Large Igneous Provinces, Continental Break-Up and Marginal Plateaus

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Introduction

• Themes
  1. Crossing the shoreline – integrating onshore and offshore records
  2. Temporal evolution
     A. Wide to narrow rift modes
     B. Orthogonal extension to transtension
     C. LIP to “hotspot”-style magmatism

Gulf of California

GSA Today 2011 v. 21
Presentation Outline

• LIPs
• Volcanic Rifted Margins
• Passive Margin Asymmetry
• Rifted Margins and Marginal Plateau Case Studies
  • Eastern Australia
  • Gulf of California
• IODP deep riser stratigraphic drilling of the Lord Howe Rise continental ribbon/marginal plateau in 2020
Large Igneous Provinces

- **Definition (Bryan & Ernst, 2008, Earth Sci Reviews):**
  1. Areal extents >0.1 Mkm² (but often >1 MKm²)
  2. Igneous volumes >0.1 Mkm³ (but often >1 MKm³)
  3. Maximum lifespans of ~50 Myr (but often <15 Myr)
  4. Igneous pulse(s) of short duration (~1–5 Myr) comprising >=75% of total igneous volume
  5. Intraplate tectonic settings or geochemical affinities
  6. Dominantly mafic or dominantly silicic (+/- ultramafic components)
LIP Types & Distribution

- **Continental Flood Basalt Provinces**
  - Eg, Siberian, Karoo, Paraná-Etendeka, Deccan, Afro-Arabia, Columbia River

- **Giant Continental Dyke Swarms, Sills & Mafic Ultramafic Intrusive Provinces**
  - Eg, Mackenzie, Warakurna, Bushveld

- **Archean Greenstone Belts (Tholeiite-Komatiite Association)**
  - Eg, Superior, Yilgarn, Bulawayan, Rae

- **Volcanic Rifted Margins**
  - Eg, India-Western Australia, North Atlantic

- **Silicic LIPs**
  - Eg, Whitsunday, Chon Aike, Sierra Madre Occidental

- **Oceanic Plateaus**
  - Eg, Ontong Java-Manihiki-Hikurangi, Kerguelen, Caribbean-Colombian, Magellan Rise

- **Ocean Basin Flood Basalts**
  - Eg, Nauru Basin, East Mariana, Pigafetta

*From Bryan & Ernst (2008)*
LIP Distribution

Global Distribution of LIPs following Pangea assembly

From Bryan & Ferrari (2013)
LIPs: Unheralded Igneous Events

Intraplate setting

From Bryan & Ernst (2008)
LIPs: Exceptional Magma Production

Volcanic output rates grouped by petro-tectonic setting

Volume of lava vs time for the CRB

Grande Ronde Basalts:
~72% of erupted volume in ~400 Kyr

From Self et al. (2014)
LIPs: Exceptional Magma Production

Ratio of extruded to intruded magma is \(~1:10\)

LCB = Lower crustal body (igneous underplate)

From Coffin & Eldholm (1993)
LIPs: Sites of Extraordinary Volcanism

1. Volume of magma emitted during individual eruptions 
   \( (10^2 - 10^4 \text{ km}^3) \)

2. Basaltic (>360 \text{ km}^3) & silicic (>410 \text{ km}^3) supereruptions

3. Discharge rates
   • Basalt: \( 10^6 - 10^7 \text{ kg s}^{-1}, \text{ yrs to decades} \)
   • Rhyolite: \( 10^9 - 10^{11} \text{ kg s}^{-1}, \text{ days to ?weeks} \)

4. Frequency of large-volume eruptions
   • One >M8 eruption every \( \sim 4000 \text{ yr} \)

5. Total volume of magma intruded and released during the 
   main igneous pulses \( (10^6 - 10^7 \text{ km}^3) \)

From Bryan et al. (2010)
Volcanic Rifted Margins

- Up to 90% of global rifted continental margins are VRMs.
Volcanic Rifted Margins

Comprise 3 well-defined components:
1) Large igneous province (LIP)
2) Seaward-dipping seismic reflector series (SDRS)
3) A thick, high velocity lower crust (HVLC)
Volcanic Rifted Margins

Volcanism occurs:

1) Pre- to syn-rift (the LIP: continental flood basalts, silicic LIP, VRM),
2) Syn-rift, forming “Seaward dipping reflector series”, and
3) Post-rift = MORB, Hotspots

Schematic VRM based on data from Ethiopia-Yemen and Atlantic margins; From Menzies et al. (2002).
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Knesel et al. (2008) Nature
Relative Timing of Volcanism & Extension

- Temporal differences between volcanic & intrusive events (eg, Yemen):
  - Volcanic stratigraphy ~31-26 Ma
  - Hypabyssal, plutonic rocks and dyke swarms <25 Ma
  - Peak extension 26-19 Ma

- Exposed intrusions biased toward dating extension

Passive Margin Mountains

- Many rifted continental margins bordered by eroded mountain ranges/escarpments
  - = permanent topographic highs (1 - >3 km) proximal to rifted margin

https://maps.ngdc.noaa.gov/viewers/bathymetry/
Passive Margin Mountains

• Present-day rift margin morphologies typified by:
  1. Offshore (coast-parallel) sedimentary basins, or continental shelf (10’s to 100’s km wide)
  2. Coastal plain (10’s to ~200 km wide)
  3. Steep escarpment (100’s m to >1 km high)
  4. Elevated inland region (100’s km wide, ~1 to 4 km high, with gentle gradient dipping cratonward)

https://maps.ngdc.noaa.gov/viewers/bathymetry/
Passive Margin Mountains

Gulf Escarpment, Baja California, Mexico

Great Dividing Range, SE Queensland, Australia
Passive Margin Mountains

Distinctive features of onshore rift margin:
1) Young ages on the coastal plain
2) Older ages inland of escarpment

Post-rift exhumation & removal of 1-4 km of material from coastal plain

Slower erosion rates behind escarpment
Passive Margin Asymmetry

- Lack of symmetry across and along rifts:
  - Passive margin mountain development
  - Continental shelf width
  - Marginal plateau development
  - Post-rift intraplate volcanism

https://maps.ngdc.noaa.gov/viewers/bathymetry/
Passive Margin Asymmetry

• Rift asymmetry can switch along rifted margin across major crustal lineaments or transform faults
  • Eg, Sth America-Southern Africa

From Lister et al. (1989, 1991)
Case Study: Eastern Australia

- **Tasman (84-52 Ma)**
- **Coral Sea (63-52 Ma)**
- **Cato Trough (65-55 Ma)**
- **Papuan**
- **Queensland**
- **Louisiade**
- **Mellish**
- **Dampier**
- **Lord Howe Rise**

**Darling River Lineament**
Case Study: Eastern Australia

Watershed, Great Dividing Range

Cretaceous-Tertiary rift basins

Watershed, Great Dividing Range
Marginal Plateau Development

- Adjacent to wide continental shelves
- Bounding areas of distributed extension/wide rifts
- Offshore from margins lacking passive margin mountain ranges

de Lépinay et al. (2016) Tectonophysics
Case Study: Gulf of California

**Red Sea:** Rupturing since 30 Ma; Old cratonic lithosphere, Orthogonal rifting

**Gulf of California:** Apparent rupturing in only 6-10 Myrs; Young orogenic lithosphere
Gulf of California

- Region of coupled magmatism and extension leading to successful rupturing
  1. Silicic LIP magmatism
  2. Basin and range-style extension
  3. Zones of high-magnitude extension
  4. SFS since ~6 Ma

Bryan et al. (2014) GSL Special Publ 385
**Sierra Madre Occidental (SMO)**

**SMO:** the youngest most continuous SLIP

**Age:** ~38-17 Ma but pulsed

**Volume:** ~400,000 km$^3$ (>1 km thick)
Temporal Compositional Trends of Magmatism

Bryan et al. (2014) GSL Special Publ 385
Timing Relationships to Extension

- Early Miocene distributed extension and bimodal volcanism

Age and kinematics of deformation: southern SMO

[Map showing geological features, including fault lines and volcanic activity, with labeled regions and time periods for each event.]
Timing Relationships to Extension

Extension since Oligocene

- Mexican B&R resulting in crustal thinning up to 20%

- Crustal thicknesses halved around margins of Gulf

-100% extension in GEP from Late Miocene to Present
Timing Relationships to Extension

Southern GoC: 11-9 Ma mafic lavas & dykes untilted. 21-20 Ma ignimbrites tilted up to 35° NE
Regional mafic volcanic pulse

- 12-10 Ma
- Along Gulf E coast & above submerged rifted blocks
- Post-dating SMO block tilting
Timing Relationships to Extension

Discovery of significant amounts of plutonic rock now exposed on submerged margins of Gulf

ROCA 2008 & BEKL 2009 cruises

Duque-Trujillo et al. (2015)
Timing of rifting in the southern Gulf of California and its conjugate margins: Insights from the plutonic record

<table>
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<th>East</th>
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**Rapid Extension, Narrow Rift Mode**

**Slow Extension, Wide Rift Mode**

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Legend:
- AFTA
- "Ar" Ar (Bl)
- "Ar" Ar (Kfs)
- "Ar" Ar (Hbl)
- "Ar" Ar (Kfs)
- U/Pb
- "Ar" Ar (Pl)
- Volcanic cited Sample
- Plutonic dated sample
- Extensional deformation
Timing Relationships to Extension

- Temporal change from wide to narrow rifting

Early Miocene (~24-18 Ma)

Mid Miocene (~18-12 Ma)
Marginal Plateaus
Key Points – Gulf of California

- Rifting across the Gulf region began ~30 Ma, well before end of subduction
  - provided a fundamental control on the style and composition of volcanism from at least 30 Ma

- Links between Sierra Madre Occidental silicic LIP volcanism and Gulf of California

- Pace and breadth of extension changed:
  - ~30-18 Ma slow & wide-rift mode
  - ~18-12 Ma faster narrow-rift mode
  - <12.5 Ma, more oblique rift kinematics
Key Points – Gulf of California

• Narrow Rift Mode ~18-12 Ma
  • Focussed volcanism, extension & exhumation within Gulf
  • Magmatic intrusions rapidly cooled and exhumed
  • Spatially-temporally coincident andesitic volcanism a product of magma mixing
  • Crustal thickness halved by 12 Ma

• Transtensional Rift Mode <12 Ma
  • Gulf unzipping to North
  • Fastening pace of rupturing
  • New locations of crustal rupturing
  • Marginal plateaus formed (abandoned & broken rift basins)
Summary

Architecture of rifted margins reflects an interplay of:

1. Pre-existing structures such as cross-orogen faults that can partition deformation

2. Syn-extensional processes
   a. LIP magmatism
      • Underplating thickens & strengthens crust, drives surface uplift
      • Facilitates rupturing process by magma lining faults
   b. Large-scale detachment fault geometry inducing asymmetry to the rift

3. Evolution of stress regimes from orthogonal extension to more transtensional regimes
   a. Abandonment of early formed rift basins and new locations of crustal rupture developed
   b. Marginal plateau formation
IODP deep riser stratigraphic drilling in the southwest Pacific: tectonics, climate and ancient life on the Lord Howe Rise continental ribbon

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The Lord Howe Rise

- Rifted continental ribbon
  - \( \approx 1600 \, \text{km} \) long
  - 400–500 km wide
- A series of ridges and basins in water depths of \( \approx 1000–4000 \, \text{m} \)
Data Coverage

- Current understanding is based on
  - 2D seismic reflection data
  - Gravity and magnetic data
  - Correlation with onshore areas
  - Limited number of dredge samples
  - Ocean drilling only as deep as the latest Cretaceous
    - DSDP 208 to 594 mbsf
    - IODP 371 to 305 mbsf (Pre-Eocene alkali basalt)

- Knowledge is limited by a lack of rock samples!
IODP Proposal 871-CPP

One deep riser drill hole through a Cretaceous rift basin on the Lord Howe Rise

- Recover a complete Cretaceous stratigraphic record from a rift basin and sample the pre-rift sedimentary succession
- Drill 2.3–2.7 km below seafloor
- 100% coring of Cretaceous strata through to total depth

Two shallow riserless drill holes to sample pre-rift basement

- 0.5–0.7 km below seafloor

Depth to base of rift sequence (Colwell et al., GA Record 2010/06)
Primary Deep & Basement Drill Sites

Currently-preferred site

- DLHR-5A
- DLHR-1B

Water

- Post-rift
- Syn-rift
- Pre-rift/early syn-rift?

Depth (m)
- ~2700 mbsf
- Basement

2 km

Bland basement

(metamorphics or granites of Gondwana-margin)
Summary

The Lord Howe Rise is a key piece in the Cretaceous global tectonic and climate puzzle.

Deep stratigraphic drilling will provide access to:
- rocks that record SW Pacific Cretaceous tectonics and climate
- a new deep environment in which to test the limits of life

IODP Proposal 871-CPP: “Gondwana margin deep drilling”
- a multidisciplinary, internationally-significant scientific project
  - addresses many challenges in the IODP 2013–2023 Science Plan
- approved by the IODP Science Evaluation Panel and Chikyu IODP Board in early 2017
- stratigraphic drilling is currently scheduled for 2020
  - subject to funding approval in 2018...