Petrologic and trace element geochemical constraints on the petrogenesis of igneous units cored during ODP Legs 170 and 205, Middle America Trench offshore Costa Rica

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Abstract

Drilling on Ocean Drilling Program (ODP) Legs 170 and 205 transected the Middle America Trench (MAT, Pacific margin offshore Costa Rica) and encountered sill-like gabbros intruded into post-16.5Ma sediments, rather than the upper volcanic portion of the igneous basement expected from seismic profiling, presumably ~24Ma East Pacific Rise (EPR) lithosphere. Plate reconstruction indicates that the sill intrusion likely occurred nearly atop the E-W trending Cocos-Nazca spreading center (CNS) during an interval of higher crustal production rates due to the proximity of the active Galapagos Hotspot. The intrusions, which may have exploited nearby tectonic boundaries, may be related to coarser igneous units of normal spreading center (EPR or CNS) crustal building or later hotspot-related overprinting. Petrographic differences and a bimodal distribution of incompatible trace element abundances and ratios allow the gabbros to be categorized into two groups.

Geochemical differences between hotspot and spreading center materials were used to characterize the affinity of these gabbros. Mixing relationships reveal the importance of regional mixing between depleted and enriched sources, represented by spreading center (EPR and CNS) and plume (Galapagos Island hotspot) sources, respectively. Modeling of partial melting and subsequent fractional crystallization processes using incompatible trace element ratios suggest that the gabbros are products of ~10% batch partial melting of a moderately (~25%) enriched mantle source dominantly in the spinel field. Inter-group variations appear to be controlled by differences in degrees of enrichment rather than fractional crystallization. The gabbroic intrusions may therefore represent periodic tapping of magma source variably enriched by the entrainment of plume material. Small differences in partial melting may be the cause of intra-group differences, although the resolution of fractional crystallization effects on incompatible trace element ratios awaits further analyses. Regionally, variations in geochemical enrichment of seafloor basalts are often associated with variation in the structure of the incoming Cocos plate; these geochemical provinces may affect the generation and geochemistry of magmas beneath the Central American volcanic arc.

Introduction:

At convergent margins, the structure of the subducting lithosphere may affect magma generation beneath the volcanic arc. Isotopic studies indicate that the geochemical composition of the oceanic crust also affects arc magma geochemistry (Ishikawa and Nakamura, 1994; Brenan et al, 1995; Elliot et al, 1997; Regelous et al,
1997; Moriguti and Nakamura, 1998; Ishikawa and Tera, 1999; Patino et al, 2000; Clift et al, 2001), although new data indicating elemental and isotopic fractionation from the subducting crust suggest that this relation may not be straightforward (Straub and Layne, 2002). The ocean floor presently subducting on the Pacific margin of the MAT has a complicated history of hotspot and spreading center interaction (Hey, 1977). The igneous basement is composed of materials formed at the East Pacific Rise (EPR) and Cocos-Nazca Spreading Center (CNS), and the long-lived hotspot beneath the nearby Galapagos Islands has thermally and geochemically overprinted the lithosphere of the incoming Cocos plate; these variations in bathymetry and composition are thought to be partly responsible for differences in the structure of the overriding Caribbean plate and possibly the geochemistry of volcanic arc lavas in Central America (Carr, 1990; Werner et al, 1999). Characterizing the bulk geochemical inventory of the subducting slab is crucial to studies tracing subduction components in arc lavas, which requires detailed analysis of the composition and volumetric contributions of both sedimentary and igneous units. The role of sediments in element recycling in subduction zones has received the bulk of the attention (e.g., Patino et al, 2000), but comparatively little work focused on the upper igneous section.

Igneous units were cored during ODP Leg 170 from the incoming Cocos Plate at the Middle America Trench off the Pacific coast of Costa Rica (Fig. 1). Drilling encountered gabbroic sill-like intrusions, as confirmed by Leg 205, with geochemical characteristics consistent with an origin related to Galapagos hotspot activity (Kimura, Silver, and Blum et al, 1997; Morris and Villinger et al, 2003, in press). The intrusive complex was unexpected, as the upper volcanic section of basement, inferred through pre-cruise seismic profiling, was thought to exist at this depth. These intrusions share some geochemical and petrologic similarities with a deeper, massive igneous complex cored near the same location on Leg 205. It has also been suggested that the deeper igneous unit on Leg 205 could represent coarser spreading center material, implying local interaction between hotspot activity of distal origin and activity related to crustal building at spreading centers (Morris and Villinger et al, 2003, in press).

This study uses new trace element analyses of Leg 170 gabbros and shipboard analyses of Leg 205 samples to generate models of mantle mixing and partial melting.
mechanisms. These models are constructed to investigate the petrogenesis and
geochemistry of the Leg 170 gabbros in relation to regional seafloor volcanism. This
represents an initial step in evaluating hotspot and spreading center interaction, which
affects the structure and composition of the seafloor, and may ultimately affect magma
generation beneath the Central American volcanic arc. The tectonic structure of the
incoming Cocos is well studied and may provide further constraints on the timing and
location of intrusion of these gabbroic units.

**Regional Geologic Background:**

*The Incoming Plate:*

The oceanic Cocos and Nazca plates are subducting beneath the western edge
of the Caribbean plate at the Central American convergent margin (Fig. 1). The oceanic
crust of the Cocos plate is characterized by variations in origin, morphology, and
thermal structure along the strike of the Middle America Trench (MAT). These
variations occur on several scales, are largely due to the conjunction of lithosphere
generated at the EPR and CNS and interactions with the Galapagos Hotspot, and affect
the composition and behavior of the subducting oceanic crust.

The initiation of the Galapagos Hotspot was likely signaled by the emplacement
of the Caribbean Large Igneous Province (CLIP) ~95Ma (Montgomery *et al*, 1994; Hauff
1997), although debate persists over the initial location of emplacement (c.f., Meschede
and Frisch, 1998; Meschede, 1998). The initiation of spreading centered on the CNS is
better constrained; the Farallon plate broke up at 22.7Ma (Barckhausen *et al*, 2001;
Meschede and Barckhausen, 2000) to form the Cocos plate to the north, and the Nazca
plate to the south (Fig. 1). Convergence of the Cocos plate beneath the MAT is broadly
similar throughout the region, with the vector oriented at ~N30°E at a rate of ~88mm/yr
(DeMets *et al*, 1990). Subduction becomes shallower beneath central Costa Rica;
subduction dip angles change considerably >100km downdip, from 84° beneath
southern Nicaragua to 60° beneath central Costa Rica just north of the subducting
Differences that exist in Cocos plate morphology and bathymetry are largely an expression of the juxtaposition of smoother lithosphere formed at the faster-spreading EPR and rougher lithosphere formed at the slower spreading CNS, historically known as the “rough-smooth boundary” (RSB of Hey, 1977; Fig. 1). Smaller-scale crustal morphological variability also exists in the region. For example, the more northerly EPR-generated lithosphere offshore southern Nicaragua is highly faulted with extensive back-tilted horst and graben structures (Kelly and Driscoll, 1998), while EPR-generated crust offshore Nicoya Peninsula has a much less faulted structure with smoother morphology. South of the traditional RSB is the seamount domain, characterized by ~40% coverage of seamounts (von Huene, 1995) and underlain by lithosphere generated at the CNS. Further south is the submarine Cocos Ridge, a track of the Galapagos Hotspot. This linear ridge is a product of extensive hotspot volcanism on the Cocos Plate, and is characterized by anomalously thick and buoyant crust with geochemistry typical of ocean island basalts (OIB; Hey, 1977, Stavenhagen et al, 1996). Analyses of basalt glasses dredged on topographic highs reveal geochemical characteristics that suggest widespread hotspot influence on seamount volcanism as far north as the Fisher Seamount, about 150km northwest of the Cocos Ridge (Werner et al, 1999; Fig. 2).

Recent correlations of magnetic anomalies have lead to a reconstruction of the history of the CNS, refinement in the tectonic segments in the Cocos plate, and a clearer definition between tectonic and morphological boundaries (Barckhausen et al, 2001; Meschede and Barckhausen, 2000). Spreading history along the CNS is characterized by rate fluctuations, southward ridge jumps, and rift propagation (Hey, 1977; Barckhausen et al, 2001; Meschede and Barckhausen, 2000). The bathymetric RSB represents the triple junction between the EPR and CNS after a ridge jump at ~19.5Ma, and is recognized by a gentle fold escarpment, with crust slightly thicker to the south (Barckhausen et al, 2001; “Ridge jump” in Fig. 2). Just to the north, the ~80km fracture zone trace (Fig. 2) represents the location of the Farallon breakup and the first generation of spreading on the CNS (22.7-19.5Ma), and corresponds to the magnetic RSB (Barckhausen et al, 2001). Thus, the magnetic and bathymetric RSBs represent the first and second generation of spreading of the CNS, respectively, which are
separated by a southward ridge jump ~ 19.5Ma. The identification of a rift propagator as an additional major tectonic boundary is significant, as its landward extension trends to an offset of Wadati-Benioff zone isodepths beneath the volcanic arc in Costa Rica, the Quesada Sharp Contortion (QSC, Protti et al, 1995; Fig. 2). The oblique orientation of the FZT and ridge jump relative to the convergence direction of the Cocos plate results in northward migration of their respective subduction locations. The orientation of the propagator parallels the convergence vector, allowing the subduction of this feature at the same position beneath the margin for some time, suggesting a link with the QSC (Barckhausen et al, 2001).

These ocean floor morphological segments (smooth, seamount, and Cocos Ridge domains) and tectonic boundaries are reflected in variations in the structure of the western Caribbean margin (von Huene et al, 1995, Barckhausen et al, 1998, Ranero et al, 2000, von Huene et al, 2000). For example, indentation of the continental slope where seamounts are subducting just south of the Nicoya Peninsula suggests significant subduction related tectonic erosion. Seafloor structural and morphological variations are expected to not only have an effect on the dynamics of the subducting materials (e.g., sediments and upper oceanic crust), but perhaps also affect the nature of magma generation and arc volcanism in the overlying plate (von Huene et al, 2000; Ranero and von Huene, 2000). For example, high-Mg andesites (“adakites”) in the Cordillera Talamanca in Costa Rica and Panama are thought to be the product of remelting of the leading edge of the Cocos ridge as it began subducting beneath southeastern Costa Rica (Abratis and Werner, 2001).

The influence of the Galapagos Hotspot on the incoming Cocos plate is revealed through morphological, thermal, and chemical overprinting. The most obvious influence of the hotspot on the incoming plate is morphological, as evidenced by the Cocos, Carnegie, Malpelo, and Coibas volcanic ridges (Fig. 3A); these hotspots tracks are characterized by thickened, buoyant lithosphere with OIB geochemistry (Werner et al, 1999; Hauff et al, 2000; Hoernle et al, 2002 and references therein). Second order influences of the Galapagos hotspot on the Cocos plate include: 1) abundant seamount volcanism, 2) numerous southward ridge jumps of the CNS toward the Galapagos Hotspot that may counteract the northward migration of the CNS, and 3) rift propagation
that may exploit newly formed lithosphere (Hey, 1977; Wilson and Hey, 1995; Meschede and Barckhausen, 2000). Paleogeographic restorations and K-Ar ages of hotspot products indicate that the currently subducting plate was overprinted by Galapagos Hotspot volcanism 12-14.5Ma, although other sources have been proposed (Fig. 3B; Meschede and Barckhausen, 2001; Werner et al., 1999). Furthermore, ~30m thick gabbroic sill, intruded into post-16.5Ma (latest Early Miocene) sediments, cored on Legs 170 and 205 shows geochemical similarities with the Galapagos Hotspot, suggesting hotspot influence even further to the north (Fig. 2). Reconstruction of the Cocos plate to ages that bracket the latest hotspot overprinting and the earliest sill intrusion (~12-16.5Ma) places the intrusion much closer to the CNS and Galapagos Hotspot influence (Fig. 4); this may suggest a link between sill intrusion and increased production rates. In a similar manner, Barckhausen et al (2001) suggest the ~14Ma Fisher Seamount chain (for location see Fig. 2) is the result of exploitation of previous zones of weakness as the plate moved over the hotspot.

Heat flow measurements have shown that significant anomalies exist seaward of the Pacific coast of Costa Rica (Global Heat Flow Database; Langseth and Silver, 1996; Kimura, Silver, and Blum et al., 1997; Fisher et al., 2001; TICOFLUX I and II and Meteor cruise 54/2 as reported in Morris and Villinger et al., 2003, in press). In particular, a sharp thermal boundary exists between lithosphere generated at the EPR and that of the CNS (Fig. 2). North of this triple junction trace, heat flow values are only 10-30% of those expected for normal lithospheric cooling of seafloor of this age (Stein and Stein, 1992); values for similar aged seafloor south of this boundary are closer to those expected. This anomalous pattern continues beneath the prism (Meteor 54/2). The existence of a basement fluid flow systems could account for the extremely low conductive heat flow on EPR lithosphere (Silver et al., 2000; Kastner et al., 2000 and references therein) and may have significant implications for alteration and shallow thermal structure in the downgoing plate.

**Caribbean Plate Geology:**

The Central American isthmus lies on the westernmost edge of the Caribbean Plate, and it can be broadly divided into three crustal provinces (Fig. 1): 1) crustal
blocks underlain by pre-Mesozoic basement rocks in the countries of Guatemala, Honduras, El Salvador, and northern Nicaragua, which are not discussed further, 2) Mesozoic to Cenozoic primitive island-arc in southern Nicaragua, Costa Rica, and Panama, and 3) thickened oceanic crust (Meschede and Frisch, 1998), likely related to the initiation of the Galapagos plume and the creation of the Caribbean plate in the Middle Cretaceous. In southern Nicaragua and Costa Rica, young and thin arc crust is built atop the western edge of this thick plateau basalt sequence; there is little isotopic evidence of crustal contamination in ascending volcanic front magmas compared to magmas ascending through pre-Mesozoic basement rocks (Carr, 1984; Patino et al, 2000). Numerous igneous complexes on the Caribbean plate are genetically related to the Galapagos hotspot plateau basalt (Meschede and Frisch, 1998) including the Nicoya, Quepos, and Herradura terranes accreted to the western coast of Costa Rica (Hauff et al, 1997; Werner et al, 1999; Fig. 3A). Hoernle et al (2002) correlated these igneous complexes to the hotspot tracks, seamounts, and the Galapagos Islands, providing strong support for the ~95Ma near-continuous eruptive history of this plume.

Segmentation of the Central American volcanic arc has been confirmed by both geophysical and geochemical discontinuities. A prominent volcanic arc offset is present between southern Nicaragua and immediately adjacent northern Costa Rica (Fig. 2). Northward, the margin is characterized by: 1) a 180-190 km arc-trench gap, 2) a 180-200 km depth to Wadati-Benioff zone beneath the volcanic arc, 3) smaller (~30-50%) volcanic output compared to the Nicoya region of Costa Rica (Patino et al, 2000; Carr et al, in preparation), 4) complete sediment subduction to the site of magma generation, and 5) more frequent earthquakes of magnitude 7 or greater, and 6) a ~20 km updip limit of seismicity (Newman et al, 2002). The Nicoya region of Costa Rica to the south shows an arc-trench gap of ~165 km, a ~120-130 km a depth to Wadati-Benioff zone (Protti et al, 1995), ~10 km updip seismicity limit (Newman et al, 2002), and probable subduction of only the basal carbonate sediment unit (Patino et al, 2000).

In sum, geophysical segmentation of the Central American volcanic arc is a reflection of the structural and morphological variations of the incoming Cocos plate. Geochemical discontinuities have also been related to variations in the downgoing slab, with a variety of mechanisms invoked, including variations in 1) sediment dynamics, 2)
timing and mechanism of deep fluid extraction (Rupke et al, 2002), and 3) slab-mantle geochemistry (e.g. Feigensen et al, 1996).

**Previous Work on Legs 170 and 205 Igneous Units:**

Drilling during Ocean Drilling Program Legs 170 and 205 transected the Middle America Trench, penetrating both the undeformed section of the incoming Cocos plate and the toe of the Caribbean plate margin (Fig. 5). Gabbros cored on Leg 170 are part of a sill complex, as revealed by Leg 205 drilling that penetrated the sill completely and drilled through ~30m of underlying sediments (Morris and Villinger et al, 2003, in press). Evidence suggests that the sill drilled on Leg 170 is composed of multiple magma injections, including increased rates of penetration (ROP) during drilling suggesting the presence of softer sediment horizons and the presence of chilled margins (Kimura, Silver, Blum et al, 1997).

Evidence from Leg 205 also supports the notion of multiple magma injections. Shipboard interpretation, pending detailed chemical analysis, of the mafic igneous units drilled during Leg 205 suggest that the upper subunit, 4A, is the equivalent of the gabbro sill encountered, but not completely penetrated, during Leg 170 (Fig. 5). A second, deeper igneous subunit, 4B, was also drilled during Leg 205; initial interpretations suggest that this unit may either be another gabbroic sill, a series of thick and slowly cooled lava flows (similar but not identical to those cored on Leg 206, see below), or records a transition from sill to extrusive basement at ~513 meters below sea level (Morris and Villinger et al, 2003, in press). Shipboard analyses of cored samples indicate repeated magnetic polarity reversals, and wireline logging shows cycles of variation in borehole diameter, density, resistivity, and P- and S-wave velocity within the lower igneous unit (Morris and Villinger et al, 2003, in press). These observations suggest multiple episodes of magma injection but cannot specify whether the intrusions occurred as part of normal igneous activity at or near the ridge crest, or as later intrusive igneous overprinting.

Shipboard analysis of 18 thin-sections from Leg 170 show that these rocks can be generally characterized as microcrystalline to fine-grained augite gabbro with medium-grained glomerocrysts of plagioclase and, less commonly, augite, in a nearly
holocrystalline matrix (Kimura, Silver, and Blum et al, 1997). Minor primary phenocryst phases include altered olivine, rare orthopyroxene, ilmenite, and magnetite. Secondary phases include zeolites, chlorite, vein-filling calcite, smectite, and products of glass alteration tentatively identified as saponite and celadonite, suggesting only low-temperature (probably less than 100°C) alteration. Textural evidence, including an increase in grain-size and the appearance of fine laminations near the base of some sections, suggest some degree of crystal settling. Accordingly, the gabbros cored on Leg 170 do not represent primitive or primary liquid compositions.

During Leg 205, several petrologic and physical property changes were identified within the igneous subunit 4B centered at ~513 meters below sea floor (mbsf). Variations in many physical properties, geochemical spikes in fluid-mobile elements, change in secondary mineralogy, increased glass and alteration, and the occurrence of a cryptocrystalline basaltic horizon has led to a suggestion that Leg 205 may have penetrated into the upper volcanic section of the basement (Morris and Villinger et al, 2003, in press).

The relationship between the igneous subunits cored during Legs 170 and 205 and their connection to seafloor igneous activity provides the impetus for further geochemical and petrological examination between these local and regional igneous “complexes”. Accordingly, comparisons are made between the samples cored on Legs 170 and 205 (collectively, “gabbros”) and regionally representative basaltic volcanism, namely, the Galapagos Islands, CNS, and EPR between 5-10°N latitude. This section of EPR lithosphere was chosen to minimize possible complications introduced by the EPR-CNS triple junction (presently ~1-3°N latitude), which did not exist when the basement underlying Legs 170 and 205 was formed.

**Methods:**

*Instrumental Neutron Activation Analysis:*

Trace element data were collected post-cruise on 16 gabbroic samples (12 from site 1039; and 4 from site 1040; see Fig. 5) by instrumental neutron activation analysis (INAA) at Washington University in St. Louis following sample irradiation at the University of Missouri Research Reactor in Columbia, Missouri. Replicate analysis on
samples previously measured by XRF was not practical because of the spectral
interferences caused by contamination from the tungsten carbide barrel used aboard
Leg 170.

Rock chips from paleomagnetic studies were ground on a diamond wheel to
remove surface contamination, soaked in an ultrasonic bath of Nanopure® (~18mΩ
resistivity) H₂O for ~5min, and dried overnight at ~110°C. Samples were split into
smaller fragments in a hydraulic press between two plastic sheets. Fragments were
then powdered in an agate ball-mill; contamination was minimized by cleaning with pure
silica sand and self-contamination cycles between powdering samples intended for
analysis. Powdered samples, ranging in weight from ~250-300mg, were encapsulated
in high-purity silica tubing with an outside diameter of ~5mm and an inside diameter of
~3.4mm before 12hr irradiation in a neutron flux of ~5x10¹³ cm⁻²·s⁻¹. During irradiation,
samples are continuously rotated to dampen effects of flux heterogeneity.

Irradiated samples were subsequently radioassayed by gamma-ray
spectroscopy, following the methods of Korotev (1996) with additional upgrades, using
four high-purity Ge detectors spaced at different lengths according to sample activity.
Samples were continuously rotated to minimize geometry effects during counting. Four
separate radioassays occurred between seven and 30 days after irradiation in order to
maximize detection of disintegrations from both short and longer-lived nuclei. Raw data
was compiled by the Canberra Genie-ESP AlphaStation 255/233, based on a Digital
Equipment Corporation (DEC) 233 MHz AlphaStation 255 (64-bit). Data was reduced
using an updated version of the TEABAGS (Trace Element Analysis By Automated
Standard reference materials JGb-1 (gabbro, Geological Society of Japan), NBS-688
(basalt, National Bureau of Standards), GSM-1 (San Marino gabbro, USGS) were run
as unknowns and received 8 (JGb-1 and GSM-1) or 9 (NBS-688) radioassays.
Estimated one-sigma precision is given in the caption to Table 1. Accuracy was
evaluated by comparing the measured and certified concentrations of JGb-1. Results
show that all elements analyzed are within one-sigma analytical error except Zr, Sm, Hf,
Ta, and Th, which are all within estimated two-sigma analytical error. The measured
concentration of Yb does not fall within two-sigma estimates of analytical error of the
certified value. However, as reported in Korotev, 1996, replicate analysis (n=4) of JGb-1 produces a mean concentration of 0.90ppm, which is within one-sigma estimates of analytical error of the measured concentration reported here.

**X-Ray Fluorescence:**

Major and selected trace elements of the gabbroic sill cored at Sites 1039 and 1040 of Leg 170 were analyzed shipboard by X-ray fluorescence. Of ~30m of gabbro cored, a total of 16 samples from site 1039 (11 samples) and site 1040 (5 samples) were analyzed; results were previously reported in Kimura, Silver, and Blum *et al*, 1997. Samples were ground in a shatterbox with a tungsten carbide barrel, resulting in significant contamination of W and lesser amounts of Ta, Co, and Nb contamination; XRF analyses of these elements are not used in this study. Estimates of external reproducibility were made though replicate analysis of basaltic standard BIR-1, and results show that major element data are precise to within 1-2%, except MnO and P$_2$O$_5$ which are precise within 5-10%, and K$_2$O, which varies by ~30% at these low concentrations (~0.03wt%, Shipboard Scientific Party, 1997). The trace elements Nb (potentially contaminated), Rb, Ce, and Ba are near or below detection limits, and other trace elements are generally precise to within 2-3%; however, trace element concentrations of BIR-1 are generally lower than the gabbroic samples cored on Leg 170 (Shipboard Scientific Party, 1997). Accuracy was evaluated by comparing the replicate analyses of BIR-1 with the certified values; results indicate that all major elements are accurate within one-sigma analytical error, except P$_2$O$_5$ and K$_2$O, which have concentrations in BIR-1 near the detection limit. Trace elements Nb, Zr, Rb, Ni, Ce, and Ba are accurate within one-sigma analytical error, while Cu, Cr, and Sr are accurate within two-sigma.

**Inductively Coupled Plasma- Atomic Emission Spectroscopy:**

Analysis of basaltic and gabbroic samples was performed on Leg 205 by shipboard ICP-AES (Morris and Villinger *et al*, 2003, in press). Estimates of precision are based on the comparison of measured values of five standards, run as unknowns, and the certified value. In general, reproducibility is estimated to better than 3% for the
major elements and 5% for the trace elements, except when concentrations approached the detection limit (Shipboard Scientific Party, 2003a). Based on replicate analyses and certified values of five references materials of basaltic composition, accuracy is estimated to be within one-sigma analytical error for the all the reported major element oxides with occasional exceptions for SiO$_2$, MgO, MnO, and Na$_2$O and all trace elements, except Sr and occasionally Ba.

Replicate analysis at Washington University of samples previously analyzed by XRF was avoided due to the shipboard powdering technique that introduced trace element contaminants, which would interfere with analytical peaks of other elements during INAA (R. Korotev, pers. comm., 2002). However, data quality can be addressed by comparison of measured concentrations of samples of the same standard reference materials used with more than one method. The results of this comparison are shown in Table 2. Major element data between XRF and ICP-AES analyses agree within 5%, except P$_2$O$_5$ and K$_2$O; available trace element data agree to within 5%, except Zr. Major element analysis is limited with INAA (gamma-ray spectroscopy), but FeO, CaO, and Na$_2$O show good agreement with ICP-AES data; available trace element data show very good agreement between Sc and Cr (<1% difference), agreement to within 10% for Sr and Ba, and poor agreement for Zr. X-ray fluorescence and ICP-AES analyses of BIR-1 are indistinguishable at the one-sigma level for the elements Ti, Al, Fe, K, Mg, Mn, Ca, Na, P, Ni, and Y (two-sigma for Si, Cr, and Sr, and three-sigma for V and Zr). For INAA and ICP-AES analyses of Jgb-1, the elements Fe, Ca, Na, Sc, Cr, and Ba are indistinguishable at the one-sigma level, while Sr and Zr are within two-sigma.

Results:

Petrography:

Six thin sections were analyzed post-cruise to assess petrogenetic relationships between the Leg 170 gabbros. Mineral assemblages and visually estimated modes agree with the shipboard findings, although rare (<1%) highly altered olivine is tentatively identified in most of the thin sections, pending microprobe analysis. Multistage crystallization is suggested by the presence of three generations of
plagioclase crystals observed in all thin sections: glomerocrysts, phenocrysts, and microphenocrysts. Plagioclase glomerocrysts are often subhedral to sub-rounded, sometimes poikolitically enclosing augite, typically ~5mm, and have An$_{60-65}$ (using Michel-Levy estimates, pending microprobe analysis). Plagioclase phenocrysts exhibit a range in sizes but are typically ≤4mm, occur as euhedral to subhedral laths and sprays with An$_{55-60}$; the larger phenocrysts are commonly An$_{55-70}$, euhedral, embayed, and have altered glass (?) inclusions and sericite weathering concentrated near the crystal core. Augite phenocrysts are commonly subhedral to rounded, ~1-2mm, but occasionally occur as ~3mm euhedral phenocrysts.

Relatively fast later stage crystallization may be suggested by sector zoning observed in some smaller phenocrysts and microphenocrysts of augite, although this interpretation of augite sector zoning is debated in the literature (see discussion in Brophy et al, 1999). Rapid crystallization is suggested by skeletal plagioclase microphenocrysts in the groundmass, which have An$_{50-55}$. Anorthite content in plagioclase glomerocrysts and phenocrysts decreases core-to-rim, indicating magma conditions becoming less calcic as crystallization proceeds; oscillatory zoning is common, particularly in larger, more Ca-rich plagioclase phenocrysts, suggesting changing magma compositions during crystallization. In general, An content also decreases with plagioclase grain size.

Two groups are discernible in these thin sections, based on the abundance and type of glass and secondary alteration phases, rock texture, and the abundance of higher-Ca plagioclase phenocrysts. The first group has common (~5-10%) amber colored glass, which is less devitrified and altered (fibrous orange-brown product) compared to the second group, which has distinctly fibrous to acicular brown-green altered glass and is clearly more altered overall (up to ~30%). The first group tends to have seriate crystal size distribution and intergranular texture, within a network of plagioclase crystals; the second group is dominantly porphyritic to intersertal with large glomerocrysts and phenocrysts (plagioclase ~An$_{65-75}$) and a microcrystalline to cryptocrystalline groundmass. There are small differences in the mineral modes for the two groups. The second group tends to have a higher proportion of larger phenocrysts of augite, more opaque phases concentrated in the groundmass, and lack olivine; the
latter may be a primary feature or due to complete replacement by secondary alteration. Finally, the second group contains a higher proportion of vesicles and possible small-scale magmatic contacts, and textural evidence suggesting a partially cumulate origin, including crystal settling and layering. Completely altered glass occurs at the interfaces of magmatic contacts, but recrystallization of primary minerals is not apparent. The first group of thin sections appears in the upper section of Hole 1039C; the second group is found in the lower section of Hole 1039C and the sole sample from Hole 1040C.

Petrographic analysis of these thin sections indicates changing magma chemistry during crystallization as well as changing crystallization rates, and indicates that these gabbros do not represent primary melts. The analyses described herein cannot determine if these are part of the same parental magma, but allow two groups to be discerned based on differences in rock texture and secondary mineral modes. Changes in chemistry, form, and size among the occurrences of plagioclase crystals found in each thin section suggest that fractional crystallization of An-rich (probably bytownite, An\textsubscript{70-90}) plagioclase from the parental magma(s) was pervasive. Changes in crystal habit and abundances in augite and olivine seem to also suggest changing magmatic conditions. Mapping of mineral chemistry through microprobe analysis of early and late-crystallizing primary phenocryst phases will further constrain the evolution of the magma and may potentially reveal parental compositions.

Geochemistry:

Three geochemical data sets are used in this study to address the issues outlined above, as discussed in the Methods section; however, no sample has been analyzed with more than one method. Interpretations drawn from comparison of these geochemical data sets, and discussed in the following sections, is therefore restricted to: 1) major elements, particularly between XRF and ICP-AES and 2) selected trace element analyses from INAA. These data are generally precise within 5% and accurate within (one-sigma) analytical error.

Rocks analyzed from Legs 170 and 205 are characterized by small variations in major element oxide composition, as is typical for ocean floor igneous environments. These gabbros are low- to medium-K (generally K\textsubscript{2}O <0.4wt%) subalkaline mafic rocks,
and show a Fe-enrichment trend characteristic of ocean floor tholeiites (Figs. 6, 7A). All samples contain between 46-50 wt% SiO$_2$ with Mg$^#$ [$=$Mg$^{2+}$/ (Mg$^{2+}$ + Fe$^{2+}$)] ranging from 0.44-0.60, consistent with their basaltic composition. Primitive basalts typically have Mg$^#$ ~0.70 (Roeder and Emslie, 1970), and these gabbroic samples have therefore experienced a significant degree of fractionation of high-Mg$^#$ phases, such as olivine and pyroxene, similar to the majority of spreading center basalts. Figure 7B shows that whole rock basalts from the EPR between 5-10°N latitude and basaltic glasses from the CNS generally exhibit slightly higher Mg$^#$ at a given SiO$_2$ as compared to Legs 170 and 205 gabbros and Galapagos Island basalts, possibly suggesting less fractionation of high-Mg$^#$ phases for spreading center basalts en route to surface. Analyses of CNS whole rock samples show slightly lower Mg$^#$ for a given SiO$_2$ and a larger range in composition than CNS basaltic glasses, reflecting the effects of fractional crystallization.

Normative mineralogy with diopside, olivine, and hypersthene, generally occurring in decreasing abundance, suggests a slightly silica-undersaturated character of the gabbros (Yoder and Tilley, 1962; Thompson, 1984; Fig 8). The gabbros from Legs 170 and 205 cluster around the center of the olivine tholeiite (di-ol-hy) field of the basalt tetrahedron of Yoder and Tilley (1962), a feature shared with the majority of spreading center basalts (White et al, 1993; Alt, Kinosha, Stokking et al, 1993). Basalts from the Galapagos Islands tend to cluster around the olivine-diopside join, suggesting moderate silica-undersaturation, although they exhibit a greater range in normative mineralogy than the spreading center glasses.

Leg 170 gabbros are trace element enriched compared to average EPR-MORB, as illustrated by (La/Sm)$_N$ >1 (Table 1). Furthermore, there appears to be a bimodal distribution in (La/Sm)$_N$ values (~1.8 and ~1.4), as well as in abundances and ratios of other immobile, incompatible trace element (e.g., Hf/Ta and Sm/Lu). Chondrite-normalized rare earth element diagrams of Leg 170 samples are shown in Figure 9A. The range in normalized abundances of the Leg 170 igneous rocks lies entirely within the fields of spreading center (EPR and CNS) and Galapagos Islands basalts (Fig. 9B). However, the REE patterns of the gabbroic samples are clearly distinct from spreading center basalts, having lower heavy REE (HREE ~16x chondritic) and higher light REE
(LREE) abundance patterns, and are similar to more enriched [i.e., higher (La/Sm)$_N$] basalts of the Galapagos Islands.

Gabbros cored from Legs 170 and 205 show moderate alteration including devitrified glass, secondary clay, and olivine alteration (Shipboard Scientific Party, 1997 and 2003a; see “Previous Work” above). Probable alteration effects on whole rock chemistry include increased abundance or variation in abundance of fluid mobile elements (e.g., Ba, K, Sr, etc.) with relatively little change in major and immobile trace elements. A comparison between XRF and ICP-AES data shows that the abundances of large ion lithophile elements (LILE) are positively correlated with loss on ignition (LOI, which approximates volatile loss and infers degrees of alteration). Similar alteration behavior between Hole 1039C and subunit 4A and between Hole 1040C and subunit 4B is suggested based on the trends observed in LILE vs. LOI. Ratios of fluid-mobile to fluid-immobile incompatible elements were used to qualitatively evaluate the extent of alteration (e.g., Rb/Zr for XRF, K$_2$O/Zr for ICP-AES, and Na$_2$O/Hf for INAA). Spikes in these ratios are found to be proximal to sediment-gabbro contacts (recovered or inferred by increased ROP), veins, vesiculated areas, or near possible magmatic contacts, as identified shipboard. Finally, gabbros that are more altered and glass rich tend to also have lower concentrations of fluid mobile elements; this may be primary or could suggest fluid-mobile element leaching during alteration.

Discussion:

The geochemical and petrological analyses of Leg 170 gabbros are used to address their possible origin, emplacement, and relationship to previously described seafloor domains in the eastern Pacific offshore Central America. The gabbros have been subdivided into two groups through petrographic differences and incompatible trace element abundances and ratios. These ratios are used to fingerprint possible source regions, form plausible mixing relationships with geochemical end-members of regional influence, and examine the depth of magma generation. Partial melting and subsequent fractional crystallization models are used to infer mechanisms that could produce the differences within and between the gabbro groups. Finally, we speculate
on hotspot influence on the geochemical makeup and thermal state of the subducting plate, which may ultimately affect magma generation beneath volcanic arcs.

Igneous Provenance:

A goal of this study is to determine the provenance of the igneous units cored on Legs 170 and 205. More explicitly, do these gabbros owe their origin to volcanism associated with normal spreading center crustal building or to distal hotspot activity? These questions have important implications concerning volumes and distances of hotspot- vs. ridge-related emplacement. These processes may alter the geochemical and thermal character of the subducting oceanic plate and, ultimately, the composition of volcanic arc magmas. Geochemical distinction is possible because hotspot and spreading center sources generally have different trace element characteristics. Petrologic relationships indicate that Leg 170 and 205 igneous rocks do not represent their original liquids, and the consequences of fractional crystallization must be addressed when attempting to elicit parental liquid composition.

The small degree of differentiation between the igneous samples cored on Legs 170 and 205 (SiO$_2$ varies by 4wt%, MgO by <2.5wt%) makes interpretation of major element trends necessarily speculative. However, the lack of coherent major element trends suggests that the gabbros have complicated histories. The major element variations are consistent with differing proportions of low-pressure fractional crystallization of olivine, plagioclase (bytownite, An$_{70-90}$), and/or augite from a more primitive magma before injection (Fig. 10A), consistent with petrographic inferences described above. Source compositional or melt degree differences could also cause the variations observed, and cannot be excluded. Small ranges in the abundances of major and minor elements of ocean floor igneous rocks largely reflect phase equilibria control, rather than differences in source composition. Source compositional differences are elicited from trace element systematics.

Minor and trace element trends are generally more coherent for Leg 170 gabbros, sometimes occurring as segments with different slopes. For example, V and TiO$_2$ are well correlated into two groups, suggesting that the presence of ilmenite and/or titanomagnetite controls the concentration of these elements in the residual liquid (Fig.
10B). Both V and Ti are highly compatible in these refractory phases but incompatible in the bulk system. The offsets suggest distinct magma sources and/or separate magma generation events, as comagmatic events are expected to form correlated linear trends. Somewhat less correlated trends are also observed in Na₂O, Ni, Cr, and Sr vs. Zr and TiO₂. The lower-TiO₂ trend includes the base of Hole 1039C, all of Hole 1040C, and all of subunit 4B from Leg 205 Hole 1253A (i.e., group 2). The higher-TiO₂ group includes all of Hole 1039C, except the lowermost two samples, and all of subunit 4A (Fig. 6B), distinctions that are similar to the petrographic groupings of Leg 170 gabbros.

The complicated history of the gabbros and relatively limited major element data set does not permit reliable fractionation normalization calculations (i.e., abundance normalization to 7wt% MgO along a derived liquid line of decent in order to minimize fractionation effects) as described in Klein and Langmuir, 1987. Therefore, this study uses immobile, incompatible trace elements and ratios in an effort to circumvent many of the complexities caused by fractionating phases and post-crystallization element mobility.

Data from INAA (this study) and previously published results of immobile, incompatible trace elements are used to determine likely source regions and address plausible melting and crystallization scenarios. As described above, the division between the two groups of igneous rocks cored from Legs 170 and 205 is revealed in incompatible trace element abundances and ratios. Group 1 is characterized by higher concentrations of incompatible elements (Nb, Hf, Ta, Zr, Th; Table 1) and higher ratios of highly incompatible to moderately incompatible trace elements such as (La/Sm)N, Ta/Hf, (Sm/Yb)N. Groups 1 and 2 have a similar average Mg# (0.52 and 0.54, respectively), indicating only slightly greater fractionation of group 1, assuming similar parental magma composition. However, small differences in degrees of fractionation alone are unable to explain the relatively larger differences in incompatible trace element ratios (and rare-earth element (REE) patterns, see below) between the two groups. Therefore, group 1 rocks are interpreted as more enriched than group 2.

Two distinct groups within the Leg 170 gabbros is also evident in the REE diagram (Fig. 9A), corresponding to groups 1 (higher REE abundances) and 2 outlined above. Because the gabbros have distinctly different slopes, fractional crystallization
alone is not expected to be the cause of the difference in REE pattern between the groups. Differences in degree of melting and source composition are mechanisms that could cause the separation and LREE enrichment; however, as discussed in a following section, a combination of small differences in source composition and melt degree best explains the available data.

Are the Gabbros part of the Igneous Basement?:

Evidence collected during Leg 205 led to one possible hypothesis that drilling may have encountered the top of the volcanic portion of igneous basement at ~513msbf (Morris and Villinger et al, 2003, in press). Below this depth the rocks are more altered and glass-rich. If this suggestion is correct, then gabbroic units recovered from deeper levels would be from coarser parts of the igneous basement, such as slower cooled sheet flows beneath quenched hyaloclastites and/or pillow lavas. Sediments are generally absent at the ridge axis of fast spreading centers, and the recovery of an unlocated boulder recording a baked sediment-gabbro contact may suggest that at least some igneous activity was located off-axis; however, the relative stratigraphic location of this contact and the observed changes at ~513mbsf is uncertain.

Drilling on ODP Leg 206 (Fig. 1) penetrated the igneous basement, and comparisons can be made with the lower igneous unit from Leg 205. Plate reconstructions place EPR-derived basement at the sites of both Leg 205 and 206 near the same paleolocation, separated by <10Ma (Shipboard Scientific Party, 2003b), although the spreading rate that generated basement drilled during Leg 206 was ~30% faster (Wilson, 1996). Leg 206 shipboard studies have revealed an upper volcanic section that is >500m and composed of multiple horizons of cryptocrystalline basalt sheet flows with numerous intervals of hyaloclastites, pillow lavas, and massive ponded lavas (Shipboard Scientific Party, 2003b). Whether the ponded lava flows of Leg 206 are the equivalent of the lower igneous complex cored on Leg 205 beneath ~513mbsf remains an intriguing question. However, the vast majority of igneous rocks cored on Leg 205 have holocrystalline matrix, while the interiors of the massive (>35m) ponded lava units cored on Leg 206 are generally fine-grained basalts (Shipboard Scientific Party, 2003b).
The textural relationships and depleted geochemistry of the basalts cored from Leg 206 are also found in basement basalts cored from Holes 504B and 896A near the Costa Rica Rift (Fig. 1), the easternmost segment of the intermediate-rate CNS (Alt, Kinosha, and Stokking et al., 1993; Brewer, Bach, and Furnes, 1996). The proposed change from sill emplacement to extrusive-basement within the lower igneous subunit (4B) cored on Leg 205 is not resolvable with available data; additional trace element analyses will be used to address this question. However, available shipboard geochemical data indicate that the subunit can be distinguished from the majority of regional (CNS and EPR 5-10°N latitude) spreading center basalts on the basis of trace element ratios.

**Source and Melt Characteristics:**

Partial melting and combined partial melting plus fractional crystallization processes were modeled in order to determine mechanisms that could replicate the incompatible trace elements ratios of the gabbros; ratios of highly incompatible trace element were used because they are relatively resistant to major changes during igneous processes such as melting (except very small degrees) and fractional crystallization and they are well characterized by INAA (in general, uncertainties for La and Sm are ~1%, Hf ~2-3%, and Ta <8% at sub-ppm concentrations; Table 1). Visually estimated modal abundances of major phenocrysts are used in the fractional crystallization modeling; additional modeling with normative mineral abundances shows little effect on fractional crystallization paths. Samples from the CNS and EPR generally have Hf/Ta > 10 with (La/Sm)N ~0.5-1.5 and plot at the lower right hand side of Fig. 11A. The Galapagos Island data have Hf/Ta < 5, as do the Leg 170 gabbros, with (La/Sm)N ~1-2.5. The Isla Floreana “main series” basalts (Fig. 11A), which are part of the Galapagos Islands, have anomalously high (La/Sm)N up to ~7; these are briefly discussed below.

The results illustrated in Fig. 11A suggest that simple (modal) batch melting of primitive mantle (PM) alone cannot explain the ratios of Leg 170 gabbros because the
modeled liquids have higher \((\text{La}/\text{Sm})_N\) for a given \(\text{Hf}/\text{Ta}\) (Fig. 11A, B, see figure caption for model parameters). Subsequent fractional crystallization modeling of these partial melts indicates that crystallizing phases would have reduced \((\text{La}/\text{Sm})_N\) at nearly constant \(\text{Hf}/\text{Ta}\); this process could explain some of the ratios observed for the gabbros. However, this is considered unlikely because the modeled fractional crystallization array (light blue line in Fig. 11B) is at a high angle relative to the trend formed by partial melting of primitive mantle, whereas the Leg 170 samples (like the Galapagos Island data) form a shallower trend. Also, the residual liquids (pink line in Fig 12B) would have a much higher \((\text{La}/\text{Sm})_N\) than is observed in any of the regional basalts. The distinct \(\text{Hf}/\text{Ta}\) ratios in groups 1 and 2 suggest that the differences between the Leg 170 gabbros are best explained as the result of similar degree partial batch melts of variably enriched mantle sources.

The slightly enriched source of the gabbros was modeled as a mixture of depleted upper mantle (EPR MORB-source) and an enriched mantle (OIB-source); determination of end-member compositions is described below. Mixing calculations show that small additions of enriched material have moderate effects on the \(\text{Hf}/\text{Ta}\) ratios of initially depleted material; the radius of curvature of the mixing line is \(\sim 6\). For example, \(\sim 15\%\) addition of enriched end-member material to the depleted end-member is adequate to achieve primitive mantle (PM) ratios; this is largely due to the low Ta abundance of the depleted end-member (0.14ppm). Thus, a mixture of depleted material with small volumetric addition of enriched material will itself appear enriched for the elements considered here. Assuming little variation due to fractional crystallization, modeling calculations indicate that group 1 gabbros are consistent with \(\sim 9\%\) partial batch melt from a mixture of \(\sim 28\%\) hotspot end-member and \(\sim 72\%\) MORB-source end-member (Fig. 11B). Group 2 gabbros are consistent with \(\sim 20\%\) melt of a slightly less enriched mixture (24% / 76%). This modeling solution is not unique, and other possible scenarios can explain the data. The most probable alternative explanation is mixing of variously depleted and enriched partial melts, as opposed to source mixing prior to melting modeled here. The calculated trend of residual solids from partial melting of PM is consistent with the observed regional spreading center basalt data (red line with circles in Fig. 11A), which may support the notion of source mixing prior to melting. This
discussion is based on incompatible trace element ratios from Leg 170 gabbros. Testing of these proposed mixing and melting relationships between groups 1 and 2 can be extended to Leg 205 once trace element data, and ultimately isotopic data, are available for Leg 205 material.

Enriched and depleted mantle compositions used in mixing calculations were extrapolated from an analysis of published geochemical data from hotspot (the Galapagos Islands and hotspot tracks) and spreading center (EPR between 5-10°N latitude and CNS) products. Published studies have variously argued for three to five end-member source compositions to explain the observed ranges and heterogeneities in isotopic composition of regional volcanic products (White et al., 1993; Kurz and Geist, 1999; Harpp and White, 2001; Blichert-Toft and White, 2001). In terms of incompatible trace elements, these end-member source compositions reduce to: 1) depleted, MORB-source, 2) enriched, OIB-source, and 3) a high incompatible trace element (ITE) source. The ITE-rich source is believed to be metasomatized mantle, possibly formed through ancient recycling of subducted crust (Bow, 1978; Bow and Geist, 1992; Geist, 1992; Harpp and White, 2001; Blichert-Toft and White, 2001), and is most prevalent in the anomalous Isla Floreana “main series” basalts (Fig. 11A; c.f., Bow and Giest, 1992). If the ITE-rich source is a unique mantle end-member, there is no evidence for significant involvement of the high ITE end-member in the gabbros (extrapolated to be (La/Sm)$_N$ ~7, Hf/Ta ~1; (La/Sm)$_N$ ~10 from Bow and Geist, 1992; Fig. 11A). However, very small (<1%) partial melts of a source compositionally similar to PM are able to reproduce trends observed in the Hf/Ta and (La/Sm)$_N$ ratios of the most ITE-rich (i.e., the Isla Floreana “main series”) samples (Fig 11A).

The comparison made here shows the greater similarity of Leg 170 (and presumably Leg 205) gabbros incompatible trace element ratios to the hotspot end-member than to the depleted mantle; the volumetric contribution of depleted end-member is likely greater (see above). The gabbros are geochemically similar to some of the most enriched CNS and EPR basalts (a minority of the population), suggesting regional influence of the hotspot source and smearing of the end-member signals, an idea that has been pointed out elsewhere (White et al., 1993, Harpp and White, 2001; Blichert-Toft and White, 2001 and references herein).
**Depth of Melting:**

Incompatible trace element ratios indicate a strong similarity between the Leg 170 gabbros and Galapagos Islands basalts, but there is geochemical evidence for different depths of magma generation. A mixing line was constructed in $\text{Sm/Yb}_N$ vs. $\text{La/Sm}_N$ space to determine possible regional mixing and melting relationships (Fig. 12). Enriched and depleted end-member ratios were chosen from published analyses of Galapagos Island basalt samples that best represent regional variation (Harpp and White, 2001); this mixing line therefore represents hypothetical mixtures of plume and ambient upper mantle, from which partial melts are generated. The Galapagos Islands typically have a higher $\text{Sm/Yb}_N$ for a given $\text{La/Sm}_N$ compared to Leg 170 gabbros, which may indicate a longer melting interval in the garnet stability field for hotspot products because Yb is highly compatible in garnet (see figure caption for Fig. 11). In the absence of garnet, clinopyroxene dominates the bulk partition coefficient, and Sm is more compatible than La in clinopyroxene. Thus, higher La/Sm for a given Sm/Yb, as observed in Leg 170 gabbros and the majority of spreading center basalts, suggests shallower melting processes.

The gabbros have higher $\text{La/Sm}_N$ and $\text{Sm/Yb}_N$ ratios than the majority of the spreading center basalts, probably reflecting their relative enrichments. However, distinctions can also be made between the gabbros: group 1 gabbros have characteristically higher $\text{La/Sm}_N$ and $\text{Sm/Yb}_N$ ratios than group 2; this may also reflect differential enrichment. An alternative explanation of the gabbros elevated $\text{La/Sm}_N$ and $\text{Sm/Yb}_N$ ratios is that they simply were not directly derived from mantle sources used here and to model regional variations. Polybaric melting, whereby melting begins in the garnet field and ends in the spinel field, is also consistent with the observed ratios but cannot be distinguished from melting in the spinel field alone.

Leg 170 data clearly do not fall on the mixing line. If source mixing is the cause of most of the differences in $\text{La/Sm}_N$ and $\text{Sm/Yb}_N$ ratios, than mixing most likely occurred before appreciable igneous processes, which can alter the ratios. Difficulties in rigorous fractionation normalization of the data prohibit a quantification of the role of fractionation crystallization in creating the gabbros higher $\text{La/Sm}_N$ at a given $\text{Sm/Yb}_N$,
but the effects of fractional crystallization can be considered. Fractional crystallization of magmas is expected to be most important in the relatively shallow (i.e., crustal) plagioclase stability field; therefore, only clinopyroxene (in the absence of garnet and spinel) is available to fractionate La from Sm (the effect on Sm/Yb is negligible). The differences between the gabbro groups are best explained by >5% partial melts (c.f. White et al., 1993; Harpp and White, 2001), the majority occurring in the spinel field, of a partially enriched source with trace element ratios intermediate between hotspot and depleted mantle end-member. Fractional crystallization overprints these processes, and residual liquid paths would mimic smaller degrees of partial melting, as shown in the differences between whole rock and glass analyses of CNS (Fig. 12). These issues will be more fully addressed once additional major and trace element analyses are completed.

Emplacement and Timing of Groups 1 and 2:

The igneous units cored on Legs 170 and 205 share many textural, mineralogical, and major element geochemical similarities (Morris and Villinger et al., 2003, in press). However, differences in petrography and incompatible trace element abundances and ratios allow a subdivision of these gabbros. In this section, the issue of physical emplacement of these distinct groups is addressed. Group 1 rocks are found in Hole 1039C (Leg 170) except for the basal few meters and as subunit 4A in Hole 1253A (Leg 205), while group 2 is found in the lowermost drilled gabbros in Hole 1039C, the entire Hole 1040C (Leg 170), and as subunit 4B in Hole 1253A (Fig. 5). The change from group 1- to group 2-type geochemistry must occur within Hole 1039C. This change, near the base (~443mbsf between cores 10R-3 and 11R-1), is marked by the occurrence of an increased ROP, which implies the presence of softer sediment horizons (Kimura, Silver, and Blum et al., 1997). Although core recovery was poor (~35%) and drilling was halted ~6m below this geochemical demarcation, available data are consistent with two geochemically separate magma injections. Group 2-type rocks are found in Holes 1039C and 1040C, ~4km distant, while group 1-type rocks are identified only in Holes 1039C and 1253A, ~1km distant, indicating that enriched group 1-type rocks may be more geographically limited (Fig. 5). That group 1 rocks were
cored at different depths in closely spaced holes argues that the unit is not a simple tabular body (Kimura, Silver, and Blum et al, 1997).

Plate reconstruction of the <16.5Ma gabbroic sills results in a paleolocation significantly closer to the CNS and Galapagos Island (Fig. 4). Meschede and Barckhausen et al (2001) place the ~24Ma EPR crust, presumed to underlie the location of Legs 170 and 205, nearly atop the plume at ~16-15Ma. At approximately the same time, the N-S trending transform faults that offset the Costa Rica and Ecuador Rifts from the CNS (see Fig. 1 for locations) may have been located close to the Galapagos hotspot (Meschede and Barckhausen, 2001). Ito et al (1997) show that crustal production rates were higher when the CNS was closer to the plume. As the CNS migrated north and approached the plume, the resulting higher crustal production rates presumably led to higher rates of magma intrusion, a possible plutonic analogy to the seamount volcanism that occurs on the Cocos plate between the locations of Legs 170 and 205 and the Cocos Ridge. Furthermore, Legs 170 and 205 are ~30km north of the EPR-CNS triple junction trace, where spreading at the CNS ended after a southward ridge jump ~19.5 Ma. It is conceivable that this abandoned spreading center may have provided a zone of previous weakness that was exploited as it migrated over the plume ~16Ma, possibly with proximal transform faults acting as magma conduits. The gabbros cored by Leg 170 and 205 may represent samples of episodic intrusion across the triple junction trace that tapped the geochemically enriched hotspot domain. This scenario is consistent with the intermediate trace element geochemistry of the gabbros and the evidence of multiple magma injections.

Conclusions:

Gabbros cored from ODP Legs 170 and 205 appear to derive from a depleted mantle that has been variably enriched by the addition of Galapagos-type material as inferred from a mantle-mixing array constructed from ranges in ratios of incompatible trace element ratios. Data from the majority of oceanic igneous basalts of the eastern Pacific margin offshore Costa Rica, including the Cocos-Nazca spreading center, East Pacific Rise, and Galapagos Islands can also be reproduced through modeling of moderate degrees of batch melting of this same range of hybrid mantles. The simplest
explanation for the observed range in incompatible trace element ratios of the regional basalts is mixing between enriched plume and depleted asthenosphere end-members followed by moderate degrees of partial melting (~10% or more) dominantly in the garnet (Galapagos Islands) or spinel (CNS, EPR, Legs 170 and presumably 205) stability fields. Trace element ratios of spreading center basalts are consistent with an origin related to the residue of partial batch melting of a primitive mantle source or, alternatively, moderate degrees of melting (probably >15%) from this residue; a more developed treatment of the effects crystal fractionation requires additional major and trace element data.

Leg 170 gabbros are more enriched than most of the spreading center basalts and are similar to less enriched Galapagos Island basalts. Mixing calculations illustrate the volumetric dominance of depleted over enriched materials in the gabbros, despite exhibiting trace element ratios indistinguishable from many enriched Galapagos Island basalts. Two groups of gabbros revealed by trace element ratios appear to sample episodes of intrusive activity originating near the CNS during an interval of elevated plume-ridge interaction, possibly exploiting a previous zone of crustal weakness such as the trace of the CNS-EPR triple junction or a transform fault offsetting nearby rifts. Thus, the gabbros may represent the intrusive equivalent of geochemically enriched hotspot related seamount volcanism offshore central Costa Rica. That the Galapagos Islands are between 30-90% enriched suggests a mixing mechanism where variable but large amounts of depleted ambient asthenospheric mantle can be incorporated over long time scales.
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Table 1:
Instrumental Neutron Activation Analysis of Leg 170 Holes 1039C and 1040C gabbros. Sample identifier gives core-section and interval number. One sigma precision for the elements FeO, Na$_2$O, Sc, Cr, Co, La, Ce, Sm, Eu, Yb, Hf is generally less than 3%; precision for the elements CaO, Tb, Lu, Ta, Th, and U is between 3-10%; 10-30% for Zr, Sr, Ba, and Nd. Values preceded by “<” are upper limits. Precision values are estimates based on counting statistics and laboratory experience with analyzing each element (Korotev, 1996). Accuracy is based on comparison between measured and certified values of JGb-1, Geologic Society of Japan gabbro. Results are similar for reference materials GSM-1 and NBS-668 (not shown), which have fewer certified values. Measured and certified values agree within the quoted one-sigma precision levels, except Zr, Sm, Hf, Ta, and Th, which are all within estimated two-sigma analytical error, and Yb, whose certified values may be in error (see text for details). Uncertainties for the trace element ratios (La/Sm)$_N$, Hf/Ta, and Sm/Lu are 0.03 (group 1 and 2), 0.2 (group 1) and 0.4 (group 2), and 0.3 (groups 1 and 2).

Table 2:
Comparison between the analyses of standard reference materials for XRF (shipboard Leg 170) and INAA (Washington University in St. Louis) with ICP-AES (shipboard Leg 205). Major element data agree within 5%, except P$_2$O$_5$ and K$_2$O, between XRF and ICP-AES analyses; available trace element data generally agree to within 5%, except Zr. Major element analysis is limited with INAA (gamma-ray spectroscopy), but FeO, CaO, and Na$_2$O show good agreement with ICP-AES data; available trace element data show very good agreement between Sc and Cr (<1% difference), agreement within 10% for Sr and Ba, and poor agreement for Zr. Leg 205 shipboard values for Fe$_2$O$_3$ were converted to FeO for comparison with INAA values. X-ray fluorescence and ICP-AES analyses are indistinguishable at the one-sigma level for the elements Ti, Al, Fe, K, Mg, Mn, Ca, Na, P, Ni, and Y (two-sigma for Si, Cr, and Sr, and three-sigma for V and Zr). The elements Fe, Ca, Na, Sc, Cr, and Ba are indistinguishable at the one-sigma level, while Sr and Zr are within two-sigma, for INAA and ICP-AES analyses.

Fig. 1:
Bathymetric map of the eastern central Pacific showing the location of the Leg 170/205 and 206 drilling area, Middle America Trench off Costa Rica, Cocos-Nazca spreading center (CNS), and the Galapagos Islands. The dotted line denotes the location of the “rough smooth boundary”; solid lines indicate the locations of the East Pacific Risa and the Cocos-Nazca spreading center. Also shown are the Costa Rica Rift, Cocos Ridge, Nicoya Peninsula, and the Osa Peninsula. The map is modified after Vannucchi et al (in press) based on a data compilation of C. Ranero.

Fig. 2:
Legs 170 and 205 Costa Rica drilling area (red box) and isochrons derived from seafloor magnetic anomalies (Barckhausen et al, 2001). Numbers indicate crustal age in million years. The fracture zone trace divides the first generation CNS crust from the EPR crust, while the triple junction trace separates crust formed at the second generation CNS and the EPR. The ridge jump records the change from CNS-1 to CNS-
2 spreading. Convergence direction and rate (arrow) (DeMets et al., 1990) and arc volcanoes (triangles) are also shown. Note the segmentation of the volcanic arc and the offset in Wadati-Benioff zone isodepths at the QSC. FS = Fisher Seamount, QSC = Quesada Sharp Contortion.

Fig. 3:
A) Regional map showing the locations of igneous complexes associated with Galapagos volcanism (from Hoernle et al., 2002). Red circle marks the location of Legs 170 and 205.

B) Predicted ages of hotspot products on the Galápagos hotspot traces. Black lines indicate Galápagos age trend; gray lines represent age trends from a second, smaller proposed hotspot centered about 500km northeast of the Galapagos hotspot (from Meschede and Barckhausen, 2001). Galapagos overprinting ages are in good agreement with K-Ar ages from basalts from Malpelo Island (Hoernle et al., 2002) and Cocos Ridge dredges (Werner et al., 1999). The presently subducting plate offshore Costa Rica was overprinted by Galapagos hotspot volcanism ~12-14.5Ma. Red circle marks the location of Legs 170 and 205.

Fig. 4:
Projection of the location of oceanic crust cored during Legs 170 and 205 from 12-16.5Ma, illustrating the proximity to the CNS and Galapagos hotspot. The Leg 170 gabbroic sill is intruded into ~16.5Ma sediments. The projection was performed through parameterizing the EPR and CNS spreading rates and directions through time. The locations of Sites 504 and 896 south of the Costa Rica Rift are also shown. The slowing rate of the dominantly E-W spreading EPR during this time interval results in the slight curve of the projection.

Fig. 5:
A) Migrated multichannel seismic profile BGR-99-44 (in Morris and Villinger et al., 2003, in press) across the Middle America Trench. Red lines = Leg 205 Sites 1253, 1254, and 1255. Thin black lines = Site 1039, 1040, and 1043 (Leg 170) locations (Kimura, Silver, and Blum, et al., 1997). CMP = common mid point.

B) Schematic igneous stratigraphic column consistent with data and illustrating preferred interpretations. The change from group 1 to group 2 type gabbroic rocks occurs within the base of Hole 1039C. This is also the location of sediment horizons inferred from drilling operations aboard Leg 170 (Kimura, Silver, and Blum et al., 1997). Subunits 4A and 4B refer to stratigraphic units used during Legs 170 and 205. Group 1 gabbros are relatively more enriched, less altered, and geographically limited compared to group 2 gabbros.

Fig. 6:
(Na2O + K2O) vs. SiO2 showing the subalkaline nature of the Leg 170 (Holes 1039C and 1040C) and 205 (subunits 4A and 4B) gabbros, and their small variation in SiO2, in relation to regional volcanic products. The Galapagos Islands samples show a variable
geochemistry typical of ocean island basalts while the spreading center basaltic glasses, with a few exceptions, are generally more compositionally restricted and strongly subalkaline. GI = Galapagos Island basalts, CNS = Cocos-Nazca Spreading Center, EPR = East Pacific Rise (between 5-10°N latitude). Also shown are the schematic melt paths for partial melting and fractional crystallization processes assuming no alteration has occurred. The Galapagos Island basalts generally have higher abundances of K than spreading center basalts, which is consistent with typical alkaline ocean island basalts. Alteration is expected to increase the concentration of K.

Fig. 7:
A) AFM diagram showing the Fe-enrichment trend typical of ocean-floor tholeiitic rocks from (tholeiitic trend redrawn from Irvine and Baragar, 1971 separating the tholeiitic from calc-alkaline series), for the Leg 170 and 205 samples and the spreading center basalts. A slight alkaline enrichment trend is detectable in some of the Galapagos data. Only samples with SiO$_2$ < 53 wt% are plotted. A = N$_2$O + K$_2$O, F = total Fe as FeO, M = MgO.

B) SiO$_2$ vs Mg# showing the small range in composition for the Legs 170 and 205 gabbros. Also plotted are samples from the Galapagos Islands, CNS whole rock basalts and glasses, and EPR basaltic glasses between 5-10°N latitude. Primary magmas are approximately Mg# = 0.7 (Roeder and Emslie, 1970) indicating that these gabbros do not represent original melts and have experienced fractional crystallization of phases with high Mg# (e.g., primarily olivine and/or clinopyroxene), as have the majority of spreading center basalts. Approximate fields for the augite, bytownite plagioclase, and olivine (Fo$_{50}$) are also shown. Crystallization of a phase would move the residual liquid composition away from the composition of the phase. For a given SiO$_2$ (i.e., degree of fractionation), the CNS basaltic glasses and EPR basalts generally showing higher Mg# than the Galapagos Island basalts and the Leg 170 and 205 gabbros; this is consistent with less fractionation of high-Mg# phases for spreading center basalts en route to surface. This relationship is less distinct for CNS whole rock basalts, also a result of fractional crystallization effects. Mg# = [Mg / (Mg + Fe$^{2+}$)] recalculated from major element analyses of EPR, CNS, and Galapagos Island basalts, after assigning all Fe to Fe$^{2+}$.

Fig. 8:
Exploded view of the normative nepheline-olivine-diopside-hypersthene-quartz basaltic tetrahedron projection after Thompson, 1984, showing the relationship of the Leg 170 and 205 gabbros to the fields of Galapagos Island basalts and MORB (redrawn after White et al., 1993). Galapagos Island basalts tend to cluster around the di-ol join, while MORB and the gabbros cluster near the center of the olivine tholeiite field, di-ol-hy.

Fig. 9:
A) Chondrite-normalized REE diagram of Leg 170, Holes 1039C and 1040C gabbros. The gabbros have been classified as group 1, with higher REE abundances, and group 2, with lower REE abundances; solid black lines are group averages. If the samples have similar parental composition, these differences are likely due to differences in
extent of partial melting; differences in source composition can also be the cause of this group separation. Group 1 includes all of the samples from Hole 1039C (Leg 170) except the two deepest cored samples; group 2 contains these lowest samples from Hole 1039C and all of the samples from Hole 1040C. Generally, these groups are characterized by modest LREE enrichment with HREE ~16x chondritic. Error bars on group averages (black lines) represent average analytical uncertainties for each group sample. Normalization values are from Lodders and Fegley, 1998.

B) Comparison of Leg 170 gabbros with the ranges in Galapagos Island basalts (green) and spreading center basalts (yellow, CNS and EPR 5-10°N latitude). While within the ranges of each field, the gabbros are more similar to enriched Galapagos Islands, having similar normalized abundances and (La/Sm)_N >1. Galapagos Island basalt data are from Harpp and White, 2001. Spreading center basalt data are from Laschek, 1985 and Allan, 1996. Normalization values are from Lodders and Fegley, 1998.

Fig. 10:
A) Variations in CaO/Al_2O_3 vs. Mg# appear to be consistent with fractionation of primarily olivine with lesser amounts of plagioclase (bytownite= An_{70-90}) and clinopyroxene (augite) from a more primary melt, but the scatter suggest a complicated history, especially for Leg 205 samples. Fractionation of bytownite and augite are inferred from petrographic analyses (see text for details). Primary magmas are thought to have CaO/Al_2O_3 ~0.77 and Mg# > 0.7. Higher CaO/Al_2O_3 and lower Mg# suggest fractionation of olivine; therefore, these gabbros do not represent melts of primary magma.

B) V and Ti are highly compatible in ilmenite (Fe^{2+}TiO_3) and titanomagnetite [Fe^{2+}(Fe^{3+},Ti)_2O_4], although they are incompatible in the bulk system (the abundances of both V and TiO_2 increase with increasing Zr and decreasing Mg#, not shown). The presence of these phases controls the residual liquid composition. The majority of Hole 1039C and all of subunit 4A form a linear trend; the remaining samples form another clear trend. Comagmatic liquids are expected to have a correlated trend, and the distinct trends may suggest different source compositions or, alternatively, separate magma generation events originating from the same source. The group that includes subunit 4B has lower concentrations of TiO_2 at a given V compared to the group that includes subunit 4A, suggesting different parent compositions. R^2 values for the trends are for samples from Leg 205 subunit 4A and 4B only.

Fig. 11:
A) Hf/Ta vs. (La/Sm)_N ratios for EPR basaltic glasses (5-10° N latitude) and CNS whole rock basalts fields with Galapagos Island basalts and the gabbros cored from Leg 170, illustrating the relative importance of mixing, partial melting, and fractional crystallization. Trajectories for batch melting of primitive mantle (PM) and subsequent fractional crystallization (shown here after 3% batch melting of PM) suggest that the gabbro field cannot be simply related to these processes. Instead, mixing between an enriched, OIB-type [high (La/Sm)_N low Hf/Ta] endmember and a depleted (MORB-source) type [low (La/Sm)_N high Hf/Ta] endmember is suggested. Numbers next to the
partial melt and residual solid lines of PM refer to the percentage of partial melting. The *pathway* differences in modal fractional melting and modal and non-modal batch melting are small, although degrees of melting vary slightly along a given path. Non-modal fractional melting produces similar pathways only when the extent of melting is <1%; higher degree melts result in higher (La/Sm)$_N$ for a given Hf/Ta, as illustrated. Scatter within fields is likely due to differences in degrees of melting, crystallization, and/or source heterogeneity. The highest (La/Sm)$_N$ values of the Galapagos Islands are from the anomalous “main series” of Isla Floreana, thought to be related to partial melting of a high (La/Sm)$_N$ metasomatically-enriched source distinct from the other islands in the Galapagos (Bow and Geist, 1992; Harpp and White, 2001; see text for details). Error Leg 170 gabbros are (La/Sm)$_N$ ±0.03 (group 1and 2); Hf/Ta ratios are ±0.2 (group 1) and ±0.4 (group 2); see Fig, 11B for approximate error ellipse.

Leg 170 data from INAA (this study) at Washington University. Galapagos Spreading Center data from Ridley et al., 1994; EPR (5-10° N latitude) data from Nui and Batiza, 1995 and references therein. Galapagos Island basalt data from Geist et al., 1995; Kurz and Geist, 1999; Naumann et al., 2002; Allan and Simkin, 2000; Reynolds and Geist, 1995; Baitis and Lindstrom, 1980. PM = primitive mantle from McDonough and Sun, 1995; DM = depleted mantle (represented by the spreading center sample with the lowest Hf/Ta and La/Sm ratios); WR = whole rock; normalization values for La and Sm from Lodders and Fegley, 1998. Whole rock analyses of CNS basalts were used due to the lack of basaltic glass data; resultant CNS data are scattered compared to EPR glass analyses, probably due to fractional crystallization effects, but remain representative of the regional spreading center field.

**Batch modal melting**: melting modes of spinel lherzolite (peridotite) following Kinzler, 1997 = 53% ol, 27% opx, 17% cpx, and 3% Al-phase (spinel):

\[ C_L = \frac{C_O}{D + F(1-D)} \]

where $C_L$ is the concentration of the liquid, $C_O$ is the concentration of the original solid (e.g., PM), $F$ is the fraction of melt produced, and $D$ is the bulk distribution coefficient of the original solid, and

\[ C_{RS} = \frac{C_O D}{D + F(1-D)} \]

where $C_{RS}$ is the concentration of the residual solid.

**Fractional crystallization**: crystallization modes approximate volume % phenocrysts in gabbroic samples (Kimura, Silver, and Blum et al., 1997):

\[ C_L = C_O F^{(D-1)} \]

where $C_L$ is concentration residual liquid and $F$ is the fraction of melt remaining, and

\[ C_I = C_O DF^{(D-1)} \]

where $C_I$ is the concentration of the instantaneous solid.

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<td>Yb</td>
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| La/Sm                                    | 1.62     | 0.68     |
| Hf/Ta                                    | 20       | 1.4      |
| Sm/Yb                                    | 3.10     | 1.65     |

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ol = olivine, opx = orthopyroxene, cpx = clinopyroxene, plag = plagioclase, sp + gt = 50% spinel + 50% garnet

End-member concentrations and ratios used in mixing calculations (following Langmuir, 1978) are taken from a survey of published values.

Melting and/or fractional crystallization in the garnet, rather than spinel, stability field results in compatibility of Sm and Hf in garnet, resulting in a shift of the partial melting paths towards the origin. However, other geochemical evidence argues against significant melting in the garnet stability field for the Leg 170 gabbros (see text for details).

Further modeling (not shown here) with non-modal batch melting (melt-entering modes: ol= -0.06, opx= 0.28, cpx= 0.67, Al-phase= 0.11, of spinel lherzolite from Kinzler, 1997) cause little change to the partial melting and fractional crystallization trajectories.

**Fig. 12:**

(Sm/Yb)_N vs. (La/Sm)_N illustrating the relationship between Galapagos Island basalt, the Leg 170 gabbros, and regional spreading center basaltic glasses. The solid line represents a hypothetical plume-asthenosphere mixing line; enriched and depleted end-members are representative enriched and depleted samples from the Galapagos Islands from Harpp and White, 2001. A location along the mixing line represents a hypothetical mantle mixing line from which partial melts would be generated and extracted. Partial melts originating from the garnet field would have higher (Sm/Yb)_N and would plot above the mixing line; melts generated in the spinel field would have higher (La/Sm)_N and would plot to the right of the mixing line, as would residual liquids from fractional crystallization (see text for details). The effect of fractionation is illustrated by the relative locations of the CNS whole rock and basaltic glass data; whole rock data are more scattered but tend towards higher (La/Sm)_N, suggesting shallow crustal fractional crystallization (see text for details). EM= enriched mantle; DM=
depleted mantle; PM = primitive mantle (McDonough and Sun, 1995); WR = whole rock; Galapagos Island, EPR, and CNS basalt and basaltic glass data extracted from the Petrological Database of the Ocean Floor, available from http://petdb.ldeo.columbia.edu/petdb/. Errors for Leg 170 gabbros are \((\text{La}/\text{Sm})_N \pm 0.03\) and \((\text{Sm}/\text{Yb})_N \pm 0.3\); approximate error ellipse also shown.
Figure 3A, B
Leg 170, Projection of Site 1253 from 12-16.5Ma

Sites 504 and 896

Nicoya Peninsula

Costa Rica Rift

Cocos-Nazca Spreading Center

Figure 4
Figure 5

sediments inferred from drilling operations

subunit 4A

subunit 4B

gabbroic

sediments

Cocos plate  Middle America Trench  Costa Rica margin

Two-way traveltime (s)
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**Table 2**
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(La/Sm)ₙ | 1.83 1.85 1.86 1.87 1.76 1.93 1.85 1.84 1.83 1.85 | 1.50 1.48 1.45 1.45 1.35 1.30 |
| Hf/Ta   | 3.4 3.4 3.3 3.3 3.5 3.3 3.3 3.4 3.5 3.5 | 4.4 4.3 4.5 4.3 4.6 4.4 |
| Sm/Lu   | 12.4 12.1 11.9 11.9 12.2 11.6 12.0 12.2 12.0 12.3 | 9.08 8.82 8.66 8.62 9.40 9.26 |  

**Table 1**

Brian Dreyer  
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6/5/2003
Figure 7B
REE analysis (INAA) of Hole 1039C and 1040C gabbros

Hole 1039C
Hole 1040C

Group 1
Group 2

Galapagos Island basalts
Spreading center basalts (CNS and EPR)

Figure 9A,B
Figure 11B

- Modal batch melting of PM
- Fractional x1 of PM-derived partial melt (instantaneous solid)
- Fractional x1 of PM-derived partial melt (mean cumulate solid = converse of liquid remaining)
- Mixing line 10% increments
- Batch melting from 24% enriched mixture
- Batch melting from 28% enriched mixture
- 5% batch melting
- 10% batch melting
- Liquid line of decent (% crystallized)
- Instantaneous solid (% melt remaining)
- To depleted mantle
Figure 12

- Melting in the garnet field
- Melting in the spinel field +/- shallow level fractional crystallization

Legend:
- 1039C
- 1040C
- GL basalts
- CNS glasses
- CNS WR
- EPR glasses (5-10 deg N)
- Mixing line, 10% increments between EM and DM
- EM
- PM
- DM