local heterogeneity. Clinopyroxenes (cpx) are homogeneous on a dredge scale, but there is a clear distinction between the western (A) and eastern (B) dredges. In Domain A, cpx Na₂O is higher (~0.9 vs ~0.4 wt%) and REE patterns are less fractionated ((La/Nd)_N: ~1 vs ~0.02).

Domain C is basalt-dominated. Peridotites display large compositional variation (lherzolites, cpx-poor harzburgites, dunites; Cr#: 0.15-0.53; LREE-depleted and -enriched samples within a single dredge). The samples with the lowest spinel Cr# also are the most LREE depleted, which means that near-fractional melting is the main process for producing their geochemical signature. Our interpretation is that the low-Cr#, LREE-depleted samples reflect the regional degree of melting resulting from adiabatic decompression melting. This regional degree of melting is therefore similar to domains A and B. The modally depleted harzburgites have REE patterns that require extensive reactive melt migration, as do the orthopyroxene-free dunites. This reactive melt transport is superimposed on the near-fractional 'background' melting, and must have been restricted to focused melt transport channels and confined infiltration zones; otherwise the LREE-depleted signature in the modally fertile lherzolites would have been easily overprinted.

Domain D consists exclusively of virtually cpx-free harzburgites and dunites (4 dredges, n=11, 40 km). The change from C to D is abrupt (<20 km). Spinel Cr#s between 0.53 and 0.63 are among the most depleted on the ocean floor, and not at all consistent with a spreading-rate dependent degree of melting. Most cpx REE patterns are LREE-enriched, one dunite is LREE-depleted, two harzburgites have hump-shaped cpx REE patterns. The distribution of breccia-hosted spinels (n=113) from Domain D show a similar range (0.50-0.65), confirming that there is no fertile peridotite relict preserved in the locally exposed upper mantle.

These results suggest that low degrees of regional partial melting in domains A, B and parts of C. From A to C, the amount of reactive melt transport seems to increase. The extreme depletion of domain D may be the result of a large-scale reaction with percolating melts. However, this is not consistent with scarcity of basalts at the surface, or even off-axis, unless there was highly asymmetrical along-axis melt focussing. The LREE enrichment in the interstitial cpx of the otherwise highly depleted harzburgites is best explained by diffuse and pervasive percolation of low-degree melts from a garnet-peridotite (or pyroxenite) source. Importantly, this signature can only be preserved if degrees of melting are low, suggesting that a strong depletion prior to upwelling underneath Gakkel Ridge is required. Accepting the presence of 'depleted blobs' in the convecting upper mantle has far-reaching implications. They may be present 'everywhere' with different scales and extents of pre-upwelling depletion. Their identification is the (fortuitous) combination of ultra-slow spreading, dense sampling and detailed petrologic and geochemical investigations. The consequence is thus that quantitative partial melting models based on the measured peridotite compositions yield a degree of melting relative to DMM, which may not have been the appropriate source. At faster spreading ridges with higher melt productivity, thinner lithosphere and therefore more extensive reactive and homogenizing melt transport, previously depleted peridotite blobs are less likely to be detected.

SEISMIC IMAGING OF OCEANIC CRUST OFF NEWFOUNDLAND: A POSSIBLE ANALOGUE FOR ULTRA-SLOW SPREADING RIDGES

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Ultra-slow spreading centers like the Gakkel Ridge and Southwest Indian

Ridge show unusual characteristics compared to most of the globe encircling mid-ocean ridge system. Unfortunately, these ultra-slow spreading segments either are not readily available to active source seismic experiments or exhibit very rough topography that makes resolving the velocity structure difficult. Although some very successful groundbreaking work has been carried out over the last few years, there still is very little information available on the internal seismic character and structure of crust and mantle that is produced in ultra-slow spreading environments.

Ultra-slow spreading appears to be characterized by much thinner than normal oceanic crust, implying either that less melt is generated than typical, or that a larger proportion of melt is retained in the mantle and never extracted to the surface. On the Gakkel Ridge, Joket et al. (2003) suggest from sonobuoy data that seismic layer 3 may be missing, perhaps indicating that the gabbroic intrusive rocks that are expected in magmatic segments are left behind in the upper mantle. Along at least one segment of the Gakkel Ridge sampled during the AMORE expedition, only serpentinized peridotites were recovered, suggesting that spreading along this segment may have been melt free. These observations of anomalously thin oceanic crust intermingled with regions of exposed serpentinized peridotite are similar to what has been observed along the non-volcanic Iberia and Newfoundland margins. The Newfoundland-Iberia rift system is unusual in that final separation of continental crust was not immediately followed by magmatic seafloor spreading. "Breakup" of continental crust was followed by mechanical exhumation of the upper mantle within a transition zone prior to magmatic crustal accretion. The transition zone is characterized by a layer of serpentinite up to several km thick with crust like seismic velocities. Where it is observed, early oceanic crust appears to be anomalously thin - only 1-4 km thick. In some areas, seismic layer 3 may also be missing. In this contribution, we present seismic reflection and refraction data from the transition zone and early oceanic crust off the Newfoundland margin. This lithosphere is inferred to have formed at spreading rates comparable to those observed along the Gakkel Ridge and thus is an excellent area for comparison studies.

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THE COMPOSITION OF THE MIDDLE AND LOWER CRUST AT ULTRASLOW RIDGES

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We present analyses and modeling of major and trace elements of whole rocks and minerals from middle and lower crustal diabase and gabbros from two ultraslow ridges. Our study suggests that the slowest spreading segments from the SW Indian Ridge and Gakkel Ridge (the Sparsely Magmatic Zone) have compositions in accordance with very low degrees of melting of a Depleted MOR Mantle (DMM). The Na₈ of the basalts in the Western Volcanic Zone (2.7-3.3) indicate low degrees of mantle melting compared to the global average, though significantly higher than that found for basalts in the sparsely magmatic zone. This observation is supported by trace element data for the same basalts.

Ultraslow spreading rates lead to strongly focused magmatic activity at widely-spaced discrete points along the axis, with the formation of axis-perpendicular volcanic ridges (Dick et al., 2003; Joket et al., 2003). Gabbroic material is exposed along steeply dipping normal faults at these ridges where seismic studies demonstrate the crust to be ~2-km thick (Jokat et al., 2003; Michael, et al., 2003). Preliminary results from the Gakkel ridge (Michael, et al., 2003) show that the basalts from the ridges have high Na₈ values and low Fe₈ values, interpreted as due to a very low degree of fractional melting of the mantle and the production of very thin crust. Existing data from the Southwest Indian Ridge supports this observation. The geophysical data and the geochemically determined melt production rates indicate total crustal thickness barely in excess of the thickness of average upper crust (Jokat et al., 2003; Detrick et al., 1987).

We find an unexpectedly large variation of trace-element mineral chemistry within our data, even where the major element mineral-chemistry of the samples is similar. For example, in the Western Volcanic Zone, we find an order of magnitude difference in incompatible trace element concentrations between two samples. The sample with the lowest concentration has clinopyroxene Mg#88, An₈₃₋₈₇ (reversely zoned plagioclase) and Fo₉₁ olivine, whereas the richest sample has clinopyroxene Mg#87.5, An_{87.8-89} (reversely zoned plagioclase) and Fo₉₁ olivine. The melt-compositions cal-

culated from the clinopyroxene compositions, however, show good correlations to the glass compositions from each ridge segment.

Gabbros from the Western Volcanic Zone are mostly primitive, whereas those from the ultraslow Southwest Indian Ridge and Gakkel Sparsely Magmatic Zone have a large range in composition. We derived models for the major element compositions of coexisting mineral phases using the "Melts" program of Ghiorso and Sack (1995), to compare to our data. Models were performed on enriched and depleted MOR magmas (Na₈ ~ 3, Fe₈=9, and Na₈=2, Fe₈ ~11). These represent, respectively, compositions expected at a slow and fast spreading ridges. The Gakkel Sparsely Magmatic Zone and the Southwest Indian Ridge gabbros indicate association with evolved magmas, but the Gakkel Western Volcanic Zone gabbros have as high as An₉₃ plagioclase, not previously detected in a gabbro at a mid-ocean ridge, although predicted by Grove et al. (1993). Such high-An plagioclases are sometimes found as MORB xenocrysts (Fisk, 1984) without clear relations to the host glasses. The high An compositions are likely not related to crystallization in the presence of water (Housh and Luhr, 1991) as this would require a different mineral crystallization-order (Gaetani et al., 1993) leading to different fractionation trends than observed.

Truly primitive gabbros, as we report for the western Gakkel are rare in ocean ridge suites, and these shed considerable new light on melt flow in the lower crust with major and trace-element clinopyroxene compositions apparently uncoupled. In situ-crystallization (Langmuir, 1989) does not explain the fractionated trace element compositions of these otherwise refractory clinopyroxene. Rather, melt-rock interactions due to porous flow are the likely explanation for high trace element concentrations in the interstitial clinopyroxene in these gabbros.

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MAGMATIC ACTIVITY IN TIME AND SPACE WITHIN AN EM-BRYONIC MAGMA-POOR OCEANIC CRUST

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It is generally accepted that rupturing of continents is followed by localized

seafloor spreading at mid ocean ridges (MOR), which are considered, on geological time scales, to be symmetric and steady state. The continuity of this process is documented by the correspondence of crustal accretion ages and magmatic ages. While these processes are well studied at present-day MOR, little is known about how stable these systems are during their embryonic stage. Even though our understanding of the mechanisms associated with extension and rifting of continents improved significantly in the last decade (Whitmarsh et al., 2001) the processes that ultimately start the MOR basalt (MORB) engine and the switch from rifting to drifting are still poorly constrained. One of the most striking results of ODP drilling along the Iberia-Newfoundland conjugate margins was the scarcity of effusive magmatism and only minor volumes of intrusive rocks (Russell and Whitmarsh, 2003) even in areas with undisputed oceanic magnetic anomalies (Srivastava et al., 2000). This observation is in conflict with numerical melting models that generally predict large volumes of MORB type melt. The genetic and temporal relationships of alkaline and MORB type magmatism associated with the onset of seafloor spreading may clarify the rift-to-drift transition. Here we present new mineral U-Pb and ^{40}Ar - ^{39}Ar age data together with Pb, Nd, Sr isotopic data from ODP samples (Leg 1277 and 1070) across the conjugate Iberia-Newfoundland magma-poor margins. We aim to document the igneous history related to the onset of seafloor spreading in the southern North Atlantic.

The onset of the rift-to-drift transition is accompanied (or triggered?) by alkaline magmatism documented by an alkaline dike from Site 1277. A biotite ^{39}Ar - ^{40}Ar age yields a minimum age for this alkaline episode of 126.5 ± 4.0 Ma, closely corresponding to the crustal accretion age of Site 1277. A contemporaneous magmatic event is documented on the Iberia margin at Site 1070 by the U-Pb age of a single zircon (127 ± 4 Ma) separated from a biotite-bearing albitite clast (Beard et al., 2002).

The pegmatitic gabbro at Site 1070 yields a 118 ± 2.2 Ma hornblende age indicating that early alkaline magmatism was subsequently replaced by E-type MORB melts. Indirect dating of the (E-) MORB type lava flows at Site 1277, suggests that the MORB type magmatism occurred prior to the Aptian/Albian boundary. The earliest magmatic history of the embryonic oceanic crust is thus characterized by alkali magmatism followed by (E-) MORB type magmas. A 113.2 ± 2.1 Ma U-Pb zircon age of a hornblende-plagioclase dike at Site 1277 indicates a revival of alkaline magmatism at the Aptian/Albian boundary. The alkaline event is contemporaneous with a morpho-tectonic event, recorded in the sedimentary architecture in the Iberia-Newfoundland margins. The event was characterized by distributed deformation affecting previously accreted oceanic crust and is probably responsible for the formation of basement highs (Peron-Pinvidic et al., submitted). The multiple emplacement of alkaline sills at Site 1276 (105 ± 2 Ma and 97 ± 2 Ma, Hart, 2005) indicates repeated alkaline magmatic activity at the Newfoundland margin. Alkaline magmatism on the conjugate Iberian margin is documented along the Tore-Madeira rise (103 to 88 Ma, Merle et al. 2005), implying alkaline magmatism on either side of the nascent mid-Atlantic ridge.

Leached plagioclase mineral separates from MORB type gabbroic clasts and alkaline dykes have similar Pb, Sr and Nd isotopic composition to present day MORB.

There are two alternatives to explain the prolonged and heterogeneous igneous history recorded at Sites 1277 and 1070: One hypothesis is the 'passage' of mantle plumes, which are widespread in the Atlantic (Duncan, 1984), an alternative hypothesis was advanced by Pe-Piper et al. (1994), that Cretaceous volcanism in Newfoundland is related to decompression melting along reactivated faults. Our isotopic data however is not in accordance with hotspot hypothesis. Similar geochemical results from the alkaline sills at Site 1276 and the Grand Banks imply an isotopic signature different from the Atlantic hotspot system (Hart, 2005; Pe-Piper et al., 1994). Merle et al (2005) suggest that the emplacement of alkaline magmas on the northern Tore-Madeira Rise is neither related to oceanic crust formation nor to plume activity. The similar magmatic history at Sites 1070 and 1277 for at least 25 million years after onset of magmatic activity suggest a common process on either side of the proto mid-Atlantic ridge. Considering the basin wide change from localized to delocalized deformation at the Aptian-Albian boundary we propose an alternative model to explain the episodic revival of intra-plate alkaline magmatism.

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GEOPHYSICAL INVESTIGATIONS IN THE ARCTIC ALONG ULTRA-SLOW RIDGES A STATUS REPORT

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Geophysical investigations in the ultra-slow spreading environment of the Arctic Ocean during the last five years revealed new and astonishing insights into the fabric of the crustal and upper mantle composition.

Data from icebreaker investigations and aero-geophysical experiments show how variable the ultra-slow oceanic crust and may be even the upper mantle is. Areas of focussed magmatism have formed elongated ridges, which reach far into the adjacent basins. However, this zone of enhanced magmatism seems to have distinct boundaries in the upper mantle, since adjacent to them amagmatic segments are present. Variations in crustal thickness vary strongly from 2-6 km with the presence of elongated traversal ridge or along axis volcanoes. That such kind of different spreading environments are stable can be shown by on- and off-axis investigations. However, gravity modelling suggests that the composition of the mantle just below the seismic Moho might be more variable than along faster ridges. To fit the recorded data large-scale density variation had to be incorporated into the model.

The westernmost termination of the Gakkel Ridge is named Lena Trough. It is located between Svalbard and North Greenland. Magnetic data along the Lena Trough show that this ultra-slow segment propagated southwards during the Cenozoic while opening the Fram Strait. Like other ridge system, ultra-slow spreading systems are obviously able to propagate into a continent. This indicates that the eastern termination of the Gakkel Ridge off the Laptev Sea shelf might not be a typical scenario for a termination of an ultra-slow spreading systems. One hypothesis might be that how such a ridge proceeds into a continent depends more on the geology and the general plate movements.

Recent results from geophysical investigations along the Gakkel Ridge and Lena Trough will be shown and discussed.

ANDREW BAIN TRANSFORM: MULTIPLE CONTINENTAL-TYPE TRANSFORM BOUNDARIES AT MID-OCEAN RIDGES

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The idea of simple, narrow, oceanic transform faults has found some exceptions in a few transforms with very large (>30 Myr) age offset, that can be included in a new class of oceanic transform boundaries, with broad complex multi-fault zones of deformation, similar to some continental strike-slip systems (Ligi et al., 2002). Along these extra-long, slow-slipping mega-transforms, relative motion involves the deformation of extraordinarily thick and cold lithosphere. Examples are the 900-km long, 100-km wide Romanche transform on the Equatorial Mid-Atlantic Ridge, and the Andrew Bain transform, that offsets the South West Indian Ridge (SWIR) about 750 km and constitutes a portion of the boundary of the Antarctic Plate. In the case of the Andrew Bain transform, given the ultraslow spreading rate of the two plates adjacent to the transform, the slip rate is very small (16 mm/yr), and the age offset is about 50 Myr.

In the austral summer 2006, an Italian research group of Institute of Marine Sciences (ISMAR-CNR) of Bologna jointly with the Geological Institute of Moscow (GIN-RAS), and with scientists from the Scripps Inst. of Oceanography (SIO), the Univ. of N. Carolina (UNCW) and Lamont-Doherty Earth Observatory, carried out a marine geological and geophysical expedition to the Andrew Bain transform, sponsored by the Italian Antarctic Research Program (PNRA). Participation of US scientist was sponsored by the National Science Foundation (NSF). The geological and geophysical data from the new expedition, combined with data previously collected (Grindlay et al. 1998; Sclater et al. 2005), provide a rather complete view of the morphology, tectonic fabric and physical structure of the Andrew Bain transform domain.

Completing the multibeam bathymetry survey of the southern and central sections of the transform domain permitted the identification of the major transform valley from the southern ridge-transform intersection (RTI) north to about 50°S. Clearly it follows the western portion of the transform valley with at least one small offset to the west. Motion along the southern section of the transform domain appears to be taken up by a series of linear offsetting transform faults. This is very different from the complex relay-basin-type motion observed in the northern section of the domain. A multi-channel seismic line across the center of the transform domain identified significant thicknesses (up to 1000 m) of sediment within the central transform valley and parallel, dipping reflectors within the en echelon topographic highs that dominate the morphology of the central portion of the domain. These reflectors appear to indicate that these oblique highs are the result of block faulting and rotation, and are not intrusive in origin.

Given the very large age offset along the Andrew Bain transform, a very strong "cold edge effect" at the ridge-transform intersection is expected. As a consequence, there should be a rather limited production of melt in the mantle close to the transform. This scenario would predict extensive exposures of mantle-derived ultramafic rocks and limited outcrops of basalts, reflecting a lithosphere nearly free of a basaltic crust layer, as described near the Romanche transform. The new samples obtained from the Andrew Bain transform, with mantle-derived serpentinized peridotite prevailing, support this scenario. In the western section of the southern ridge axis impacting the Andrew Bain transform, pillow basalts have been recovered together with minor gabbros and one mantle peridotite. Compositionally they vary from troctolitic to olivine-bearing gabbro and oxide-bearing gabbro. Mantle peridotites have granular to porphyroclastic to mylonitic textures. They vary from harzburgitic to lherzolitic terms, deeply serpentinized, with strong modal variability in orthopyroxene content. Seven dredges have been carried out along the western wall of the Andrew Bain transform valley, moving northward from the southern RTI. Sampling sites were spaced

about 30 km apart, each corresponding to roughly 4 Myr in time. Recovered rocks are mainly granular to porphyroclastic mantle peridotites, modally ranging from harzburgite to lherzolite. These samples show a strong variability in the opx/ol ratio, similarly to the peridotites recovered along the ridge axis. Several high-T gabbroic intrusions cut the mantle assemblage, forming centimetric veins and patches. Gabbroic veins are also present as low-T intrusion along cracks, but they are usually strongly altered. Minor gabbroic and dunitic samples have been recovered together with oficalcitic breccias cemented by carbonate.

MINERAL CHEMISTRY OF GABBROS FROM THE KANE CORE COMPLEX (MID-ATLANTIC RIDGE): FOCUSED CRUSTAL ACCRETION AND MELT-ROCK REACTION

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The Kane Core Complex, situated at 23° N on the Mid-Atlantic Ridge, exposes 2-3 m.y. old gabbros and peridotites, which represent the plutonic foundation of nearly an entire 2nd order ridge segment. The southern part of the complex, marking the former segment center, is characterized by abundant gabbros, as well as dunites in the peridotites, indicative of abundant melt delivery from the mantle to the crust. Gabbroic rocks show a wide range of compositions, but are dominated by primitive rocks (troctolites and olivine gabbros). The troctolites are very primitive, with abundant spinel, olivine up to Fo₈₉, and plagioclase up to An₈₃. Oxide gabbros and oxide gabbro-norites constitute the most evolved part of the gabbro spectrum, with clinopyroxene Mg# and An as low as 61 and 37, respectively. Further to the north, towards the segment end, primitive gabbros are lacking, with the most primitive rocks being olivine gabbros with Fo₇₉ and An₆₃. Instead, gabbros, oxide gabbros and gabbro-norites predominate.

These data suggest that the Kane Core Complex resulted from focused crustal accretion; magma delivery was localized at the segment center, giving rise to abundant gabbros and primitive compositions, whereas less melts, with more evolved compositions, were emplaced away from the segment center. The along-axis variations in lithology and composition can be explained by two possible models. In the first, central melt injection and fractionation is followed by along-axis melt transport to emplace more evolved gabbros towards the segment end. In the second model, melts rising to the lower crust near the segment end start fractionating in the lithospheric mantle, which is below the solidus of MORB melts due to enhanced cooling near the Kane transform, thus leading to evolved compositions of melts once they reach crustal levels.

Clinopyroxene Mg#s are high in many gabbros (up to 90), particularly in poikilitic olivine gabbros. The Mg#s both extend to higher values, and are higher at a given An content of associated plagioclase, than expected for fractional crystallization. In addition, Cr contents of some of the clinopyroxenes are unusually high (up to 13,000 ppm). Clinopyroxene oikocrysts enclose resorbed plagioclase, and are in reaction relationship with olivine. This indicates that the clinopyroxenes do not form part of an equilibrium fractionation assemblage, but that they result from a reaction between olivine-plagioclase-spinel cumulates and pyroxene-saturated percolating melts. The percolating melts dissolve olivine and minor plagioclase and spinel, enriching the melt in Mg and Cr, thus crystallizing clinopyroxene with high Mg# and Cr contents. An additional factor in controlling the clinopyroxene Mg# may be that the crystal mush buffers the Mg# of the percolating melt to high values due to the fast diffusion of Fe and Mg. High-pressure crystallization is thus not required to explain high-Mg clinopyroxenes in oceanic gabbros.

OS ISOTOPIC COMPOSITIONS OF ABYSSAL PERIDOTITES FROM GAKKEL RIDGE: IMPLICATIONS FOR HETEROGENEITY IN THE OCEANIC MANTLE

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High partition coefficient of Os in some minerals (e.g., sulfides and metal

alloys) and segregation of these minerals in silicate minerals render Os isotopic heterogeneities in the upper mantle to be preserved for a long time rather than being homogenized by mantle convection. Unradiogenic $^{187}\text{Os}/^{188}\text{Os}$ ratios in the abyssal peridotites have been generally suggested to record the ancient partial melting events in the abyssal peridotites.

Abyssal peridotites including fifteen lherzolites, two harzburgites and one plagioclase peridotite of two dredge hauls (PS66-238 and HLY0102-D70) from Gakkel Ridge have been chosen for this study. The eleven PS66-238 samples are ultra-fresh, whereas the seven D70 samples are highly altered. Very low spinel Cr# ($\text{Cr\#}=11.6\text{--}28.2$) suggested that these samples are among the most fertile abyssal peridotites. The bulk Al_2O_3 contents of all the plagioclase-free samples are below 3% (1.57–2.9 wt%), whereas the plagioclase peridotite has a little higher Al_2O_3 content (3.04%). The $^{187}\text{Os}/^{188}\text{Os}$ ratios range from very unradiogenic (0.1139) to the value (0.1301) approximate to the primitive upper mantle (PUM, 0.1296 ± 0.0006). The most unradiogenic $^{187}\text{Os}/^{188}\text{Os}$ ratios in two relatively refractory harzburgites give paleo-Proterozoic Re-depletion ages ($T_{\text{RD}}=2.2\text{--}2.3$ Ga, relative to PUM), which record the ancient partial melting events in these samples.

The samples from both dredge hauls give indistinguishable Os isotopic values, whereas Os concentrations of PS66-238 samples (3.8–6.7 ppb) are higher than those of D70 samples in a whole (1.7–4.1 ppb) (Fig. 1a). In PS66-238 samples, no correlation is observed between $^{187}\text{Os}/^{188}\text{Os}$ ratios and the partial melting indicators (e.g., spinel Cr# or bulk Al_2O_3 contents), whereas seven D70 samples display good correlations (Fig. 1b). Trace elements data of the residual clinopyroxenes can only be explained by refertilization, which cannot have affected the Os isotopic compositions.

The ultra-fresh PS66-238 peridotites have a cm-thick brown-yellow weathering rim, which was separated and analyzed for four samples. Os concentrations and $^{187}\text{Os}/^{188}\text{Os}$ ratios of weathered rims and corresponding fresh cores are virtually identical, suggesting that Re-Os systematic has not been affected significantly by low-temperature oxidative seawater alteration.

The difference between PS66-238 and D70 samples in Os concentrations can not be explained by other processes, e.g., partial melting, melt infiltration, serpentinization or weathering. This, together with the big range of $^{187}\text{Os}/^{188}\text{Os}$ ratios in the Gakkel abyssal peridotites, suggests that the depleted MORB mantle (DMM) is heterogeneous in PGE and Os isotopic compositions on a local and regional scale.

THE TECTONO-MAGMATIC EVOLUTION OF OCEANIC CORE COMPLEXES: THE EXAMPLE OF THE CHENAILET OPHIOLITE IN THE WESTERN ALPS

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The Chenailet Ophiolite in the Franco-Italian Alps represents a well-preserved ocean-floor sequence that was affected by low-grade Alpine metamorphism and was only weakly deformed during its emplacement in the Alpine nappe stack. Previous authors interpreted the voluminous pillow lavas showing a MORB signature¹ and overlying gabbros and serpentinized peridotites as an oceanic crust formed at a slow spreading ridge. Based on the similarity between the rock types and structures reported from ultraslow spreading ridges and those described here, we propose that the Chenailet Ophiolite may serve as a field analogue for seafloor sequences formed at slow to ultra-slow magma-poor ridges.

Mapping of the ophiolite body in the Chenailet area enabled to identify an oceanic detachment fault that extends over a surface of about 16 km² capping exhumed mantle and gabbros onto which clastic sediments have been deposited. The footwall of the detachment is mainly formed by altered mafic and ultramafic rocks. The mantle rocks are strongly serpentinized lherzolites and subordinate harzburgites and dunites². Microstructures reminiscent of impregnation (e.g. opx+plg corroding cpx), and cpx major and trace element chemistry indicate that primary spinel peridotite is (locally) replaced by plagioclase-bearing assemblages. Pyroxene thermometry on primary minerals indicates high temperatures of equilibration ($\geq 1200^\circ\text{C}$) for the mantle rocks. Gabbros range from troctolite and olivine-gabbros to Fe-Ti gabbros and show clear evidence of synmagmatic deformation³, partially obliterated by retrograde amphibolite and low-grade metamorphic conditions. In sections perpendicular to the detachment within the footwall, syn-tectonic gabbros and serpentinized peridotites grade over some tens of meters into cataclases that are capped by fault gouges. Petro-structural inves-

tigations of the fault rocks reveal a syn-tectonic retrograde metamorphic evolution. Clasts of dolerite within the fault zone support the idea that detachment faulting was accompanied by magmatic activity. Hydrothermal alteration is indicated by strong mineralogical and chemical modifications along the fault zone. Gabbro and serpentinized peridotite, together with serpentinite cataclases occur as clasts in tectono-sedimentary breccias overlying directly the detachment fault. This demonstrates that the fault was exhumed at the seafloor and exposed to submarine weathering, before it was covered by sedimentary and/or basaltic rocks.

Across the whole Chenailet Ophiolite, volcanic rocks directly overlie either the detachment fault or the sediments. In several places, N-S trending high-angle normal faults have been mapped. These faults truncate and displace the detachment fault leading to small domino-like structures. The basins, limited by these high-angle faults are some hundreds to some few kilometres wide and few tens to some hundreds of meters deep. Because these high-angle faults are sealed locally by basalts and obliterated by volcanic structures, we interpret these high-angle faults as oceanic structures being active during the emplacement of the basalts. The alignment of porphyritic basaltic dykes parallel to, and their increasing abundance towards the high-angle faults suggest that they may have served as feeder channels for the overlying volcanic rocks.

Our observations suggest that the Chenailet Ophiolite represents an exposed remnant of a fossil oceanic core complex, which preserves a large-scale detachment fault capping mantle rocks and gabbros, and which preserves primary contacts to sediments consisting of reworked basement. Detachment faulting is followed by syn-magmatic normal faulting resulting in the emplacement of laterally variable, up to 300 meters thick massive lavas and pillow basalts covering the exhumed detachment fault. These 3D-observations are important because they demonstrate that large-scale detachment faults may be buried under volcanic sequences suggesting that detachment faulting is presumably more common than suggested by dredging or morpho-structural investigations of the seafloor at (ultra-) slow-spreading ridges.

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VOLATILE AND TRACE ELEMENT CONSTRAINTS ON SOURCES OF GAKKEL MORB

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Initial results from AMORE 2001 show three distinct magmatic-tectonic zones along Gakkel Ridge [1,2]. The Western Volcanic Zone [WVZ: $8^\circ\text{W} - 3^\circ\text{E}$] has several elongate volcanic highs with no offsets. The Sparsely Magmatic Zone [SMZ: $3^\circ\text{E}-29^\circ\text{E}$] extends from a sharp boundary at 3°E where the axis abruptly becomes 1000 m deeper and only peridotites are exposed on the axial valley floor for 120 km, and there is sparse volcanism for ≈ 250 km. The Eastern Volcanic Zone [EVZ: $29^\circ-85^\circ\text{E}$] has localized volcanic centers separated by lengthy sections of tectonized seafloor. All MORB from the WVZ are enriched in Ba and H_2O at a given level of mantle enrichment (i.e., La/Sm) compared to MORB globally and from EVZ. A remarkable transition in the composition of the Arctic mantle coincides with the bathymetric boundary. There is a gradient in $\text{H}_2\text{O}/\text{Ce}$ and Ba/Nb which is steepest at about 3°E . To the east, basalts resemble Pacific MORB in $\text{H}_2\text{O}/\text{Ce}$ and Ba/Nb. To the west, $\text{H}_2\text{O}/\text{Ce}$ and Ba/Nb remain high along the WVZ, through Knipovich and Jan Mayen Ridges and south to Iceland [3]. Sr-Nd-Pb-He isotopic data provide additional information about this distinctive geochemical province [4]. EVZ lavas resemble Pacific MORB

in their isotopic characteristics. WVZ lavas have high Sr and low Nd isotope ratios, like Indian MORB: a "DUPAL" signature [5]. There is a sharp isotopic boundary in the SMZ [4]. Because WVZ MORB compositions extend toward quaternary volcanic rocks in nearby Spitzbergen, Goldstein et al. ([4]) suggest they formed with some contribution from subcontinental lithospheric mantle (SCLM), a process also considered for Knipovich R. and Iceland [6,7]. Furthermore they propose that the presence in the western Arctic asthenosphere of SCLM with residual phlogopite and amphibole, stranded during the recent continental breakup in this region [8], is responsible for the distinctive chemical signature of the WVZ [4].

As a test and refinement of this hypothesis, we examine here concentrations and ratios of H_2O , K_2O , Ba, Rb, Cl and F in basalts from Gakkel Ridge as well as in amphibole and phlogopite from Spitzbergen. For the distinctive MORB from the WVZ and the SMZ, we calculate the "excess" amounts of these elements that are present in their source by subtracting from each basalt the contribution of the "normal" depleted-enriched asthenosphere, which is taken to be similar to the EVZ and MORB globally. (The contribution of Ba to a MORB from normal asthenosphere, for example, is calculated by first determining Ba/Ce versus La/Ce for EVZ or global MORB. Then, the asthenospheric Ba/Ce at the MORB's La/Ce is multiplied by the Ce concentration in the MORB). We then examine ratios of the elements in the "excess" to constrain which phases (amphibole and/or phlogopite) could be present in the putative SCLM contribution. We use the amounts (in ppm) calculated for the "excess", corrected for crystal fractionation and partial melting, to estimate the abundance of these phases in the overall source.

Results –For WVZ basalts, the high calculated H_2O/K_2O ratios in the "excess" indicate that amphibole is dominant and that phlogopite is much lower in abundance. Nevertheless, Ba/Rb ratios suggest a small amount of phlogopite. The amount of amphibole in the aggregate WVZ source (asthenosphere + SCLM) diminishes from about 0.7% at $8^\circ W$ to $\approx 0\%$ near the discontinuity at $3^\circ E$. The "Type 2" variety of Spitzbergen amphibole [9,10], approaches the WVZ basalts' source most closely for isotopic [4], trace element and volatile ratios. Ratios involving Fluorine are consistent with this scenario. Ratios involving Chlorine are problematic. Cl/K in MORB from WVZ is too high compared to the EVZ to be caused by either amphibole or phlogopite, suggesting participation of another phase, or a contribution from asthenospheric enrichment. An alternative, that shallow assimilation caused an increase in Cl and Cl/K along WVZ is less likely because the increase is too well-correlated with other trace element ratios.

Enriched MORB on the western side of the SMZ ($9^\circ E$ – $14^\circ E$) have isotopic ratios like the WVZ [4] and very high Ba/La and K/La. H_2O , H_2O/Ce and H_2O/K are only moderately enriched, and Ba/ H_2O is higher than along WVZ. The ratios allow for a greater role for phlogopite and less amphibole. The boundaries of the MORB source region with high H_2O/Ce may extend beyond those of the isotopically-defined region [4]. In the SMZ, the transition for the trace element and volatile ratios is not as sharp as it is for the isotopic ratios. H_2O/Ce , Ba/La and Ba/Nb ratios remain high beyond $25^\circ E$ along Gakkel Ridge. Toward the west, distinctively high H_2O/Ce , Ba/La and Ba/Nb ratios continue beyond Gakkel ridge and at least to Iceland.

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SPREADING ASYMMETRY ON THE GAKKEL RIDGE

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The reappraisal of existing conceptions based on geophysical data in the

Eurasian basin has done to clear the nature of the spreading asymmetry on the Gakkel ridge. The isochrons of Eurasian basin formation were identified on basis of the new compiled magnetic anomaly map. Recent bathymetry and gravity data were analyzed also. Magnetic isochrons and continent – ocean transition derived from Bouguer gravity were used for calculations of stage poles, spreading rates and asymmetry. The analysis of both asymmetry and spreading rates through the time (across of the chrons) and the space (along the chrons) was carried out.

The results of provided analysis determined that spreading rates calculated from the Euler poles and the rates obtained from isochrons conform well. Spreading rates variations with time observed on the Gakkel, the Mid-Atlantic and Rejkjanes ridges are similar. The full spreading rate fell down from 30 – 35 mm per year at the period of the initiation of the opening (about 56 Ma) till 12 – 15 mm per year at the time of anomalies 18 -13 (40– 33 Ma). Thereby the Gakkel ridge has turned into the ultraslow spreading class just after anomaly 18 (40.3 Ma). It is established that spreading on the Gakkel Ridge was asymmetric from the initial opening. The early spreading was high oblique at some places. The region 60° - $75^\circ E$ marked by abrupt change in the asymmetry pattern. The distribution of asymmetry is nonrandom and caused probably by axis jumps at the period of anomaly 20-24 (43 - 53 Ma). The spreading rates in the Nansen basin have been greater than one in the Amundsen basin from anomaly 18 – 20 time till present in the eastern part of the Gakkel Ridge.

It is necessary to note that quality of magnetic data in the eastern part of the Eurasian basin is lower than one in the western part. Therefore presented findings need to be checked.

MANTLE-CRUST EVOLUTION AND MAGMATIC ACTIVITY DURING CONTINENTAL BREAKUP AND OCEAN OPENING RECORDED BY THE EXTERNAL LIGURIDE OPHIOLITES (NORTHERN APENNINES, ITALY)

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The record of the Ligurian Tethys ophiolites from the Alpine belt provide relevant clues about the architecture of the continent-ocean transition and the processes operating during continental breakup and inception of ocean spreading. In particular, remnants of a fossile continent-ocean transition similar to that of the modern non-volcanic continental margins are preserved in the Jurassic External Liguride ophiolites (Marroni et al., 1998). These ophiolites consist of fertile lherzolites, MOR-type basalts and rare gabbroic intrusives occurring as large olistoliths within Cretaceous sedimentary melanges, together with continental crust bodies exhumed during the Mesozoic rifting phases preceding the oceanization and locally displaying primary relationships with the ophiolites.

The mantle rocks are spinel and spinel-plagioclase lherzolites that represent unroofed subcontinental lithosphere of the former Adria-Europe system (Rampone et al., 1995; Montanini et al., 2006). Recent studies have shown that they have been extensively affected by refertilization by asthenospheric melts during the Ligurian Tethys formation (Piccardo et al., 2004). Peridotite bodies which escaped melt contamination and intrusion contain garnet pyroxenites layers preserving evidence for an early equilibration stage at deep levels of subcontinental lithosphere (Montanini et al., 2006). They record a lithospheric thinning history culminated into mantle exhumation at the ocean-floor and development of a serpentinization-related hydrothermal activity. The low-pressure (< 0.9 GPa) portion of the exhumation path was related to the Upper Triassic-Lower Jurassic rifting that led to continental break-up.

In this framework, basaltic magmas were emplaced as (i) massive and pillow lavas, locally erupted on slices of Variscan granitoids or covered by radiolarian cherts, (ii) dykes crosscutting mantle lherzolites and gabbroic rocks. The basalts display nearly flat REE patterns, high Y/Nb (~ 5-14) characteristic of N-MORB liquids, remarkable Zr enrichment ($Zr/Zr^* = 1.1-1.6$) and high (Sm/Yb)_{DM} ratios (1.4-1.8). Nd isotope compositions are close to typical depleted mantle (initial ϵ_{Nd} from +7.7 to +9.6).

The gabbros occur as small meter-sized bodies intruding mantle lherzolites or decametric to hectometric slide-blocks. The latter are locally crosscut by microgabbro bodies and basalt dykes, and/or locally covered by radiolarian cherts. The gabbroic rocks include troctolites, olivine-bearing to olivine-free gabbros, Fe-Ti oxide-bearing gabbros and diorites. Trace element and Nd isotope composition are consistent with crystallization from N-MORB

liquids. The gabbroic rocks a metamorphic evolution starting with synkinematic crystallization of neoblastic clinopyroxene + plagioclase \pm titanian pargasite \pm ilmenite \pm spinel along high-temperature shear zones ($\sim 850^\circ\text{C}$), followed by widespread development of subgreenschist metamorphic assemblages under static conditions. An upper amphibolite-facies event ($T \sim 650^\circ\text{C}$) testified by synkinematic plagioclase + Ti-poor hornblende in places overprints the high-T shear zones.

The gabbro intrusion into mantle undergoing rifting-related exhumation started in Lower Jurassic before continental separation (Tribuzio et al., 2004), marking the onset of magmatic activity along the External Liguride margin, followed by post-rift extrusion of basaltic flows and intrusive emplacement of minor gabbroic bodies, locally exhumed at ocean-floor. The igneous characteristics of basaltic and gabbroic rocks are mainly accounted for by melting of a MORB-type depleted asthenospheric source. Trace element modelling shows that low-degree ($\leq 6\%$) fractional melting of a depleted mantle in the spinel stability field accounts both for the absence of significant LREE depletion in the basalts (in agreement with the results of Vannucci et al., 1993) and for the occurrence of positive Zr anomalies (see also Kempton and Casey, 1997), but cannot explain the elevated (Sm/Yb) ratios. On the other hand, melting of a mixed source of spinel peridotite with small amounts of garnet pyroxenite (e.g. the SOC average pyroxenite after Hirschmann & Stolper, 1996) can explain both the Sm/Yb and the Zr enrichments. The garnet signature would be therefore enhanced by relatively low degree of melting of the peridotite source during the early stages of oceanization.

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MANTLE DOMAIN BOUNDARIES IN NASCENT OCEANIC CRUST: EXAMPLES FROM THE SOUTHERN NORTH ATLANTIC AND THE 'FOSSIL' PIEMONTE LIGURIAN OCEAN

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Mantle peridotites from the conjugate Iberia-Newfoundland rift and from the Alps permit the characterization of the scale of upper mantle heterogeneity in extensional systems that pass from evolved stages of rifting to early seafloor spreading. The existence of several mantle domains exposed close to the sea-floor along volcanic and non-volcanic rifted margins provide important clues to constrain the processes by which new oceanic crust is formed. Here we summarize the results from two areas that show many similarities to systems like the Gakkel ridge and the Lena trough. Serpentinized spinel peridotites of the abyssal Newfoundland margin drilled during ODP Leg 210 at Site 1277 have relic mineral compositions similar to the most depleted abyssal peridotites worldwide. Melting of the Newfoundland mantle occurred in the spinel peridotite field and probably exceeded the cpx-out phase boundary for some samples. Using proposed spinel peridotite melting models and experimentally derived phase diagrams, the Newfoundland harzburgites can be modeled as a residue after extraction of 14 to 20-25% melting. We compare major and trace element compositions on mantle minerals from site 1277 and previously drilled sites on Iberia, showing that the southern North Atlantic upper mantle between Iberia-Newfoundland (at $\sim 120\text{my}$) houses geochemical discontinuities between ODP sites 1070 and 1277, and the Iberia abyssal plain and the Galicia bank. The peridotites from the conjugate Iberian margin are, on average, less depleted, heterogeneous, and provide evidence for local equilibration in the plagioclase stability field. This can either be explained by an

inherited, primary, Ca-richer composition of the Iberia peridotite, or, alternatively, by local melt impregnation and stagnation during continental rifting, and thus refertilizing previously depleted peridotite.

Petrological studies from peridotites have shown that different mantle domains characterize the former Piemonte Ligurian ocean. Although the distribution of these domains depends on paleogeographic reconstructions, a consistent picture has emerged from studies over the last 30 years in different parts of the Alps and Apennine, where the remnants of the Piemonte Ligurian ocean are exposed. Thermally undisturbed, heterogeneous, proterozoic to Permian subcontinental mantle (spinel lherzolites, harzburgites and dunites, garnet pyroxenites layers and locally phlogopite-hornblende veins) formed the ocean floor next to thinned continental crust. This 'subcontinental domain' is separated (by ductile shear zones?) from an 'infiltrated domain', with mostly fertile plagioclase peridotite, and minor spinel harzburgite and dunite. These peridotites exhibit a complex history of regional-scale melt infiltration and melt/rock reaction and thereby erasing most of the ancient history ('thermochemical erosion' or 'asthenospherization'). They are juxtaposed with highly depleted lherzolites and dunites that reflect local zones of MORB type melt extraction ('extraction domain'). The spatial distribution of mantle domains in the Piemonte Ligurian ocean is reflected by regional thermal gradients established by pyroxene thermometry.

Plutonic rocks related to the opening of the Piemonte Ligurian ocean are scarce and form isolated dikes and bodies that crystallized in the mantle. MORB-type volcanism (T-N-MORB composition) is highly focused and its volume increases from the 'subcontinental domain' to the 'infiltrated domain'. The chemical characteristics of the volcanic rocks suggest a transition from T-to N-MORB magmatism, and, possibly, a decreasing 'garnet signature' from the continental to more oceanic domains. Any 'initial seafloor spreading' model must account for the fact that the ocean-continent boundary contains mantle domains that are thermally undisturbed by the convecting asthenosphere, domains that provide evidence for regional-scale melt infiltration and melt/rock reaction and thereby erasing most of the ancient history, and domains that are characterized by focused melt transport.

ISOTOPE GEOCHEMISTRY OF LENA TROUGH

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Extremely enriched non-hotspot related MORB compositions are more difficult to explain than comparable OIB's, where enriched components may be derived from plume materials. The mantle sources of highly incompatible trace element enriched MORB (E-MORB) are classically interpreted as reflecting a mixture of depleted MORB mantle source and enriched material. This enriched material is related to either "plum" derived material, or mantle metasomatism by melt or fluid, mantle heterogeneity related to recycled material. Moreover, both MORB and E-MORB are considered as an accumulation of melts generated at different depths and at different degrees of partial melting, sampling various components within the source. As a consequence, the lower the degree partial melting, the higher the probability to sample highly fertile components in the source. In order to investigate highly fertile components in MORB source, we focus our research on slow to ultra slow spreading ridges.

Here we present a trace element and Sr-Nd-Pb-Hf isotope study of lavas collected from Lena Trough, Arctic Ocean during the ARK XX-2 cruise (2004) of PFS Polarstern (Alfred-Wegener Institute, Bremerhaven). Lena Trough is considered as an ultra-slow rift (7.5 mm/yr effective full-rate), and connect the Mid-Atlantic ridge (MAR) to Gakkel Ridge in the Arctic Ocean. We present results obtained on 23 samples, 11 collected in the central part of Lena trough and 12 from the northern part.

Lavas found in the central part of Lena Trough are alkaline with an extreme enrichment in incompatible trace elements ($\text{Ba/Th} = 350 \pm 50$), with unusual trace element ratios for oceanic basalt, such as $\text{Nb/U} = 69$ to 74, and a garnet signature with $(\text{Dy/Yb})_{\text{PM}} = 1.20$ to 1.39. The $(\text{La/Sm})_{\text{PM}}$ ranges from 1.43 to 1.78. The Central Lena Trough basalts display isotope variations with $^{87}\text{Sr}/^{86}\text{Sr}$ ratio ranging from 0.70361 to 0.70390, $^{143}\text{Nd}/^{144}\text{Nd}$ from 0.51283 to 0.51290 ($\epsilon_{\text{Nd}}: +3.7$ to $+5.2$), $^{176}\text{Hf}/^{177}\text{Hf}$ ratio from 0.28313 to 0.28322 ($\epsilon_{\text{Hf}}: +11.60$ to $+14.92$) and $^{206}\text{Pb}/^{204}\text{Pb} = 17.752$ -17.884; $^{207}\text{Pb}/^{204}\text{Pb} = 15.410$ -15.423, $^{208}\text{Pb}/^{204}\text{Pb} = 37.544$ -37.670. In contrast, northern Lena Trough lavas have lower $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70306-0.70340), higher $^{143}\text{Nd}/^{144}\text{Nd}$ (0.51302-0.51308; $\epsilon_{\text{Nd}}: +7.5$ to $+8.6$) and $^{176}\text{Hf}/^{177}\text{Hf}$ (0.28323-0.28325; $\epsilon_{\text{Hf}}: +15.01$ to $+16.06$), higher and homogeneous Pb isotope com-

posiotsn ($^{206}\text{Pb}/^{204}\text{Pb}$: 17.986-17.995, $^{207}\text{Pb}/^{204}\text{Pb}$: 15.432-15.440 and $^{208}\text{Pb}/^{204}\text{Pb}$: 37.778-37.795).

Due to the limited available database, so far, for Arctic MORB, we compare Central Lena Trough lavas with those from the northern part of the MAR. This present study extends towards the North the observation done along MAR with isotopes (Pb-Nd-Hf) by Blichert-Toft et al., 2005 [1]. While Central Lena Trough group displays low $e_{\text{Nd-Hf}}$, similar to Jan Mayen lavas, they have also significantly lower $^{206}\text{Pb}/^{204}\text{Pb}$. This clearly differentiates Central Lena Trough lavas from these from Jan Mayen. There is also similarity between Mohns-Knipovich and Central Lena Trough lavas in e_{Hf} vs. e_{Nd} diagram. In this plot, Central Lena Trough lavas with Mohns and Knipovich ridges MORB define a distinct trend relative to other MAR MORB, with higher e_{Hf} at a given e_{Nd} . In $^{208}\text{Pb}/^{206}\text{Pb}$ vs. $^{207}\text{Pb}/^{206}\text{Pb}$, Central Lena Trough lavas plot along a line, parallel to the principal component 1 define by Blichert-Toft et al., 2005 [1], with a higher $^{208}\text{Pb}/^{206}\text{Pb}$ at a given $^{207}\text{Pb}/^{206}\text{Pb}$.

First, we have examined the relative behavior of each element during partial melting using log-log diagrams. Based on the slope of each correlation between two elements, we have defined trace element source proxies (Th/U, Nb/Ta, Hf/Pb, Ba/U...). While these source proxies are constant versus $(\text{La}/\text{Sm})_{\text{PM}}$, as expected, Sr-Nd-Pb-Hf isotope systems display significant correlations with $(\text{La}/\text{Sm})_{\text{PM}}$ and also $(\text{Dy}/\text{Yb})_{\text{PM}}$. The correlation for $^{87}\text{Sr}/^{86}\text{Sr}$ is positive with $(\text{La}/\text{Sm})_{\text{PM}}$ and $(\text{Dy}/\text{Yb})_{\text{PM}}$ ratios. Correlations are negative for $^{143}\text{Nd}/^{144}\text{Nd}$, $^{176}\text{Hf}/^{177}\text{Hf}$, Pb isotopes ratios and $(\text{La}/\text{Sm})_{\text{PM}}$ and $(\text{Dy}/\text{Yb})_{\text{PM}}$ ratios.

In order to explain these variations of trace element and isotope compositions, we propose a three endmember mixing model. These endmembers are the Depleted MORB Mantle (DMM), the component C and the lower continental crust. This model, introducing few amount of lower continental crust (~1-2%) into a DMM-C mix, can reproduce Sr-Nd-Hf-Pb isotopes systematic and trace element composition. This model is an alternative explanation to resolve the apparent decoupling of Nd-Hf isotopes and Pb isotopes, without invoking a disequilibrium melting [1]. This three-endmember mixing model is consistent with observations done along MAR based on a statistical approach [1]. The presence of the lower continental crust is likely related to the vicinity of Svalbard and Greenland continental margins. Correlations between isotopes and $(\text{Dy}/\text{Yb})_{\text{PM}}$ ratio are interpreted as reflecting a garnet bearing phase related to the lower continental crust.

In summary, this study reveals mantle heterogeneity in terms of mineralogy where lower crust and mantle mineralogies are associated. A consequence of lower continental crust presence is that the area can be considered as a transition zone between continent and ocean basin. Finally, this study illustrates how important it is to combine trace element and isotope studies, especially to interpret Pb-Pb isotopes linear arrays. Also interpretation based on a limited number of samples, converges with these done with a statistical approach.

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OCEANIC CORE COMPLEXES NEAR THE RODRIGUEZ TRIPLE JUNCTION: IMPLICATION FOR INTERACTION BETWEEN THE SEAFLOOR -HYDROTHERMAL ACTIVITY-ECOSYSTEM

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The interaction between biosphere and lithosphere plays important role in evolution of earth and life. Along mid-ocean ridges, especially through hydrothermal system, rocks / fluid / ecosystem are interacted each other and form an integrated system. The interaction ranges from micro-scale to mega-scale (segment scale ~ several tens to hundreds kilometer) and here we focus on mega-scale interaction where the tectonic setting controls or constraints the hydrothermal activity and / or the ecosystem developed there. Recent findings in ultramafic hosted hydrothermal vent system along the Mid-Atlantic Ridge (MAR) is an example of the former linkage. We present here another good example in the southernmost Central Indian Ridge.

The Central Indian Ridge (CIR) is categorized into intermediate spreading

systems and its southern end forms a R-R-R triple junction with SWIR and SEIR. The southern CIR shows slow-spreading morphology, where the axial valley develops along the ridge crest and an oceanic core complex has been reported near the southernmost segment. Two hydrothermal fields were reported in southern CIR, Edmond and Kairei. Edmond field is located approximately 160 km from the triple junction, and is considered as usual basalt-hosted hydrothermal field. The Kairei hydrothermal field is located near the triple junction and shows unique character in its hydrogen rich fluids and unique ecosystem. The similar hydrothermalism was observed along the Rainbow and Logachev sites along the MAR, which are both ultramafic hosted and the nature of fluid is controlled by serpentinization of ultramafic rocks.

New geophysical mapping and submersible dives reveal the geology and tectonics around the Kairei site. The vent is, contrary to expectation, surrounded by basalt pillow and massive flows. However, an exhumation of lower crust/ mantle materials was discovered about 15 km east of the hydrothermal vent. The area consists of two topographic highs, which displays quite different morphology from ubiquitous abyssal hills. We named the structure "Uraniwa Hills", for it is located at the backyard (uraniwa in Japanese) of the Kairei site. The northern hill is a dome-like seamount, whose diameter of the hill is about 4 km. The southern hill is a rectangular shaped high extending 5~6km in the same direction, that is nearly parallel to the plate motion direction. Two parallel corrugations are recognized on top of the southern hill. The general morphology is very similar to the oceanic core complex located at the western off-axis of the segment, though the size is much smaller. During two dives at the Uraniwa Hills, gabbroic rocks have been recovered. On the northern slope of the northern hill, olivine-rich gabbroic rock, troctolite, dominates the recovered samples. A weathered Pl-dunite was also sampled from the 3170m WD of the northern hill. These observations strongly suggest that the URANIWA Hills is a shallowly exposed primitive gabbroic body, a sort of oceanic core complex. The existence of olivine-gabbro and dunite in shallower part of the hills may lead to the serpentinization of these rocks through seawater circulation, that may contribute to form unique hydrothermal fluid in Kairei field. Top of the hills is covered by basaltic rubbles, which may relate to the later magmatic spreading.

At the opposite side of the Kairei field, another oceanic core complex was reported near 25°S [Mitchell, et al., 1998]. We conducted detailed geophysical mapping all over the core complex as well as submersible. The core complex extends about 23 km in plate motion direction and about 13 km parallel to the axis. The core complex consists of two parts, southern rectangular high with relative height of 1800 m and northern terrace, which is about 500 m deeper than the southern part. On the top of both southern high and northern terrace, a series of corrugation with wavelength of 1~2 km is clearly developing parallel to the plate motion direction. Three submersible dives reveal that both the lower part of oceanic crust and the uppermost mantle are exposed at the eastern slope of the core complex, currently shallower than 2200m WD. On the top of the corrugations, several deformed rocks (mylonite, cataclastite, and schists) were recovered and striations parallel to the corrugation was widely observed on the seafloor. These results indicate that the corrugated surface is a detachment fault surface. The Four steep scarps perpendicular to the corrugation also develops, that might be normal faults formed under the extension near the ridge axis after the exhumation of lower crustal section along the detachment fault. South of the 25°S core complex, the exposure of mantle rocks was also reported at the top of a small conical hill [Hellebrand, et al., 2002], which displays the morphology similar to the northern hill of the Uraniwa Hills.

The existence of oceanic core complexes indicates that the southernmost CIR has experienced avolcanic, melt-starved spreading phase in these 1 m.y. The other part of the ridge and its off-axis are generally characterized with well-organized abyssal hills, so the unusual avolcanic setting near the triple junction may be related to the eastward propagation of SWIR where the melt starved spreading is attributed to the underlying cold mantle. The unique geochemistry and ecosystem of the Kairei hydrothermal field also seems to reflect this tectonic setting.

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PRE-OCEANIC RIFTING IN THE JURASSIC LIGURIAN TETHYS, A FOSSILE SLOW SPREADING OCEAN: THE MANTLE PERSPECTIVE

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Ophiolitic peridotites outcropping along the Alpine-Apennine orogenic belt (Lanzo, Erro-Tobbio, External and Internal Ligurides, Corsica), represent subcontinental lithospheric mantle which was exposed to the sea-floor of the Jurassic Ligurian Tethys ocean. Strong effects of extensional deformation along km-scale shear zones indicate that the subcontinental mantle underwent progressive exhumation in relation to extension and thinning of the lithosphere, which led to rifting and drifting of the Ligurian Tethys basin. Recent field, structural, petrologic and geochemical investigations on these peridotites evidence their extreme structural and compositional heterogeneity. Main rock types are: i) porphyroclastic to tectonite-mylonite spinel lherzolites; ii) coarse granular, pyroxene-depleted spinel peridotites (harzburgites and dunites); iii) granular plagioclase-enriched peridotites. Field relationships indicate that: i) pristine porphyroclastic-tectonitic lherzolites (hereafter referred to as *lithospheric spinel lherzolites*) are transformed to coarse granular, pyroxene-depleted spinel peridotites (*reactive spinel peridotites*); ii) km-scale areas of the pre-existing spinel-facies rocks are significantly enriched in plagioclase and micro-gabbroic aggregates (*impregnated plagioclase peridotites*); iii) spinel and plagioclase peridotites are cut by bands and channels of spinel harzburgites and dunites (*replacive spinel peridotites*).

Lithospheric spinel lherzolites show micro-structural records (i.e. opx+sp clusters, spinel exsolution in pyroxenes, complete spinel-facies equilibration) which indicate: i) upwelling from garnet- to spinel-facies conditions, ii) equilibration under cooling at spinel-facies conditions. This composite subsolidus evolution might be related to their isolation from the convecting asthenosphere and accretion to the subcontinental thermal lithosphere. Reactive spinel peridotites (harzburgites and dunites) show structural and compositional features evidencing that they were formed by melt-peridotite interaction at spinel-facies conditions. Mineral reactions (pyroxene dissolution / olivine precipitation) suggest that they were formed by interaction with pyroxene-undersaturated, silica-poor liquids. Geochemical modeling indicates that these liquids correspond to MORB-type melt increments formed by rather low degrees ($\pm 6-7\%$) of fractional melting on spinel-facies DM asthenospheric mantle source.

The formation of these early melt-related rocks testify for: i) the first incoming of MORB-type melts in the extending mantle lithosphere, and ii) the inception of decompression partial melting in the underlying, upwelling asthenosphere. Plagioclase peridotites have structural and compositional features suggesting their hybrid nature, consisting of a mantle spinel peridotite matrix enriched in plagioclase and micro-gabbroic aggregates by melt interstitial crystallization. The diffuse replacement of orthopyroxene on kinked mantle olivine, and the abundance of orthopyroxene in the magmatic patches, indicate that the percolating melts were more silica-rich than typical MORBs. Accordingly, these rocks represent the products of peridotite refertilization by silica-saturated melts under plagioclase-facies conditions. Geochemical modeling suggests that the percolating liquids were melt increments generated by $<1-6\%$ fractional melting of spinel-facies DM asthenospheric mantle source.

Replacive spinel peridotites, which cut, in form of m- to decameter-wide channels, all the pre-existing rock-types, were formed by reactive and focused porous flow percolation of undersaturated melts along pre-existing structural (shear zones) and compositional discontinuities. Once formed, these high porosity/high permeability channels were preferential ways for MORB melts delivery to shallow crustal levels. Formation of gabbroic dikes in the dunite channels suggest that the percolating melts were later squeezed in fractures, marking the transition from porous flow to diking. Later on, discrete MORB gabbroic bodies and Mg- to Fe-gabbroic dykes intruded the pre-existing rock types, which were frequently deformed to plagioclase-facies tectonite-mylonite peridotites.

Subsequently, the ultramafic rocks were locally transformed to amphibole- and chlorite-bearing peridotite mylonites, and finally, serpentinite mylonites.

Field and structural relationships between deformed and melt-related rock types clearly evidence that the extensional processes, testified by the development of different types of shear zone structures (tectonites and mylonites), preceded, flanked and followed the melt percolation events, and that the melt-modified mantle lithosphere was uplifted by tectonic processes towards the sea-floor of the growing Jurassic basin.

The pre-oceanic rifting stages in the Ligurian Tethys were, accordingly,

dominated by the lithosphere extension which caused: 1) the progressive tectonic-metamorphic exhumation of the mantle lithosphere, 2) the near-adiabatic upwelling and decompression melting of the asthenosphere, and 3) the formation and uprise of MORB-type melts from the molten asthenosphere through the extending mantle lithosphere. These processes were linked and mutually dependent. Wide areas of the lithospheric mantle protolith underwent structural and compositional modifications induced by percolation and interaction with melts formed by decompression partial melting of the asthenosphere.

The resulting scenario illustrates the composite interplay of tectonic-metamorphic and melt-related events which characterized the exhumation of the subcontinental lithospheric mantle to the sea-floor of the Jurassic Ligurian Tethys ocean.

MANTLE PROCESSES IN THE THERMAL BOUNDARY LAYER: EVIDENCE FROM THE LANZO SOUTH PERIDOTITE (NW-ITALY)

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This work summarizes recent results of field, petrographic-structural and geochemical investigations on the spinel and plagioclase peridotites from the southern domain of the Lanzo Massif (Western Alps). Mantle peridotites show extremely variable compositions ranging from spinel lherzolites, harzburgites and dunites to plagioclase-enriched peridotites.

Field evidence indicates that: i) pristine porphyroclastic spinel lherzolites are transformed to coarse-granular, cpx-poor spinel harzburgites and dunites; ii) spinel peridotites are pervasively overprinted by plagioclase enrichment and transformed to plagioclase peridotites; iii) spinel harzburgite and dunite channels and bodies replace the plagioclase peridotites.

Pristine porphyroclastic lherzolites, outcropping in the northern flank of Mt. Arpone, are variably deformed and show diffuse pyroxenite banding. These peridotites show micro-structural evidence of a composite subsolidus evolution, suggesting provenance from deeper (asthenospheric) mantle levels and accretion to the conductive mantle lithosphere. These mantle protoliths are locally transformed to coarse-granular spinel harzburgites and dunites, which show textures (i.e. pyroxene dissolution, olivine precipitation) and geochemical characteristics (i.e. sinusoidal to convex-upward Cpx REE patterns) reminiscent of melt/rock interaction. Geochemical data and modeling suggest that the injected melts represent melt increments produced by 1-5% of fractional melting of spinel-facies DMM.

Plagioclase peridotites are hybrid rocks resulting of pre-existing spinel peridotites and variable enrichment of plagioclase and micro-gabbroic material. The impregnating melts were formed by near-fractional melting of a spinel-facies asthenospheric source and attained silica saturation, as testified by widespread orthopyroxene replacement on mantle olivine, during open-system migration in the thermal boundary layer.

At Mt. Musine', metre-wide, coarse granular spinel harzburgite and dunite bodies and decametre-wide dunite masses replace the precursor plagioclase peridotites. Most of these replacive peridotites have interstitial, magmatic clinopyroxene with trace element compositions that equilibrated with N- to T-MORB. Some harzburgite bands show peculiar refractory Cpx compositions characterized by low incompatible trace element contents. These samples are believed to document transient geochemical features acquired by the uprising melts during the onset of their interaction with the ambient plagioclase peridotite.

Spinel harzburgite and dunite bodies cross-cutting the plagioclase peridotites are interpreted as replacive channels exploited for focused and reactive migration of silica-undersaturated melts with aggregate MORB compositions. These melts were unrelated to the silica-saturated melts, which formed the pre-existing plagioclase peridotites. Successively, the MORB upraise occurred along open fractures, now represented by the gabbroic dikes.

Spinel and plagioclase peridotites from the southern domain of the Lanzo Massif record the interplay of tectonic-metamorphic and melt-related events, and their relative timing, thus allowing us to infer the following scenario:

1) pristine spinel lherzolites were fully equilibrated at spinel-facies condi-

tions in the mantle lithosphere;

2) these mantle protoliths underwent different stages of melt-peridotite interaction, from reactive percolation at spinel-facies conditions to melt impregnation at plagioclase-facies conditions;

3) migrating melts were MORB-like and formed by partial melting of the MORB asthenosphere;

4) asthenosphere partial melting most probably was induced by near-adiabatic decompression of the MORB asthenosphere, which upwelled in response of the lithosphere extension and thinning leading to opening of the Ligurian Tethys;

5) the extending mantle lithosphere was significantly heated by the uprising hot asthenosphere whilst the upward migration of the asthenospheric melts and the melt-peridotite interaction processes produced its compositional variability (both pyroxene-depletion and refertilization); accordingly, the mantle lithosphere was "asthenospherized" and underwent thermo-mechanical erosion.

The documented complexity of rock types and mantle processes describes a composite tectonic and magmatic scenario that can be hardly reconciled with an "asthenospheric scenario", i.e. the interpretation of the southern body of the Lanzo Massif as an upwelling asthenosphere mantle diapir, which suffered in-situ partial melting and in-situ redistribution and crystallization of part of the produced melts.

The recognition of remnants of lithospheric mantle rocks, which suffered variable melt-rock reaction processes induced by exotic MORB-type melts, allow to propose a "transitional scenario", caused by asthenosphere/lithosphere interaction. This scenario envisages that pristine subcontinental lithospheric mantle was progressively exhumed during pre-oceanic stages of lithosphere extension and thinning, and was significantly modified by interaction with uprising MORB-type melts formed in the underlying asthenosphere. Decompression melting of the asthenosphere was induced by near-adiabatic upwelling in response of the ongoing lithosphere extension and thinning, which was related to the pre-oceanic rifting stages of the Ligurian Tethys ocean.

THE BRACCO GABBROIC MASSIF: WITNESS OF AN INNER CORNER SIDE OF A JURASSIC LOW SPREADING RIDGE

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The Bracco gabbroic Massif (Eastern Liguria) has been interpreted as a fossil magma chamber of the Jurassic Western Tethys Ocean. It is part of the oceanic "basement" of the Vara Unit, which pertains to the Internal Ligurides domain. The gabbroic massif consists of a stratified alternation of melatroctolites, troctolites, olivine gabbros, gabbros and plagioclases. The ultramafic terms are concentrated toward the stratigraphic base of the gabbroic massif that shows a "normal" stratigraphic polarity. The magmatic layering is marked by both compositional and more often granulometric variations. The layering is often deformed (iso-orientation and flattening of minerals, especially plagioclase) and lightly folded, indicating a tardomagmatic flux of the cumulitic crystal-mush. During cooling, but still at a high gradient (around 700°C), the gabbroic massif was affected by HT-LP oceanic metamorphism and shearing in which mylonitic (flaser) structures, associated to brown hornblende, pyroxene and high-Ca plagioclase paragenesis formed. These structures cut the magmatic layering with variable angle. Successively, both layers and mylonites were cut by basalt dykes and veins characterised by the presence of hornblende-oligoclase (retrogressive oceanic metamorphism, 600 to 500°C).

Previous (Cortesogno et al., 1987) and new (Principi et al., 2006) structural data on the orientation of the structures above described show that the magmatic layering was deformed and sheared before the occurrence of the basalt dykes and hornblende-oligoclase veins. These latter could be related to the brittle tectonic regime of normal faulting in an oceanic ridge zone. In this hypothesis, the Jurassic paleostress frame could be represented assuming that Sigma 1 corresponded to the angle bisector of the conjugate planes of these structures. Hence s_1 and s_3 have to lie in a horizontal plane; s_3 was normal and s_2 was parallel to the basalt dykes and hornblende-oligoclase fracture planes. If the paleostresses of these brittle/magmatic events can be tentatively inferred, much difficult is to define those of the shearing deformation. The orientations of this latter are more dispersed and are cut by the brittle structures and dykes at various angles. Regarding the tectonics where these shear structures formed, several hypotheses have been advanced, spacing from a lithospheric detachment to diapir rise along a transform. In this paper, we exclude an origin linked to pre-oceanization (subcontinental) detachments. The lack of continental extensional allochthonous and debris in the sequence above the gabbro and in the whole Internal

Ligurid domain, and the age of the gabbros, that is very close to that of the overlying oceanic radiolarian cherts (Vara Succession), excludes, in our opinion, a sub-continental rift environment. The high thermal gradient characteristic of a MOR, allows HT ductile shearing at few thousand meters below the ocean bottom and is consistent with an oceanic origin of the mylonitic structures of the Bracco Massif. Analogous mylonitic structures in cored gabbros have been repeatedly found in the Atlantic and Indian oceans.

Western Tethys was likely a very slow spreading ocean, accordingly the models of Mutter and Karson (1992) and Tucholke and Lin (1994) may be suitable modern analogues. In these models, the alternation of magmatic and amagmatic phases is considered. The position of the ridge segment terminations in relation to the active or inactive movements in the first and second order transform faults allows the formations of topographic highs (IC, Inside Corner) or lowlands (OC, Outside Corner) during the amagmatic phases when tectonic movements are prevalent. According to these models during IC and OC development a complex rotation resulting from the combination of along axis vertical rotation and of transversal axis horizontal rotation occurs.

Cortesogno et al. (1987) made a reconstruction of the ocean bottom of the Bracco-Levanto ophiolitic unit and interpreted the Bracco massif as a paleohigh with respect to the Levanto ophiolites, which show a thick sequence of basalt, breccias and sediments, that they considered as a paleobasin. Principi et al. (2004) suggested that the Bracco area could be interpreted as an IC and the Levanto area an OC. According to this hypothesis we can consider that the shearing stage occurred when the Bracco gabbroic massif was still in a buried during the first stage of the rotational rising of an Inside Corner.

The brittle structures (hornblende-oligoclase veins and basalt dykes) instead, formed when the Bracco gabbros underwent a major rotation with respect to the ridge axis and reached a higher topographic position.

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MANTLE PROCESSES AT SLOW SPREADING EXTENSIONAL SETTINGS: INSIGHTS FROM THE LONG-LIVED LITHOSPHERIC EVOLUTION OF THE ERRO-TOBBIO PERIDOTITES (LIGURIAN ALPS, ITALY)

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A key feature of the lithosphere forming at passive margins and slow- to ultra-slow spreading extensional settings is the shallow exposure of km-scale sectors of lithospheric mantle. The Alpine-Apennine ophiolites constitutes a well known analogue of such settings, as they were formed during passive extension of the Europe-Adria continental lithosphere and opening of the slow-spreading Jurassic Ligurian Tethys ocean. Most of these ophiolites, e.g. the Erro-Tobbio (ET) Unit (Ligurian Alps, Italy), mainly consist of subcontinental mantle peridotites which were exposed at the sea-floor, thus providing insights on the petrologic processes which govern the tectonic exhumation of the lithospheric mantle. The ET peridotites represent old (pre-Jurassic) subcontinental mantle which was tectonically denuded during early rifting stages of the Europe-Adria lithosphere. Exhumation likely started during Permian and occurred along km-scale lithospheric shear zones which enhanced deformation and recrystallization from spinel- to plagioclase-facies conditions (Rampone et al., 2005, Hoogerduijn Strat-

ing et al., 1993). Ongoing research have revealed that the peridotites experienced multiple stages of melt/rock interaction and various melt intrusion events (Piccardo et al., 2004; Rampone et al., 2004, 2005; Borghini et al., 2006). Here we present an overview of this multi-stage melt migration and intrusion history, which record progressive exhumation of the ET mantle from deep lithospheric depths to shallow environments.

The oldest intrusion event in the ET peridotites is represented by the diffuse occurrence of cm-scale pyroxenite bands. They often display isoclinal folds, their primary intrusion relationships being transposed by old deformation events. Pyroxenites (mostly spinel websterites) display variable bulk Al_2O_3 (5.92–10.16 wt%) and CaO (7.52–10.89 wt%) contents, and variably fractionated REE spectra, marked by LREE depletion ($\text{Ce}_N/\text{Yb}_N = 0.034\text{--}0.15$) and absent Eu_N anomaly. Their compositions are similar to those of spinel websterites from the French Pyrenees (Bodinier et al., 1987), and indicate an origin as high-P cumulates. In a few pyroxenite layers, clinopyroxenes hold an unusual trace element signature (high Sc: 120–155 ppm and V: 765–913 ppm contents, strong MREE/HREE fractionation: $\text{Sm}_N/\text{Yb}_N = 0.21\text{--}0.43$). Similar compositions were documented in clinopyroxenes from Zabargad spinel pyroxenites (Vannucci et al., 1993) and interpreted as inherited from a precursor garnet-bearing magmatic assemblage. The likely occurrence of garnet in the primary magmatic assemblage constrains the depth of intrusion and crystallization at $P > 15\text{--}20$ kbar (Hirschmann and Stolper, 1996), and it is consistent with preserved opx+spinel+cpv clusters in the spinel peridotites, indicative of garnet-bearing peridotite protoliths.

Folded pyroxenite layers and host peridotites are overprinted by a stage of annealing recrystallization at spinel-facies depths (Hoogerduijn Strating et al., 1993). Textural and compositional features of the ET spinel peridotites, e.g. i) development of olivine coronas around pyroxenes, i) increasing modal olivine (up to 85 wt%) at rather constant bulk Mg values, point that they experienced diffuse melt migration by reactive porous flow. Melt/rock interaction (causing olivine precipitation and pyroxene dissolution reactions) occurred at high melt volumes in the spinel-facies field (Piccardo et al., 2004; Rampone et al., 2004, 2005a).

At shallower lithospheric depths, the ET peridotites were diffusely impregnated by melts. Melt impregnation is documented by significant enrichment of interstitial plagioclase, and crystallization of unstrained poikilitic orthopyroxene replacing deformed mantle olivine and clinopyroxene. Reacted clinopyroxenes, in spite of overall REE increase, preserve strong LREE depletion ($\text{Ce}_N/\text{Sm}_N = 0.006\text{--}0.011$). Textural and geochemical features thus indicate that melt impregnation was related to diffuse porous flow migration of opx-saturated depleted MORB-type melts (Piccardo et al., 2004; Borghini et al., 2006).

In the Southern sector of the ET unit, impregnated peridotites are intruded by a discrete hectometre-scale cumulate body (mostly troctolites) showing gradational, interfingering contacts with the host mantle rocks. Subsequent intrusion events are revealed by the occurrence of variably thick (cm- to m-scale) dykes and thin dykelets of olivine gabbros crosscutting peridotite foliation and magmatic layering in the cumulates. Overall, bulk-rock and mineral compositions of the intrusives indicate that they represent variably differentiated cumulus products crystallized from rather primitive N-MORB-type magmas at moderate P conditions (3–5 kbar) (Borghini et al., 2006). Sm-Nd internal isochrons on ol-gabbros have yielded an age of 180 ± 14 Ma, thus pointing to the Jurassic emplacement of the ET mantle at shallow lithospheric environments. Structural and geochemical features of melt impregnation and melt intrusion products point to a progressive change in melt composition and dynamics. Peridotite impregnation was caused by diffuse migration of opx-saturated depleted melts. The subsequent intrusion events originated by MORB-type aggregated magmas which did not experience significant compositional modifications during ascent. The transition from porous flow melt migration to emplacement of magmas in fractures, most likely reflects progressive change of the lithospheric mantle rheology, across the ductile to brittle transition, during extension-related uplift and cooling of the ET mantle.

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AUTONOMOUS EXPLORATION FOR HYDROTHERMAL VENTING ON THE GAKKEL RIDGE

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The isolated hydrodynamic nature of the Arctic Basin and the ultra-slow spreading nature of the plate boundary make the Gakkel Ridge a key target for biological, chemical, and geological studies of deep-sea hydrothermal venting. However, the presence of permanent pack ice over the Gakkel Ridge precludes utilization of the deep submergence assets, such as submersibles and remotely-operated-vehicles, commonly used to find, characterize, and sample vent fields in the open ocean. This combination of compelling science and technical challenge motivates the development of new platforms for autonomous exploration of the Gakkel Ridge. While the autonomous underwater vehicle (AUV) ABE has pioneered the use of autonomous platforms for finding deep-sea vent fields, the Gakkel mission is more difficult because autonomous sampling is also required. This scenario is conceptually identical to future astrobiology missions to the Jovian moon Europa, where internal tidal forces are believed to produce volcanic eruptions into an ice-covered ocean, thereby providing a potential habitat for chemosynthetic biological communities. We have developed two new AUVs that are designed to enable autonomous exploration for vent fields on the Gakkel Ridge, including autonomous sampling with computer vision and manipulation, with funding from the US National Aeronautics and Space Administration. With funding from the US National Science Foundation we will test these vehicles at a suspected methane hydrate site on the Chukchi Plateau in October, 2006, and then conclude with a full-scale expedition to the Gakkel Ridge in 2007.

GRAIN GROWTH IN SPINEL AND PLAGIOCLASE PERIDOTITES: A TIME-RESOLVED EXPERIMENTAL STUDY ON TEXTURAL EVOLUTION

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A distinctive feature of passive continental margins and ultra-slow spreading oceanic settings is the large sea-floor exposure of mantle peridotites. In these geodynamic environments, tectonic exhumation of the lithospheric mantle can induce subsolidus recrystallization of spinel peridotites at plagioclase-facies conditions.

Although the knowledge of phase equilibria at relatively low temperature are needed in order to properly locate the spinel to plagioclase transition as a function of the complex compositional variability of mantle peridotites (for this aspect see Borghini et al., this volume), a complete picture of mantle dynamics require a systematic study on the textural evolution as a function of pressure, temperature and time. As a complementary insight on the subsolidus origin of plagioclase peridotites and on a reliable prediction of the spinel to plagioclase reaction, textural aspects are here taken into account. The aim of this study is therefore to quantify, on an experimental basis, textural parameters like size and spatial grain distribution. These features will allow to define the mechanism that controls the grain growth rate, to unravel the competing effects of ripening and pinning, and to contribute to predict the rheological properties of plagioclase and spinel peridotites.

High pressure experiments have been carried out at Dipartimento di Scienze della Terra, Milan, using a single stage piston cylinder apparatus. Dry peridotite compositions have been modeled in the complex system ($\text{CaO-Na}_2\text{O-FeO-MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-Cr}_2\text{O}_3\text{-TiO}_2$). Gels seeded by spinel s.s. and anorthite were used as starting materials in order to promote crystal growth at subsolidus, dry conditions. For the bulk compositions investigated see Borghini et al. (this volume).

Experiments have been performed at pressures from 0.5 to 1.0 GPa and at temperatures between 900 and 1100°C. Three series of experiments were conducted at different time duration, from 10^3 to 10^6 seconds at 1100°C and 1.0 GPa, 1100°C and 0.5 GPa and 1000°C and 1.0 GPa. Experimental run products were inspected by SEM/BSE images and analysed by

EDS/WDS microprobe. Powder X-ray diffraction spectra have been collected using both conventional light and synchrotron radiation at the ESRF, Grenoble.

Textures were found to be significantly sensitive to run time, showing similar evolution at the three different P-T conditions investigated. Although X-ray diffraction pattern analysis always confirm the good crystallinity of the samples, experiments lasted 10^3 and 10^4 seconds did not show a texture resolvable at SEM. Nucleation was probably the dominant process in these time resolved experiments. Further characterizations at the TEM scale are planned. On the contrary, in longer time duration experiments, textures can be carefully characterized at the SEM scale. Grain size of all phases increased and the fine-grained texture became coarse-grained texture from 10^3 to 10^6 seconds time duration experiments. In longer time duration experiments the solid-state grain boundary adjustment produced triple junction among phases and polygonal grain shape characterized the major phases orthopyroxene, clinopyroxene and olivine. All these textural evidences suggested that the grain coarsening became the dominant process from 10^4 to 10^6 seconds.

In the spinel-bearing experiments (1100°C and 1.0 GPa) the texture observed in longer runs was the result of a polygonal aggregate of orthopyroxene, clinopyroxene, olivine and spinel. The grain coarsening is particularly evident for spinel grains. In 10^5 seconds time duration experiment the spinel was clustery distributed at most in crystals that had linear dimensions $< 0.5 \mu\text{m}$. Only few grains had a diameter that exceeds $2 \mu\text{m}$ up to a maximum of $4 \mu\text{m}$. In 10^6 seconds time duration experiment the spinel grains were randomly distributed, their average size was $2 \mu\text{m}$ and the number of crystals with size $< 0.5 \mu\text{m}$ strongly decreased. In both cases most of the coarse spinel grains were zoned with spinel seeds at the core and Cr enrichment at the rim.

In the plagioclase-bearing experiments (1100°C and 0.5 GPa) and in longer runs plagioclase grains grew in the framework interstices formed by the larger and euhedral crystals of orthopyroxene, clinopyroxene and olivine. Anhedral plagioclase crystals did not form triple junctions with grains of other phases. Plagioclase was an abundant phase and had a linear average size of $5 \mu\text{m}$. Preliminary estimates of plagioclase modal abundance, by mass-balance calculations and Rietveld method, have furnished values ranging 6-8 wt% in the plagioclase peridotite at 0.5 GPa, 1100°C.

The differences in textural development found in experiments run in the field of spinel and in the field of plagioclase suggest a different kinetics evolution. This result is encouraging and may be used as a starting point to explore the mechanism and the key factors controlling the grain growth rate of spinel and plagioclase peridotites.

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BIOLOGICAL STUDIES AT HYDROTHERMAL VENTS IN POLAR REGIONS VIA AUTONOMOUS EXPLORATION AND SEAFLOOR SAMPLING

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The coupling between geological processes and organisms at hydrothermal vents provides a singular opportunity to study how fundamental planetary processes shape the evolution of life. These tightly-linked geological-biological systems have yielded a global network of extraordinarily productive chemosynthetic communities. The spatial and temporal variability within this network has created distinct biogeographic provinces that are influenced by a variety of factors. Ridge systems that are geographically, hydrographically and/or topographically isolated (e.g., our Eastern Arctic field area) are more likely to have developed distinctive endemic species and ecosystems. In such areas, the probability of discovering novel species and ecological strategies is greatly enhanced, producing a dramatic leap in our understanding of the spectrum of marine biodiversity and evolutionary processes. For example, knowledge of the timing of the hydrographic "closure" of Arctic-Atlantic interchange and the comparison of extant species from the Arctic and Atlantic can be used to identify biogeographic barriers or filters to dispersal that act on evolutionary time scales to structure biodiversity in the deep sea. The Arctic and Antarctic Oceans represent the final pieces of the global puzzle. Through coordinated survey strategies using the autonomous underwater vehicles Jaguar and Puma, as well as a towed real-time imaging and discrete sampling system, we will determine how these potentially unique ecosystems relate other previously sampled biogeographic regions. Both autonomous adaptive photographic imaging sur-

veys and benthic sampling will be used to how the distribution, abundance, and variation in biological community structure relate to hydrothermal activity and geological features. With detailed genetic investigation of recovered fauna, we will assess the role that geographic isolation has played in the evolution of Arctic vent fauna. We hypothesize that a hydrographic barrier between the North Atlantic and Arctic prevent or inhibit along-axis transport and communication of vent-endemic fauna into (and out of) the North Atlantic. The long-standing lack of a deep-water connection presents a hydrographic, bathymetric, and biogeographic barrier that bisects the Gakkel and Mid-Atlantic Ridge into distinct provinces and unique fauna on the Arctic seafloor. Similar hypotheses that identify barriers to dispersal, putative biogeographic boundaries, and characterization of vent ecosystems on other polar ridges will provide insights into processes controlling basin-scale evolutionary migrations and adaptations applicable to other deep-water marine systems, including planned studies along the Bransfield Strait and East Scotia Ridge in the Southern Ocean.

MICROSEISMICITY STUDIES YIELD INSIGHT INTO THE ACTIVE RIFTING PROCESSES OF ULTRASLOW-SPREADING RIDGES

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We present the results of a pilot study of the microearthquake activity of Gakkel ridge and explain our newly started comprehensive and comparative microearthquake study of ultraslow-spreading ridges.

During the international and multidisciplinary Arctic Mid-Ocean Ridge Expedition (AMORE) in 2001, the Alfred Wegener Institute for Polar and Marine Research undertook a first attempt at recording the seismic activity of Gakkel Ridge using drifting ice-floes as platforms for small-aperture seismological arrays. The unconventional technique proved successful and we recorded and localised numerous small earthquakes in the Western Volcanic Zone (WVZ) near 4°W, the Sparsely Magmatic Zone (SMZ) near 16°E and in the Eastern Volcanic Zone (EVZ) near the volcanic center at 85° which showed a long-lasting and strong swarm of teleseismically recorded earthquakes and a submarine eruption in 1999.

The microearthquake activity is preferentially concentrated on exposed terrain like the steep rift valley walls or volcanic ridges. We note higher levels of activity on the northern rift valley wall than on the southern rift valley wall in the WVZ and the SMZ. We further made a rare in-situ observation of a submarine eruption by recording a swarm of explosive seismoacoustic signals. These sounds originate at the seafloor of the large volcanic center near 85°E in an area where a massive hydrothermal plume was detected in the water column.

The pilot study proved the feasibility of microearthquake studies in ice-covered oceans but the limited data set and localisation accuracy hindered a detailed geological interpretation. We therefore initiated an improved and systematic microseismicity survey of ultraslow-spreading ridges. The plans for this project will be presented.

INTRAPLATE MAGMATISM OF THE DE LONG ISLANDS: POSSIBLE RELATIONSHIPS WITH PROPAGATION OF THE ULTRASLOW-SPREADING GAKKEL RIDGE INTO PASSIVE CONTINENTAL MARGIN OF THE EASTERN ARCTIC BASIN

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Synthesis of petrological, geochemical, and isotopic data on volcanic rocks and a related suite of xenoliths in the De Long Islands in the eastern sector of the Arctic basin is presented with the aim of reproducing the geochemical nature of the mantle sources of basaltic magmatism and its geodynamic environment in the continental shelf of the North-East part of Laptev Sea, southeast of its intersection with the southern termination of the Gakkel Ridge. The main tool of this research was the comparative analysis of the isotopic characteristics of magmatic products on islands of this archipelago

situated at different distances from the oceanic margin of the shelf. The reconstructed magmatic evolution at De Long Islands implies its close relations with the activity of a plume mantle source that occurred beneath the continental shelf of the Laptev Sea and was responsible for pulses of magmatic activity in this area of the eastern sector of the Arctic over the past 124 m.y. The volcanic activity at De Long Islands is determined to have become systematically younger from the offshore boundary of the continental shelf in the Laptev Sea (Bennett Island) inward the shelf (Zhokhov Islands) and farther southeastward (Vil'kitskii Island).

ARCTIC LENA TROUGH IS NOT A MID-OCEAN RIDGE

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The North American-Eurasian plate boundary traverses the Atlantic and Arctic oceans. Over most of that length, it is a Mid-Ocean Ridge that spreads between about 23 mm/yr (MAR) and 10 mm/yr (Gakkel Ridge) full rate. The northern MAR and the Gakkel ridge are connected by a deep linear feature called Lena Trough.

Until about 10 million years ago, Lena Trough was not an oceanic domain at all, but a continental shear zone through a narrow isthmus of continental crust that connected the American and Eurasian plates. Its opening was, significantly, the most recent and final event in the separation of the North American from the Eurasian continent, and opened the gateway for deep water circulation between the Arctic and North Atlantic oceans. Models for the tectonic configuration of Lena Trough have until now differed only in the number and length of fracture zones and spreading segments thought to be present.

Lena Trough is a deep fault-bounded basin with depths of 3800-4200m, and irregular, steep valley sides that are oblique to the spreading direction. Basement horst structures outcrop as sigmoidal ridges with steeply dipping sides project out of the valley floor, but these are not traceable to any parallel structures on either side. Ridge-orthogonal topography is simply absent (ie no segments trending parallel nor fracture zones perpendicular to Gakkel Ridge). Most faults trend approximately SSE-NNW, an obliquity with respect to Gakkel Ridge (SW-NE) of about 55 degrees.

The basement ridges are composed nearly entirely of mantle peridotite, as are the valley walls. Only at the northern and southern extremities of Lena Trough do basalts appear at all. The Northern basalts show strong chemical affinities to those of Gakkel Ridge, and can be considered a part of the Gakkel volcanic system. The rare southernmost basalts, however, are quite unique. They are alkali basalts with K₂O up to 2 weight percent, highly incompatible element enriched and occupy a corner of isotope space known as EM1, and bear more resemblance to alkaline rift magmas than to mid-ocean ridge volcanics.

Thus Lena Trough is not a Mid-Ocean Ridge (in any event there is no ridge there), but represents a recent transition form between a continental rift and an oceanic one. The Lena Trough is also the only known modern analog of the Iberia Margin, the conjugate Newfoundland Margin, as well as the ophiolite complexes of the Western Alps. It is significant that there is no evidence for low-angle detachment at Lena Trough. Instead, the thick lithosphere at Lena Trough results in decidedly thick-skinned rift tectonics, with steeply dipping fault surfaces and relatively narrow basement blocks. Ultraslow spreading ridges are often thought of as a model for the rifts that initiate continental breakup. If this is so, then Lena Trough must give us some cause for re-thinking. At Lena Trough, there are no identifiable low-angle normal detachment faults similar to those observed at the Mid-Atlantic ridge and postulated for the Iberia Margin and Western Alpine regions. On the other hand, as Lena Trough is quite young, it is possible that there simply has not yet been sufficient time to develop such structures.

Our current research focuses on the nature of the mantle rocks underlying Lena Trough. Are they oceanic in nature, derived by partial melting, followed by conductive cooling as they rose beneath the Lena Rift, or are they continental, possibly hundreds of millions of years old? What are the geochemical markers that distinguish between these two cases? What is the significance of basalt erupted in the otherwise amagmatic Lena Trough? Are their sources reflected in the rest of the NAM-EUR plate boundary rift system?

RIDGE GEOMETRY AND MAJOR ELEMENT CHEMISTRY ALONG THE ULTRASLOW-SPREADING SOUTHWEST INDIAN RIDGE (9°-25°E): THE ROLE OF PROCESS VERSUS SOURCE DURING MORB GENERATION

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We report MORB volatile and major element concentrations along a single 1050-km first-order spreading segment of the ultraslow-spreading Southwest Indian Ridge. This segment consists of two supersegments with strikingly different geometry. To the east is a 630 km long orthogonal spreading (< 5° obliquity) supersegment that dominantly erupts N-MORB with progressive incompatible element enrichment from east to west. To the west is a 400 km long oblique spreading (up to 56°) supersegment with two robust volcanic centers erupting alkali basalt and E-MORB with three intervening amagmatic accretionary segments. In the latter, mantle peridotite is emplaced directly to the seafloor with only scattered N-MORB and E-MORB flows. At 16°E, where the easternmost amagmatic segment joins the orthogonal supersegment, there is a remarkable break in physiography, crustal structure, and chemistry, but not in axial linearity. We attribute the contrasts across this discontinuity to the enhanced and non-linear influence of mantle thermal structure on mantle and melt flow and melt generation at ultraslow-spreading rates. Along the orthogonal supersegment moderate and rather constant degrees of partial melting effectively sample the bulk mantle source, thus the enrichment to the west is largely a function of a changing mantle composition. On the oblique supersegment, however, suppression of mantle melting due to enhanced conductive cooling with slower mantle upwelling means that the bulk source is not uniformly sampled and thus "process" rather than "source" dominates basalt generation.

Although much of the local major element heterogeneity is explained by polybaric fractional crystallization with varying amounts of H₂O, the remaining major element variations, specifically elevated K₂O contents in E-MORB, likely result from mixing of depleted peridotite and K-rich eclogite partial melts. Regardless of the exact nature of the enriched component, this model for MORB generation illustrates the dramatic influence of variation in mantle thermal structure at spreading rates < 20 mm/yr, while simultaneously providing insight into the mantle melting process and nature of the source, so often obscured at faster rates where higher extents of melting more directly sample the mantle bulk composition.

ORIGIN OF GARNET PYROXENITES FROM A NON-VOLCANIC RIFTED MARGIN (EXTERNAL LIGURIDE OPHIOLITES, NORTHERN APENNINE, ITALY)

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The External Liguride units (Northern Apennine, Italy) contain remnants of a Middle Jurassic ocean-continent transition similar to modern West Iberian margin. In particular, the External Liguride mantle peridotites preserve a subcontinental lithospheric origin (Rampone et al., 1995) and are in places characterised by garnet-bearing clinopyroxenite to websterite layers (Montanini et al., 2006). The garnet clinopyroxenite layers (up to 1.5 metres in thickness) consist of garnet and Al₂O₃- and Na₂O-rich clinopyroxene; rutile, graphite and sulphides are locally present as accessory phases. The garnet websterite layers are up to 8 cm in thickness and have high modal amounts of orthopyroxene. The garnet-bearing mineral assemblages record a thermobarometric equilibration at ca. 1100 °C and 2.8 GPa for the subcontinental lithosphere. The garnet equilibration was followed by a de-

compression to spinel- and plagioclase-facies conditions, in turn overprinted by a low-pressure retrograde evolution that resulted in continental break-up (Montanini et al., 2006).

The clinopyroxenites may be subdivided into two groups. Group 1 clinopyroxenites have lower mg#, Cr and Ni, and higher TiO₂ and MnO than group 2 clinopyroxenites. The latter do not preserve the high-pressure mineral assemblage, which is inferred on textural and microchemical grounds. The websterites differ from the clinopyroxenites in the higher mg# (similar to that of the enclosing peridotites), Cr and Ni, and in the lower Al₂O₃, CaO and Na₂O.

The REE pattern of group 1 clinopyroxenites is characterised by extreme LREE depletion. Some of the selected samples display weak positive Eu anomaly and nearly flat MREE and HREE, similar to included garnets. Another set of group 1 clinopyroxenites displays a gradual increase from LREE to HREE, lacks positive Eu anomaly and has high amounts of Sc and V; these geochemical features are paralleled by included garnets. Group 2 clinopyroxenites show variable LREE fractionation, positive Eu anomaly and nearly flat HREE. The REE pattern of websterites is characterised by slight LREE depletion and lack of significant Eu anomaly, and is subparallel at higher concentration levels to that of enclosing peridotites.

Garnet and clinopyroxene separates from the pyroxenites provided a narrow range of oxygen isotope values, which are close to typical mantle compositions. On the other hand, Sm-Nd and Lu-Hf isotope analyses gave wide variations. As a whole, the geochemical data indicate that most garnet clinopyroxenites were derived from plagioclase-rich mafic cumulates, which underwent an event of partial melting in the garnet stability field. Nonetheless, a high-pressure cumulus process has been inferred for the origin of group 1 clinopyroxenites with enriched HREE and no positive Eu anomaly. The garnet websterite layers record chemical exchange processes under spinel- to plagioclase-facies conditions, in relation to interaction with the enclosing peridotites and/or migration of melts.

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DEVELOPMENT OF LONG-LIVED NORMAL FAULTS AT MAGMA-LIMITED MID-OCEAN RIDGES

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Throws of normal faults on most slow- to ultra-slow spreading ridges normally range from a few hundred meters to a few kilometers. Over the past decade, however, exceptionally long-lived normal faults (detachment faults) have been increasingly identified in multibeam bathymetric data, not only on ridges that are extending at the slow end of the spreading-rate spectrum, but also on intermediate-rate ridges that are characterized by low magma supply (e.g., the Southeast Indian Ridge in the Australia-Antarctic Discordance). Duration of slip on these faults is typically 1-2 m.y., resulting in seafloor exposure of exhumed footwall rocks over distances of tens of kilometers. The footwalls, termed megamullions, characteristically have a domed shape and are corrugated by distinctive mullion structures that parallel fault-slip direction. They also expose gabbros, serpentinized peridotites, and fault rocks (mylonites, cataclases, fault breccias) at their surfaces, demonstrating both the fault-related origin of the features and their exhumation of deep crust and mantle lithosphere. Most megamullions exhibit elevated residual gravity anomalies, typically 10-20 mGal, which is equivalent to crustal thinning of at least 1-2 km. These features, and the fact that megamullions tend to form at the ends of spreading segments where magma supply is low compared to segment centers, indicate that they are formed by detachment faults during periods of reduced magmatism compared to normal spreading. The residual gravity anomaly commonly decreases across a megamullion termination and onto younger crust, suggesting that the fault forming the megamullion is abandoned when there is an increase in magmatism. However in some regions where magma supply appears to be extremely limited, the residual gravity anomaly increases across the megamullion termination (e.g., in the region of the Fifteen-Twenty F.Z.), indicating that fault slip ceased when magma supply was reduced. Thus megamullion formation may be limited largely to a window wherein magmatic and tectonic extension strike a rather delicate balance.

According to this 'Goldilocks hypothesis', magma supply must be neither too large nor too small in relation to extension rate, but 'just right'.

To test this hypothesis, we examined the frequency of occurrence of megamullions versus average axial depth (as a proxy for magma supply) of the enclosing ridge segments for about one hundred mid-ocean ridge segments that represent the full spectrum of global spreading rates. The results show that megamullion formation is associated with a limited axial-depth range between about 3500 and 4800 meters (within a total depth range of 1400-6100 meters), which supports our hypothesis. Plotted against spreading rate, megamullions occur over a wide range of values (~18 to 75 mm/yr full rate), indicating that that magma supply rather than spreading rate is the key factor controlling their formation.

We also conducted numerical modeling to examine how the balance between tectonic and magmatic extension may affect duration of fault slip. Results indicate that detachment faults develop readily when magmatic accretion accounts for about half of total plate separation, that slip duration decreases toward more magmatic conditions, but that long-lived slip persists to very low values of magma supply. However, fully tectonic extension produces a chaotic pattern of relatively short-duration faults (up to a few 100 k.y.) related largely to complex bending stresses in both fault footwalls and hanging walls. Thus, combined geological and modeling evidence suggests the following progression of fault patterns with decreasing melt supply, beginning when about half of plate separation is taken up by tectonic extension: a) detachment-fault formation of corrugated megamullion domes, b) long-lived detachment faults without megamullion characteristics, and c) shorter-lived faults associated with amagmatic extension. These characteristics may provide important constraints on interpretation of tectonic versus magmatic extension on ultra-slow spreading ridges such as Gakkel Ridge.

A QUANTITATIVE ASSESSMENT OF MELT ORIGIN VERSUS SUBSOLIDUS FORMATION OF PLAGIOCLASE IN GAKKEL RIDGE PERIDOTITES

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Three different processes are believed to account for the presence of plagioclase in mantle peridotites - (1) subsolidus breakdown of spinel during transition from spinel to plagioclase facies conditions following the reaction $\text{cpx} + \text{opx} + \text{al-sp1} \rightarrow 2 \text{Fo} + \text{An} + \text{Cr-sp2}$, (2) crystallization of an in-situ formed melt and (3) crystallization of a transient exotic melt. The first two processes are closed system processes whereas the third should show open system characteristics.

We have performed quantitative models for these three different scenarios to look at the trace element behaviour of clinopyroxene and plagioclase during the different cases of plagioclase formation. The models use the Workman & Hart (2005) DMM trace element composition and different starting modal compositions and account for different types (pure fractional and critical) and degrees of melting.

Plagioclase peridotites are widespread on slow-spreading ridges such as the Gakkel Ridge. We performed a detailed study on very fresh plagioclase and spinel peridotites from the westernmost point of the „magma-starved“ region of Gakkel Ridge.

Plagioclase peridotites from Gakkel Ridge are characterized by strong compositional variation on thin section scale in all phases. Ion probe investigation of cpx grains reveal wide core-rim variations with a decrease in the plagiophile elements (Al, Sr, Eu) and an increase in Ti, Cr, Zr, V and REE to the rim. The plagioclases have less distinct compositional variation on grain scale but differ on thin section scale. They are generally characterized by strong depletion of the LREE ((La/Sm)_N ~ 0.1) without a significant Sr-anomaly.

Plagioclase-free peridotites from the same dredge haul were analyzed as well as they represent the potential protoliths. They are homogeneous on thin section scale in both major and trace elements. They have fertile to moderately depleted REE-pattern (La/Yb ~ 0.03-1.3). Even though they show no visible plagioclase in thin section two samples reveal a small negative Sr-anomaly in cpx.

We applied the models to our Gakkel Ridge data set in order to assess and quantify the role of the different processes.

Pure subsolidus breakdown of spinel to form plagioclase cannot account for the observed modal proportions and trace element characteristics of silicate phases in the Gakkel Ridge plagioclase peridotites. The maximum modal amount of plagioclase that can be produced by subsolidus break-

down with the complete consumption of spinel in fertile DMM is 3.1%. Plagioclase peridotites usually still contain some spinel and it is more realistic to account for only partial consumption of spinel. In the case of a compositional change of spinel Cr# from 0.1 to 0.5 (assumed to be a realistic upper limit of spinel Cr#s observed in plagioclase peridotites) reduces the maximum amount of plagioclase to 2.8%. The typical plagioclase-bearing peridotite contains roughly 2.5% plagioclase except at the Romanche Fracture Zone (Dick et al., 1989). Our samples have a slightly higher modal amount of 4.5 and 6.1% respectively, indicating that pure breakdown is less likely compared to other abyssal plagioclase peridotites. Nevertheless, Dick et al. (1989) noted that the average abyssal plagioclase peridotite contains slightly more pyroxene relative to olivine than plagioclase-free peridotites whereas in the case of subsolidus formation it should be the opposite due to pyroxene consumption strengthening further the importance of melt impregnation in plagioclase peridotite genesis.

An important element sensitive to the different scenarios and therefore indicative in both clinopyroxenes and plagioclase is Sr (even more than Eu). Most of the observed negative Sr-anomalies in cpx and Sr-concentrations in plagioclase cannot be produced by pure subsolidus formation of plagioclase but require the involvement of a melt. An in-situ formed melt can be ruled out by the trace element composition of the silicates. Furthermore, the low REE-concentrations of plagioclase call for a depleted melt which is also supported by the relatively high An-contents (76-94). Trace element ratios distinct for the different processes and degrees of depletion allow us to further constrain the nature of the melt involved.

From our data so far we propose that plagioclase peridotites on Gakkel Ridge formed mainly by impregnation of a transient depleted melt at low pressures. The relatively widespread melt stagnation features and the concomitant lack of extrusives at the central segment of Gakkel Ridge indicate that recent melting has almost completely ceased or was never high and freezing of the melt (due the thick lithospheric lid) most likely lead to only short travel distances of the melt.

Overall, our models will allow more quantitative constraints on the melt formation, extraction, and stagnation in the central part of Gakkel Ridge and plagioclase peridotites in general.

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MULTISTAGE EVOLUTION OF THE FOREARC PERIDOTITES FROM THE IZU-BONIN-MARIANA SUPRA-SUBDUCTION ZONE

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The abyssal peridotites recovered from forearc regions are of particular relevance for the comprehension of the tectonic, geodynamic and petrologic pa-

rameters inducing the onset of the intra-oceanic subduction, the evolution of the Supra-Subduction Zones (SSZ) and the associated arc magmatism.

A new opportunity to document the petrologic features of forearc peridotites has been provided by drilling at Site 1200 during Ocean Drilling Program (ODP) Leg 195. In this Site, the top of the South Chamorro Seamount, located in the Mariana forearc, was cored, and several fragments of serpentinised mantle peridotites were recovered. Although the degree of serpentinisation of these samples is rather large, the occurrence of relics of the primary and secondary mineral assemblages allowed us to document a series of re-crystallisation events at high-T, mantle, conditions. In addition, the major and trace element composition of bulk rock and minerals of some peridotite samples recovered during the previous ODP Leg 125 at Conical Seamount (Site 779A; Mariana forearc) and Torishima Seamount (Site 784A; Izu-Bonin forearc) has been investigated.

The collected peridotites have a strongly refractory modal composition, ranging from spinel harzburgite to orthopyroxene-bearing spinel dunite. The clinopyroxene modal content is in the range of 0 to 4% by volume.

Bulk rock major and trace element composition indicates that the spinel harzburgites experienced very large degrees of partial melting ($\geq 18-19\%$). The depletion episodes were followed by the percolation of ascending melts. Such a process is revealed by the following petrochemical features: exsolved and deformed orthopyroxene porphyroclasts are ubiquitously replaced by clinopyroxene-bearing fine-grained assemblages; interstitial clinopyroxenes (Cpx) are locally concentrated in clusters or pseudo-veins;

the variation of the bulk rock major element composition does not match the trends expected for refractory residua after basalt removal;

the trace element mineral chemistry is not correlated with the variation of the modal and chemical composition of bulk rock. Trends to dunite modal composition are believed to be the product of the melt-peridotite interaction rather than due to partial melting.

Valuable information on the geochemical composition and fractionation trends of the migrating melts can be obtained by the trace element composition of the interstitial Cpx.

The geochemical composition of the Cpx from the South Chamorro samples is strongly heterogeneous and three different Types have been recognised.

Type 1 Cpx are strongly depleted in LREE ($\text{Pr} = 0.02 \times \text{C1}$), with HREE at 2-3 $\times \text{C1}$ level. These compositions are virtually in equilibrium with melt increments produced by 15% fractional melting of spinel-facies DMM. Type 3 Cpx are characterised by an extreme depletion in incompatible trace elements (e.g. REE patterns have maximum at $\text{Lu}_N = 0.73-1.25$; $\text{Ti} = 30$ ppm; L-MREE are below LA-ICP-HRMS detection limits, the latter being $0.1-0.01 \times \text{C1}$ in the pertinent range), unravelling the percolation of ultra-depleted melts. Low-Al amphibole in apparent chemical equilibrium with the clinopyroxene occurs in these samples. Type 2 Cpx have trace element contents in between to those of the Types 1 and 3, which are characterised by a fractionation in the M-HREE region steeper than that expected for equilibrium with liquids produced by fractional melting of a spinel-facies source ($\text{Sm}_N/\text{Ho}_N = 0.08-0.14$; $\text{Ho}_N/\text{Yb}_N = 0.21-0.46$) at the given HREE level ($\text{Yb}_N = 2.1-2.7$). Trace element features similar to Type 2 Cpx are displayed by the Cpx from Conical peridotites ($\text{Yb}_N = 2.3-2.5$), which show an even stronger MREE-HREE fractionation ($\text{Sm}_N/\text{Ho}_N = 0.05-0.08$; $\text{Ho}_N/\text{Yb}_N \approx 0.55$). Geochemical modelling indicates that such a steep HREE-MREE fractionation can be the result of the late migration of ultra-depleted melts through a MORB mantle column. The migration of extremely depleted melts is also recorded by the trace element composition of the Cpx from the Torishima peridotites ($\text{Lu}_N = 0.9-1.4$), which, however, are often relatively enriched in LREE (e.g. $\text{Pr}_N = 0.22$; $\text{La}_N/\text{Yb}_N = 0.05$) and Sr with respect to those from both South Chamorro and Conical seamounts. The trace element composition of the putative liquids calculated in equilibrium with the Torishima Cpx suggests a possible boninitic affinity.

Thus, according to the geochemical affinity of the percolating melts, it is proposed that the mantle sequence of the Marina forearc was a MORB lithosphere interacting with MORB to arc magmas. Differently, the geodynamic evolution of the Izu-Bonin forearc was only characterised by the migration of arc magmas.

