

Reconciling Extension from Brittle Faulting, Subsidence, and Kinematic Reconstructions: Lessons from the Woodlark Basin*

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Abstract

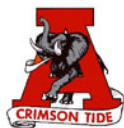
In contrast to ancient rift margins where many of the mechanisms vital to the formation of the margin have long since been hidden, the Woodlark Basin of Papua New Guinea offers the opportunity to study active rift processes. Near the rifting-to-seafloor spreading transition the asymmetric rift system comprises large tilted fault blocks on the southern margin and a principally unfaulted northern margin that has subsided more than 3 km. As is often the case, estimates of extension derived by examining brittle faulting fall short of those calculated through subsidence. However, by including multiple phases of faulting and sub-resolution faulting, this gap can be closed - resulting in a total of 111+/-23km of extension. Assuming Airy isostasy, the extension calculated from subsidence along the same profile is 115+/-45 km. Though these estimates are in close agreement, it remains that locally a mechanism such as lower-crustal flow must be important.

Extension can also be estimated by fitting Euler poles to fracture zones and magnetic chrons in the oceanic lithosphere. This gives an estimate of more than 200 km of extension since 6 Ma. Given that the basin has been opening since at least 8.4 Ma, this estimate far exceeds those predicted by brittle extension and subsidence. Can these extension estimates be reconciled? Estimates of brittle extension have so far ignored the potential role of metamorphic core complexes (MCC). At an MCC the upper crust has been removed - a 30 km wide MCC represents 30 km of extension. MCCs have not yet been identified along the study profile, but an MCC that has been dissected by normal faults may not be visible. The extension discrepancy may also be explained by a detachment between the mantle lithosphere and the upper crust. In this case, estimates of extension from Euler pole kinematics should not agree with other estimates.

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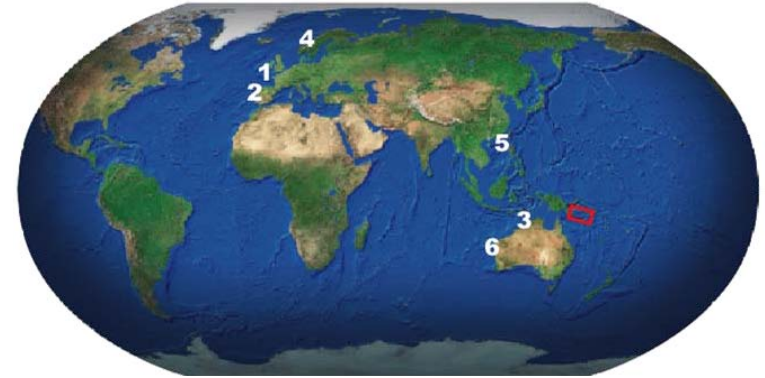
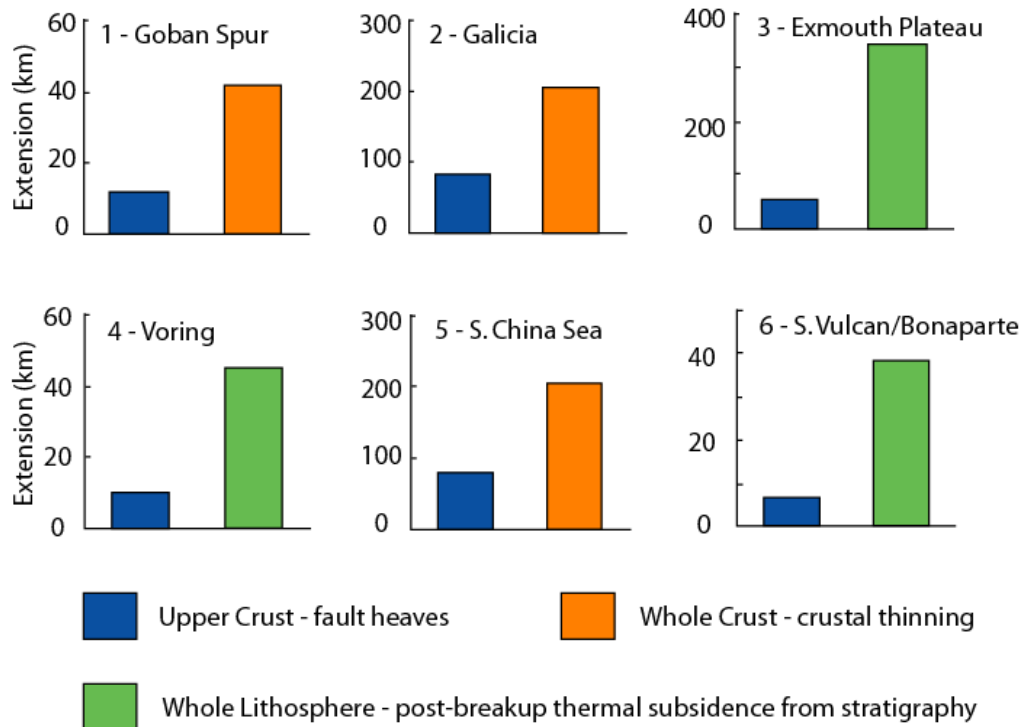
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AAPG International Conference and Exhibition, Cape Town, South Africa
Monday Oct. 27, 4:45-5:05 pm



Ancient Margins



Modified from Davis and Kusznir [2004]

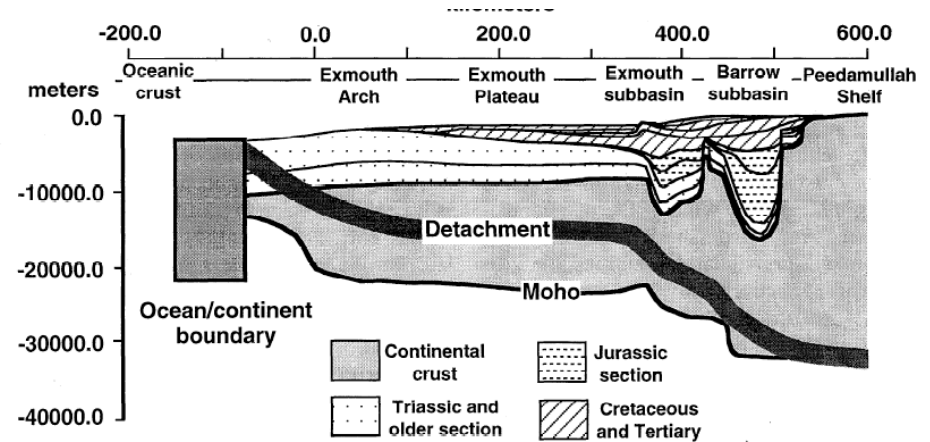
Problem: There is typically not enough extension as expressed through brittle faulting

- The lower crust and mantle lithosphere accommodate a greater amount of extension than the upper crust
- Someone has to have a space problem!

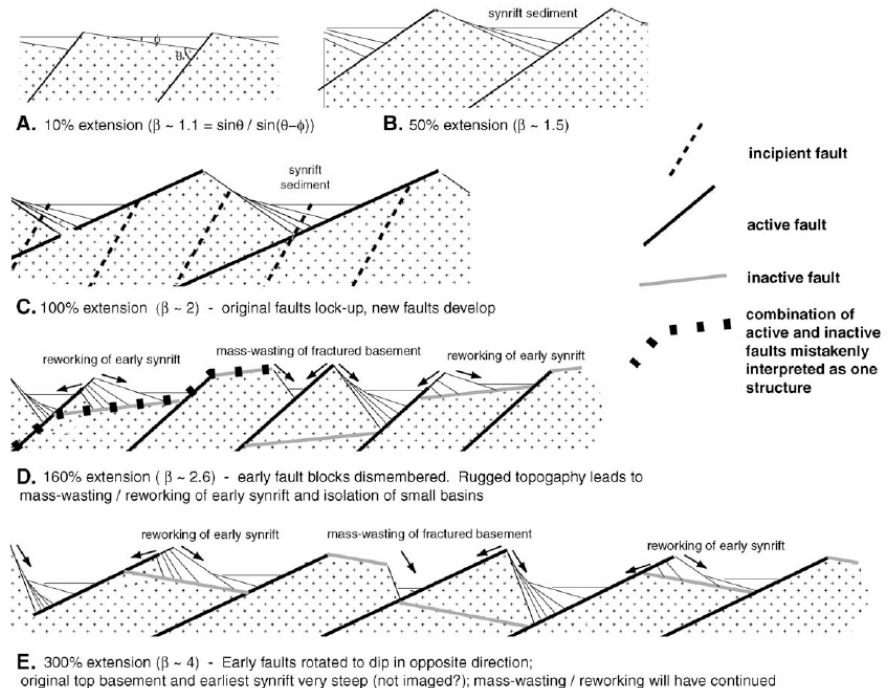
In this presentation we will add another extension estimate to the mix.....

How has this Problem been Tackled?

- Depth dependant extension [Driscoll & Karner, 1998]
 - Decoupling between upper and lower lithosphere by a distinct detachment or distributed shear
 - Lithospheric volume must balance at some distance
- Polyphase faulting [Reston, 2005]
 - Faults rotate to a low angle and are then cross-cut
 - Difficult to recognize in the geology
- Sub-resolution faulting [Walsh et al., 1991]
 - Maximum of 60% of observed faulting

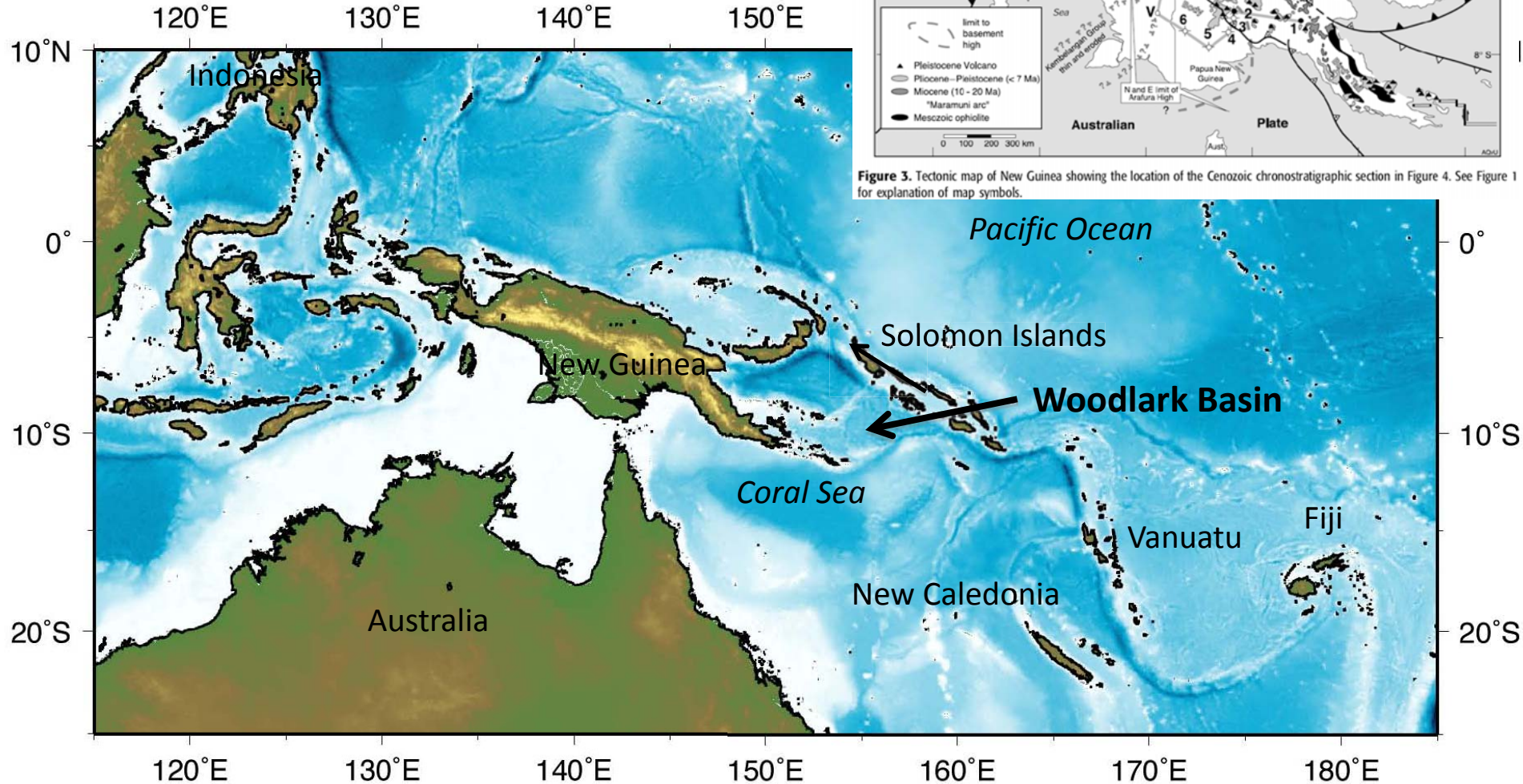
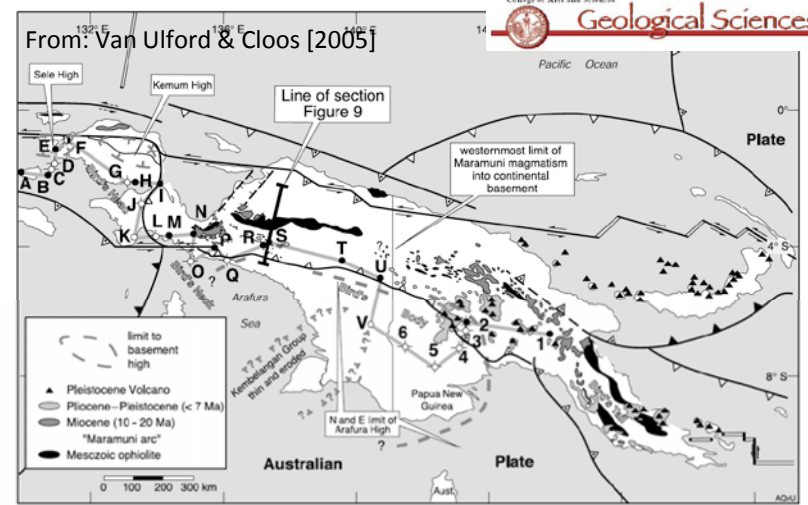


From Driscoll & Karner [1998]

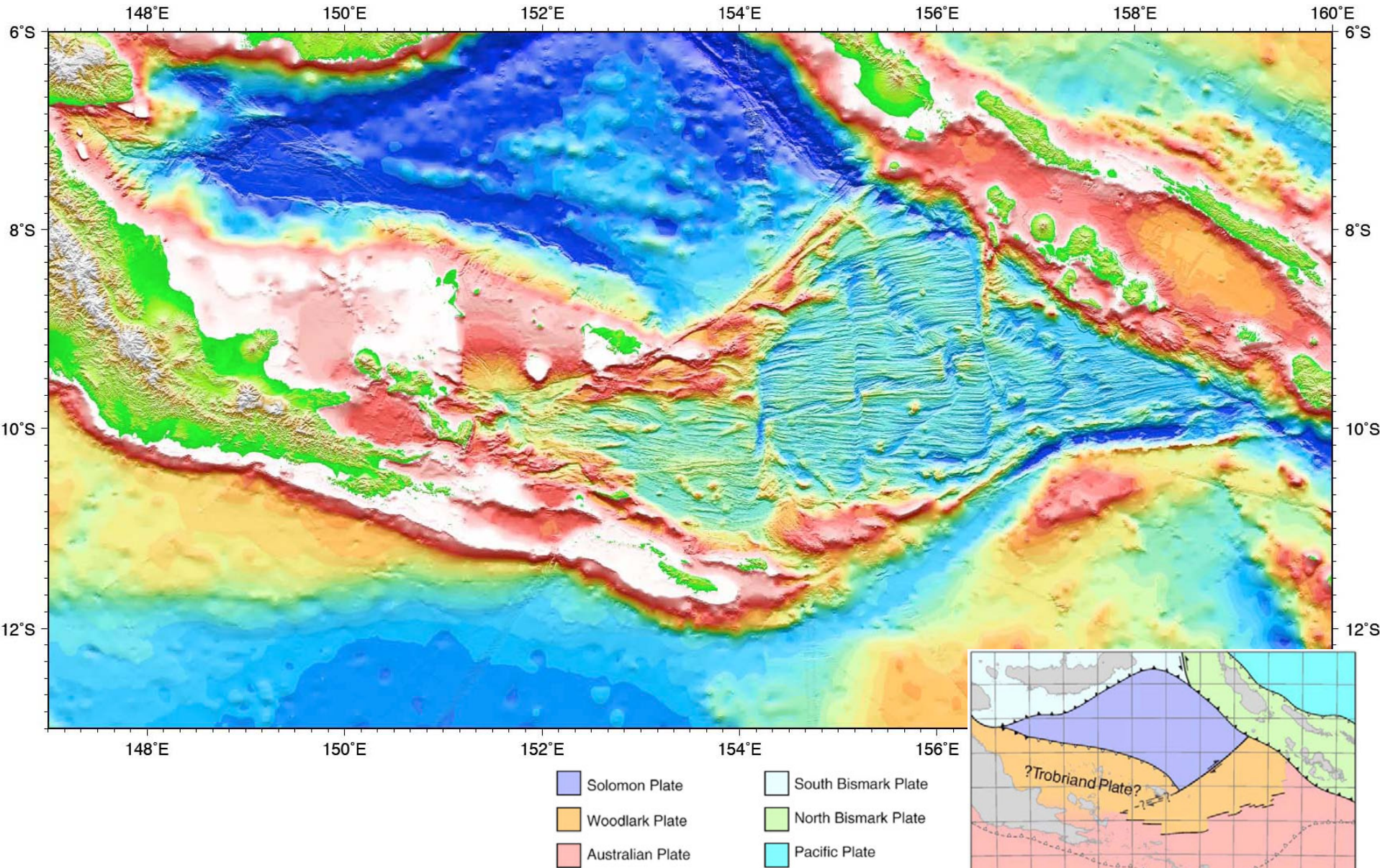


From Reston [1995]

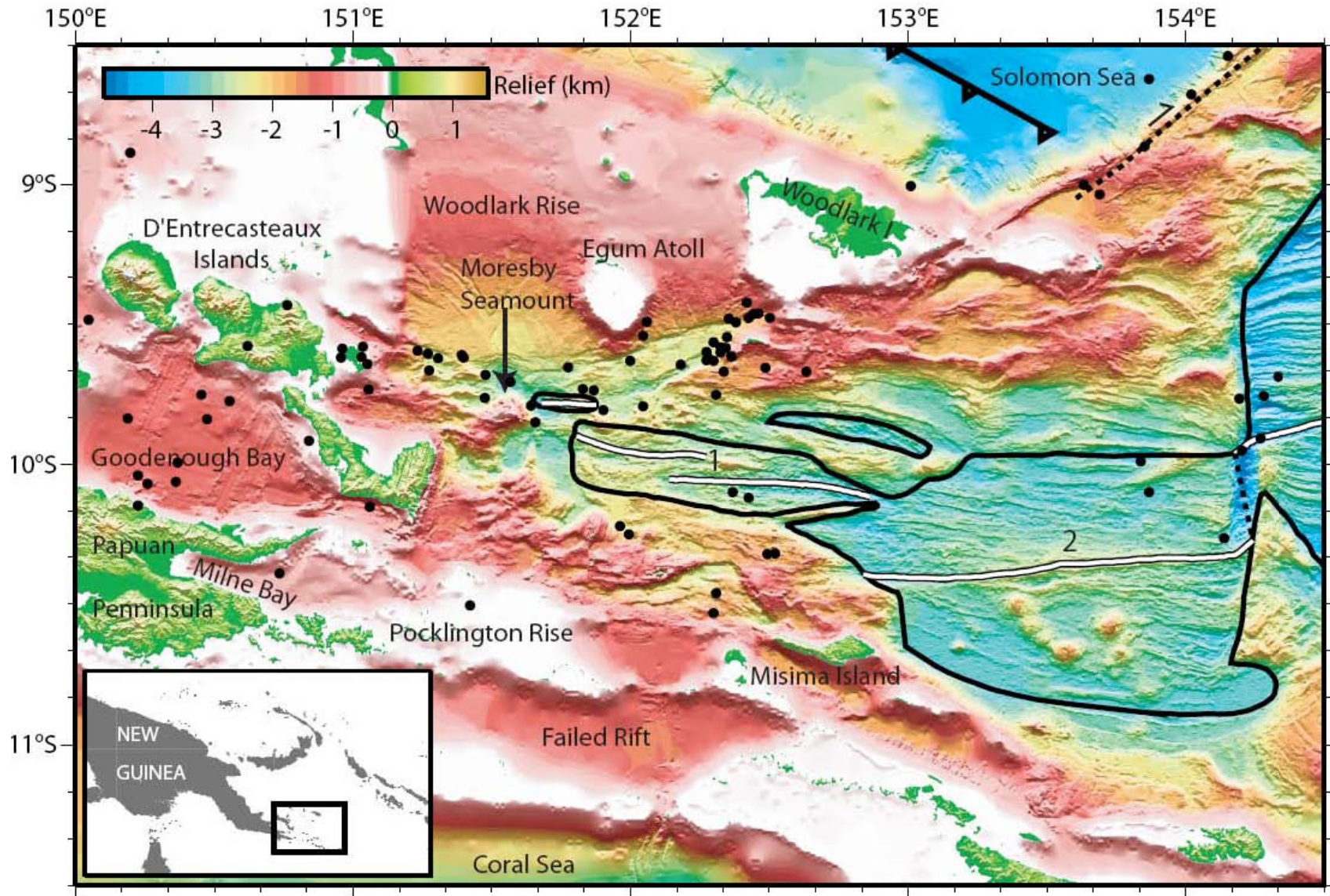
Regional Setting of a Modern Analogue



Woodlark Basin



Rifting to Seafloor Spreading Transition



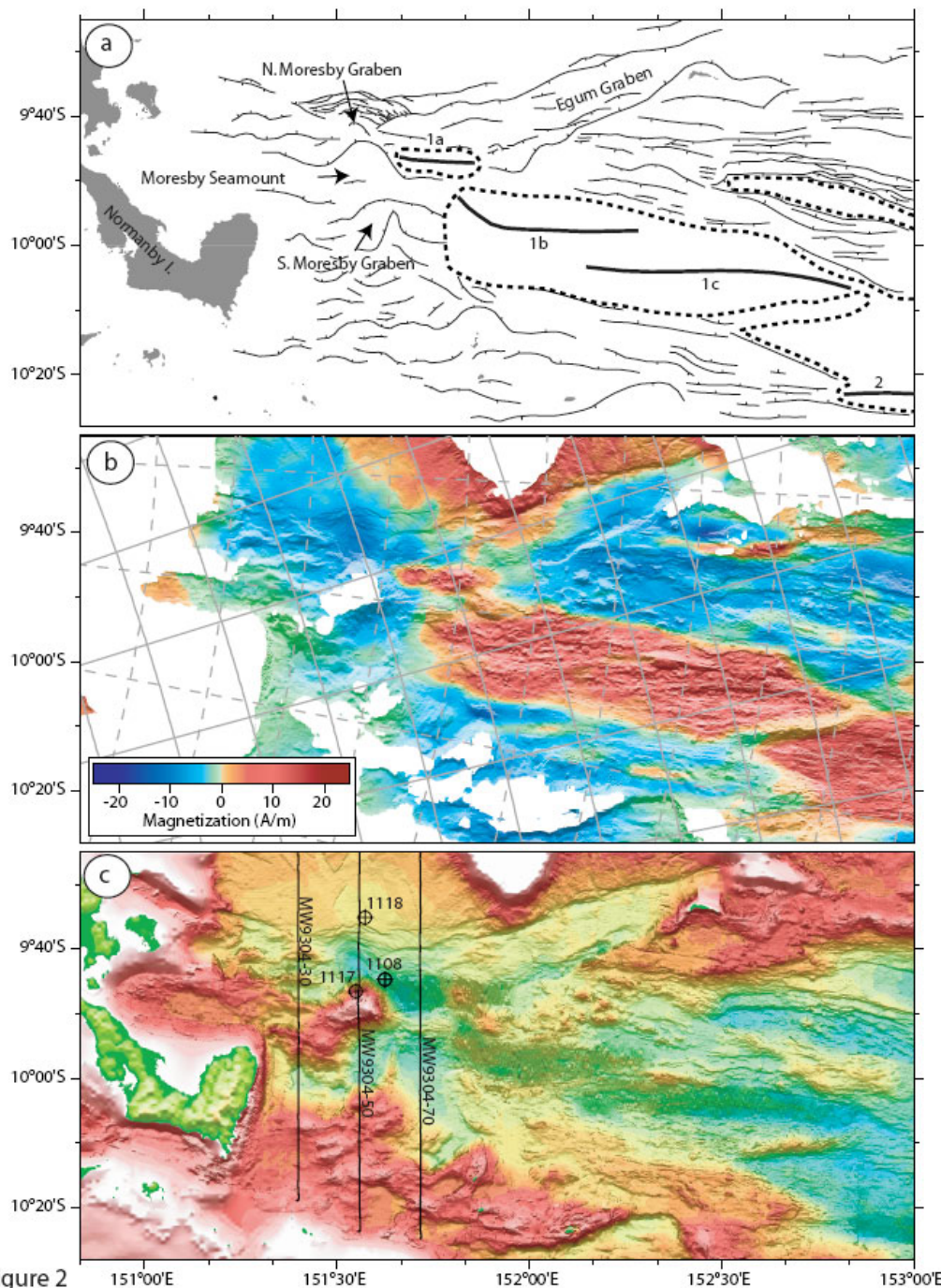
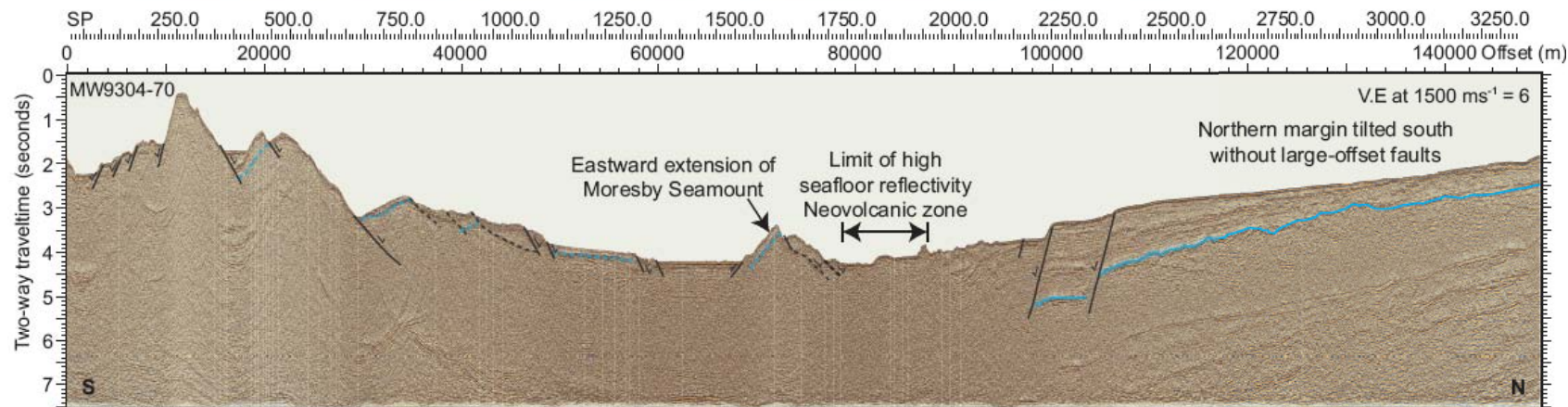
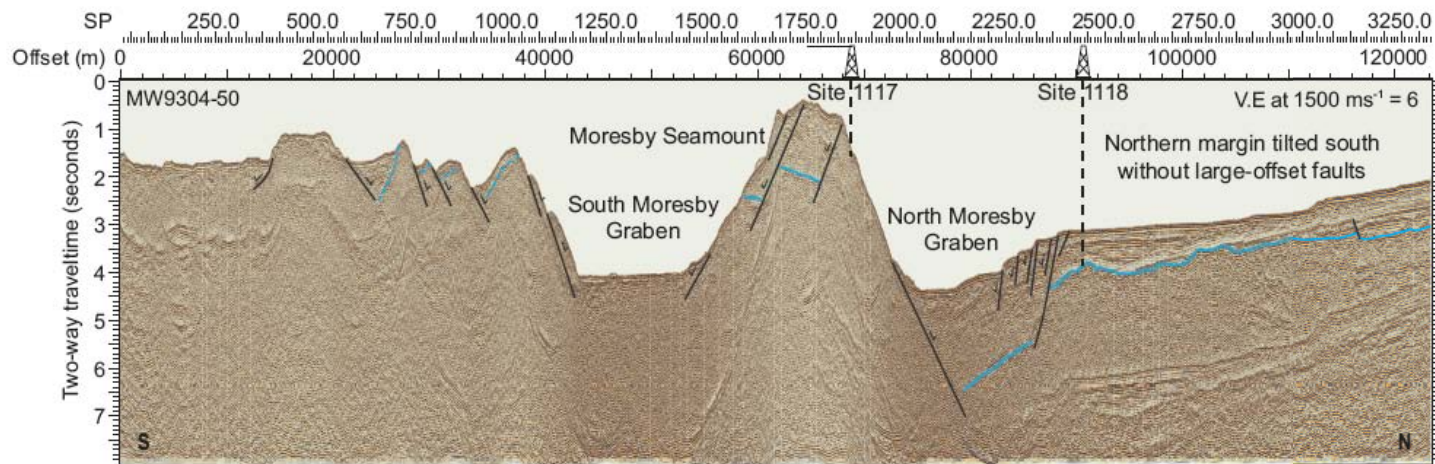
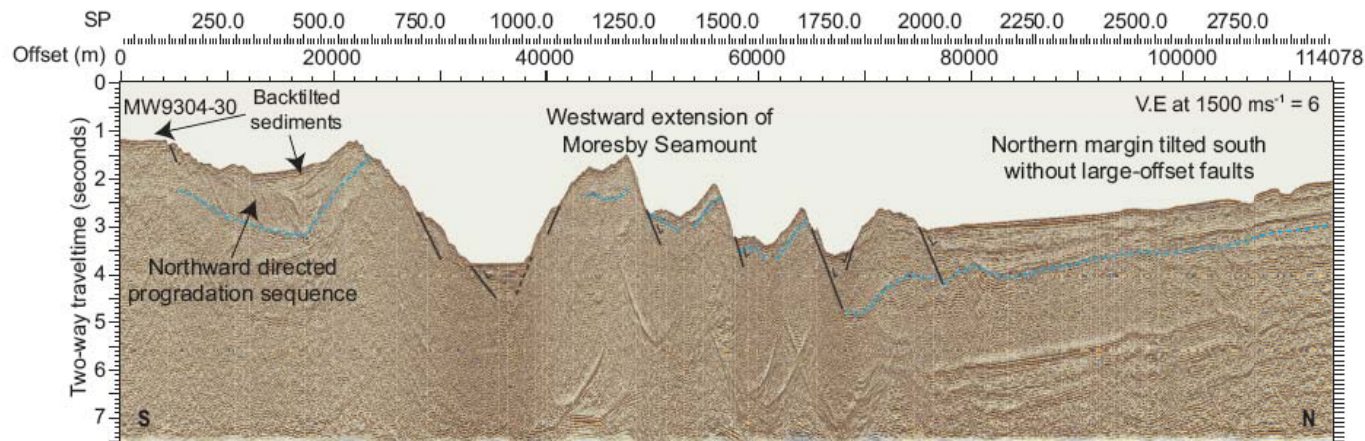


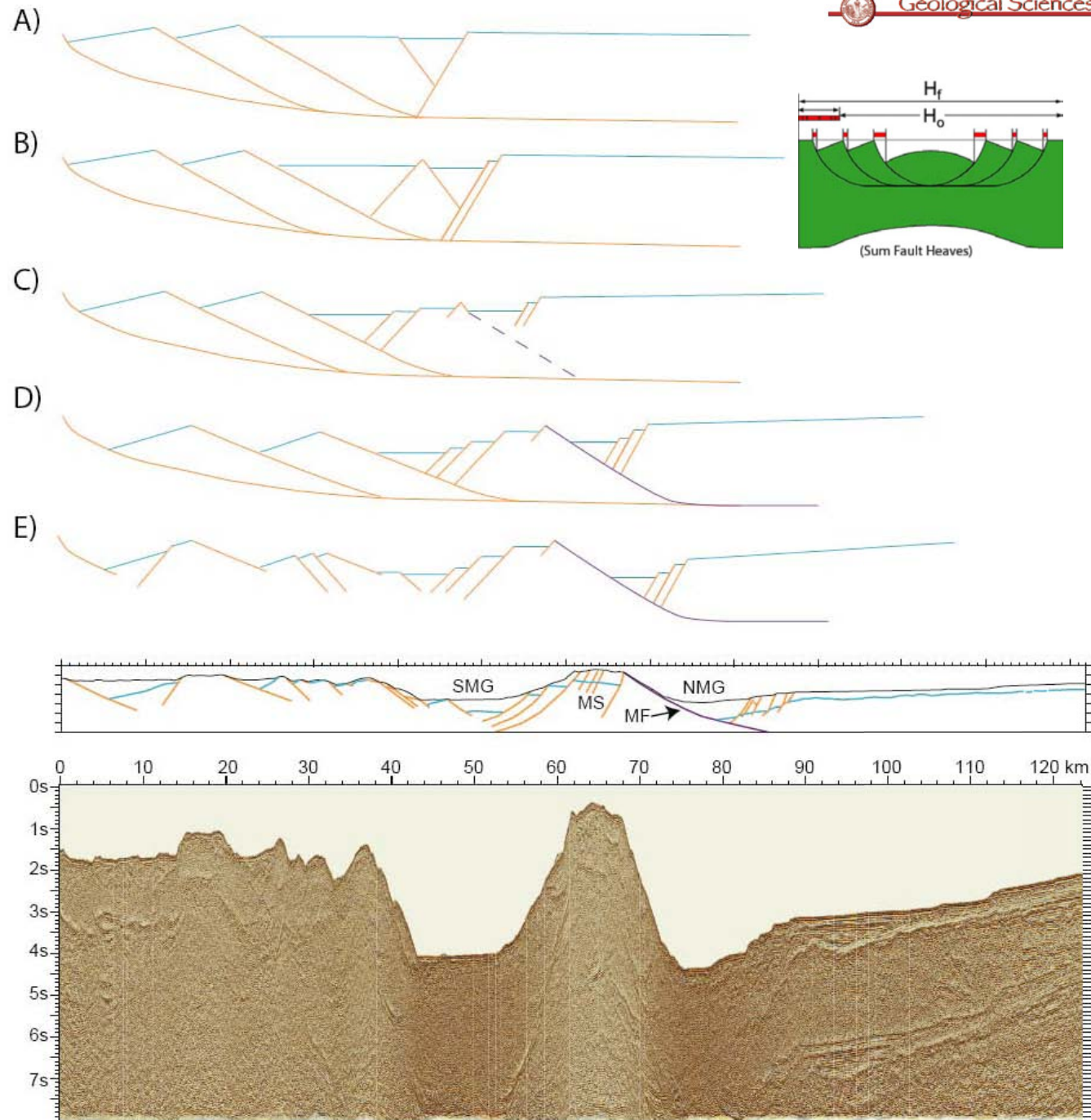
Figure 2

- Major faults in the vicinity of the rifting-to-spreading transition and the active neovolcanic zones.
- Limit of oceanic crust is dashed.
- Seafloor magnetization illuminated from the north by bathymetry.
- Oceanic crust formed since the start of the Brunhes chron (0.78-0 Ma) has a positive magnetization.
- Bathymetry illuminated from the north and overlain by acoustic imagery.
- Note location of seismic lines and ODP Sites 1108, 1117, and 1118.

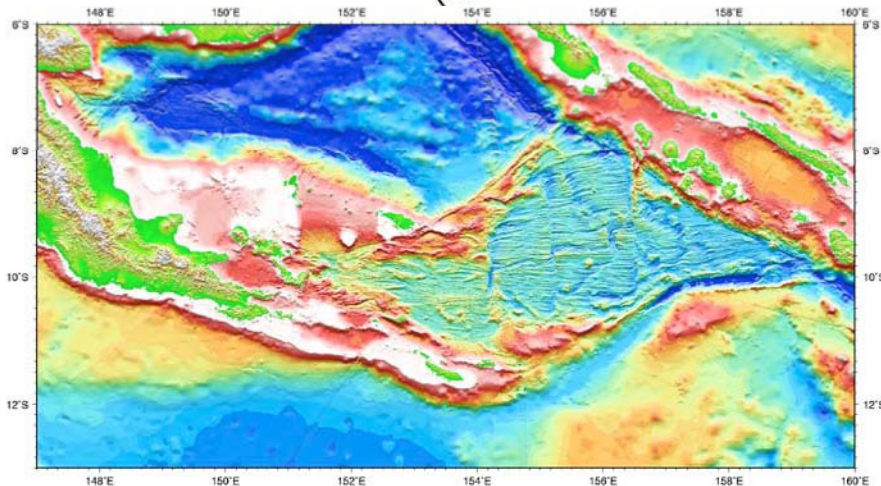
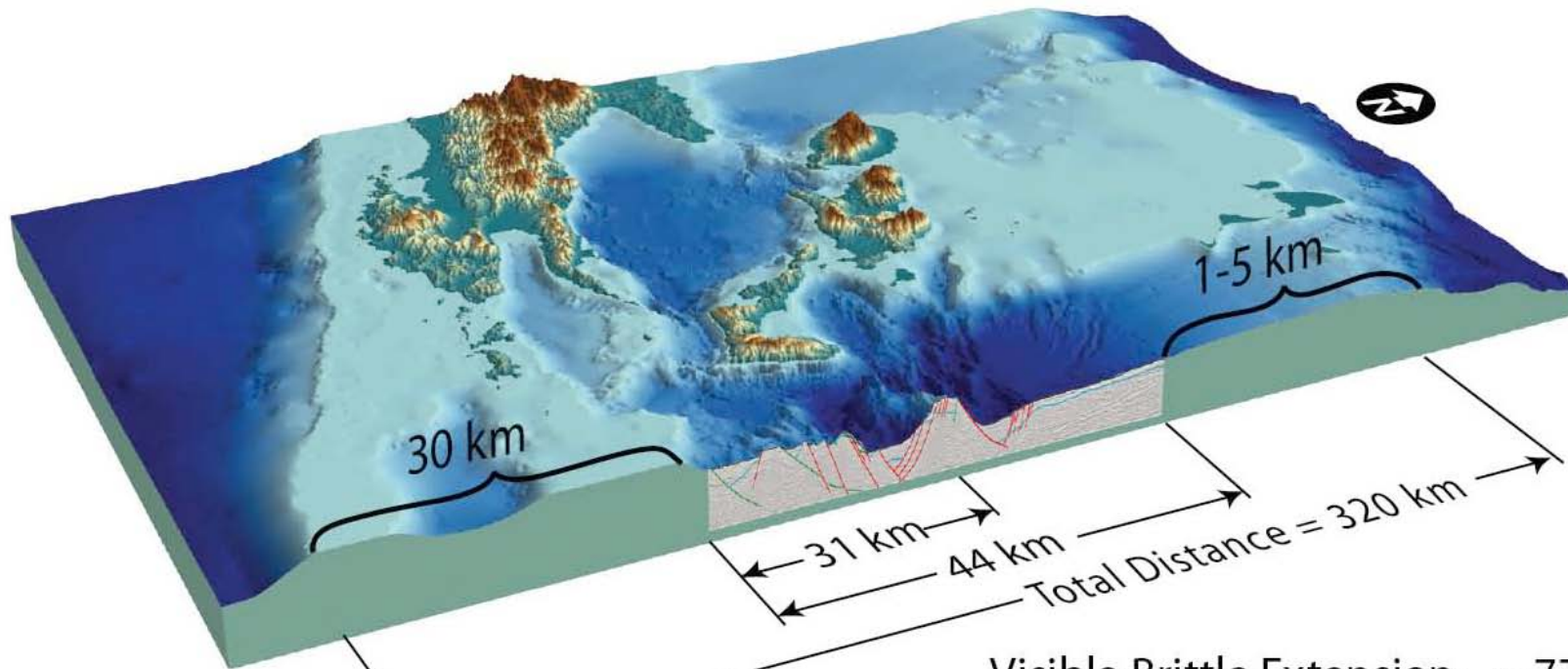


Structural Evolution

- Northern part of line based on ODP results [Taylor & Huchon, 2002]
 - Depth and timing of subsidence on northern margin is well constrained
 - Southern margin is unconstrained
- Only two phases of faulting used
 - Mafic basement allows rotation of faults to low angles [Taylor & Huchon, 2002]
- 44 km of extension, 31 km of which is south of Moresby Seamount

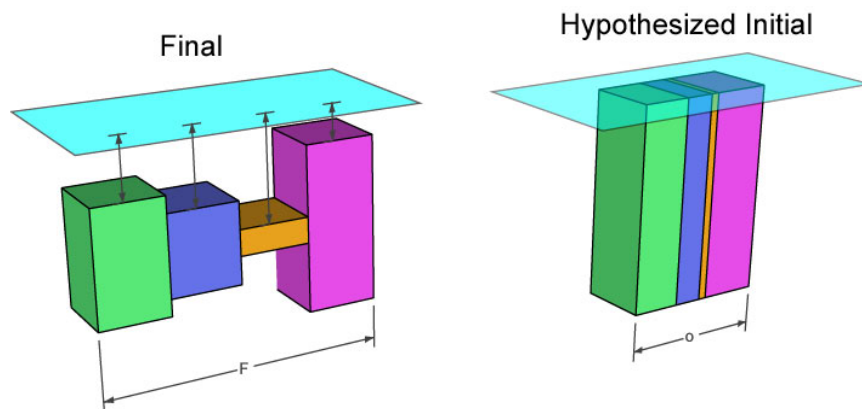


Extension from Brittle Faulting



Visible Brittle Extension = $\sim 77 \pm 12$ km
 Subseismic Extension = ~ 34 km
 Total Brittle Extension = $\sim 111 \pm 23$ km
 Brittle $\beta = \sim 1.5$

Extension from Subsidence



$$\beta = \left(1 - \frac{h_{sb}}{\left[\frac{(\rho_m - \rho_{cc})}{(\rho_m - \rho_s)} h_{cc} - \frac{1}{1.16\sqrt{\pi}} \frac{\rho_m \alpha_v (T_1 - T_0) y_{LO}}{(\rho_m - \rho_s)} \right]} \right)^{-1} \quad (1)$$

Where

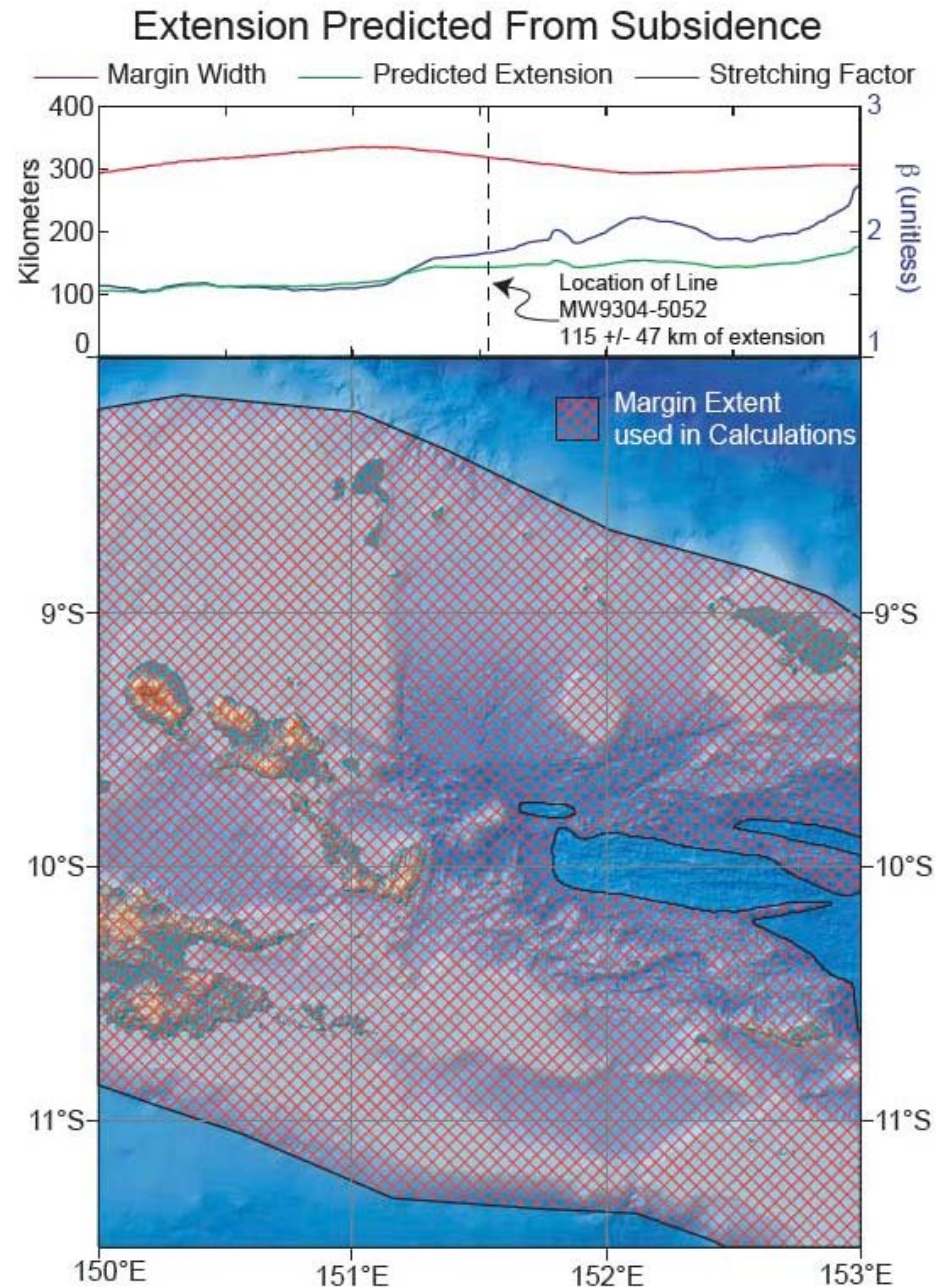
h_{sb}	Thickness of sedimentary basin
ρ_m	Mantle density
ρ_s	Density of basin infill
α_v	Thermal expansion coefficient of mantle
T_0	Surface Temperature
β	Crustal thinning factor $\left(\frac{\text{Pre-rift Thickness}}{\text{Stretched Thickness}} \right)$
y_{LO}	Pre-rift thermal lithospheric thickness (depth to T_1 isotherm)
ρ_{cc}	Density of continental crust
h_{cc}	Pre-rift crustal thickness
T_1	Asthenosphere Temperature

Many assumptions

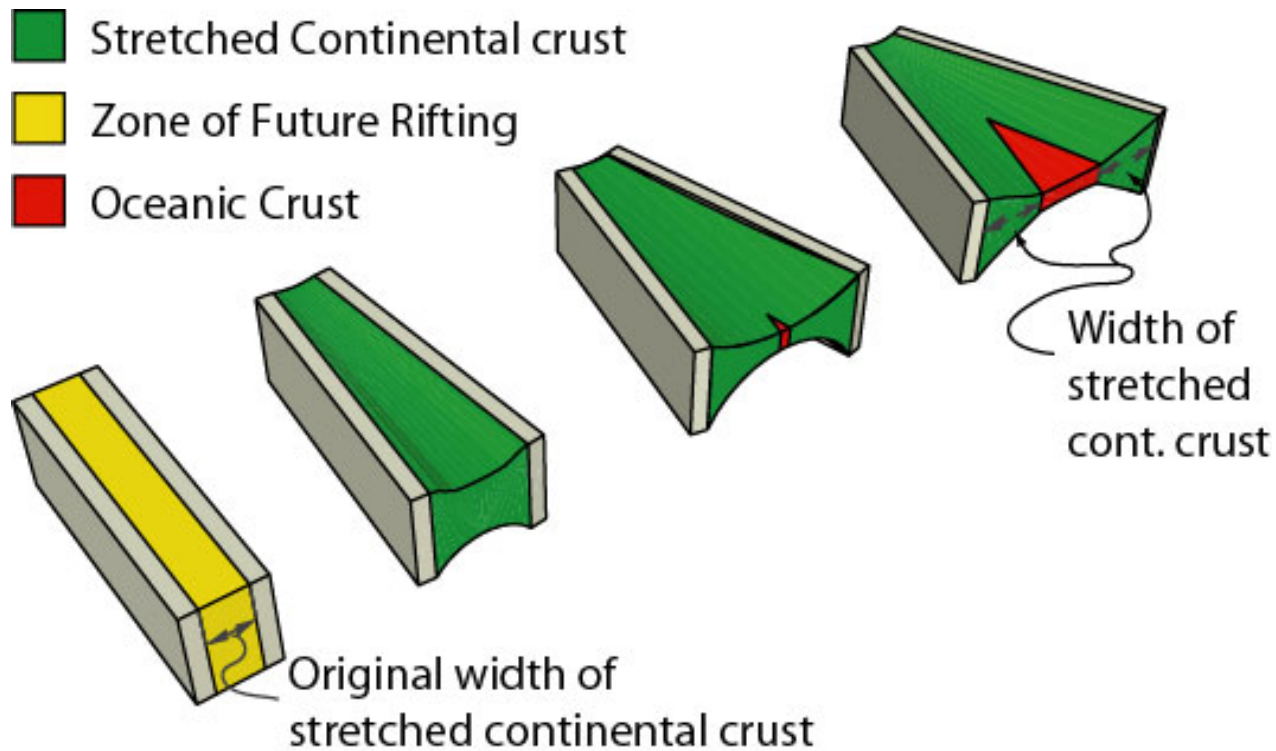
- Conservation of crustal volume – i.e. no lower crustal flow
 - Models for the area require lower crustal flow – 1) formation of metamorphic core complexes; 2) subsidence of northern margin
 - Crustal flow towards rift center = underestimate of extension
- Sediments are up to 2 km thick, but very thin over much of the basin
- Airy isostasy - underestimates extension if there is significant flexural rigidity
- Instantaneous rifting - overestimates extension if the lithosphere has had time to cool
- Highly dependant on pre-rift crustal thickness - 50 km [Finlayson, 1976]
- Highly dependant on paleo-elevation
 - If crust at sea-level is 35 km thick, 50 km thick crust = 2.3 km of paleo-elevation
 - Minimum estimate of extension comes from assuming 35 km thick crust
 - Crustal density of 2800 kg/m³, mantle density of 3300 kg/m³, 160 km depth to 1300 °C isotherm, volumetric expansion coefficient of $3 \times 10^{-5} \text{ K}^{-1}$ -similar to forsterite

Extension from Subsidence

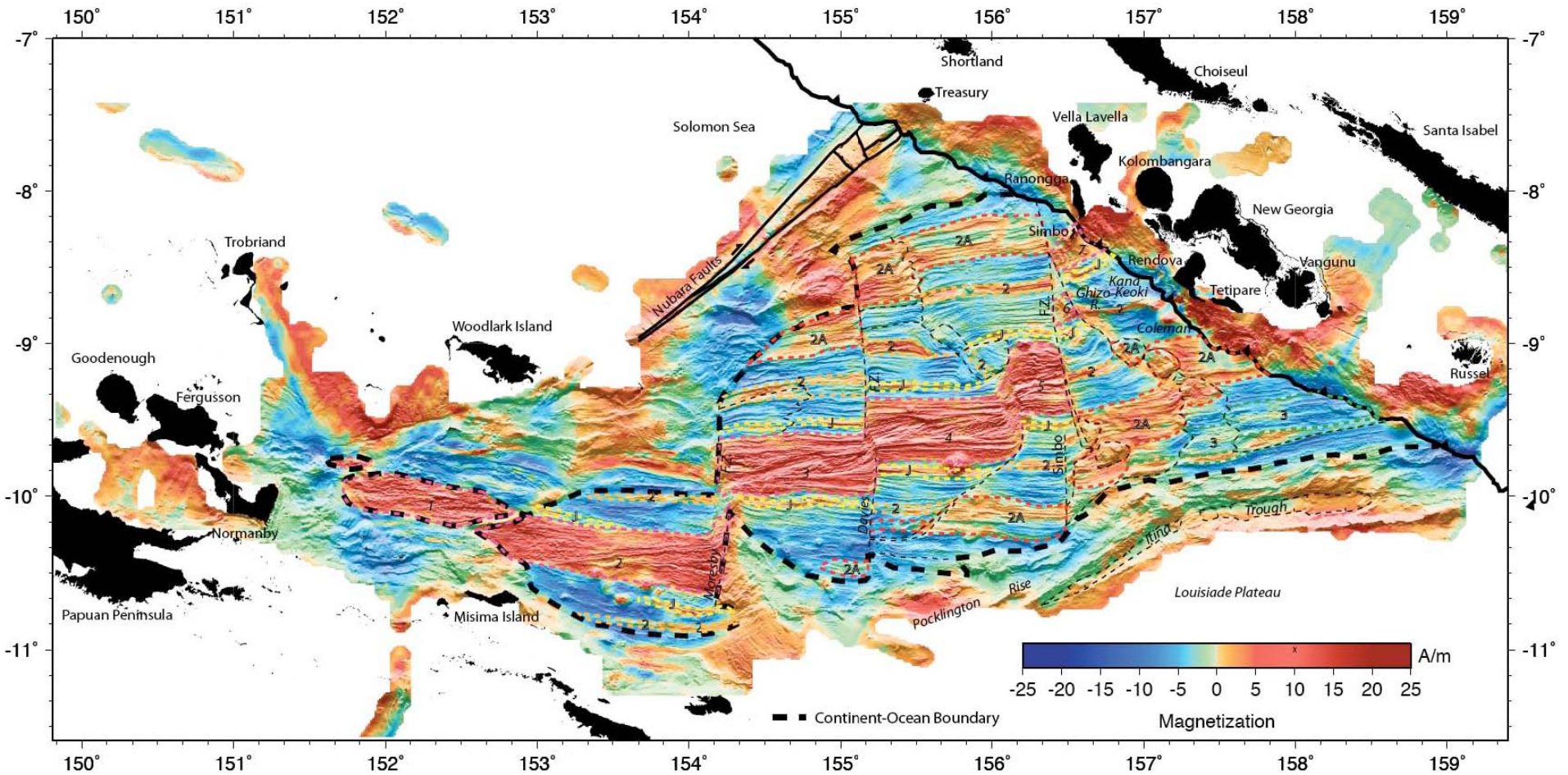
- ~ 115 km (s 47 km) at the longitude of seismic reflection line MW9304-5052
- Marginally more than that predicted for brittle extension (subsidence estimate has much larger error bars)
- Including flexure would increase this number



Extension from Plate Kinematic Reconstructions



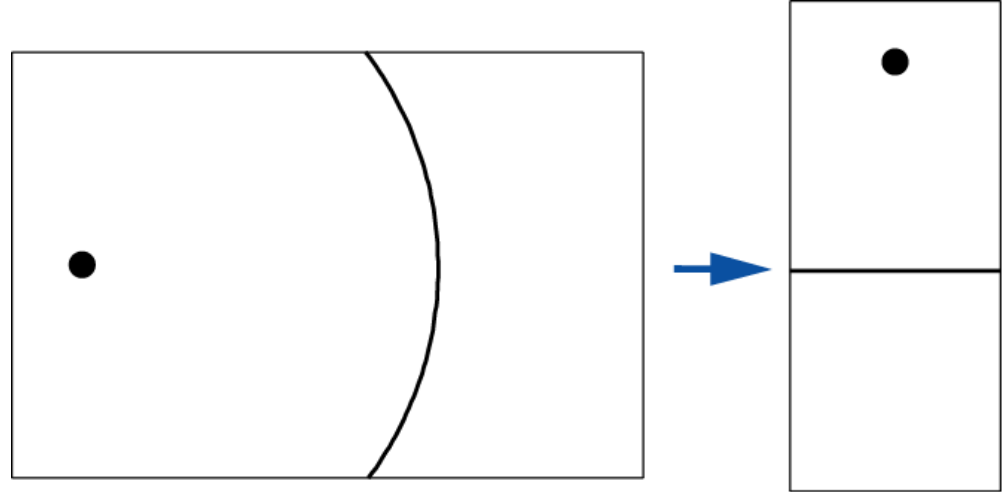
Woodlark Basin Seafloor Magnetization



Predicting Extension from Euler Poles: Principles

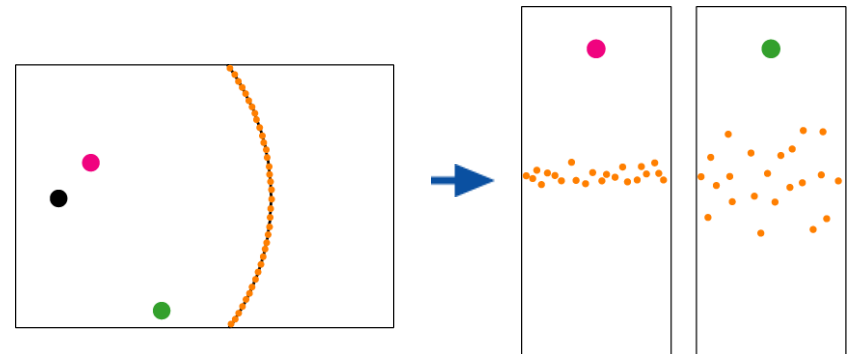
Projection of transform fault into coordinate system relative to pole

- Becomes a straight line



Numerous poles can be tried – the one that creates the straightest line is the correct Euler pole

- Grid search is used to find the best fit pole



Similar methodology can be used for fitting spreading rate information and rotating isochrons back together

- Very powerful tool when data from many source is combined

Predicting Extension from Euler Poles: Error Prediction

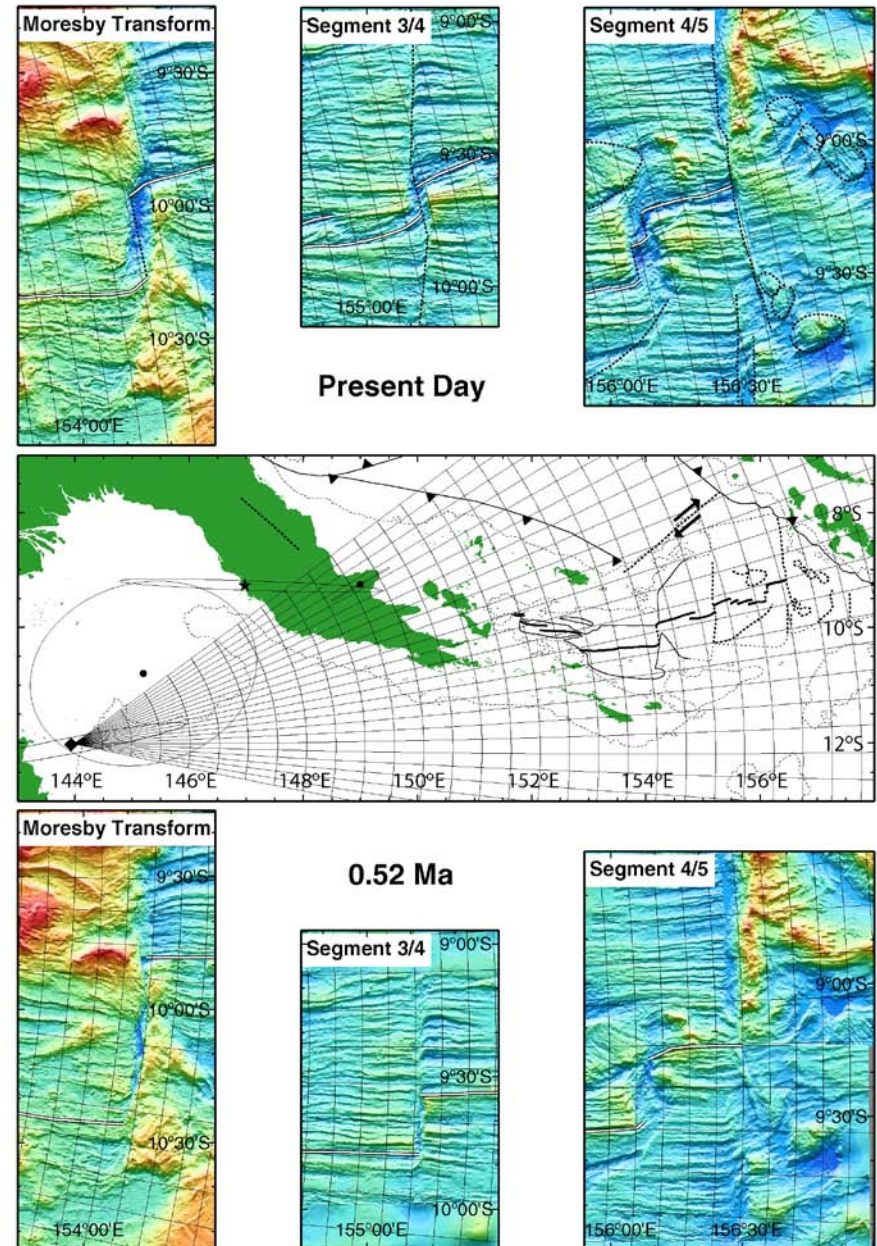
- Bootstrap sampling randomizes error in calculations [Efron and Tibshirani, 1986]
 - Works by replicating calculations over a large number of bootstrap samples
 - Each sample contains the same number of data points as the original data, but *randomly* draws the data from the original set
 - For each sample, calculate statistic of interest
- Density function of Wilson [1993] and Zellmer and Taylor [2001]

$$d = \sum_{n=1}^{ns} \exp\left[\sum_{i=1}^3 \frac{-(P_i - S_{n,i})^2}{AV_i}\right]$$

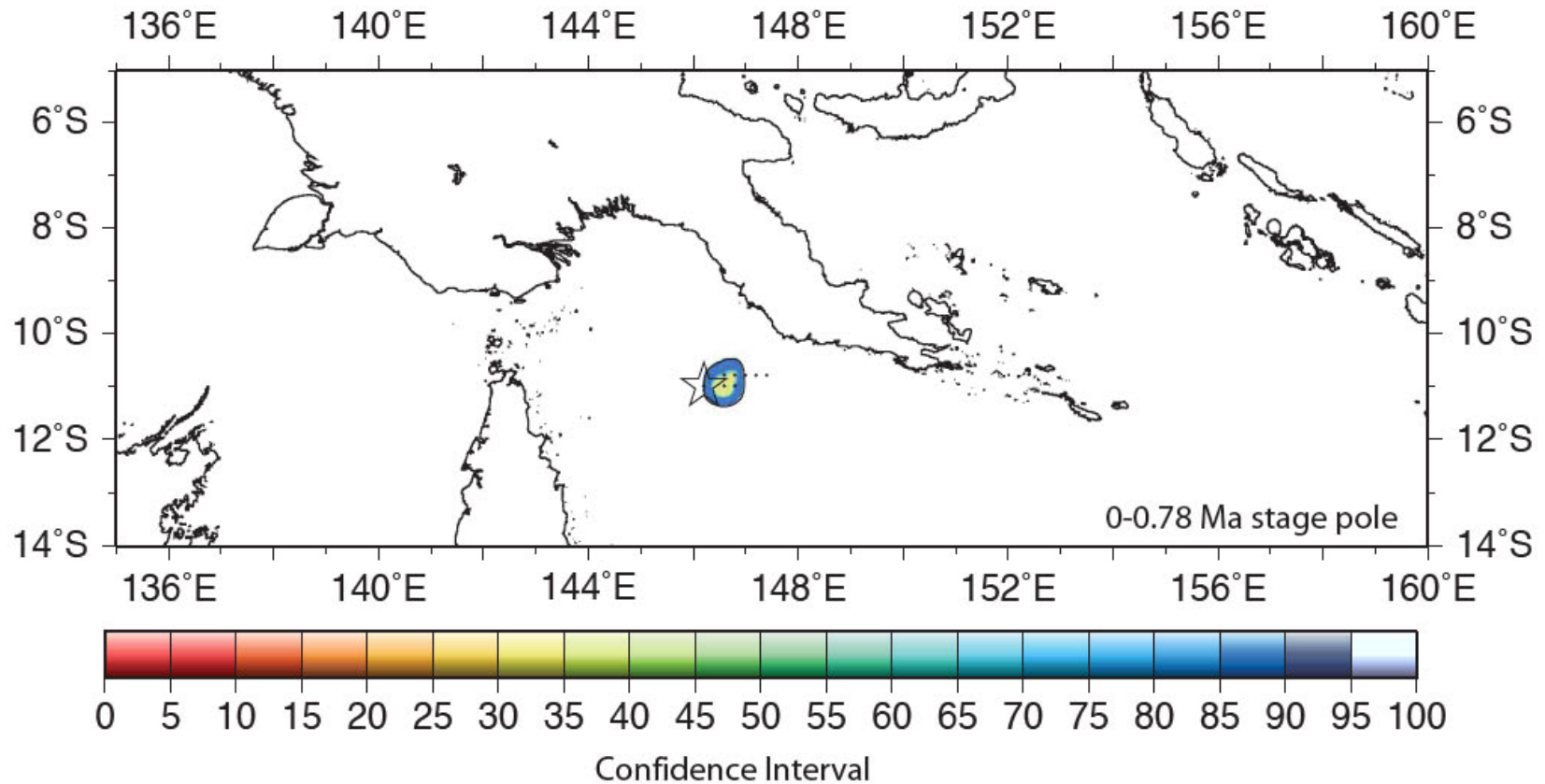
- P_i is a trial point
- S_n is the set of solutions
- V_i is the variance about the principal axis
- A is a smoothing factor
- Solutions near the pole contribute a value near 1, those far away have a negligible impact

Predicting Extension from Euler Poles

- Orientation of fracture zones, transform faults, and variations in spreading rate used as input to the model
- Seafloor isochrons modeled and incrementally removed [*Goodliffe, 1998*].
- 0.52 Ma –present pole is at 143.93°E , 12.02°S .
 - Within error limits of GPS results [*Tregoning et al., 1998*].
 - Predicts strike slip motion on the Gira fault [*Davies et al., 1984*], and alignment of satellite cones on Mount Victory [*Nakamura, 1977*]
- 3.0-0.52 Ma pole is at 146.98°E , 9.27°S

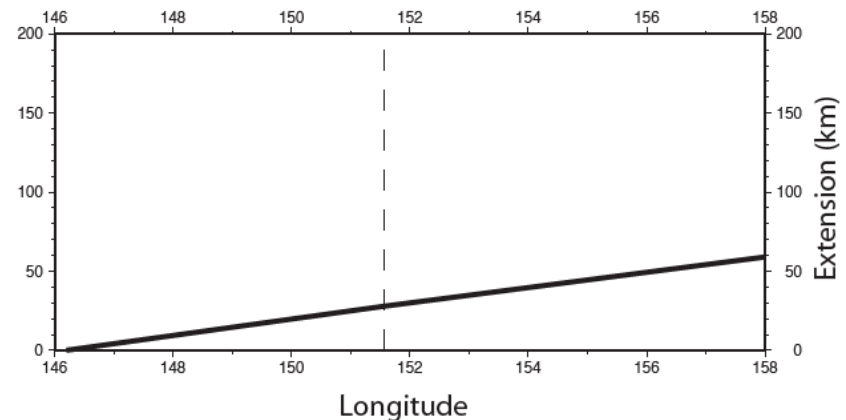


Predicting Extension from Euler Poles

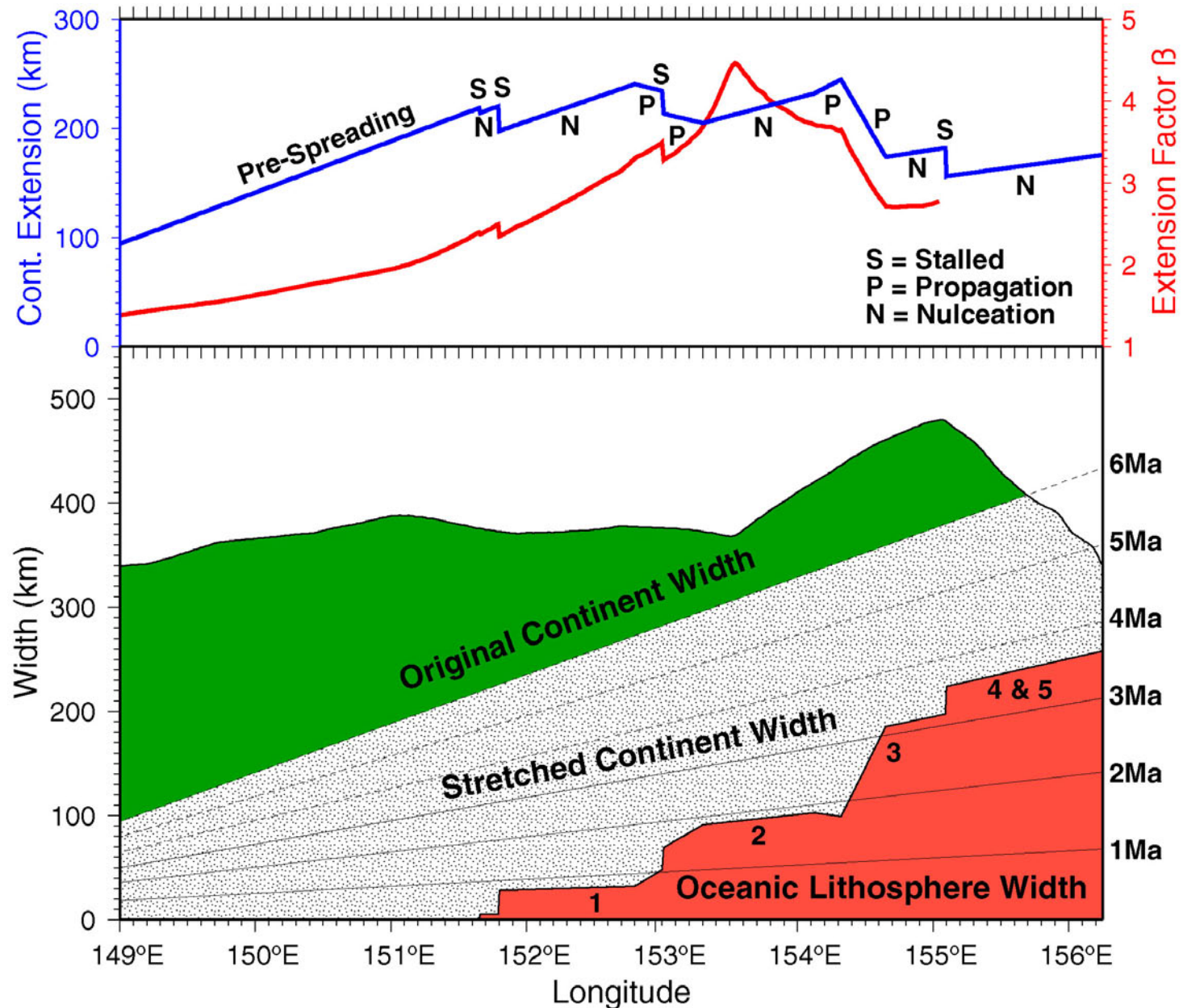


Best-fit Euler pole solution can be found for isochrons and/or fracture zones (above)

- Each includes a prediction of extension around the pole (right)
- A pole can be found for each isochron



Rift Evolution Through Propagation and Nucleation



Predicting Extension from Euler Poles

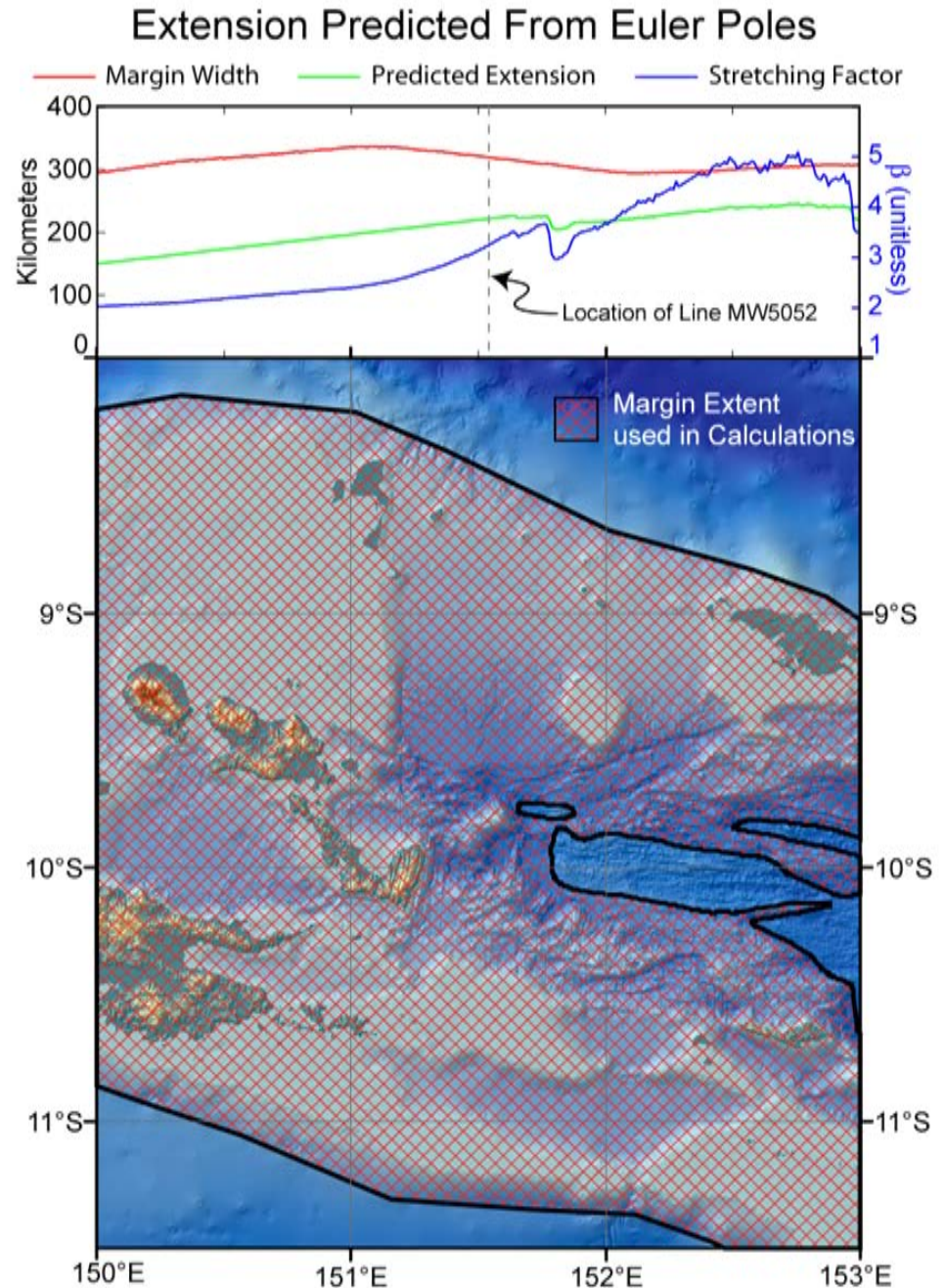
Predicted extension = 220 km

Margin width = ~320 km

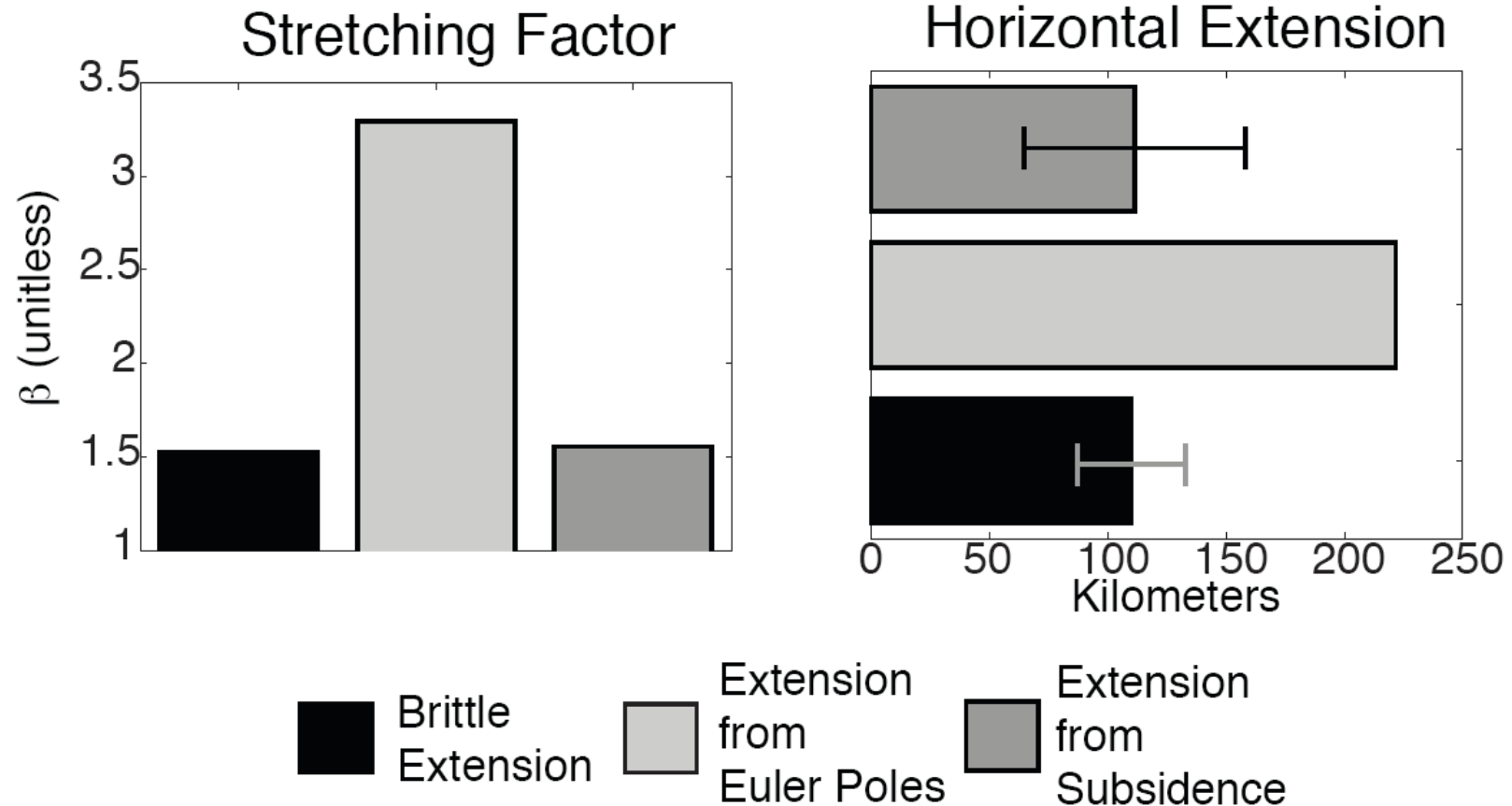
Original width = $320 - 218 = \sim 100$ km

Extension factor (β) = $320/100 = 3.2$

Assuming extension began ~6Ma (underestimate) and derived poles are valid to 6Ma



Extension Estimates from Three Sources

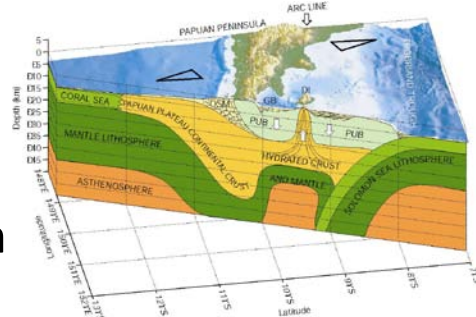


Why the discrepancy?

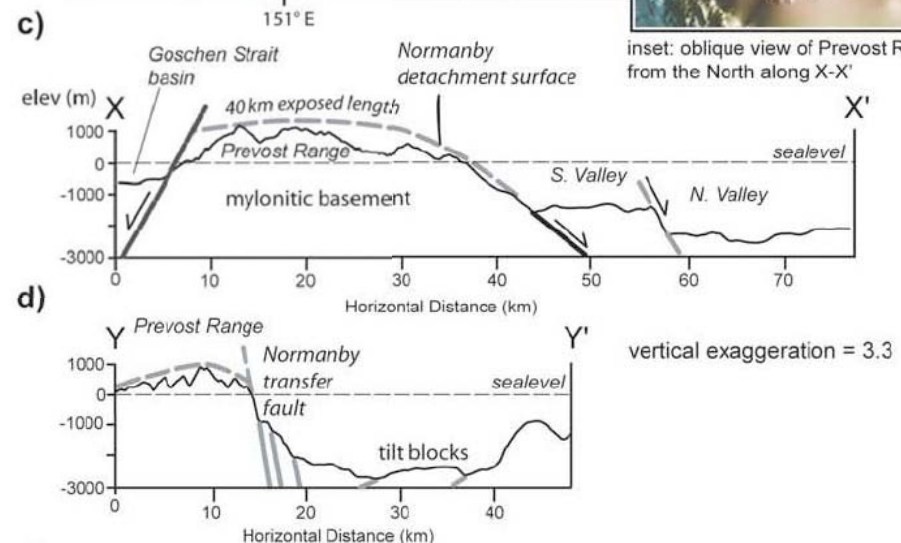
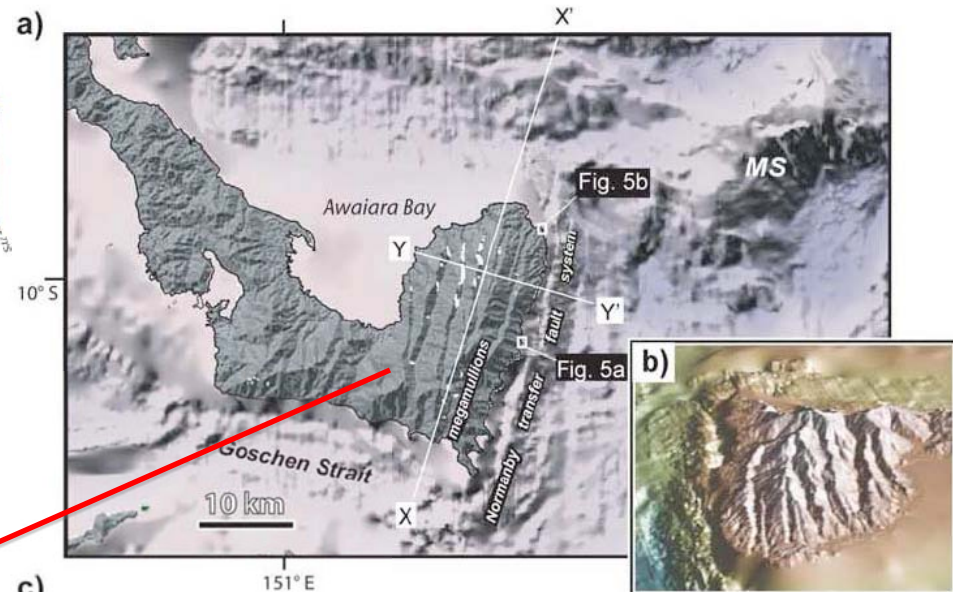
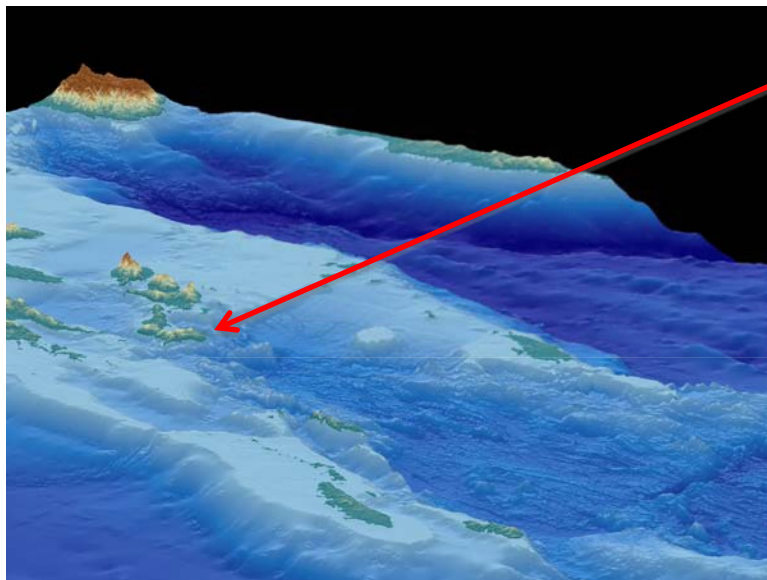
- Brittle extension and subsidence wrong?
 - Definitely possible, but probably not by a factor of two
 - Errors in subsidence assumptions?
 - Unrecognized polyphase faulting?
- Plate movement estimates wrong?
 - More accurate estimates in the works
 - Only small changes anticipated
- New mechanism?

Could Core Complexes be the answer?

- An unrecognized core complex might represent missing extension
- Almost 40 km in the case of Normanby Island



From Martinez et al. [2001]

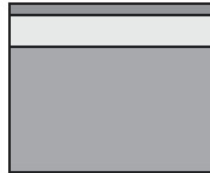


From Little et al. [2007]

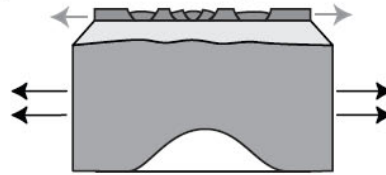
Model

- Upper crust decoupled from the mantle lithosphere
- Upper crust responds passively to extension of the mantle lithosphere
- Upper crust moves with the mantle lithosphere once the asthenospheric mantle necks through
- Predicts greater lower than upper crust extension
- The model only requires that the middle/lower crust is the weakest portion of the lithosphere

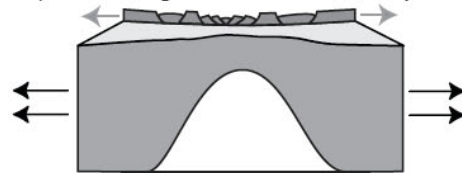
1) Pre-Rift



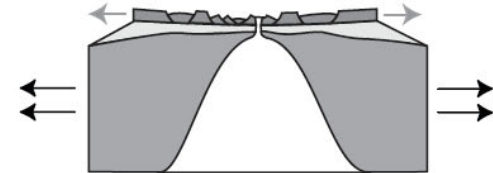
2) Initiation of Rifting



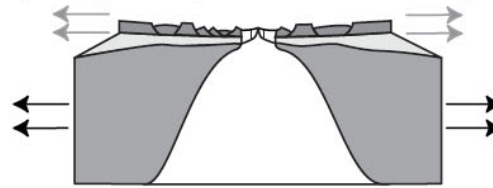
3) "Necking" of Mantle Lithosphere



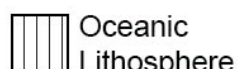
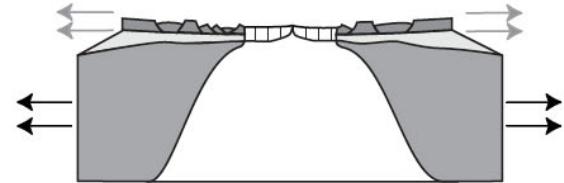
4) Initiation of Seafloor Spreading



5) Margins Separate at Full Velocity



6) Seafloor Spreading Continues

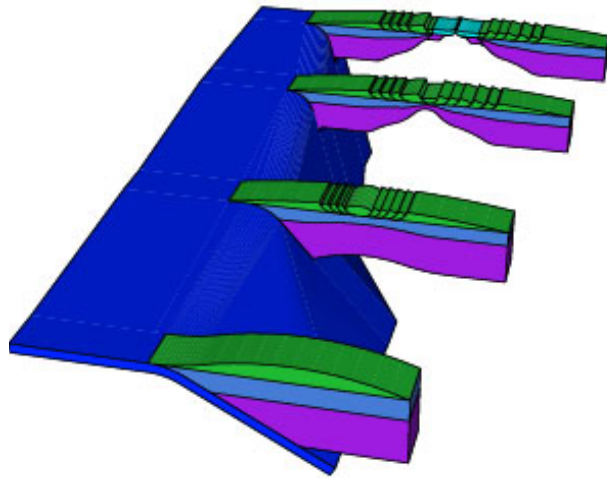


→ Upper Crustal Velocity

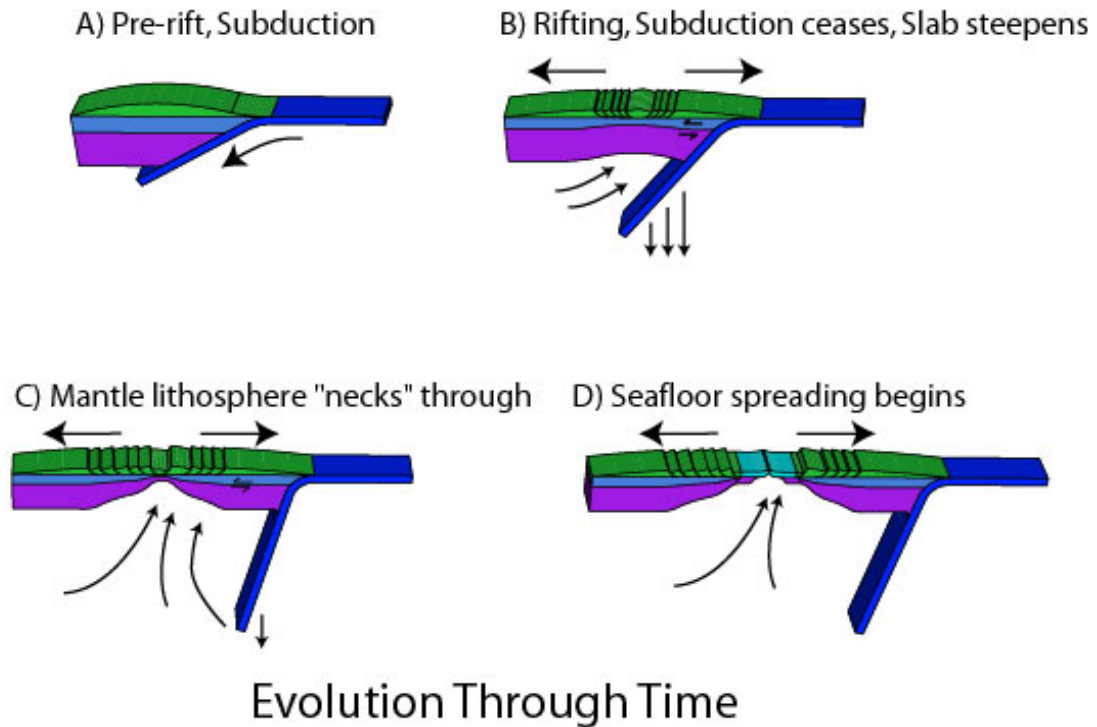
→ Velocity of Mantle Lithosphere

What happens at boundaries??

- Slab steepening?



Along-strike Temporal Analogues



Conclusions

- Extension as estimated through subsidence is still greater than that estimated by subsidence
 - Gap is smaller than before
 - Including flexure would widen this gap
- Extension as estimated through plate kinematic reconstructions is much greater (x2)
 - Suggests a different mechanism – upper crust only moves with mantle after the onset of seafloor spreading

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