Magma Migration, Storage and Evolution in the Galápagos Region

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The Importance of Magma Supply
and its relationship to mantle melting

Magma Chamber Processes ... as deduced from
Volcano Morphology
Petrology

Galápagos Spreading Center
Galápagos Archipelago and Northern Galápagos Platform
The Western Galápagos Spreading Center

From west to east (toward hotspot)
- Ridge axis gets shallower
- Crust thickens
- The overall rate of crustal production* (“magma supply”) approximately doubles

* Crustal production rate = crust thickness x spreading rate

Calculated curve uses Nuvel1 spreading rates and smooth fit to seismic data of Canales et al., 2002.
Mid-ocean ridges are nearly unique among global volcanic provinces because seafloor spreading allows for time (and hence, rates) to be known.
With increasing magma supply:

- Axis shoals, axial high develops.
- Axial topography becomes smoother.
- Depth to top of magma chamber steps up.
- Eruption rate increases.
Magma Composition and Magma Supply

Low supply, W. of 95.5°W
- High Mg#
- Low alkalis, N-MORB
- low H$_2$O

High supply, E. of 96.7°W
- low, variable Mg#
- alkali-rich E-MORB
- water-rich magmas

Note: Inverse relationship between Mg# (~temp) and magma supply
- true for global MORB

Cushman et al., 2004
Generally similar compositional relations on the eastern GSC

Christie et al., 2005
Melting and “Source” Correlate with Magma Supply

With increasing magma supply (proximity to hotspot)
- Incompatible elements are enriched (lower F?)
- more radiogenic isotopic compositions

Christie et al., 2005
Ingle et al., 2010
Magma Supply and Extent of Partial Melting

**Hydrous Mantle Melting**
- Depresses the solidus
- Produces a large volume of deep, low-degree melts

[Asimow & Langmuir, 2003]

Result is increased crustal thickness (melt production) with chemical signature of low average extents of partial melting

Cushman et al., 2004
Mantle Flow and Melting Models

- predict lower mean F with increasing crustal thickness toward the hotspot

The Galápagos hotspot is not very “hot” ($\Delta T \sim 10-30^\circ$)
Lessons from the Galápagos Spreading Center

As the hotspot is approached along the GSC

- Magma supply rate and crustal thickness increase
- Melting extent decreases with greater contribution from deep, hydrous melting
- Magma chambers get shallower in the crust
- Axial morphology changes from axial valley to axial high
- Eruption rate increases (more frequent eruptions with smaller volumes) (Colman et al., this meeting)

- Axial morphology closely reflects underlying aspects of underlying magma chamber
- Galápagos hotspot is not very hot
Three (maybe not very distinct) Sub-provinces of the Galápagos Region
Hard to tell time; hence, difficult to constrain rates
Not much mass wasting (e.g., compared to Hawai‘i); hence, few good sections
Every generalization has an exception
Melting within the archipelago compared to GSC
Volcanic Morphology and Magma Chambers
Volcanic/magmatic “evolution”
Volcan Wolf lavas are enriched in incompatible elements compared to most, but not all, of those from the GSC.
Volcan Wolf lavas have lower SiO₂ and CaO/Al₂O₃ compared to most, but not all, of those from the GSC.

These data all suggest lower mean extents of melting than for (most) GSC lavas.

Geist et al., 2005
Melting might be deeper (and possibly hotter?) than beneath the GSC. Lower F results from terminated melting beneath a thicker lithospheric lid.

- This is a different explanation for decline in extent of melting near the hotspot than that proposed from studies of axial lavas from the GSC.
Water in Galápagos Archipelago Magmas

Melt inclusion data affected by open-system processes
- Degassing
- Crustal interaction
- Seawater assimilation

Koleszar et al., 2009
Jury still out on controls on mantle melting in the Galápagos Region*

• Along the GSC, melting and source variations are moderately well known and magma is strongly focused to the ridge axis

• It is a far more difficult problem within the archipelago
  Mantle might be more complicated; melting extents, temperatures are harder to constrain, and melt supply is widely distributed over significant spatial areas and multiple volcanoes

How is magma distributed from the center of upwelling to the individual volcanoes?

* My opinion – but see new hypothesis for deep CO$_2$-induced melting beneath the archipelago by Geist et al. (this meeting)
Volcanic Morphology, Magma Supply, and Magma Chambers

Galápagos DEMs from Dr. Marc Souris, IRD
http://www.rsgis.alt.ac.th/~souris/ecuador.htm
Calderas
Only(?) form over shallow magma chambers (even if we don’t understand the mechanism)

Variations in presence/absence, size, depth

Figure from Yun et al., 2006
Galápagos volcanoes differ from Hawaiian volcanoes
- lack of strongly preferred orientation of radial rifts, at least in subaerial part of edifice
- presence of circumferential fissures

Is this why there is so little mass wasting in Galápagos?

Rift systems on Fernandina
[Geist et al., 2006]
Circular (arcuate) volcanic construction on the GSC near 95°W

2 m-resolution Reson 7125 multibeam mounted on AUV Sentry

Geologic contact
Large, off-axis, circular mound structure near 92°W
Magma chambers can hide (mix out) deeper level processes.

Relationship between caldera depth and pressure of fractionation.
Relationship between caldera depth and pressure of fractionation

Sierra Negra 2005 eruption
Deformation consistent with eruption from sill-like body at 1.9 km depth
Magma evolution at different levels in complex magma systems

Geist et al., 2005

Geist et al., 2008
Volcanoes with calderas are more active than those without.
Some caldera volcanoes have not had historical eruptions.
Some historical eruptions have occurred on volcanoes without calderas.
Galápagos volcanism slightly more dispersed than in Hawai‘i

The appropriate comparison for productivity is volumetric eruption rate, e.g.

Kīlauea: \(40-50 \times 10^6 \text{ m}^3/\text{yr}\)

Mauna Loa: \(20-30 \times 10^6 \text{ m}^3/\text{yr}\)
Galápagos Volcanic “Stages” [Geist et al., 1998]

**Juvenile:** [Fernandina, Cerro Azul, Wolf, maybe Darwin]

- Deep, narrow caldera
- Numerous historic eruptions
- 5-6 wt % MgO basalts from shallow magma chambers
Later Evolution: [Sierra Negra, maybe Darwin]
Broader, shallower calderas
Magmatic evolution in lower crust (deeper magma chambers ?)
Stage II: [Alcedo, Pinzón, Santiago]  
Highly differentiated lavas  
Irregular supply to magma chambers in the lower crust or near the Moho
Stage III: [Santa Cruz, San Cristobal, Floreana]

No caldera, no long-lived magma chamber

Chemically/isotopically diverse magmas from upper mantle
Temporal vs. Spatial Variation
No volcano is observed to have more than one “stage” of volcanic, petrologic or geochemical evolution.
- In either case, suggests lower supply (and less melting?) to east
Volcanoes with calderas:
Fernandina, Cerro Azul, Sierra Negra, Alcedo, Wolf

But not Ecuador
And not Darwin (few data)
Pinzón, and the platform islands Pinta, Marchena and Genovesa are not distinguished from caldera volcanoes in these plots.
Lavas from Rabida, Santiago and some samples recovered from the submarine flanks of Fernandina are more alkalic with lower CaO/Al₂O₃.
Different Magma Types at Fernandina

Both normal and high-K lavas on western submarine flank

Geist et al., 2006
Samples from Santa Cruz, Santa Fe, San Cristobal, & Roca Redonda plot in a relatively restricted range …at relatively low CaO/Al$_2$O$_3$. 
Floreana data scatter widely
Gradients in extent of partial melting (arrows point high to low)
Gradients in Magma Supply
Highly Differentiated Lavas on Alcedo, Pinzón, Rabida and Santiago
Chemical variations consistent with differentiation, rather than hydrous crustal melting
Chemical zonation within selected hotspots

Not same scale
Volcanic ridges radiate away from a point north of Santiago.

Melts derived from previously depleted mantle are erupted along channels that represent tensional cracks from plume-ridge-transform interaction.

[Harpp & Geist, 2002; Sinton et al., 2003; Mittelstaedt & Ito, 2005]
Some things we (I) don’t know

1. The distribution of mantle geochemical provinces (especially the nature of the depleted components)
2. Variations and amounts of magma supply within the archipelago

3. Melt delivery from the upwelling hotspot to individual volcanic constructions

4. Why so many variables trend NE

Harpp & White, 2001
Sm/Yb and melting parameters derived by inversion of chemical data

Gibson & Geist, 2010

Villagomez et al., 2011

Thickness of high seismic velocity lid

Sm/Yb and melting parameters derived by inversion of chemical data

Gibson & Geist, 2010
5. Whether chemical/morphological variation in Galápagos volcanoes really represents temporal evolution?

Does Santa Cruz represent a volcano that began life like Fernandina and then evolved by progressive subsidence, infilling of the caldera, and reduced melting and magma supply?