

EUG XI



Symposium LS02

Structure, Composition and Accretion
of the Oceanic Crust: Geophysical, Petrological
and Geochemical Constraints

Convenors

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LS02

Structure, Composition and Accretion of the Oceanic Crust

Wednesday AM Session

LS02 : WEam01 : F2

Accretion of Oman and United Arab Emirates Ophiolite

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The south-eastern and central domains (from Wadi Tayin to Haylayn and possibly Sarami massifs) of the Oman-United Arab Emirates ophiolite belt incorporate a 40-50 km-wide and possibly over 200 km long new ridge segment, oriented NW-SE, which is opening into a 1-2 My older lithosphere oriented NE-SW. The northern domain (from Khawr Fakkan to Hilti massifs) is well explained by a model of propagating (Aswad) and failing (Fizh) ridge segments of nearly parallel NNW-SSE orientation which are separated by a 10-20 km-wide transform zone covering the north of Fizh massif. This new synthesis integrates and updates the partial syntheses achieved so far at smaller scales. It illustrates again the contrast observed in this ophiolite belt between locally simple ridge segments organised around mantle diapirs and the tectonic complexity of the two larger domains, with, as an example, sheared mantle, vertical Moho and dismembered lower crust with hydrous contamination, near the tip of ridge propagators. The relation between the northern and central-southern domains is obscure because the paleomagnetic results suggest that, with respect to the central-southern domain, the northern domain should have rotated 130 degrees clockwise during no more than a couple of million years.

LS02 : WEam02 : F2

Seismic Structure of EPR Magma Chamber: New Constraints from the 9°03'N OSC

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The 9°N segment has been extensively studied over the past decades and conflicting models have been proposed to explain the origin of the 9°03'N OSC. In 1997 and 2000, three seismic survey were undertaken near this OSC to study the relationship between patterns of magma supply and the rise axis segmentation. We will present an overview of multichannel, wide-angle seismic imaging and compliance analyses which have provided new constraints on the magma supply at the 9°03'N OSC.

The 20 by 20 km ARAD-3D (Anatomy of a Ridge Axis Discontinuity) reflectivity survey reveals the intricate structure of the melt lens at upper crustal levels [Kent et al., 2000]. A processing technique (range-gated stacking) utilizing amplitude variation with offset (AVO) characteristics of lens reflector gives insight into fine-scale variations of its physical properties, and therefore of its nature (e.g., melt versus mush). Tomographic inversions show that a strong crustal low velocity zone (LVZ) underlies both limbs of the OSC and part of its basin. At shallow depth, this LVZ underlies the melt lens reflection imaged by the reflectivity survey. Deeper in the crust, the low velocity bodies seem focused beneath the two N-S extremities of the basin. Evidence for a lower crustal melt body also arises from new compliance data. This deep melt body is asymmetric and shifts west of the rise axis. Similarly to the upper crustal melt lens, the deeper body is anomalously wide just north of the OSC [Crawford et al., 2000]. Tomographic inversions of mantle refracted P-waves image a continuous region of low velocity in the shallow mantle [Dunn and Toomey, 2000].

These seismic results show evidence for a robust magma supply beneath the axial discontinuity. Therefore, the OSC is not remotely supplied by melt sources located at ridge segment centers. In addition, the conjunction of the different analyses should provide some important insight on how magma rises in the crust and focuses towards the neo-volcanic zone.

Kent et al., *Nature*, **406**, 614-618, (2000).

Crawford et al., *Fall AGU abstract*, (2000).

Dunn and Toomey, *Fall AGU abstract*, (2000).

LS02 : WEam03 : F2

Three-Dimensional Reflectivity Image of the Melt Sill and Moho- Implications for Crustal Accretion Process at Fast Spreading Centres

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Moho (named after Mohorovicic, 1909) is a boundary separating the differentiated crust from the depleted mantle. As over seventy percent of the Earth's crust is created at ocean spreading centers, it is fundamental to understand when the Moho is formed and how the crust is accreted during its formation and evolution. Geodynamical studies suggest that the lower crust is formed in a single thin crustal magma reservoir (Henstock et al., 1993; Phipps Morgan and Chen, 1993) whereas petrological studies suggest that it is formed in thin melt sills at different depths in the crust (Kelmen et al., 1997). Using three-dimensional seismic reflection images, here we report that Moho is present right beneath the ridge axis and crustal magma chamber, which suggests that the Moho is formed at zero-age. The absence of any other large observable melt sills between the crustal magma chamber and Moho at zero-age places limits on the contribution of secondary melt sills to the accretion process, and therefore supports the geodynamical model, a single melt-sill model, of crustal accretion processes at fast ocean spreading centers. The presence of zero-age Moho also provides constraints on the mode of melt delivery from the mantle into the upper crustal magma reservoir and on the efficiency of the crustal accretion process.

Mohorovicic, A., *Jb. Met. Obs. Zagreb*, **9**, 1-63, (1909).

Henstock TJ, Woods AJ & White RS., *J. Geophys. Res.*, **98**, 4143-4154, (1993).

Phipps Morgan J & Chen J, *J. Geophys. Res.*, **98**, 6283-6297, (1993).

Kelemen P, Goga K & Shimizu N, *Earth Planet. Sci. Lett.*, **146**, 475-488, (1997).

LS02 : WEam04 : F2

Lower Crustal and Moho Melt beneath the East Pacific Rise, 9°-10°N, from Seafloor Compliance Measurements

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We report lower crustal shear velocities and corresponding melt estimates beneath the East Pacific Rise from 9°-10°N, determined from seafloor compliance measurements. We measured seafloor compliance, the low-frequency seafloor deformation under ocean waves, at 35 sites along and across the EPR. Compliance measurements are particularly sensitive to low velocity bodies and to melt because the measured displacement signal is inversely proportional to the crustal shear velocity. A line of compliance measurements across the rise axis at 9°48'N reveals an asymmetric and narrow (5-7 km wide) lower crustal melt body centered beneath the rise axis. A second line of compliance measurements at 9°33'N reveals an identical melt body shifted 0.7-0.8 km west of the rise axis. We will present a joint compliance-seismic refraction analysis of this site to improve constraints on the melt amount in this body. A third line of compliance measurements at 9°08'N, just north of an overlapping spreading center (OSC), reveals a much broader melt body with even lower shear velocities. The compliance data also reveal melt or mush at the Moho beneath the rise axis and at sites 9-10 km east of the rise axis, but not in between. The narrowness of the melt zone to the north, the change in its width near the OSC, and the bimodal distribution of Moho melt/mush support a broad upwelling model with deep hydrothermal circulation controlling the amount and location of crustal melt.

LS02 : WEam05 : F2

Geochemical and Volcanological Development of the East Pacific Rise; 9°-10° N

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Alvin dive observations, side-scan data and over 600 lava samples have been collected during nine different research cruises to the East Pacific Rise in the 9° 17'N to 10° N region since 1991. Multidisciplinary research has principally focused on the axial summit collapse trough (ASCT) from approximately 9° 30' to 9° 56', the crestal plateau up to 4 km off-axis around 9° 30-32'N and 9° 49-52'N, and around the small overlapping spreading center at 9°37' N. Alvin video and 35 mm still photography have been used to plot the distribution of various lava types and sea floor morphologies facilitating the correlation of lava geochemistry with sample location and inferred geologic history. Age-dating of the lavas using U-isotope disequilibrium techniques provides temporal constraints on eruptions and magmatic processes. A documented eruption in 1991-1992 (Haymon et al., 1993) has been established by both field observation and by Po-Pb dating (Rubin et al. 1994). Analysis of the physical volcanology of the different lava terrains has yielded estimates of eruption volumes, effusion rates and eruption times (Gregg, et al., 1996). Detailed mapping, sampling and hydrothermal studies have shown that the observed morphologic segmentation (e.g. overlapping spreading centers, devials along the ridge is directly related to the volcanic and hydrothermal segmentation of the ridge crest. Major element, trace element, and radiogenic isotope data indicate the most recent magmatic event associated with the present ASCT erupted relatively homogeneous and mafic basalts compared to the surrounding, older lavas. The distribution of basalt types is not symmetric across the crestal plateau in any of the areas studied in detail. T-and E-type MORB only exist in small areas (< 1 km²) on the crestal plateau and appear to be related to abyssal hill formation and prominent off-axis scarps or fissures from which pillows were erupted. Field observations indicate that some off-axis lavas (up to 4 km from the ridge axis) appear to be much younger than surrounding lava flows (Perfit et al., 1994). Young ages for these samples are indicated by their measured (²³¹Pa/²³⁵U and ²²⁶Ra/²³⁰Th) disequilibria activity ratios. The results confirm that a significant terrain up to ~2.5 km away from the ASC on the crestal plateau has been affected by off-axis volcanism. Relatively voluminous and mafic volcanism appears to be related to new magmatic episodes whereas off-axis volcanism is characterized by more evolved (and sometimes enriched) lavas fed from smaller and cooler magma bodies. Geochemical evidence does not support the derivation of off-axis lavas from a more depleted portion of the subaxial melting regime. These results have significant implications for the magma transport and the development of the uppermost oceanic crust.

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Haymon, RM et al, *Earth Planet. Sci. Lett.*, **119**, 85-101, (1993).

Perfit, MR, Fornari, D, Bender, J, Langmuir, Cand Haymon R, *Geology*, **22**, 375-379, (1994).

Rubin, KH, Macdougall, JD and Perfit, MR, *Nature*, **368**, 841-844, (1994).

LS02 : WEam06 : F2

Origin of the Lowermost Oceanic Crust: Trace-Element and Isotopic Composition of Layered Gabbros from the Oman Ophiolite

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Accretionary processes at mid-ocean ridges are currently under debate, particularly those concerning the lower oceanic crust to which direct access is for the most part lacking. Ophiolites provide a unique opportunity to study spatial and temporal relationships between melting residues

and overlying cumulates, and may also provide information on mantle source composition and scales of heterogeneity. In order to address these issues we present high-precision, low-level concentration determinations of Th, U, Nb, Zr, Hf, and other trace elements, as well as Nd and Pb isotopic data from layered gabbros from the lower crustal section of the Oman ophiolite (Sumail area). We sampled a short (1.5 m) coherent interval of individual gabbro layers which vary in thickness between 25 and 30 cm.

MgO is nearly constant between the layers, whereas mg# systematically increases from bottom (0.81) to top (0.86), consistent with increasing Cr concentrations (~100 ppm in the lowermost layer and ~900 ppm in the uppermost layer). However, SiO₂ and TiO₂ also systematically increase upwards (from 46 to 50% and from 0.1 to 0.3%). Al₂O₃ decreases slightly and is highly correlated with Sr concentration (Al/Sr = 675 ± 12), reflecting decreasing amounts of cumulus plagioclase. Th and U concentrations of the gabbro layers are extremely low (down to 5 ppb Th and 2 ppb U), but similar to highly refractory gabbros associated with supra-subduction zone magmatism (Pfänder et al., 2000). Other trace element (Hf, Zr, Nb) concentrations are also within the ppb-range, indicating a highly depleted mantle source. Initial ε_{Nd} values (95 Ma) are constant (8.5 ± 0.4). Present day ¹⁴³Nd/¹⁴⁴Nd increases from bottom to top due to increasing Sm/Nd ratios, reflecting successive melting increments from the same source. Therefore, each layer appears to represent a single batch of melt emplaced over another. This implies an effective removal of individual melt batches from the source, and a discontinuous mechanism which may be controlled by physical boundary conditions. However, it remains unclear how cumulate layers can be produced from sill-like intrusions.

Our results indicate that the gabbro layers are not derived by successive fractionation from a single melt body, ruling out a magma chamber origin. This is consistent with the models suggested by others (e.g. Boudier et al., 1996; Kelemen et al., 1997), who proposed a sill-like origin for the gabbro layers emplaced within the lowermost oceanic crust of the Oman ophiolite. Our data further support a model in which the lower oceanic crust grows from bottom to top by successive emplacement of mafic melt batches, rather than by accumulation of cumulus minerals. The observed invariance in isotopic composition suggests a restricted, homogeneous melting region or reequilibration of heterogeneous melt batches.

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LS02 : WEam07 : F2 Fluid Flow Patterns in Fast-Spreading EPR Crust Exposed at Hess Deep

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Tectonic exposures of a volcanic sequence and sheeted dyke complex over 4-km-wide zone at Hess Deep (equatorial Pacific) were explored by the submersible Alvin during two dive programs. Alteration patterns provide a ~60,000 year record of fluid-rock interaction for a section of crust that likely formed at the same segment along the fast-spreading EPR. Significant spatial heterogeneities were delineated on the basis of hydrothermal mineral assemblages and their compositions, the degree of replacement of clinopyroxene, and their whole rock geochemistry. Fluid flow pathways delineated on the basis of whole rock O-isotope data show heterogeneity on a spatial scale of hundreds of metres that has hitherto not been identified in modern oceanic crust. Two centres (400 m wide) of focused fluid flow were identified. The first is located near the sheeted dyke - volcanic transition in an area of intact, massive sheeted dykes. Samples are moderately to highly altered to chlorite- or amphibole-dominated assemblages, O-isotope depleted (2.9-4.4%), and metal-depleted. These characteristics are consistent with formation within a hydrothermal discharge zone, however, the extent of alteration is not as great as for those spatially associated with

volcanic hosted sulphide deposits. We attribute this difference to the much shorter duration of active EPR vent sites, in comparison to those that form at slower spreading ridges. The second centre is located within the basal sheeted dykes in an area of pervasive fracturing and dyke rotation. Samples have similar mineral assemblages and O-isotope depletion (2.9-4.4%) to the first centre, however, samples are not metal-depleted. We envision that this centre of enhanced fluid flow formed during a period of tectonism at a spreading axis. Elsewhere, mineralogical and geochemical characteristics systematically change with depth and are indicative of hydrothermal recharge zones where temperatures and water/rock ratios increase and decrease, respectively. These trends are similar to those documented at Ocean Drilling Program Hole 504B. We propose that the spreading history of a fast-spreading ridge segment can create significant lateral heterogeneity in fluid flow and alteration patterns within sheeted dyke complexes.

LS02 : WEam10 : F2 Deep, Near-Axis Hydrothermal Circulation at Oman Fast-Spreading Ridge

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Recent data from the Oman ophiolite crustal section covering a large spectrum of issues suggest that high-T hydrothermal circulation could reach the Moho, even at fast spreading ridges. - Abundant hornblende veins cross-cut the layered gabbro section down to the Moho (Nicolas et al., 2001), calibrating temperatures up to 825°C (Manning et al., 2001). - High-T hydrous phases are identified as oriented inclusions in plagioclases in lower layered gabbros (Boudier et al., unpublished), and all minerals from the lower gabbros show random water contents by infrared spectrometry (Forneris, 1997). - Isotopic composition of Sr points to a shift toward a sea-water contamination pole in gabbroic dikes cross-cutting the shallow mantle (Benoit et al., 1996), as well as in clinopyroxenes in the impregnated dunites of the Moho-Transition-Zone (MTZ) (Montillet, 2000). - Bore isotopic compositions point to sea-water contamination during serpentinization of shallow-level mantle (Itier and Lecuyer, 1998). These data confirm previous oxygen isotope studies that suggested a multistage sea-water contamination in the gabbro section of the Oman ophiolite (Gregory and Taylor, 1981). The deep and high-T sea-water contamination evidenced by the Oman ophiolite lower crustal section and MTZ, could represent normal steady conditions at fast-spreading ridges. Alternatively, it could result from particular conditions at the tip of opening ridge segments (Boudier et al., 2001). The development and importance of hydrothermal/magma interactions down to the crust/Moho-Transition-Zone interface is still little known, although such processes might control the thermal structure of oceanic lithosphere close to fast-spreading systems, as represented by the Oman ophiolite.

LS02 : WEam11 : F2 Structure of the Central Indian Ridge Near 19°S: Influence of the Reunion/Rodrigues Hotspot

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We present an analysis of multibeam bathymetry and gravity data collected during the Magfond2 cruise of the N/O Marion Dufresne. The survey covered the flanks of the Central Indian Ridge between 18.5°S and 20°S, up to 4 Ma off-axis. This part of the CIR is characterized by an anomalously shallow axis and enriched axial MORBs, suggestive of a hotter mantle probably due to an interaction between the ridge and the Reunion/Rodrigues hotspot. The new bathymetry data reveal low-relief abyssal hills, 300-500 m high, 3-5 km wide, and up to 100 km long. They are frequently bounded by faults on the side facing the axis, and rounded facing away from the axis. These abyssal hill characteristics are similar to those observed on intermediate-spreading centers, and contrast with the rougher abyssal hills observed farther south on the CIR. A series of jogs of the axial valley forms a 15 km offset around 18°45'S. The W shape of its off-axis trace implies that the

offset has migrated north between 4 Ma and about 1.5 Ma, and has been migrating south since then. Three other discontinuities, at 19°S, 19°25'S and 19°45'S have offsets of about 5 km only. Their traces are marked by series of bathymetric saddles, and small-offset sinuosities in the abyssal hills. The second-order segments they bound have axial depth variations lower than 800 m. Off-axis, however, bathymetric highs are observed near the center of the segments on the eastern flank of the ridge. The Mantle Bouguer Anomaly map shows two small-amplitude, negative anomalies associated with the two bathymetric highs. These anomalies are superimposed on a broader regional negative anomaly, centered on the ridge segment at 19°30'S. The pattern is asymmetric, displaying more negative values on the west flank, towards a group of small off-axis, elongated ridges. The residual mantle Bouguer anomaly displays a similar pattern. The negative anomalies are suggestive of thicker crust and/or hotter mantle beneath the ridge axis and the western ridge flank. The asymmetry of the gravity anomalies, and the good correlation between both the regional and more localized MBA lows and the off-axis ridges suggest an influence of the Reunion hotspot on accretion processes and volcanic construction near the CIR axis. The thermal influence, however, is relatively weak at the scale of our survey, and appears to spread over a larger area, certainly due to the large distance of about 1000 km between the ridge and the hotspot.

LS02 : WEam12 : F2 Wavelet Analysis of Deep-Tow Magnetic Profiles: Modelling the Magnetic Layer Thickness over the Central Indian Ridge

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Marine magnetic anomalies are attributed to horizontal variations of magnetization intensity in the magnetic source layer which is usually considered to be the highly magnetized extrusive basalts layer. These magnetization contrasts are controlled by several factors, whose contributions is highly debated: variations of the magnetic layer thickness, variations in magnetic properties of the source material or fluctuations of the geomagnetic field intensity or direction, including polarity reversals. The magnetic layer thickness near oceanic spreading centres is poorly constrained and previous studies were limited to fast spreading ridges. Hence, most studies of marine magnetic data concern the intensity of the remanent magnetization and are neglecting source thickness variations. However some authors proposed that short source thickness variations also cause short-wavelength magnetic anomalies. During a recent cruise (Magfond2; Dymant et al., 1999) over the Central Indian Ridge (CIR, 19°S) three high-resolution deep-tow magnetic profiles have been acquired, extending symmetrically from the axis out to 4 Ma old crust. Initial interpretation of these data was based on classical inversion techniques in the Fourier domain and concluded that the observed short-wavelength magnetic anomalies primarily reflect intensity fluctuations of the geomagnetic field during the past 4 Ma. The validity of this interpretation is limited by the a priori assumption that the magnetic source layer has a constant thickness. We now re-analyse these data using a wavelet-based technique that does constrain magnetic layer thickness variations. This study has two purposes: one is to test whether the previous interpretation that short-wavelength magnetic anomalies reflect field intensity variations is further supported by an analysis of the magnetic layer thickness; the other is to constrain the temporal variations of the thickness of the magnetic source in order to better understand the architecture of CIR crust. Powerful techniques exist that perform an automatic characterisation of potential field sources along profiles, especially to find their depth (e.g. analytic signal and Euler's deconvolution). Forward iterative methods have been used to adjust the layer thickness along surface and deep-tow marine magnetic profiles. Moreau et al. (1999) have shown that the analysis of potential fields with a continuous wavelet transform avoids a number of drawbacks of the previous methods. Sailhac et al. (2000) subsequently developed a technique using 1-D complex wavelets to characterise local and extended synthetic magnetic sources such as vertical and inclined steps and proposed an automated method for the estimation of source depth and thickness.

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We demonstrate with synthetic examples analysis that this method may be successfully applied to marine magnetic profiles and allows us to model magnetic layer thickness variations with time on the CIR.

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LS02 : WEam13 : F2 Off-Axis and Along-Axis Segment Characteristics: Insights from a 3D Thermal Modeling

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Many observations along the Mid-Atlantic Ridge segments suggest a correlation between surface characters (length, axial morphology) and the thermal state of the segment (Detrick et al., 1995; Tonnerre, 1996; Thibaud et al., 1998). Thibaud et al. (1998) classify segments according to their thermal state: "colder" segments shorter than 30 km show a weak magmatic activity, and "hotter" segments as long as 90 km show a robust magmatic activity. The existence of such a correlation suggests that the thermal structure of a slow spreading ridge segment explains most of the surface observations. Here we test the physical coherence of such an integrated thermal model and evaluate it quantitatively. The different kinds of segment would constitute different phases in a segment "life" (Thibaud et al., 1998), the segment evolving progressively from a "colder" to a "hotter" so to a "colder" state. Here we test the consistency of such an evolution scheme.

To test these hypotheses we have developed a 3D numerical model for the thermal structure and evolution of a slow spreading ridge segment. The thermal structure is controlled by the geometry and the dimensions of a permanently hot zone, imposed beneath the segment center, where is simulated the adiabatic ascent of magmatic material. To compare the model with the observations several geophysical quantities which depend on the thermal state are simulated: crustal thickness variations along axis, gravity anomalies (reflecting density variations) and earthquake maximum depth (corresponding to the 750°C isotherm depth). The thermal structure of a particular segment is constrained by comparing the simulated quantities to the real ones. Considering realistic magnetization parameters, the magnetic anomalies generated from the same thermal structure and evolution reproduce the observed magnetic anomaly amplitude variations along the segment. The thermal structures accounting for observations are determined for each kind of segment (from "colder" to "hotter"). The evolution of the thermal structure from the "colder" to the "hotter" segments gives credence to a temporal relationship between the different kinds of segment. The resulting thermal evolution model of slow spreading ridge segments may explain the rhomboedric shapes observed off-axis (Gente et al., 1995).

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LS02 : WEam14 : F2 Long-Lived "Superpropagators" on the Carlsberg Ridge between Chrons 26-20 (58-42 Ma)

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Recent reinterpretations of magnetic anomaly data in the Arabian Sea and Eastern Somali Basin (Chaubey et al., 1998; Dyment, 1998) have shown that, between C26-C20 (58-42 Ma; "C" stands for Chron), seafloor spreading along the Carlsberg Ridge was mainly accommodated by a series of en-echelon propagating ridge segments. Such a systematic ridge propagation resulted in a tremendous spreading asymmetry: ~65% of the oceanic crust generated between C26r-C24r (58-54 Ma; "r" means reversed magnetic polarity interval) lies on the African plate, and ~75% of the crust created between C24r-C20 (54-42 Ma) is on the Indian flank. The direction of propagation reversed from eastward to westward at C24r. These observations may reflect the position of the Carlsberg Ridge relative to the nearby Deccan-Reunion hotspot.

Free air gravity anomaly maps derived from satellite altimetry confirm these interpretations. In the Arabian Sea, the inner pseudo-faults of the seven C24r-C20 westward propagators are marked by subtle ~N70°E linear anomalies. In the Eastern Somali Basin, the outer pseudo-faults of these propagators correspond to a single, narrow and quite prominent anomaly. This observation suggests that the same structure acted as a pseudo-fault for all the different propagators during their westward migration. The outer pseudo-fault represents the main discontinuity in the oceanic lithosphere formed near a propagator, as it directly juxtaposes lithospheres of different ages. We consider that the outer pseudo-fault of the westernmost propagator was a thermomechanical boundary which guided subsequent propagation of ridge segments located further east. The seven C24r-C20 westward propagators could then be regarded as the expression of a single, larger tectonic feature that we name "superpropagator".

Interestingly, the three C26-C24r eastward propagators observed in the Eastern Somali Basin are associated with several N75°E oriented inner-faults matching a single outer pseudo-fault in the Arabian Sea; thus they can also be interpreted as an other superpropagator. It should be noted that the outer pseudofaults of the two superpropagators are both roughly parallel to the C27 lineations, which date the onset of seafloor spreading along the Carlsberg Ridge.

We therefore define a superpropagator as a set of en-echelon ridge segments propagating toward the same direction along the same outer pseudo-fault. The evolution of the two superpropagators resulted in a perfect - although slightly delayed - spreading asymmetry: between the propagating tips of the westernmost and easternmost segments of the C24r-C20 superpropagator, all the oceanic crust created at the Carlsberg Ridge was finally captured by the Indian plate. Depending on the duration of its activity, the outer pseudo-fault may evolve into a major lithospheric discontinuity which keeps focussing further ridge propagation. In such a context, the outer pseudo-faults can certainly be regarded as the major tectonic discontinuities between the two plates, since the ridge segments and transform zones - the true plate boundary - are transient and unstable features.

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Wednesday PM Session

LS02 : WEpm25 : F2 Crustal Thickness and Mantle Temperature: Implications from Ophiolites

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The composition and thickness of ocean crust are related to one another because the extent and nature of melting of the mantle control both. The systematics of this relationship constrain a number of quantitative models of ocean ridges, and have broader implications as well for the temperature distribution in the mantle, the nature and distribution of mantle heterogeneity, and the proper interpretation of seismic studies of ocean ridges. Ocean crust composition can be determined quite accurately through mid-ocean ridge basalts (MORB), but ocean crustal thickness is an indirect measurement based on deep sea seismic experiments. Seismic experiments, however, only measure crustal velocity, and velocities may not relate directly to crustal thickness because the velocity of serpentinized mantle is similar to the velocity of lower gabbroic ocean crust. Therefore the question remains: is the seismically measured thickness that of ocean crust, or ocean crust plus altered mantle? Indeed, recent geological data from ocean ridges (eg Cannat et al, 1995) has raised the possibility that seismic velocities that have been interpreted to represent igneous ocean crust may be serpentinized peridotite, and therefore that the thickness of the crust by seismic methods may have been significantly overestimated, particularly at slow spreading ridges. Furthermore, the complex tectonics and three dimensional structure of slow-spreading ridges make crustal thickness measurements there suspect. Ophiolites, pieces of old ocean crust preserved on continents, potentially provide another way to determine the relationships between crustal composition and crustal thickness, because the compositions of the igneous materials provide the crustal chemistry, and the actual igneous crustal thickness can be measured by geological methods. But there has been long-standing controversy over what ophiolites actually represent, among suggestions that they are formed in the back-arc basin environment, or in other geological environments not observed presently along continental margins. Indeed, chemical discriminant diagrams have been devised that separate most ophiolitic rocks from those of normal ocean ridges. Here we show that for moderately incompatible elements, basalts from ocean ridges and from ophiolites share coherent chemical systematics, and that these systematics relate regularly to crustal thickness. However, the relationships between chemistry and crustal thickness in ophiolites are offset from the seismic determinations from ocean ridges by about 2 km, with ophiolite crustal thickness being significantly thinner for the same chemical composition. The coherence among chemical signals, and offset when crustal thickness is considered, suggests either that seismically determined crustal thickness has a systematic error with respect to real geological thickness, or that special circumstances lead to preservation of ophiolites with thinner crust than is prevalent in the ocean basins today. A clear test of these two hypotheses is possible through deep drilling of the sea floor.

LS02 : WEpm26 : F2 Constraints on Melt Generation at Very-Slow Spreading Ridges from Geophysical and Geochemical Measurements

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There is a strong correlation between geophysical measurements by wide-angle seismics and gravity of the igneous crustal thickness at very slow-spreading oceanic ridges and geochemical inferences from rare earth element (REE) concentrations in basalts of the total amount of melt generated in the mantle. The best data comes from a series of studies on the South-West Indian Ridge (SWIR), where we purposefully made geophysical surveys and dredges of seafloor basalts in the same locations. We demonstrate that this correlation also holds across all mid-ocean ridge spreading rates by using data from the global dataset of 'normal' oceanic ridges as well as from other very-slow spreading centres including the Cayman Trough, Gakkel,

Knipovitch and Mohns Ridges. In the few areas, all on the SWIR, where sufficiently dense surveys have been made to characterise individual segments, we show that the consistency between geophysical and geochemical measures of melt thickness also holds for variations in average melt thickness between adjacent ridge segments.

This consistency suggests that less than 10% of the melt generated is frozen in the mantle before it reaches the crust and that serpentine probably represents only a small percentage of the material above the Moho. The melt is well mixed on a segment scale, probably in high level magma chambers, but the melts remain distinct between segments. The REE concentrations of basalts from very slow-spreading ridges are higher than those from normal oceanic ridges, which is directly indicative of reduced mantle melting, and they show characteristic light REE enrichment, interpreted as caused by a deep tail of small percentage wet melting. An abrupt decrease of melt thickness occurs at full spreading rates below about 20 mm/a, pointing to the importance of conductive cooling inhibiting melting of the upwelling mantle at very slow-spreading centres.

LS02 : WEpm27 : F2 Structural Signature of Core Complex Formation on Slow-Spreading Oceanic Crust

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The episodic formation of large domal massifs at the inside corners of ridge-transform intersections leaves a profound imprint on the structure of the oceanic crust. These features are most commonly found on the flanks of slow spreading centers but they have also been observed at intermediate rate ridges. We will conduct a field experiment at one of the clearest examples of an 'oceanic core complex' during November/December, 2000. Our new findings from the Mid-Atlantic Ridge 30N site will be presented at this meeting. We will summarize initial interpretations of deep-tow sidescan sonar, submersible mapping and sampling, seafloor gravity, and deep-tow video data.

LS02 : WEpm28 : F2 Southwest Indian Ridge 61 to 70°E: Melt Supply Variations to an Ultra-Slow Spreading Ridge

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The Southwest Indian Ridge (SWIR) between the Rodrigues TJ (70°E) and the Melville FZ (61°E) is anomalously deep (mean depth greater than 4700 m), suggesting a small average crustal thickness (less than 3 km; Cannat et al., 1999), and anomalously low temperatures in the sub-axial mantle. Yet, this 1000 km-long portion of the SWIR comprises a few high relief segments, with along-axis gravity variations pointing to substantial variations in crustal thickness, from values similar to the regional average near segment ends, up to more than 7 km at segment centers. Seismic data obtained over one of these high relief segments yield similar crustal thicknesses (Muller et al., 1999). The average crustal thickness of high relief segments in the 61 to 70°E region is therefore more than the regional average, suggesting localized enhanced melt supply from the sub-axial mantle to the crust.

Along-axis bathymetry and gravity variations indicate that, at present, high relief segments are few (3) and spaced by more than 250 km. Available off-axis bathymetry and gravity data are scarce, but enough to show that the building of high relief segments lasts only a few myrs at a given location. Seafloor morphology and gravity observations suggest that this process involves the formation of large (more than 10 km in diameter) volcanic constructions, a significant part of the melt supplied from the mantle being erupted to the seafloor. The transition to the low magma supply seafloor typical of this deep portion of the SWIR involves large-offset normal faulting, in some cases leading to the formation of a core complex on one plate, while most of the volcano and its crustal root are carried to the other plate.

We discuss three hypotheses for the uneven along-axis distribution and limited duration of enhanced melt supply events in this overall magma-poor portion of the SWIR: a) short diapiric events in the sub-axial mantle; b) melting of small and unevenly distributed volumes of enriched sub-axial mantle; or - the local pooling of melt that has migrated along the base of a sloping axial lithosphere.

Cannat M, **Rommevaux-Jestin C**, **Sauter D**, **Deplus C** & **Mendel V**, *Journal of Geophysical Research*, **104**, 22825-22843, (1999).

Muller MR, **Minshull TA** & **White RS**, *Geology*, **27**, 867-870, (1999).

LS02 : WEpm29 : F2 Focused and Distributed Magma Supply on the Southwest Indian Ridge

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One of the most striking features of the ultra-slow spreading Southwest Indian Ridge (SWIR, full rate 15 mm/yr) between 49° and 70°E is the common occurrence of very large non-transform discontinuities (NTDs), offset up to 70 km) sometimes longer than segments. Between Gauss transform fault (TF; 54°E) and Atlantis II TF (57°E), mantle Bouguer anomaly (MBA) highs, almost non-existent central magnetic anomalies and lower backscattering strength relative to the segment centres suggest thin crust and reduced volcanic production in such large NTDs (offset > 40 km). Large MBA lows beneath short segments indicate strongly focused magma supply in this region. By contrast, between Novara TF (58°E) and Melville TF (61°E), TOBI images of the SWIR axial valley reveal that areas of recent volcanism are distributed throughout low amplitude MBA negative anomalies and that volcanic constructions also occur in the large NTDs (offset > 25 km). This suggests less focused accretion processes which have resulted in along-axis weak crustal thickness variations and/or low density contrasts. We propose that several closely spaced magma sources are aligned along-strike and feed the volcanic systems through dikes. In both ridge portions, the satellite-derived gravity anomaly map shows that most of the off-axis traces of the NTDs are easy to follow for the last 40 m.y. However, between Novara TF and Melville TF, a long-lived off-axis trace becomes unrecognizable in crust of about anomaly 5 age (10 Ma) on each flank. We suggest that a change in the direction and rate of spreading has induced a reorganization of the axial segmentation and introduced additional instability into the crustal accretion processes resulting in a change in focus of magmatic activity.

LS02 : WEpm30 : F2 The Building of High Volcanic Massifs at Mid-Oceanic Ridges with Very Low Extents of Melting

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The eastern portion of the very slow spreading South West Indian Ridge (SWIR), between 61°E and the Rodrigues triple junction, has an average axial depth of 4700 m, suggesting a particularly cold thermal regime. The axial morphology, however, varies considerably along axis. Some portions of the axial valley are uniformly deep while others are filled with large massifs at segment centers, that are about 2.5 km above the adjacent seafloor. Basalts are systematically dredged from these massifs suggesting that they are volcanic constructions, while serpentinized peridotites are frequently found in adjacent deep sections. Moreover, the large negative Mantle Bouguer Anomaly correlated with the shallow massifs demonstrates that they are associated with a thickening of the crust. Geochemical and petrological investigations on the dredged basalts bring

some information on the amount of melting and the process of melt delivery to the surface. The chemical composition of the basaltic glasses dredged all along this portion of the SWIR axis shows that the extent of melting remains extremely low, independently of the axial depth. This suggests that the building of the large volcanic massifs results from magma focussing and not from local variations in the melting regime. The basalts sampled from the volcanic massifs commonly contain abundant plagioclase phenocrysts up to 1 cm in size. These crystals typically display a simple and inverse zonation, with a more sodic core. They contrast with the phenocrysts from the basalts dredged from the shallower portions of the ridge located to the west that display either very complex or normal zonations. The inverse zonation can be explained by crystallization at higher pressure, which favors the incorporation of sodium in the plagioclase cores. We propose that the paradox of building large volcanic massifs in a context of very low magma production can be explained by the very cold thermal regime and therefore the presence of a thick lithosphere. The ascending magma is trapped beneath the lithosphere lid until it builds enough overpressure to break through to the surface. We infer that the cores of the plagioclase phenocrysts crystallize at depth, when the magma is trapped beneath the lithosphere. The presence of a magma body results in the local thermal erosion of the base of the lithosphere which favors the lateral migration and focussing of liquids.

LS02 : WEpm31 : F2 Magmatic to Amagmatic Spreading Segments along the Ultra-Slow Spreading Southwest Indian Ridge

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In 1997, during the FUJI (French, U.K., Japan Interridge) cruise, fine scale side-scan sonar (TOBI) images have been obtained along two parts of the axial valley of the ultra-slow spreading Southwest Indian Ridge (SWIR, 16 mm/yr). The seven segments (four to the east of Melville transform fault and three to the west) covered by these images appear to illustrate different stages in magmato-tectonic processes of segment evolution. Segments 11 (63°55'E) and 16 (59°20'E) are strongly magmatic showing fresh volcanic features (mostly hummocks) with almost no trace of faulting or fissuring. On the contrary, the bathymetric high corresponding to segment 9 (64°49'E) shows no trace of volcanic feature but a series of closely spaced faults and fissures. Between these two extremes, segments 8 (65°36'E), 10 (64°27'E), 15 (59°54'E) and 17 (58°40'E) are associated to axial volcanic ridges partially faulted and/or fissured. In these cases, tectonic and volcanic processes interact: some volcanic features are disrupted by faults and/or fissures while some others, fresh hummocks or lava flows, cover faults and/or fissures. According to volcano-tectonic cycle models (Kappel and Ryan, 1986; Gente, 1987) axial ridges are built during volcanic periods and then split and moved to the flanks during tectonic episodes. In this cycle, the first two segments (11 and 16) are in constructional stages while segments 8, 10, 15, 17 are at the end of volcanic stages, beginning of tectonic stages, and segment 9 is at the end of the cycle, corresponding to the complete tectonic dismemberment of an axial volcanic ridge. Since a tectonic phase is observed within the 15 km-wide axial valley at segment 9, we can speculate that the length of the tectonic periods is at least 0.9 m.y. In the same way, we propose that the volcanic periods are at least 0.4 m.y. long, since segments 11 and 16 are 6 km wide. This suggests that a volcano-tectonic cycle for the ultra-slow spreading Southwest Indian Ridge is at least 1.3 m.y. long. This length may vary along-axis with different parameters like mantle temperature, magma supply and melt migration. Furthermore, the abyssal hills pattern of the Southwest Indian Ridge, on each side of the Gallieni fracture zone (52°20'E), where off-axis bathymetric data are available, exhibits different wavelengths suggesting that the length of volcanic and tectonic periods also vary with time.

Kappel ES & Ryan WBF, *J. Geophys. Res.*, **91**, 13925-13940, (1986).

Gente P, *These de doctorat*, (1987).

LS02

Structure, Composition and Accretion of the Oceanic Crust

LS02 : WEpm34 : F2 Unusual Depletion in Moderately Incompatible Elements on the Southwest Indian Ridge between 49° and 69°E

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One of the coldest and slowest part of the mid-ocean ridge system lies on the Southwest Indian Ridge (SWIR) between 49° and 69°E, close to the Rodrigues Triple Junction. Among the unique features of this area east of the Melville Fracture Zone (MFZ, 61°E) are: its propagation northeastward at a rate about 3 times the spreading rate of 11-15 mm.year⁻¹, a deep chaotic ridge topography (4000-5000 m), high upper mantle seismic wave velocities and thin oceanic crust (4-5 km on average). The section west of the MFZ displays normal sea-floor terrain, similar to those from slow spreading ridges.

Analyses of basaltic glasses sampled during the EDUL cruise (R/V Marion Dufresne, summer 1997) reveal the occurrence of two magmatic provinces, separated by the MFZ. When compared to global systematic relationships for ridge axis, samples east of the MFZ form the end-member of the N-MORB array as a function of Na_{8,0} and Fe_{8,0}, as would be expected for low degree partial melts in an unusually cold mantle. Despite their apparently normal coldspot signature they are depleted in Si_{8,0} for a given Fe_{8,0} compared to the global array. Following the order of increasing compatibility, the trace elements (Ce, Eu, Zr, Ti, Yb and Y) are progressively offset toward lower abundance relative to Atlantic and Pacific spreading centers for a given Na_{8,0}. In addition they have higher values of Na_{8,0} and Sr versus (Sm/Yb)₀ compared to the global array. This excess of Sr and Na_{8,0} may best be explained by high pressure fractionation which suppressed the extent of plagioclase crystallisation. The anomalously low abundances of Ti, Y, HREE relative to the global array appear to be coupled to an enriched source composition at the SWIR, while the most incompatible elements do not show such correlations. This implies that petrogenetic processes controlling the partitioning of highly and moderately incompatible elements are distinct and temporally decoupled.

A single process cannot explain the complexities of the data. The melts produced east of the MFZ in the coldest melting environment present the characteristics of high-pressure fractionation (suppression of plagioclase crystallisation). These melts also define the most extreme depletions in moderately incompatible elements and the lowest Nd-isotope ratios. The latter may result from an 'old?' heterogeneity of the Indian Ocean mantle which is preferentially sampled in this low degree partial melting environment. The lack of significant correlation of the most incompatible elements and the isotope compositions may reflect a recent enrichment event that has affected the mantle of the SWIR.

LS02 : WEpm35 : F2 ODP Hole 735B: A Glimpse at Crustal Accretion and Geochemical Fractionation within Oceanic Layer 3

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An almost complete 1500 m thick section of gabbroic layer 3 has been drilled at the slow-spreading SW Indian Ridge during Ocean Drilling Program Legs 118 and 176 (Dick et al., 2000). The core sampled a stack of about five 100-500 m thick units which were most likely emplaced in separate intrusive events. The time sequence of the different events is not known, and contacts between some units are of a tectonic nature. We report on the major and trace element data of about 300 samples representative for the entire section. The different units have distinct geochemical characteristics and variation trends. The trace element abundances (in particular of the rare earth elements, REE) exhibit large first-order variation as a result of changes in modal cumulate mineralogy (ranging from primitive troctolites to highly evolved FeTi-oxide gabbros) and of variations in the amount of trapped intercumulus

liquid. The occurrence of troctolitic gabbros at the base of several units attests to the primitive nature of some intruded liquids. All units show upward differentiation trends which can be reproduced satisfactorily with a fractional crystallisation model, allowing for adcumulus growth and simultaneous compaction and residual melt expulsion. There are very few constraints on the amount of residual liquid that spilled over or was injected into overlying units. A considerable fraction of the residual melt must have been trapped in the plutonic section and gave rise to the formation of highly evolved liquids from which FeTi-oxide gabbros crystallized and of residual plagiogranitic or granitic veins and pods. Many of the those evolved samples are highly enriched in REE and show pronounced negative Eu-anomalies. Moreover, samples from several highly altered veins and veined zones turned out to be very enriched in REE. This is evidence that fluid-rich residual liquids were the main agents of metasomatic alteration in specific sections of the core.

Trace element data are not at variance with a model in which the entire core section of Hole 735B was ultimately derived from the same or very similar parental magma. As a result the H735B data are very informative with respect to the range of rock compositions that can be present in the oceanic plutonic section. The data also put constraints on the trace-element mass balance of the entire oceanic crust.

Dick HJB, Natland JH et al, *EPSL*, 179, 31-51, (2000).

LS02 : WEpm36 : F2 Cryptic Mineral Variations Resulting from Propagating Alteration during Igneous and Metamorphic Vein Formation in Gabbroic Rocks from Hole 735B: Results from ODP Leg 176 (Atlantis II Transform Fault, Southwest Indian Ridge)

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ODP Leg 176 (Oct-Dec, 1997) deepened the hole 735B from 500 m (ODP Leg 118; Oct-Dec, 1987; Robinson, Von Herzen et al., 1989) to 1500 m, with a recovery of about 87% (Dick et al., 2000). The entire section consists of composite gabbros, mainly olivine gabbros associated with numerous ferrogabbroic and minor felsic intrusions (Dick et al., 2000). The alteration occurred in three stages: 1) high-temperature granulite- to amphibolite-facies which is most important and coincides with ductile-brittle deformation beneath the ridge, 2) minor greenschist-facies alteration during lateral uplift at the ridge transform-intersection under static conditions, and 3) late post-uplift low-temperature alteration with formation of abundant smectite veins, often in previously unaltered areas. The present study aims to describe and understand the modes of propagation of the hydrothermal alteration outside the veins invading the gabbroic complex. A preliminary study of large thin sections by microprobe analyses revealed that, from the very low-temperature alteration up to the amphibolite facies, the alteration was not penetrative and limited to the immediate vicinity of the vein walls. However, sections of the cores may be near completely altered when alteration areas coalesce inside vein clusters. According to the primary and secondary mineralogy, congruence is largely respected. The high temperature facies (amphibolite to granulite facies) are related to the gabbros intruded by other oxide riched gabbros and felsic melts. There, the mineral compositional variations appear more complex. As the compositional data were not easily reliable to optical observations, because of different scales of observation between the microscope and the microprobe, microprobe and optical scanning of the thin sections were carried out. Microprobe scanning gave a good image of the chemical elements distribution, but is time consuming and limited to small areas. The optical scanning presents the advantage of better locating the spots of the analyses at the scale of the thin section and gives the best image of the alteration distribution at lower magnification. This method is able to outline some critical optical contrast variations (not artefacts) which are not visible under the microscope, or when directly looking at the thin sections. Furthermore, when playing with the scan parameters, it allows to evidence cryptic variations at the scale of the thin section, particularly in feldspathic phases, and to rely them with composition. This work yields to a different approach of the debated problem on the relationships between igneous, metamorphic and possible transitional processes occurring at the fragile-ductile boundary during migration of the cracking fronts in relation to multiple intrusion processes. In particular, the

igneous or metamorphic origin of the veins containing diopside or diopside+anorthite observed in some particular composite rocks.

Robinson PT, Von Herzen RP et al., *Proc. ODP, Init. Repts., 118: College Station, TX U.S.A. (Ocean Drilling Program)*, (1989).

Dick HJB, Natland JH et al, *Earth Planet. Sci. Lett.*, 179, 31-51, (2000).

LS02 : WEpm37 : F2 Tectonics and Magmatism of the Knipovich Ridge, the Northern Atlantic: Initial Results of the Knipovich-2000 Cruise

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Japanese and Russian cooperation research cruise (the Knipovich-2000 Cruise) was conducted at Knipovich Ridge, an ultraslow (14 mm/y) and oblique spreading system in the Northern Atlantic, by using R/V Logachev in September 2000. The ORE sidescan sonar (30 kHz, 2.4 km swath) was towed along the axis of the Knipovich Ridge with the along axis coverage of 60%. The ORE deep-tow sonar images confirmed intensive volcanic activity at most of the topographic highs in the center of the rift. Specifically four large seamounts in the rift valley of the Knipovich Ridge all appeared as active volcanoes with abundant fresh lava flows and pillow mounds. They are identified as the centers of four fundamental segments of the Knipovich Ridge. The scale of each segment is about 100 km. We further identified smaller-order segmentation with a length of about 20 km. The fault pattern is clearly imaged throughout the swaths of the ORE sonar. Most of the faults are apparently orthogonal to plate motion between the Eurasian and the North American plates, but does not fit completely with the NUVEL-1 plate motion model. The combination of ORE sonar images and TV grab operations turned out to be a strong tool for understanding the geology in the rift. TV grab operations provided bottom video images at the same time as it returned invaluable rock samples. The resultant data set provide useful ground truth that will aid in sonar image interpretation. The sonar images of the axial volcanoes made it possible to recover fresh basalt samples from the bottom. At four sites at the axial volcanoes fresh basaltic samples were obtained with abundant glass. The northernmost dredge results from the rift wall came out with unexpected hard sedimentary rocks. Although the reason for these outcrops of hard (= old?) sedimentary rocks in the rift wall is puzzling, the dredge results will constrain a unique tectonic history at the very northern end of the Knipovich Ridge. A focused survey was conducted at the Logachev rift mountain at 76° 40' N with additional mapping by ORE deep-tow, a transect of heatflow measurements, deployment of OBS seismic network, TV grab observation with fresh basalt samples. As the Logachev rift mountain is the largest volcanoes in the Knipovich Ridge, further composite analyses of all of the obtained data are expected to provide a fundamental contribution to the understanding of tectonics and magmatism of the Knipovich Ridge.

LS02 : WEpm38 : F2

New Evidences of Hydrothermal Activity on the Knipovich Ridge, Norwegian-Greenland Basin

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The Knipovich Ridge is a northern continuation of the Mid-Atlantic Ridge (MAR) located between the Greenland and Spitsbergen. The Knipovich Ridge orthogonally joins the Mohs Ridge on the south and is limited by the Molloy fracture zone on the north. The Knipovich Ridge features ultra-slow spreading rates (0.7 cm/year; DeMets et al., 1990) and has an oblique orientation of the rift valley relative to the spreading direction (Crane, 1991). Some of hydrothermal indications in the central part of the Knipovich Ridge were detected in the course of cruises onboard RV 'Professor Logachev' (1996) and RV 'Akademik Mstislav Keldysh' (1998) (Cherkashev et al., 1997; 1998).

New data on tectonics, magmatism, and hydrothermal processes in the rift valley of the Knipovich Ridge have been obtained during an international cruise "Knipovich-2000" onboard RV 'Professor Logachev' (September 2000). The axial zone of the rift valley was mapped by a side-scan sonar towed at a speed of 2 knots at 150 m above sea-floor. Side-scan sonar was fitted with a CTD system (SBE 19), light back-scattering (Sea Tech LSS 6000), and pH sensors. Investigations also included sediment coring and hydrocast studies using Seabird 911 plus CTD-rossette with twelve 5 L Niskin bottles and pH sensor. Water samples were analyzed aboard to determine methane content, microbial (ATP) abundance, and other hydrochemical parameters.

Metal-enriched sediment layer with the outstanding hydrothermal input was detected in the core from the central part of the ridge. The age of this layer was estimated as 13 000 b.p. based on planktonic foraminiferal composition.

Water-column studies showed several hydrothermal indications: 1. At least five temperature anomalies at the near-bottom profile along the ridge axis. 2. The anomalous particle concentration in near-bottom water at the southern part of the ridge, which is also characterized by anomalous methane content, pH and bacterial abundance (ATP). The order of the particle-concentration anomaly (10 mV) is comparable to those above the known hydrothermal fields in the Atlantic. 3. A noticeable methane anomaly in near-bottom water at the northern part of the ridge.

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Wednesday PO Session

LS02 : WEpo01 : PO

On Magmatic Processes at Fast-Spreading Ridges as Revealed in a Xenolith from the Mush Zone beneath the East Pacific Rise at 9° 50'N

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In this study we examined a gabbro xenolith within a sheet flow, that may have erupted in 1991 or 1992, collected by the submersible Alvin during dive 2737 in the axial summit caldera of the East Pacific Rise at approximately 9° 50' N. The xenolith is composed of plagioclase, olivine, augite, spinel, sulfide, and glass; the latter produced from rapid ascent and chilling of the interstitial melt. The overall texture, crystal abundances, the presence of interstitial quenched melt, and the fact that the xenolith remained intact, indicate that the xenolith was part of the rigid crust zone, which still maintained significant intergranular porosity. The xenolith has an equigranular texture, average grain size is 3 mm, excepting several larger blebs of sulfide. Plagioclase is the dominant crystalline phase intergrown with lesser olivine and spinel and 10-15% glass. The large sulfide blebs are enriched by 2-3 orders of magnitude for some elements) in Cu, Co, Ni, Zn, Se, and Pb compared to small sulfide blebs within the interstitial glass. Olivine (Fo86-84, Cr = 260-236 ppm, Ni = 760-680 ppm, Co = 135-130 ppm) and Mg-Al chromite (mg* = 0.52, Cr* = 0.73, Ti* = 0.10) crystallized from a melt with mg* = 60, slightly more evolved than the host melt (mg* = 63). Glass inclusions in olivine have variable molar Ca/Al from 1.42 to 1.58 (host Ca/Al = 1.42), molar K/Ti identical to the host (0.11), Zr/Nb = 44-49 (host = 38), Hf/Ta = 20-28 (host = 12). Plagioclase anhedral and subhedral have thick fritted rims; the texture is due to an abundance of glass inclusions. The plagioclase cores are either regularly zoned outward from An 84 to An80 with oscillatory zoned fritted rims (An86-78) or oscillatory zoned (an83-76) with regularly zoned fritted rims (An81-79 with a narrow outer rim of An88). Glass inclusions in fritted rims have mg* values from 0.66 to 0.5, Zr/Nb = 40-48, Hf/Ta = 19-28. The interstitial glass is more evolved (mg* = 0.59) than the host basalt, with higher Ti, Fe, Na, K, P, Rb, Sr, Zr, Nb, Ba, Hf, Ta concentrations, and lower Mg, Ni, Co, Cr. The Zr/Nb and Hf/Ta ratios (64 and 28) are also distinct from the host basalt. The detailed major and trace element geochemistry of the xenolith phases indicate that at least three melts of different compositions were present in the subsurface magma reservoir. These are represented by the host basalt, the interstitial glass and the glass inclusions in olivine and plagioclase. The consistency in the range of Zr/Nb and Hf/Ta ratios in glass inclusions from both olivine and plagioclase also indicates that the glasses are samples of a range of melts distinct from both the host and interstitial melts, suggesting open system behavior within the subsurface magma reservoir.

LS02 : WEpo02 : PO

Insights into Ridge-Hotspot Interaction on the Juan de Fuca Ridge: Geochemical Investigations of Axial Seamount and Adjacent Rift Zones

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The location, structure and anomalous size of Axial Seamount are a consequence of excess volcanism related to the interaction between the Cobb Hotspot and the Juan de Fuca Ridge. Voluminous fresh lavas, active hydrothermal

venting and recently documented seismic/volcanic events in the summit caldera and along the north and south rift zones attest to a sustained magmatic event over at least the past decade. Detailed geologic mapping and sampling have identified and recovered young-looking pillows along the North Rift Zone and sheet and lobate flows believed to have erupted during the 1998 T-phase swarm along the South Rift Zone. Basalts from Axial's summit have relatively homogeneous compositions and do not show a clear geochemical signature associated with an enriched mantle sources or plume. Axial lavas include typical N-MORB and transitional varieties but not enriched types (E-MORB) like those recovered from the Cobb-Eickelberg seamount chain to the northwest or other major oceanic seamounts. Compared to lavas from the axis of the Cleft Segment, Axial lavas are slightly enriched in incompatible elements but have overlapping Sr and Nd isotopic compositional ranges, although the range for Axial Seamount lavas is offset to less radiogenic values (Cleft Segment ⁸⁷Sr/⁸⁶Sr = 0.70246-0.70267; Axial Seamount = 0.70237-0.70253). However, MORB erupted along the CoAxial segment just to the north, are significantly more incompatible element depleted and less radiogenic than Axial lavas and must be derived from a mantle source quite distinct from that which feeds the seamount and adjacent north rift zone. The homogeneous nature of Axial caldera lavas, their rather evolved compositions (average MgO = 7.45 ± 0.2) and the plagioclase-rich nature of many of the samples suggest the presence of a long-lived, well-mixed magma chamber or lens beneath the summit. Conversely, lavas sampled from small on- and near-axis seamounts that surround Axial Volcano or punctuate its north and south rift zones are commonly more primitive and incompatible element depleted than lavas from Axial proper. This suggests that very depleted sources exist proximal to Axial Volcano, and that melts derived from these sources and erupted on nearby volcanic constructs do not experience significant fractionation and therefore likely bypass extended residence in crustal magma chambers. Axial Seamount appears, to be mainly a consequence of a thermal anomaly in the mantle rather than one associated with a typical "enriched" mantle plume. However, if the excess magmatism is related to more extensive source melting and the regional mantle is anomalously depleted, then MORB erupted at Axial Seamount could reflect the addition of some enriched material, along with additional heat, to mantle beneath this portion of the Juan de Fuca Ridge.

LS02 : WEpo03 : PO

Volcanic Cyclicality and Crustal Accretion at the Cleft Ridge Segment, Juan de Fuca Ridge

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The intermediate-rate Cleft ridge segment is the most volcanically active segment of the JdFR system but it shows a morphology more comparable to faster rate spreading centers. A common theme found in models of crustal accretion at the JdFR is the hypothesis of cyclicality in the accretion process. This prevailing hypothesis for the formation of the ridge and valley terrain suggests that during magmatic periods an axial volcanic ridge forms at the axis of spreading; then during the following amagmatic period this ridge splits in half and rafts away to each side of the axis. In 1998, Cleft Segment, was mapped by the high resolution Simrad EM300 multibeam system which has a 30 m pixel size relative to 120 m of typical swath bathymetry. This resolution is fine enough to trace the magmatic, tectonic, and hydrothermal evolution over geologically short time scales (100-100,000 years). A series of 9 dives during a July 2000 cruise using the MBARI ROV Tiburon collected basalt samples and magnetic field data across the ridge axis and up to 5 km off-axis. Two dives surveyed the walls of the adjacent Blanco Fracture Zone where it is draped by extensive lava tubes and pillows of basaltic andesite. The spatial and temporal variability/evolution of magmatism on the southern Cleft segment has apparently changed from being inflated and magmatically robust (EPR-like) to rifted and more tectonically dominated (MAR-like). Results from the EM300 data suggest that ridge-parallel faults and fissures, including the 'cleft', are oriented at 025. Ridge-parallel faults occur on both sides of the axial valley, although discontinuous segments step over in an echelon fashion on the west side. Long ridge-parallel structures are offset by shorter segments that are conspic-

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ously oblique to the fractures connecting en echelon steps (049) appear to be controlled by the direction of absolute plate motion (313). This change in orientation may reflect the transition from a robust volcanic system with ridge parallel eruptions and extensional faults to a magma-starved system where plate-parallel extension dismembers the upper crust and controls the distribution of dike intrusions and eruptions. Small volumes of off-axis volcanism occur along fissures and from point-sources; in some cases these seem related to the formation of abyssal hills and rift-bounding faults. The intersection between the southern Cleft Segment and the Blanco Fracture Zone marks a zone of extensive magmatic fractionation. Thus the Cleft Segment/Blanco Fracture Zone offer a unique opportunity to assess models of volcanic cyclicity in crustal accretion processes.

LS02 : WEpo04 : PO Recharge, Discharge and Routes of Fluid Flow within a Young Oceanic Crust (Eastern Flank of the Juan de Fuca Ridge, NE Pacific)

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Following numerous cruises that explored the features of fluid circulation in the Eastern flank of the Juan de Fuca ridge, the Retroflux 2000 expedition took place in September 2000 to map zones of discharge of basement fluids to the deep ocean and areas where seawater eventually penetrating basement could recharge the ridge flank low temperature hydrothermal system. The primary targets for heat flow measurements and coring were basaltic outcrops, seamounts and subcrops already identified during previous cruises as preferred locations for fluid discharge/recharge. Coring was planned in zones of heat flow anomalies. Ninety three cores (up to 7 meters in length) were collected during this expedition. Porewaters were extracted at sea by centrifugation and analyzed on board for chlorinity, Ca, Mg, pH, alkalinity, and nutrients. In upwelling areas where heat fluxes are high, sediment porewaters display a rapid Mg depletion and Ca enrichment with depth consistent with a fluid in basement that has reacted with basalt at temperatures of about 60°C. In contrast, porewaters from cores with no flow display seawater composition altered by diagenetic reactions (constant Mg and Ca contents, alkalinity increasing with depth due to organic matter oxydation and sulfate reduction). Data collected during Retroflux revealed that several outcrops (called Grinnin' Bare, Wuzza Bare and Zona Bare) are locations of focused hydrothermal discharge, associated with heat flow that can locally be as high as 2 W/m². At Grinnin' Bare, the upward flow through the sediment is found in cores located along the eastern side of the outcrop which seems to be bounded by a fault. Altered sediments containing Mn-oxides were recovered on this fault area. At Zona Bare, porewater Mg profiles indicate a rapid fluid upwelling through the sediment at rates up to 20 cm/year, which may indicate the presence of a spring, like those previously found at Baby Bare. Sediments recovered at Zona Bare contained clams and Mn oxides. On the contrary, the large Grizzly Bare outcrop seems to be a recharge area as indicated heat flow and pore-water data. These data will be used to further constrain the pattern of fluid circulation on the Eastern flank of the Juan de Fuca ridge.

LS02 : WEpo05 : PO Deep-Sea Exploration and Sea-Surface Magnetism on the Central Indian Ridge at 19°S: Initial Results of Cruise Gimmnaut

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In May-June 2000, the first dives of deep sea submersible Nautile in the Indian Ocean have been carried out during cruise GIMNAUT of R/V L'Atalante on the Central Indian Ridge (CIR) at 19°S. Cruise GIMNAUT was mainly devoted to the problem of accurate dating methods for recent processes at mid-ocean ridges, with a particular attention to the combined use of existing geochemical absolute dating methods for recent Mid-Ocean Ridge Basalt on one hand, the observation of a dated and continuous sequence of the recent geomagnetic intensity variations on the other hand. The CIR at 19°S, the latitude of the Rodrigues Ridge, is a good target area to address this topic because rock samples are enriched in trace elements required for an optimal quality of the ages. We have realized two transects of the CIR from the axis to the Brunhes-Matuyama magnetic polarity boundaries (~800 ka) on both the African and Indian flanks. These transects intersect the CIR axis at 19°11'S and 19°29'S (9 and 8 dives). Direct visual geological observation and continuous vector magnetic field acquisition has been carried out along each dive. Rock samples have been collected at about 150 sites. Complementary surface geophysical data have been acquired during the nights. Some preliminary conclusions can be derived from the direct observation as follows: a) all observed and sampled rocks are basalts, with a majority of pillow lava and a large number of dykes, in agreement with the presumed hot / magmatic character of the CIR at 19°S; b) the rapid deposition of pelagic sediment shows that active tectonics is focused in the inner valley floor and on the inner walls; similarly, active volcanism mostly occurs inside the inner valley floor; c) despite reported signs of possible hydrothermal plumes in the water column, no active hydrothermal vent has been observed, although evidence of pervasive hydrothermal circulation is widespread.

The dense coverage of sea-surface magnetic anomaly data allows the computation of equivalent magnetization on a 1 km-interval grid assuming a 500 m-thick magnetic layer. In addition to anomalies 1, J, 2 and 2A, secondary linear features agree well with previously recognized tiny wiggles of geomagnetic origin (Pouliquen et al., J. Geophys. Res., in press). Within the axial anomaly, at least four of such features flank the Central Anomaly Magnetic High (CAMH) on both sides. Along-axis variations of the equivalent magnetization are associated with the faint, second-order, segmentation depicted by the bathymetry, with higher equivalent magnetization values at segment ends and lower values at segment centers, as observed on other spreading centers.

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LS02 : WEpo06 : PO 3D Inversion of Magnetic Data Collected in Five Areas of the Mid-Atlantic Ridge Axis between Azores and Equator

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We investigate the distribution of seafloor magnetization by 3D inversion using the generalized inverse method [Menke, 1984; Tarantola, 1987]. In order to specify the mode and rate of accretion at slow spreading centers, five areas on the MAR were surveyed during three cruises (GEOFAR, 1993; OCEANAUT, 1995; and St-PAUL, 1998) sponsored by IFREMER. Close spaced magnetic profiles were carried out, which results are displayed here, as magnetization distributions, that enable determination of opening rates during the time intervals [0-780] and [0-1700] Ka; respectively B/M limit, and Olduwai event (Candee and Kent, 1995). a) Menez-Gwen is a volcano located on the MAR at 37°50'N. In this area the rate of spreading is

28.8 mm/y for the Brunhes period and 29.4 mm/y since the Olduwai event. The kinematic model NUVEL-1 (DeMets et al. 1990) at this place gives an opening rate of 26.2 mm/y during the last 1.7 Ma. b) Lucky-Strike is an axial volcano located at 37°20'N. The inversion of the magnetic data leads us to determine a spreading rate at 23 mm/y and 24.7 mm/y respectively, for the two time intervals. Computed with the Nuvel-1 model, the rate is 26 mm/y. A ridge jump may be suspected during Brunhes. c) OH1 is the first accretion segment located just South of the Oceanographer transform near 34° 50'N. The opening rates are 21.8 mm/y and 22.9 mm/y during the last 780 ka and 1.7 Ma. Nuvel-1 gives 26.6 m/y since Olduwai. d) OH3 is the third segment south of Oceanographer near 33° 50'N. The estimated spreading rate is 20.8 mm/y and 24.8 mm/y, respectively for the two intervals. Nuvel-1 model indicates 26.9 mm/y. d) St-Paul is a short axial segment located close to the Equator at 0°40'N, and "jammed" between two transforms of the St-Paul system. As magnetic surveys near the equator have to be carried out carefully, a magnetic station reference was used for diurnal variation corrections. The opening rate obtained is abnormally high for the Brunhes period (43.6 mm/y), but is only 33 mm/y for the last 1.7 Ma; The Nuvel-1 model gives an opening rate of 31.4 mm/y since anomaly 2. For the four first regions there is good agreement with Nuvel-1 model, but a discrepancy of 40% is observed for the St-Paul area. We think that such a difference does not result from errors. Previous works on the equatorial MAR axis suggested a magmatic starved area. The Nautile dives, during the St-Paul cruise (1998), confirmed the scarcity of the extrusives and the abundance of outcrops of deep-seated rocks (ultramafics, gabbros). Taking these observations together, we interpret the abnormal extension of the Brunhes anomaly as an effect of delayed magnetizations during progressive serpentinization favored by off-axis deepening of faulting and hydration.

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LS02 : WEpo07 : PO A Thermo-Mechanical Model of Accretion of the Oceanic Crust at Fast-Spreading Mid-Ocean Ridges Considering the Effect of Deep Off-Axis Hydrothermal Circulation and Distributed Melt Injection

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Recent thermal models obtained from seismic observations at the East Pacific Rise (EPR) has shown that the off-axis thermal structure of the axial magma chamber is incompatible with purely conductive cooling, suggesting that heat removal by hydrothermal circulation can be effective up to depth of 5-6 km. This interpretation is in good agreement with the bimodal distribution of the nucleation rate inferred from the quantitative textural study of gabbros from the Oman ophiolite and interpreted as the result of enhanced igneous cooling of gabbros > 2 km above the Moho Transition Zone (MTZ).

To investigate the effect of deep off-axis hydrothermal convection on the thermal structure and accretion of the oceanic crust, we have constructed a new thermo-mechanical model of crustal flow beneath fast spreading ridges. Previous numerical models imposed injection of melt at the MTZ and/or an upper melt lens below the sheeted dyke complex by jumps in the external boundary conditions of the model. They also imposed the shape of the temperature field by setting arbitrary conditions at the top of axial magma chamber. To simulate a more realistic scenario, our numerical model takes into account boundary conditions in the center of the modeling box. Also, the temperature boundary condition at the top of the model is the sea bottom temperature and no assumptions are made on the initial temperature structure. In the center of the axial magma chamber the melt is injected with a "needle" with adjustable porosity allowing the simulation of different configurations of melt injection (i.e. distributed or not throughout the

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magma chamber). The shape of the magma chamber is not longer imposed in our model, but computed from the steady state reached by the thermal field considering the heat diffusion and advection and the latent heat of crystallization. The motion equation is solved for a temperature and phase dependent viscosity. The thermal diffusivity is also dependent on temperature and depth, with a higher diffusivity in the upper plutonic crust to account for more efficient hydrothermal cooling at these crustal levels.

Our preliminary results indicate that deep off-axis hydrothermal circulation highly influences the shape of the axial magma as well as the flow lines and the cooling rate of gabbros at different crustal levels. It is expected that only limited combinations of enhanced off-axis heat removal and melt injection modes in the axial magma chamber can reproduce satisfactorily the cooling rate and foliation pattern observed in gabbros from the Oman ophiolite, as well as the thermal and melt distribution deduced from seismic studies at EPR.

LS02 : WEpo08 : PO

Can we Distinguish between Serpentinised Peridotites and Gabbros from their Physical Properties? Insights from the GEOMAN Experiment

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A classical problem in marine geophysics is to assign a lithological significance to the seismic Mohorovicic discontinuity: is it the mantle crust boundary or is it a serpentinization front in the mantle? This still unresolved question arises from the similar seismic velocities of gabbros and serpentinised peridotites. In February 1998, we conducted a series of small-scale seismic, electrical and electromagnetic experiments in the Oman ophiolite. We also studied the microstructures and the physical properties (P-wave velocity, electrical conductivity, porosity, ...) of serpentinised harzburgites, serpentinised wehrlites and gabbro samples from the field stations. The field, lab, and model data, all show a seismic anisotropy consistently stronger in peridotites than in gabbros. The compared laboratory data on electrical and seismic properties also show systematic differences between gabbros and peridotites, the latter being generally more conductive, with a higher contribution of surface electrical conductivity (related to higher alteration). The comparison of our field and laboratory measurements allows us to discuss the property changes due to changing scale from a few cm (sample) to several hundred m (field). If the results at the sample scale can be extended to a larger scale, they suggest that i) the anisotropy of seismic velocities, and ii) the compared electrical and seismic properties may help to discriminate between gabbros and serpentinised mantle in the oceanic lithosphere.

LS02 : WEpo09 : PO

Silicic Rocks in Iceland: Composition and Distribution during the Brunhes Epoch

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Silicic rocks are relatively rare within oceanic crust. There are exceptions though, Iceland being one of them, where significant amounts of silicic material has been formed. The silicic rocks in Iceland are mainly found within central volcanoes both within rift zones and within flank zones. Most of the central volcanoes have only produced minor amounts of silicic rocks in few eruptions. The larger volumes of silicic rocks occur in those central volcanoes where there has been a considerable topographic buildup, or in areas where the rift zone changes direction or is laterally shifted.

In this study 90 samples were chosen for a detailed geochemical study. They include samples from all central volcanoes that have erupted silicic rocks during the Brunhes magnetic epoch (<0,8 Ma). The silicic rocks in Iceland classify as rhyolites, dacites and trachytes. Rhyolite is by far the most common, dacites and trachytes are relatively rare. The rhyolites can be tentatively separated into two groups: low-alkali rhyolites and alkalic rhyolites. The alkalic rhyolites, some of which are peralkaline, have only been found in the flank zones, while low-alkali rhyolites are mostly confined to the rift zones. The silicic rocks in Iceland are relatively Fe-rich and Ca-poor compared to silicic rocks in general. This has been interpreted as indicating low pressures of formation and specifically a relatively low water-pressure in the source, both of which increase the stability of plagioclase relative to pyroxene. A striking feature of REE-patterns of silicic rocks from Iceland is the similarity in the shape of the patterns. This may indicate a similar process of formation for all of them. There are slight differences though in the slopes and absolute concentrations in rocks from different volcanoes. This can be seen for example in the ratios of La to Sm and Ce to Yb. This may to some degree reflect different compositions in the source materials.

It has been shown with some certainty that silicic rocks in Iceland have not formed by near-liquidus processes (evolution from basaltic melt by separation of crystals at temperatures close to the liquidus temperatures of the melts), but rather by near-solidus processes (as near-minimum melts in basaltic rocks). Because of the high viscosity of these relatively dry, relatively metaluminous melts it may be difficult to segregate the near-minimum melts from the source rocks. It is hypothesized here that this happens by deformation-induced melt-segregation. Relatively rapid tectonic movements may result in squeezing the silicic melt out of the source rock and into veins and dykes. These rapid tectonic movements could be rapid inflation or deflation within central volcanoes or rapid movement in shear zones which are formed where the rift zones change direction or are shifted laterally.

LS02 : WEpo10 : PO

Basalts from DSDP Leg 28, Sites 265, 266, 267 and 274: Similarities and Differences between Indian and Pacific Mantle Domains

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New major and trace elements, and Sr-, Nd-, and Pb-isotope data have been acquired on 15 basalt samples drilled during DSDP Leg 28 from Sites 265, 266, 267 and 274. These samples have been provided by Ocean Drilling Program East Coast Repository. Sites 265, 266 and 267 are located at about 110° E longitude. South of the Southeast Indian Ridge (SEIR), just West of the Australian-Antarctic Discordance (AAD), whereas Site 274 is located at 173° E longitude, South of Emerald Basin and East of Antarctica, and thus it should be within Pacific lithosphere. Samples are tholeiitic basalts with fresh to slightly altered olivine, clinopyroxene, and plagioclase micro-phenocrysts. Secondary smectites and carbonates are sometimes present. Many trace element ratios distinctive of Indian- and Pacific-type mantle signatures, such as Zr/Ba, Rb/Ba and Ba/La, in all analyzed basalts are in the ranges for Indian mantle signatures, confirming previous results on other DSDP samples from the same sites. However, some specific trace element ratios, for instance Y/Nb, Zr/Nb, La/Ta, Ta/Zr indicate significant differences between samples from Sites 265, 266 and 267 on one hand, and those from Site 274 on the other hand. Differences in isotopic characteristics have been found among basalts from the four sites. Basalts from Site 265 show the most radiogenic ⁸⁷Sr/⁸⁶Sr, in the range 0.70341-0.70350, and the least radiogenic ¹⁴³Nd/¹⁴⁴Nd, in the range 0.5129-0.5130; basalts from Sites 266 and 267 have similar Sr- and Nd-isotope ratios, with radiogenic ⁸⁷Sr/⁸⁶Sr in the range 0.7030-0.7032, and ¹⁴³Nd/¹⁴⁴Nd in the range 0.5130-0.5131; basalts from Site 274 show the least radiogenic ⁸⁷Sr/⁸⁶Sr, in the range 0.7027-0.7028, and the most radiogenic ¹⁴³Nd/¹⁴⁴Nd, up to 0.5131. Differences among samples from each site have been found also in Pb-isotope ratios, the least radiogenic basalt being that from Site 267 (²⁰⁸Pb/²⁰⁴Pb = 18.00, ²⁰⁷Pb/²⁰⁴Pb = 15.46, ²⁰⁸Pb/²⁰⁴Pb = 37.73), the most radiogenic one that from Site 274 (²⁰⁸Pb/²⁰⁴Pb = 19.02, ²⁰⁷Pb/²⁰⁴Pb = 15.51, ²⁰⁸Pb/²⁰⁴Pb = 38.51). In summary,

basalts from Sites 265, 266, and 267 have geochemical and isotopic features typical of Indian-type MORB, in accordance with their location close to the AAD. Basalts from Site 274 show some trace element ratios, and radiogenic ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd features still in the ranges of Indian-type MORB, notwithstanding location well within Pacific domain, far East of the AAD. On the contrary, some trace element ratios, and Pb-isotope ratios are well in the range of Pacific-type MORB, suggesting that Indian- and Pacific-mantle domains have been separated in that area.

LS02 : WEpo11 : PO

Magmatic History of Plagioclase Phyric Basalt from the Mohns Ridge, Norwegian Greenland Sea

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Neovolcanic, en echelon ridges and marginal highs of the ultraslow and oblique spreading Mohns ridge were sampled during the SUBMAR-2000 cruise. Both aphyric and plagioclase phyric basalts were sampled from the central rift and from the flanks. Many of the samples that were recovered are highly plagioclase phyric with up to 30% plagioclase phenocrysts that may reach 3 cm in diameter. The megacrysts show pronounced zoning, evidence for resorption and renewed growth, and melt inclusion are present in multiple distinct zones in many of the crystals. The anorthite content range from An₈₉ to An₉₂, and both normal, reverse and more complex zoning patterns are observed. Melt inclusion analyses as well as isotopic analyses of samples taken with micro-drill from profiles across individual crystals are presently carried out. These results will be discussed in terms of magma chamber dynamics at ultraslow spreading ridges.

LS02 : WEpo12 : PO

REE and Trace Elements in Mineral Phases: Igneous Partitioning and Seafloor Alteration in Gabbroic Rocks from 23°N (Mid-Atlantic Ridge)

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Clinopyroxenes, plagioclases and amphiboles of 6 gabbro sampled in ODP Leg 153 (MARK area) were analyzed by SIMS technique to investigate RE, trace and volatile element distribution from igneous to low temperature hydrothermal conditions.

The parent rocks were high to low Mg# troctolites, olivine-gabbros, gabbros, and Fe-Ti oxide-gabbros, preserving magmatic and metamorphic textures. The rocks underwent granulite to actinolite - oligoclase facies and subsequent metamorphic processes at decreasing temperatures. The steps are:

- 1) Ductile deformation and re-equilibration under anhydrous to hydrous conditions at 750°<T<1000°C and P = 0.3 GPa.
- 2) Ductile to brittle deformation and phase reactions controlled by fluid diffusion for 600°<T<700°C and P = 0.2 GPa.
- 3) Brittle deformation with mineral re-equilibration and growth, under conditions such as 350°<T<600°C and P < 0.2 GPa.

Igneous clinopyroxenes show CI-chondrite normalized patterns depleted in LREE, and nearly flat for HREE. The fractionation of REE patterns in metamorphic clinopyroxenes mimic that of primary ones. In granulite clinopyroxenes from anhydrous assemblages $SREE_{\text{igneous}} = 16.66-18.22$ ppm and $SREE_{\text{metamorphic}} = 15.82$ ppm. REE CI-normalized patterns for igneous plagioclase are strongly fractionated. REE and trace are scarcely mobilized in granulite facies.

Titanian hornblende show LREE-depleted patterns, $La_N/Sm_N = 0.10-0.33$, $La_N/Yb_N = 0.10-0.30$. In transitional regime Mg-hornblende to actinolitic hornblendes develop in gabbros and tschermakitic hornblendes in the oxide-gabbros, (Ti in the range 8645 - 16795 ppm). Analysed amphiboles are a) pseudomorphous on igneous clinopyroxene, b) epitaxial overgrowth on clinopyroxene, c) filling-vein with plagioclase. a) and b) show similar patterns for RE and trace elements, as in titanian amphi-

LS02

Structure, Composition and Accretion of the Oceanic Crust

bole. Hornblende c) has higher REE; Ba and Sc are constant whereas Sr, Zr, Ti, Cr decrease. In brittle regime, two textures are significant: a) pseudomorphic on pristine phases b) in vein. The normalized RE and trace elements in the pseudomorphic amphibole a) are similar, or in part increased, to values in the igneous clinopyroxene and largely overlap the pattern of higher T amphiboles. The patterns of filling-vein amphiboles evidence increased element abundances likely for exotic supply with fluids.

The RE and trace element distribution in igneous phases indicates that they act as reservoirs, contributing to the overall rock content, their abundances reflecting the degree of fractionation of the liquids. RE and trace element contents in high grade metamorphic phases express a marked heritage from igneous ones. The content of RE and trace elements in hornblendes mirrors that of igneous or secondary clinopyroxene. Also the textural control is significant to the RE and trace elements partitioning. Fluids possibly exsolve from evolved melts, with a large contribution from modified seawater. At lower T the partitioning is controlled by rock- or water-dominated conditions. Volatiles record progressive dilution of the magmatic elements, whereas the amphiboles become more enriched in the oxy-component.

LS02 : WEpo13 : PO

Comparative Laser Ablation ICP-MS Analyses on Amphiboles from two Gabbros from Vema Fracture Zone and Montgenèvre Ophiolite Complex: Some Petrologic Implications

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The Laser-Ablation ICP-MS method appears as very convenient to get in situ quantitative major and, particularly, trace elements data on very small volumes. The aim of this presentation is to discuss about the REE results and subsequent implications of a first series of 70 selected measurements performed on the amphiboles associated with two high-level type gabbros.

The Vema Fracture Zone (Equatorial Atlantic) and the Montgenèvre Ophiolite Complex (Western Alps), interpreted as expressions of slow spreading systems, present comparable lithologies. Beside peridotitic tectonites, members of a strongly differentiated cumulate gabbro sequence, are common. The oceanic gabbro was sampled during the Equatorial Atlantic-Vema campaign (IFREMER, 1988).

These gabbros are characterized by the presence of fine-grained intergrowths of complexly zoned amphiboles. This reflects a range of conditions from primary crystallization to late-magmatic, and post-magmatic alterations. The latter developed during oceanic metamorphism, and for the Montgenèvre specimen, also possibly during the Alpine metamorphism.

Coupled with microtextural parameters and microprobe analyses, these quantitative data allow to better constrain the chemistry of the concerned amphiboles according to their period and conditions of crystallization.

The Montgenèvre ophiolite is well known for its large preservation from Alpine metamorphism. The recognition of such an imprint superimposed on the oceanic one would supply significant informations about the last episodes of the oceanic crust's life down to the ophiolite story.

The reduction of these REE data and their interpretation according to different patterns of distribution leads to the distinction, either for Vema or Montgenèvre amphiboles, of 3 groups based on the type of amphiboles: -primary, -intermediate, and -secondary types. The "primary type" gathers together light brown to brown amphiboles of edenitic composition interpreted as primary to late-magmatic. The "intermediate type" assembles light brown to dark green sometimes bluish amphiboles. These varieties could have crystallized concomitantly with the primary one but under possible interactions with seawater. They plot along the trend between tremolite and pargasite (Leake et al., 1997). The "secondary type" gathers together secondary light green to colorless amphiboles of ferro-actinolitic to tremolitic compositions resulting from post magmatic hydrothermal alteration or later metamorphism.

Some evidences result from the distinction of these groups: -the negative Eu anomaly of primary amphiboles. -the distinct positive Eu anomaly of the Vema and Montgenèvre secondary amphiboles. However this distinction is not without raising some questions, among which how to explain: -the positive Eu anomaly of some primary, edenitic amphiboles; -the lower abundances of REE within all the Montgenèvre amphiboles; -why the intermediate groups show contrasting Eu anomalies; -why in Montgenèvre amphiboles, the intermediate group has higher abundances than primary amphiboles.

The final interpretation involving complementary measurements should give better evidences on the metamorphic processes undergone by the Montgenèvre ophiolite complex during Alpine orogeny.

LS02 : WEpo14 : PO

The Oceanic Lithosphere of the Jurassic Ligurian Tethys: Inference from Petrology and Geochemistry of the Ligurian Ophiolites

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Ophiolites exposed along the Western Alpine - Northern Apennine chain represent the oceanic lithosphere of the Ligurian Tethys which separated, during Late Jurassic - Cretaceous times, the Europe and Adria plates. Representative sampling of the oceanic lithosphere which floored the Jurassic Ligurian Tethys are the Ligurian (Voltri Massif and Northern Apennine) ophiolites. They show peculiar stratigraphic and structural relationships: they consist of a peridotite basement, intruded by gabbroic bodies, stratigraphically covered by pillowed basaltic flows and Late Jurassic oceanic sediments. Ligurian ophiolitic gabbros derive from MORB-type basaltic magmas and have intrusion ages in the range 185-160 Ma: Triassic ages are documented for the ophiolitic gabbros of Montgenèvre (Western Alps). Basaltic volcanites show tholeiitic composition and MORB affinity: U/Pb dating yield 160-150 Ma for the oceanic volcanism of the whole Ligurian Tethys. Mantle peridotites from the External Liguride Units (Northern Apennine) have fertile composition and display a complete equilibrium recrystallization under spinel-facies conditions at 1000-1100°C. Nd model ages indicate Proterozoic times for isolation from the convective asthenospheric mantle and accretion to the subcontinental lithosphere. Mantle ultramafics from the Internal Liguride Units (Northern Apennine) are depleted peridotites produced as refractory residua after fractional melting on a MORB-type asthenospheric mantle source: Nd model ages yield a Permian age (275 Ma) for the depletion event. Proterozoic and Permian model ages are widespread in the orogenic peridotites of the Western Mediterranean area and the Alpine system. Ligurian peridotites record a composite subsolidus tectonic-metamorphic evolution from subcontinental lithospheric depths to the ocean floor, i.e. km-scale tectonite-mylonite shear zones and subsolidus transition to plagioclase- and to amphibole-bearing assemblages. Plagioclase-facies reequilibration has been dated by Sr-Nd systematics on plagioclase-clinopyroxene pairs: they give 273-313 Ma for the Erro-Tobbio (Voltri Massif) peridotites and 165 Ma for the External Liguride peridotites. The Ligurian ophiolites represent the spatial association of: (1) Proterozoic and Permian subcontinental lithospheric mantle peridotites, (2) Triassic to Jurassic MORB-type gabbroic rocks, intruded in the peridotites, (3) Late Jurassic MORB-type basaltic volcanites. This peculiar association cannot be reconciled with present-day mature oceanic lithosphere, where the mantle peridotites and the associated gabbroic-basaltic crust are linked by a direct co-genetic relationship. The large exposure of mantle peridotites at the sea-floor, and the long story of subsolidus decompressional upwelling recorded by the peridotites, are in favour of a geodynamic evolution driven by the passive extension of the Europe-Adria continental lithosphere. Passive extension caused: (1) the progressive exhumation and late tectonic unroofing at the sea-floor of the subcontinental lithospheric mantle, and (2) the passive upwelling of the asthenospheric mantle, which underwent decompressional partial melting and produced MORB-type parental magmas for the early (Permian - Triassic - Jurassic) gabbroic intrusions and for the Late Jurassic oceanic basaltic extrusion.

LS02 : WEpo15 : PO

Magmatic and Hydraulic Breccias in Corsican Ophiolitic Plagiogranites (France)

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Leucocratic rocks have been described in Corsican ophiolites, especially in the Inzecca massif (Ohnenstetter and Ohnenstetter, 1980). A continuation of their study is justified: i) by accumulation of data on numerous other ophiolitic plagiogranites, allowing detailed comparisons; ii) on a wider scale, by recent advances in techniques and concepts on oceanic ridges and ophiolites.

In spite of the overlapping of several metamorphic stages in Corsican plagiogranites (mineral assemblages including albite, jadeite, glaucophane, actinolite, chlorite, epidote...), the primary relationships between the different rocks and the magmatic textures are still recognizable. The leucocratic rocks mainly comprise albites with accumulative textures and fine-grained albite-granite. Magmatic differentiation including accumulation processes and segregation of residual liquids can account for the rock diversity. Petrochemical considerations indicate a parental magma with a typical N-MORB composition.

Leucocratic rocks display different kind of association with the other components of the ophiolitic complex. The Rospigliani series, possibly related to a transform-fault zone, contains abundant magmatic breccias (Ohnenstetter, 1979): albite-granites often enclose Fe- and Ti-rich doleritic enclaves with fine-grained crenulate margins. Another kind of breccia has been observed in the Inzecca Valley. It is composed of angular fragments of albite in a dark matrix. Size of fragments varies from a few millimetres to ten centimetres. These characteristics are typical of hydraulic breccias. The presence of doleritic enclaves in plagiogranites suggests pulses of basic or intermediate magmatic liquids at the very end of the existence of small magmatic reservoirs. Moreover, injection of relatively primitive, hot magmatic liquids in largely crystallized magmas can induce the formation of hydraulic breccias (Barbarin et al., 1995).

The generation of Corsican ophiolites probably took place along a slow spreading ridge. The geological setting and the petrochemical characteristics of Corsican plagiogranites clearly distinguish them from plagiogranites present in ophiolites formed in other geodynamic contexts.

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LS02 : WEpo16 : PO

Evidences for Chemical Segmentation in the Haylayn Massif (Oman Ophiolite) from its Ultra-Depleted Mantle Part

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The Haylayn massif is one the 11 distinct blocks located in the central part of the Oman ophiolite which exposes a large and well preserved crustal and mantle sections beneath a paleo-spreading center. Based on the crustal thickness variation, some authors (Juteau et al., 1989; Reuber et al., 1991) have proposed that the Haylayn's massif would represent a simple segment of the paleo-ridge formed by three large magmatic chambers. These later are located to Wadi Bani Ghafir, Wadi Haymilyah and Wadi Bidit respectively from south to north. Our structural data realized along three crosscuts through Haylayn's block agrees with the segmentation proposed, while a fourth smaller magmatic chamber located to northward (Wadi Gharba) could be also suggested. The Haylayn's mantle section is mainly constituted by harzburgites Cpx-free. Despite the strong modal heterogeneity of peridotites, the Opx and olivine chemistry not displays significant Mg# variation along the Haylayn segment. Nevertheless,

the spinels show high Cr# contents, well correlated with the higher crustal thickness. The rare earth element concentrations in peridotite are homogeneous, highly depleted from HREE to MREE (1.4<Lu<5.5 ppb and 50<Yb/Eu<300). These rocks are interpreted as mantle residues after >20-25% melt. Lu concentrations are well-correlated with the Cr# of spinel and high crustal thickness, suggesting major collecting zones for melt extractions. According to this data we propose that the Haylayn massif would represent a single paleo-segment where the melt extraction is channeled by four small diapirs 12 km-spaced probably providing from a largest asthenospheric upwelling.

**LS02 : WEpo17 : PO
Paleo-Oceanic Islands and Seamounts in
Caledonian Folded Areas, Gorny Altai and
Salair, Russia**

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Oceanic islands and seamounts are widely distributed over the territory of present-day oceans, nearly as much as active continental margins. In folded areas, volcanic and plutonic assemblages of active continental margins are commonly well preserved, whereas oceanic crust units are greatly involved in subduction. Usually only small fragments of oceanic crust are found in accretionary wedges. In evolutionary interpretations and identification of ancient oceans, great attention is paid to ophiolites, which are typical elements of oceanic crust.

We analyzed recent-day morphological structures in oceans and performed special geological-geochemical studies of oceanic crust fragments in Vendian-Cambrian accretionary prisms in Central Asia. The obtained data showed that only the fragments of oceanic islands and seamounts were preserved after the subduction. Those fragments together with ophiolites give us the main knowledge about the tectonic processes and geodynamic environments that existed in ancient oceans. Topographically, oceanic islands and seamounts are well expressed as the structures formed over hot spots. After oceanic islands and seamounts collided with a continental margin, the former are either submerged into a subduction zone, or piled up (blocked). The latter process results in the generation of reverse flows in accretionary wedges and transportation of high-pressure metamorphic rocks to the surface.

In Gorny Altai and Salair we studied geodynamic units of a Vendian-Cambrian island-arc system. The evolution of the island arc was analogous to that of the active margin of the western Pacific. Structural, geochemical and geochronological data showed that the fragments of the Paleo-Asian ocean are mainly composed of paleo-oceanic island units and in less degree of various types of ophiolites. Our data showed that this collision occurred in the Early-Middle Cambrian. The oceanic island/island arc collision and reverse flows in the accretionary wedge were mainly responsible for the exhumation of high-pressure rocks.

**LS02 : WEpo18 : PO
Accretionary Tectonics of the Sea of Okhotsk
Region**

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Accretionary Tectonics of the Sea of Okhotsk Region
Tectonic analysis of the southwestern part of the region was done in connection with the preparation of the Tectonic Map of the Sea of Okhotsk region, at a scale of 1:2 500 000. In continental Eurasia, west and north of the Sea of Okhotsk, terranes joined the Siberian craton. This process became most conspicuous from the Late Carboniferous. In the Mongolian-Okhotsk belt, east of the sea, it was finished at the latest Jurassic, while in the Magadan region it was over in the Early Cretaceous. Beginning with the Albian, along the new-formed continental lithospheric plate with a total thickness of the Earth crust over 40 km, a subduction zone shaped, along which the paleo-oceanic Kula plate submerged under the continent. The Okhotsk-Chukotka volcano-plutonic belt was formed over the subduction zone. The belt evolved up the Campanian. The type of subduction and volcanism in that period were similar to the Andean ones. The collision of the Sea of Okhotsk plate with the continent occurred at the 75 Ma boundary and led to wedging up of the subduction zone, termination of

volcanism, and deformation of the belt volcanic formations. The Sea of Okhotsk plate is most likely, composed of volcanic rocks with seismic velocities of about 60-62 km/sec; their thickness amounts to 20 km. On the whole, the structure of the plate is homogenous both vertically and laterally. The Deryugin and Tinro pull-apart basins with 10 km thick Miocene sediments are situated at the marginal parts of the plate. On the whole, the thickness of the sedimentary cover on the Sea of Okhotsk plate from the Paleocene to Quaternary is 1-2 km. In the Early Cretaceous, the Sea of Okhotsk plate was, most likely, the northern part of the Shatsky Rise. The crust thickness of the deepwater South-Okhotsk basin is up to 7 km, and its sedimentary layer reaches 3.5-4 km. It is regarded to be a relict of the Kula plate, the age of its oceanic crust being Campanian (73-74 Ma). The West Kamchatka microplate with continental crust, is situated east of the Sea of Okhotsk plate. In the latest Cretaceous, it joined the Sea of Okhotsk plate. Small terranes, that made up a complicated accretionary prism, bordered in the east on the West Kamchatka microplate during the Eocene-Lower Miocene. Subduction under that prism started from the Middle Oligocene, first being accompanied by plunging relicts of the Kula plate and then of the Pacific plate. Two volcanic arcs developed on the Kamchatka Peninsula.

