Magma Migration, Storage and Evolution in the Galápagos Region

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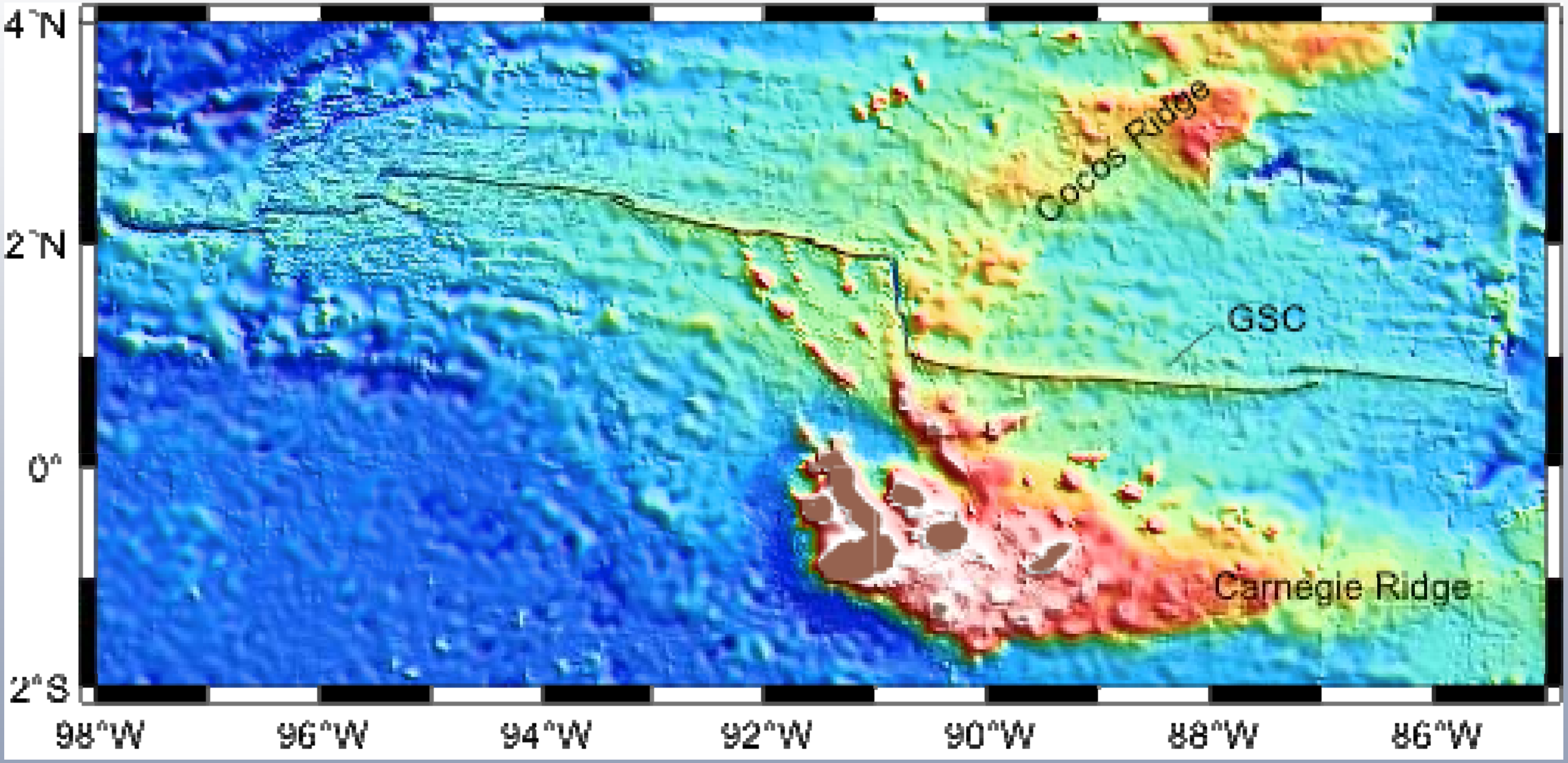


The Importance of Magma Supply

and its relationship to mantle melting

Magma Chamber Processes … as deduced from

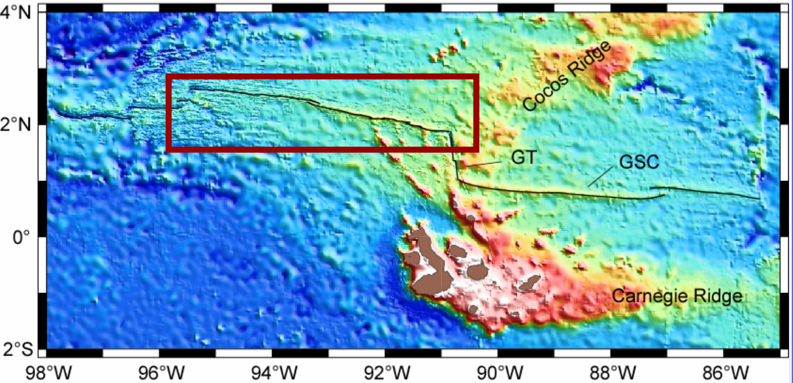
Volcano Morphology

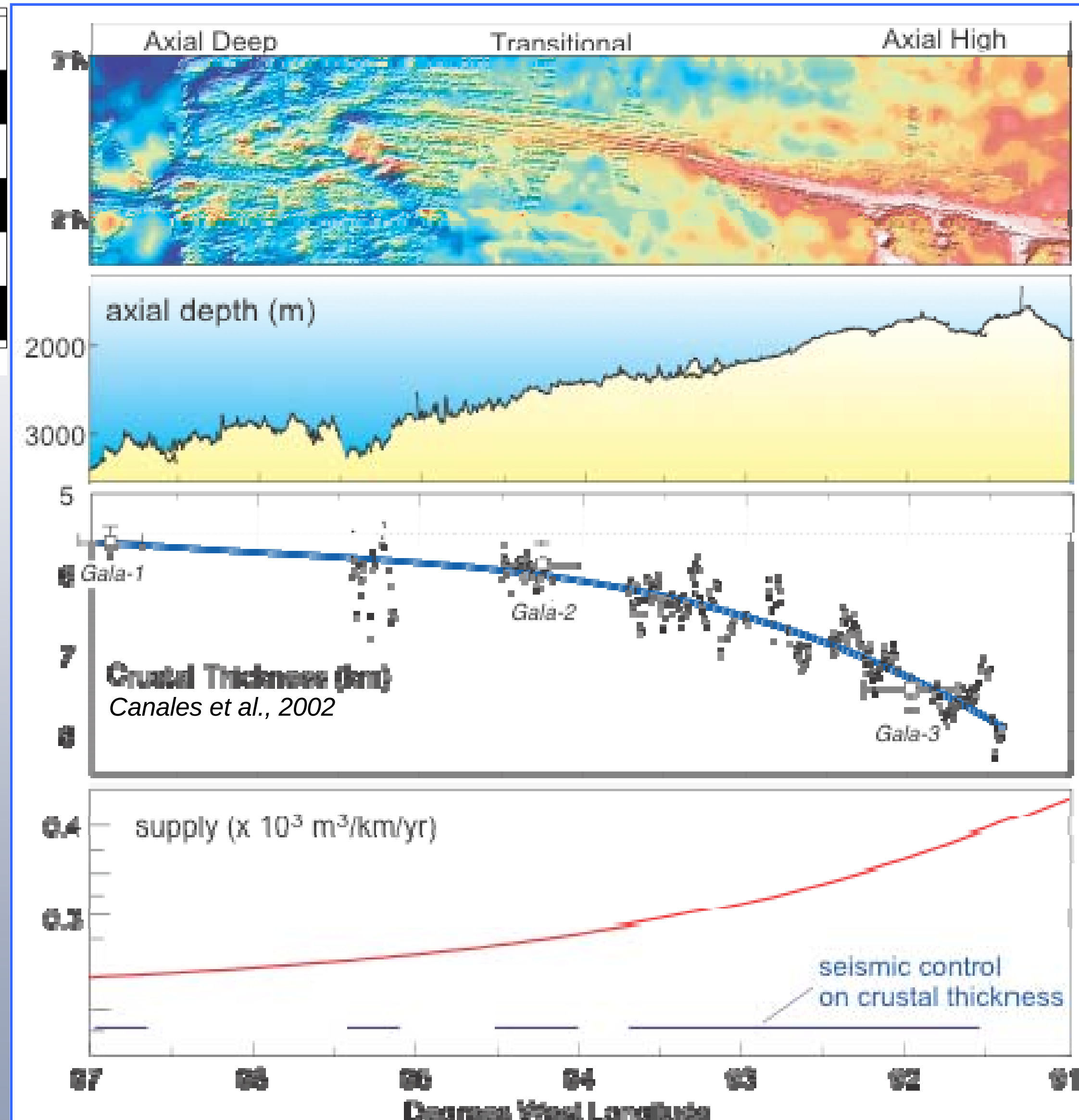
Petrology

Galápagos Spreading Center

Galápagos Archipelago and Northern Galápagos Platform

The Western Galápagos Spreading Center





<u>From west to east (toward hotspot)</u>

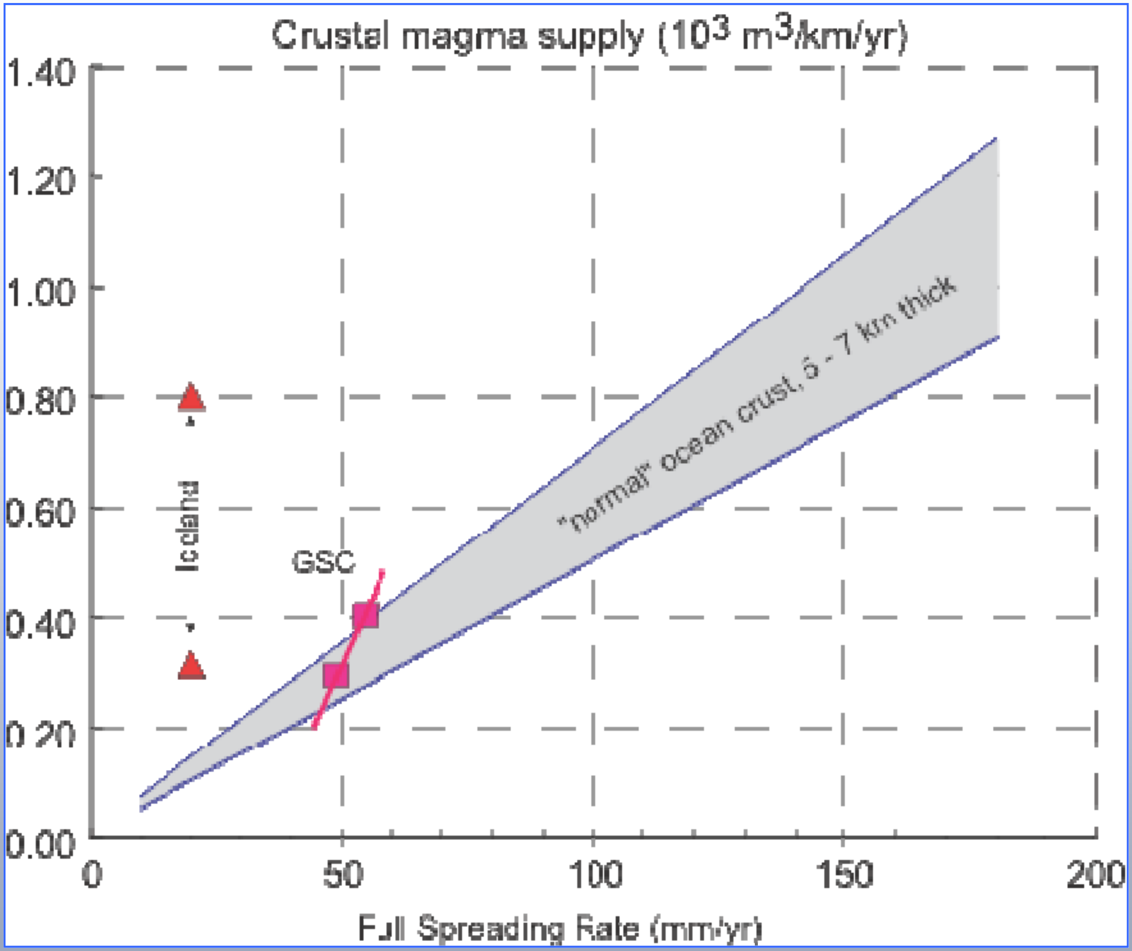
- Ridge axis gets shallower
- Crust thickens
- The overall rate of crustal production* ("magma supply") approximately doubles

* 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.

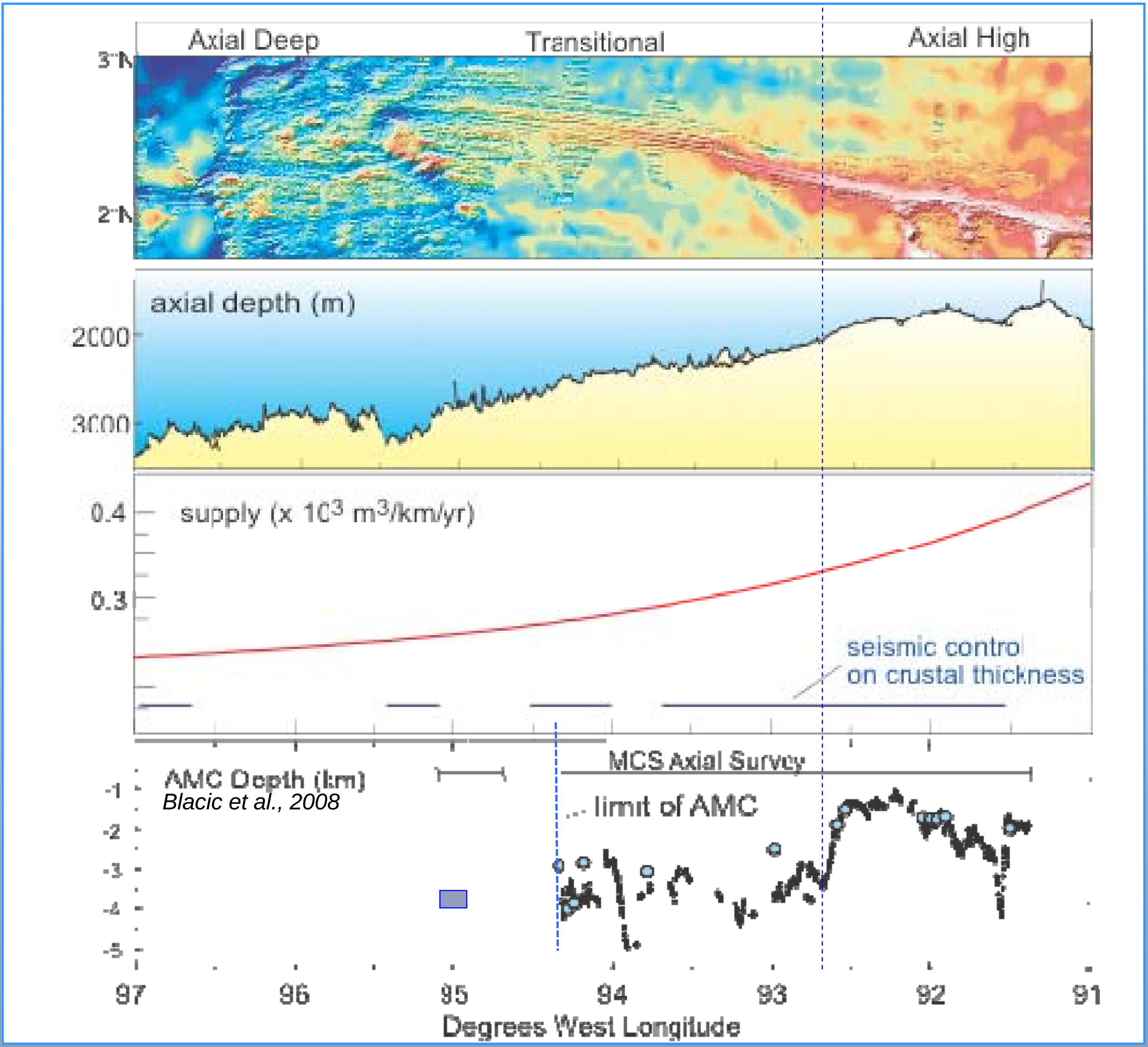
Magma Supply on Mid-Ocean Ridges

Approximated by crustal thickness x spreading rate



Mid-ocean ridges are nearly unique among global volcanic provinces because seafloor spreading allows for time (and hence, rates) to be known.

Magma Supply, Magma Chambers and Volcanic Eruptions



<u>With increasing magma supply:</u>

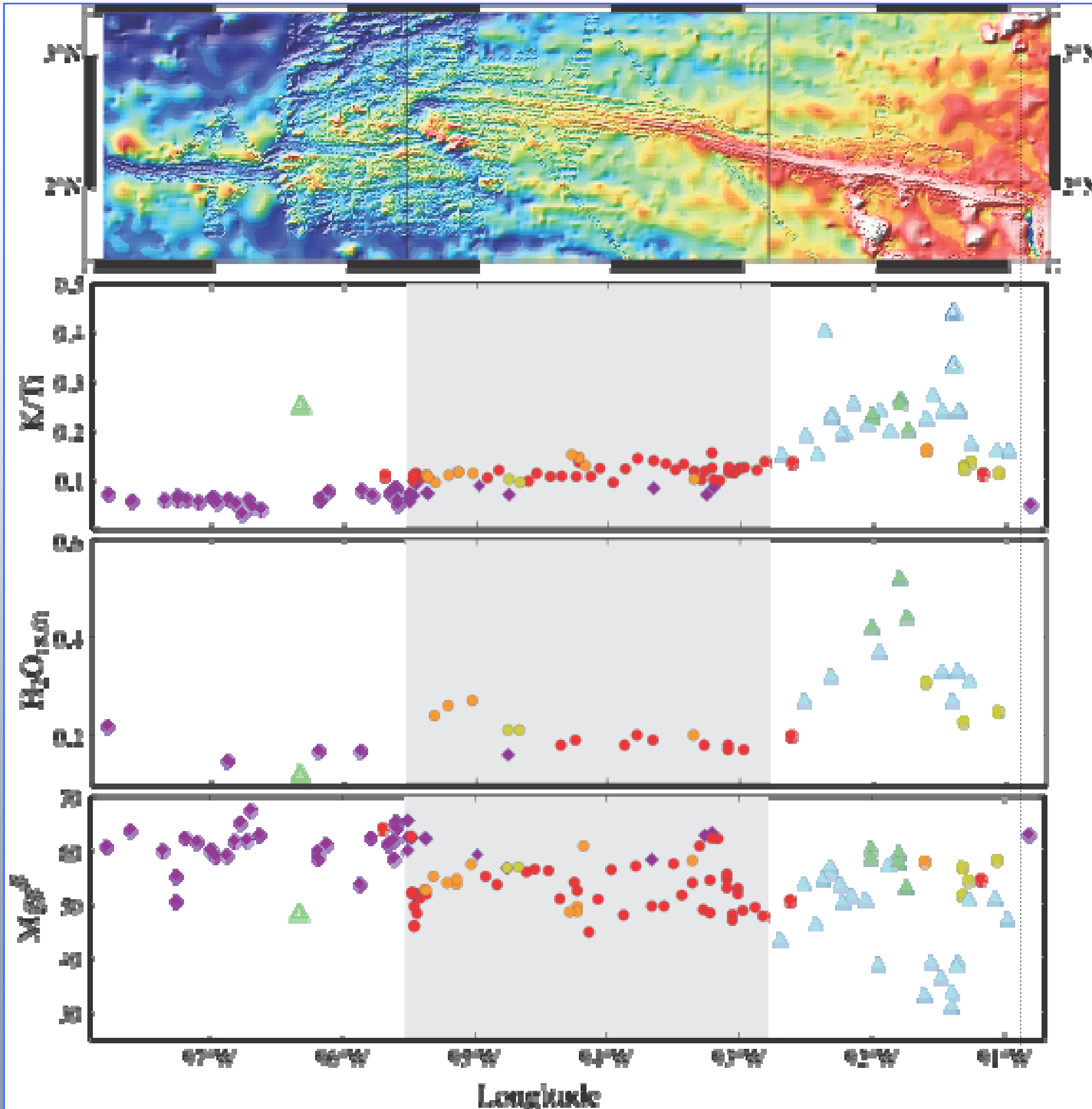
• Axis shoals, axial high develops.

• Axial topography becomes smoother

• Depth to top of magma chamber <u>steps up</u>

•Eruption rate increases

Magma Composition and Magma Supply



<u>Low supply, W. of 95.5°W</u>

- High Mg#
- Low alkalis, N-MORB
- low H_2O

<u>High supply, E. of 96.7°W</u>

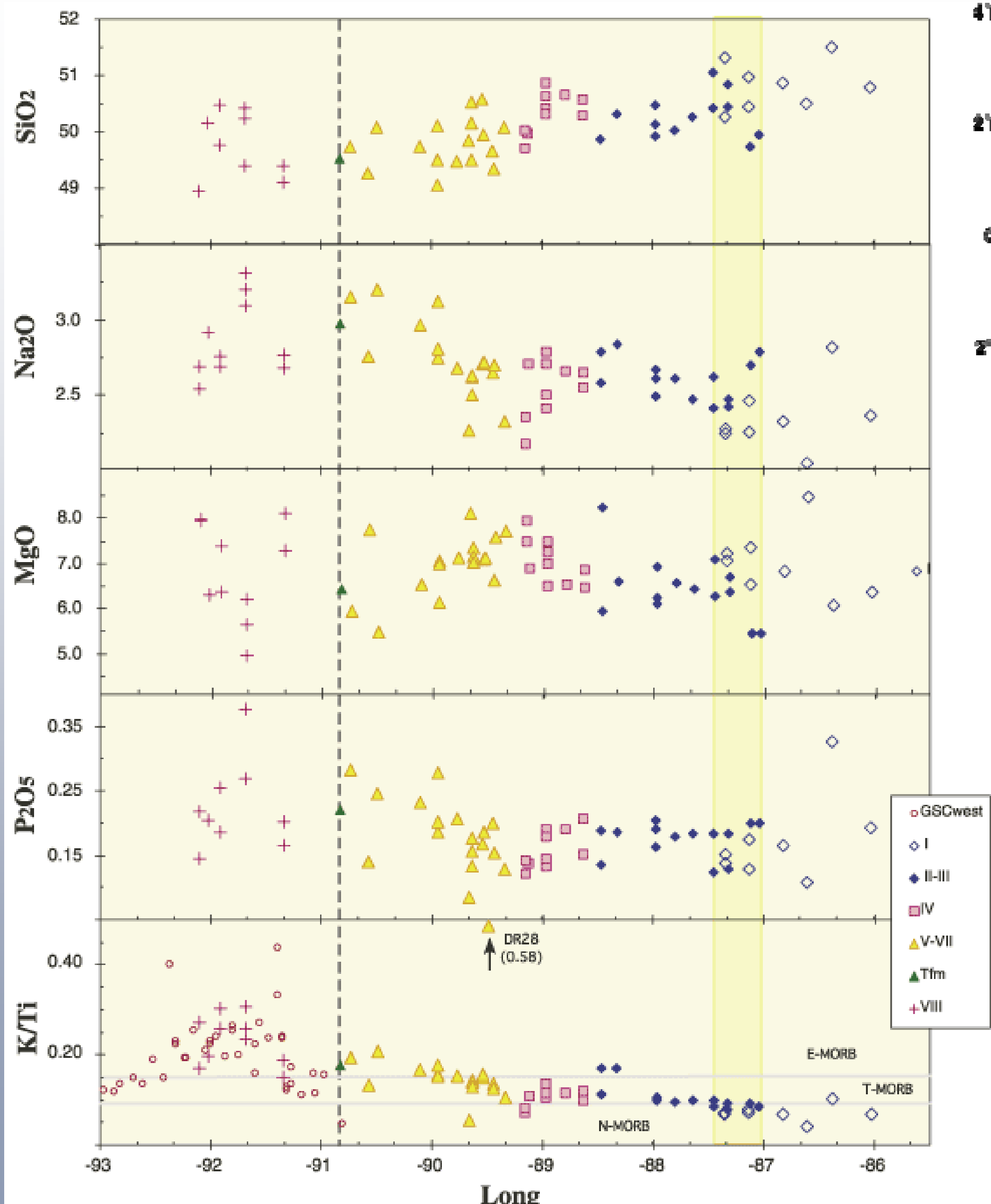
- low, variable Mg#
- alkali-rich E-MORB
- water-rich magmas

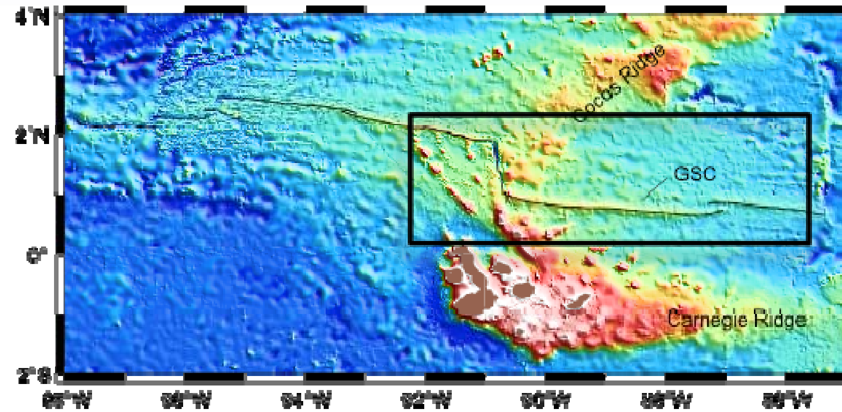
<u>Note</u>:
Inverse relationship between Mg# (~temp)and magma supply

- true for global MORB

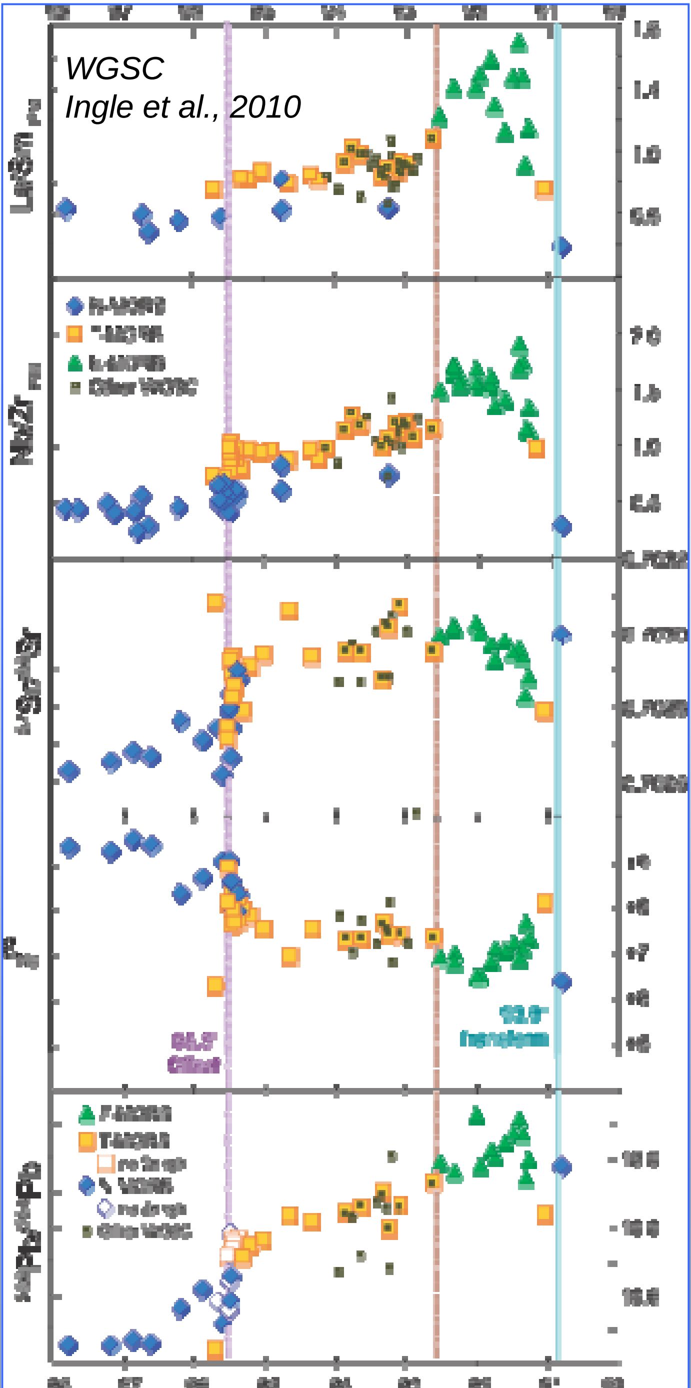
Cushman et al., 2004

Generally similar compositional relations on the eastern GSC





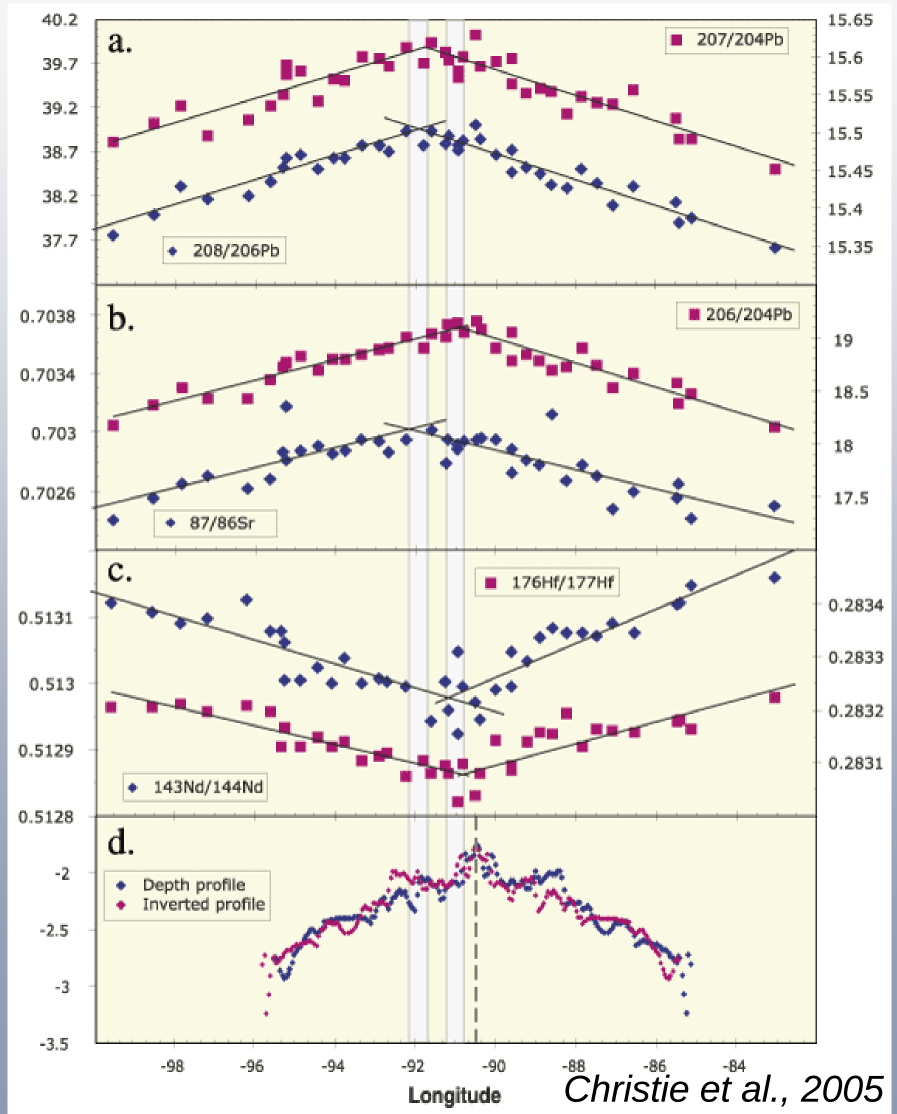
Christie et al., 2005



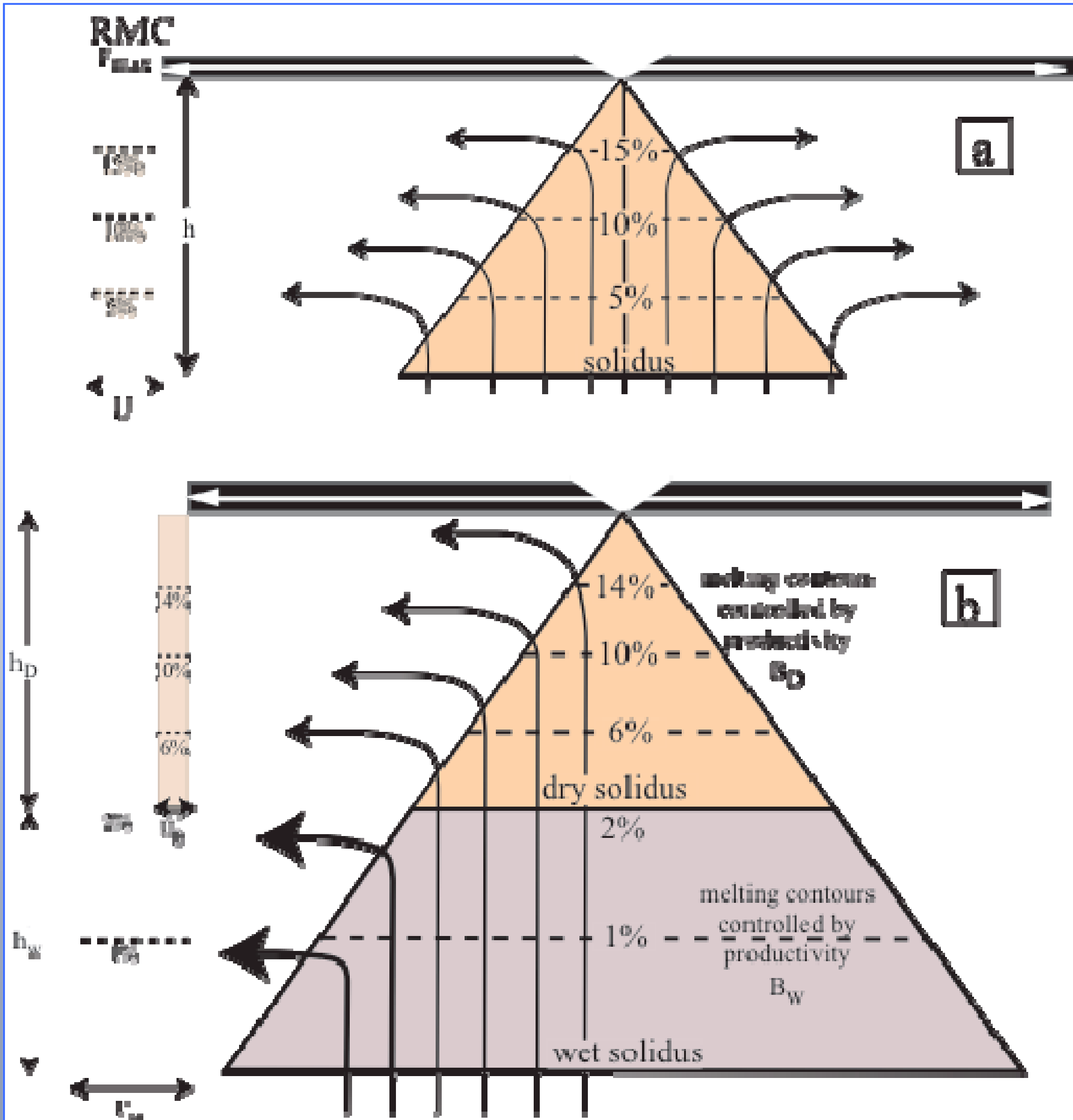
Melting and "Source" Correlate with Magma Supply

With increasing magma supply (proximity to hotspot)

- Incompatible elements are enriched (lower F?)
- more radiogenic isotopic compositions



Magma Supply and Extent of Partial Melting



<u>Hydrous Mantle Melting</u>

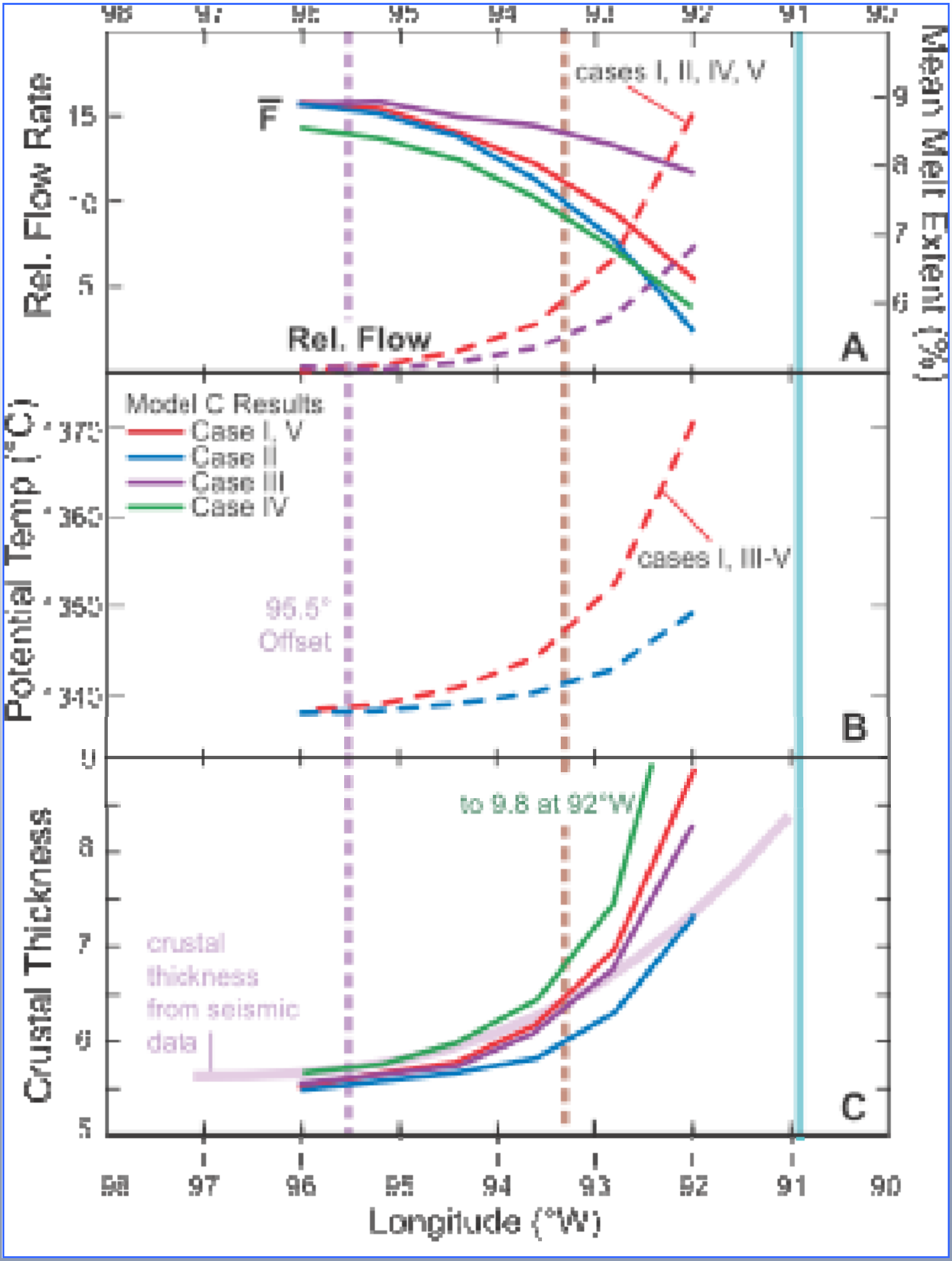
- Depresses the solidus
- Produces a large volume of deep, low-degree melts

[Asimow & Langmuir, 2003]

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

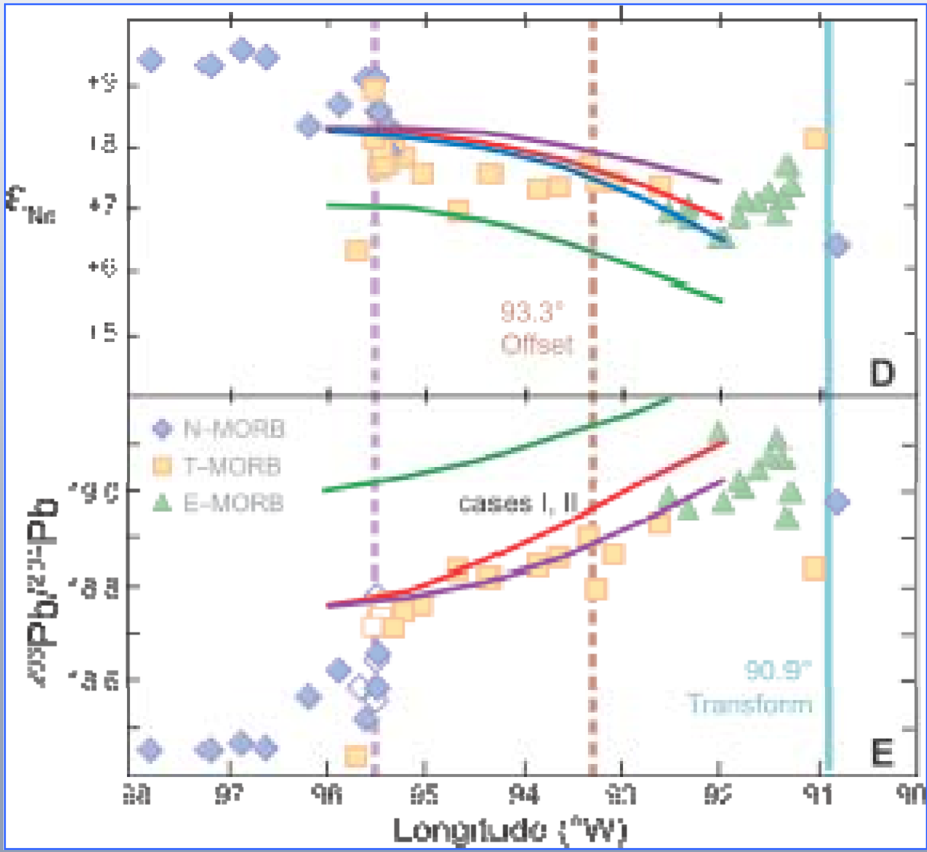
Cushman et al., 2004

Mantle Flow and Melting Models



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

The Galápagos hotspot is not very "hot" (ΔT ~10-30°)



Ingle et al., 2010

Lessons from the Galápagos Spreading Center

<u>As the hotspot is approached along the GSC</u>

- Magma supply rate and crustal thickness increase

- Melting extent <u>decreases</u> with greater contribution from deep, hydrous melting

- Magma chambers get shallower in the crust

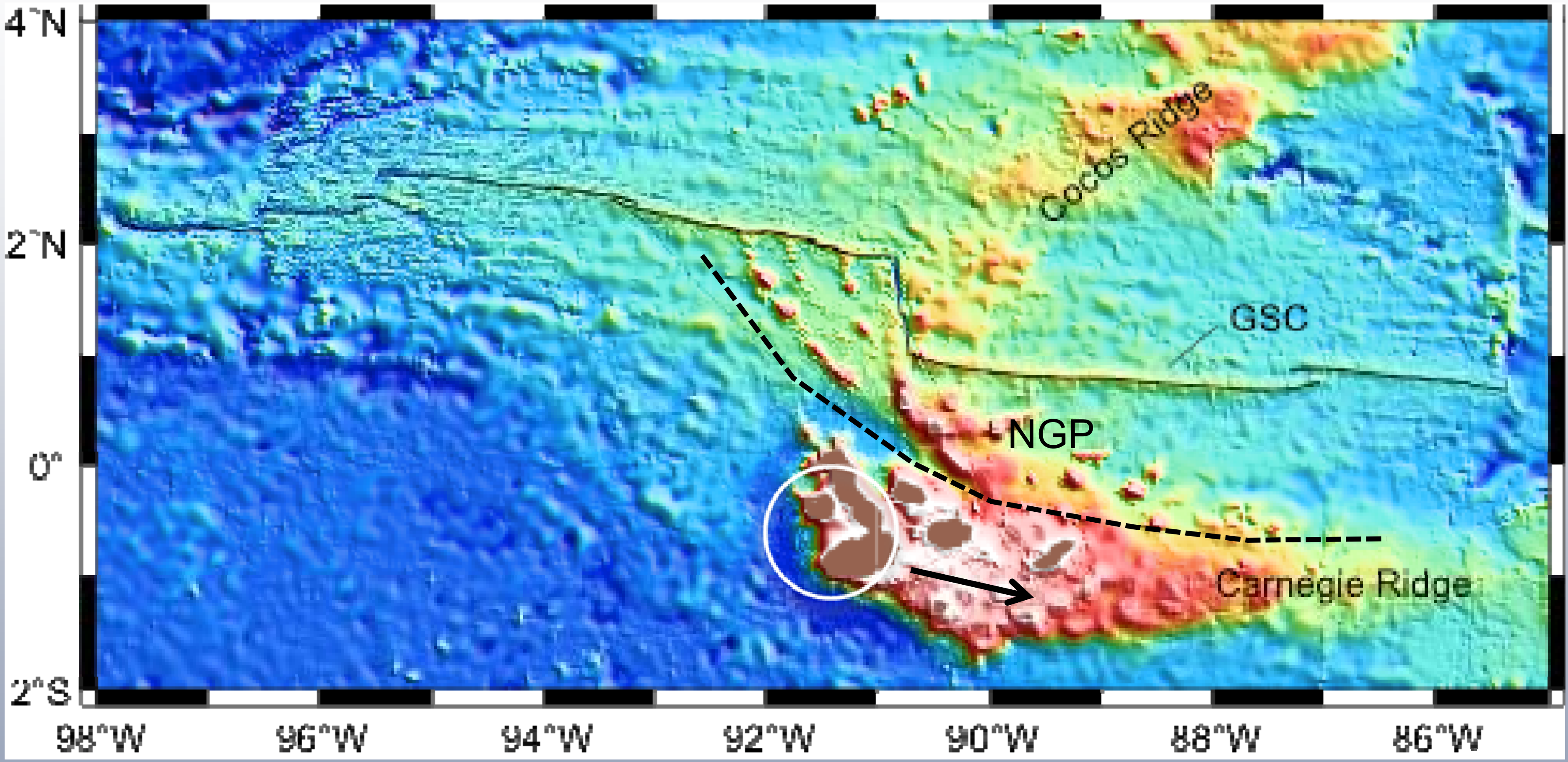
- Axial morphology changes from axial valley to axial high

- 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

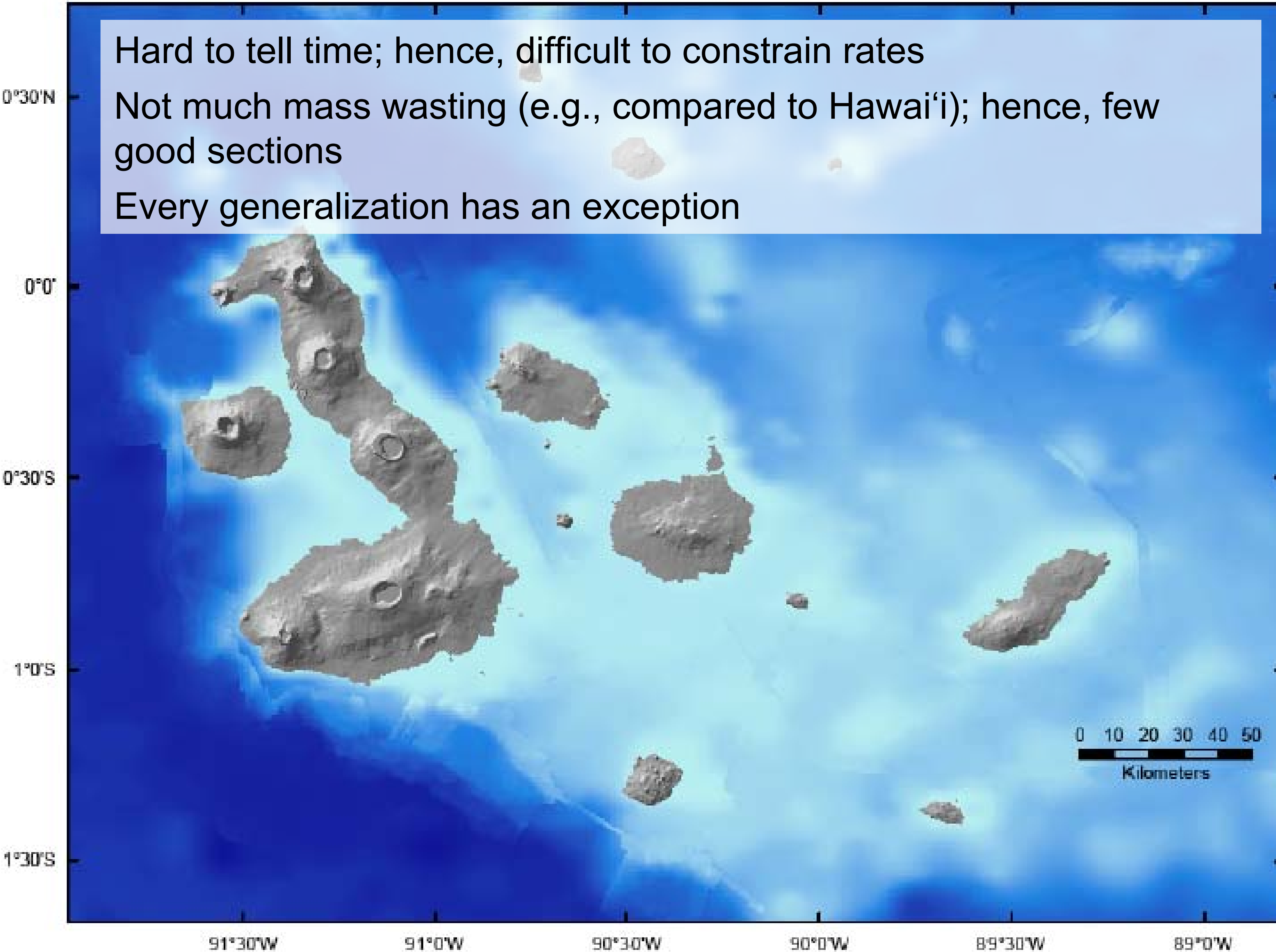
Three (maybe not very distinct) Sub-provinces of the Galápagos Region



Hard to tell time; hence, difficult to constrain rates

Not much mass wasting (e.g., compared to Hawai‘i); hence, few good sections

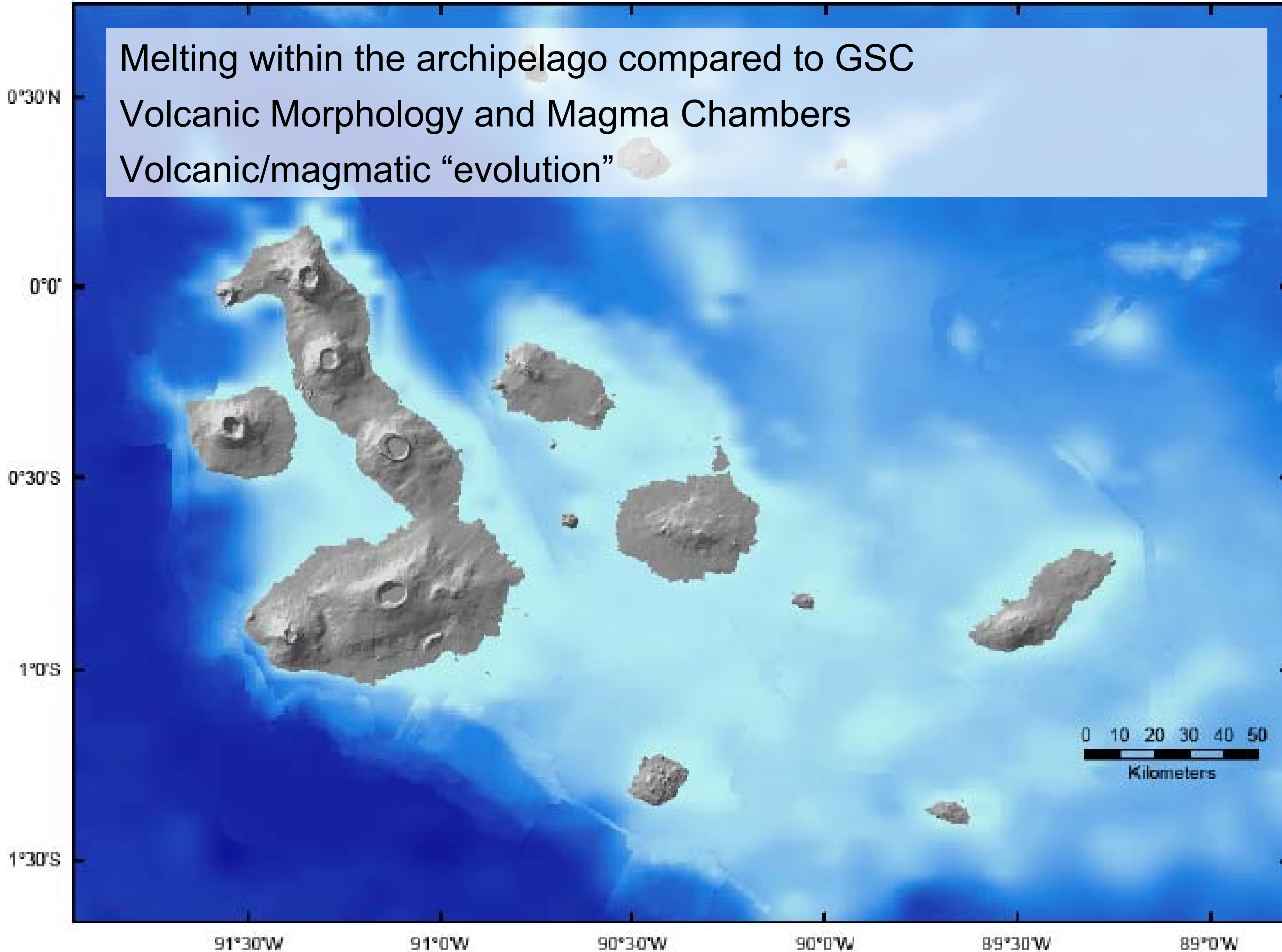
Every generalization has an exception



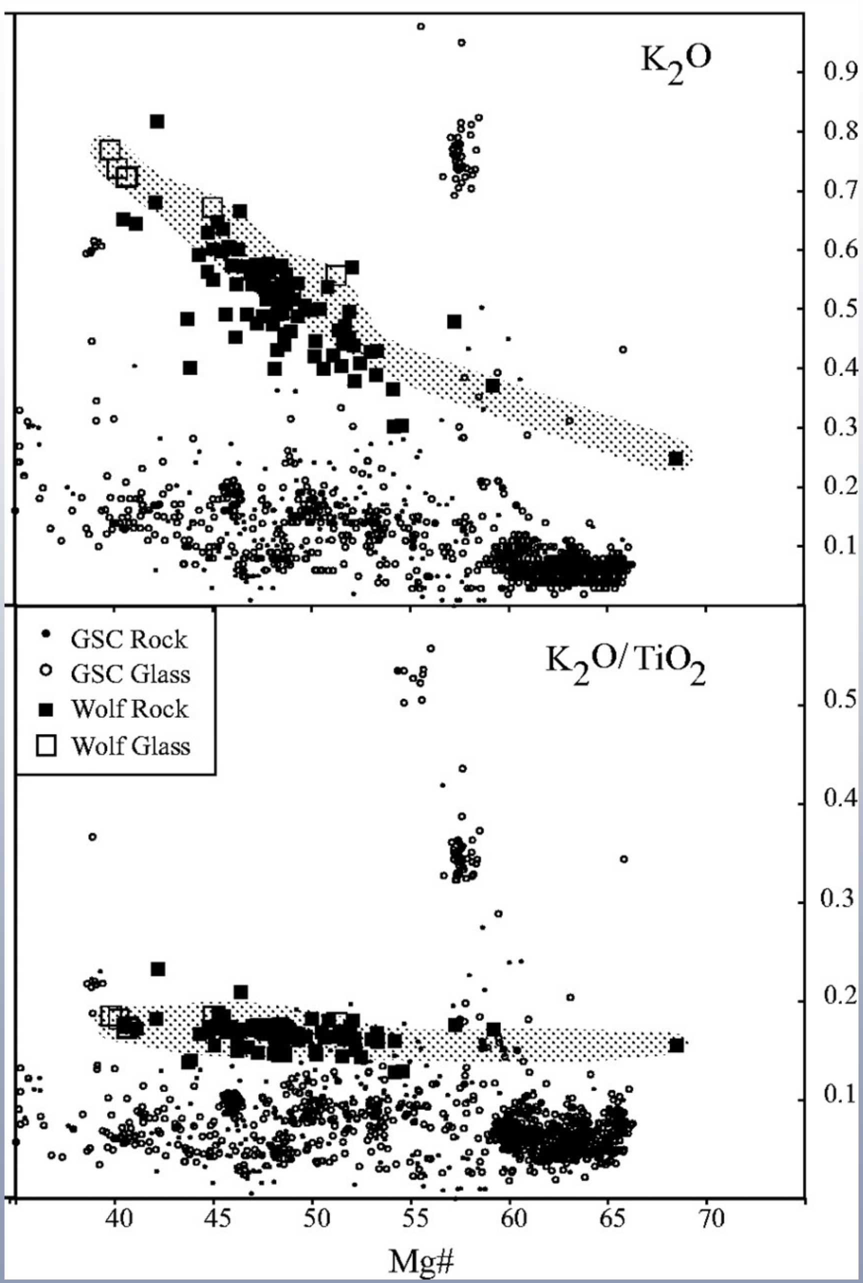
Melting within the archipelago compared to GSC

Volcanic Morphology and Magma Chambers

Volcanic/magmatic "evolution"



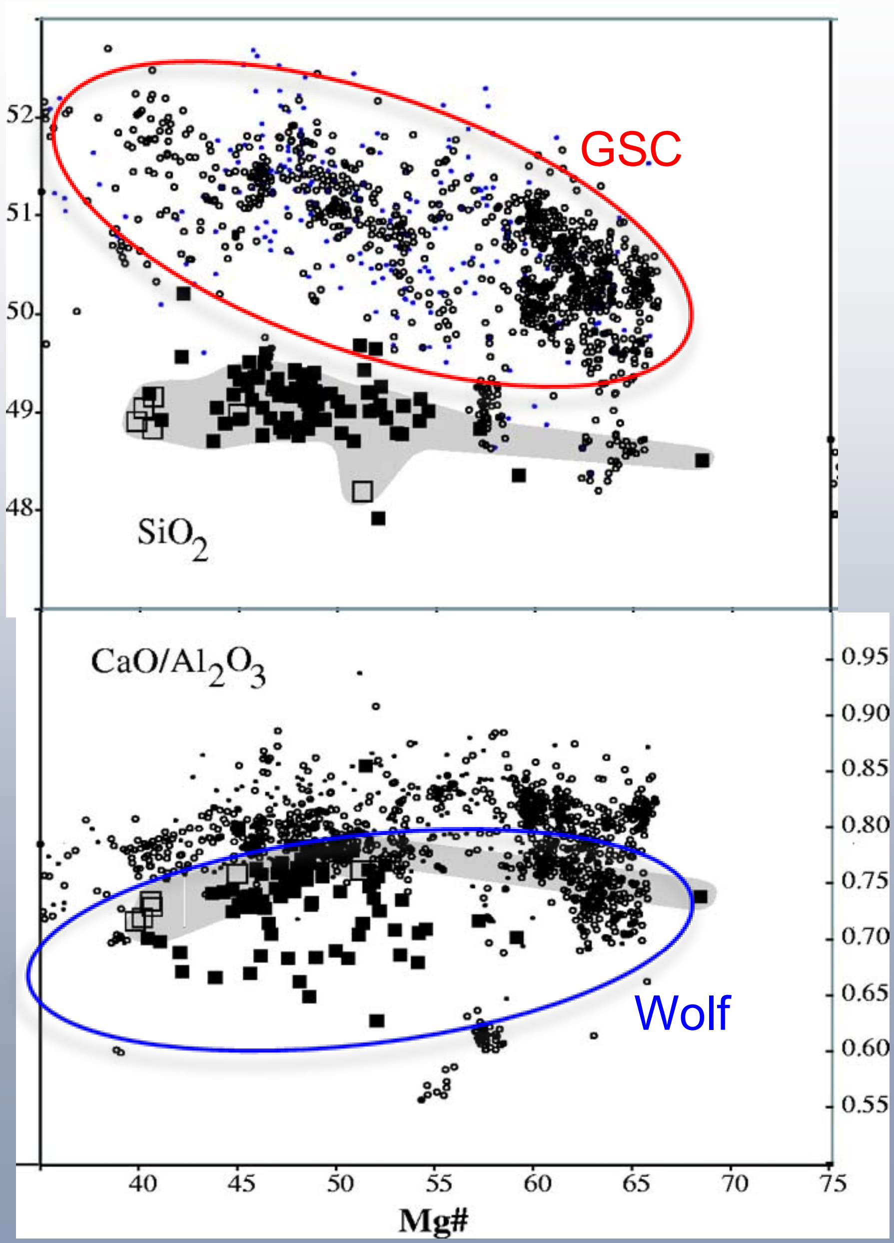
Melting Extents within the Archipelago compared to GSC



Volcan Wolf lavas are enriched in incompatible elements compared to <u>most, but not all</u>, of those from the GSC

Geist et al., 2005

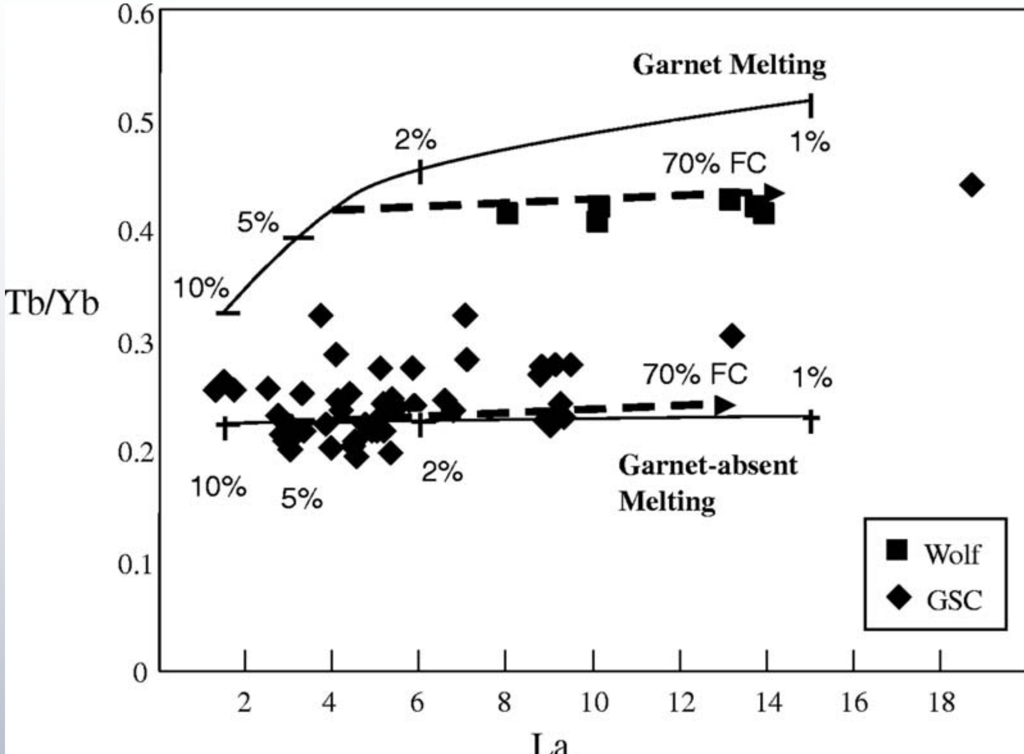
Melting Extents within the Archipelago compared to GSC

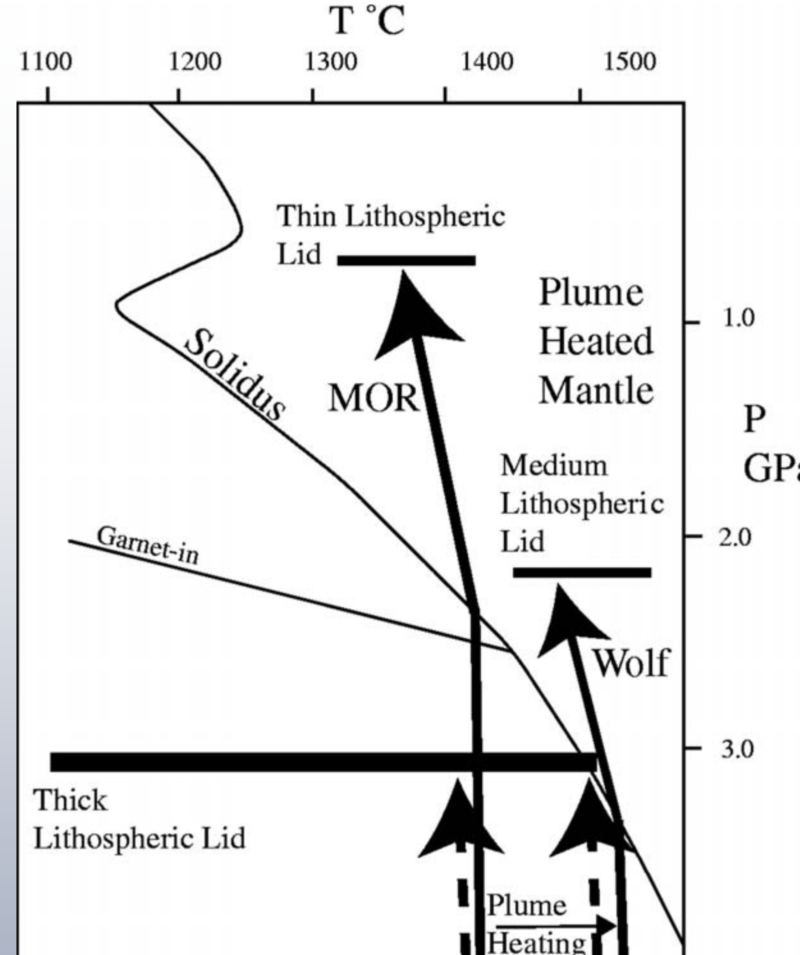


Volcan Wolf lavas have lower SiO_2 and CaO/Al_2O_3 compared to <u>most, but not all,</u> of those from the GSC

These data all suggest lower mean extents of melting than for (<u>most</u>) GSC lavas

Geist et al., 2005





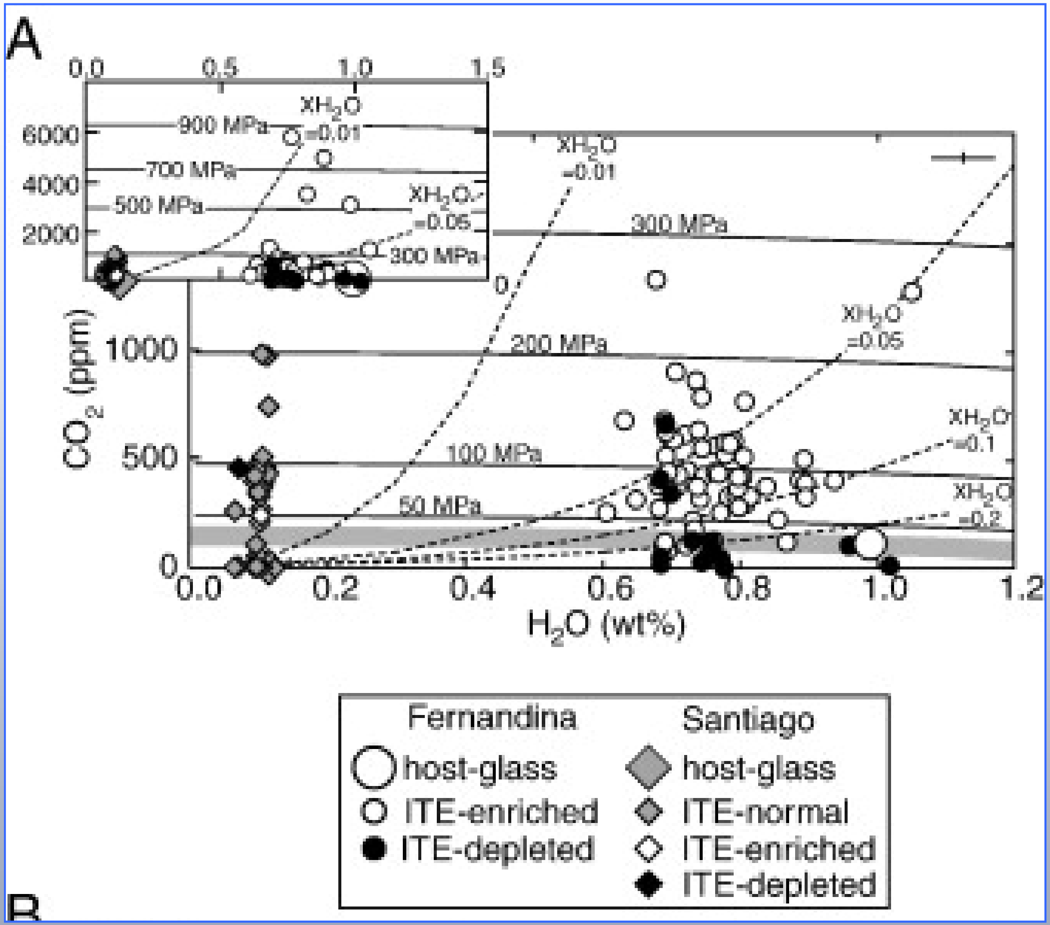
Geist et al., 2005

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



Koleszar et al., 2009

Melt inclusion data affected by open-system processes

- Degassing
- Crustal interaction
- Seawater assimilation

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?

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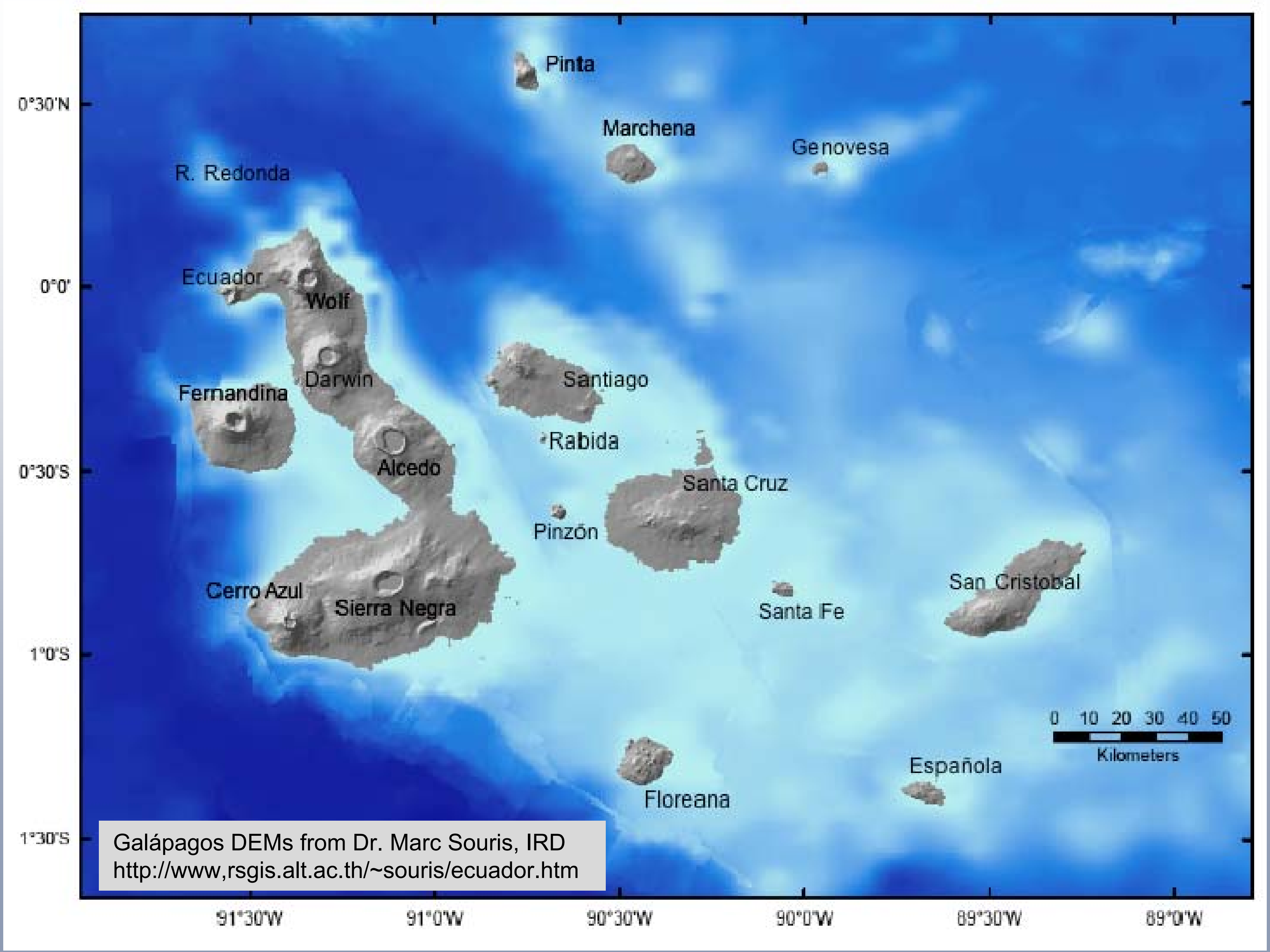
* My opinion – but see new hypothesis for deep CO_2-induced melting beneath the archipelago by Geist et al. (this meeting)

Volcanic Morphology, Magma Supply, and Magma Chambers



Calderas

Only(?) form over shallow magma chambers
(even if we don't understand the mechanism)

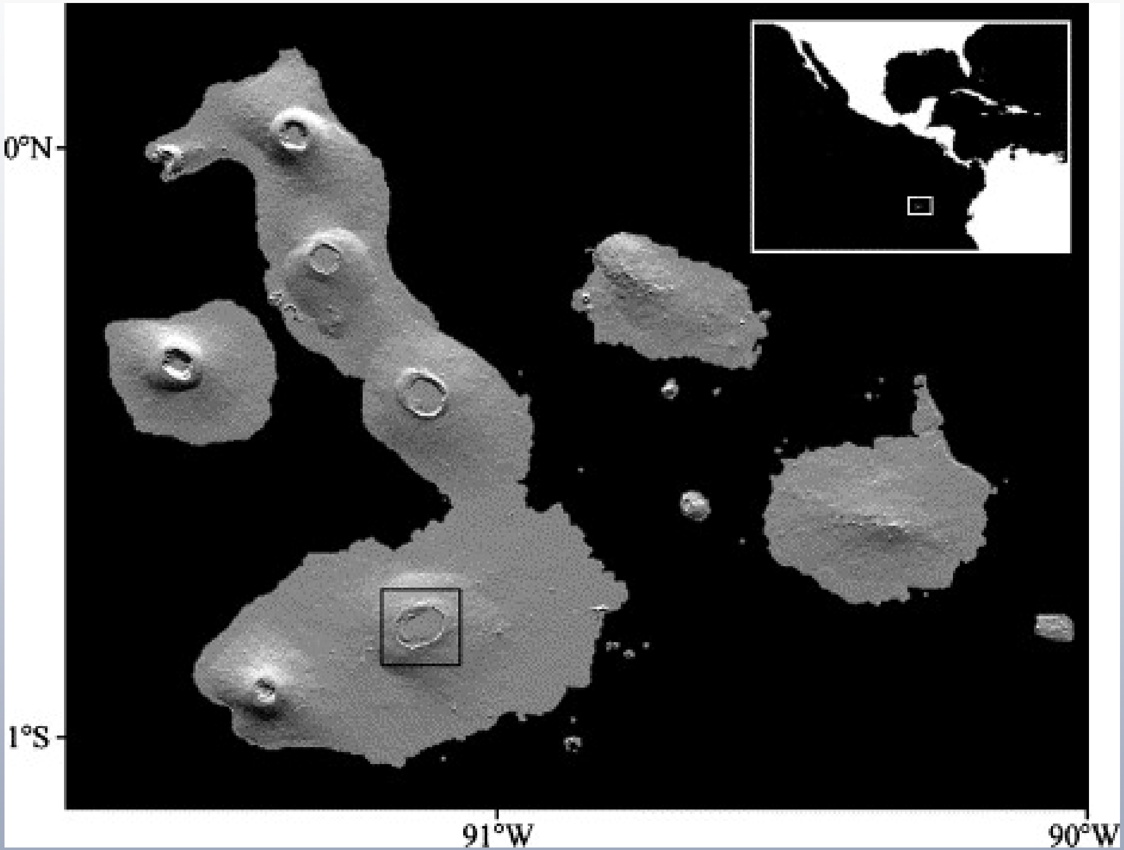
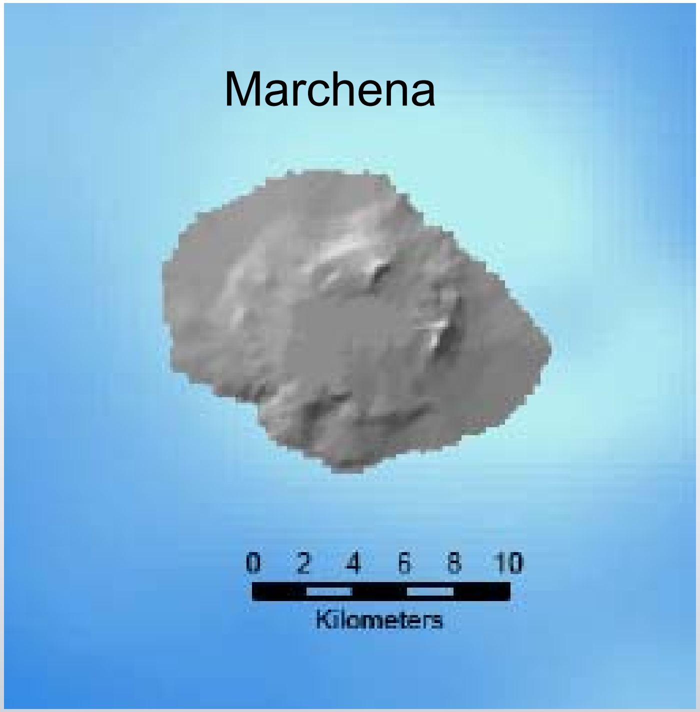
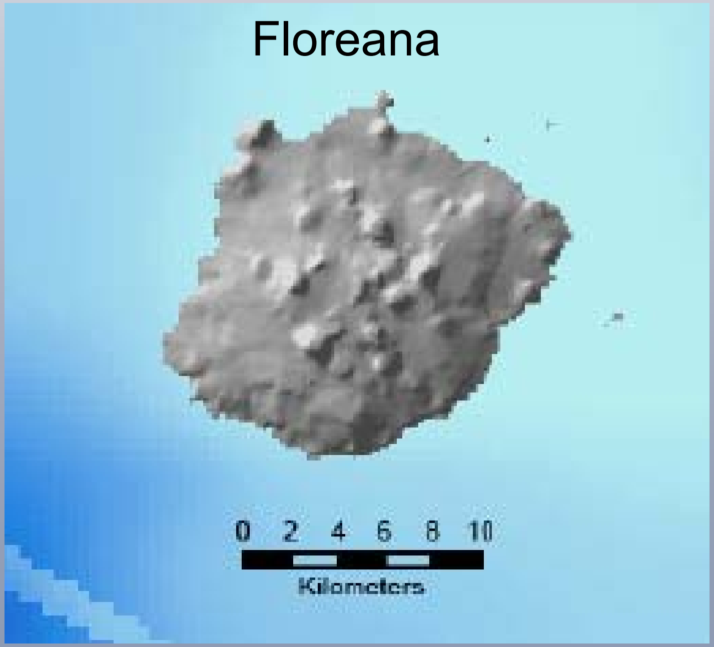


Figure from Yun et al., 2006

Variations in presence/absence, size, depth

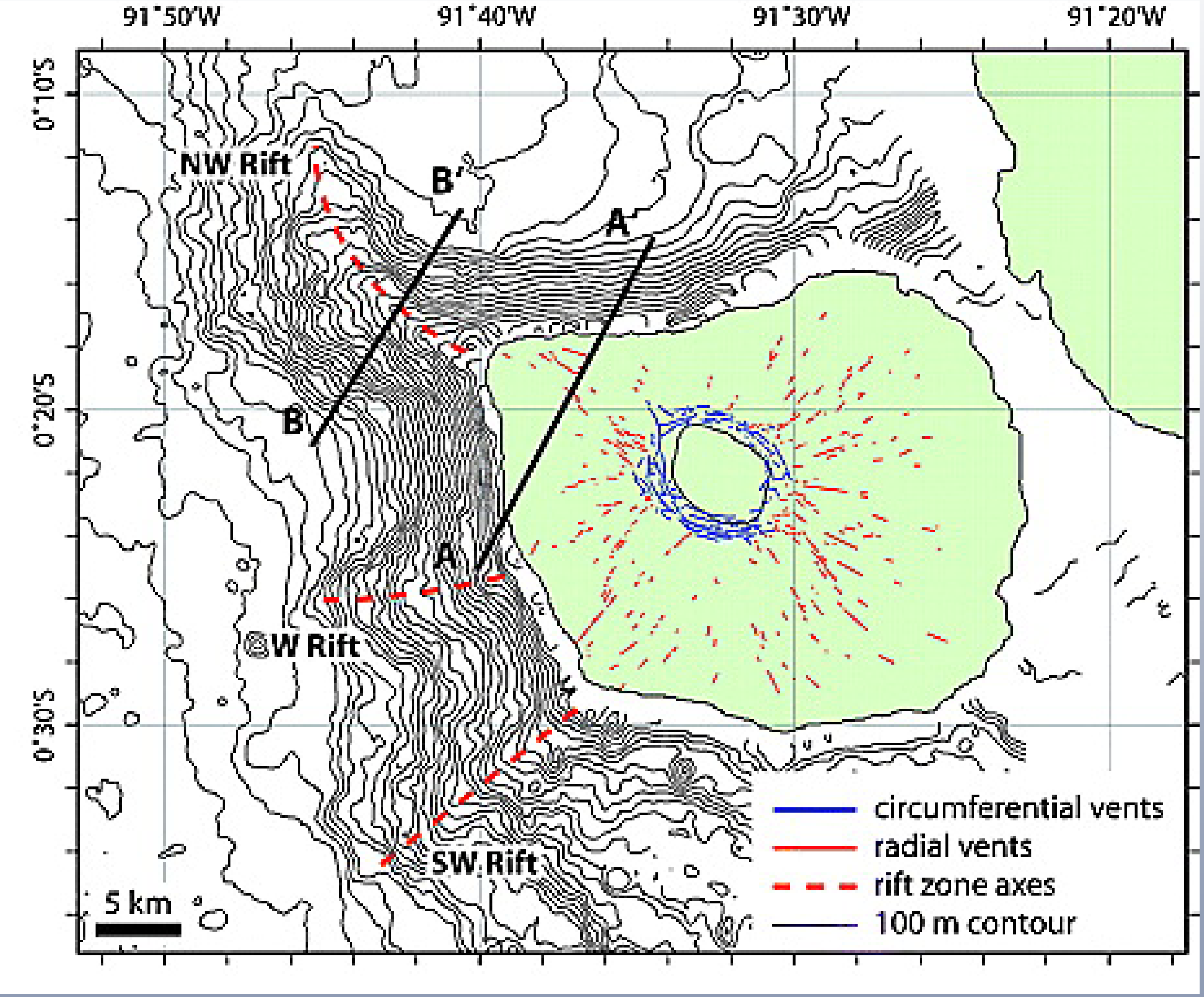




Galápagos volcanoes differ from Hawaiian volcanoes

-lack of strongly preferred orientation of radial rifts, at least in subaerial part of edifice

- presence of circumferential fissures

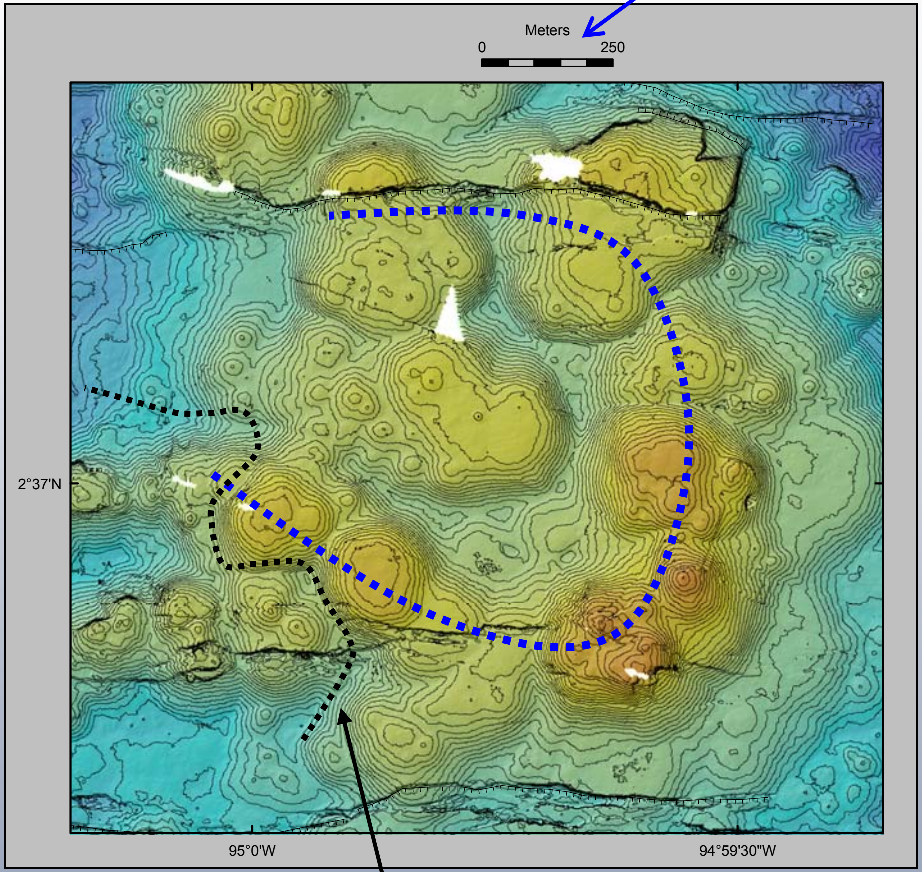


Is this why there is so little mass wasting in Galápagos?

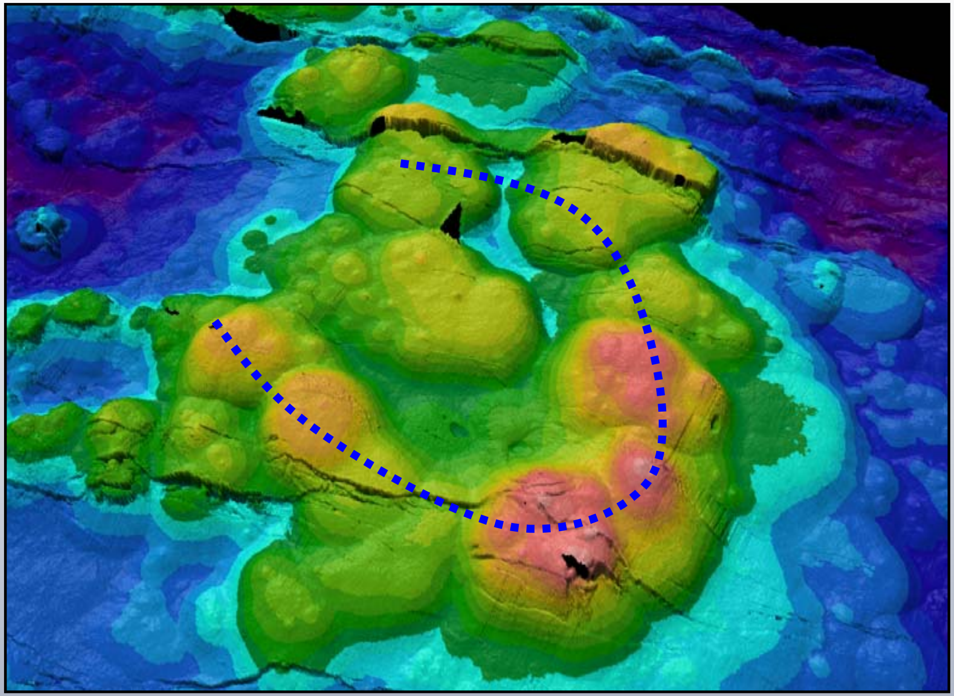
Rift systems on Fernandina
[Geist et al., 2006]

Circular (arcuate) volcanic construction on the GSC near 95°W

200-m scale bar

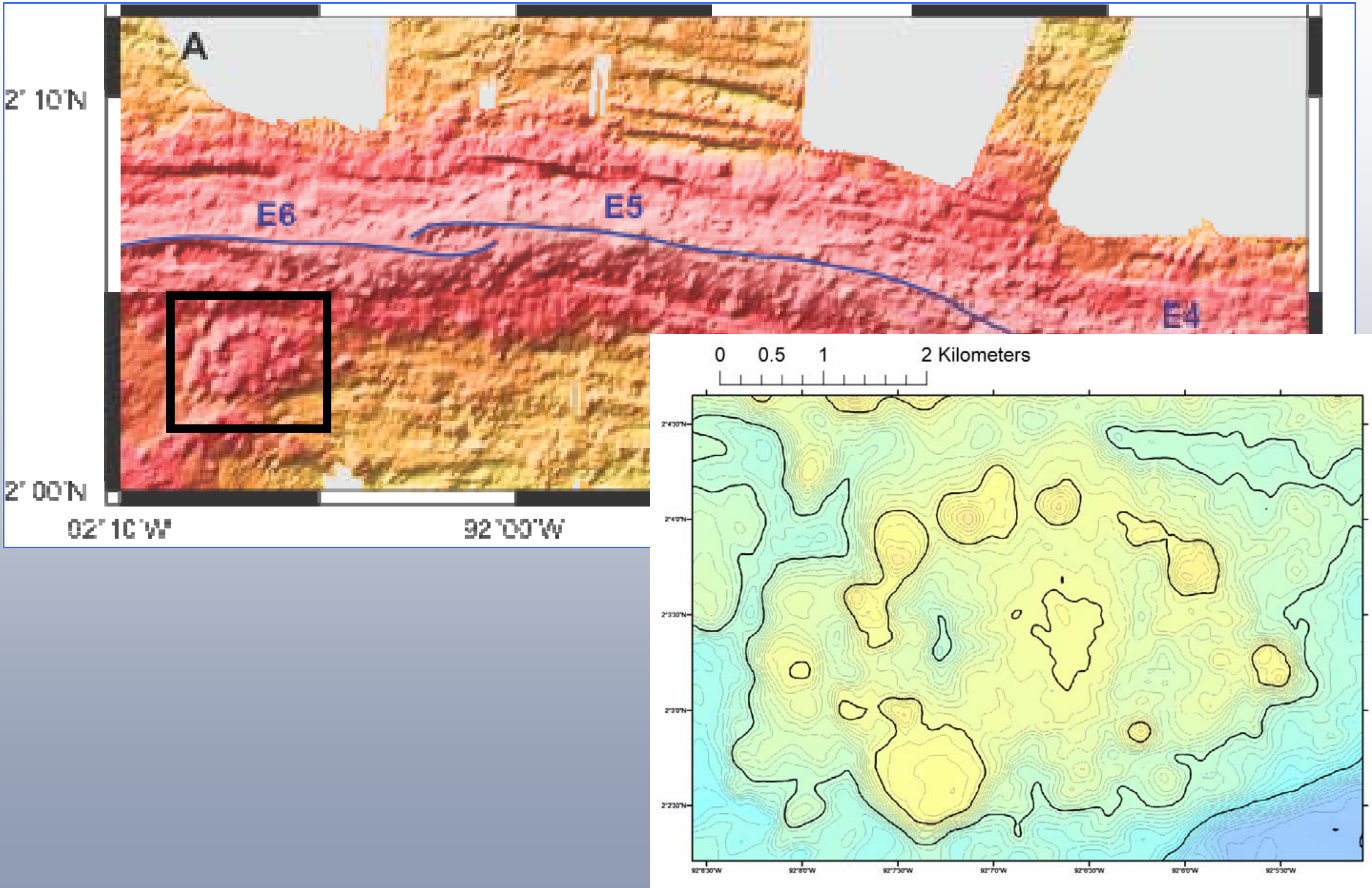


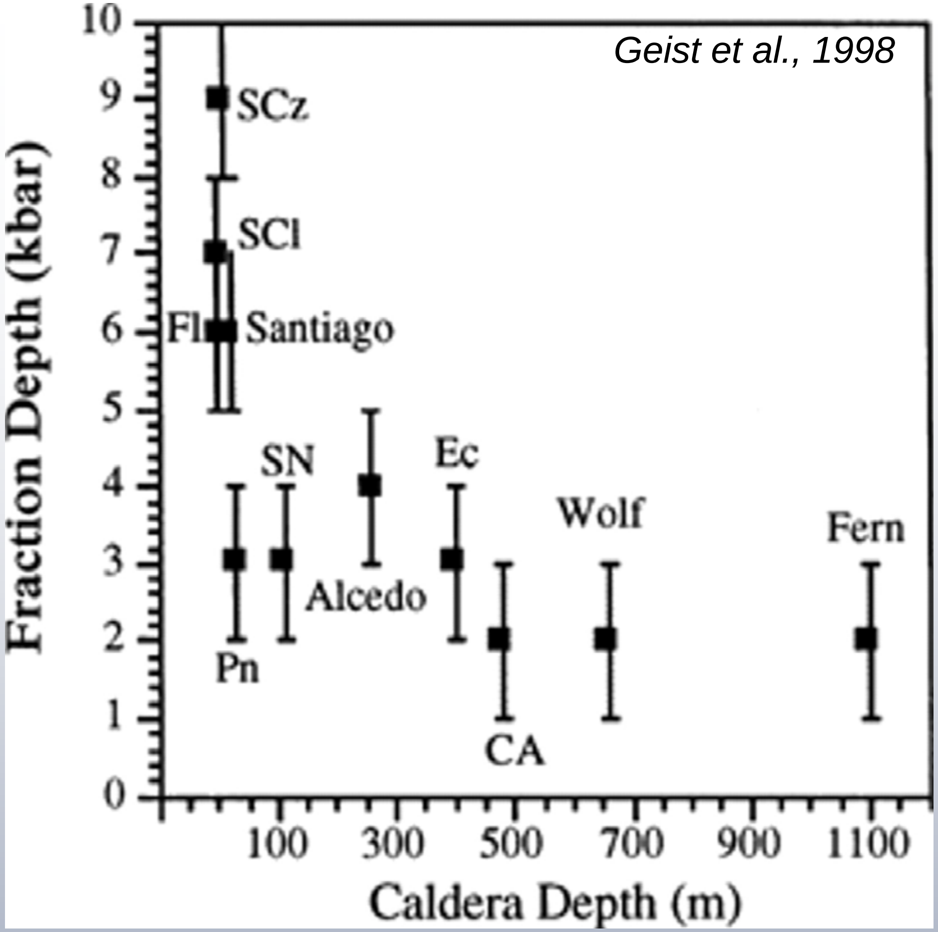
Geologic contact



2 m-resolution Reson 7125 multibeam mounted on AUV Sentry

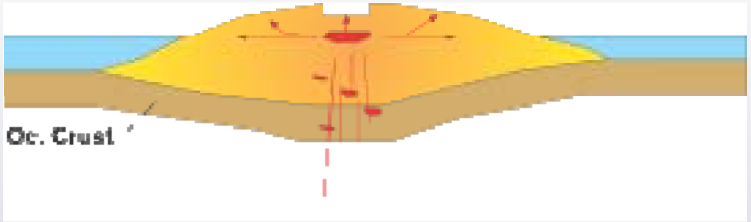
Large, off-axis, circular mound structure near 92°W

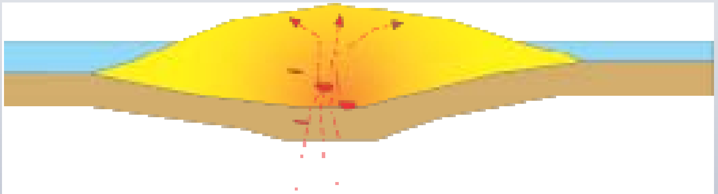


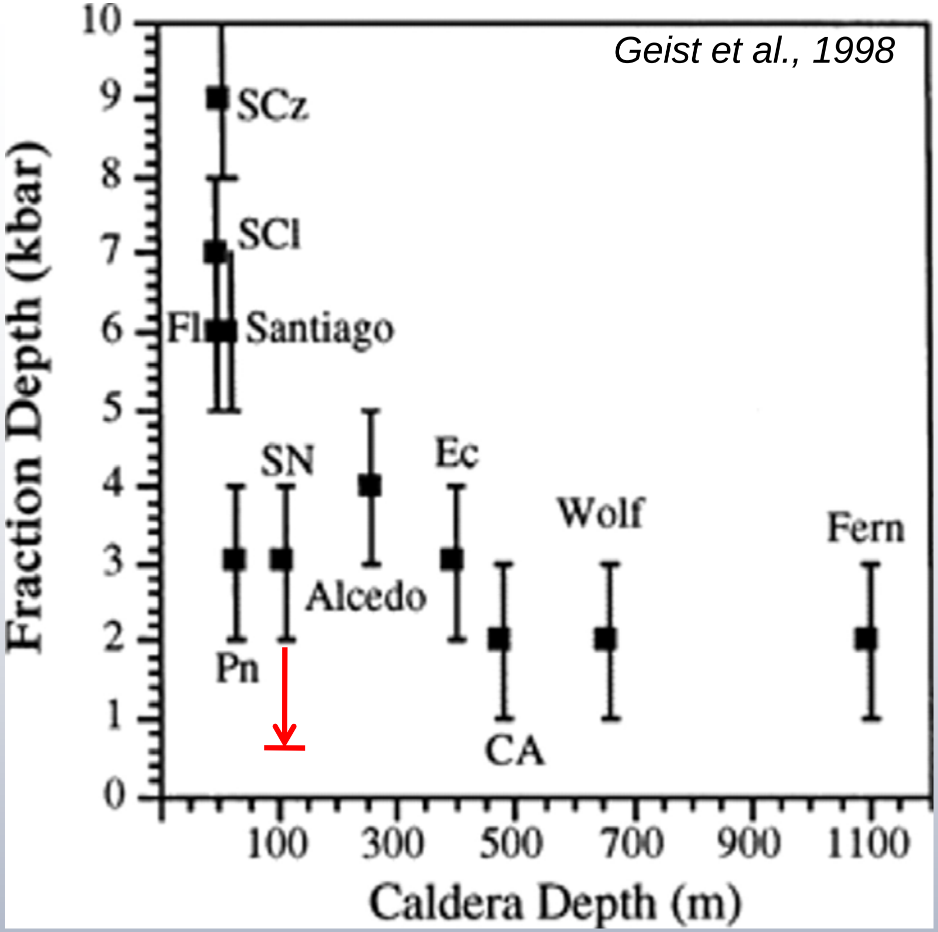


Relationship between caldera depth and pressure of fractionation

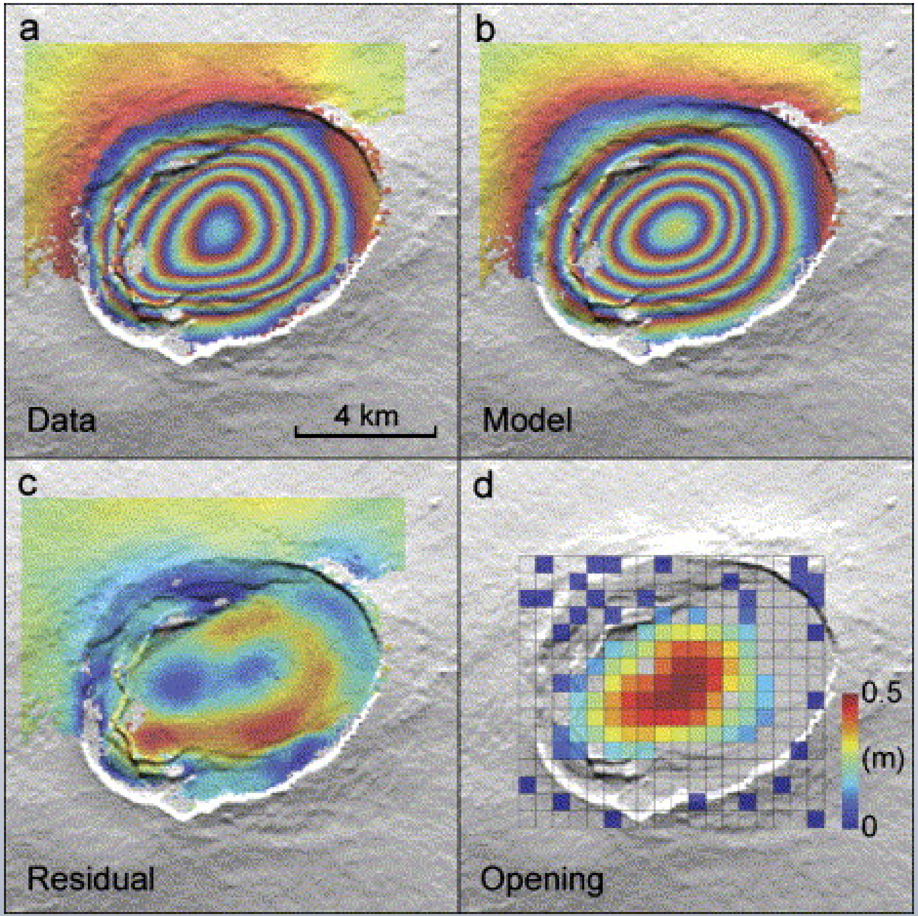
Magma chambers can hide (mix out) deeper level processes







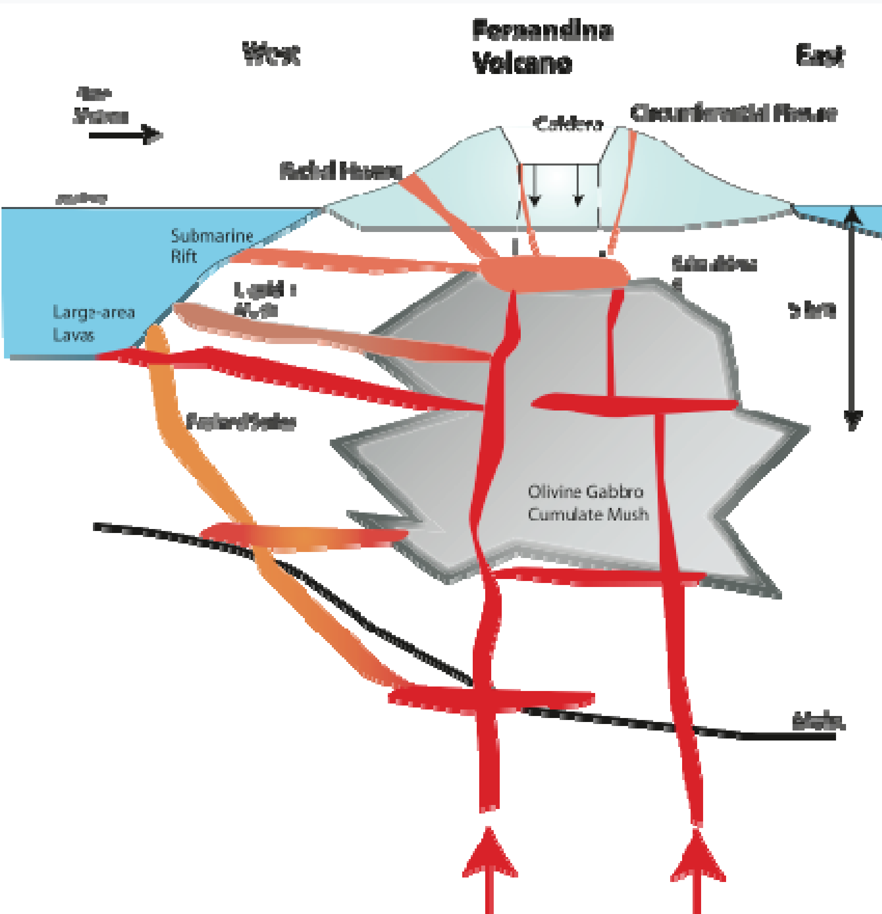
Relationship between caldera depth and pressure of fractionation

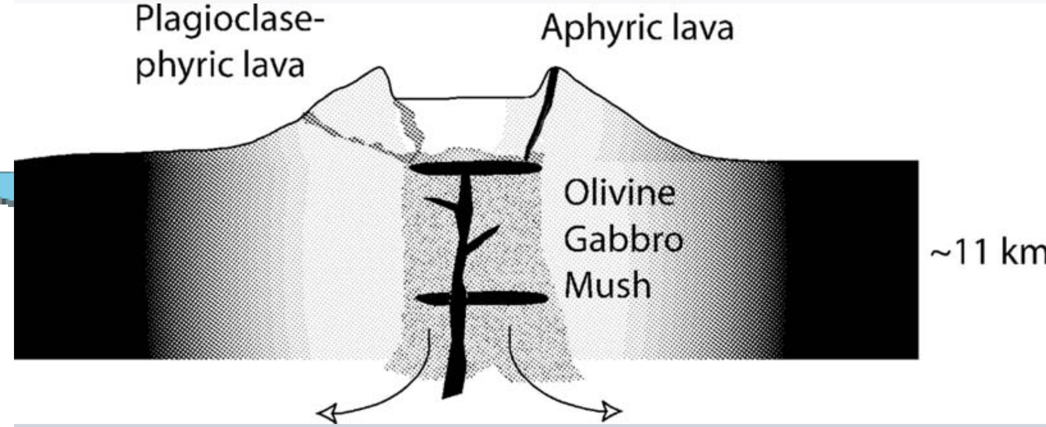


Yun et al., 2006

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





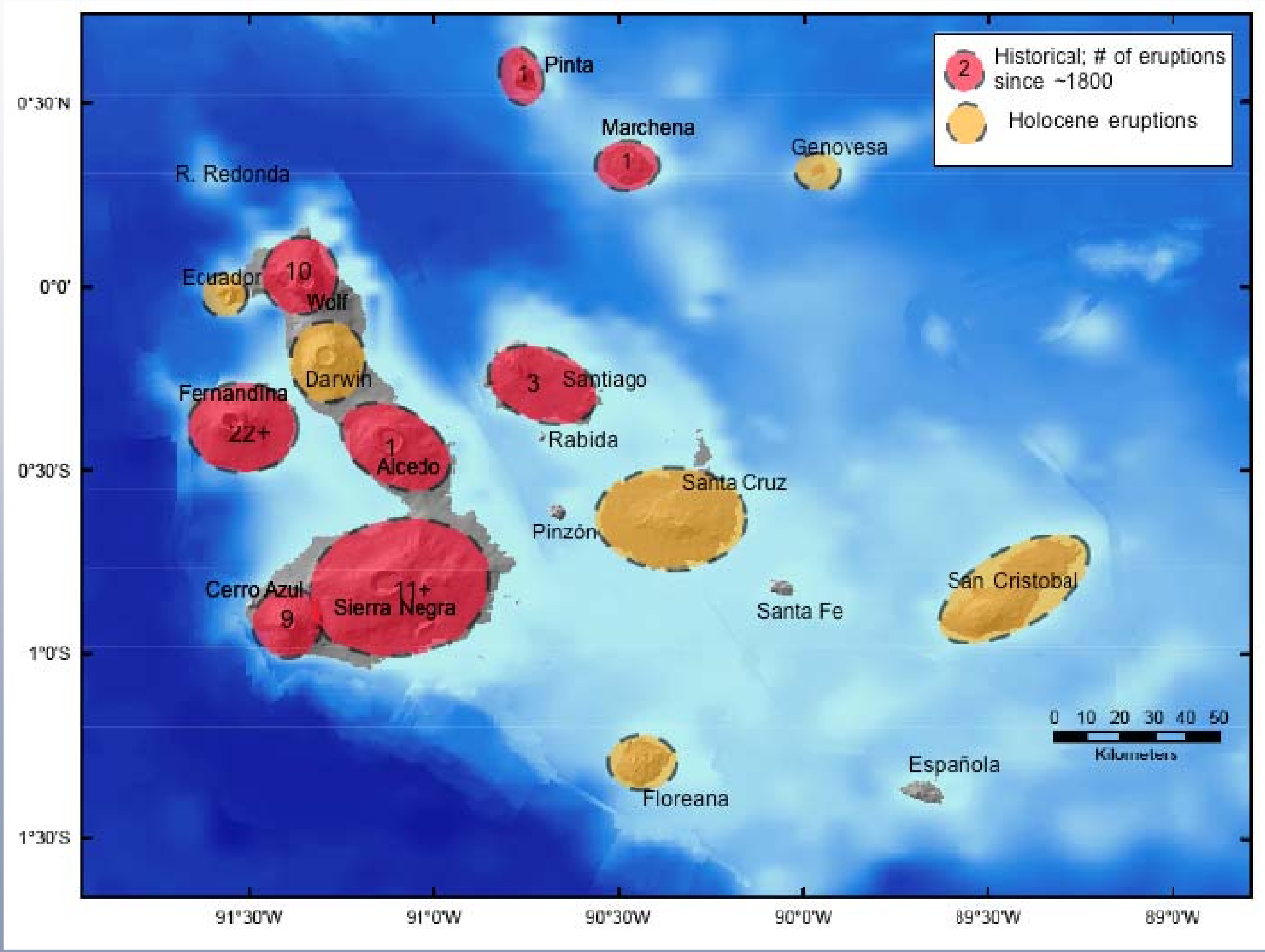
Geist et al., 2005

Geist et al., 2008

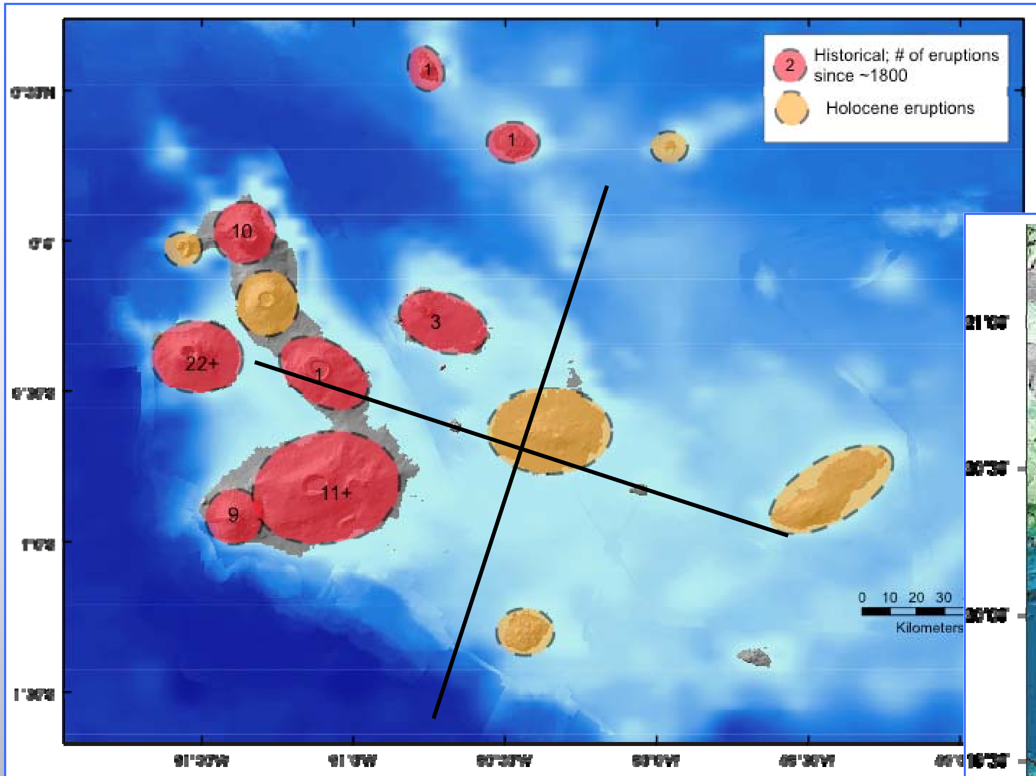
Volcanoes with calderas are more active than those without

Some caldera volcanoes have not had historical eruptions

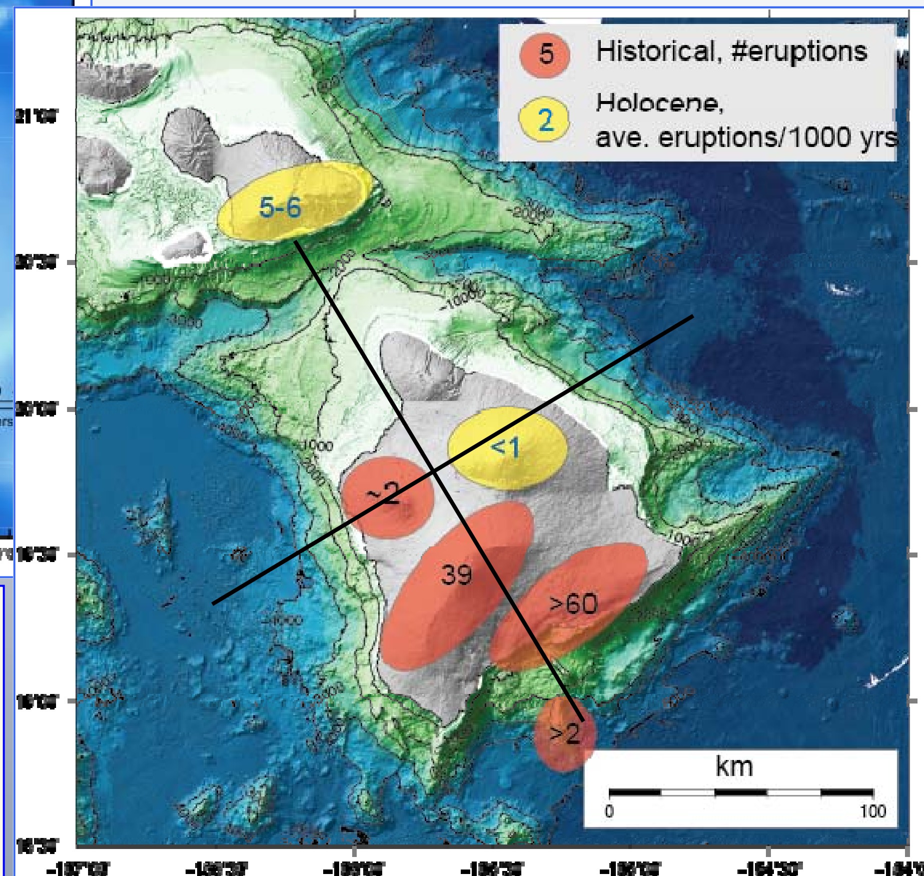
Some historical eruptions have occurred on volcanoes without calderas



Galápagos volcanism slightly more dispersed than in Hawaiʻi



Maps at same scale
bar is 200 km long



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

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

Mauna Loa: $20\text{-}30 \times 10^6\ m^3/yr$

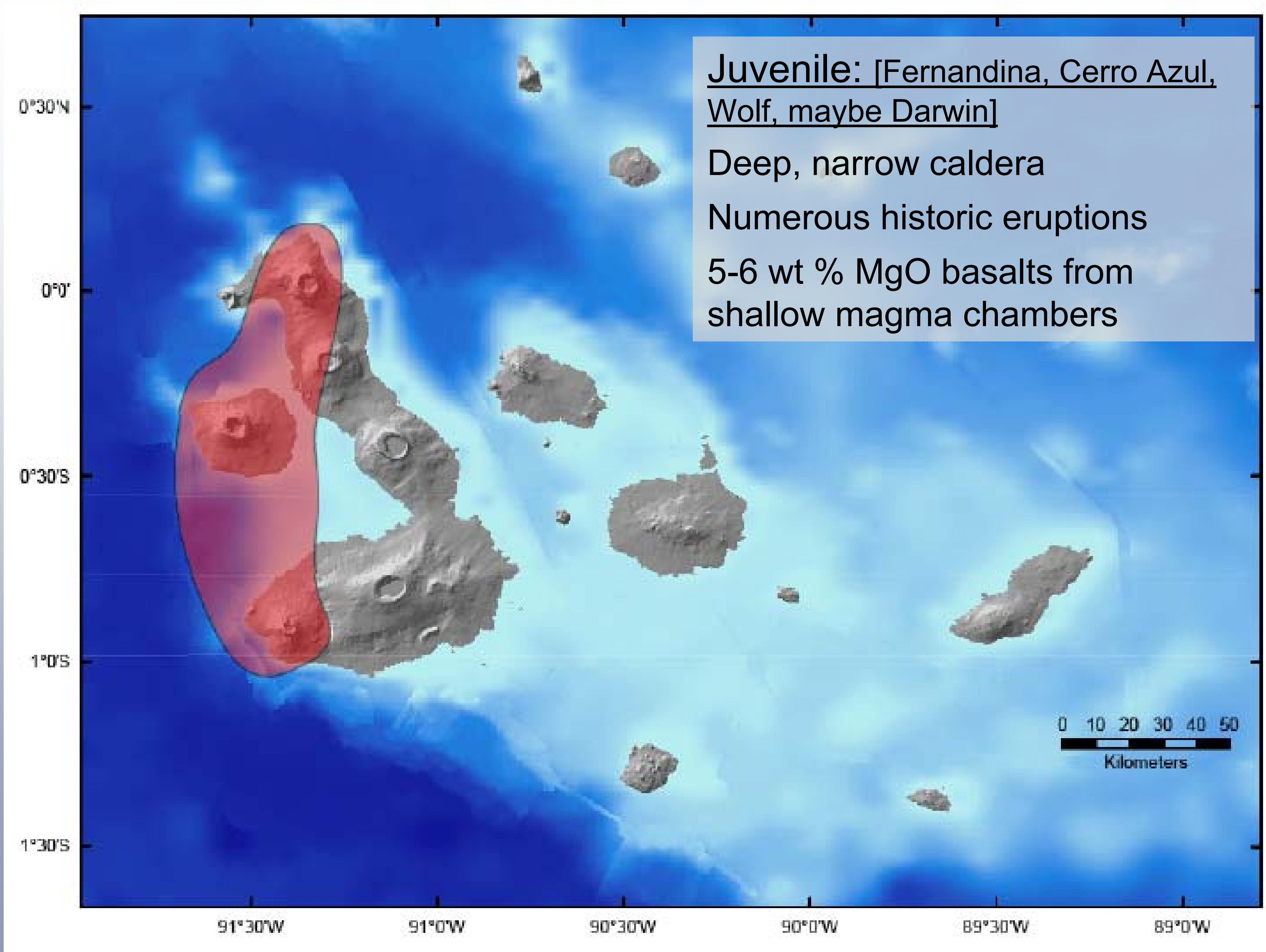
Galápagos Volcanic “Stages” *[Geist et al., 1998]*

<u>Juvenile: [Fernandina, Cerro Azul, Wolf, maybe Darwin]</u>

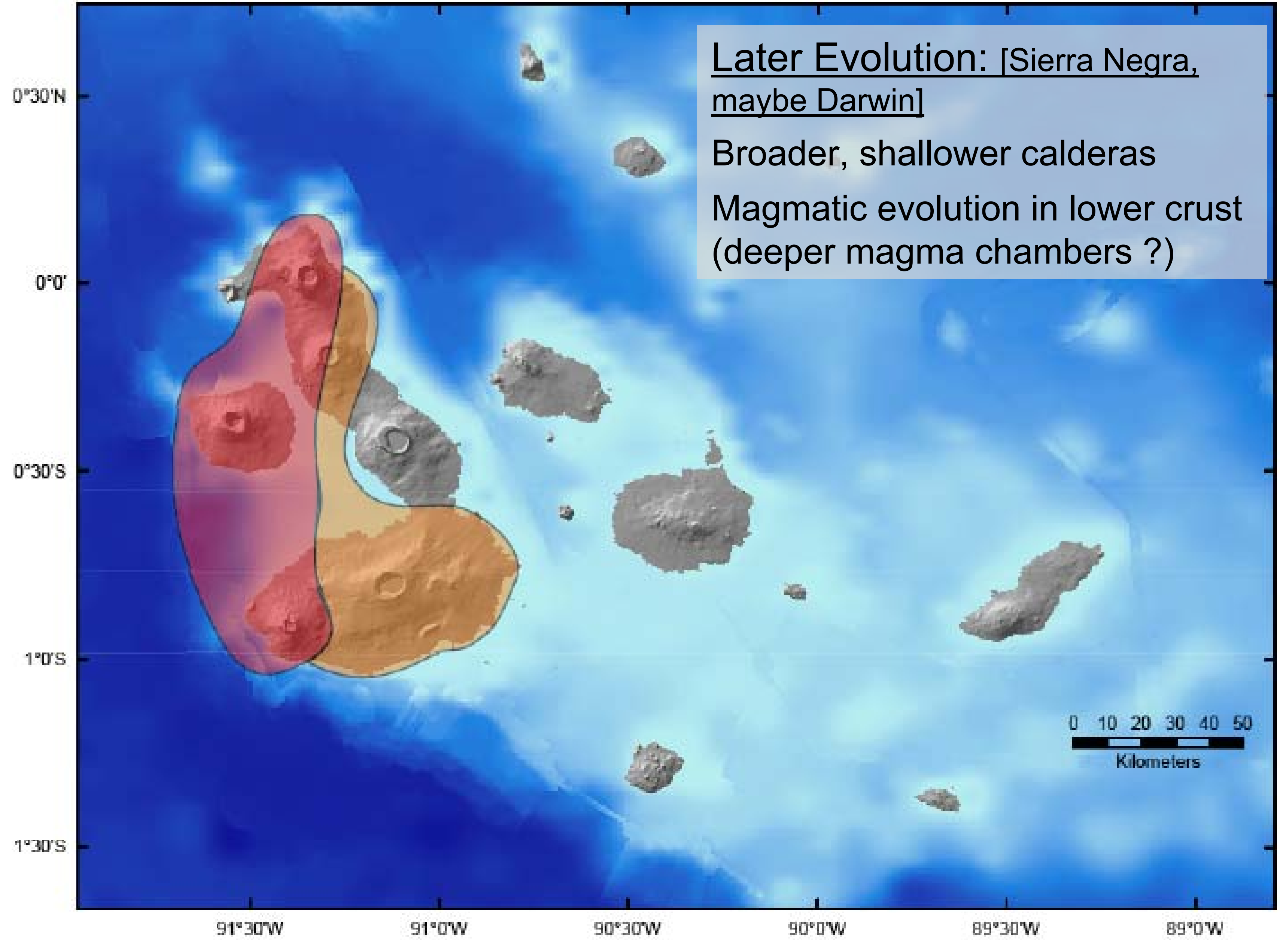
Deep, narrow caldera

Numerous historic eruptions

5-6 wt % MgO basalts from shallow magma chambers



Galápagos Volcanic "Stages" *[Geist et al., 1998]*



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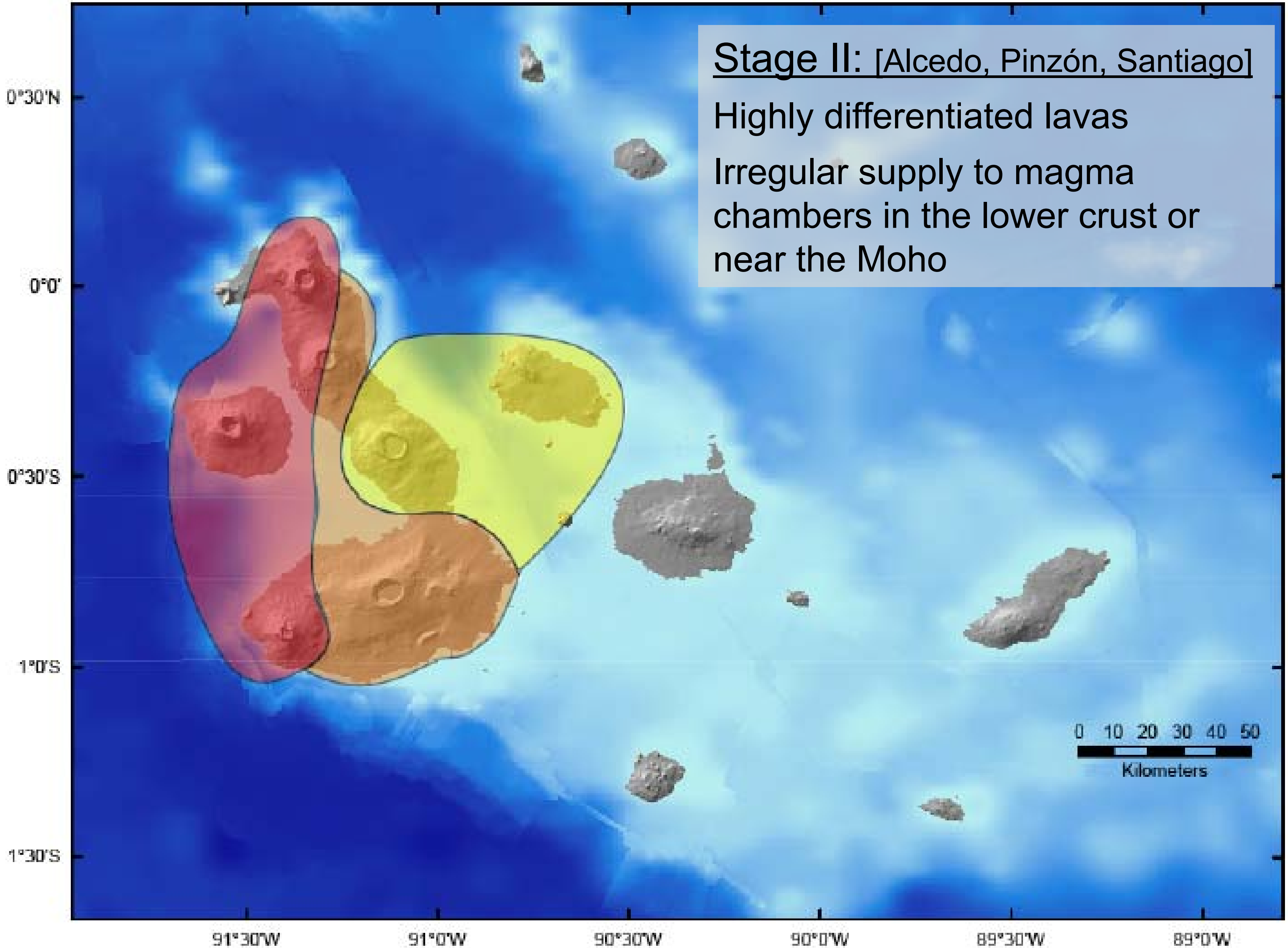

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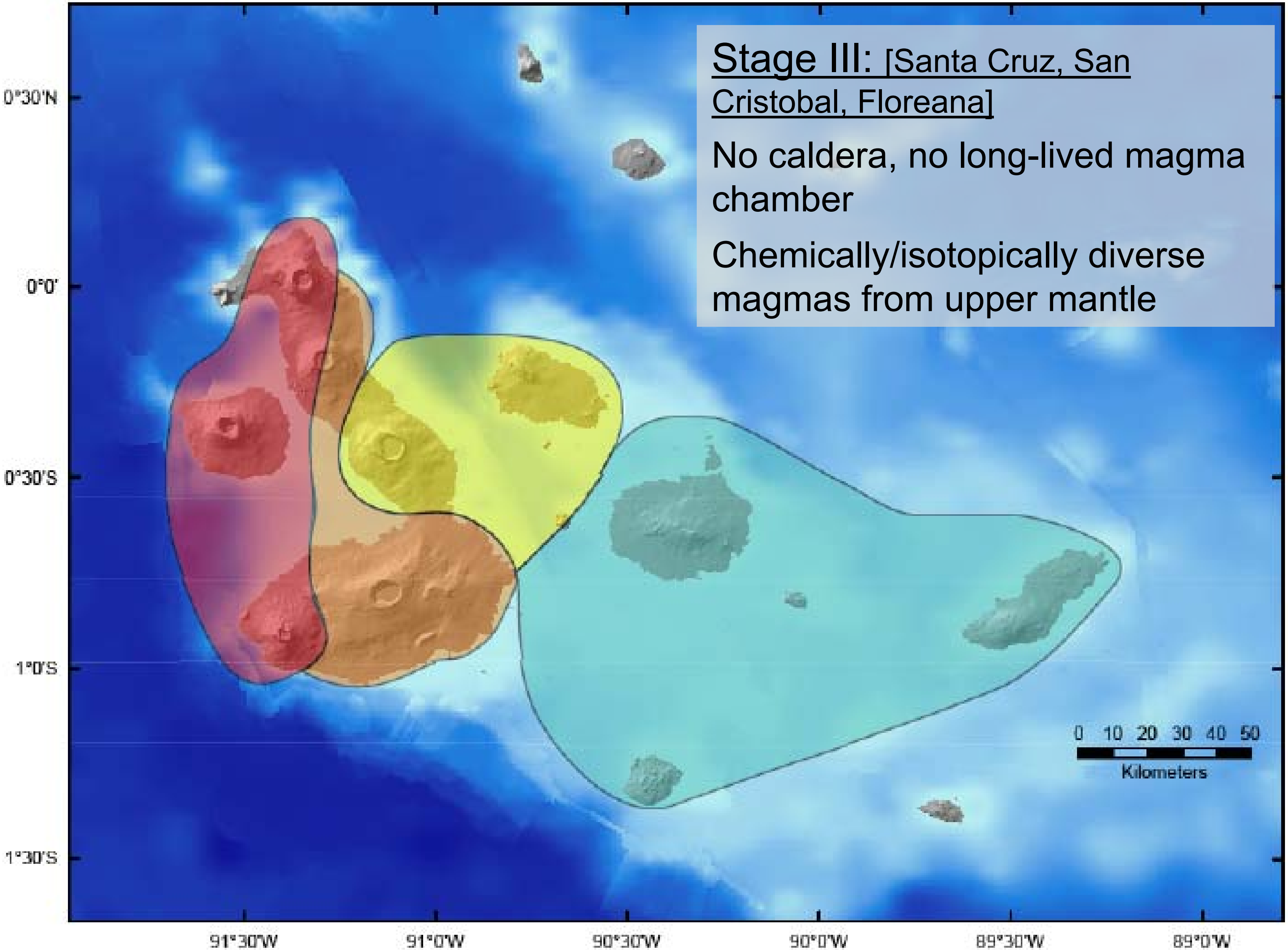
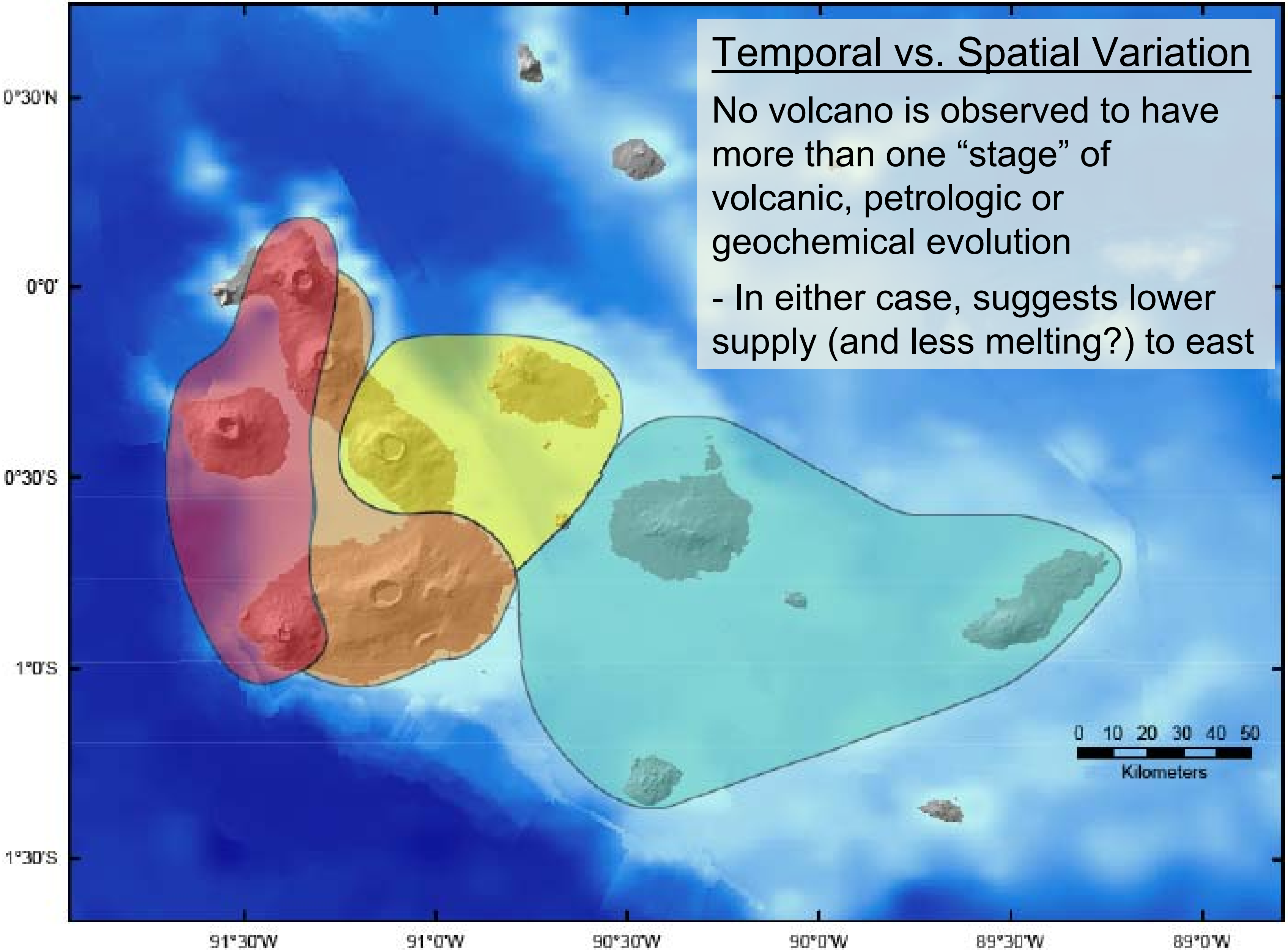


<u>Stage III:</u> <u>[Santa Cruz, San Cristobal, Floreana]</u>

No caldera, no long-lived magma chamber

Chemically/isotopically diverse magmas from upper mantle

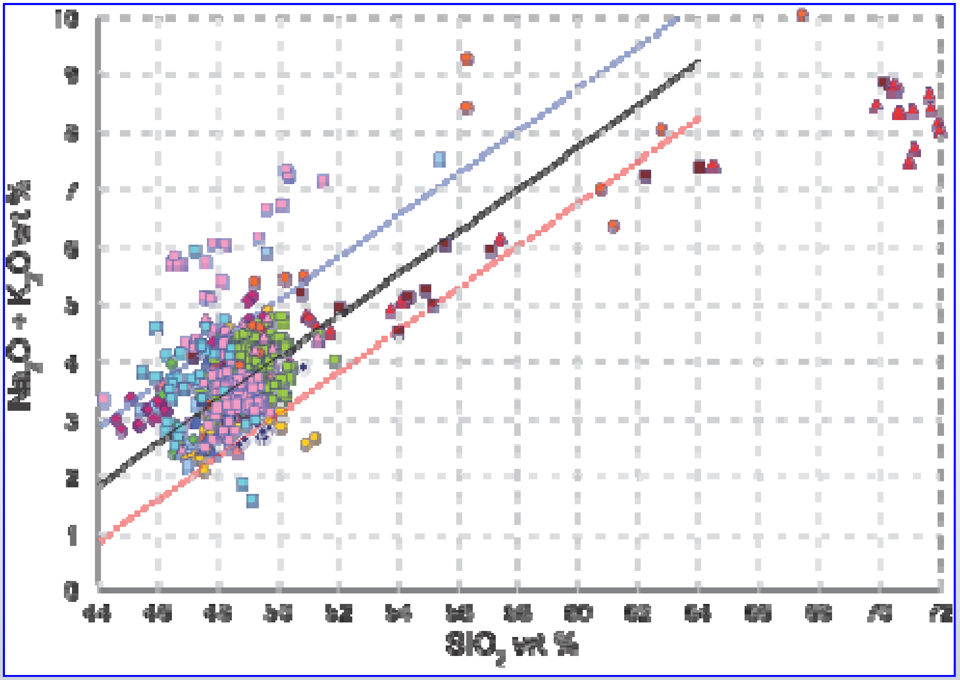
Galápagos Volcanic "Stages" *[Geist et al., 1998]*



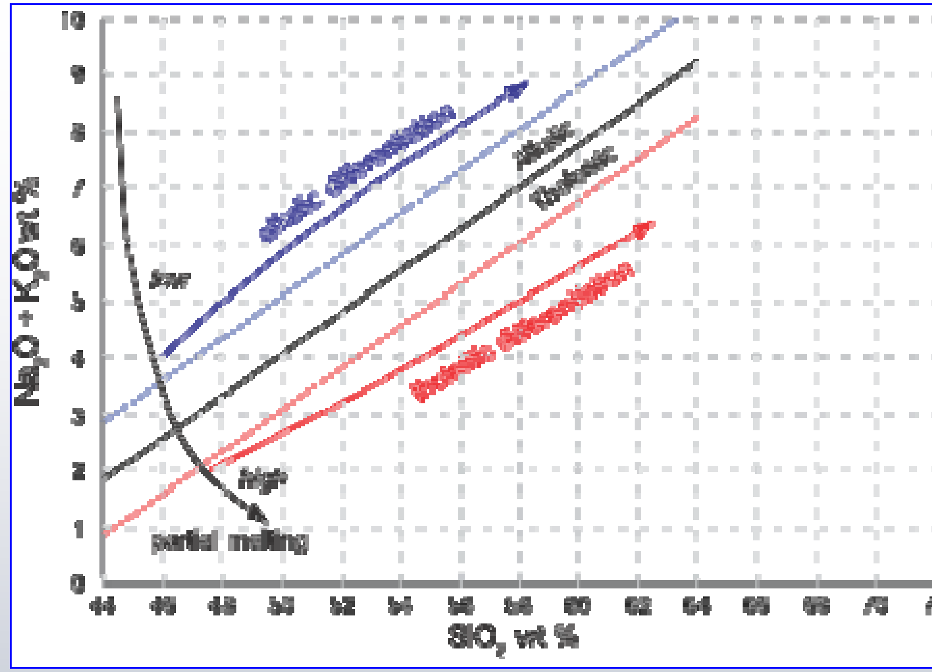
Temporal vs. Spatial Variation

No volcano is observed to have more than one "stage" of volcanic, petrologic or geochemical evolution

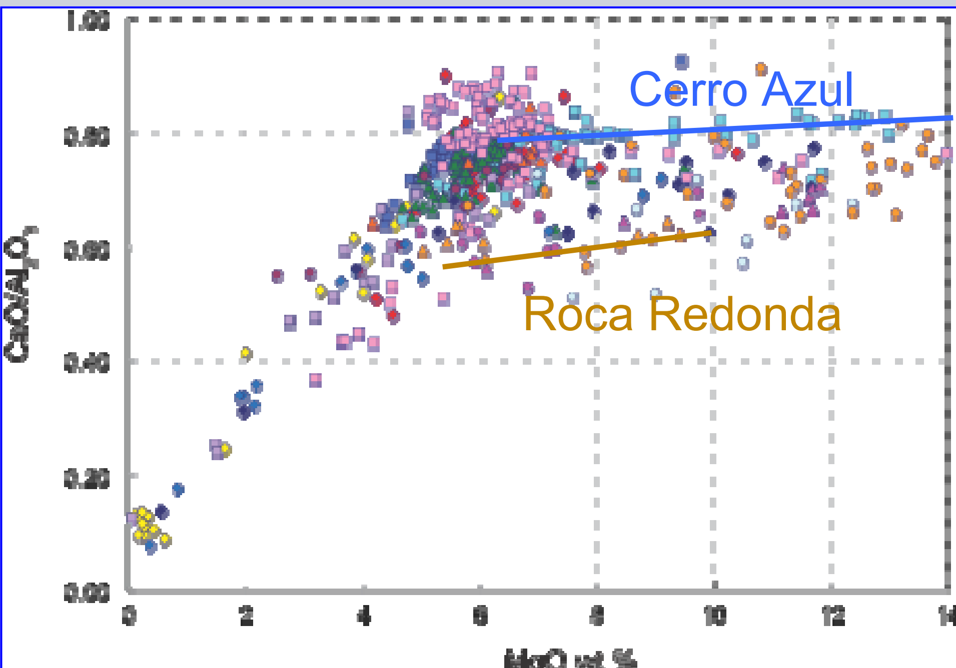
- In either case, suggests lower supply (and less melting?) to east



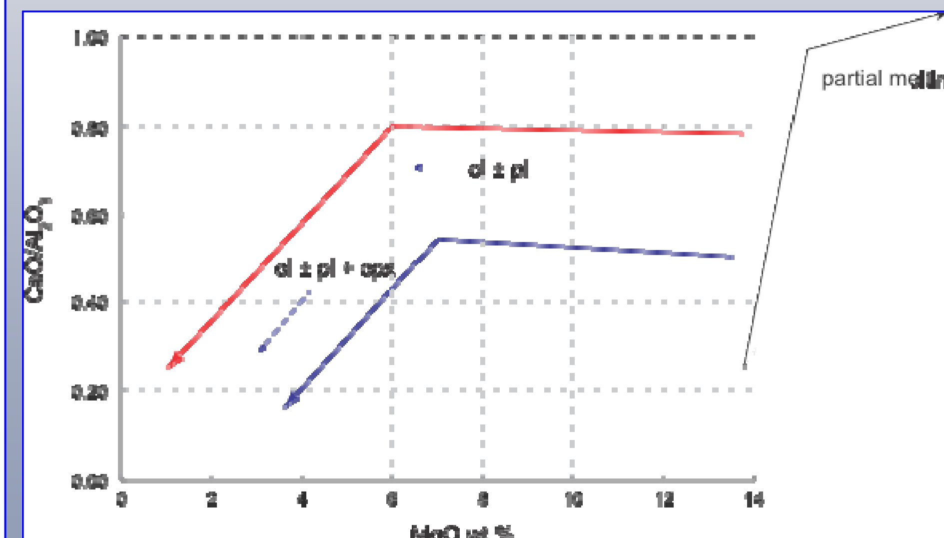
$Na_2O + K_2O$ wt %
SiO_2 wt %



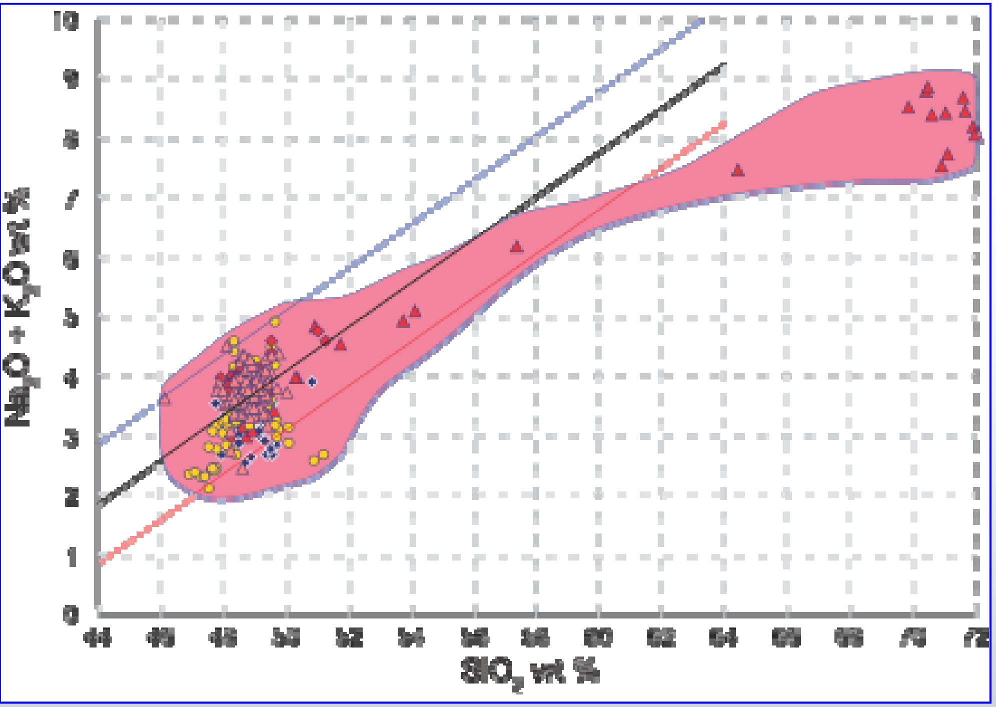
$Na_2O + K_2O$ wt %
SiO_2 wt %
alkalic
tholeiitic
low
high
partial melting

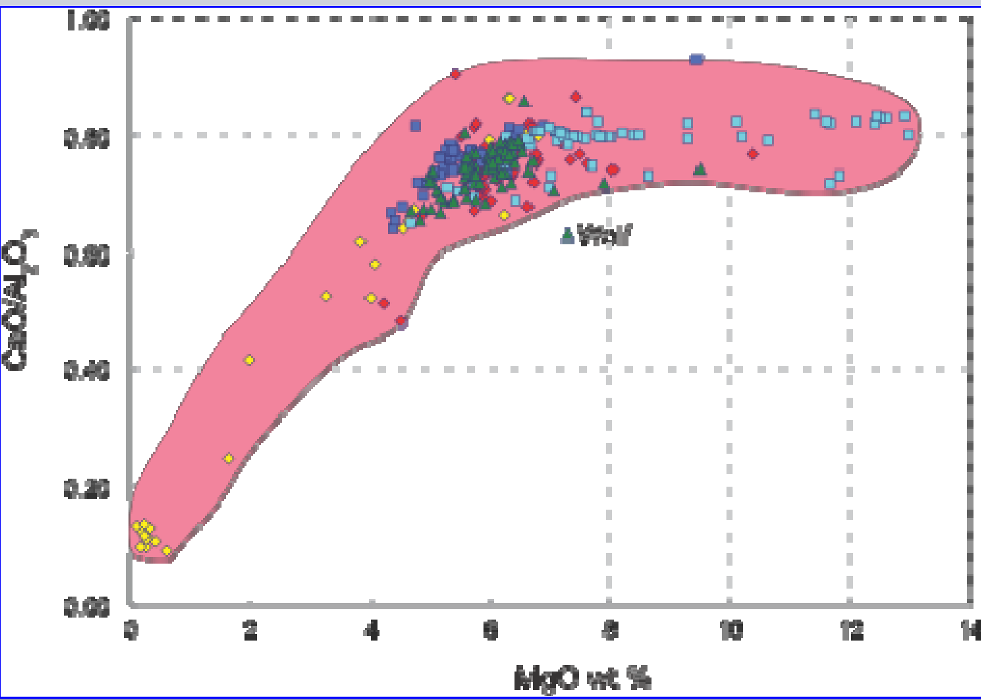


Cerro Azul
Roca Redonda
CaO/Al_2O_3
MgO wt %



partial melting
ol ± pl
ol ± pl + cpx
CaO/Al_2O_3
MgO wt %

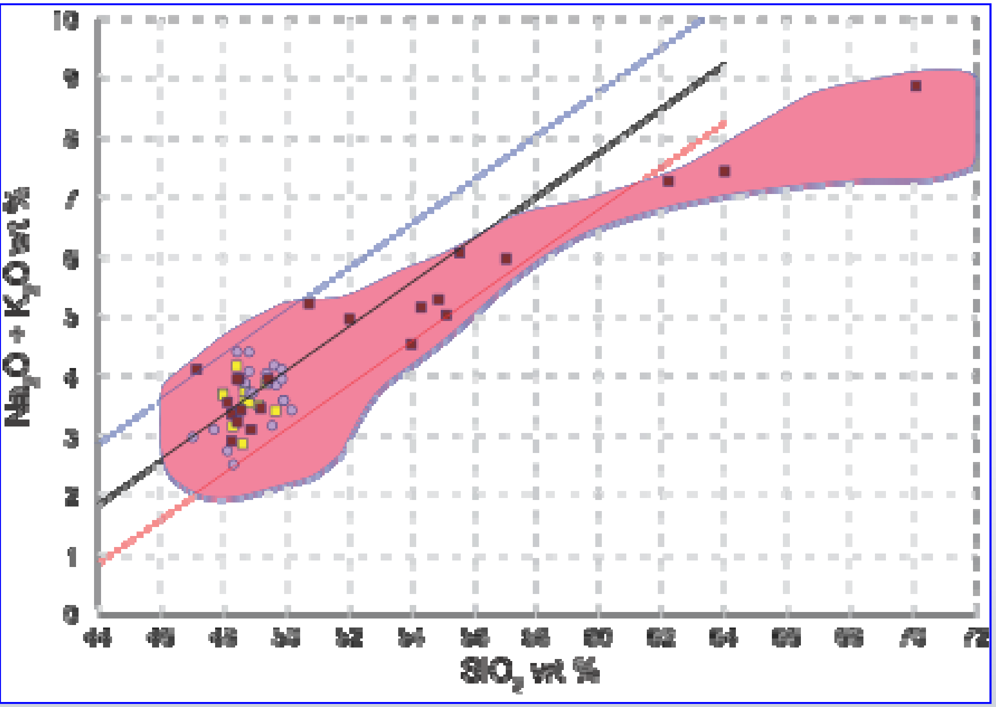




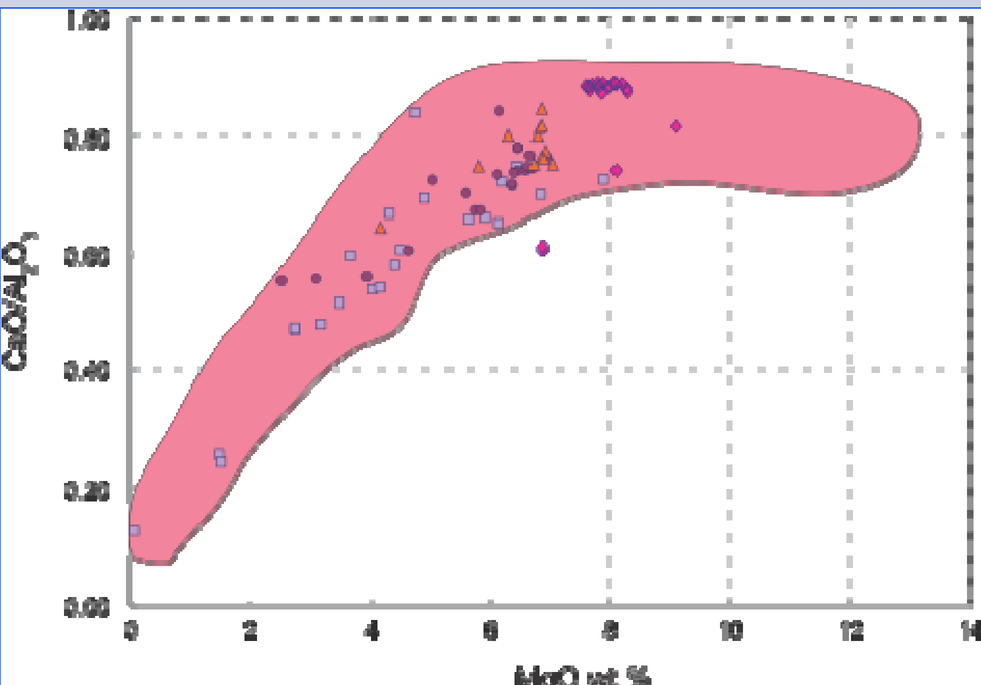
Volcanoes with calderas:

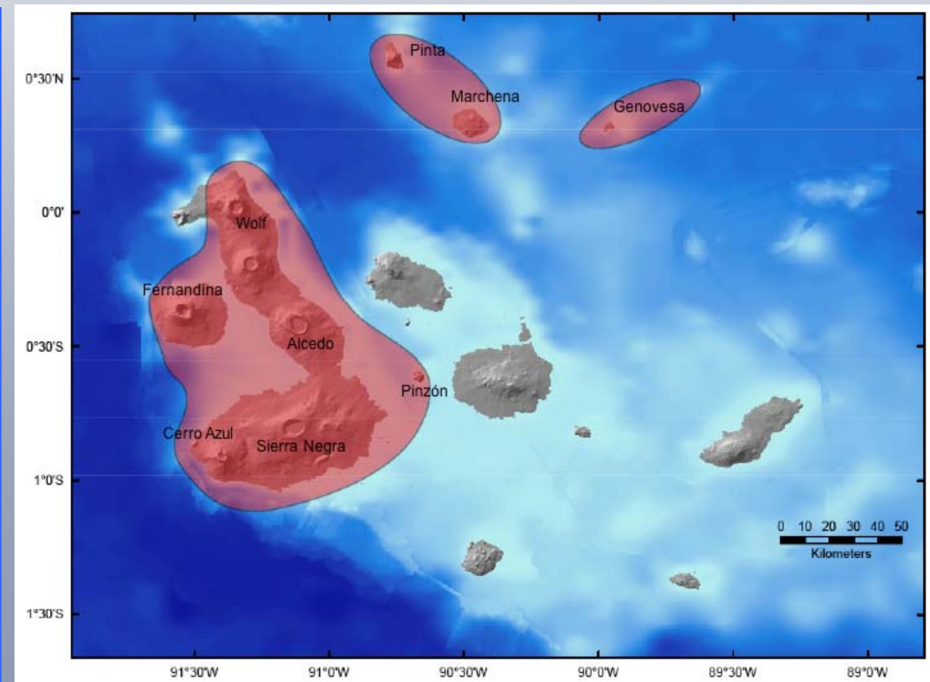
Fernandina, Cerro Azul, Sierra Negra, Alcedo, Wolf

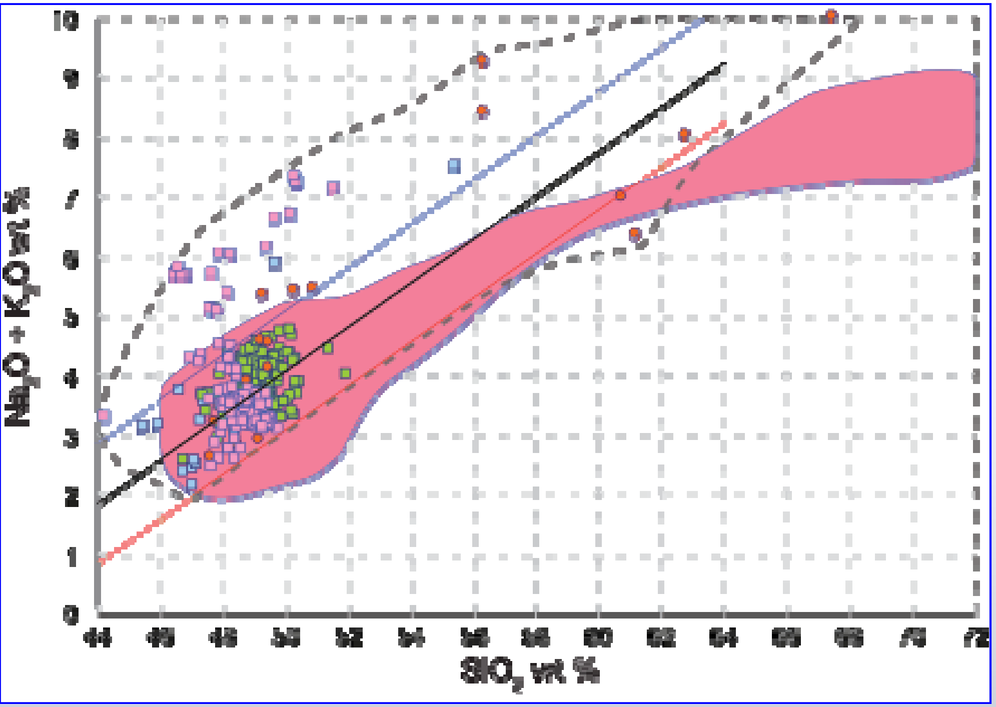
But not Ecuador
And not Darwin (few data)



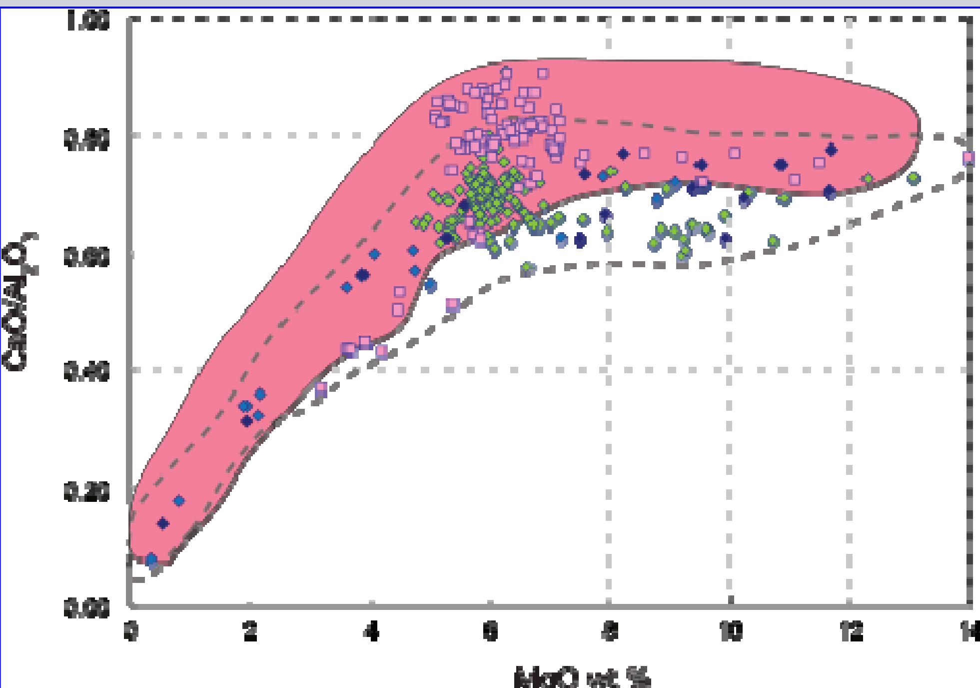
Pinzón, and the platform islands Pinta, Marchena and Genovesa are not distinguished from caldera volcanoes in these plots

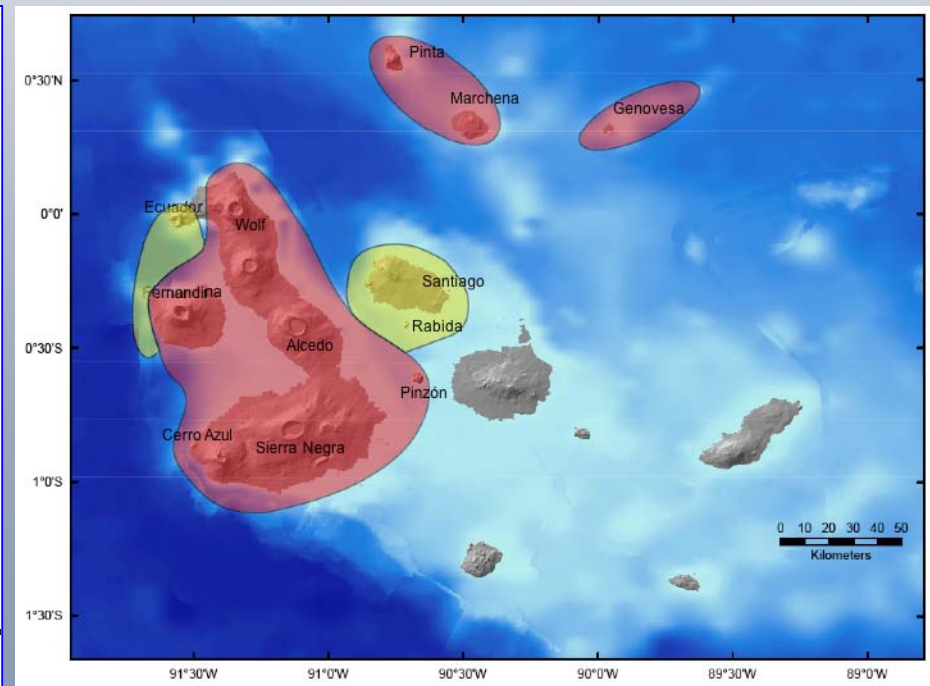




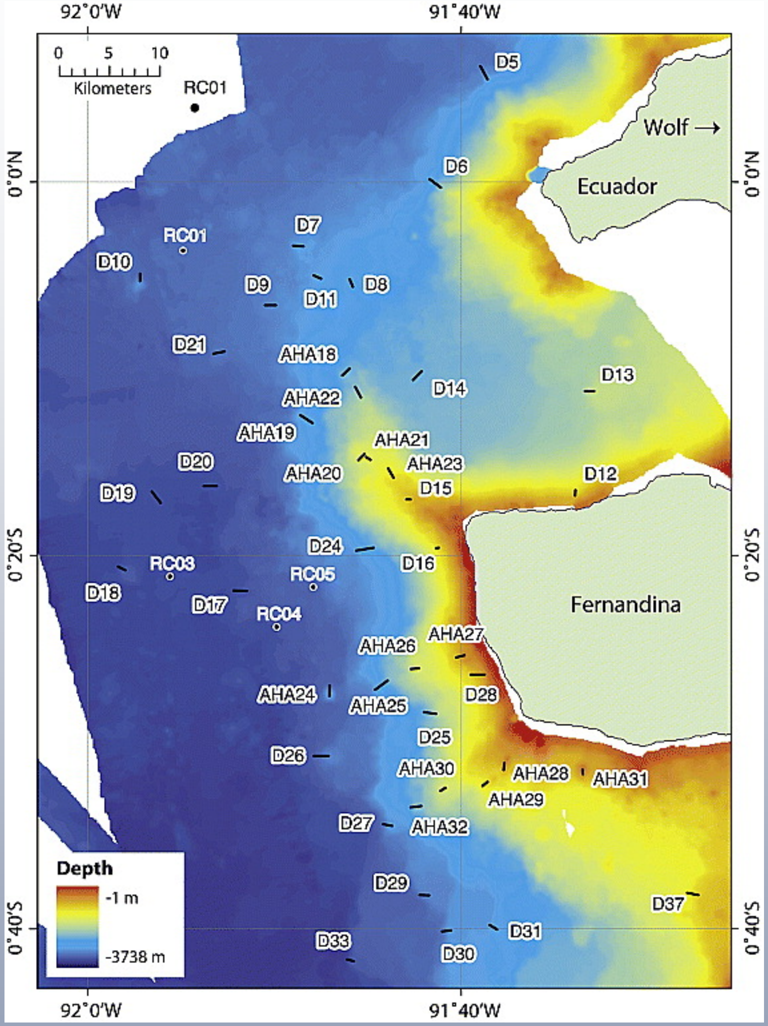


Lavas from Rabida, Santiago and some samples recovered from the submarine flanks of Fernandina are more alkalic with lower CaO/Al_2O_3



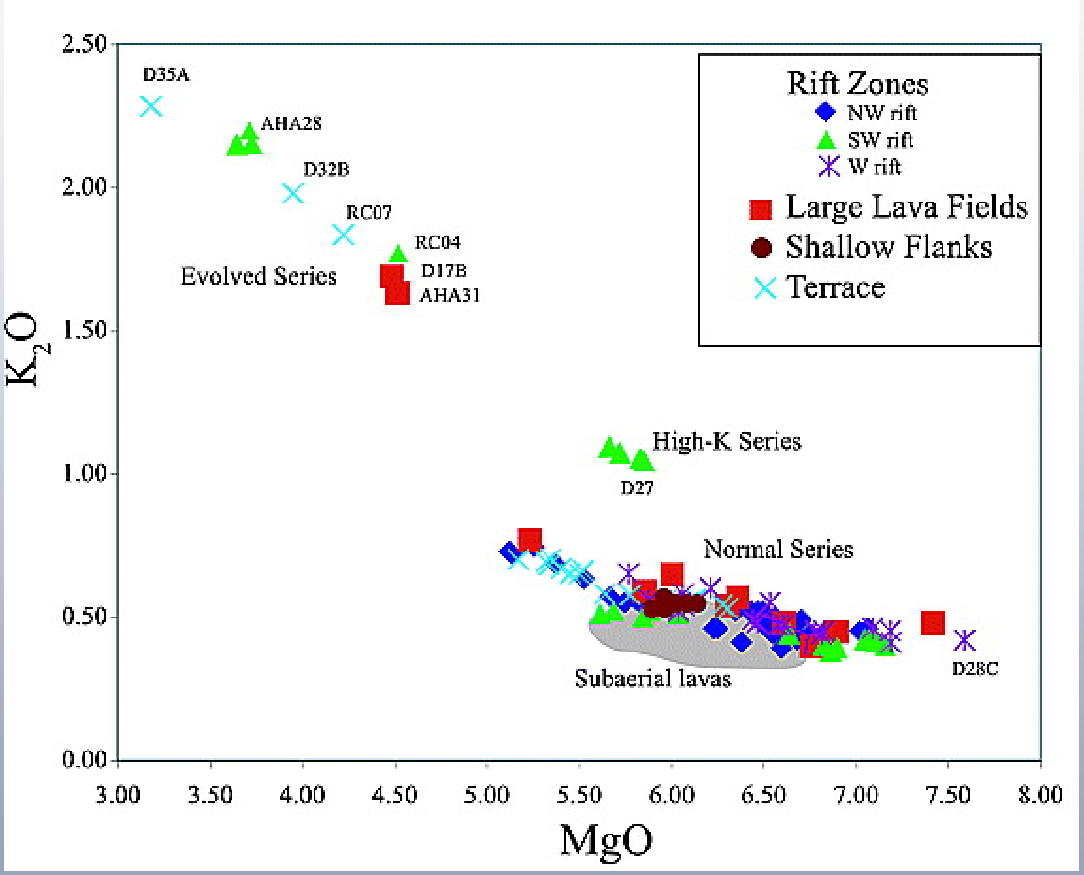


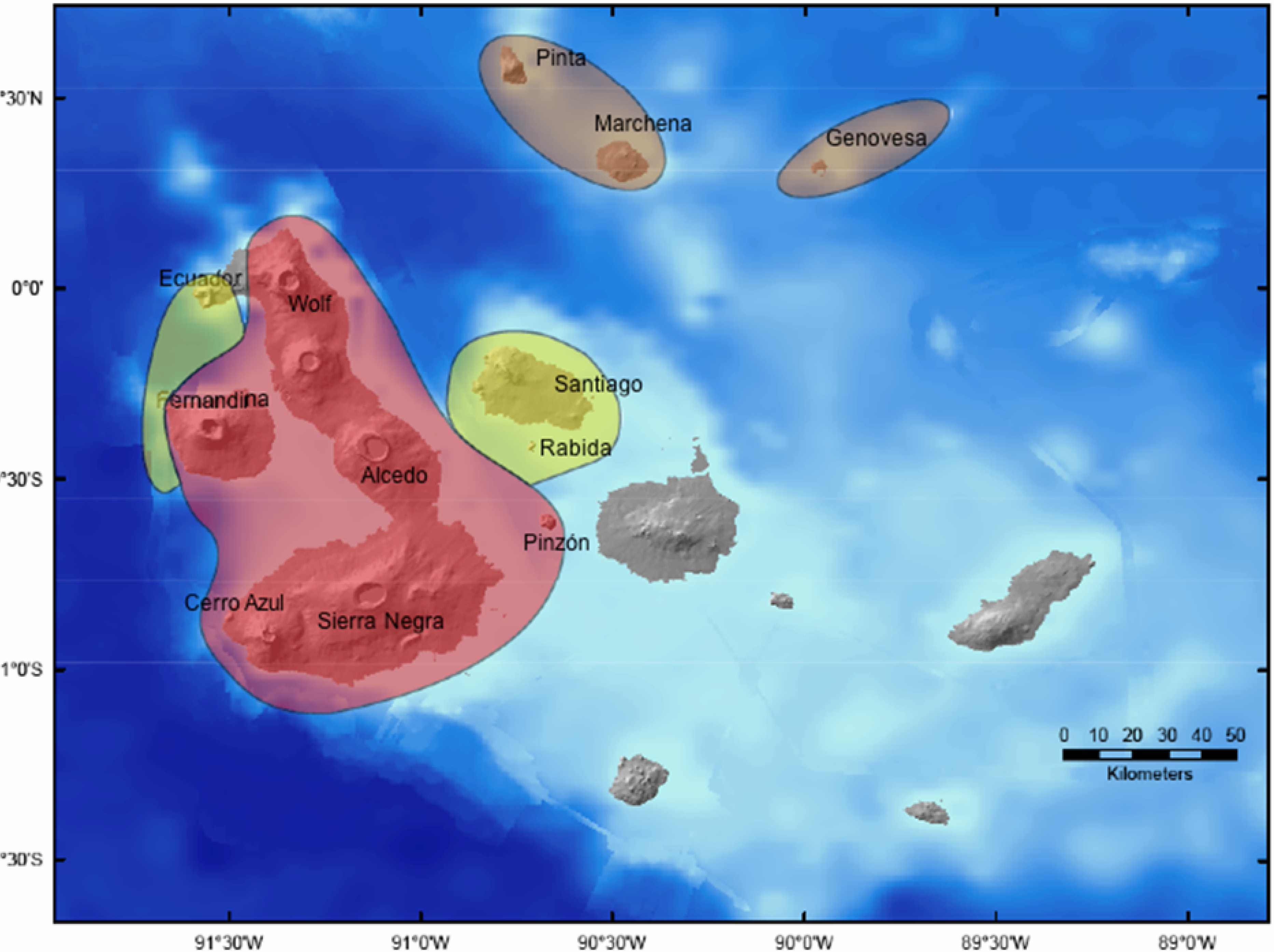
Different Magma Types at Fernandina

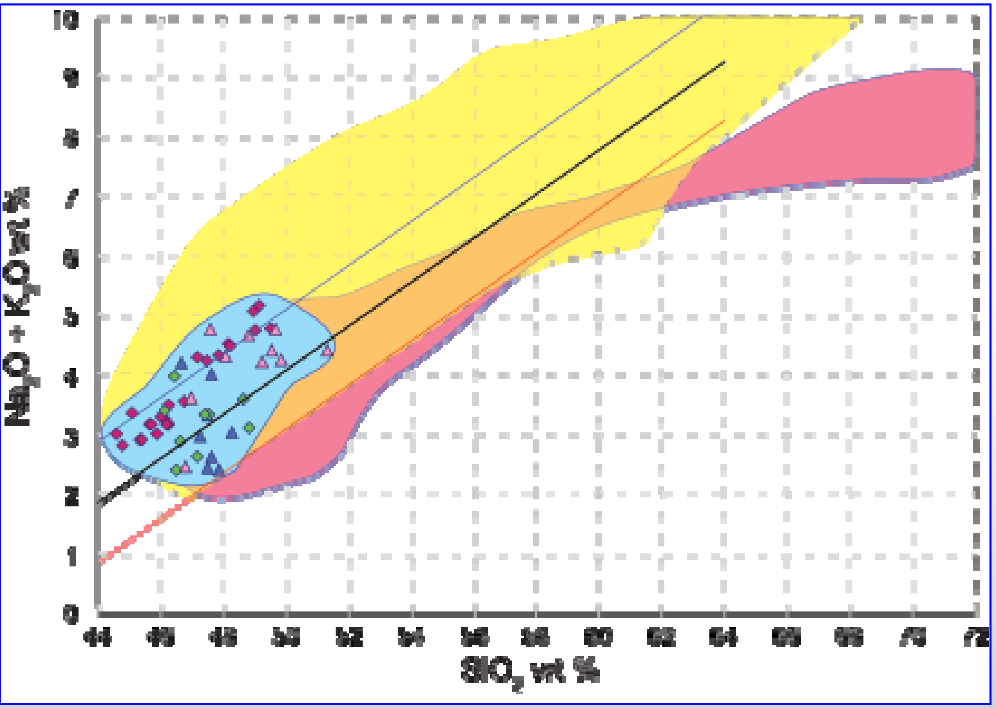


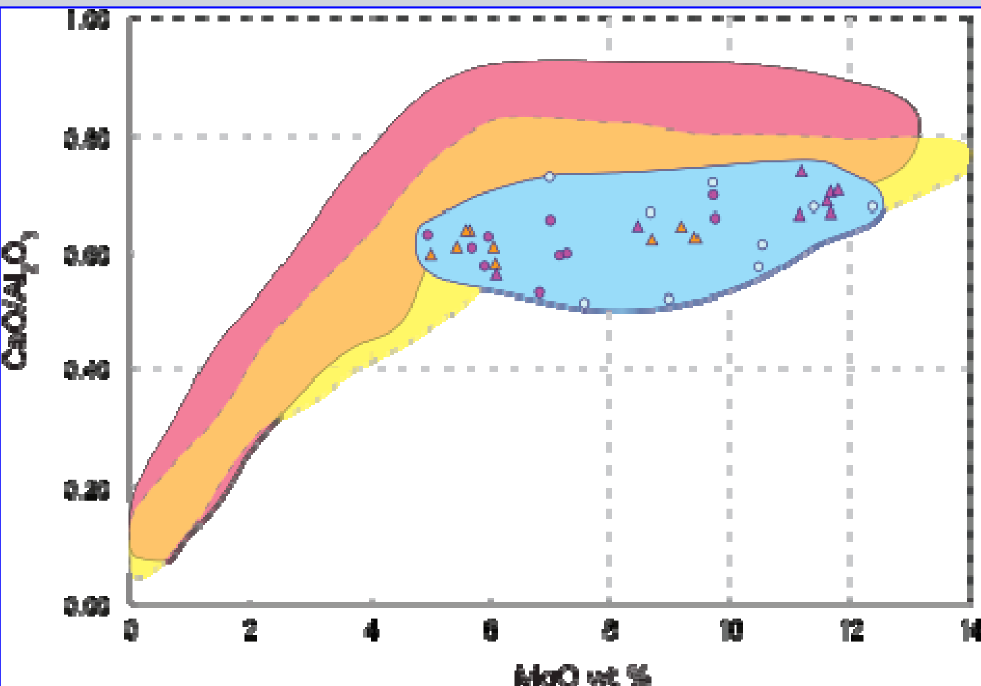
Geist et al., 2006

Both normal and high-K lavas on western submarine flank



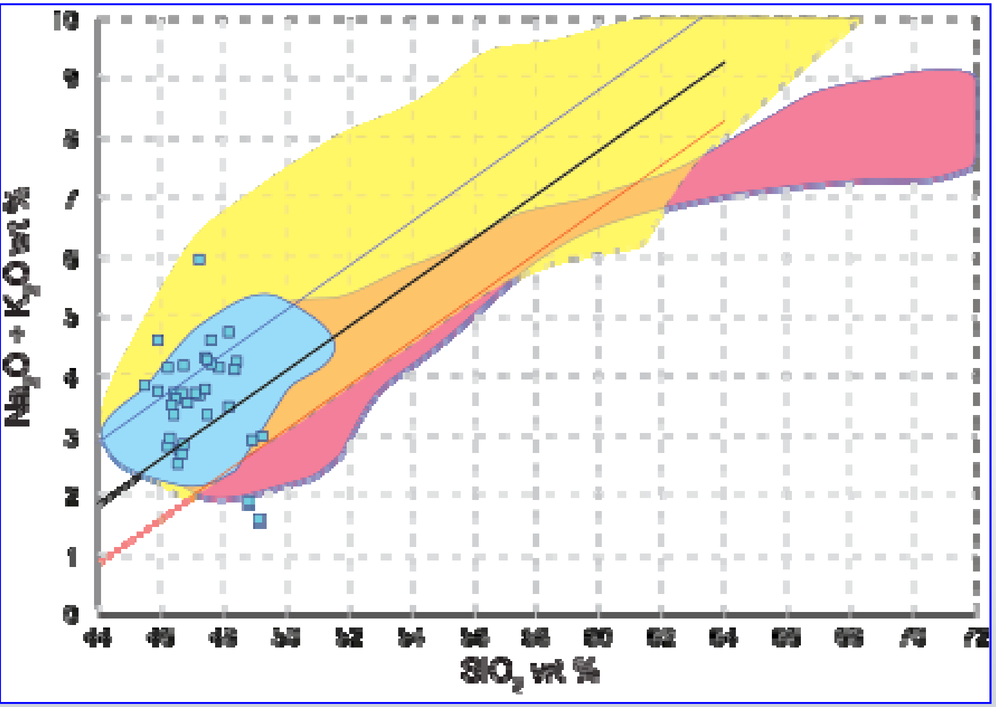

Pinta
Marchena
Genovesa
Ecuador
Wolf
Santiago
Fernandina
Rabida
Alcedo
Pinzón
Cerro Azul
Sierra Negra
°30'N
0°0'
°30'S
1°0'S
°30'S
91°30'W
91°0'W
90°30'W
90°0'W
89°30'W
89°0'W
0 10 20 30 40 50
Kilometers



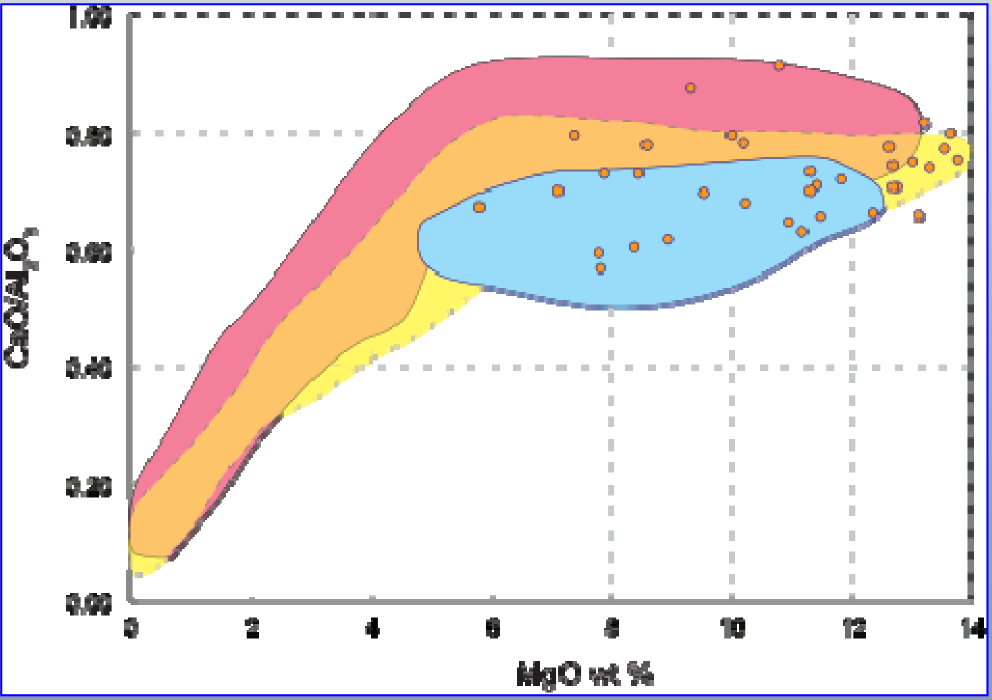


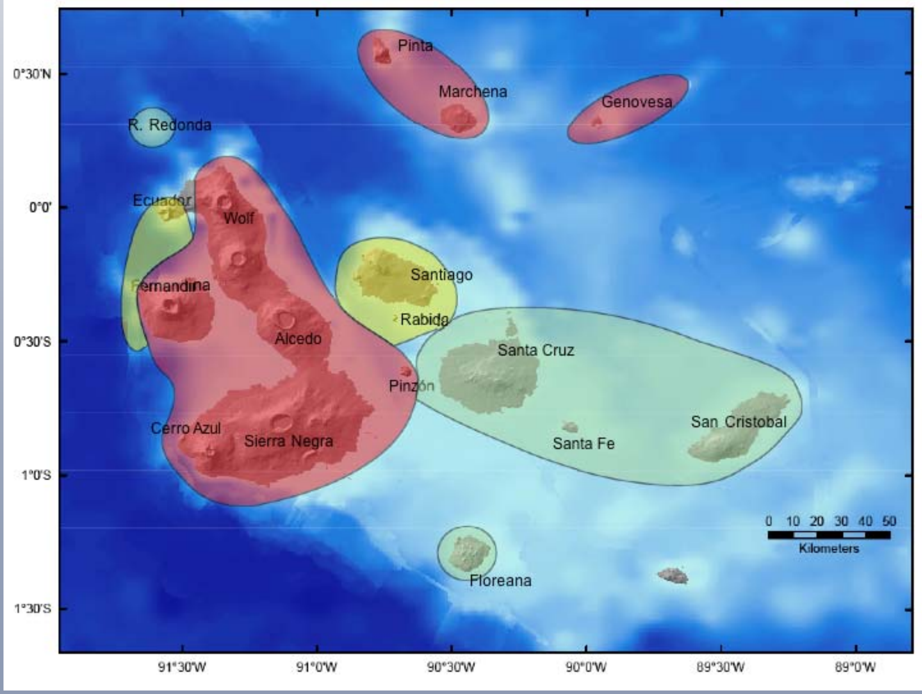
Samples from Santa Cruz, Santa Fe, San Cristobal, & Roca Redonda plot in a relatively restricted range

…at relatively low CaO/Al_2O_3.

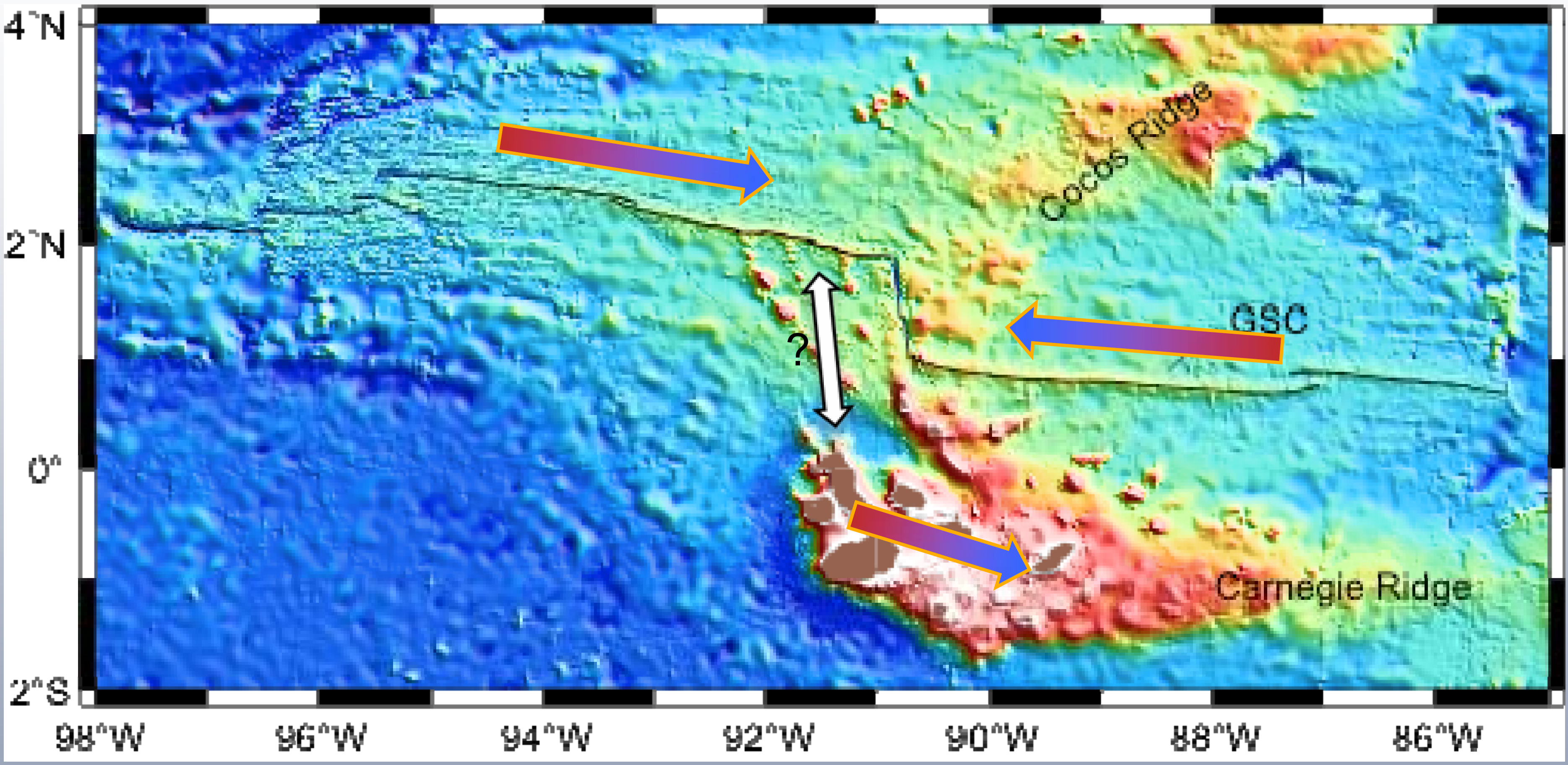


Floreana data scatter widely

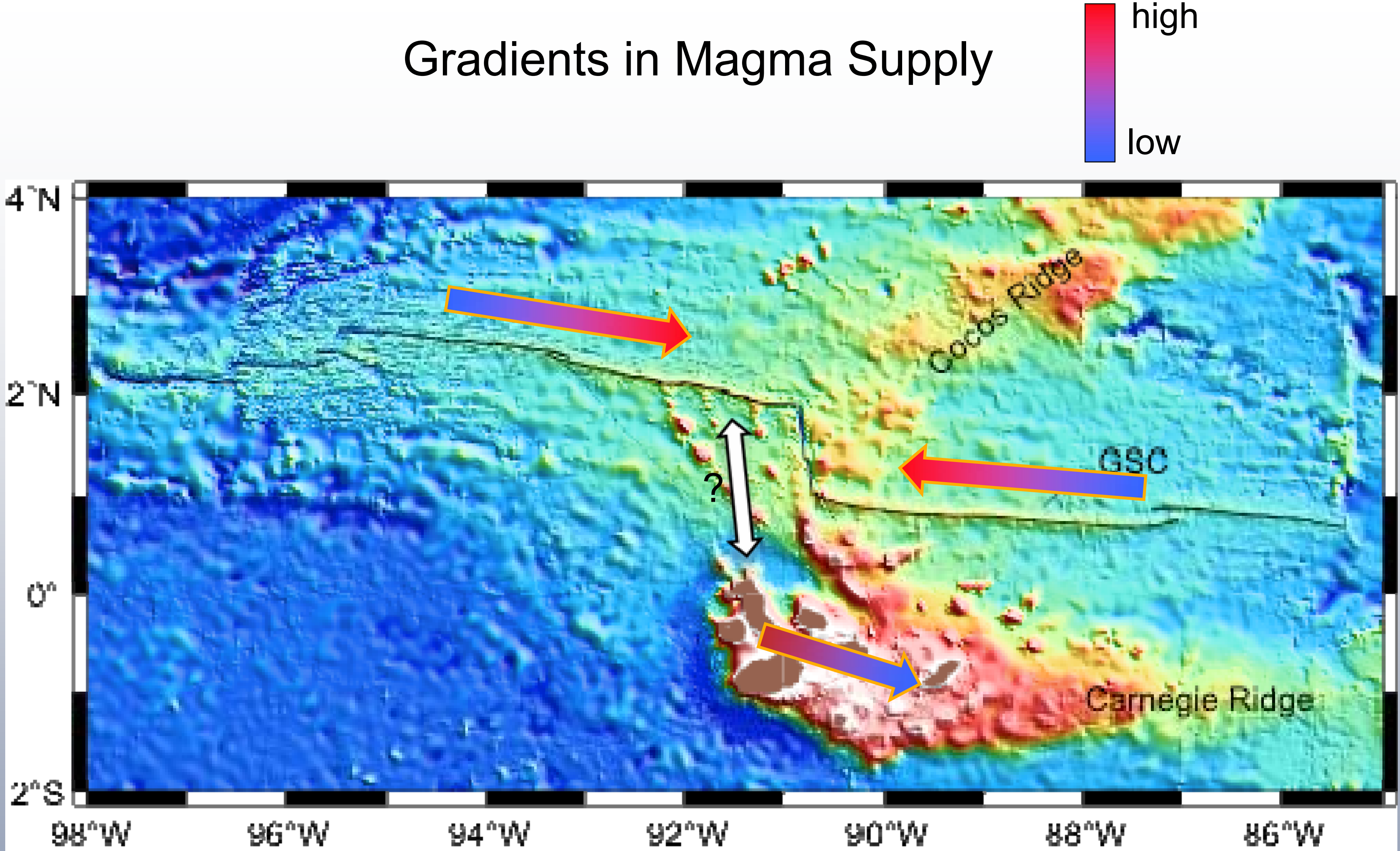




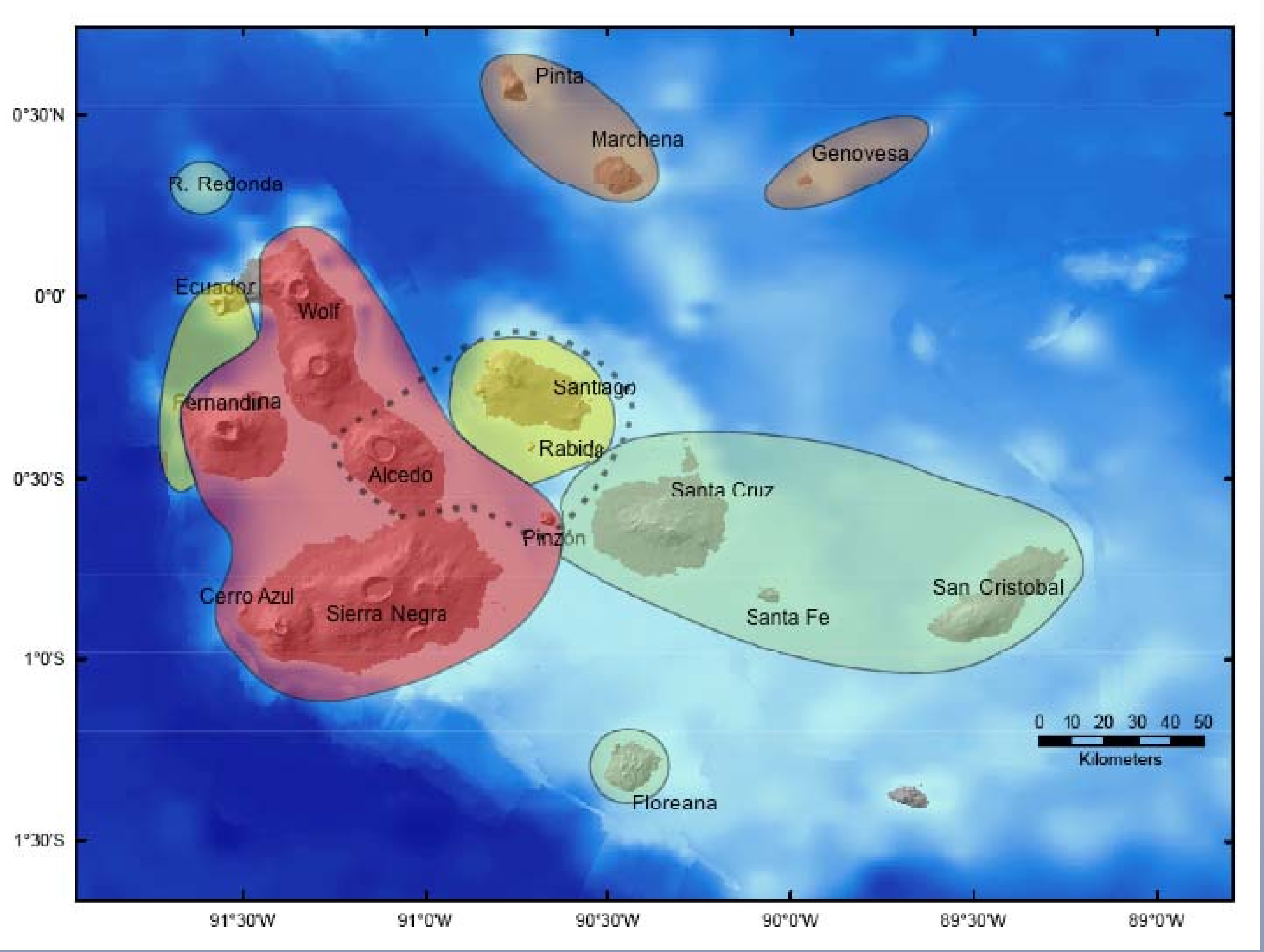
Gradients in extent of partial melting (arrows point high to low)



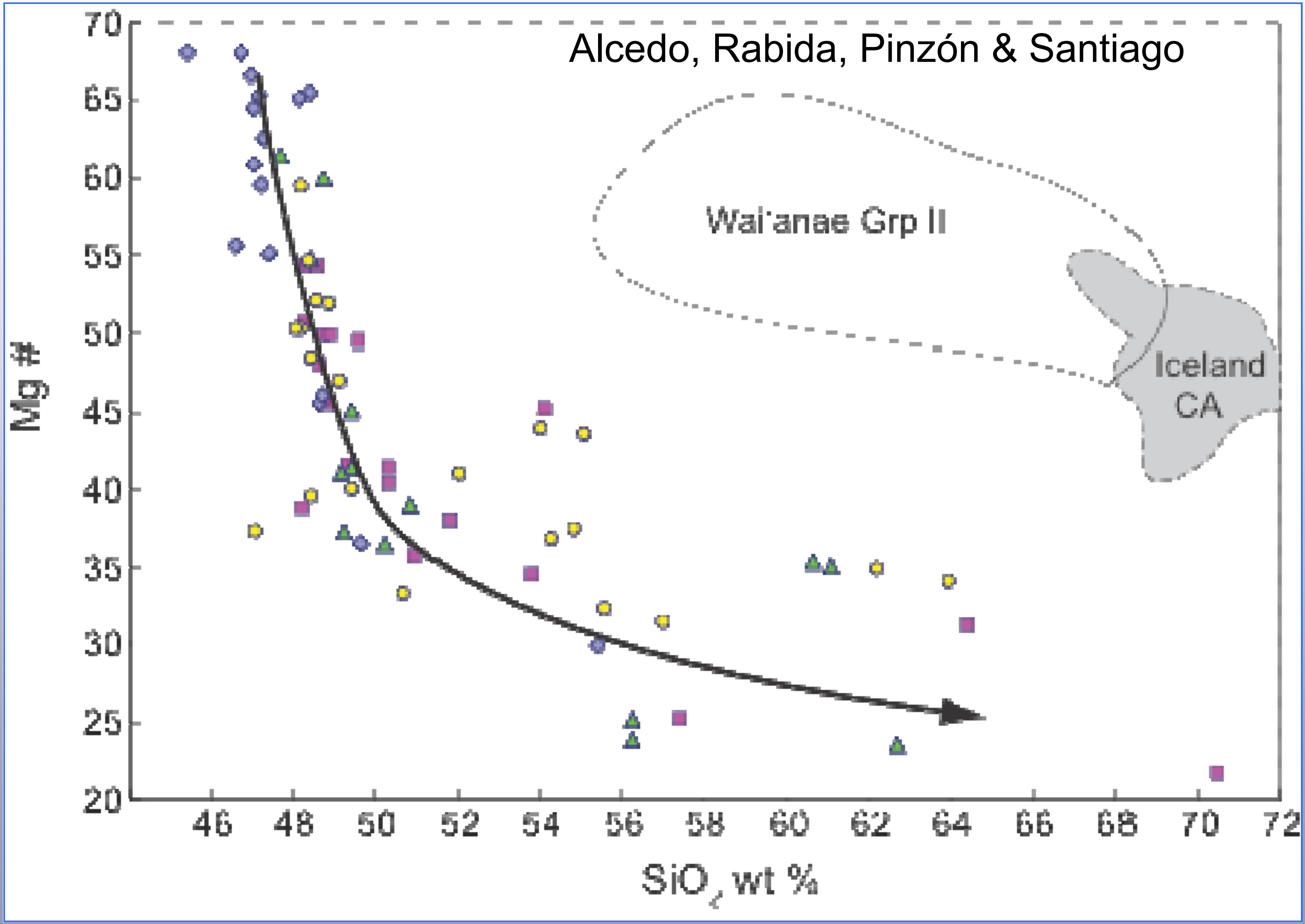
Gradients in Magma Supply

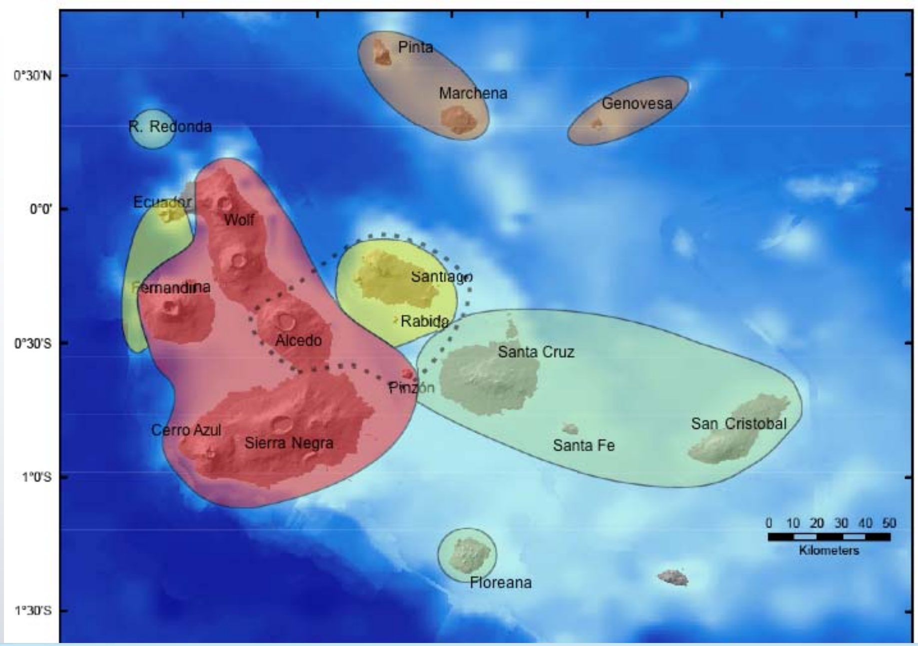


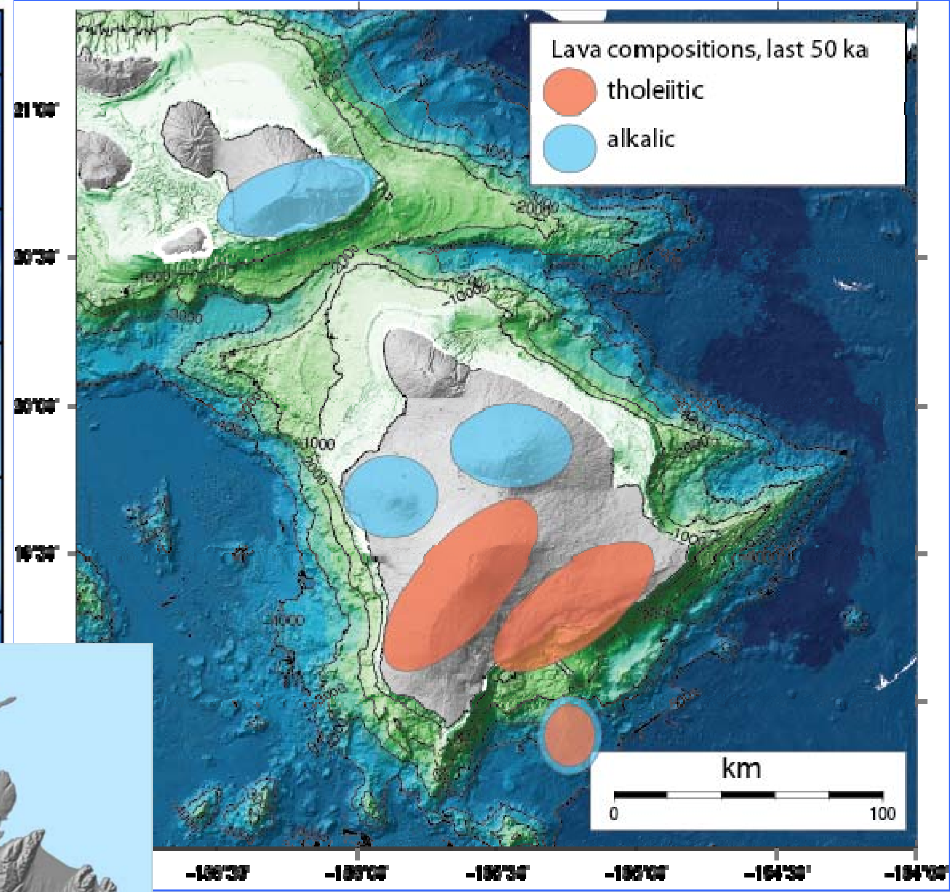
Highly Differentiated Lavas on Alcedo, Pinzón, Rabida and Santiago

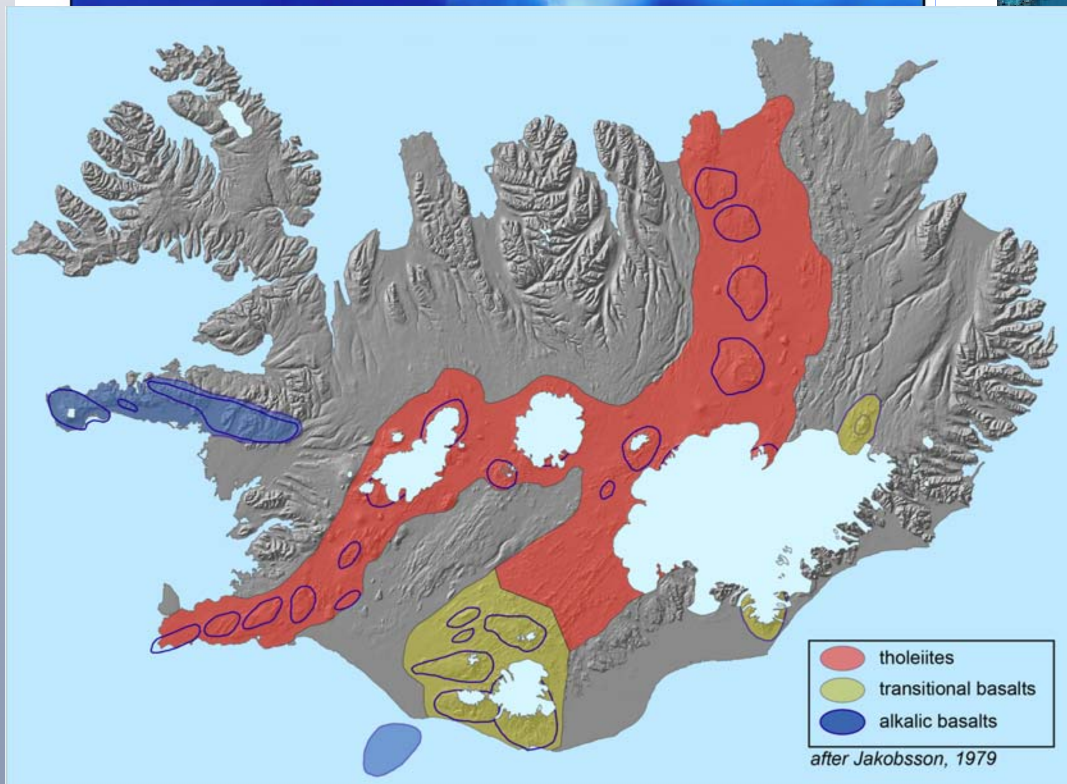


Chemical variations consistent with differentiation, rather than hydrous crustal melting



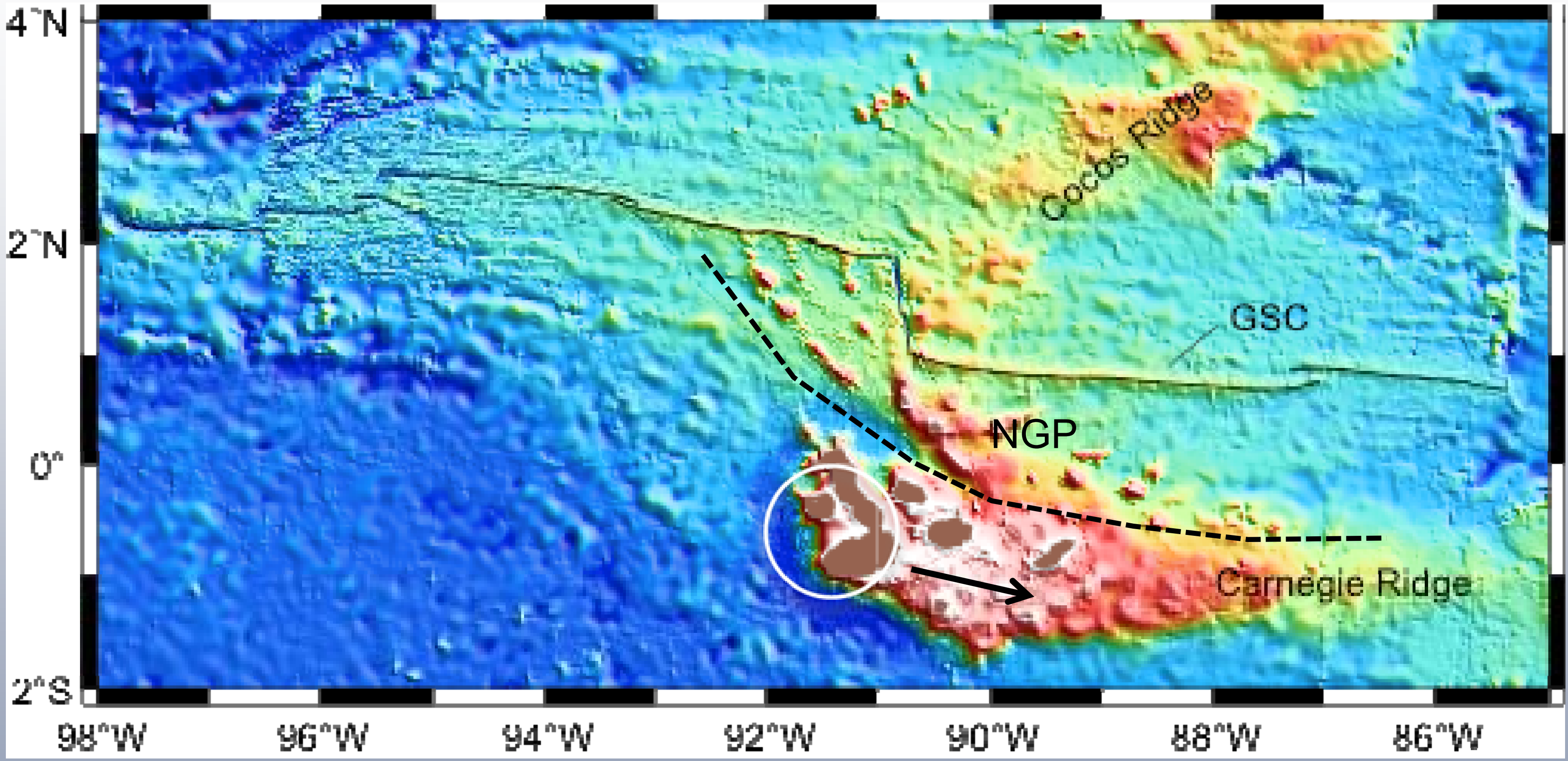






Chemical zonation within selected hotspots

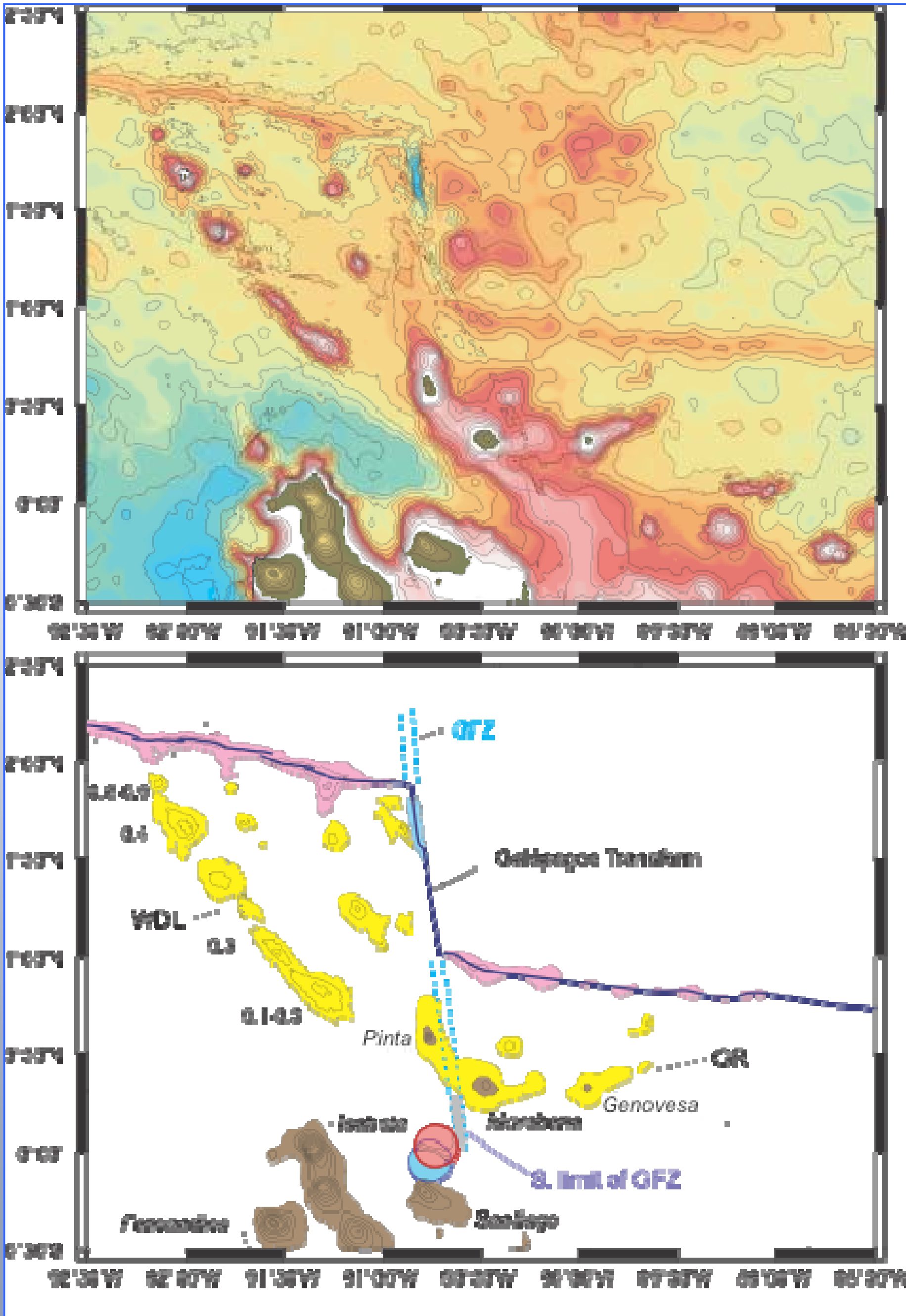
Not same scale


4˚N
2˚N
0˚
2˚S
98˚W
96˚W
94˚W
92˚W
90˚W
88˚W
86˚W
Cocos Ridge
GSC
NGP
Carnegie Ridge

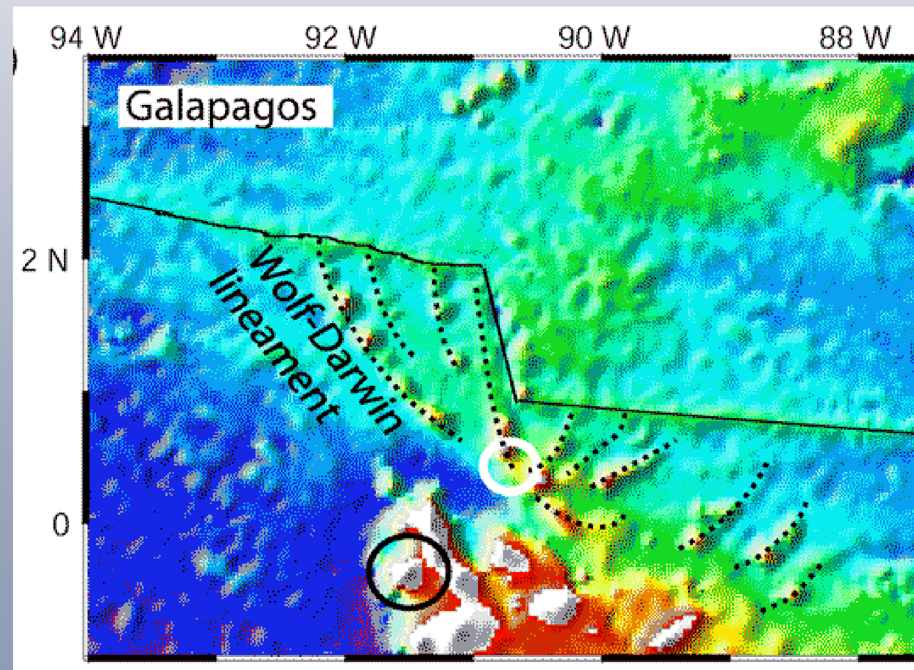
Volcanic ridges radiate away from a point north of Santiago

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; Mittelstaet & Ito, 2005]



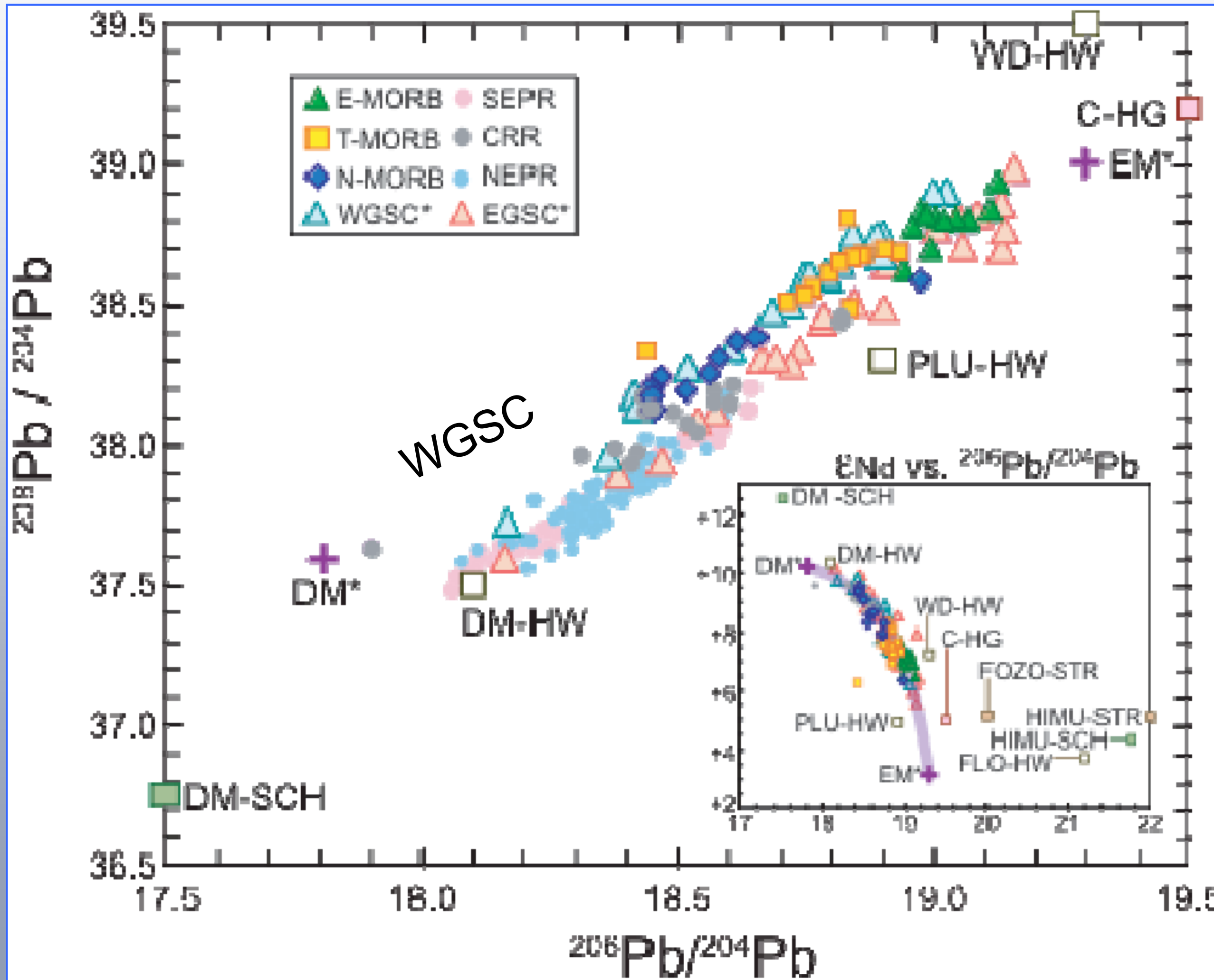
Sinton et al., 2003



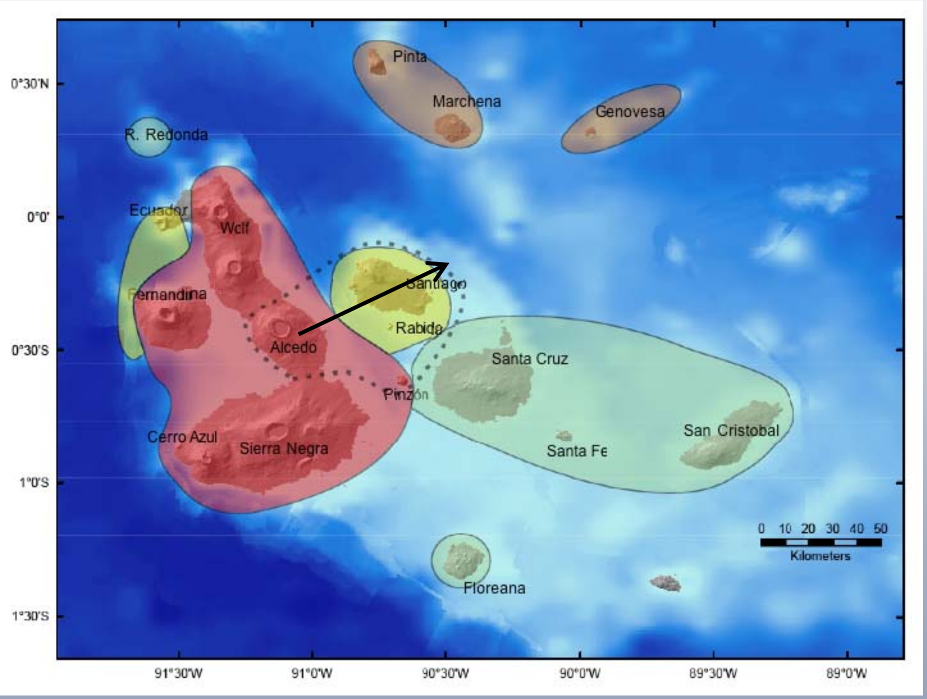
Mittelstaedt & Ito, 2005

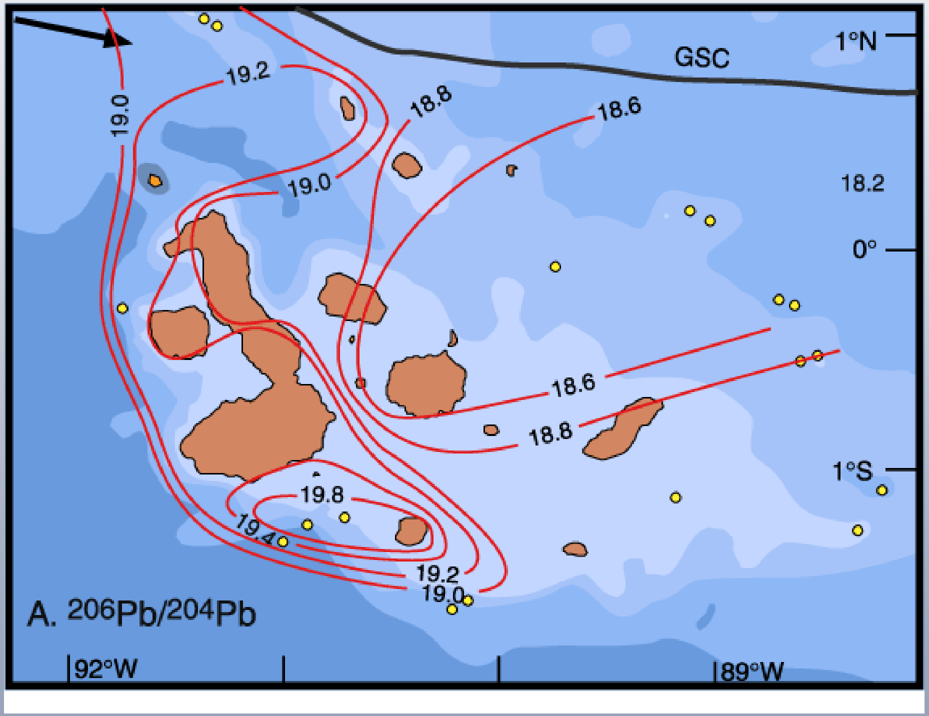
Some things we (I) don't know

1. The distribution of mantle geochemical provinces (especially the nature of the depleted components)

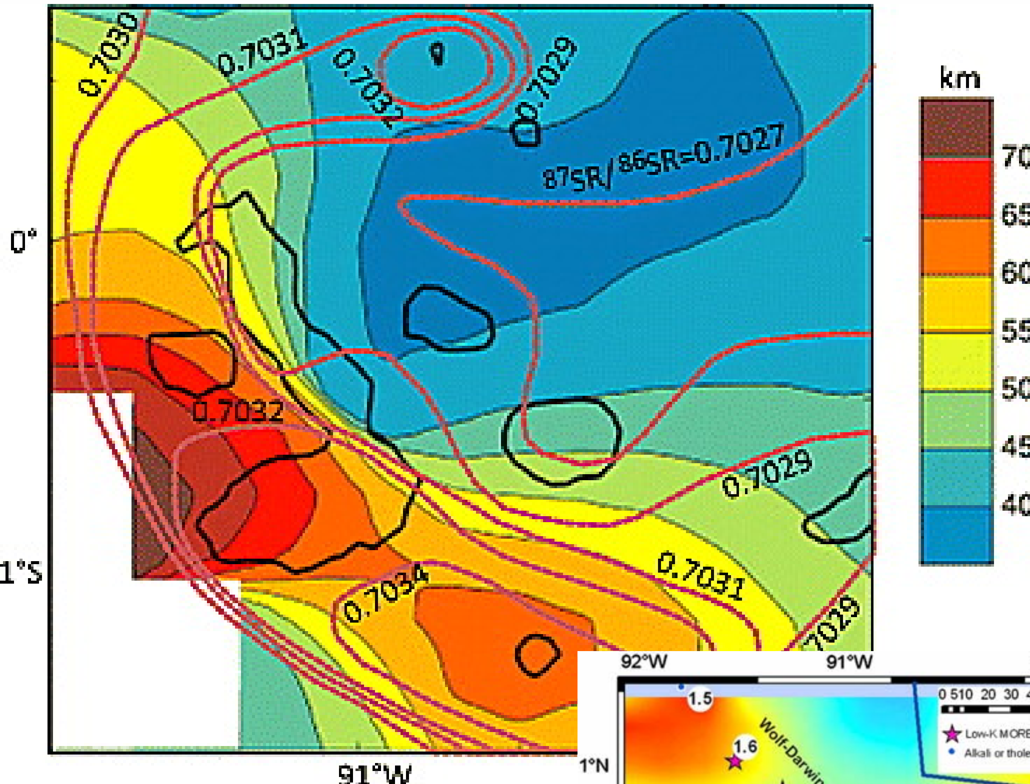


2. Variations and amounts of magma supply within the archipelago
3. Melt delivery from the upwelling hotspot to individual volcanic constructions
4. Why so many variables trend NE





Harpp & White, 2001

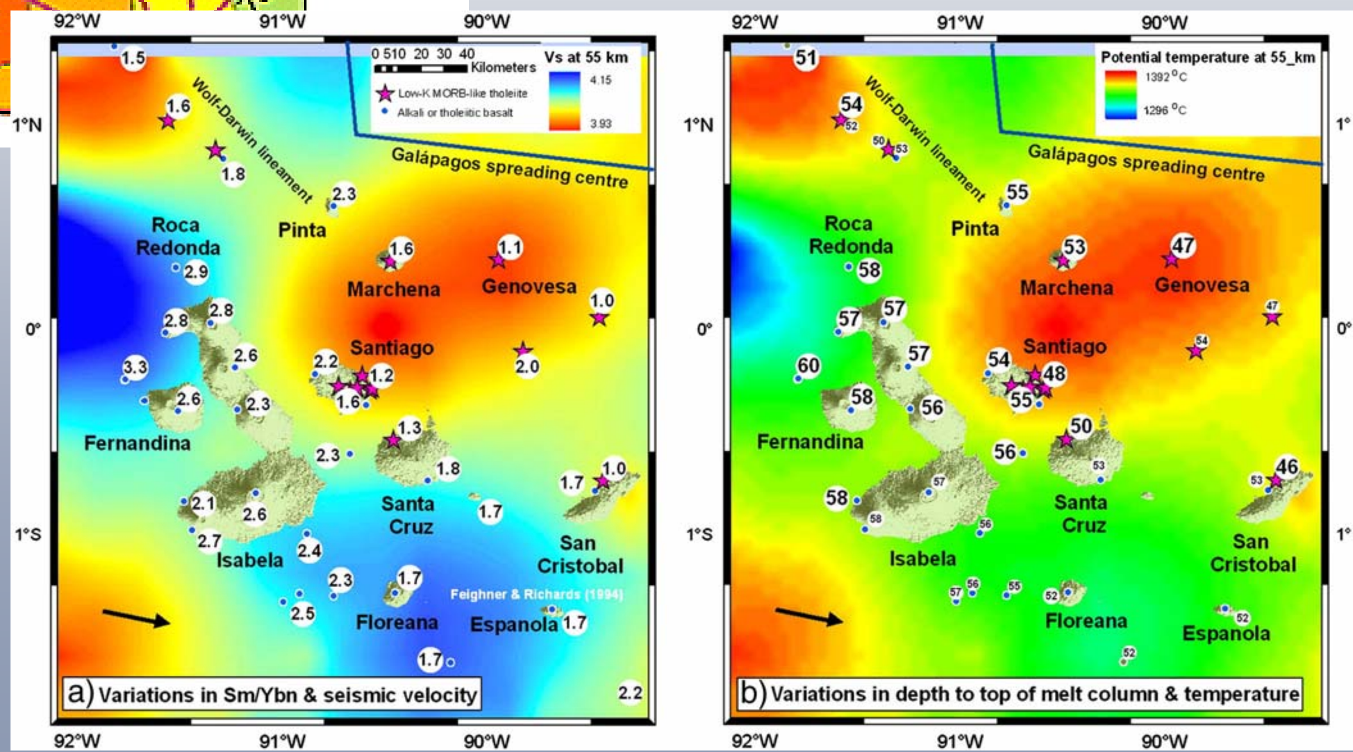


Thickness of high seismic velocity lid

Villagomez et al., 2011

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?