

V22G-05 1700h

Laser-Ablation (U-Th)/He
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Over the past decade, ultraviolet laser microprobes have revolutionized the field of ⁴⁰Ar/³⁹Ar geochronology. They provide unprecedented information about Ar isotopic zoning in natural crystals, permit high-resolution characterization of Ar diffusion profiles produced during laboratory experiments, and enable targeted dating of multiple generations of minerals in thin section. We have modified the analytical protocols used for ⁴⁰Ar/³⁹Ar laser microanalysis for use in (U-Th)/He geochronology studies. Part of the success of the ⁴⁰Ar/³⁹Ar laser microprobe stems from fact that measurements of Ar isotopic ratios alone are sufficient for the calculation of a date. In contrast, the (U-Th)/He method requires separate analysis of U+Th and ⁴He. Our method employs two separate laser microprobes for this process. A target mineral grain is placed in an ultrahigh vacuum chamber fitted with a window of appropriate composition to transmit ultraviolet radiation. A focused ArF (193 nm) excimer laser is used to ablate tapered cylindrical pits on the surface of the target. The liberated material is scrubbed with a series of getters in a fashion similar to that used for ⁴⁰Ar/³⁹Ar geochronology, and the ⁴He abundance is determined using a quadrupole mass spectrometer with well-calibrated sensitivity. A key requirement for calculation of the ⁴He abundance in the target is a precise knowledge of the volume of the ablation pit. This is the principal reason why we employ the ArF excimer for ⁴He analysis rather than a less-expensive frequency-multiplied Nd-YAG laser; the excimer creates tapered cylindrical pits with extremely reproducible and easily characterized geometry. After ⁴He analysis, U and Th are measured on the same sample surface using the more familiar technique of laser-ablation inductively coupled plasma mass spectrometry (LA-ICPMS). Our early experiments have been done using a frequency-quintupled Nd-YAG microprobe (213nm). While the need to analyze U+Th and He in separate ablation experiments results in considerably worse spatial resolution than that typically possible for ⁴⁰Ar/³⁹Ar laser microprobe dating, it is possible to site the LA-ICPMS ablation pit within a few microns of the pit used for He extraction, or to simply re-occupy and enlarge the original ablation pit. The potential effective spatial resolution of the technique is thus on the order of a few tens to roughly 100 microns. As a proof-of-concept exercise, we have applied this technique to fluorapatite from Cerro de Mercado, Durango, Mexico, which has a generally accepted (U-Th)/He age of 32.1 ± 3.4 Ma (2 sigma) based on single-crystal fusion analyses reported by House et al. (2000, EPSL). Using the approach described above, we made 48 separate age measurements on a 12 mm polished section cut through a single crystal of Durango fluorapatite perpendicular to its c axis. The measured dates yield a mean of 34.9 ± 5.1 Ma (2 sigma), with a total dispersion of dates comparable to that reported by House et al. Much of the apparent age variation observed in both studies is due to documented U+Th heterogeneities in single crystals of the Durango fluorapatite. Nevertheless, the consistency of the laser ablation and conventional results for this material is striking. Compared to conventional laser and furnace methods of (U-Th)/He geochronology, the laser microprobe approach offers substantially improved spatial resolution, and the ability to avoid (or at least minimize) alpha-ejection corrections. In addition, the method affords improved sample throughput, such that age estimates for homogeneous materials can be made with considerably higher precision based on a larger number of analyses.

V22G-06 1715h INVITED

Problematic Samples for Apatite
(U-Th)/He Dating: Some Possible
Causes and Solutions

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Seven years of experience with (U-Th)/He dating reveals a subset of granites and gneisses (perhaps 10%) which yield apatites problematic for the method. Here I document these challenging samples and provide possible explanations and solutions. Rocks from some areas (e.g., Himalayas and Taiwan) tend to yield apatites in which every grain is broken, precluding accurate α emission correction. We developed a protocol in which the grain fragments are abraded to eliminate the α -ejection-affected surfaces. The now opaque fragments are immersed in appropriate refractive index oil, rendering inclusions remarkably visible for hand-picking. By eliminating the need to simultaneously

have good morphology and freedom from inclusions, this technique greatly increases the population of datable grains. Results of a case study from Taiwan will be presented, as will modeling which shows how removal of outer edges must bias He ages, especially when cooling is slow.

More problematic are seemingly good apatites that yield irreproducible and anomalously old He ages. The following observations apply to these rocks: strong geographic control, with problem samples common in some areas (e.g., Transantarctic Mtns) but absent elsewhere (e.g., Coast Mtns); highly variable U,Th among apatite grains (up to 2-3x); REEs (now measured on every dated apatite) have LREE depletion, compared with LREE enrichment in most non-problematic apatites. These observations are consistent with problematic apatites occurring preferentially in S-type granites, which have precipitated monazite (Sha and Chappell, 1999). Flux melting indicates that inclusions cannot explain the aberrant ages, and modeling and ion probe measurements suggest that U,Th zonation is not a likely cause either. A possible role for implantation of He from neighboring monazites is consistent with abrasion experiments yielding younger cores than obtained from whole grains. If this explanation is correct, it may be impossible to obtain meaningful He ages on such samples. In any case it seems prudent to reproduce all He age determinations to insure data quality.

V22G-07 1730h INVITED

Cosmogenic ²⁶Al and ¹⁰Be Depth
Profiles in High-level Terrace Gravels
Demonstrate Early Pleistocene
Entrenchment of the San Juan River
in the Canyonlands Region of UtahDarryl E Granger¹ (765-494-0043; dgranger@purdue.edu)Amy J Wolkowsky¹ (arapacz@purdue.edu)Marc W Caffee¹ (mcaffee@physics.purdue.edu)¹Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, United States

Cosmogenic ²⁶Al and ¹⁰Be measured in a vertical profile can be used to date sedimentary deposits such as alluvial terraces, provided that the profile is deep enough to shield the lowest portion from secondary cosmic-ray neutrons and muons. Radioactive decay at depth lowers the ²⁶Al/¹⁰Be ratio with time, allowing sediments to be dated up to 5 million years old. Accurate dating requires correction for post-depositional production of ²⁶Al and ¹⁰Be, which can be important at depths up to 10-20 meters. Production at depth can be extrapolated from the upper portion of the profile. Here we present data from two terraces 150 meters above the San Juan River, Utah, near the towns of Bluff and Mexican Hat. The terraces are on the brink of the canyon upstream from the entrenched Goosenecks for which this river is known. These terraces and others grade evenly to the rim of Glen Canyon on the Colorado River, and thus constrain the age of canyon incision east of Grand Canyon. The terrace at Bluff is mantled with over 11 meters of gravel, while at Mexican Hat the gravel is 6 meters deep. These gravels have previously been correlated with glacial deposits in the San Juan mountains. The alluvium is capped by Stage IV-V pedogenic carbonate. We collected sediment from a profile 11.7 meters deep at Bluff, and 5.5 meters deep at Mexican Hat. We also collected a sample for cosmogenic surface exposure dating to compare with the profile dating method at Bluff. Our cosmogenic profiles yield an age of 1.36 (+0.20/-0.15) My for the deposit. The average incision rate of the San Juan River at this site is thus 113 +/- 16 m/My, a value that is similar to many others in the Colorado River system, but nearly 5 times slower than incision rates that have been inferred from nearby cosmogenic nuclide exposure dates on terraces and pediments. To test a possible source for this discrepancy, we measured ²⁶Al and ¹⁰Be in a sample collected from the undisturbed terrace surface. We determined that the effective surface exposure age of this deposit is only 625 thousand years, only half the true age of the terrace. This discrepancy underscores the caution that must be taken when interpreting very old surface exposure ages, which are known to be sensitive to erosion at the surface. These data suggest that Glen Canyon on the Colorado River is at least 1.3 million years old, and that incision rates in the Canyonlands area are similar to those downstream in Grand Canyon, Marble Canyon, and on the Little Colorado River.

V22G-08 1745h

Preliminary Estimate of Production
Rates for Terrestrial Cosmogenic ³⁸Ar
from CalciumKim B Knight¹ (kimmer@eps.berkeley.edu)Paul R Renne^{1,2} (prenn@bgc.org)Ken A Farley³ (farley@gps.caltech.edu)¹Department of Earth & Planetary Science, University of California, Berkeley, CA 94720-4767, United States²Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, CA 94709, United States³Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, United States

Cosmogenic ³⁸Ar, dominantly produced from targets of Ca and K (and to a lesser extent from Fe and Ti), has been used in extra-terrestrial studies for decades. Recent measurement of terrestrial cosmogenic ³⁸Ar (Renne et al., 2001) primarily produced by high-energy spallation on calcium has shown potential as a useful addition to stable noble gas cosmogenic geochronology. Terrestrial cosmogenic production rates for both ³⁸Ar_C and ³⁶Ar_C have not yet been empirically constrained, however, in part because simple atmospheric corrections to measured ³⁸Ar/³⁶Ar ratios are impossible. We have employed a different methodology, after Turner et al., 1971, to quantify calcium derived ³⁸Ar_C production. Our method requires irradiation of mineral separates, using neutron activation to create ³⁷Ar as a proxy for the cosmogenic target calcium via the reaction ⁴⁰Ca(n,α)³⁷Ar. The extent of conversion due to irradiation is monitored using co-irradiation of a standard with a known composition including [Ca] and [Cl], known age and no cosmogenic exposure, analogous to standards used in ⁴⁰Ar/³⁹Ar dating. Approximately 15-30 mg of sample is loaded into a mass spectrometer and degassed incrementally with a CO₂ laser. Measured isotopes are corrected for backgrounds, mass discrimination, radioactive decay and additional argon isotopes produced in the irradiation. Step-wise degassing allows construction of a "cosmochron" plot of ³⁸Ar_C/³⁶Ar vs. ³⁷Ar_{Cα}/³⁶Ar, with a slope representing the ³⁸Ar_C/³⁷Ar_{Cα}, and an intercept ideally being that of atmospheric ³⁸Ar/³⁶Ar (~0.188). Deviations from atmospheric ³⁸Ar/³⁶Ar ratios imply sample disturbance or further complexity. We have used this irradiation method to successfully measure ³⁸Ar_C from calcium bearing minerals including diopside, clinopyroxene, garnet, sphene and apatite. A first order approximation can be made of the production of ³⁸Ar_C from calcium by using the better-known cosmogenic ³He production rate. In this study, we collected samples primarily from the Antarctic Dry Valleys, where long exposure histories relative to low erosion rates and high latitude, along with a diverse range of lithologies maximizes cosmogenic dosage and potential target minerals. We have measured both ³He_C and ³⁸Ar_C in samples with identical exposure histories, using mineral pairs where necessary due to the limited application of ³He_C to olivine, clinopyroxene and apatite. ³He_C is normalized to total mineral mass, reflecting its production from a range of target atoms, while ³⁸Ar_C is normalized to grams of Ca. Complementary measurement of these two cosmogenic isotopes yields a strong linear correlation of ³⁸Ar_C atoms/g Ca and ³He_C atoms/g sample with a slope of ~0.9 ± 0.4 (MSWD of 1.5), demonstrating that spallation dominated pathways and energies for formation of cosmogenic ³He and ³⁸Ar are consistent to a first order. These data also provide an estimate of ³⁸Ar_C production on calcium as ~100 atoms/g Ca-year at high latitude, sea-level, significantly lower than the 200 atoms/g Ca-year production estimate calculated by Lal, 1991. Further geological calibration and modeling are underway to refine these estimates.

URL: <http://eps.berkeley.edu/~kimmer/38Ar.html>

V22H MCC: 3008 Tuesday 1600h

Crustal and Mantle Processes in
Ophiolites and Ocean Crust
Generation V (joint with GP, OS, T)Presiding: H J Dick, Woods Hole
Oceanographic Institution; J E Snow,
Max-Planck-Institut für Chemie

V22H-01 1600h

The Thetford Mines Ophiolite Complex:
Focus on the Petrology, Mineralogy
and Geochemistry (REE, PGE) of a
Supra-Subduction Mantle SectionPhilippe Page¹ (418-654-2647; ppage@nrca.nrc.gc.ca)Jean H. Bedard² (418-654-2671;
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The Ordovician Thetford Mines Ophiolitic Complex of southern Quebec preserves a complete ophiolite sequence, with a 5 km thick mantle section, a 1.5 - 2.5 km thick ultramafic and mafic cumulate crust, subdivided into Dunitic, Pyroxenitic and Gabbroic Zones; a partly-eroded sheeted dyke complex, subvolcanic breccias, tholeiitic (subordinate) and boninitic (dominant) lavas and associated dacitic flows, followed by a fore-arc flysch deposit. Mantle rocks are mostly harzburgite tectonites with diffuse compositional layering. Most rocks exhibit porphyroclastic to weakly deformed, nearly equigranular coarse textures. Dunite forms irregular masses and dykes (< 0.1 - 5 m). The larger dunitic conduits may contain massive chromitite pods and nodules at their centers, while smaller dunitic may contain chromite stringers. Occasional pyroxenite dykes are also encountered. Chromian spinels in harzburgites show a wide range in Cr₂O₃ and Al₂O₃ content, with Cr# varying from 0.28 to 0.71. Dunite spinels have Cr# from 0.41 to 0.86. Olivine is magnesian (Fo = 90.4 to 92.0 in harzburgite, and from 90.5 to 94.9 in dunite), NiO-rich (0.38 - 0.49 wt%) and MnO-poor (< 0.15 wt%). Orthopyroxene is magnesian (En = 90.3 - 93.0), Ca-poor (Wo from 0.86 to 2.41, av.: 1.51) and has low to moderate Al₂O₃ (1.10 - 3.18 wt%). Diopside clinopyroxene represents 1-7 modal %, has En_{49.1} - 51.3, Wo_{47.0} - 50.2, and is slightly poorer in Al₂O₃ than opx, with 1.08 - 2.61 wt%. All phases have low TiO₂ (spinel: 0-0.054 wt%, opx: 0.001-0.025 wt% and cpx: 0.007-0.046 wt%). The whole rock chemistry of the TMOc mantle peridotites have low to moderate CaO and Al₂O₃ contents (0.01 - 1.52 and 0.07 - 1.38 wt% respectively). They have U-shaped REE chondrite-normalized patterns, and are depleted in most incompatible elements, e.g. HREE from 0.05 to 0.5 x chondrite. Primitive mantle-normalized PGE patterns for harzburgite show negative to slightly positive slopes with Pd/Ir ranging from 0.21 to 3.1 and Pt/Ir ranging from 0.20 to 8.60. Dunites show the same tendencies (negative to slightly positive slopes) but with lower concentrations of Pd and Pt, with Pd/Ir ranging from 0.01 to 0.60 and Pt/Ir from 0.007 to 2.26. The refractory mineralogy, low whole-rock CaO, Al₂O₃ and HREE imply that the mantle peridotites are slightly to highly melt-depleted residues. However, the TMOc peridotites show enrichment in LREE and some of them show preferential enrichment of Pt-Pd over Ir-Os. This enrichment, which cannot be explained by partial melting, could be attributed to metasomatism of previously-depleted peridotites in the mantle wedge by a subducted slab-derived fluid or melt.

V22H-02 1615h

Thermochemical Erosion of Mantle Lithosphere by Melt/Rock reaction in the Lanzo peridotites (Italy), and Implications for the Transition from Rifting to Ultra-Slow Seafloor Spreading

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A review of existing data together with recent field, petrographic, petrologic and geochemical data from the Lanzo peridotites in northern Italy provides new ideas on the scales and causes of chemical heterogeneity in mantle rocks evolving from rifting to ultraslow seafloor spreading. We propose that large masses of plagioclase peridotite with a fertile composition in Lanzo and elsewhere are hybrid rocks created by melt infiltration and melt/rock reaction superposed on an 'old' lithospheric history. The collected dataset allows us to address the igneous history of the Lanzo peridotite after their accretion to the conductive lithosphere and prior to their seafloor exposure in mid Jurassic time. Our data show that diffuse porous flow of ascending liquids produced by the underlying hot asthenosphere

dissolved clinopyroxene (cpx)+spinel and precipitated orthopyroxene (opx)+plagioclase (plg)+olivine, forming opx+plg-rich peridotite. Migrating liquids became progressively saturated in cpx, and then precipitated microgranular aggregates of cpx-bearing gabbro. Melt/rock reaction in the stability field of plagioclase produced variably depleted light rare earth element (REE) patterns in cpx (La_N/Sm_N and La_N/Yb_N in the range of 0.006-0.25 and 0.006-0.36, respectively) with high absolute middle REE contents (Gd_N : 11 to 29 chondrite), $Gd_N/Yb_N > 1$ and negligible to significant negative Eu anomalies. Sr_N always shows a marked negative anomaly. Migrating liquids, which infiltrated peridotite and formed gabbroic rocks span a wide range of compositions from silica-rich single melt fractions to T- and N-MOR basalts, characteristic of the melting column beneath mid-ocean-ridges. Later, diffuse porous melt flow was replaced by focused porous flow, producing a system of discordant dunite bodies. Upon cooling, liquids migrating in dunite channels became progressively saturated in cpx and plg, forming interstitial cpx at olivine triple points followed by cpx+plg megacrysts and gabbro veinlets within the dunite, and gabbro dykelets within plagioclase peridotites. Calculated liquids in equilibrium with cpx have REE slopes and concentrations similar to MORB crystallized from low percentage aggregate liquids (less than 5%). Subsequent cooling was accompanied by intrusion of km-scale gabbroic dikes evolving from troctolite to Mg-Al and Fe-Ti gabbros. Explanations for the progressive evolution of the melt migration mechanism from diffuse to focused porous flow of melt and finally diking include the competing effects of heating of the thermal lithosphere by ascending magmas from the hot asthenosphere below and conductive cooling by exhumation from above. The change in the melt migration mechanism suggest that the rheology of the mantle was modified from 'lithospheric' to 'asthenospheric' and back again. It is possible that the softening of the thermal lithosphere by melt impregnation could have played a fundamental role in the mechanisms of extension and the establishment of an ultra-slow spreading ridge.

V22H-03 1630h INVITED

Igneous Crystallization Beginning at 20 km Beneath the Mid-Atlantic Ridge, 14 to 16 N

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ODP Leg 209 drilled 19 holes at 8 sites along the Mid-Atlantic Ridge from 14°43 to 15°44 N. All sites were previously surveyed by submersible, and were chosen to be < 200 m from peridotite or dunite exposed on the seafloor; outcrops of gabbroic rock were also near some sites. One primary goal of Leg 209 was to constrain melt migration and igneous petrogenesis in this region where residual peridotites are exposed on both sides of the Ridge axis. At Sites 1269 and 1273, we penetrated 112 m of basaltic rubble; recovery was poor (3.7 m) and holes unstable, so drilling was terminated. Lavas form nearly horizontal surfaces overlying cliffs exposing peridotite and gabbro. At 6 other sites, we drilled a mixture of residual peridotite and gabbroic rocks intrusive into peridotite. We penetrated 1075 meters at these 6 sites, and recovered 354 m of core. Drilling at Sites 1268, 1270, 1271 and 1272 recovered 25% gabbroic rocks and 75% residual mantle peridotite. Core from Site 1274 is mainly residual peridotite, with a few m-scale gabbroic intrusions. Core from Site 1275 is mainly gabbroic, but contains 24% poikilitic lherzolite interpreted as residual peridotite "impregnated" by plagioclase and pyroxene crystallized from melt migrating along olivine grain boundaries; these impregnated peridotites were later intruded by evolved gabbros. Impregnated peridotites are also common at Site 1271, and present at Sites 1268 and 1270. The overall proportion of gabbroic rocks versus residual peridotites from these 6 sites is similar to previous dredging and submersible sampling in the area. The proportion of gabbro is larger than in "amagmatic" regions on the ultra-slow spreading SWIR and Gakkel Ridges. Impregnated peridotites from Site 1275 have "equilibrated" textures and contain olivine, 2 pyroxenes, plagioclase and Cr-rich spinel. Their whole rock Mg#, Cr# and Ni are high, extending to residual peridotite values. 87 MORB glasses from 14 to 16°N with Mg# from 60 to 73 [from PetDB] could be plagioclase lherzolite saturated at 0.54 GPa (± 0.14 GPa, 2σ) and 1220°C ($\pm 16^\circ$ C, 2σ) [Kinzler & Grove, JGR 92]. Impregnated peridotites and olivine gabbroites at other sites contain all or most of these minerals, have similar compositions, and record similar conditions. Melts entered the thermal boundary layer beneath the Mid-Atlantic Ridge at about 20 km depth [e.g., Sleep, JGR1975; Reid & Jackson, MGR 82; Grove et al JGR 92; Cannat JGR 96; Michael & Chase CMP 97; Braun et al., EPSL 00], and began to crystallize within impregnated peridotites and as discrete plutons intruding peridotite.

25% gabbro in the upper 20 km of an oceanic plate would correspond to 5 km of "normal" oceanic crust. 25% gabbro (7.2 km/s) + 75% peridotite (8.2 km/s) yields a "mantle" Vp (8 km/s). Residual mantle peridotites from Leg 209 Sites N and S of the 15°20 Fracture Zone are among the most depleted from the mid-ocean ridges. No regional compositional gradient is evident. Most gabbroic rocks are evolved gabbroites that are not complementary to MORB; instead, they result from complete, near-fractional crystallization of migrating melt at depth. Site 1268 gabbroites, together with impregnated peridotites, may be primitive cumulates complementary to MORB. As reported elsewhere at this meeting, high temperature shear zones and faults accommodated nearly all of the subsolidus deformation associated with corner flow and exhumation of residual peridotites and high pressure igneous rocks.

V22H-04 1645h

On the significance of composition gradients across dunite-harzburgite interfaces in ophiolites.

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It has been suggested that dunite dikes or veins found in harzburgite hosts in the mantle sections of ophiolites are high porosity channels through which basaltic magmas were extracted from their source regions. The formation of such channels may involve pervasive melt flow and reactive dissolution that should leave geochemical fingerprints in the dunite and the harzburgite. Indeed, variations in mineral compositions across dunite-harzburgite contacts have been documented in several ophiolites. This study focuses on the distances over which mineral compositions vary in the dunite and harzburgite, referred to as (composition) boundary layers. Field observations suggest that the boundary layers whether in harzburgite or dunite are typically less than one third of the dunite width. The data also suggest a correlation between boundary layer thickness and dunite width. In order to understand the origin and significance of the concentration gradients we carried out a numerical study that simulates melt flow, diffusion and crystal-melt exchange in a 2D periodically distributed porous dunite and harzburgite matrix. Melt velocities were calculated from a prescribed pressure distribution and permeability structure according to Darcy's Law. Transport properties used in the calculations are similar to those used by Morgan and Liang (2003). Development of composition boundary layers in the dunite and harzburgite depends on a number of factors including, (1) porosity, (2) melt flow rates in the dunite and harzburgite, (3) flow directions, (4) time, (5) crystal-melt exchange rate, (6) rate of dunite-harzburgite interface migration, (7) deformation, and (8) subsolidus reequilibration. Here, we focus on our simulations for the first three. Where steady-state melt flow is parallel to the dunite-harzburgite interface, the thickness of the boundary layers is proportional to the square root of the melt velocity. Since the velocity in the dunite channel is generally larger than in the harzburgite matrix, the boundary layer thickness in the harzburgite is predicted to be larger than in the dunite. When there is a significant component of melt flow across the dunite-harzburgite interface, the relative boundary layer thickness between the two rock units is different. For instance, the boundary layer thickness in the harzburgite becomes smaller than in the dunite when there is a significant component of melt flux flowing from the harzburgite into the dunite. The permeability has a pronounced effect on the boundary layer thickness. The width of the boundary layer in the harzburgite is comparable to or smaller than that in the dunite if the porosity of the harzburgite is much smaller than that of the dunite. In summary, composition gradients developed around the dunite-harzburgite contact are expected to be sensitive to the permeability structures of the dunite and harzburgite, melt flow rates, and flow directions. Limited geochemical field observations indicate that the dunite boundary layer is generally thicker than the harzburgite boundary layer for narrow dunitic (< 10s cm), whereas the harzburgite boundary layer is commonly comparable to or slightly thicker than in the dunite for wider dunitic (> 1 m), though exceptions are common. With more detailed field, laboratory, and numerical studies we hope to be able to infer the rate and time scales of melt extraction and possibly permeability structures of the mantle from the composition gradients measured at dunite-harzburgite contacts.

V22H-05 1700h

Excess Olivine and Positive FeO-MgO Trend in Bulk-rock Abyssal Peridotites as a Consequence of Porous Melt Migration Beneath Ocean Ridges

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Abyssal peridotites (AP) are mantle melting residues for mid-ocean ridge basalts (MORB) [1-4]. Recent studies [5-8] have confirmed the complementary relationship between MORB and AP, but also revealed the hidden complexities in these peridotites such as olivine addition [5-7] and melt refertilization [7,9,10]. These same studies [5,6] have immediately excited serious debates on AP petrogenesis [11-15]. These debates are stimulating and healthy towards an improved understanding of ocean ridge magmatic processes. However, a straightforward interpretation [5,6] has been widely misunderstood because of the influence of [13]. A clarification is necessary. Niu, Langmuir and Kinzler [5] showed that a positive FeO-MgO trend exists in bulk-rock AP samples reconstructed using mineral modes and compositions [3,4]. Such a positive trend is inconsistent with AP being simple melting residues, but consistent with AP being melting residues plus excess olivine [5,6]. Using their *site averages* of reconstructed bulk-rock AP data, Baker and Beckett [13] countered that the positive FeO-MgO correlation by Niu *et al.* [5] is an artifact and there is no evidence for significant olivine accumulation in AP. The clarification here includes the following valid statements: (1) the *site averages* by [13] simply cannot be derived from their own *unaveraged* data; (2) the unaveraged data by [13], as expected, do show a positive FeO-MgO trend as shown by [5,6]; (3) the positive FeO-MgO trend is not an artifact as this trend is also clear in the unaveraged data of [13]; (4) excess olivine is already evident in the original modal data [3,4]; and (5) olivine addition is observed petrographically [7]. Therefore, the positive FeO-MgO trend defined by bulk-rock AP samples is characteristic of AP. Addition of olivine in AP is a consequence of cooling of ascending melts migrating through advanced residues in the "cold" thermal boundary layer beneath ocean ridges [5,6]. This is consistent with bulk-rock trace element data; excess olivine correlates with elevated abundances of incompatible elements (trapped melts) [7]. As olivine addition and incompatible element enrichments are observed on thin-section scales, AP record porous melt migration although dunite channels could be volumetrically more important in melt transport [16]. Massif and ophiolitic peridotites should differ from AP if they did not have the same histories as AP had beneath ocean ridges. References: [1] Dick *et al.*, *Earth Planet. Sci. Lett.*, 69, 88-106, 1984; [2] Michael and Bonatti, *Earth Planet. Sci. Lett.*, 73, 91-104, 1985; [3] Dick, *Geol. Soc. Lon. Spec. Pub.*, 42, 71-105, 1989; [4] Johnson *et al.*, *J. Geophys. Res.*, 95, 2661-2678, 1990; [5] Niu *et al.*, *Earth Planet. Sci. Lett.*, 152, 251-265, 1997; [6] Niu, *J. Petrol.*, 38, 1047-1074, 1997; [7] Niu and Hékinian, *Earth Planet. Sci. Lett.*, 146, 243-258, 1997; [8] Niu and Hékinian, *Nature*, 385, 326-329, 1997; [9] Elthon, *J. Geophys. Res.*, 97, 9015-9025, 1992; [10] Niu and Greig, *Eos Trans. AGU, Suppl.*, 81 (48), F1282, 2000; [11] Walter, *J. Petrol.*, 40, 1187-1193, 1999; [12] Niu, *J. Petrol.*, 40, 1195-1203, 1999; [13] Baker and Beckett, *Earth Planet. Sci. Lett.*, 171, 49-61, 1999; [14] Asimow, *Earth Planet. Sci. Lett.*, 169, 303-319, 1999; [15] Lundstrom, *Nature*, 403, 527-530, 2000; [16] Kelemen *et al.*, *Nature*, 375, 747-735, 1995.

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Varieties of Melt-Rock Interactions in Abyssal Peridotites

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Ocean Drilling Program cores of abyssal peridotite from Hess Deep (Leg 147) and near the Kane Fracture Zone (Leg 153) exhibit features suggesting that a variety of melt-rock interaction processes can influence their compositions. Shallow intrusion into peridotite by melt veins can produce small gabbroic intrusives, with local interaction with the host peridotite, leading to local enrichments in peridotite incompatible element budgets and changes in peridotite modes. This process reveals nothing about proposed reactive porous flow or melt-entrapment processes that might be influencing peridotite geochemistry at greater depth. Given the limited extent of our outcrop (one core diameter), it is possible that the gabbroic intrusive could be unsampled, but that the chemical effects could be present in the core and mistaken for some other type of melt-rock reaction. The presence of these gabbroic veins in both suites of drilled peridotites shows that this type

of process has demonstrably changed the geochemistry of parts of these cores. Other processes that could influence the geochemistry of these rocks include: 1. Melt-entrapment; the effects this have on the mode of peridotite will depend on the pressure at which the melt is entrapped and crystallizes and on the composition of the melt; if this occurs at shallow levels, then plagioclase will be present and the occurrence of melt-trapping will be obvious, but if it occurs at greater depths, then the melt will crystallize no plagioclase and the process will be cryptic. 2. Reactive porous flow; this process could also be cryptic, because in the absence of a set of samples that clearly represents simple melt-residues, the baseline against which modal and geochemical changes have occurred is lacking. Both suites of peridotites studied show evidence for Na enrichments, but in different styles. The Kane suite is pervasively enriched in Na above the amount that should be present based on fractional melting models, in samples that are distal from shallow gabbroic intrusives. The Hess Deep suite shows local enrichments in Na by a factor of > 30 over baseline Na levels. The causes of these different enrichment styles are being investigated and we are determining abundances of strongly incompatible trace elements in CPX by ion probe to constrain the histories of these suites.

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Dissolution kinetics of oceanic lower-crustal cumulate-minerals and the potential effect of the melts on ascending magmas

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The most primitive Atlantis Bank (SWIR) olivine-gabbros have augite oikocrysts surrounding more evolved plagioclase chadacrysts. In addition, this coarse type of augite commonly shows reverse zoning. The observations motivated an experimental study. We investigated the kinetics of melting of the grain-boundaries between mineral-pairs commonly found in lower ocean-crust, and discovered rapid melting rates and melt-compositions that may explain the phenomenon.

In our study, An₆₂ and An₅₄ plagioclase were melted together with Fo₇₃ or Fo₈₂ and with Mg#86 augite. The experiments were distributed over a melting interval of 1240-1330°C and 1180-1300°C respectively. No melting was observed below 1210°C (augite - An₅₄) and 1255°C (Fo₈₂ - An₅₄). Plagioclase is buoyant in the melt, therefore the minerals were melted with the heavier mineral on top, to preserve a short distance between them. The duration of the experiments varied from 30 minutes to 24 hours. The solidus for the plagioclase-clinopyroxene-olivine system was determined to be 1150°C, and the solidus for augite-plagioclase and olivine-plagioclase was inferred to be 5°C and 40degC higher, respectively, on the basis of previous studies.

Olivine, the mineral that experiences the fastest internal solid-state diffusion, has very narrow (tens of μm) or no observable diffusion gradient along the actively melting surface, indicating that the melting rate is similar to or faster than the diffusion rate for Fe/Mg in olivine. Some recrystallization occurred in the melt close to olivine, away from the most active melt interface.

Plagioclase and clinopyroxene grains melted without internal diffusion of major elements in the crystals. Augite starts disintegrating internally at the highest temperatures, but does not show any sign of preferential melting of exsolution lamellae or preferential melting of different crystal faces. Plagioclase show a very narrow (10μm) jagged reaction zone, but no significant anisotropy of melting is apparent.

The melting rates for augite and plagioclase appear to be dependent on the ΔT above solidus for the grain-boundary in question. Therefore, at a given temperature, plagioclase melts slower when in contact with an olivine than when in contact with an augite. For instance, An₅₄ plagioclase at 1290°C melts 0.54-mm/hr when in contact with augite, but only 0.17-mm/hr in contact with olivine. The minerals of the augite-plagioclase pairs melt at comparable rates to the plagioclase of the plagioclase-olivine pair, relative to the solidus. However, the olivine of the pair melts at a slightly slower rate.

The results indicate that the grain-boundaries of normal gabbros from ocean ridges will melt very efficiently at a temperature of 1240 or higher. Stopping of xenoliths is the most efficient method of reheating wall-rock material by ascending melts. A 20cm xenolith may be thermally reequilibrated in 8 hours. Heat produced during crystallization will balance that consumed in the melting of existing cumulates. The latter melts will have higher Mg#s than expected expected from equilibrium conditions i.e. appear to be more primitive

melts than the ones that produced the cumulates. Mixing of these high Mg# melts and the xenocrysts with the enclosing magma will make the resulting magma appear more primitive than the original. This process may have caused the large augites at Atlantis Bank to have higher Mg# than what equilibrium-conditions would suggest.

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Melt Transfer Mechanisms in the Lower Ophiolitic Crust: Examples from the Bay of Islands, Thetford-Mines, Betts Cove and Annieopsquotch

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Field evidence from the Bay of Islands (BOI) and Annieopsquotch (AN) ophiolites (dominantly tholeiitic, boninitic subordinate) implies that open sill-like melt bodies were up to 30m thick, and were emplaced at all crustal levels. At BOI, melt segregation appears to have proceeded in tandem with near-pervasive high-temperature deformation, leading to dynamic recrystallization of cumulates. Comparing results of inverse trace element models to compositions of potential lavas suggests that cumulates retained low residual porosities (5-7%). Expelled Fe-H₂O-rich residual magma migrated laterally and up along shear zones. At AN, 10-30m thick tabular bodies are composed either of massive granular micro-diabasic gabbro, or are zoned from coarse olivine-gabbro bases to gabbroic tops. Downward-growing feldspar dendrites in the coarser bodies, and comb-layered apophyses issuing from their upper contacts, imply that they are sills. The granular to micro-diabasic bodies have textures similar to some AN dykes and lavas; and dykes issuing from their upper contacts also imply an intrusive origin. There is no evidence for deformation in any AN rocks, but residual melt porosities of the order of 10-15% yield inverse trace element model solutions similar to those of dykes and lavas. In contrast, at Betts Cove (BC), which is dominated by boninitic magmas, macrocyclic sequences 300+m thick that show progressive cumulus modal evolution suggest the existence of substantial open chambers. Primary size-graded beds 0.5-2m thick of harzburgite suggest deposition from episodic crystal-charged influxes of replenishing magma into an ambient melt-filled chamber. In one harzburgitic cumulate bed, cm-scale faceted orthopyroxene phenocrysts filled with olivine inclusions are aligned parallel to bedding, but abundant (20-30%) intercumulus clinopyroxene and plagioclase oikocrysts show no sign of flattening, suggesting post-compaction crystallization of a porous cumulate. Inverse trace element models from these rocks yield good matches with the dominant low-Ti boninitic lavas for residual porosities of c.25%. At BC, many orthopyroxenite layers embedded within the dominant harzburgitic-lherzolitic cumulates jog up-sequence, or link up with discordant pyroxenitic dykes when traced along-strike, and may represent fossil melt-escape channels. At BC, the junction between the layered cumulates and the sheeted-dyke complex is interpreted as an extensional decollement zone which has been injected by km-scale bodies of gabbro, which can be related to slightly younger intermediate-Ti boninitic lavas. This gabbro has major, 200-m scale apophyses that penetrate the overlying sheeted dykes and underlying cumulates. Cross-cutting relationships between sheeted dykes and intrusive gabbros show that these gabbros also belong to the spreading phase. Gabbros injected into the cumulates reacted with them to form pyroxenitic reaction zones. At Thetford-Mines (TM), another boninitic-related ophiolite, cumulates at the base of the crust are affected by high-temperature plastic deformation and are layered parallel to the moho. Low assumed residual melt porosities (c.10%) yield inverse trace element models that match lava compositions. The upper half of the crust is dissected into tilted (40-90 degrees) Km-scale blocks by syn-volcanic, dyke-parallel paleo-normal faults. The faults are surrounded by igneous breccias, and are injected by undeformed peridotitic and pyroxenitic intrusions, demonstrating their syn-oceanic timing and role in the transfer of melt towards the surface