Large Igneous Provinces, Continental Break-Up and Marginal Plateaus

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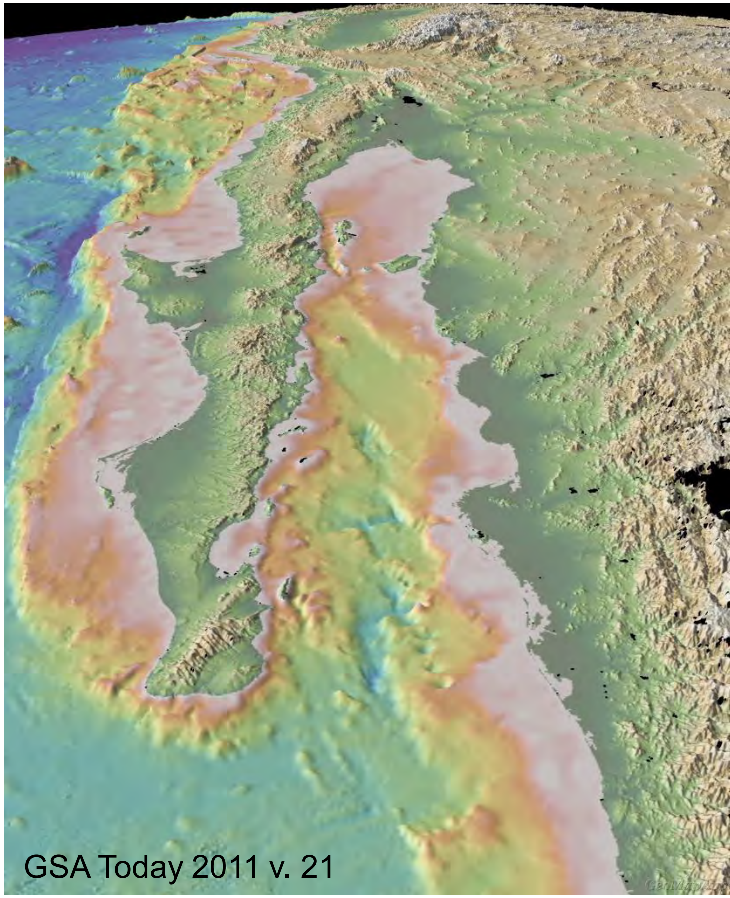
Introduction

- 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

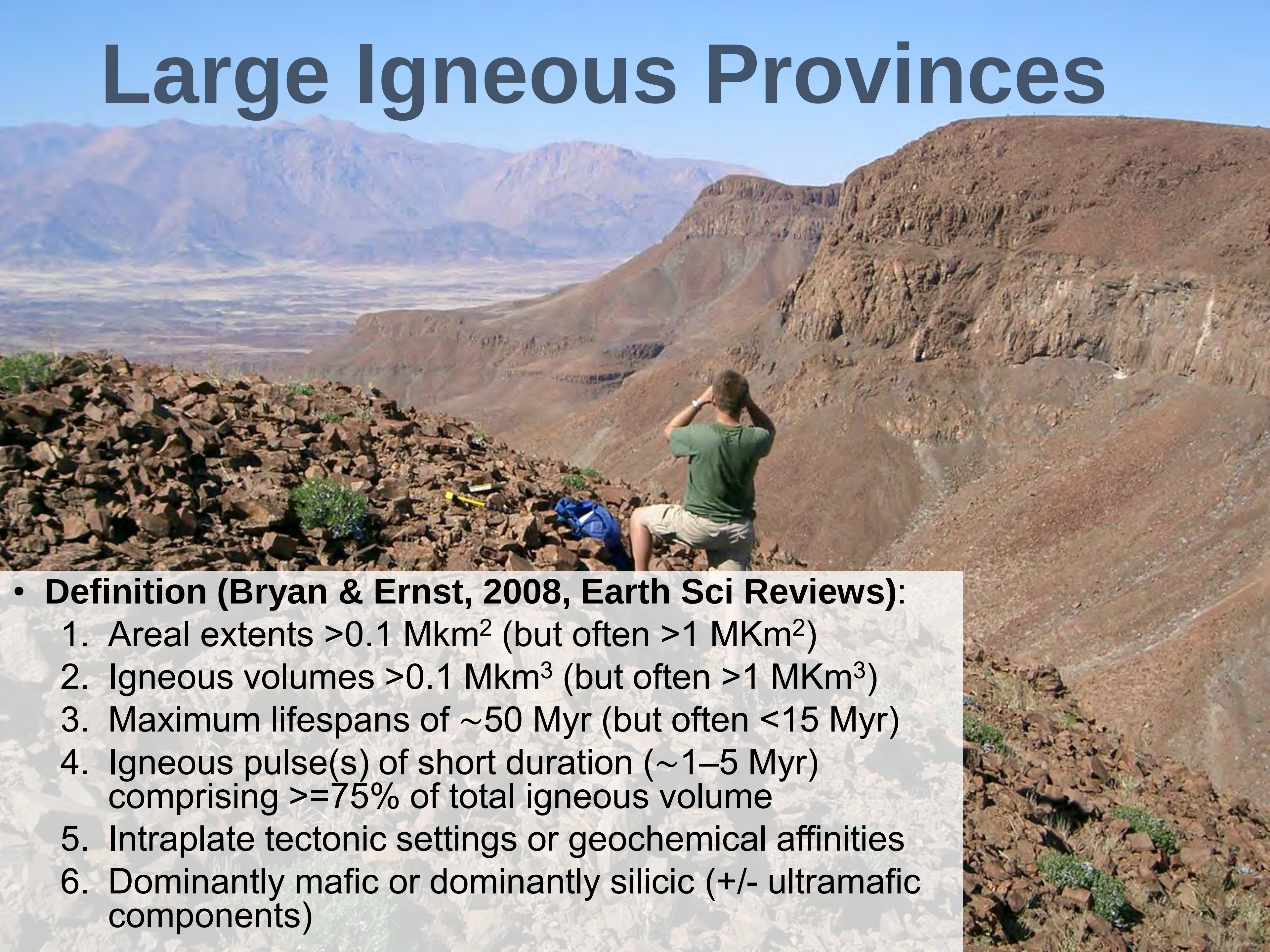
Gulf of California



Presentation Outline

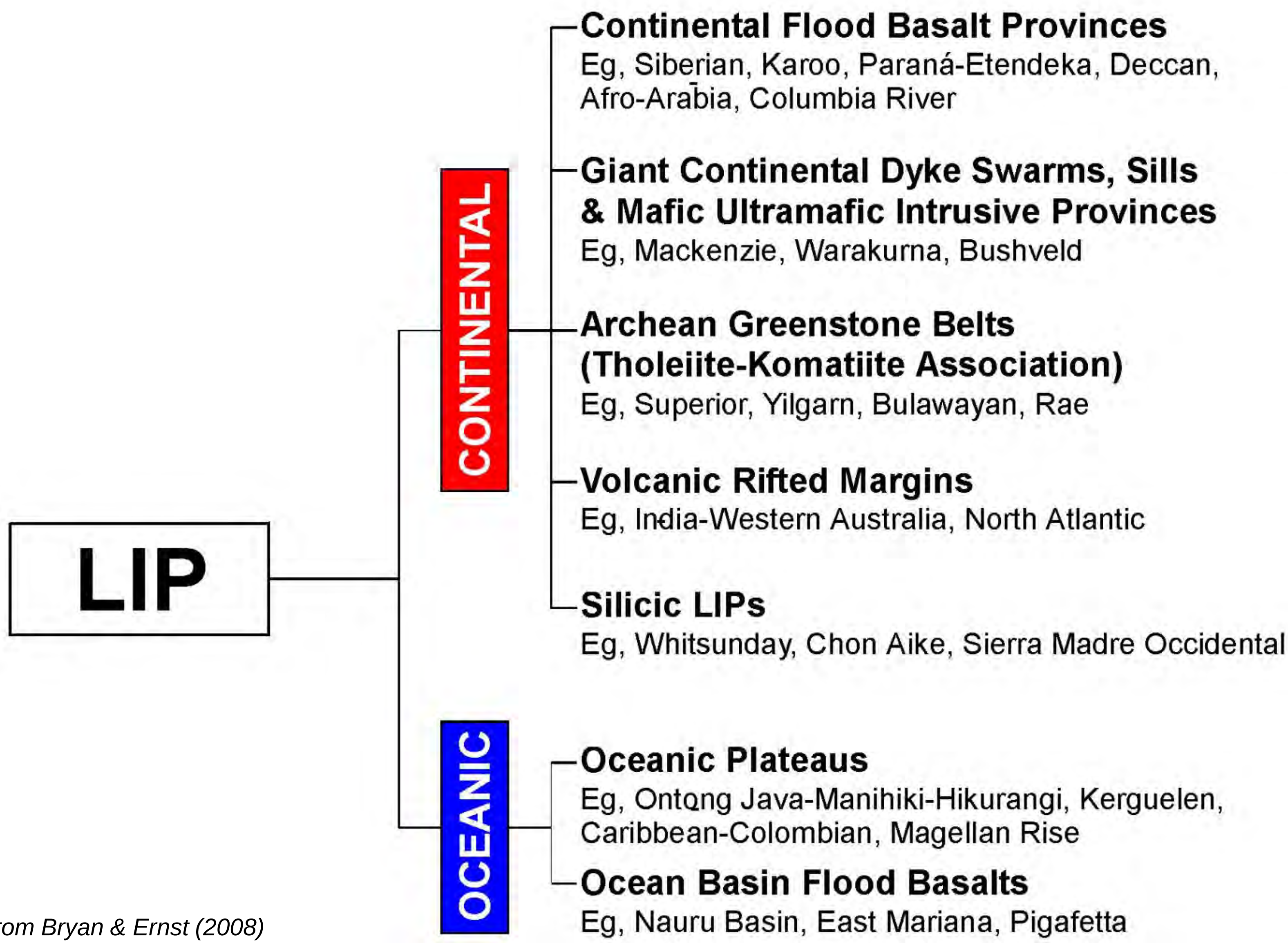
- LIPs
- Volcanic Rifted Margins
- Passive Margin Asymmetry
- Rifted Margins and Marginal Plateau Case Studies
  - Eastern Australia
  - Gulf of California
- IODP deep riser stratigraphic drilling of the Lord Howe Rise continental ribbon/marginal plateau in 2020

Large Igneous Provinces



- **Definition (Bryan & Ernst, 2008, Earth Sci Reviews)**:
  1. Areal extents >0.1 Mkm^2 (but often >1 MKm^2)
  2. Igneous volumes >0.1 Mkm^3 (but often >1 MKm^3)
  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)

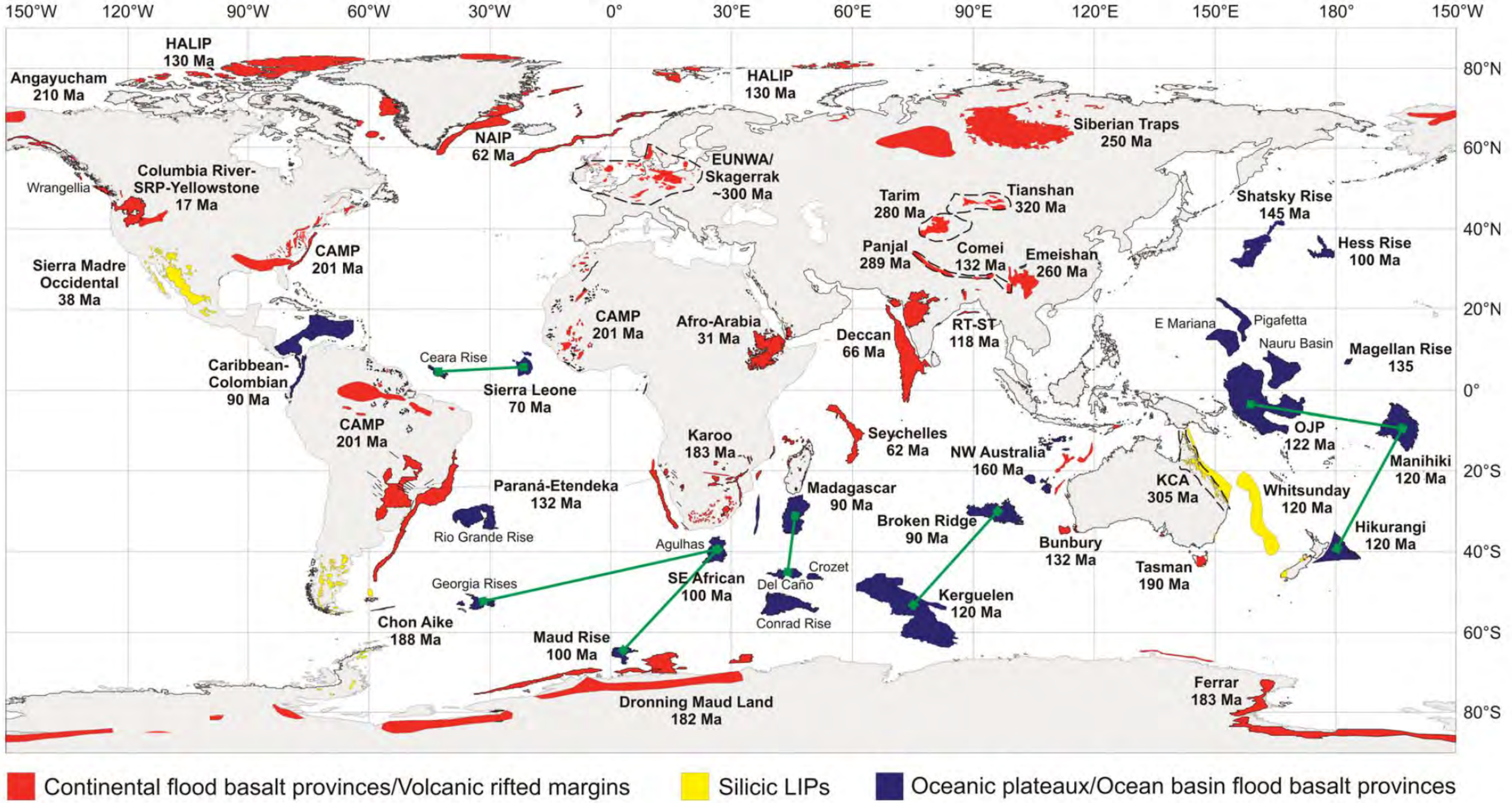
LIP Types & Distribution



From Bryan & Ernst (2008)

LIP Distribution

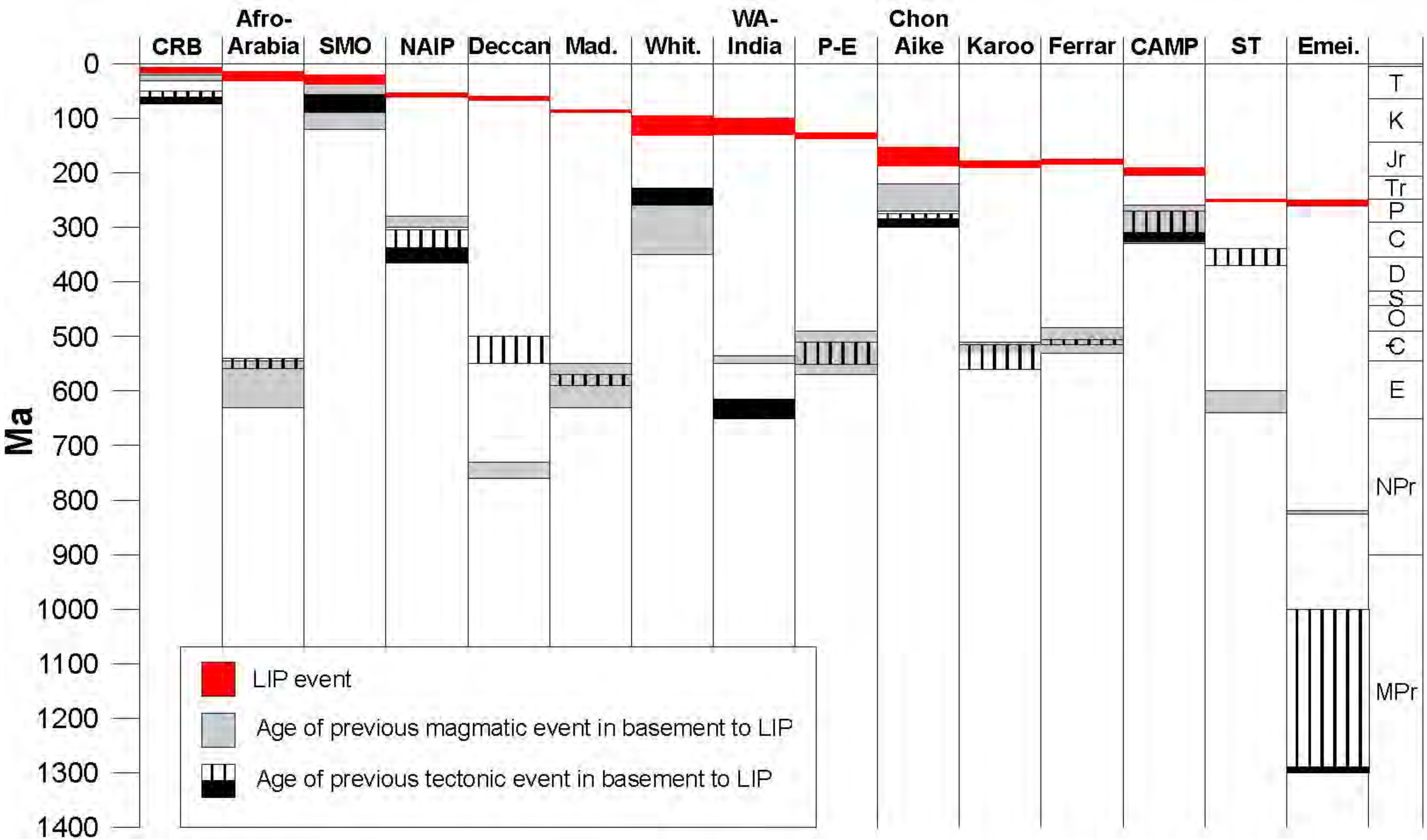
Global Distribution of LIPs following Pangea assembly



From Bryan & Ferrari (2013)

LIPs: Unheralded Igneous Events

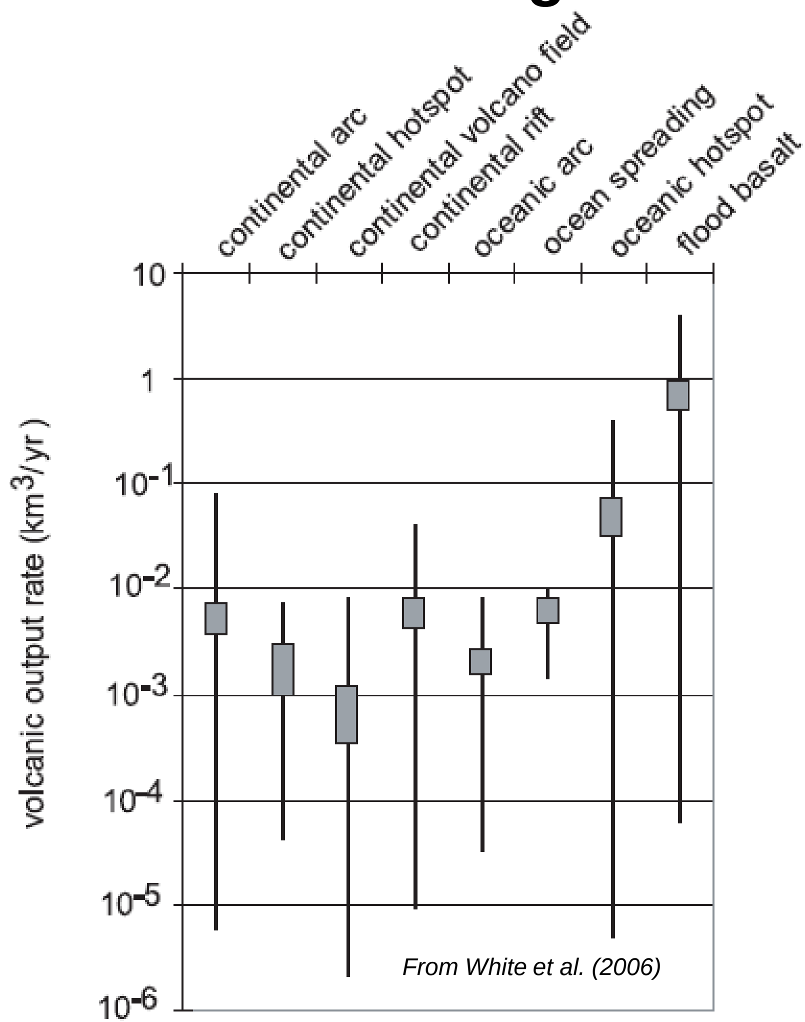
Intraplate setting



From Bryan & Ernst (2008)

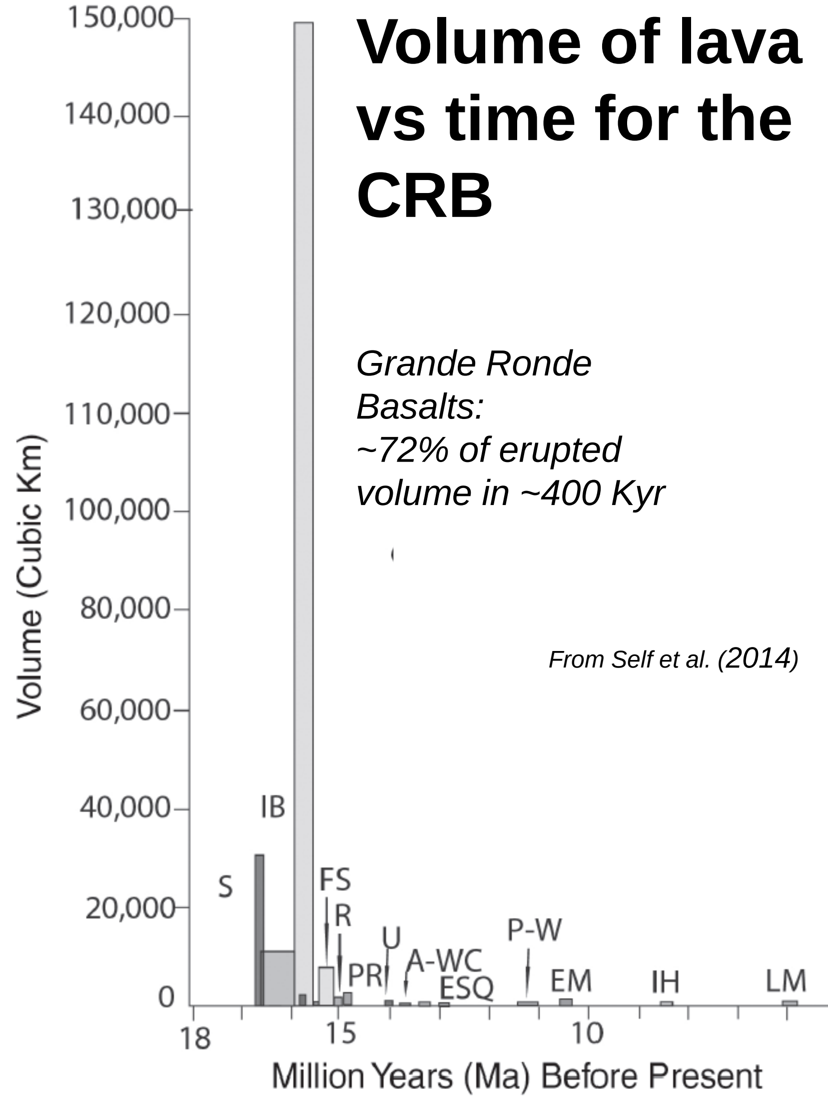
LIPs: Exceptional Magma Production

Volcanic output rates grouped by petrotectonic setting



From White et al. (2006)

Volume of lava vs time for the CRB

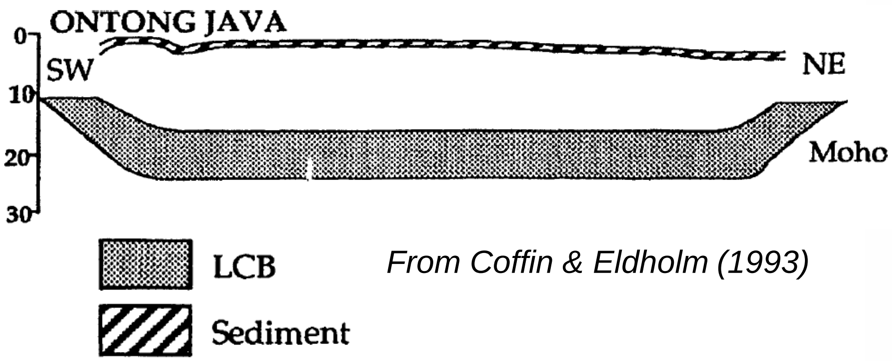


Grande Ronde Basalts:
~72% of erupted volume in ~400 Kyr

From Self et al. (2014)

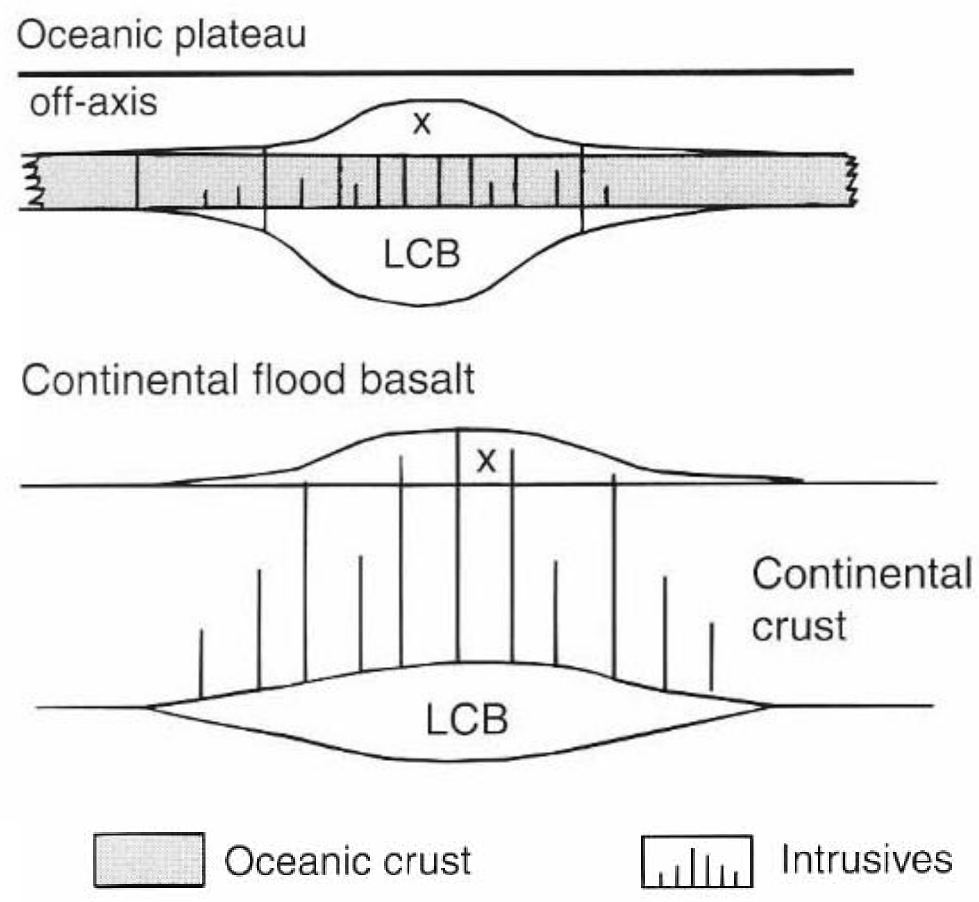
LIPs: Exceptional Magma Production

Ratio of extruded to intruded magma is ~1:10



From Coffin & Eldholm (1993)

LCB = Lower crustal body
(igneous underplate)



From Coffin & Eldholm (2001)

LIPs: Sites of Extraordinary Volcanism

1. Volume of magma emitted during individual eruptions (10^2–10^4 km^3)

2. Basaltic (>360 km^3) & silicic (>410 km^3) supereruptions

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

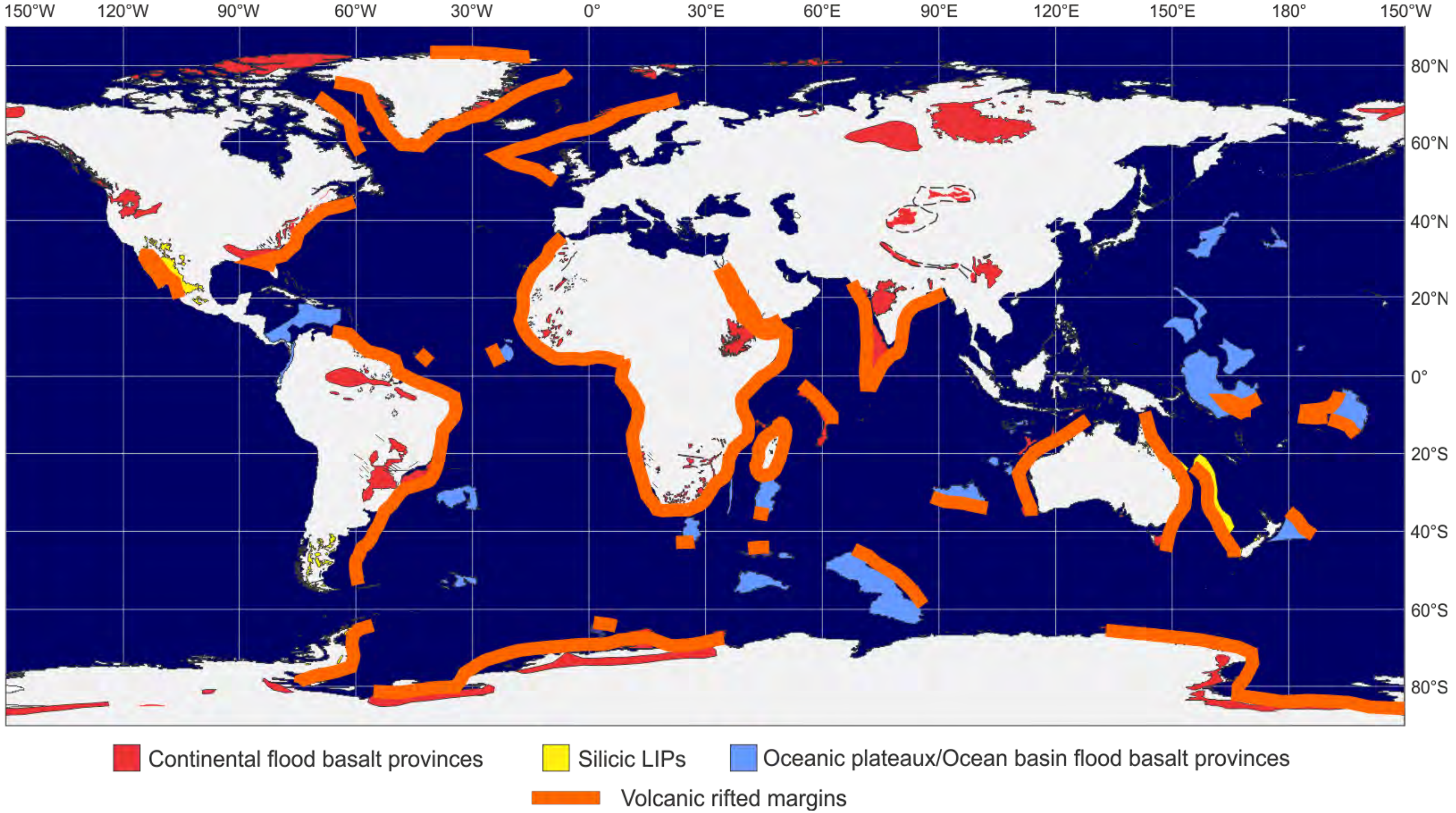
4. Frequency of large-volume eruptions
   - One >M8 eruption every ~4000 yr

5. Total volume of magma intruded and released during the main igneous pulses (10^6 – 10^7 km^3)

From Bryan et al. (2010)

Volcanic Rifted Margins

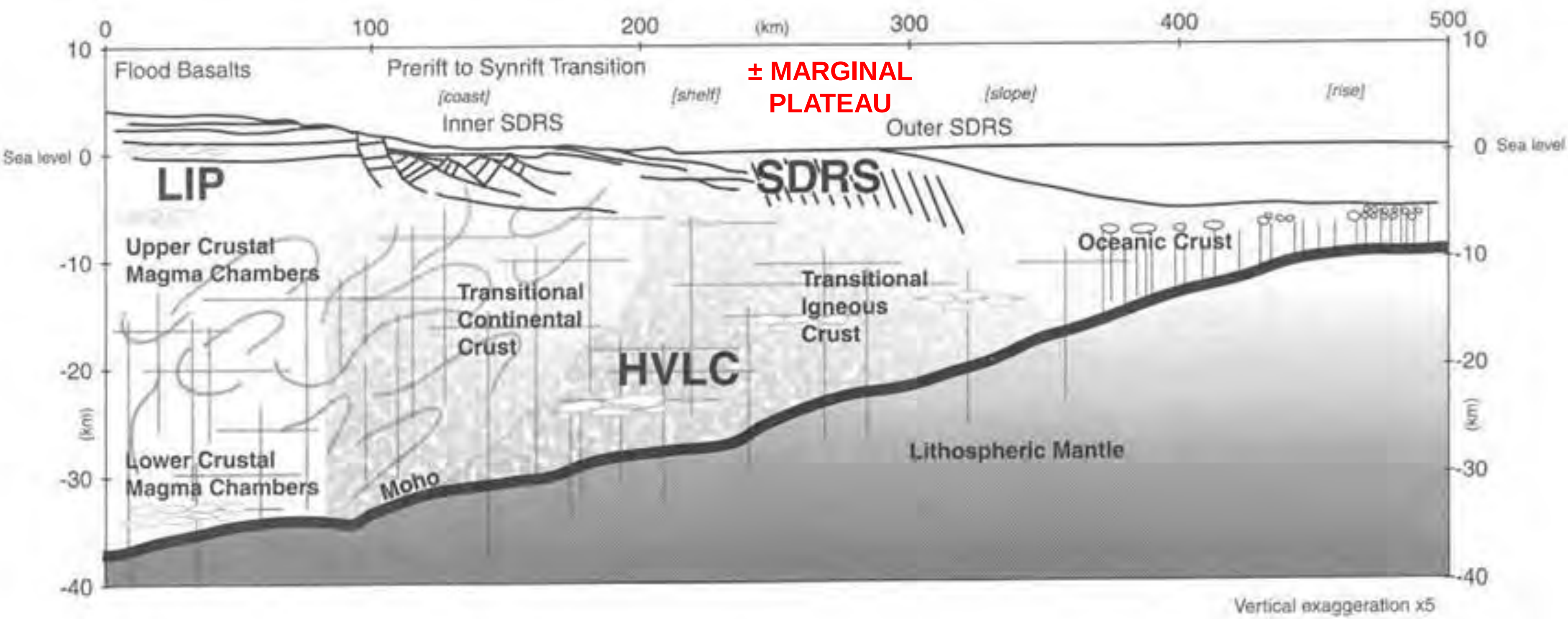
- Up to 90% of global rifted continental margins are VRMs



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)

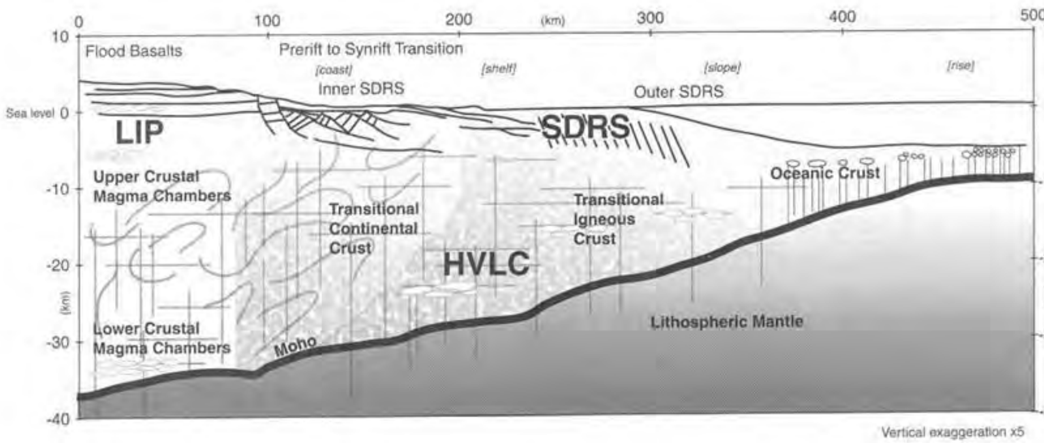


Schematic VRM based on data from Ethiopia-Yemen and Atlantic margins; From Menzies et al. (2002).

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



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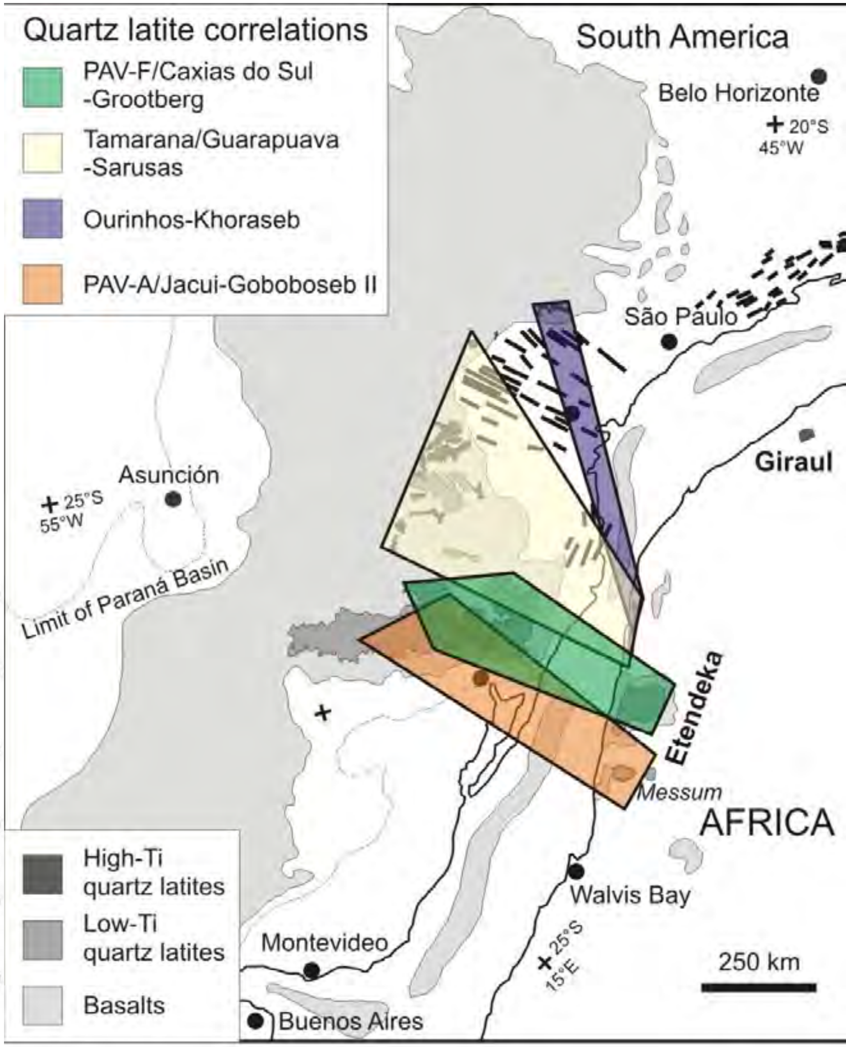

Bryan et al. (2010) Earth-Science Reviews

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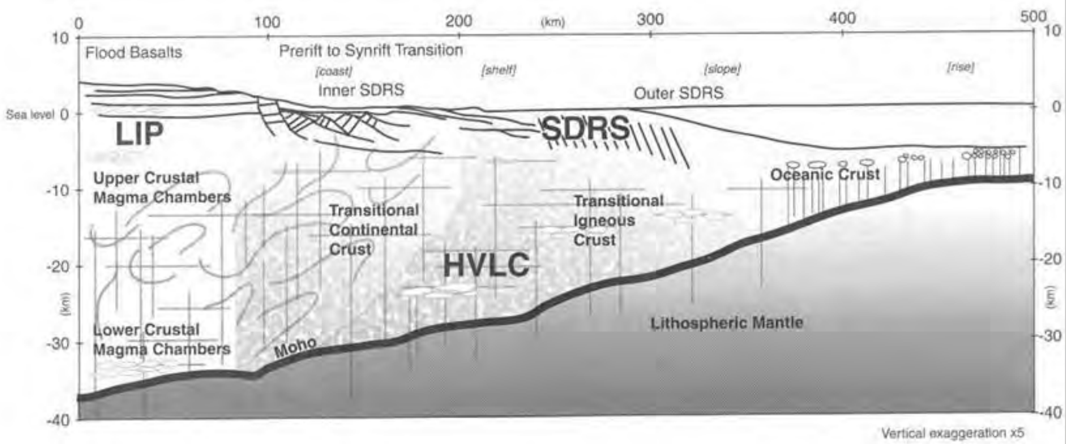

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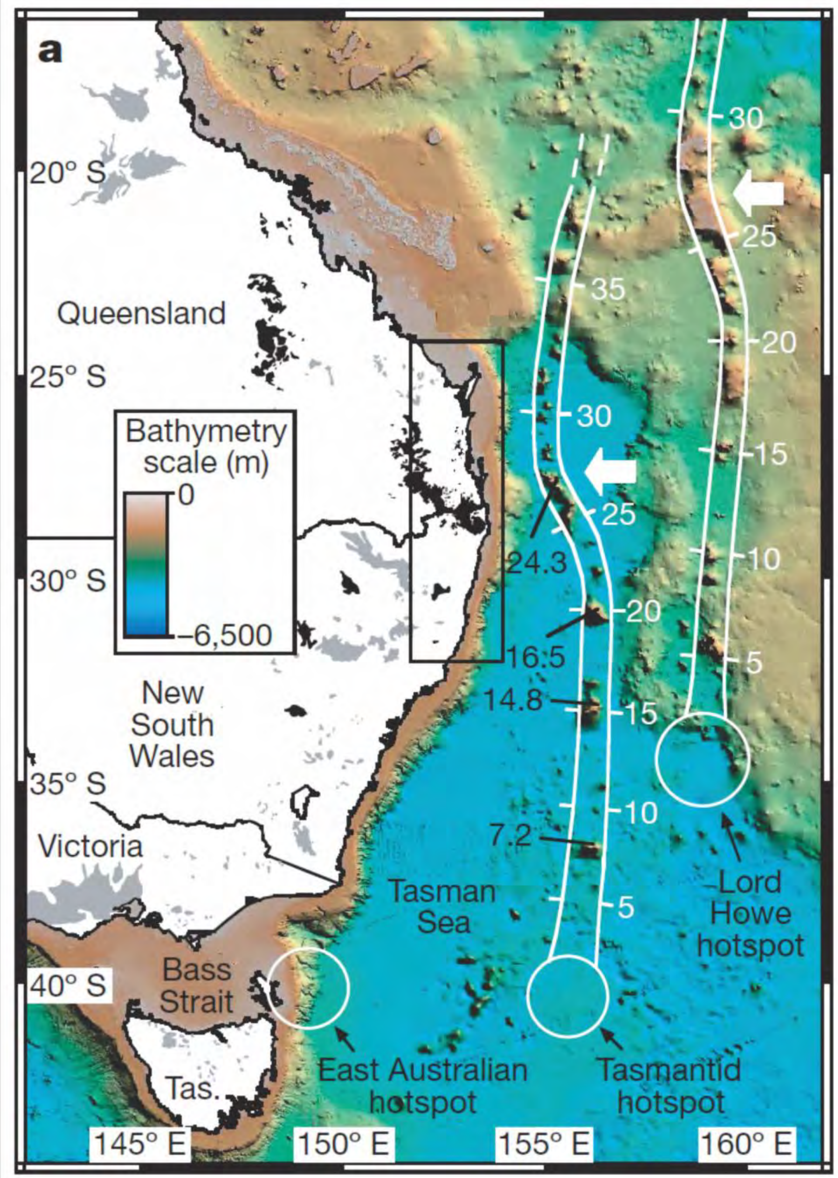
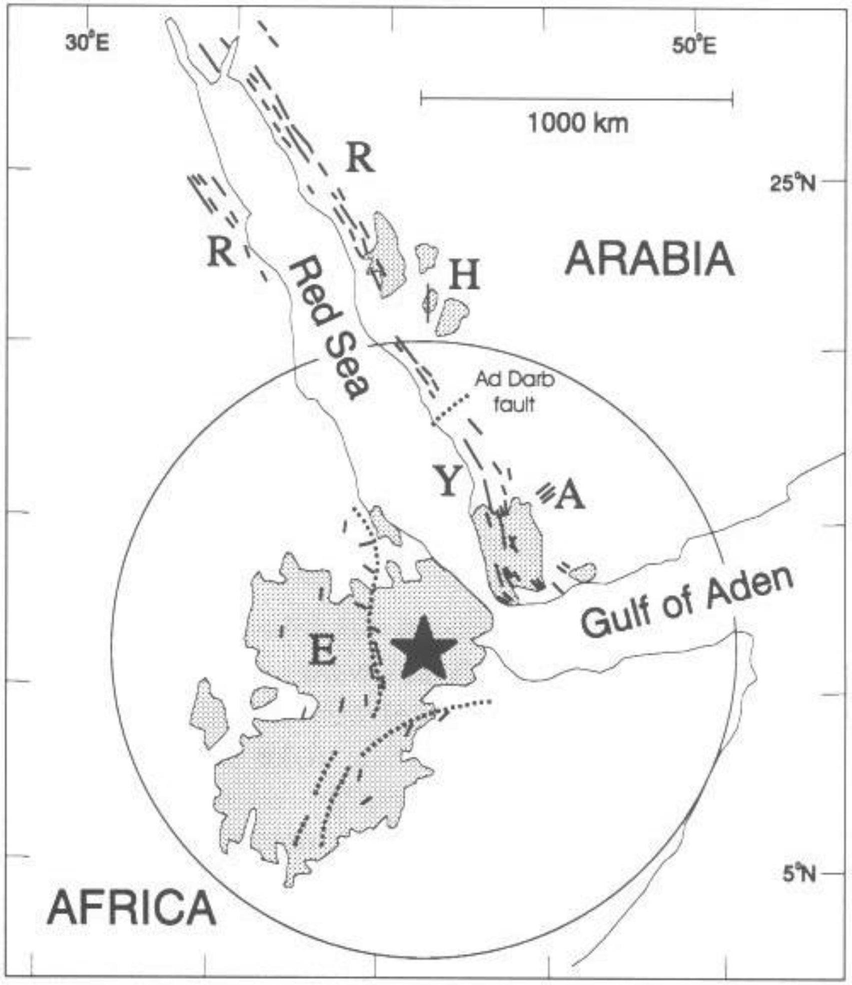


Knesel et al. (2008) Nature

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

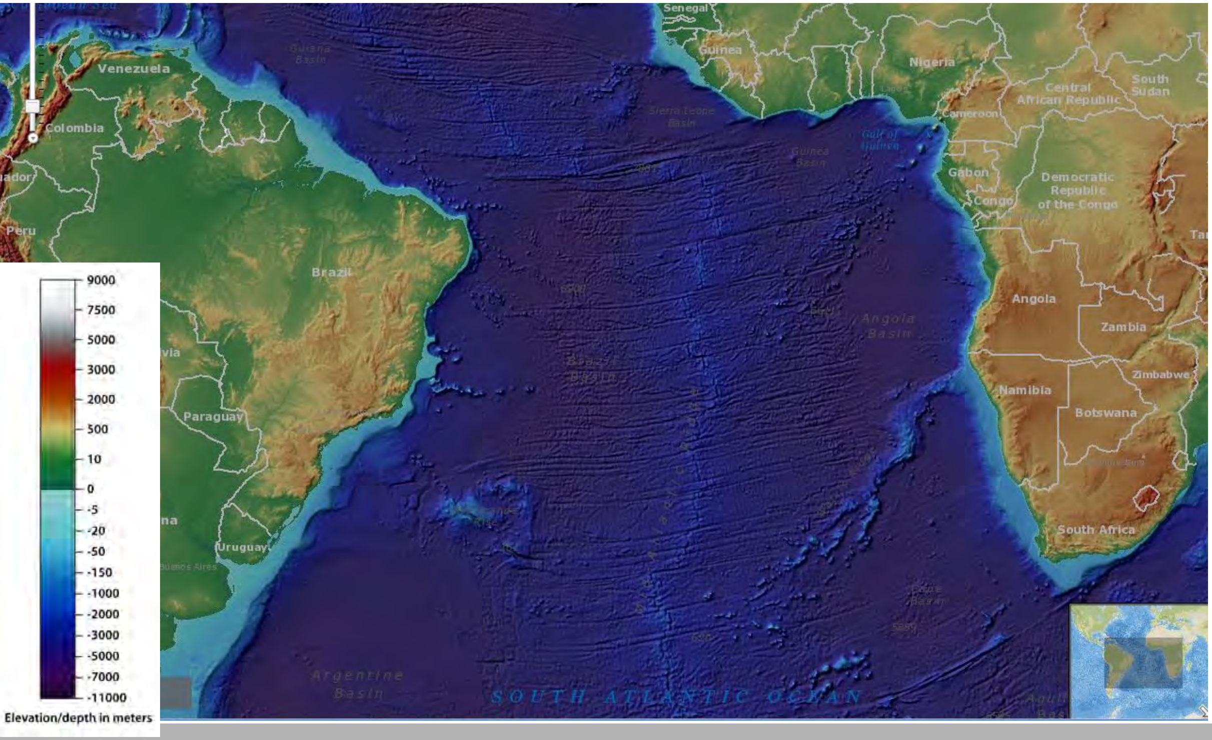
- Exposed intrusions biased toward dating extension



From Ernst & Buchan (1997) Geophys Monograph 100.

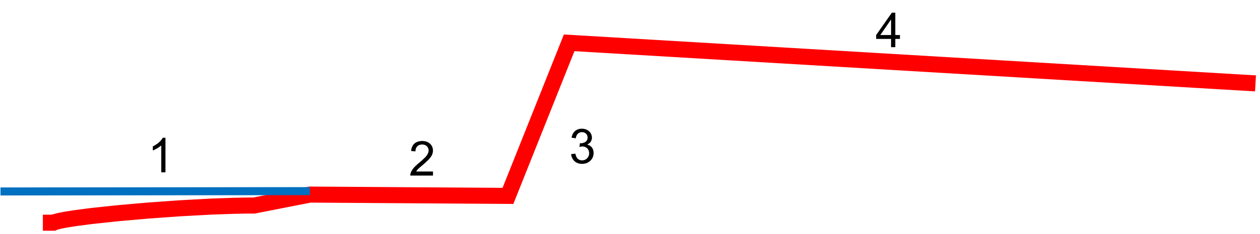
Passive Margin Mountains

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



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

Passive Margin Mountains

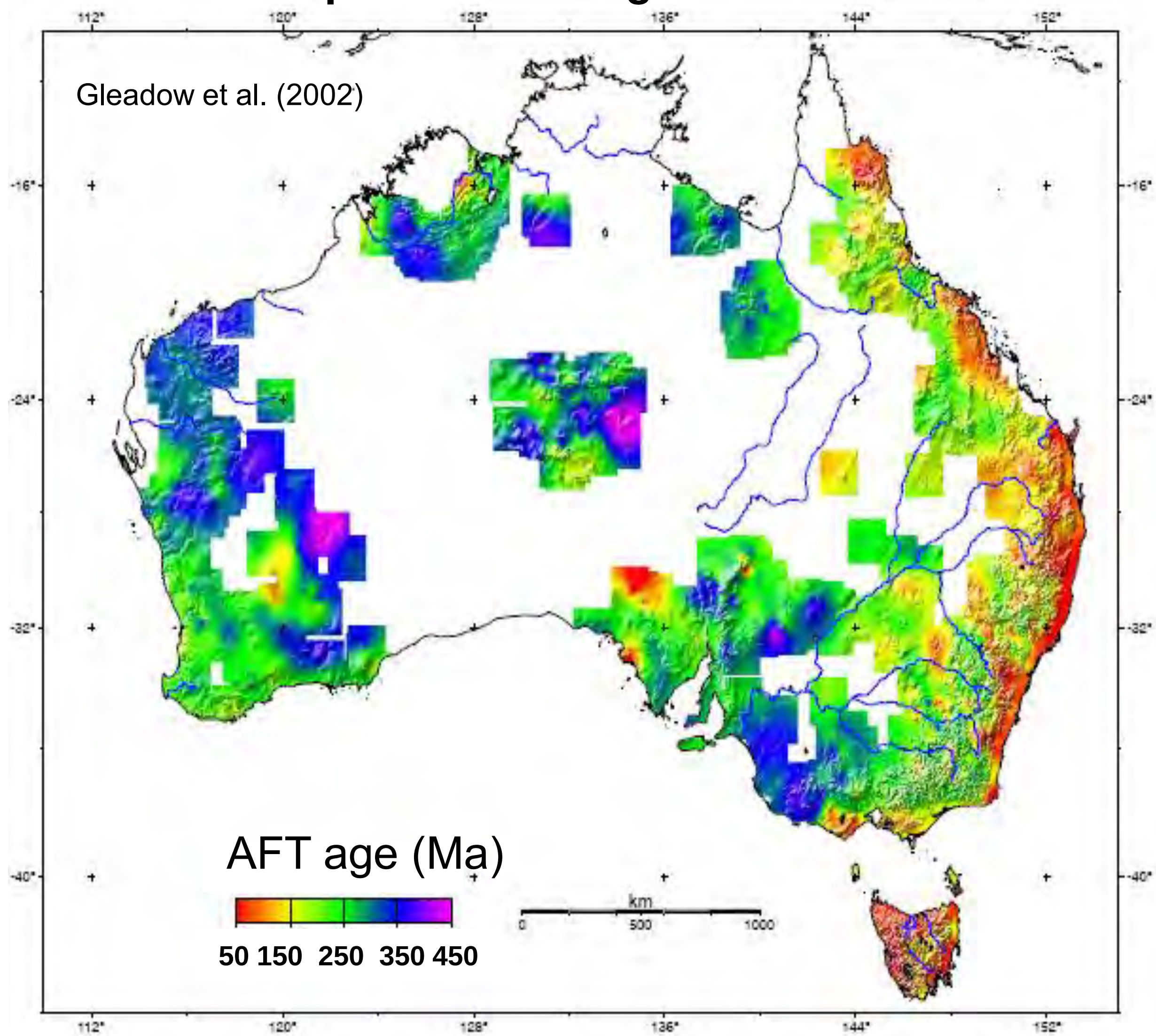
Distinctive features of onshore rift margin:

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

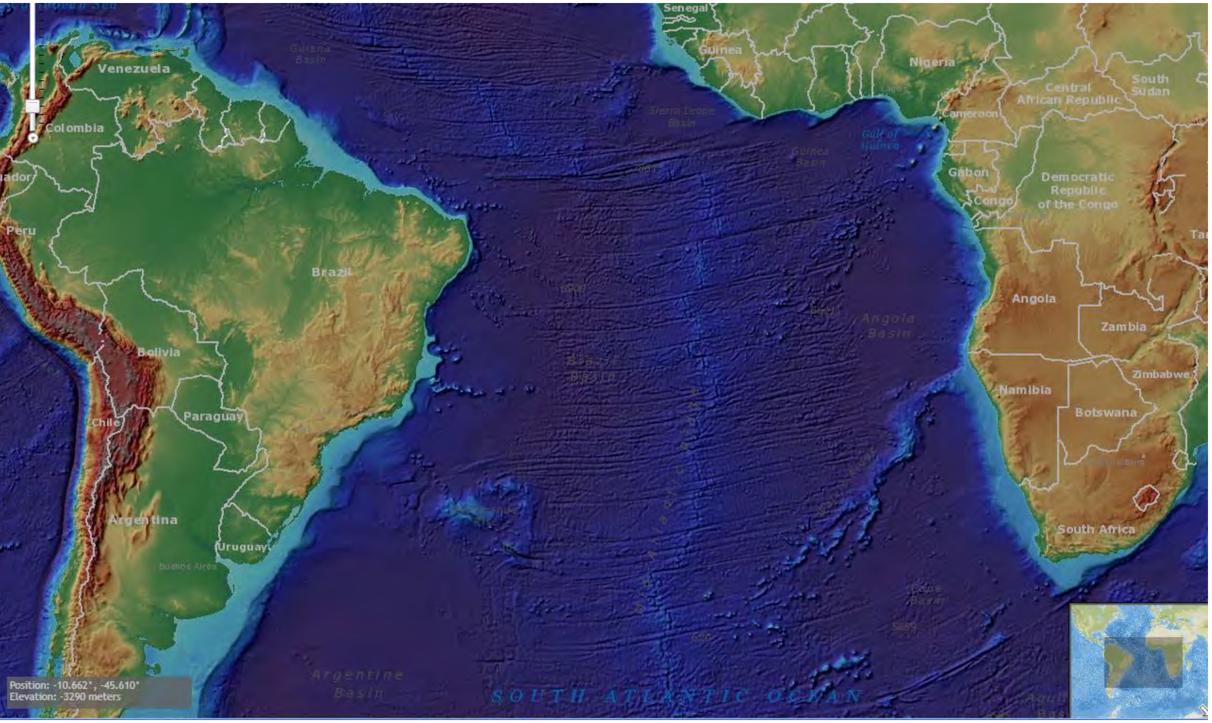
Slower erosion rates behind escarpment

Interpolated AFT Ages across Australia



Passive Margin Asymmetry

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



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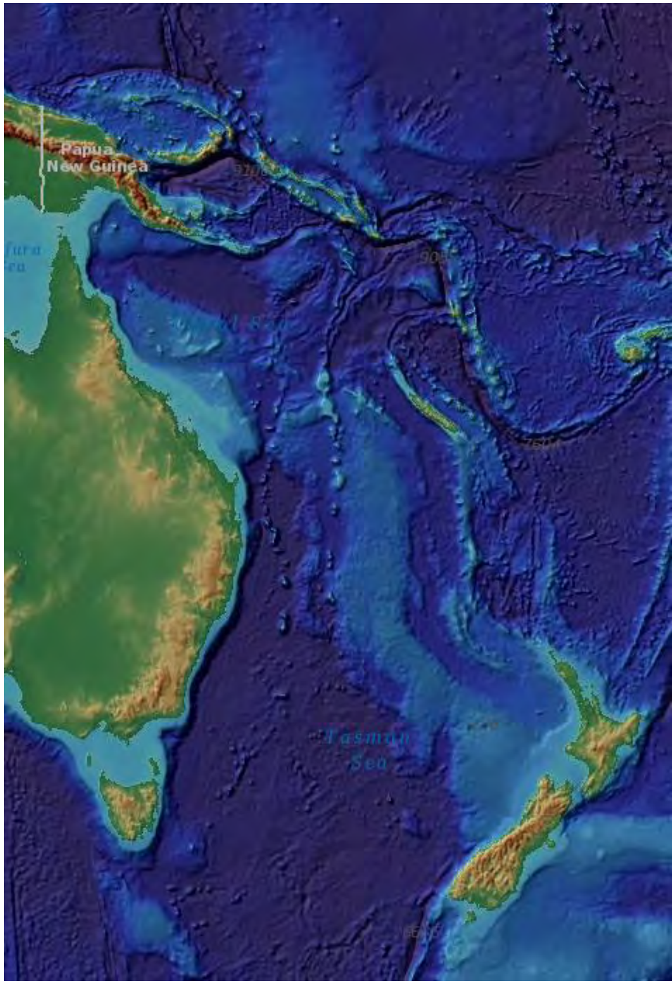
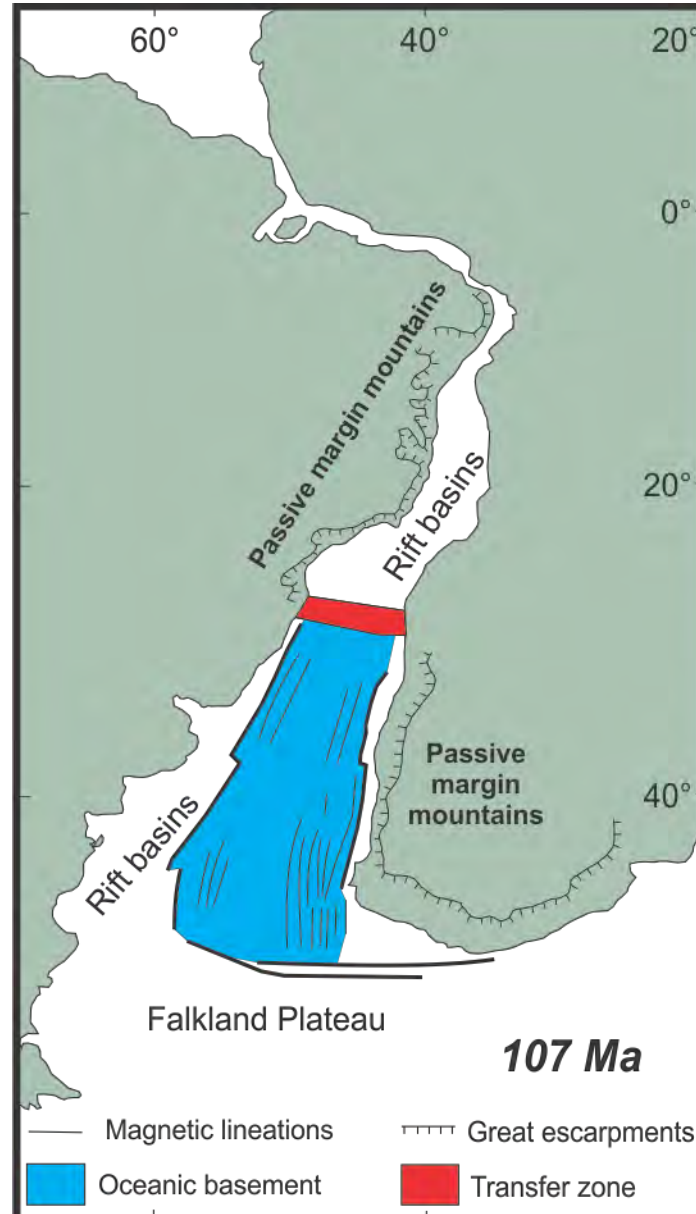


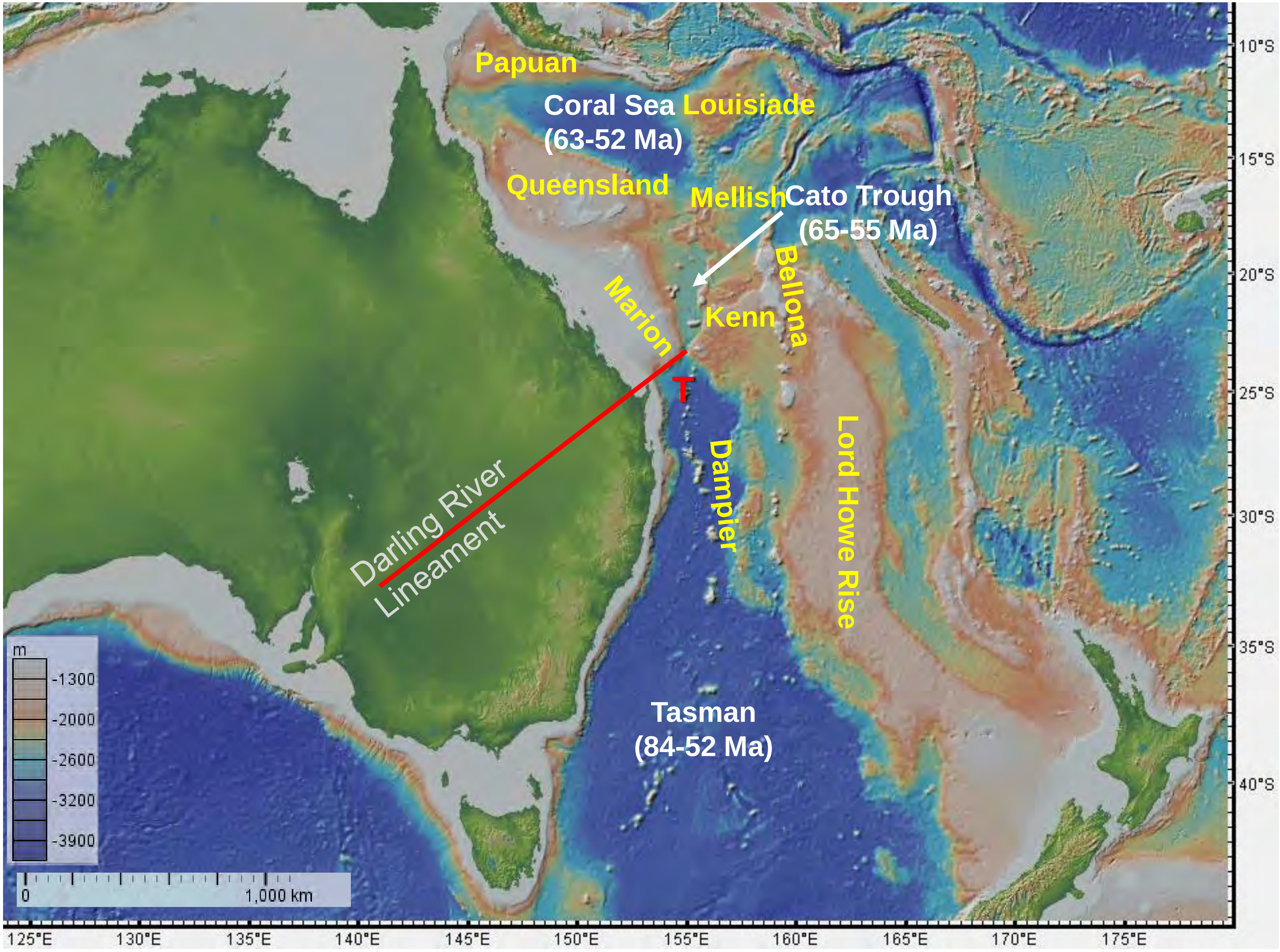
Passive Margin Asymmetry

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

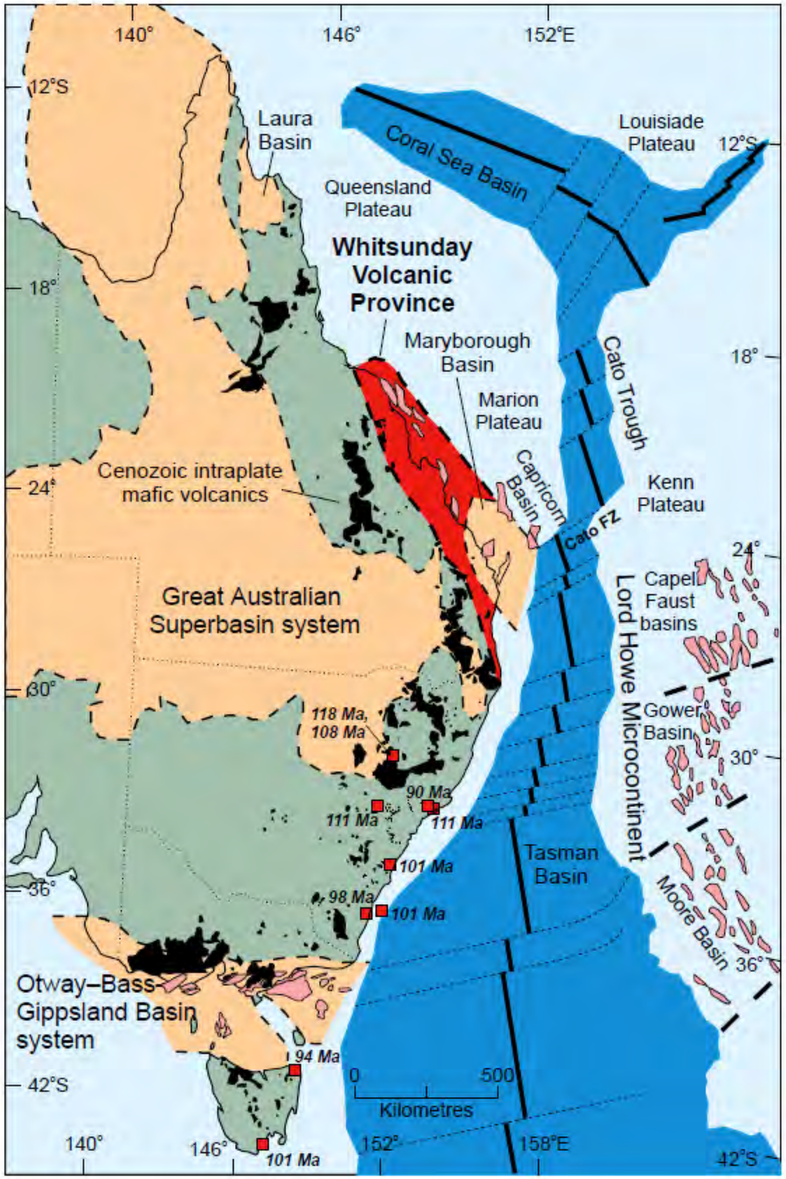


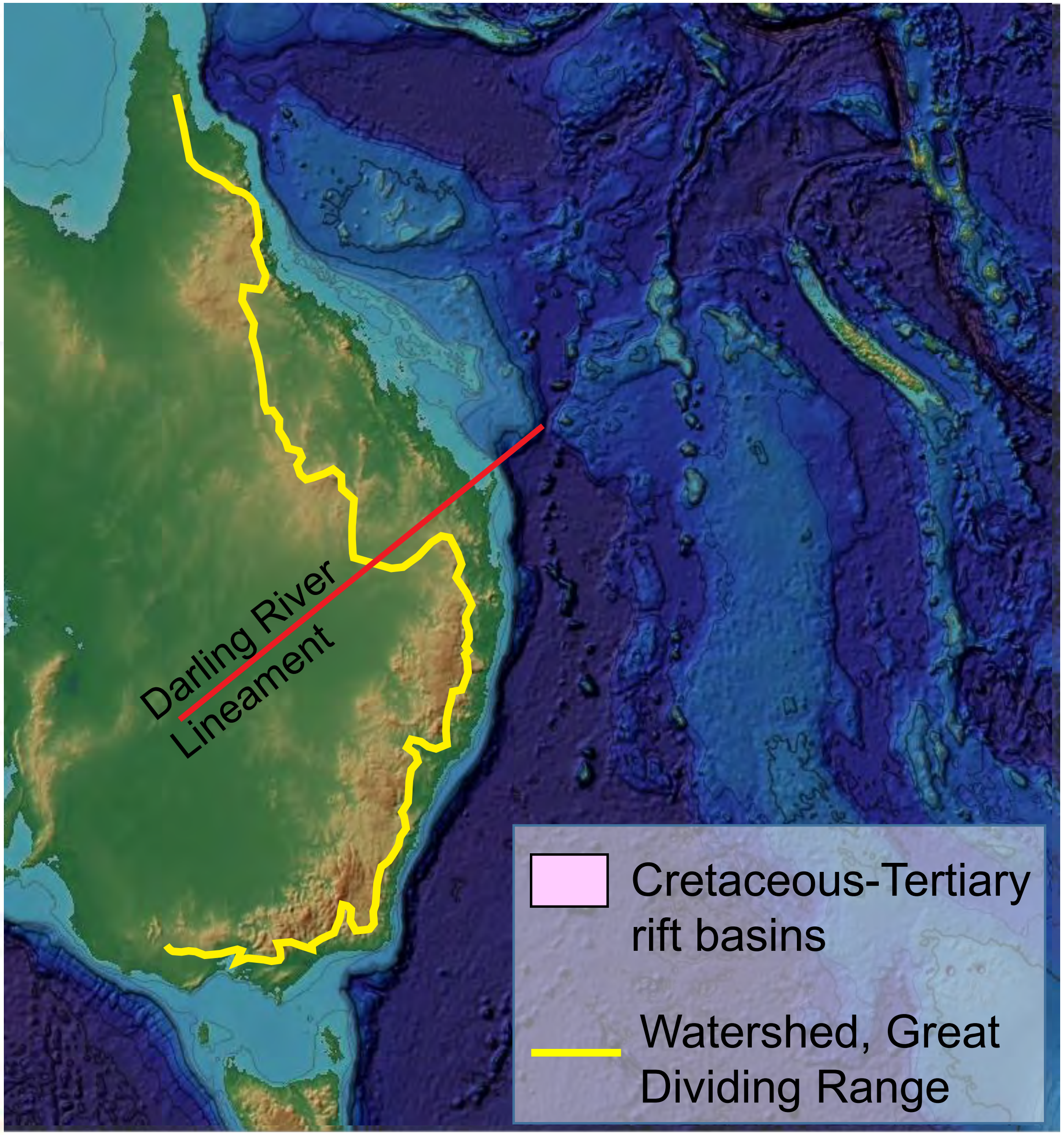
From Lister et al. (1989, 1991)

Case Study: Eastern Australia



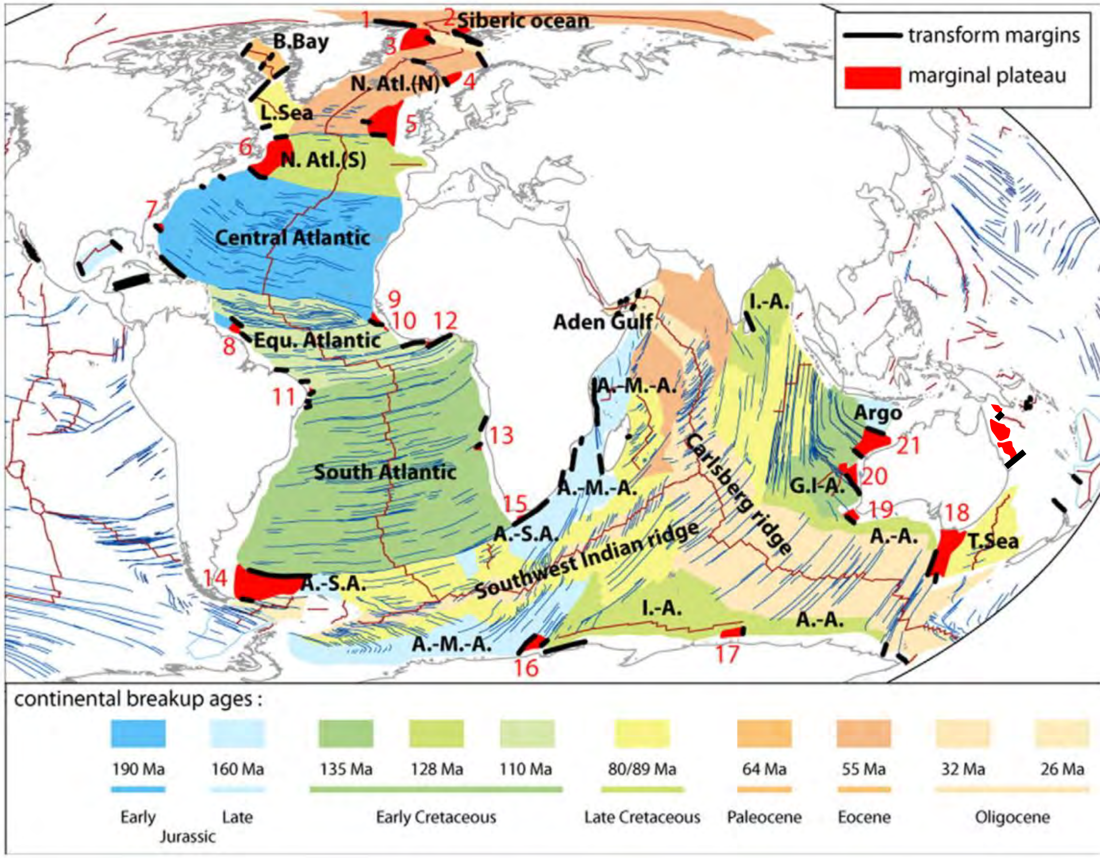
Case Study: Eastern Australia





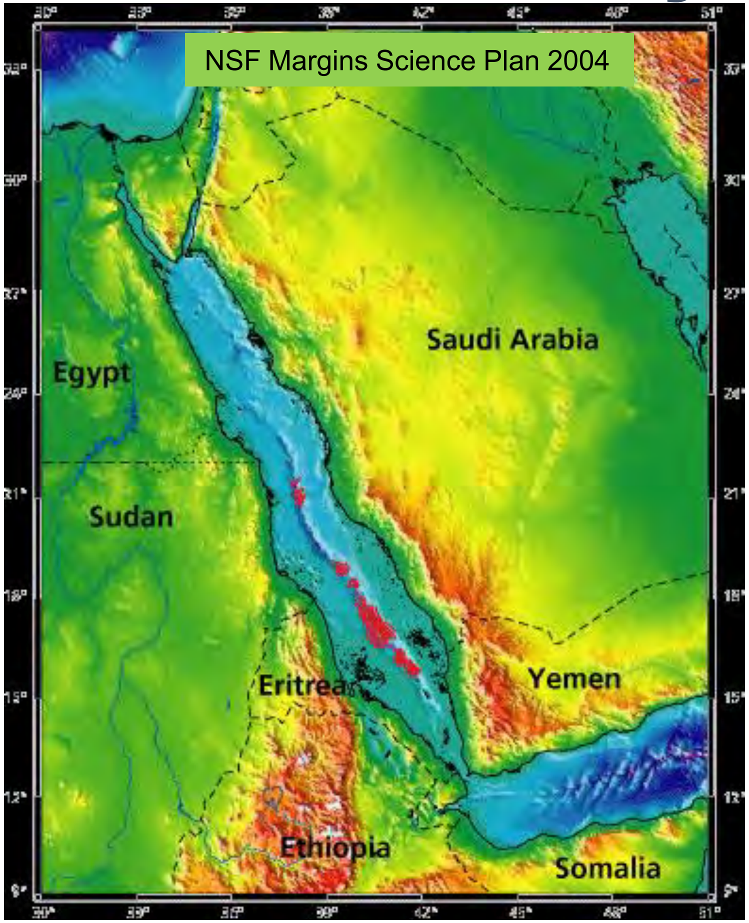
Marginal Plateau Development

- 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



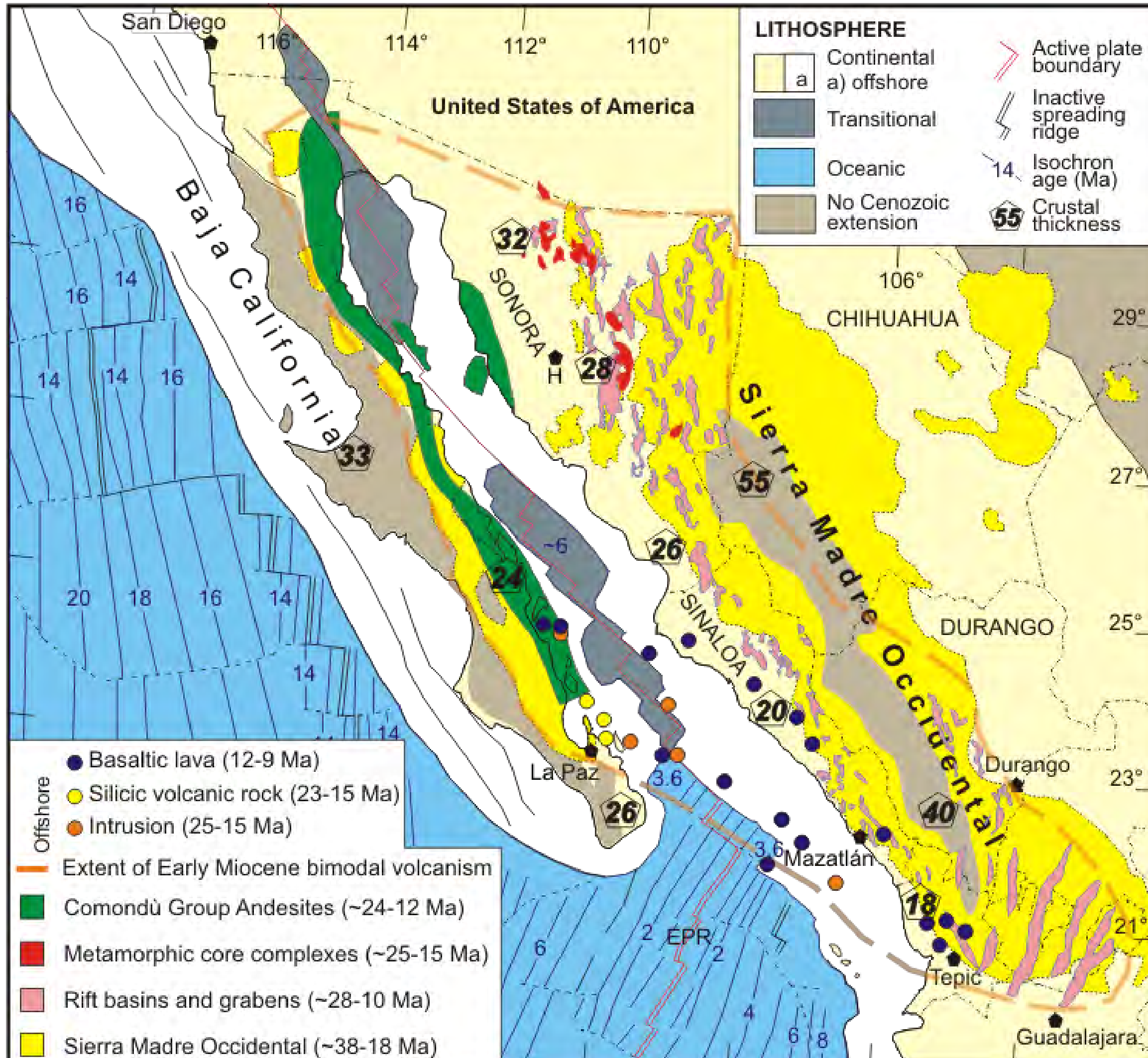
Red Sea: Rupturing since 30 Ma; Old cratonic lithosphere, Orthogonal rifting

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

MARGINS
to understand the complex interplay of processes that govern the evolution of continental margins

Gulf of California

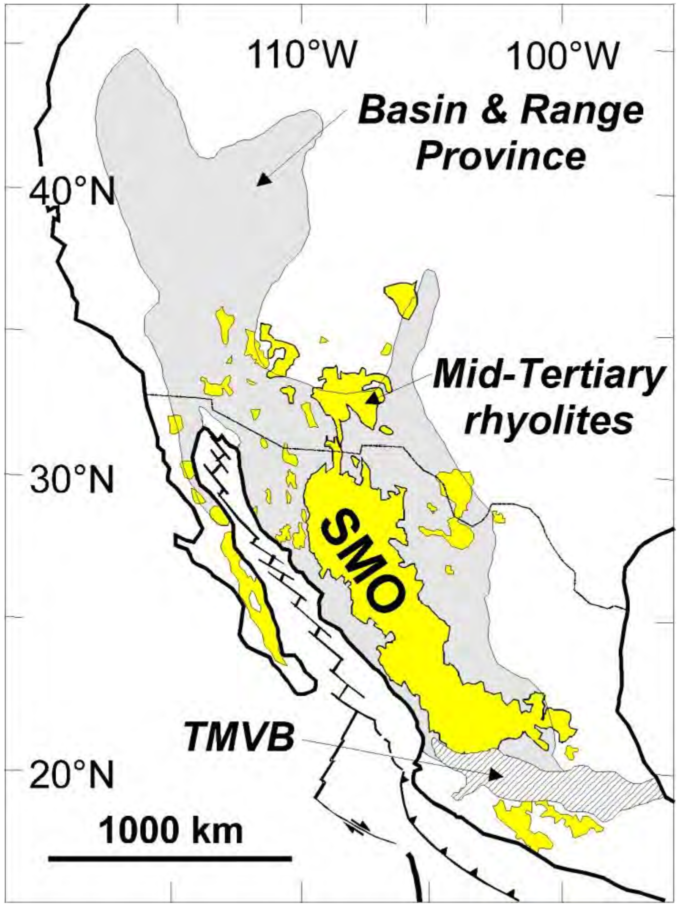
- Region of coupled magmatism and extension leading to successful rupturing
  1. Silicic LIP magmatism
  2. Basin and range-style extension
  3. Zones of high-magnitude extension
  4. SFS since ~6 Ma

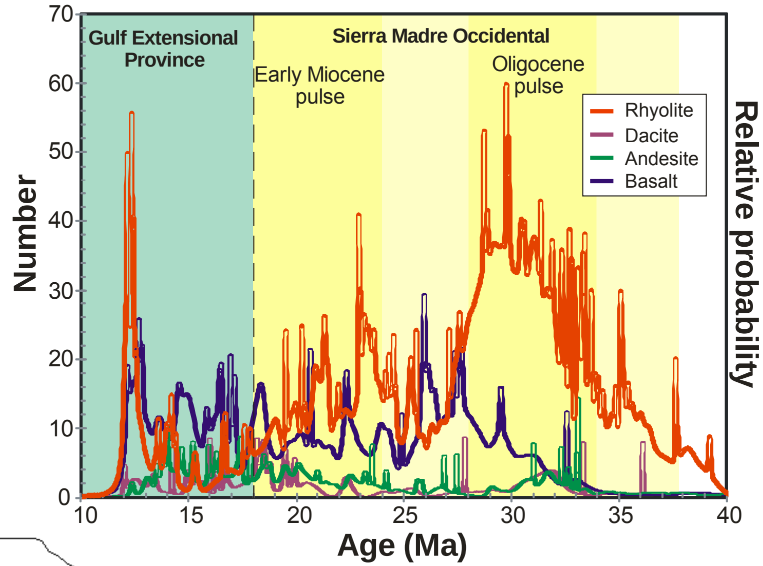


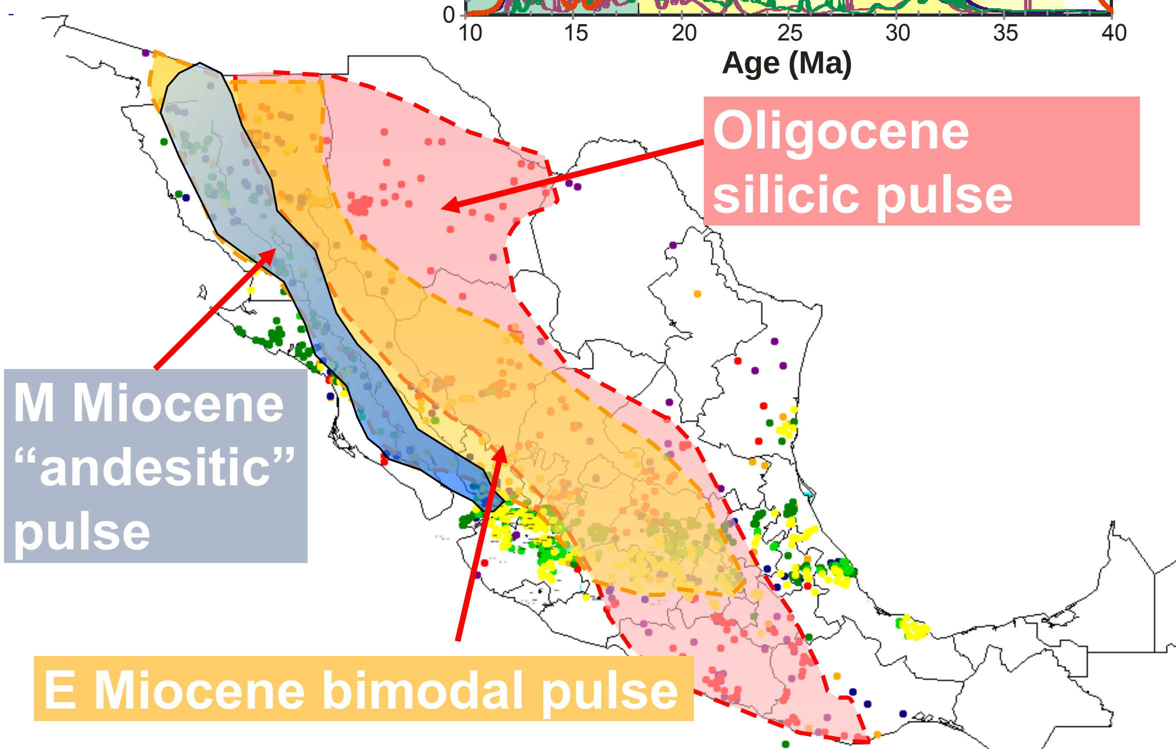
Bryan et al. (2014) GSL Special Publ 385

Sierra Madre Occidental (SMO)

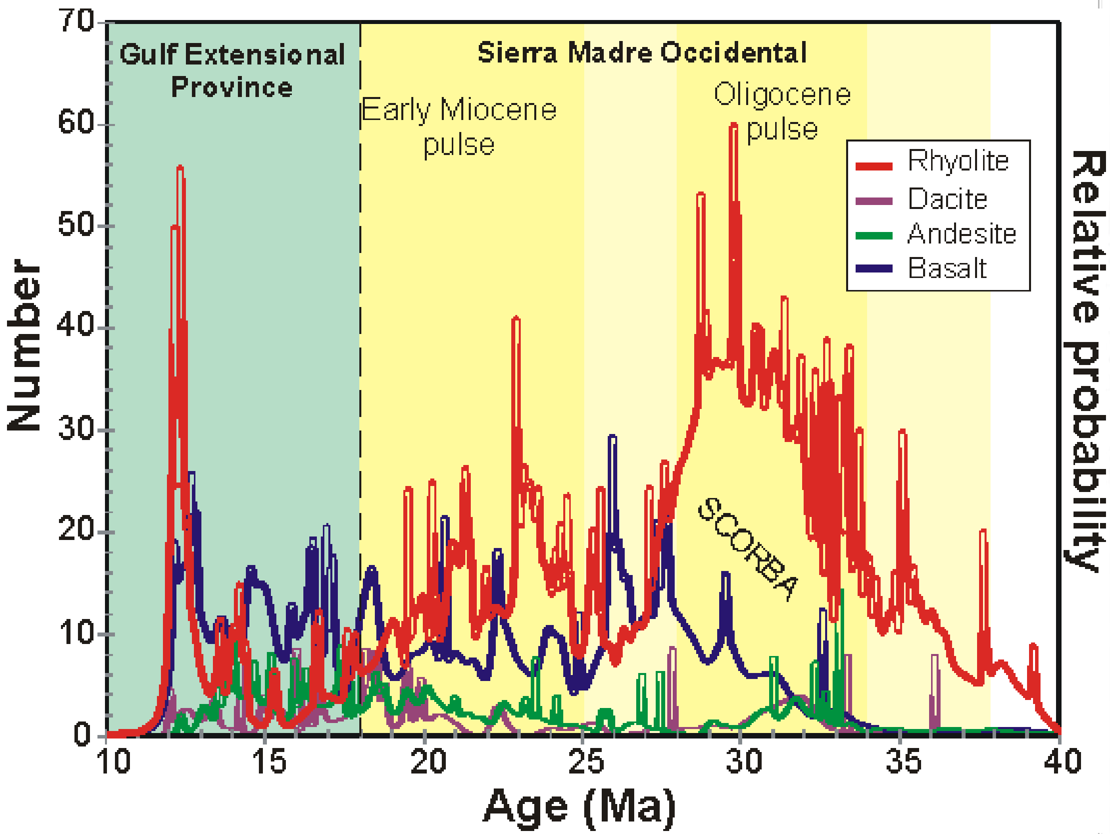
SMO: the youngest most continuous SLIP
Age: ~38-17 Ma but pulsed
Volume: ~400,000 km^3 (>1 km thick)

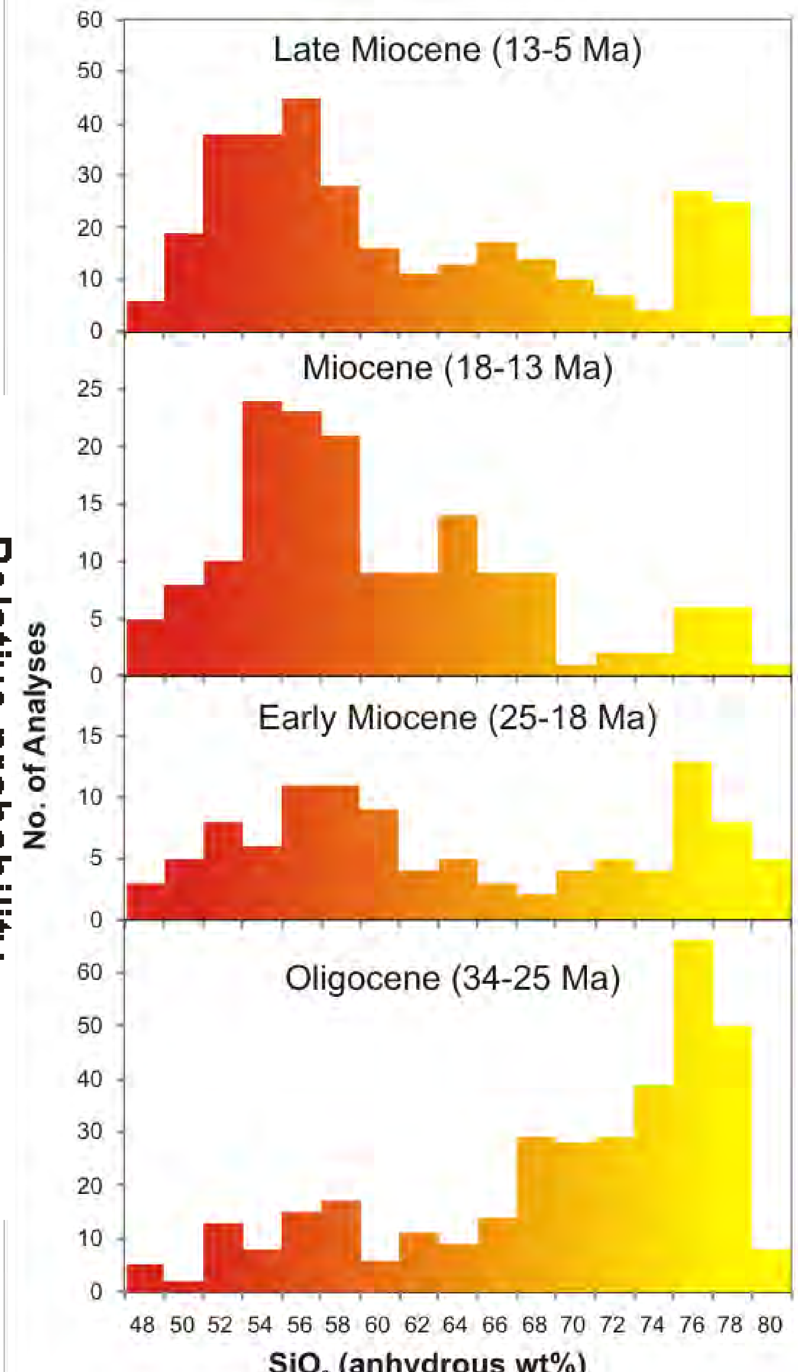






Temporal Compositional Trends of Magmatism



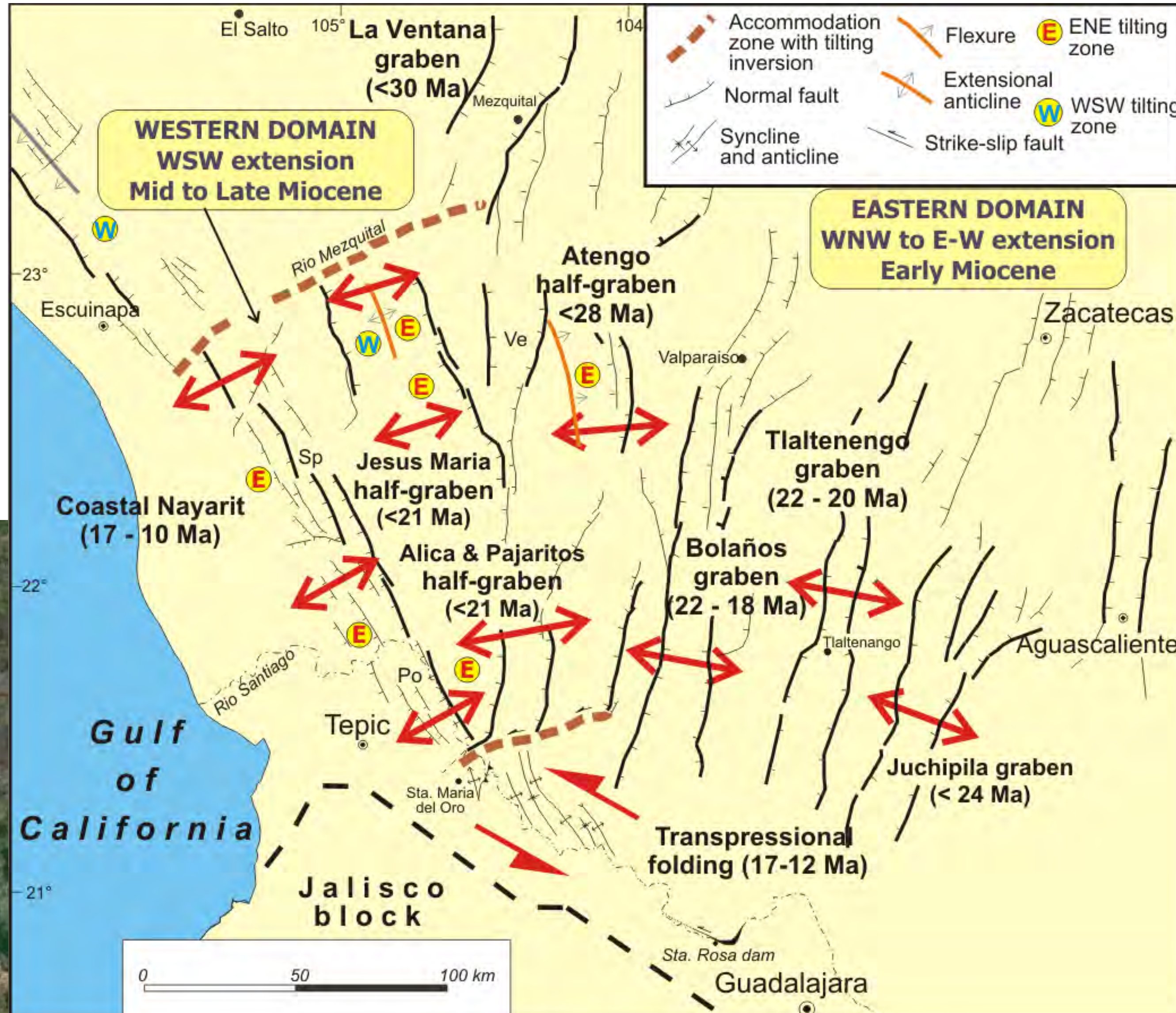


Bryan et al. (2014) GSL Special Publ 385

Timing Relationships to Extension

- Early Miocene distributed extension and bimodal volcanism

Age and kinematics of deformation: southern SMO



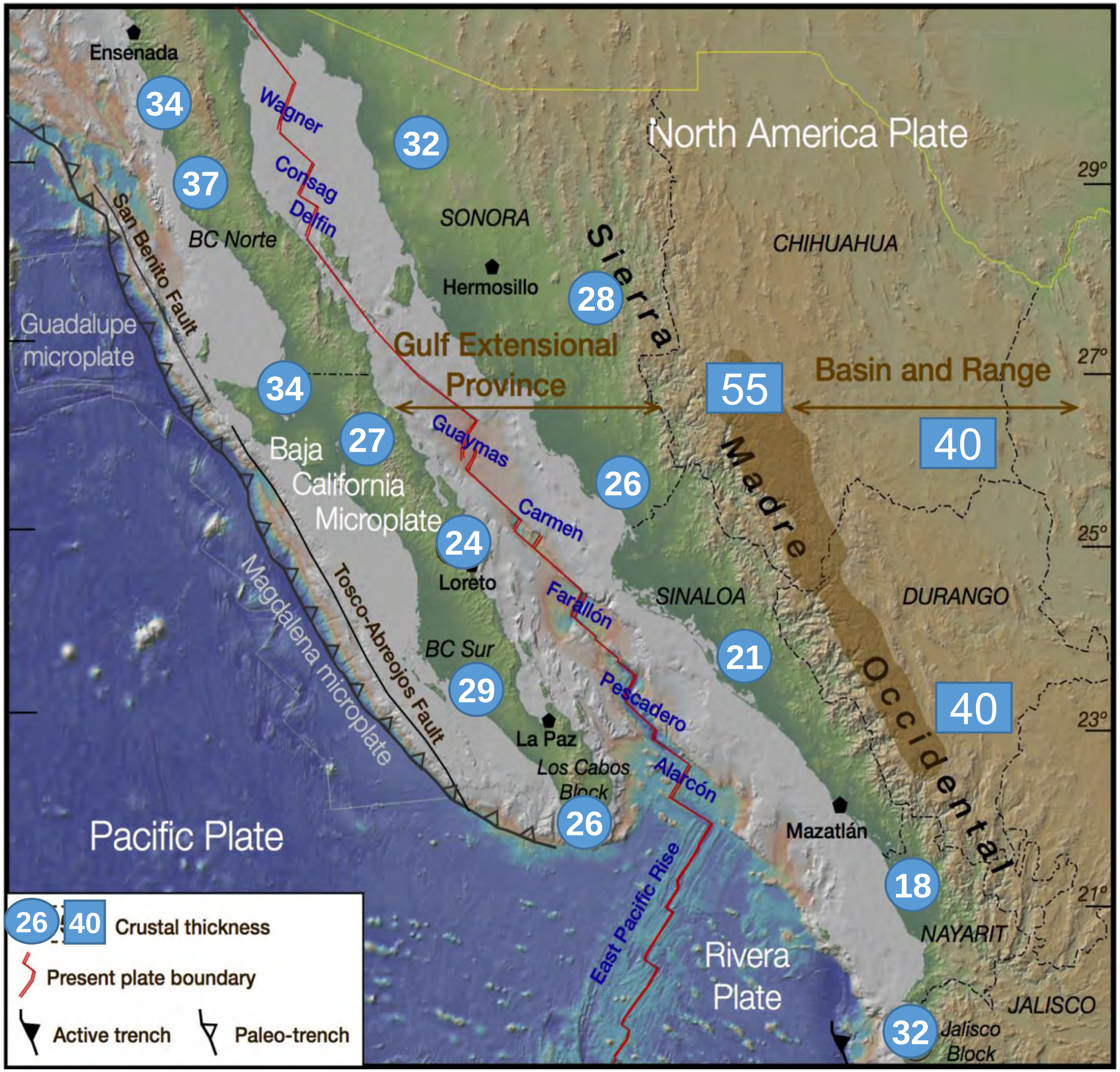
Timing Relationships to Extension

Extension since Oligocene

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

- Crustal thicknesses halved around margins of Gulf

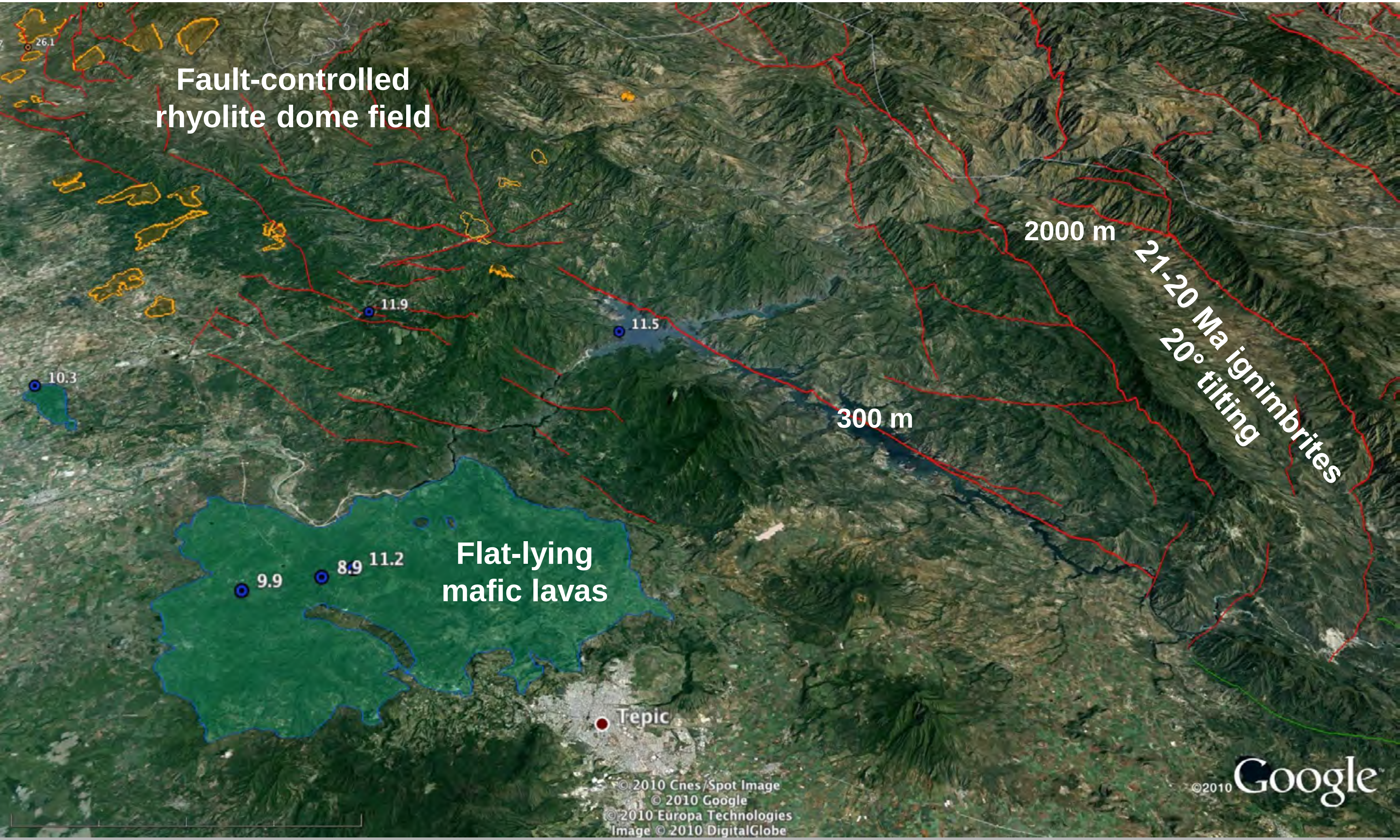
-100% extension in GEP from Late Miocene to Present



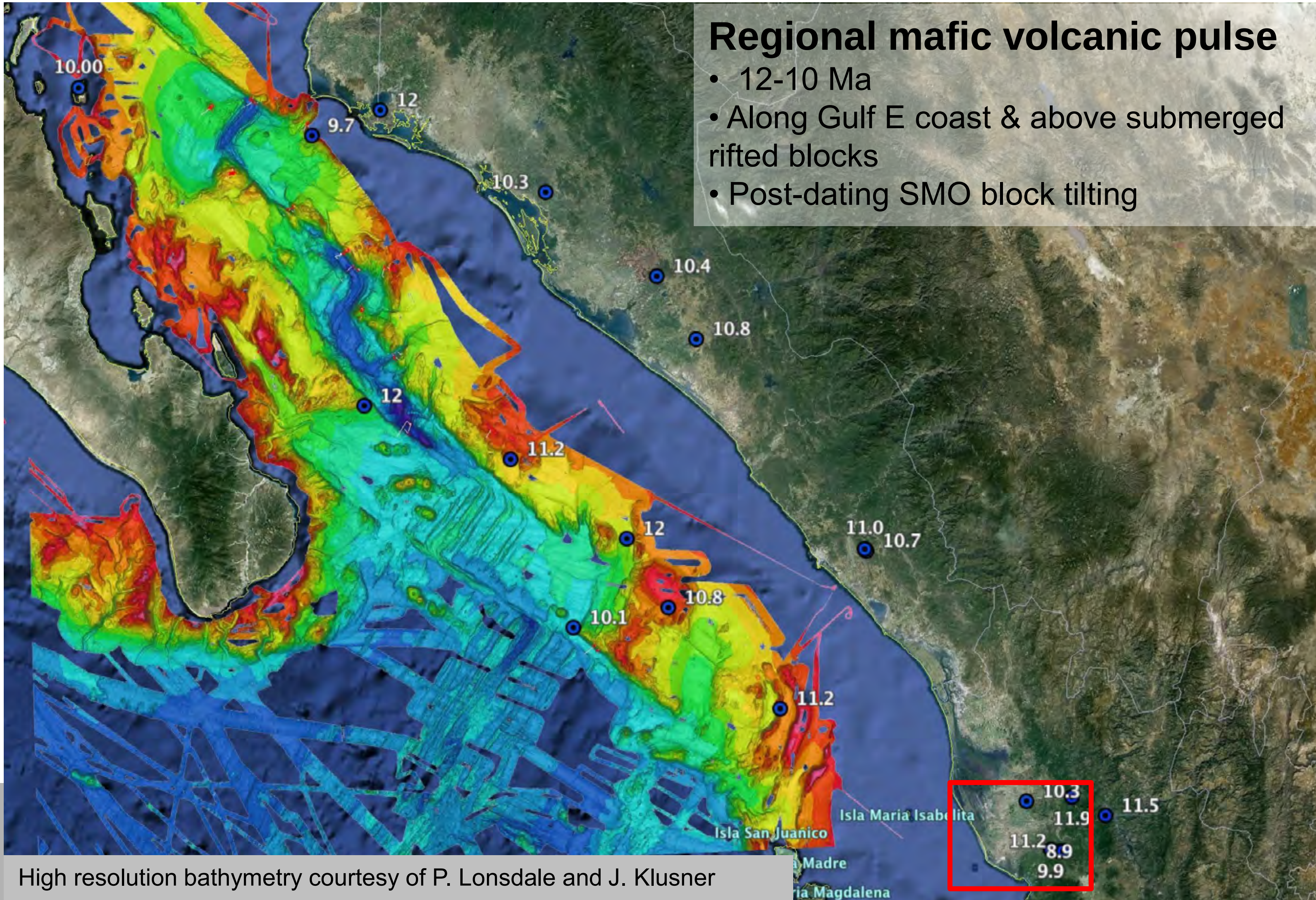
Ferrari *et al*. (2017) Earth-Science Reviews

Timing Relationships to Extension

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



Timing Relationships to Extension



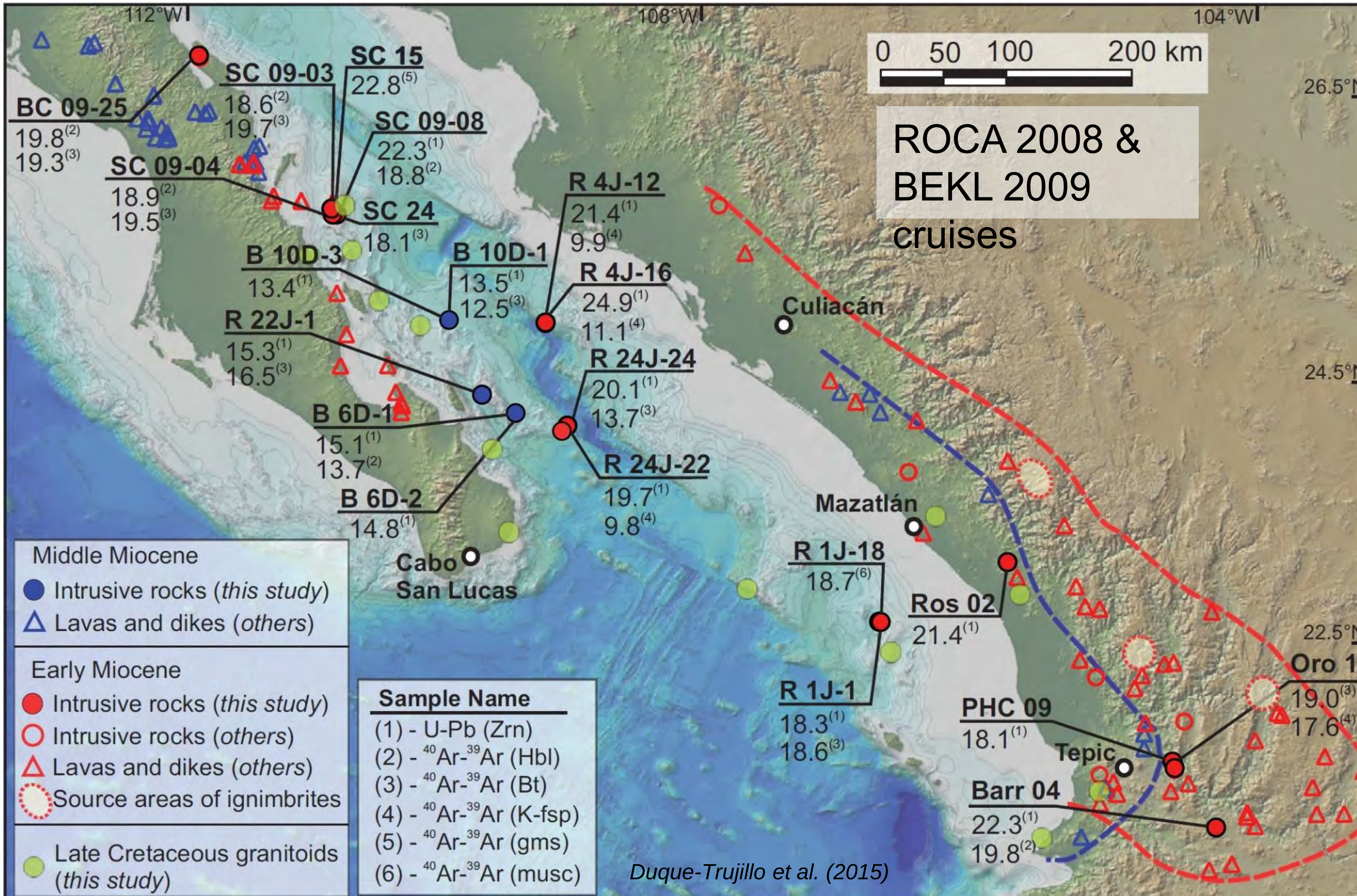
Regional mafic volcanic pulse

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

High resolution bathymetry courtesy of P. Lonsdale and J. Klusner

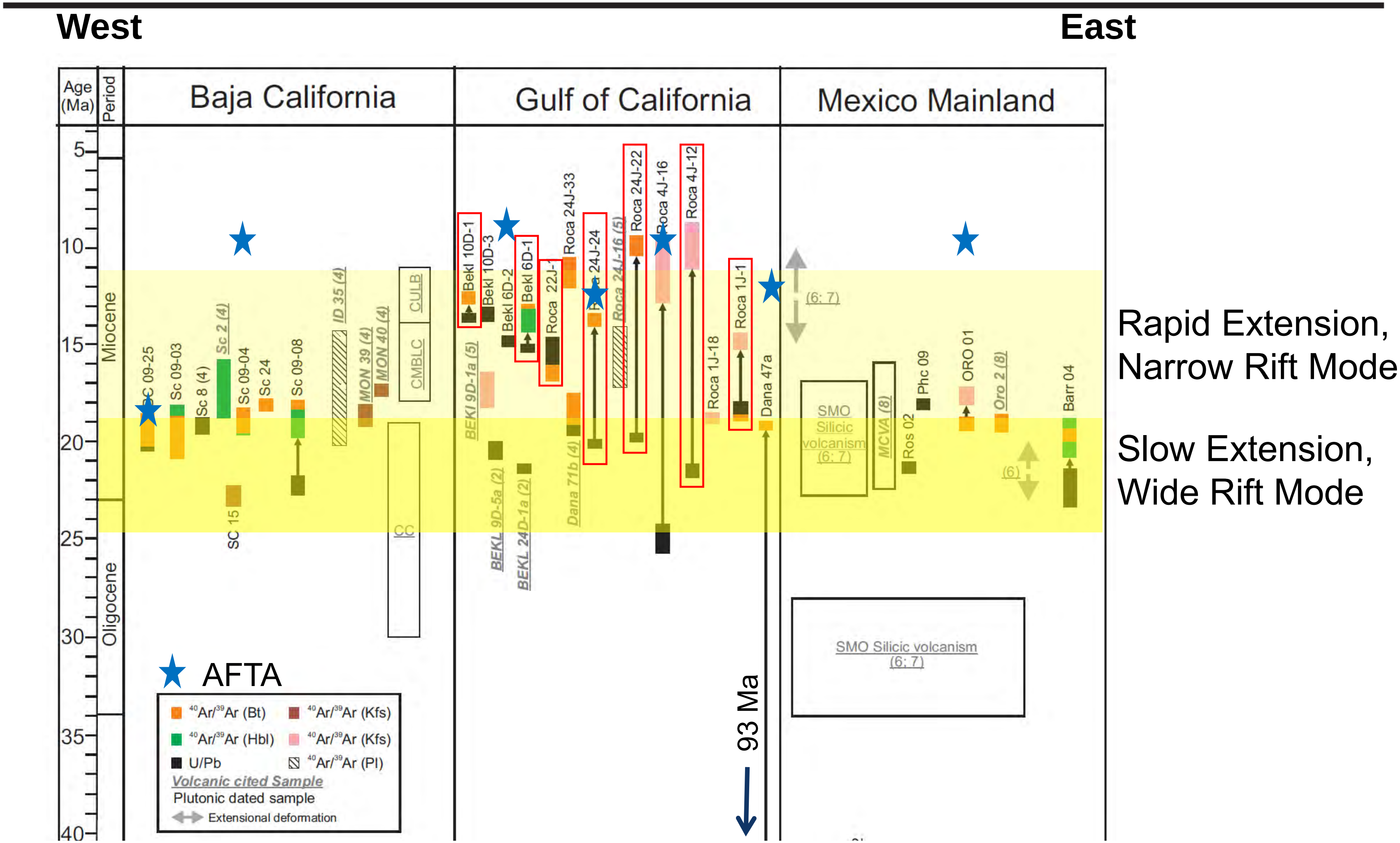
Timing Relationships to Extension

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



GSA Bulletin; May/June 2015; v. 127; no. 5/6; p. 702–736; doi: 10.1130/B31008.1

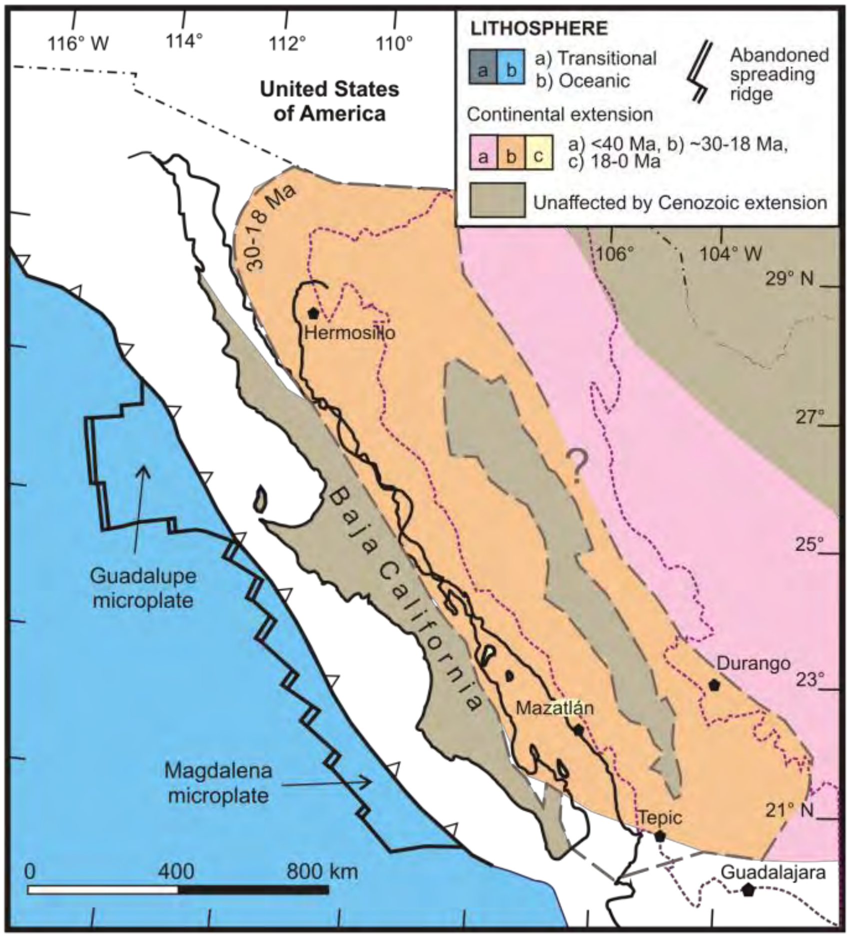
Timing of rifting in the southern Gulf of California and its conjugate margins: Insights from the plutonic record



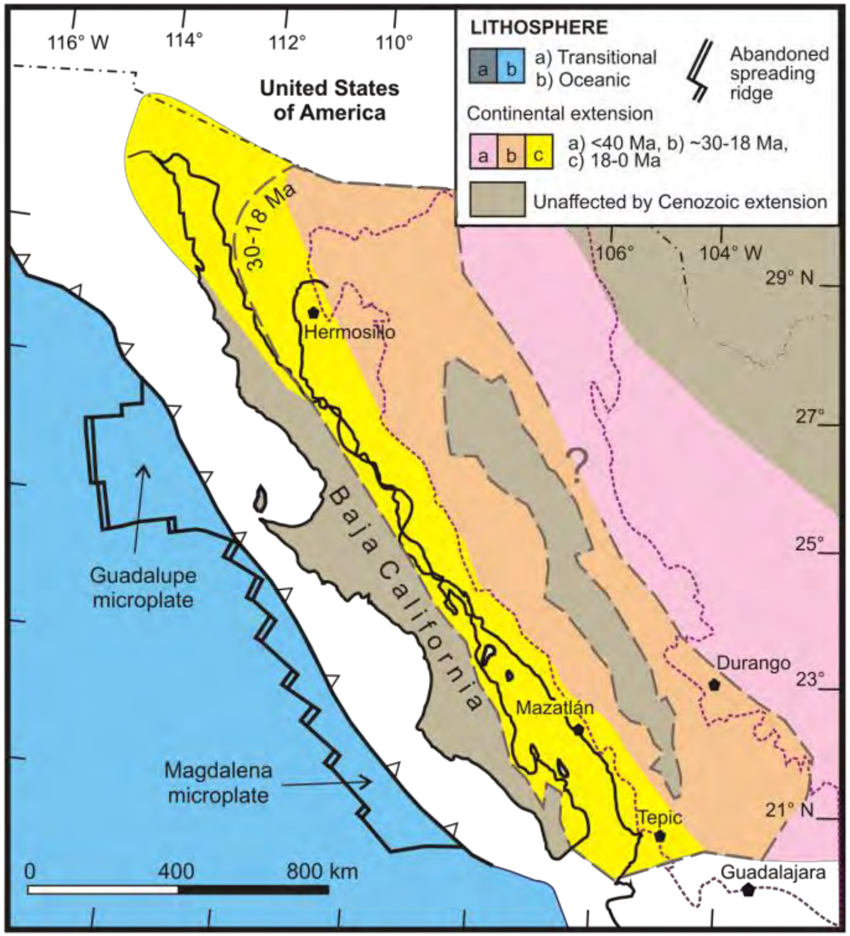
Timing Relationships to Extension

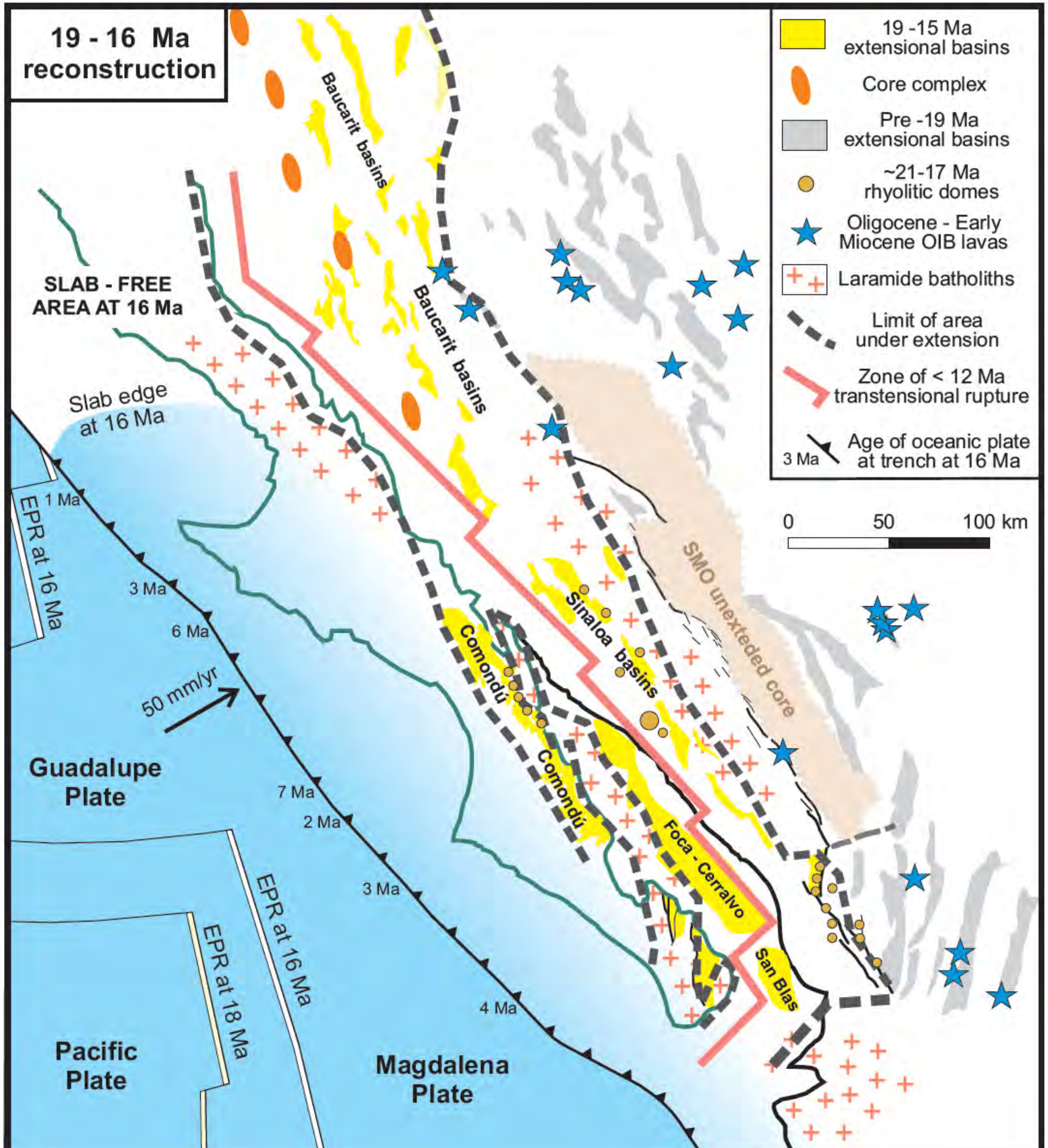
- Temporal change from wide to narrow rifting

Early Miocene (~24-18 Ma)

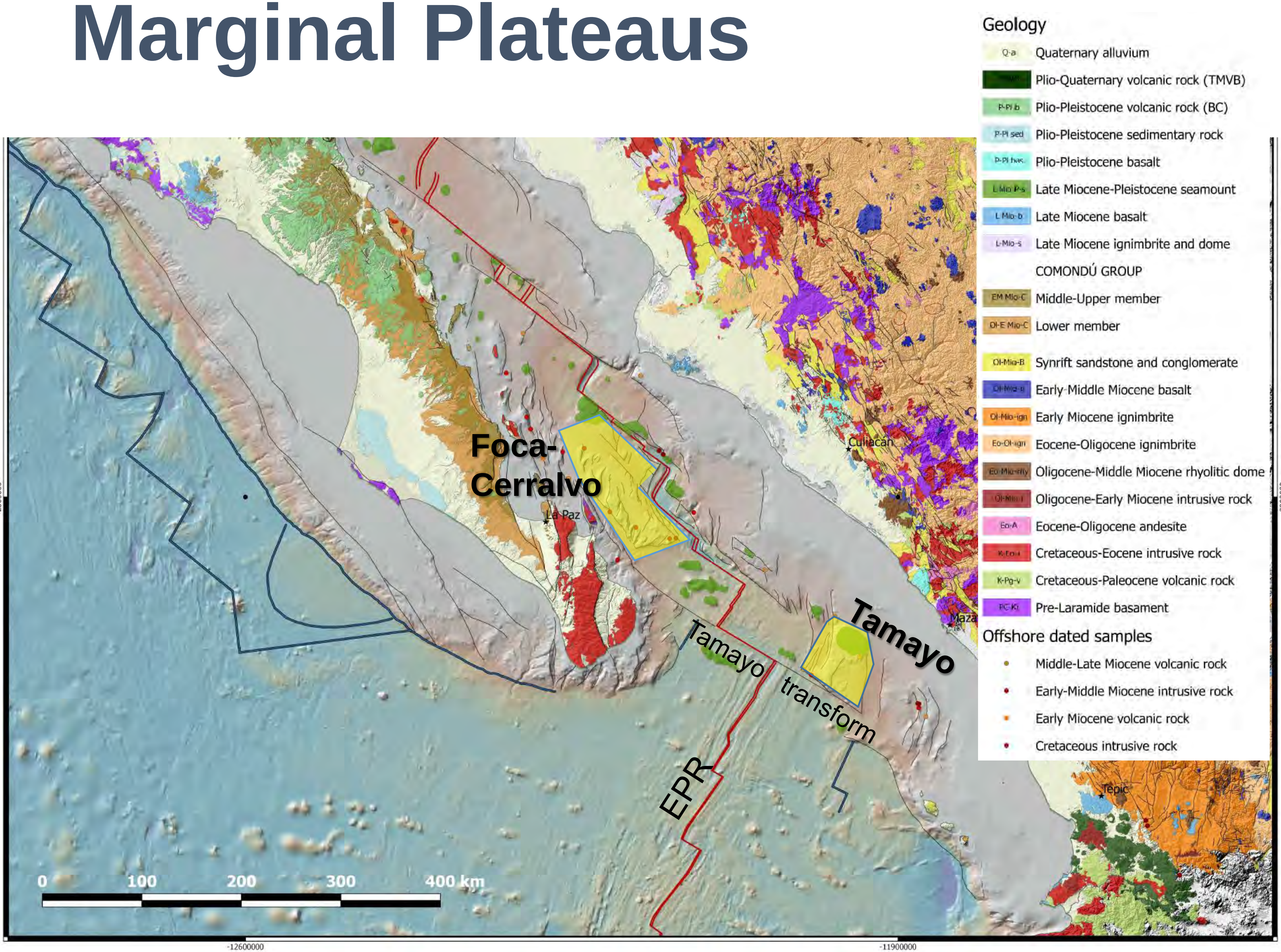


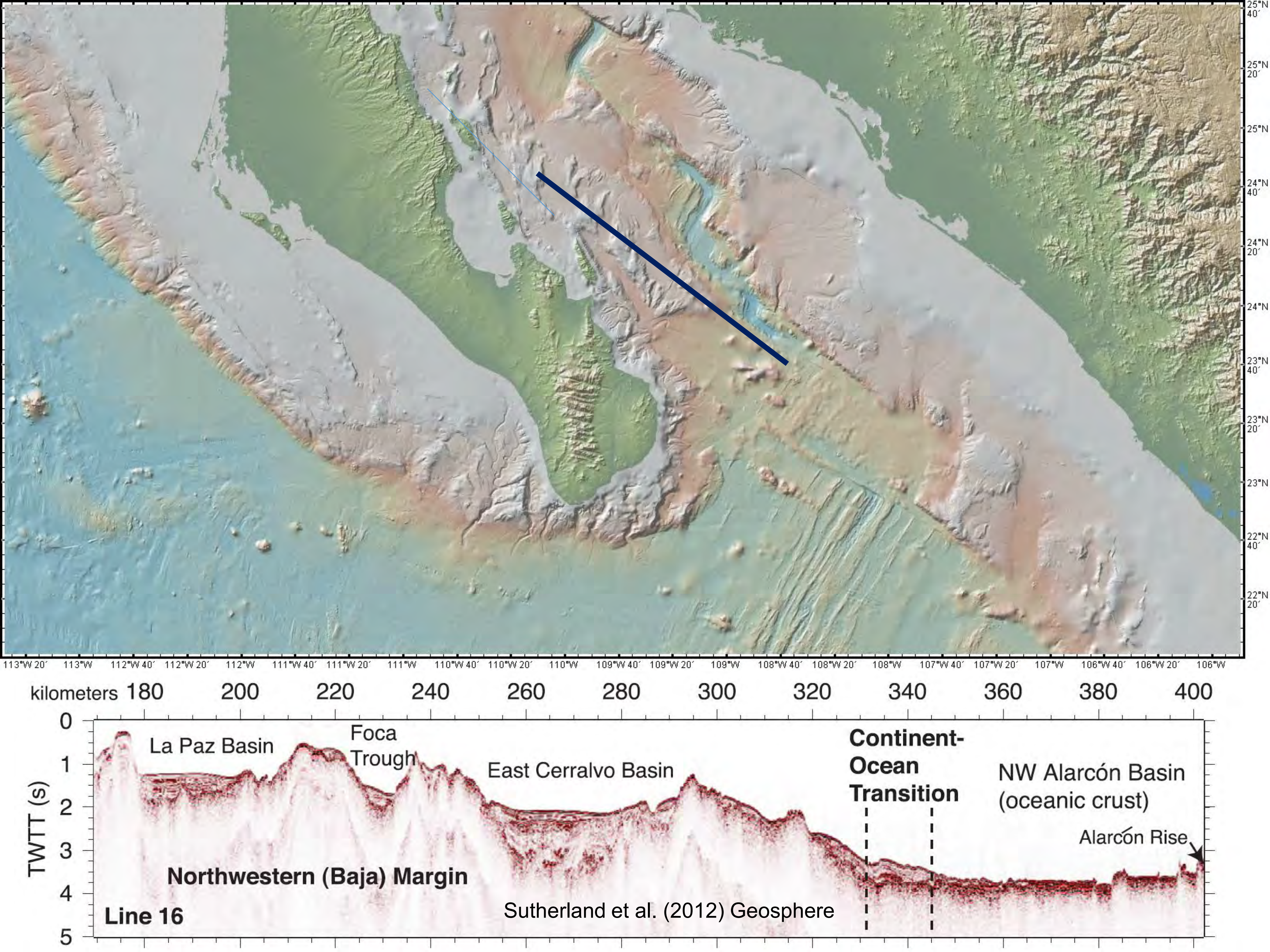
Mid Miocene (~18-12 Ma)




19 - 16 Ma reconstruction
19 -15 Ma extensional basins
Core complex
Pre -19 Ma extensional basins
~21-17 Ma rhyolitic domes
Oligocene - Early Miocene OIB lavas
Laramide batholiths
Limit of area under extension
Zone of < 12 Ma transtensional rupture
3 Ma
Age of oceanic plate at trench at 16 Ma
0
50
100 km
SLAB - FREE AREA AT 16 Ma
Slab edge at 16 Ma
Baucarit basins
Baucarit basins
SMO unexteded core
Sinaloa basins
Comondú
Comondú
Foca - Cerralvo
San Blas
EPR at 16 Ma
1 Ma
3 Ma
6 Ma
50 mm/yr
Guadalupe Plate
7 Ma
2 Ma
3 Ma
4 Ma
EPR at 16 Ma
EPR at 18 Ma
Pacific Plate
Magdalena Plate

Marginal Plateaus





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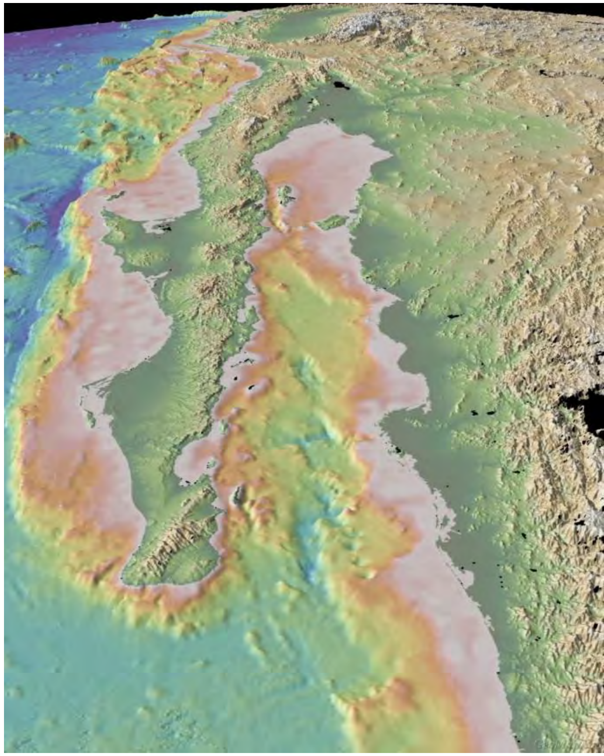
5
La Paz Basin
Foca Trough
East Cerralvo Basin
Continent-Ocean Transition
NW Alarcón Basin (oceanic crust)
Alarcón Rise
Northwestern (Baja) Margin
Line 16
Sutherland et al. (2012) Geosphere

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

Australian Government

Geoscience Australia

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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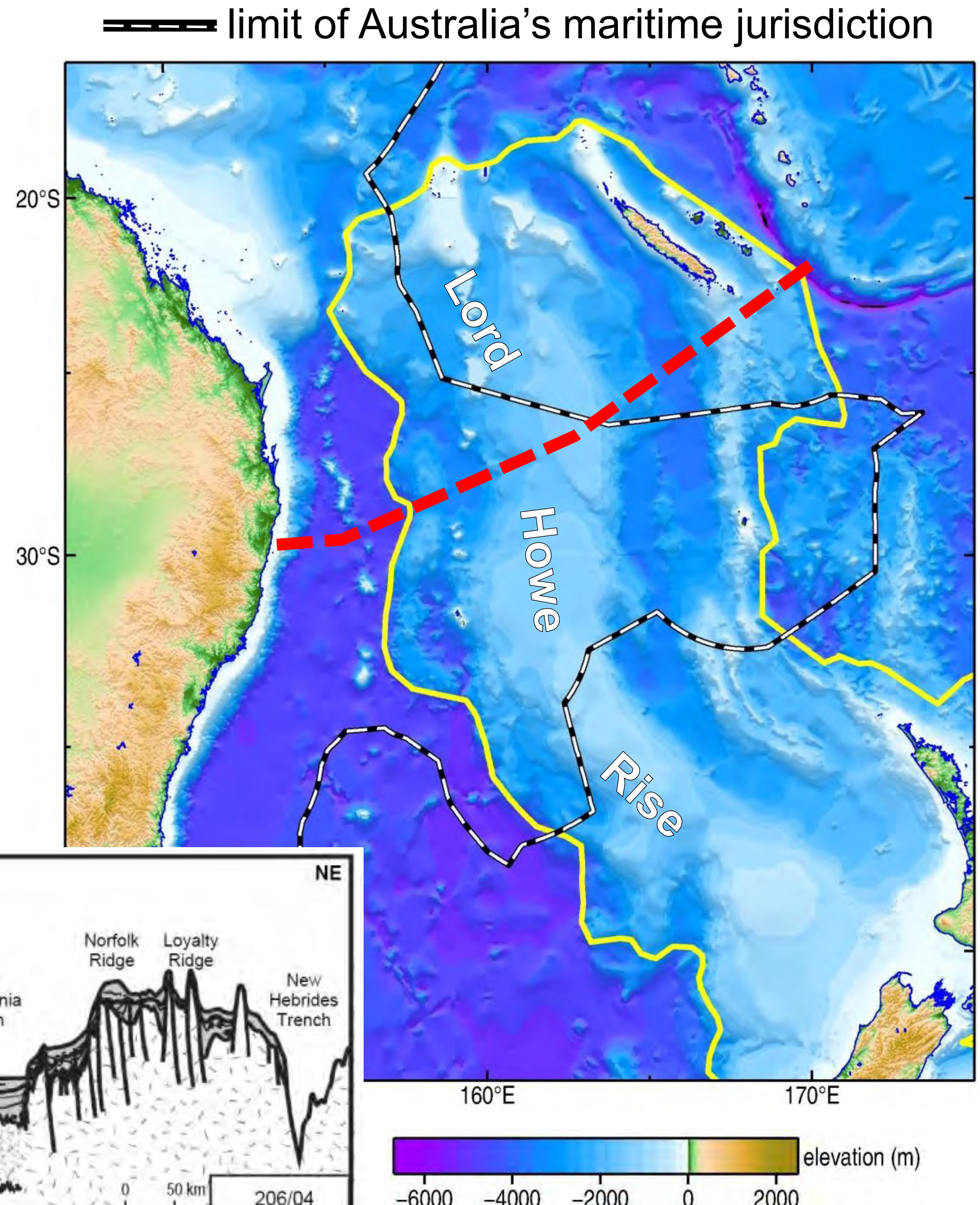
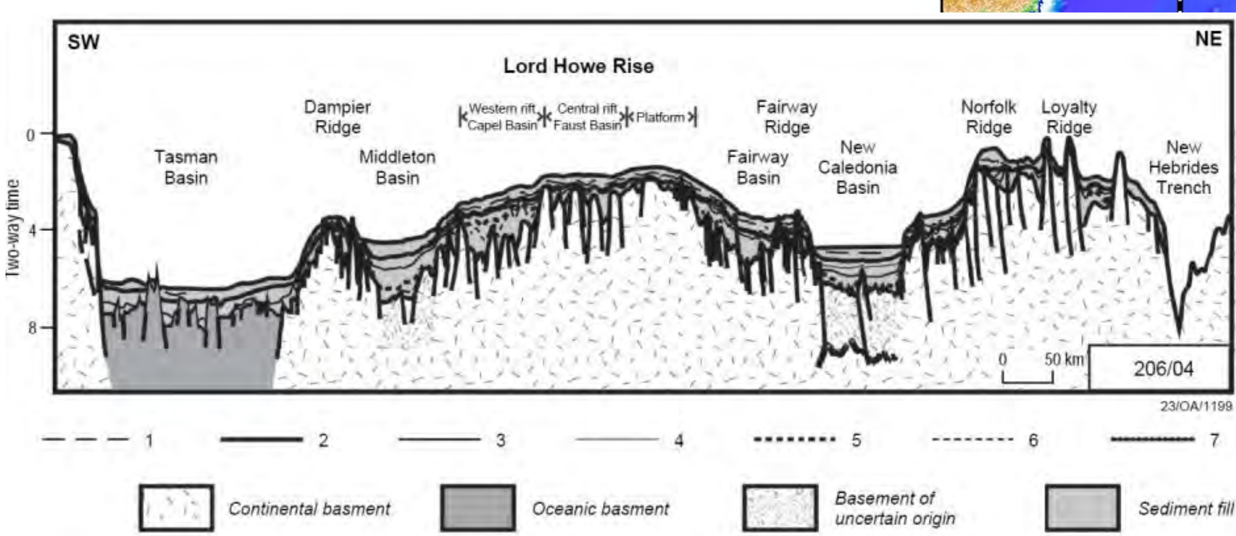
The Lord Howe Rise

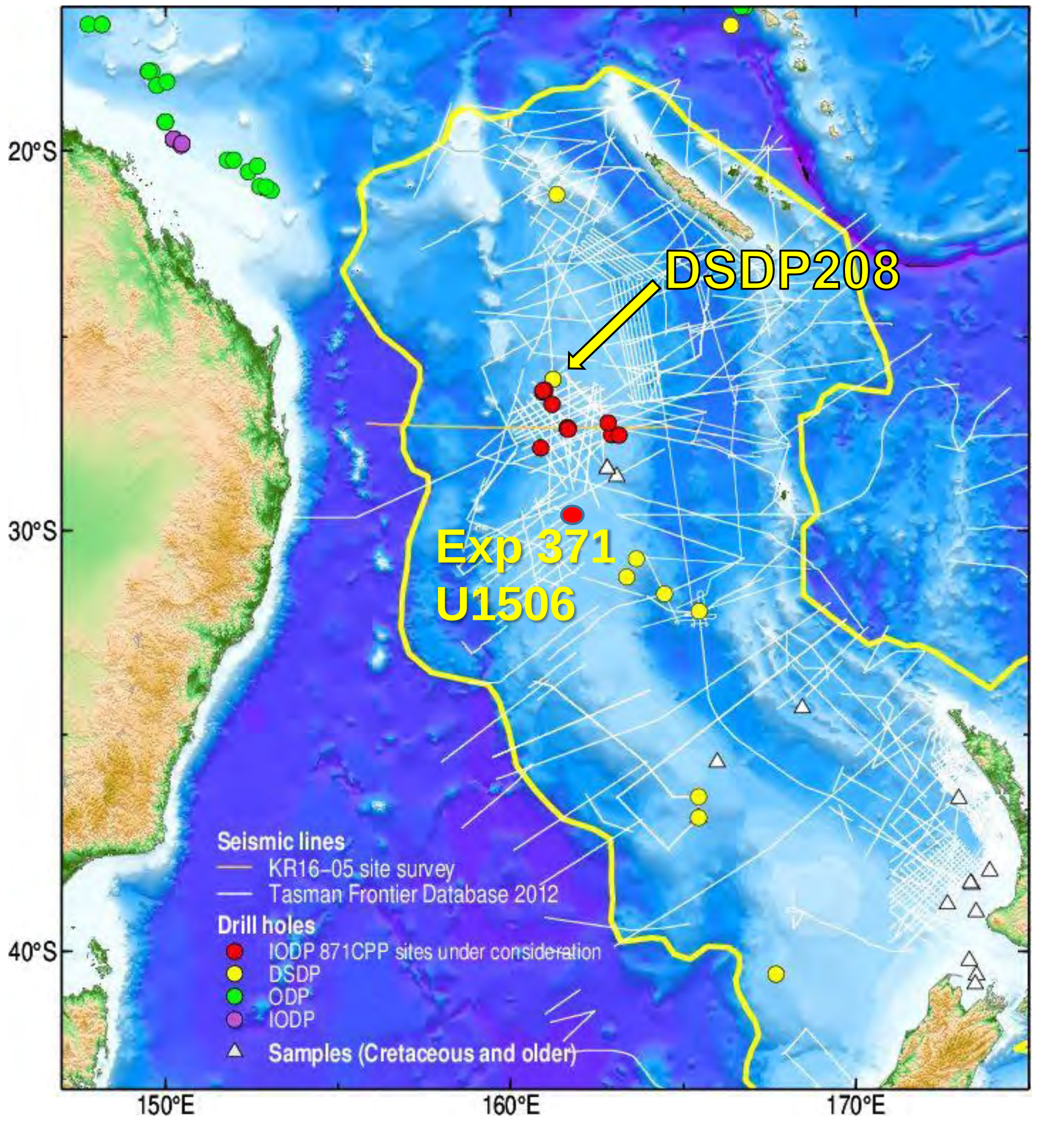
- Rifted continental ribbon
  - ~1600 km long
  - 400–500 km wide
- A series of ridges and basins in water depths of ~1000–4000 m





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

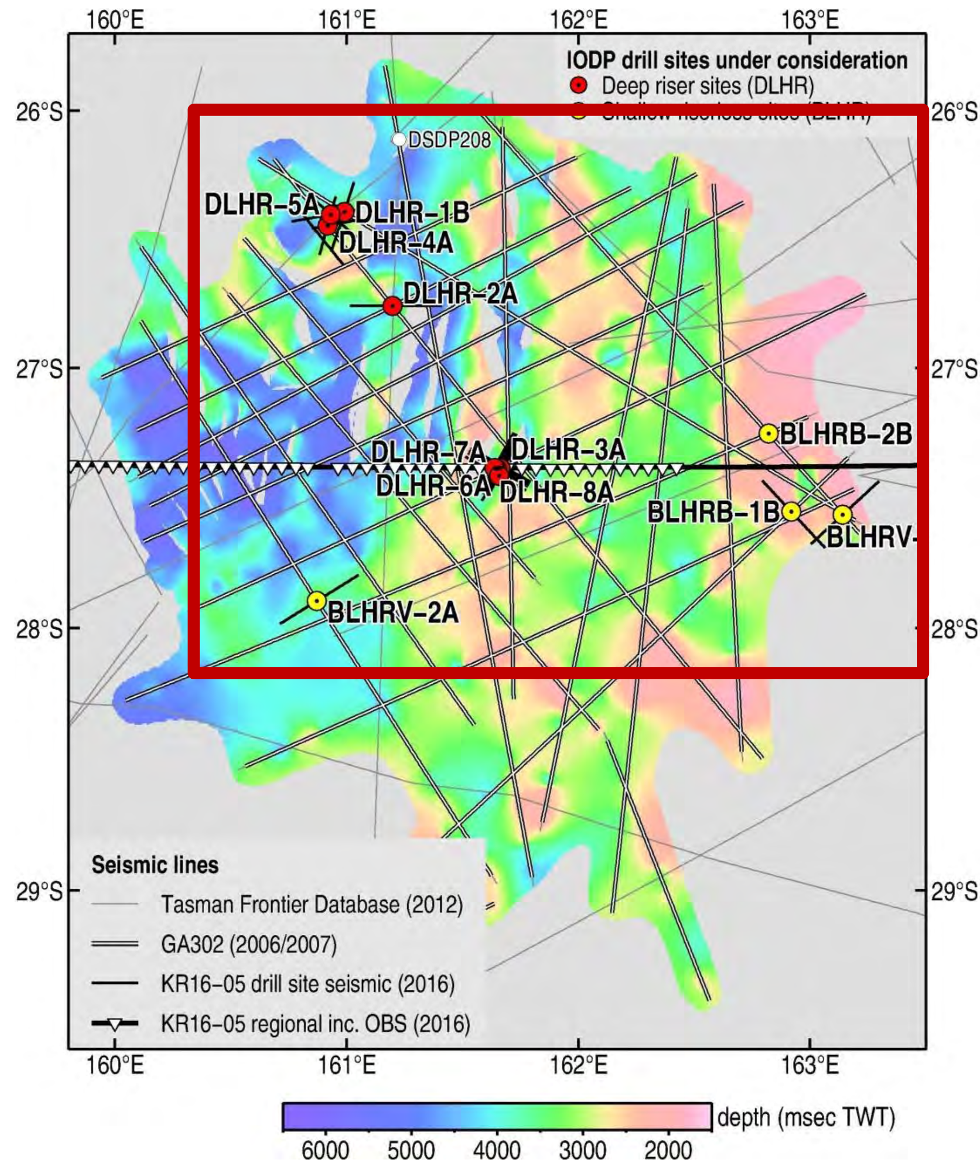
One deep riser drill hole through a Cretaceous rift basin on the Lord Howe Rise

- 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

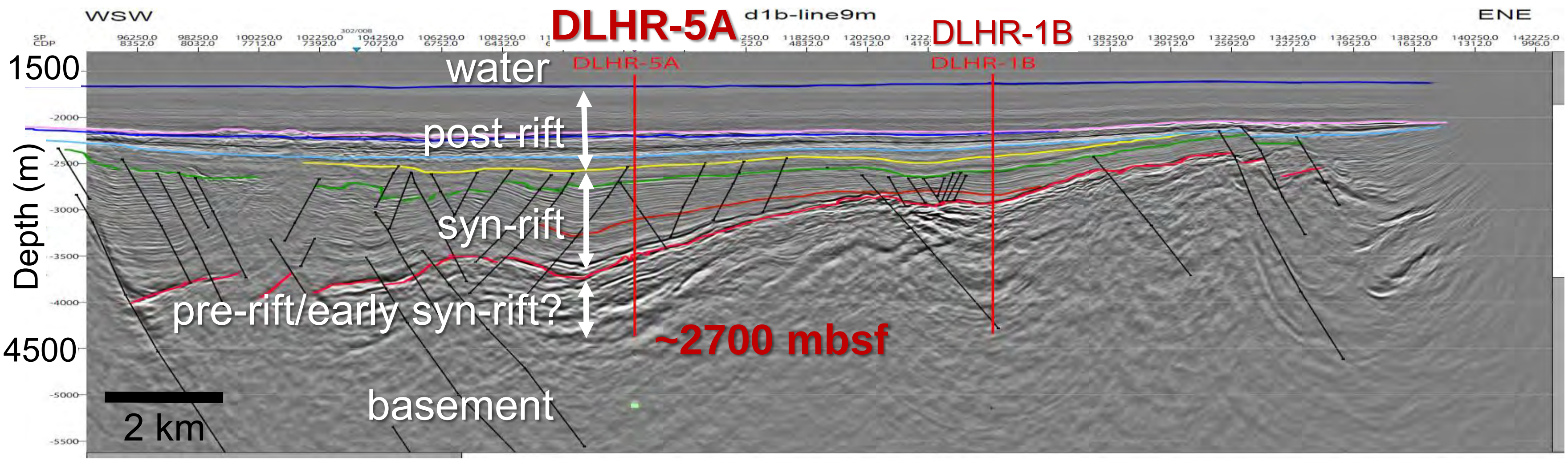
- 0.5–0.7 km below seafloor

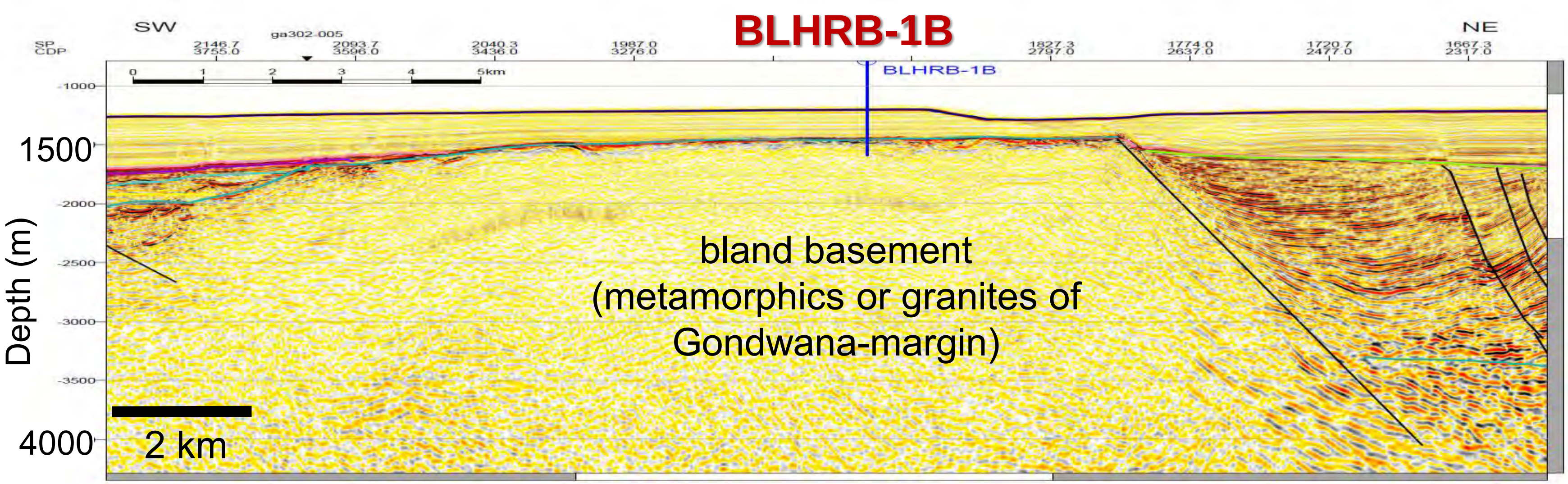
Depth to base of rift sequence
(Colwell et al., *GA Record 2010/06*)



Primary Deep & Basement Drill Sites

Currently-preferred site





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...