Week 2 - Ocean Ridge Volcanism

Map of the global mid-ocean ridge system.

outline:

Ridge structure and terminology, segmentation
Locus of volcanism
  width of neovolcanic zone
  fissure vs point source constructs
  volcanic/tectonic histories
Eruptions
  frequency, style and size
  along axis variations
  Magma chamber depth
  brief mention of lava chemistry
  more about Submarine forms and Effusion rate
Slow-Spreading Mid-Ocean Ridge
Slow spreading ridges like the Mid-Atlantic Ridge can have vertical relief of up to a 1000m at the axial valley.

Fast-Spreading Mid-Ocean Ridge
like the EPR. The axial trough is 10s of m deep, as are the fault scarps.

Figure 2. Topography of spreading centers. (A) Cross-sections of typical fast-, intermediate-, and slow-spreading ridges based on high resolution deep-tow profiles. The neovolcanic zone is noted (the zone of active volcanism) and is several kilometers wide; the zone of active faulting extends to the edge of the profiles and is several tens of kilometers wide. After Macdonald et al. (1982).

Macdonald et al. 2001, Fig 2
Figure 2

(B) Shaded relief map of a 1000 km stretch of the East Pacific Rise extending from 8° to 17° N. Here, the East Pacific Rise is the boundary between the Pacific and Cocos plates, which separate at a “fast” rate of 110 mm/yr. The map reveals two kinds of discontinuities: large offsets, about 100 km long, known as transform faults and smaller offsets, about 10 km long, called overlapping spreading centers. Colors indicate depths of from 2400 m (pink) to 3500 m (dark blue). (C) Shaded relief map of the Mid-Atlantic Ridge. Here, the ridge is the plate boundary between the South American and African plates, which are spreading apart at the slow rate of approximately 35 mm/yr. The axis of the ridge is marked by a 1–2 km deep rift valley, which is typical of most slow-spreading ridges. The map reveals a 12 km jog of the rift valley, a second-order discontinuity, and also shows a first-order discontinuity called the Cox transform fault. Colors indicated depths of from 1900 m (pink) to 4200 m (dark blue).
First-order segments are hundreds of kilometers long, persist for millions to tens of millions of years and are bounded by relatively permanent, rigid-plate transform faults. The underlying processes differ somewhat in fast- and slow-spreading centers.

These segments are sub-divided into several second- or third-order segments, bounded by a variety of non-rigid discontinuities. These smaller segments lengthen, shorten, or even disappear in 10 million to 100,000 years, respectively.

At the finest scale, fourth-order segments, about 10 kilometers long, may survive for only 100 to 10,000 years. These segments are the products of dike intrusion events, the fundamental units of crustal creation.

Figure 1. A possible hierarchy of ridge segmentation for (A) fast- and (B) slow-spreading ridges (after Mutter and Kidd, 1985). S1-S4 are ridge segments of order 1-4, and D1-D4 are ridge axis discontinuities of order 1-4. As both fast- and slow-spreading centers, first-order discontinuities are transform faults. Examples of second-order discontinuities are overlying spreading centers (OSCs) on fast-spreading ridges and oblique shear zones on slow-spreading ridges. Third-order discontinuities are small OSCs on fast-spreading ridges. Fourth-order discontinuities are deviations from axial linearity (wobbles) resulting in slight bends or lateral offsets of the axis of less than 1 km on fast-spreading ridges (Langevin et al., 1996). This four-tiered hierarchy of segmentation is probably a continuum. It has been established, for example, that fourth-order segments and discontinuities can grow to become third-, second-, and even first-order features and vice versa in both slow- and fast-spreading centers (Cande and Mankinen, 1982; Cande et al., 1991; Cande et al., 1996; Cande et al., 1995; Pzena and Mankinen, 1996).
Segment boundaries and Mid-ocean ridge axis depth

A SLOW

\[ \text{25°N} \]

\[ \text{30°N} \]

3000 m

B FAST

\[ \text{10°N} \]

\[ \text{15°N} \]

3000 m

C SUPERFAST

\[ \text{20°S} \]

\[ \text{15°S} \]

3000 m

Figure 1. Axial depth profiles for (A) slow-spreading, (B) fast, and (C) ultrafast-spreading ridges (after [Haxby and Delaney, 1993]; original references are [Haxby and Delaney, 1992; Haxby et al., 1990; Delaney et al., 1990]). Discontinuities of orders 1 and 2 typically occur at local depth maxima (discontinuities of orders 3 and 4 are indicated here). The segments at faster spreading rates are longer and have smoother, lower-amplitude axial depth profiles. These depth variations may reflect the pattern of mantle spreading.

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crustal magmatic processes
associated with ridge segmentation

Petrologic consequences of rift propagation on oceanic spreading ridges

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- Transform fault effect
- Rift propagation effects
Figure 3. Schematic diagram of a ridge crevasse system. The red lines are the locations of ridge crevasse systems (Gill et al., 2010) and those of a spreading center (Gill et al., 2010). The black lines represent the ridge axis. The red lines are the locations of ridge crevasse systems (Gill et al., 2010) and those of a spreading center (Gill et al., 2010). The black lines represent the ridge axis. The red lines are the locations of ridge crevasse systems (Gill et al., 2010) and those of a spreading center (Gill et al., 2010). The black lines represent the ridge axis.

Figure 11. A geological interpretation for along-axis variations in a scarp height and more closely spaced scarps near mid-segment on a slow-spreading center. Cross-section through segment center (top) shows more closely spaced, smaller-thickness faults than at the segment ends (bottom). Focused mantle upwelling near the segment center region of the lithosphere and thinning of the lithosphere with increased melt supply creates a thicker crust. In contrast to fast-spreading centers, there may be very little melt redistribution along strike. Near the segment ends, the lithosphere will be thicker and magma supply is less creating thinner crust. Along axis variations in scarp height and spacing reflect these along axis variations in lithospheric thickness. Arcuate extension across the larger faults near segment ends may also thin the crust, especially at mid-ocean ridge flanks. Modified from Shaw (1992).
Zone of volcanic construction at ridges is more inflated at most segment centers (shallower depth, wider)

Figure 6 Profiles of the along-axis cross-sectional area, depth, and axial magma chamber (AMC) seismic reflector for the EPR 9-13 N. The locations of first- and second-order discontinuities are denoted by vertical arrows (first-order discontinuities are named); each occurs at a local minimum of the ridge area profile, and a local maximum in ridge axis depth. Lesser discontinuities are denoted by vertical bars. There is an excellent correlation between ridge axis depth and cross-sectional area; there is a good correlation between cross-sectional area and the existence of an axial magma chamber, but detailed characteristics of the axial magma chamber (depth, width) do not correlate. Updated from Scheirer and Macdonald (1993) and references therein.

Figure 7 Cross-sectional area of the East Pacific Rise versus MgO content of basalt glass (crosses from EPR 5-14 N, solid circles from 13-23 S). There is a tendency for high MgO contents (interpreted as higher eruption temperatures and perhaps higher magmatic budget) to correlate with larger cross-sectional area. Smaller cross-sectional areas correlate with lower MgO and a greater scatter in MgO content, suggesting magma chambers which are transient and changing. Thus, shallow, inflated areas of the ridge tend to erupt hotter lavas. Updated from Scheirer and Macdonald (1993) and references therein.

Macdonald 2001
Figure 9 Schematic summary of along-axis variations in spreading center properties from segment end (discontinuity of about 1.5–2.0 km) to segment center. Increasing ridge width with fast spreading rates and decreasing ridge width with slow spreading rates. A large number of parameters correlate well with location within a given segment, indicating that segments are distinct, independent units of crustal accretion and deformation. These variations may reflect a fundamental segregation of the supply of melt beneath the ridge. (Less than 1% of the ridge has been studied in sufficient detail to create this summary.)

Macdonald 2001

Figure 9a Magma supply model for mid-ocean ridges. (See references in Bussuet al., 1989.) (A) represents a segment with a robust magma budget, generally a fast spreading ridge. (B) represents a segment with a moderate magma budget, generally a fast spreading ridge. (C) represents a segment with a slow magma budget, generally a slow spreading ridge with an axial high (MST). (D) represents a slow spreading ridge with an axial low (MST).

Macdonald 2001
Global variations in MORB composition (away from hot spots)

**magma differentiation signatures**
Rubin and Sinton, 2007

![Graph showing Mg# vs. spreading rate (cm/yr)](image)

11000+ MORB glasses (major elements)
2100 glasses + whole rocks (majors/traces/isotopes)
Mostly from PetDB plus some literature not yet there

Data manipulation basics:
- 37 ridge "sections" – 50 to 500 samples in each
- No hot spot influenced MORB
- No off axis lavas (4% of PetDB)
- Rejection of bad data (1.6%)

**morphological signatures**
Small, 1998

![Spreading rate legend](image)

Global variations in MORB composition (away from hot spots)

**Backscatter maps:**

A. “Rough”
   topography
   common at slow
   spreading (i.e. low
   melt supply)

B. and C.
   Rough and
   smooth examples
   at intermediate
   spreading rate

D. Smooth crust at
   fast spreading rate

Perfit and Chadwick, 1998, Fig 5
Global distribution of submarine hydrothermal vent sites (above) and areas of survey coverage (right), Baker and German, 2004.

Neovolcanic zone (NVZ):

Most active volcanism occurs here.

Width increases as spreading rate decreases

Volcanic style transitions from fissure fed to more point source as width increases

Crustal textures vary appropriately
Slow.
more point source constructs and wider NeoVolcanic Zone

Fast.
more continuous volcanic source and rarer point-source constructs in the NVZ

Perfit and Chadwick, 1998, Plate 1

point-source constructs (aka volcanic sea mounts) outside the “neo-volcanic zone” are aligned with plate motion

Figure 7. Neo-axial seamounts adjacent to (a) the northern EP (modified from Schreiner and Macdonald, 1993). Grey
shaded areas have complete bathymetric coverage and numerous ~200 km long are shown as filled circles. (b) The LPF
showing seamounts with (open circles) and without (solid circles) offset calanites or crusts (modified from Hammond
[1997]). Arrows show azimuth from center of volcano to center of collapse structure to center.
Deeper magma bodies at slower spreading.

Also, no steady state melt lens in magma chambers at low spreading rate but yes at faster rates (Sinton and Detrick, 1992)

Magma supply variations cause predictable links between magma chamber depth and magma chemistry

Rubin and Sinton 2007; Rubin et al., 2009
Shallower = more differentiated

Deeper = less differentiated

Spreading rate

Shallow

Deep

Magma Temp.

HOTTER (less differentiated)

COOLER (more differentiated)

High Magma Supply (e.g., faster spreading) = shallower chamber
Petrologic Model for Crustal Formation
On the East Pacific Rise 9°- 10° N

Modified from Perfit et al. (1994)

EPR 9°- 10° N SEISMIC MODEL (Dunn et al. 2000)
Passive Flow Model for Melt Delivery to the Northern East Pacific Rise

Schematic Geology of the EPR
What can mapping tell us?

Nested Surveys

Increasingly higher resolution

Topography
Lava Flow Surface types
Faulting

9°-10° N Ridge Crest Characteristics

Axial collapse Troughs in Young Volcanic Terrain
Sheet and Lobate lava flows
No Rift Valley Shallow Fault Scarp
Off-axis Pillow Mounds
Abyssal Hill Formation 2-3 km from Axis
Focused Venting
Tectonomagmatic Model for AST Development

Volcanic-tectonic cycles:
periodicity and relative intensity vary throughout the ridge system as a rough function of magma supply and spreading rate

Volcanic and Tectonic Interpretation of DSL-120A Sidescan Data

(Fornari, Soule, Escartin et al., work in progress)
Subaerial lava channel issuing from a small vent

Off-axis lava channel complex
Integrating sidescan interpretation, detailed mapping and sampling, with geochemistry and petrology.

From Soule et al. 2005 G3

Crustal and Magmatic Evolution

lava composition distribution. We’ll discuss this more later.

Some questions for now:
Are variations spatial or temporal or both?

What causes the variations in chemistry:
- Surficial processes: flow differentiation? Vapor contamination
- Magma chamber processes? Crustal plumbing? melt lens segmentation?
- Different mantle sources? Depleted vs Enriched
- Variable extents/depths of melting?
We learn a lot about volcanic crustal accretion by studying volcanic deposits from individual eruptions.

We'll return to this topic to discuss some of these later in the semester, but here are a few generalizations.
Lava flow morphology

Figure 8. Lava morphology vs. spreading rate (modified and expanded from Bonatti and Harrison [1983]). Values only take axial distributions into account. Additional data added from the EPR -9°30'N-32N (shown as 9°30'N Off-axis and Axial pair). Two values (Axial and Total) are also shown for the EPR -12°50'. Diagram shows the dominance of sheet flows at fast-spreading centers and pillow lavas at slow-spreading centers. Although data are limited, it appears that pillows are more abundant than sheet flows in off-axis areas on some fast-spreading ridges; a feature that may be related to the low effusion rate of off-axis volcanism.

Perfit and Chadwick, 1998, Fig 8

Generally higher effusion rate

Generally lower effusion rate

Figure 9. (a) Effusion rate and lava viscosity vs. lava flow morphology for submarine basalt on a 1% slope. Dashed lines separate fields of effusion rate and solid lines for a polar最有变化 (Gregg and Fink [1992]). Three scales from laboratory simulations show that effusion rate is probably the dominant influence on submarine lava morphology. (b) Correlation between laboratory-derived values and measurements of lava effusion rates and distance of flow from spreading center. (c) Schematic diagrams showing characteristic sequence of morphologic types of flows developed for several venting areas and spreading rates, for radial (radial) and linear (linear) geometry to the experiments. Solufluvial crust is indicated by shading (Perfit and Chadwick [1998]) and Gregg and Fink [1992]).
Sinton et al., 2002, JGR

- Some trends with magma supply (spreading rate), but the relationships are not likely statistically significant.
- At the present rate of progress it will probably take a few centuries before the data are sufficient to be truly meaningful.

Heterogeneities of some MORB flows/flow sequences


- MORB HI based on 10 basaltic major elements.
- > 11 analyses per flow except "ODP" flow (8 analyses).
- Almost all BBQ and Cleft Mounds heterogeneity is on LLDs.
- Most Gorda and Serocki flow heterogeneity is in parental magmas.
Compositional Heterogeneity and Spreading Rate

More heterogeneity at slower spreading.

Also recall the previous slide showing
more compositional heterogeneity in large volume lava flows.

Both are consistent with:

1. steady state magma chambers occur at higher melt-supply rates, Sinton and Detrick, 1992, Perfit and Chadwick, 1998, reducing the potential for compositional heterogeneity.

2. inverse relationship between spreading rate and flow volume (Perfit and Chadwick, 1998).