Evidence for Depth Dependent Lithosphere Thinning During Continental Breakup in the Woodlark Basin*

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Abstract

Understanding how the continental lithosphere thins during continental breakup and sea-floor spreading initiation is key to understanding the continental breakup process, ocean-continent transition structure, and rifted margin subsidence and heat flow history. We have determined thinning for the lithosphere and crust in the region of propagating continental breakup and sea-floor spreading in the Woodlark Basin, western Pacific. Thinning factors have been determined for the whole lithosphere from subsidence analysis, whole continental crustal from gravity inversions, and upper crust from fault analysis. Subsidence analysis using flexural backstripping of 2D cross-sections near the Moresby Seamount in the region of pre-breakup continental lithosphere thinning gives whole lithosphere thinning factors 0.5 to 0.8 increasing eastwards towards the propagating tip of sea-floor spreading, and indicates that subsidence requires substantial crustal thinning.

Gravity inversion has been used to determine Moho depth, crustal thickness and thinning factors; predicted thinning factors from gravity inversion are similar to those obtained from flexural backstripping and Moho depths from gravity inversion are consistent with those from receiver function analysis. Fault analysis of seismic reflection data show upper crustal thinning factors of between 0.1 to 0.4 for the vicinity of the Moresby Seamount, substantially lower than thinning factors predicted for the whole lithosphere and continental crust, indicating depth-dependent lithosphere stretching and thinning. Crustal thicknesses predicted from gravity inversion immediately to the east of the Moresby Seamount are greater than expected for oceanic crust; it is inconclusive whether this region is thick oceanic crust, attenuated continental crust or thin continental crust with volcanics.

AAPG Cape Town
October 2008

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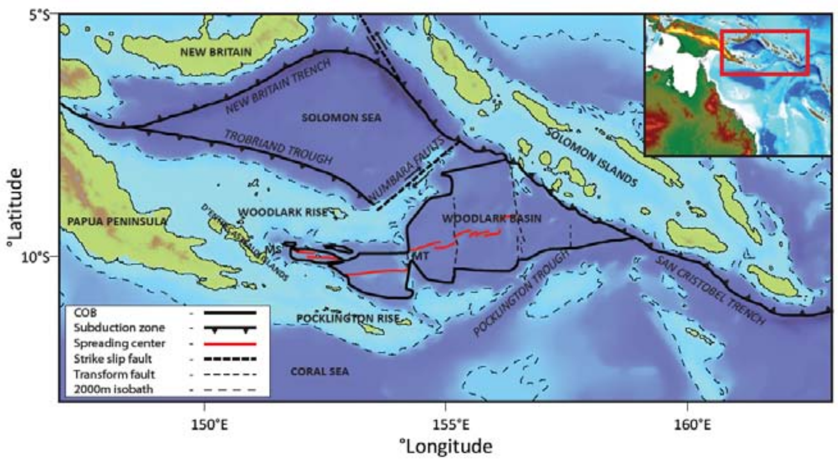


MM2
Margin Modelling Phase 2

Acknowledgements:
MM2 Partners - BP, ConocoPhillips, Statoil, Shell, Petrobras, TOTAL, BG, BHP-Billiton
Collaborators – Alan Roberts, Robert Hooper, Garry Karner +

Aims

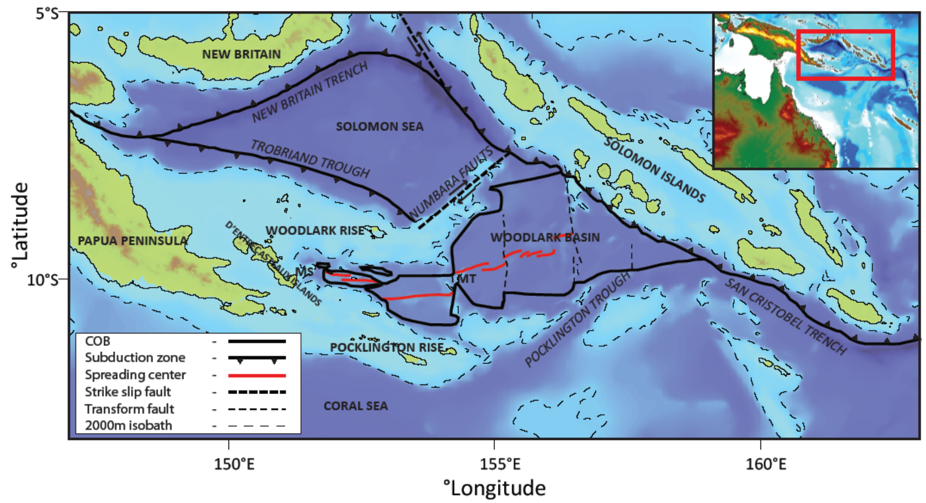
•To understand how continental lithosphere thins leading to continental breakup and sea-floor spreading initiation.

•Key to understanding:

- •continental breakup process
- •ocean-continent transition structure
- •predicting rifted margin subsidence and heat flow history

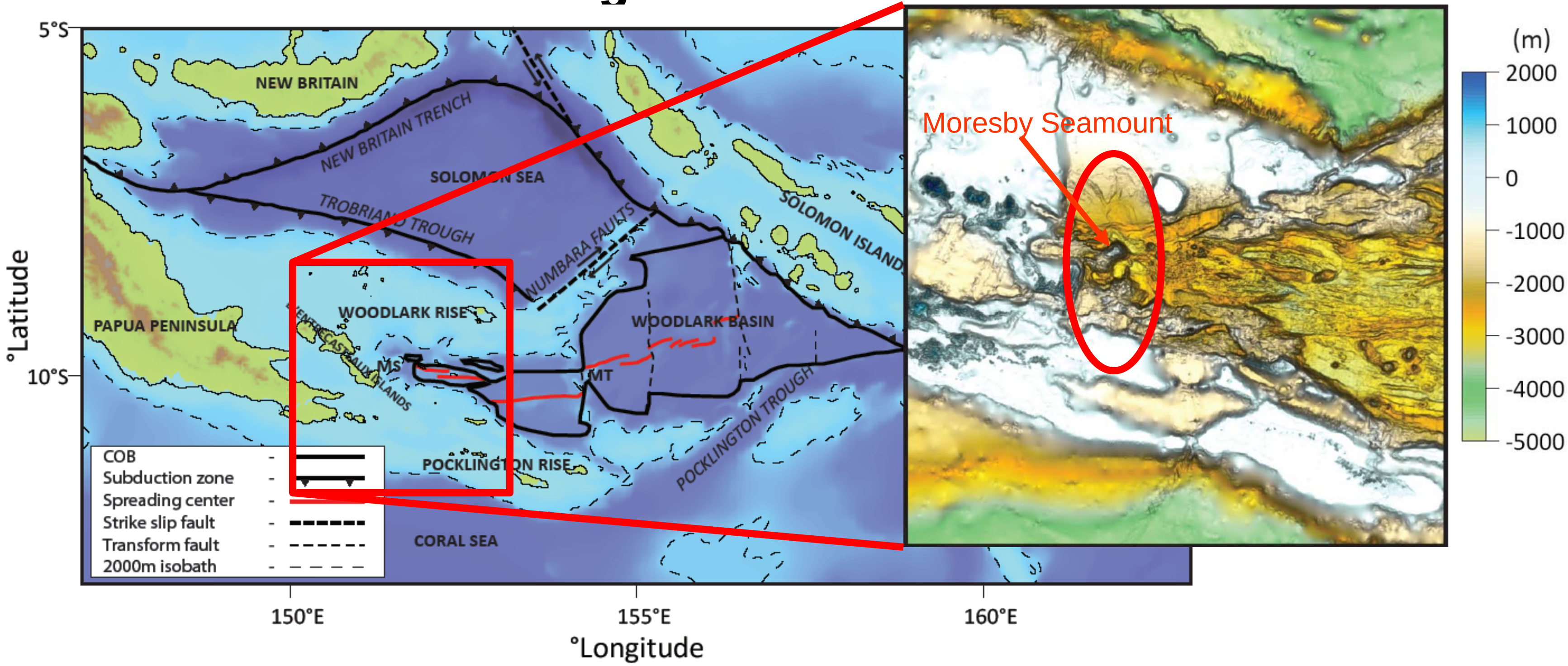
Woodlark Basin - Background

- Woodlark Basin provides a modern day example of continental breakup
- Extensive public domain data set
- Thin sediments



- Located in Western Pacific east of Papua New Guinea
- Young ocean basin
  - rifting commenced ~8.4Ma
  - oldest oceanic crust ~ 6Ma
  - westward propagating into continental lithosphere
  - continental lithosphere thinning and subsidence west of propagating tip
- pre-breakup, syn-breakup and post-breakup process observable at present time

Woodlark Basin - Background



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  - westward propagating into continental lithosphere
  - continental lithosphere thinning and subsidence west of propagating tip
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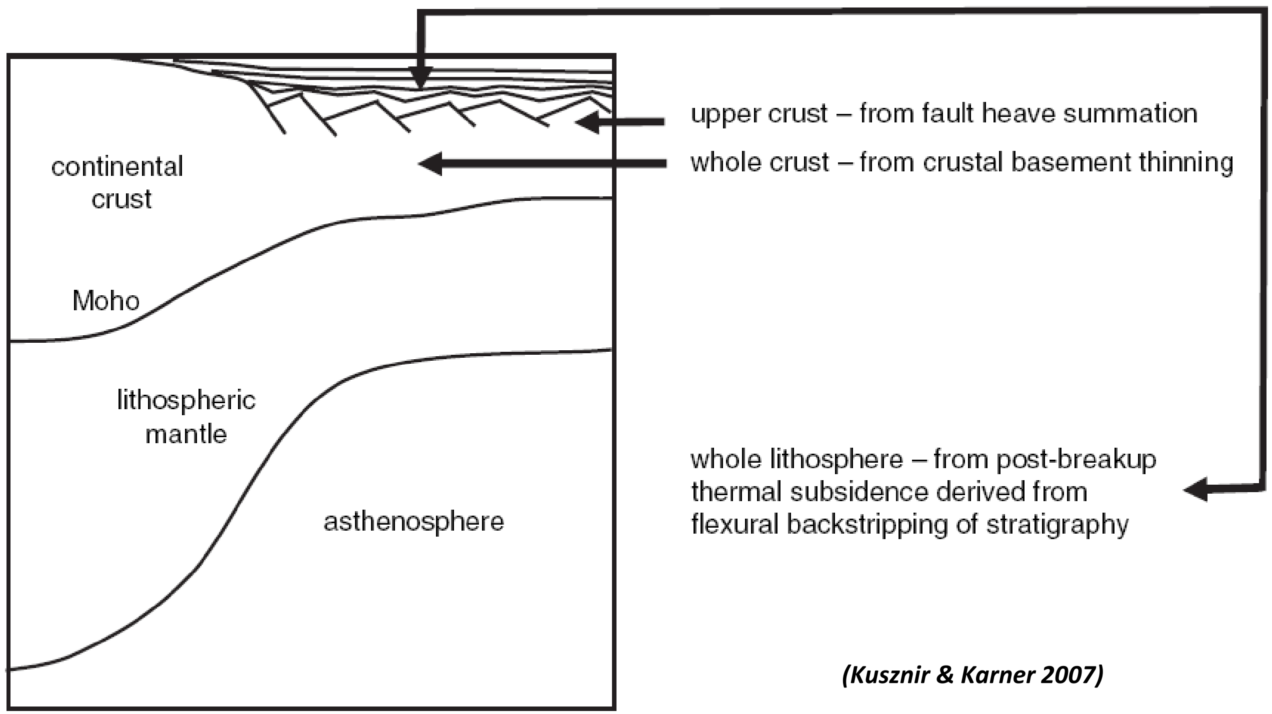
Stretching & Thinning of Continental Lithosphere

Measure at 3 levels:

- Upper crust
- Whole crust
- Whole Lithosphere



(Kusznir & Karner 2007)

Stretching Factor

- β = Final length/Initial Length

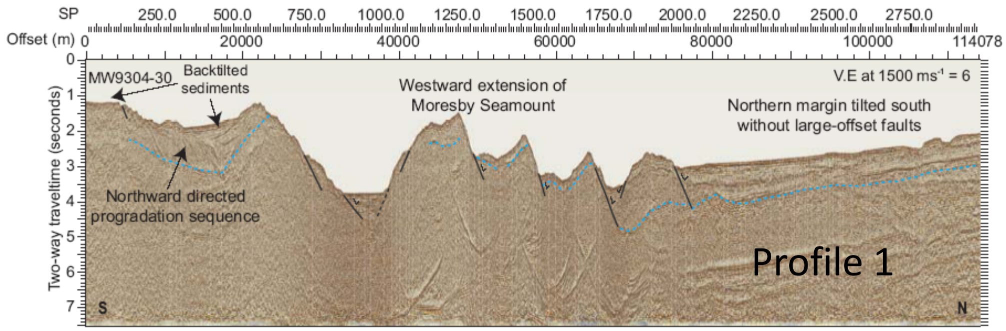
Thinning Factor

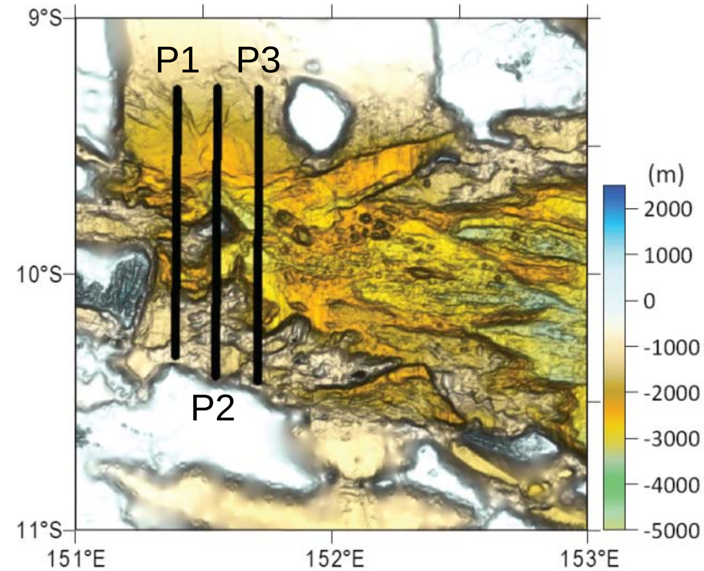
- $\gamma = 1 - 1/\beta$

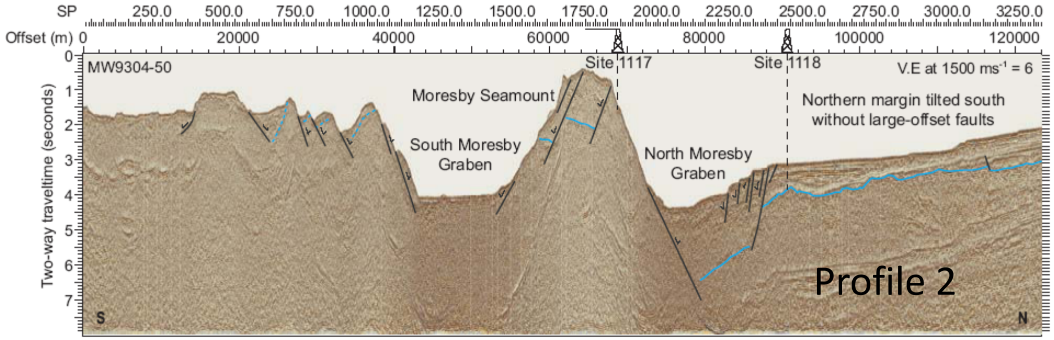
Data – Woodlark Basin

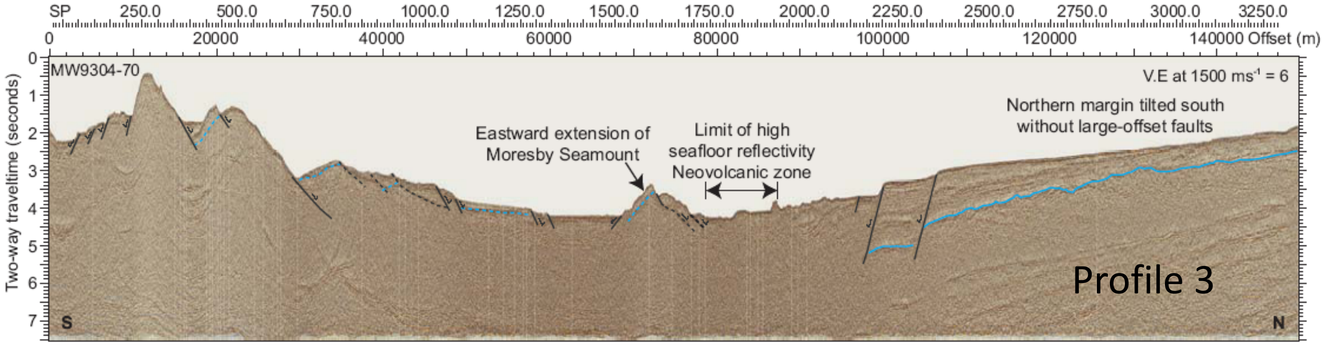
Seismic reflection profiles

(Goodliffe & Taylor 2006)







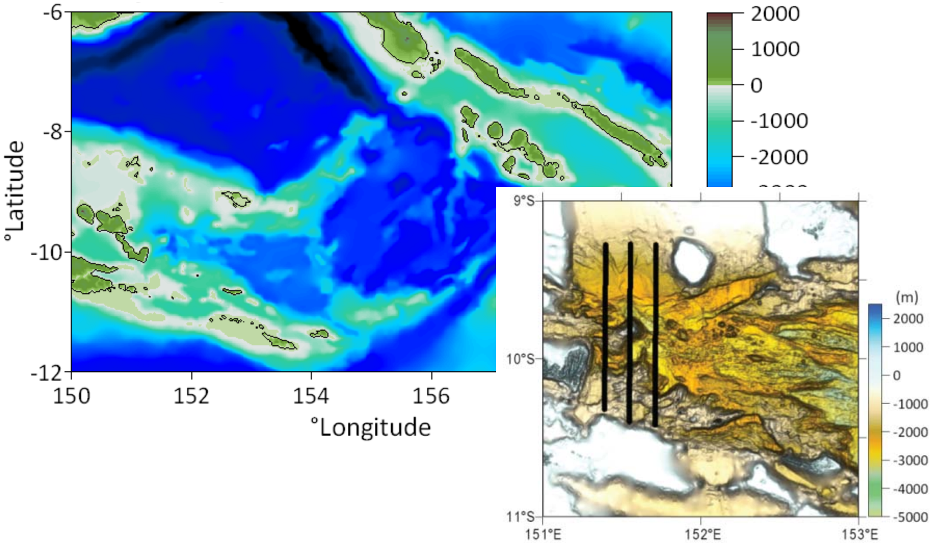


Data – Woodlark Basin

Map Data

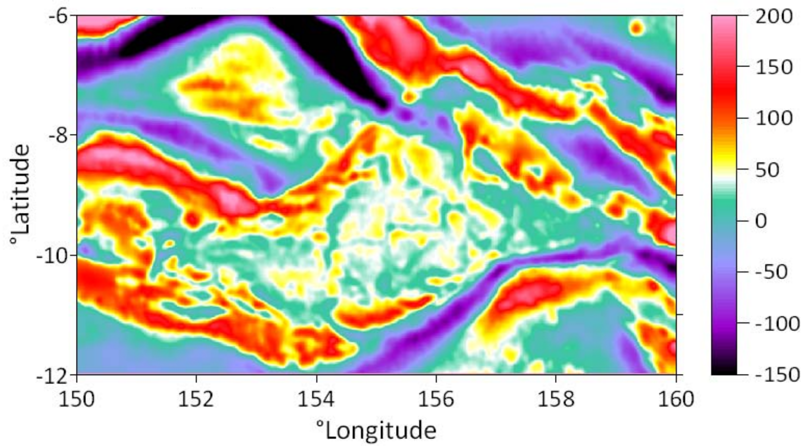
Bathymetry (m)

(Gebco 2003; Goodliffe & Taylor, 2007)



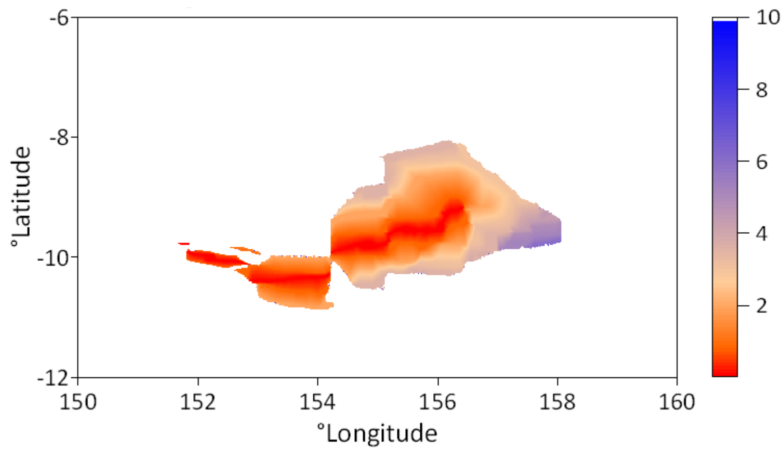
Free-air gravity (mgal)

(Smith & Sandwell 1997)

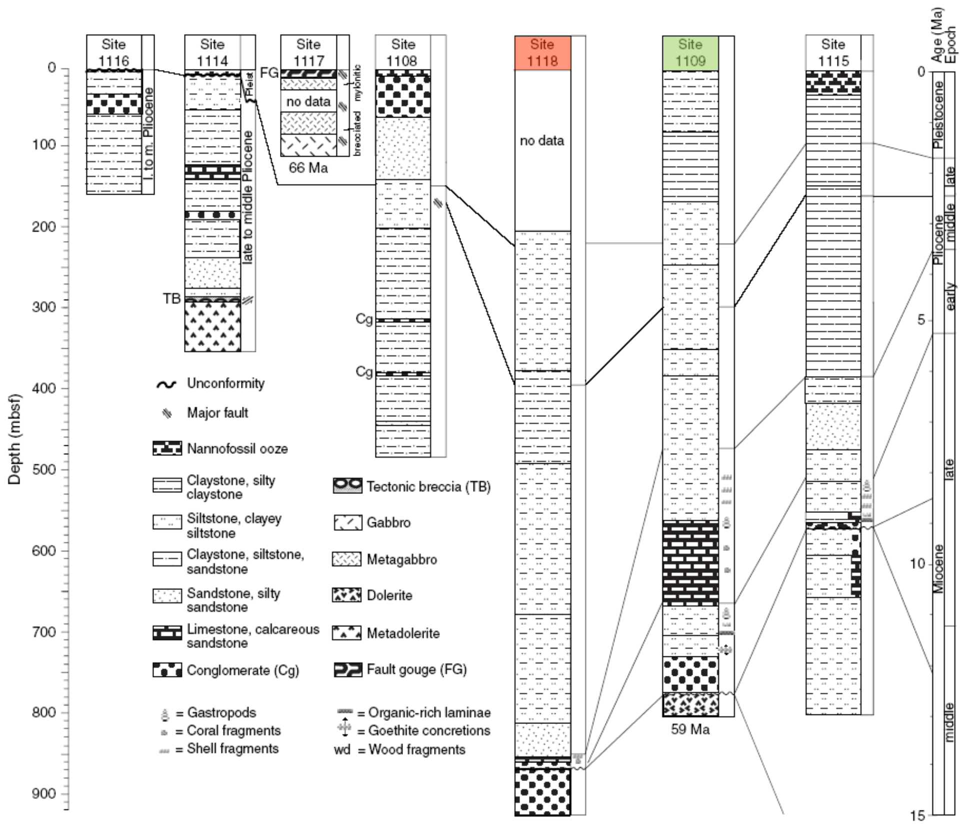


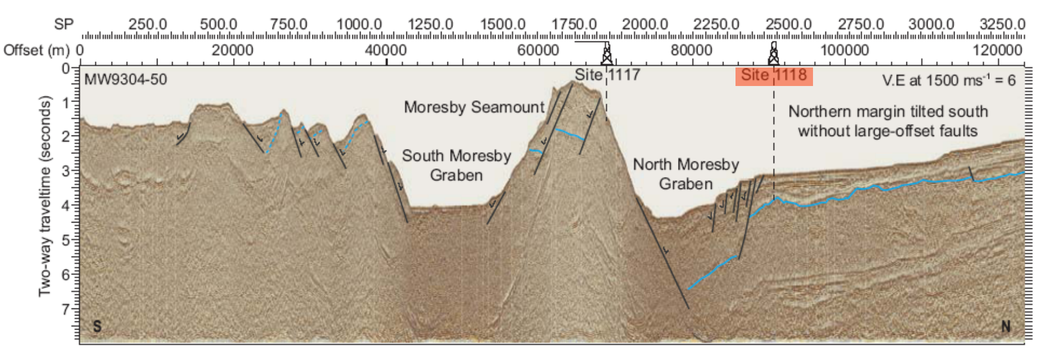
Ocean age isochrons (Ma)

(Goodliffe 1998)



Data – Woodlark Basin

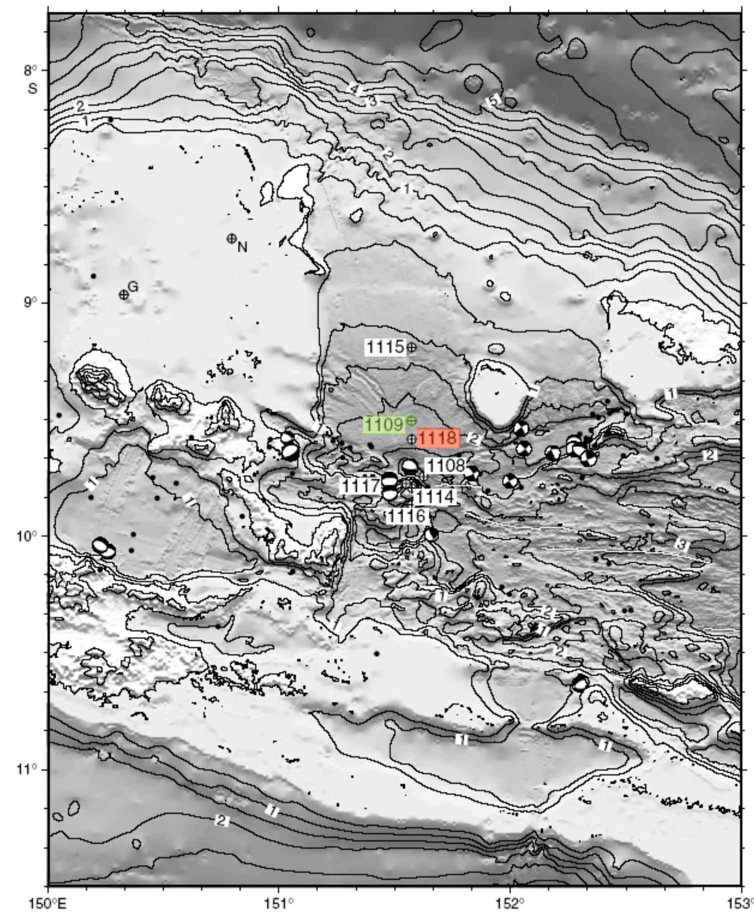




Well Data

(Taylor & Huchon 2001)

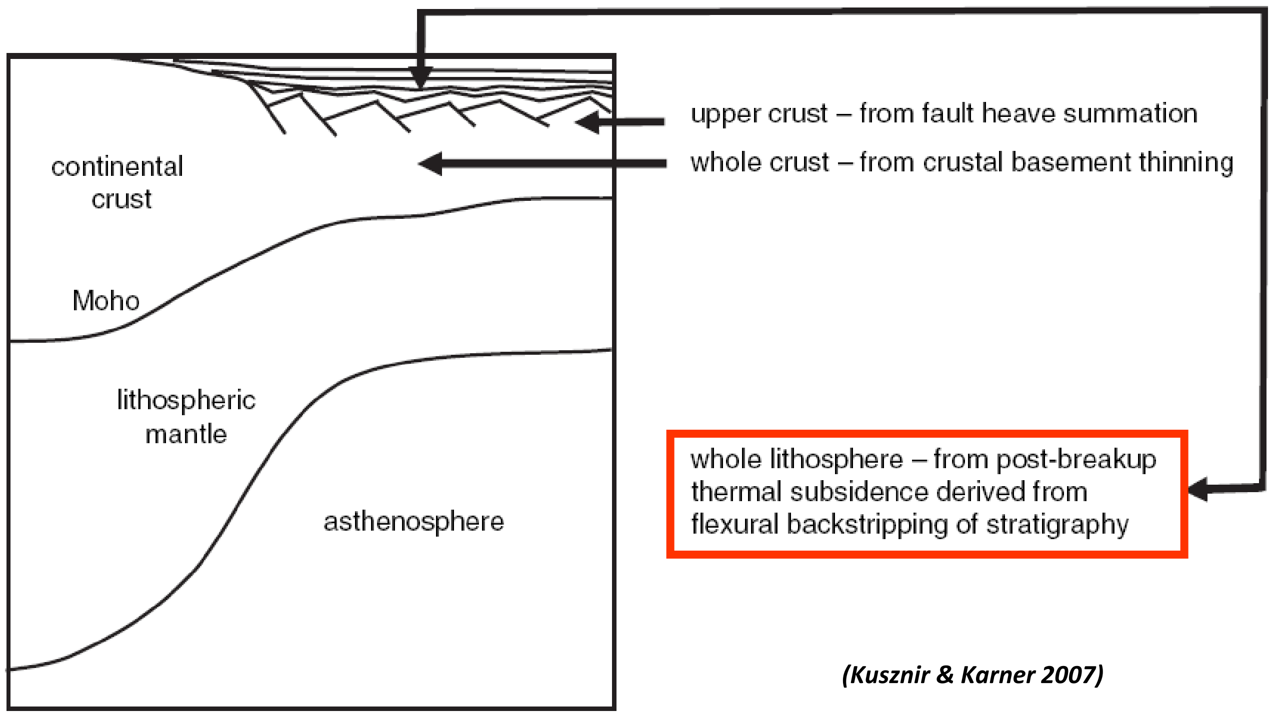
- Unconformity - 8.4Ma
- North Moresby Graben - wood deposits found above unconformity



Stretching & Thinning of Continental Lithosphere

Measure at 3 levels:

- Upper crust
- Whole crust
- Whole Lithosphere



(Kusznir & Karner 2007)

Stretching Factor

- β = Final length/Initial Length

Thinning Factor

- γ = 1-1/β

Stretching & Thinning of Continental Lithosphere

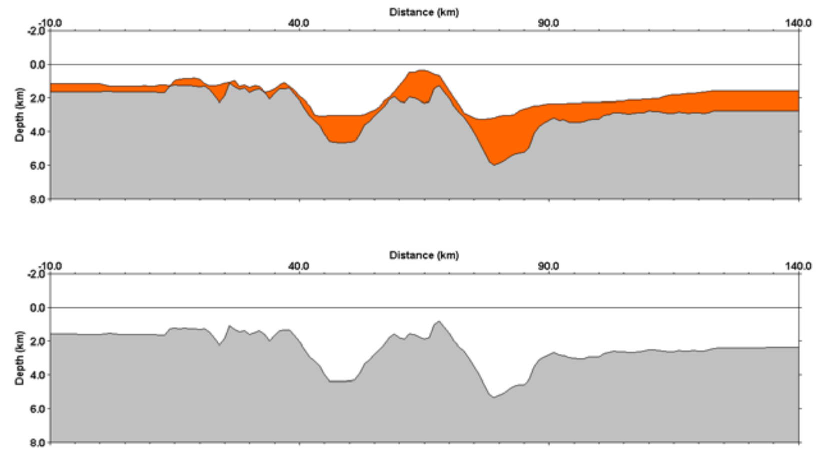
Methodology

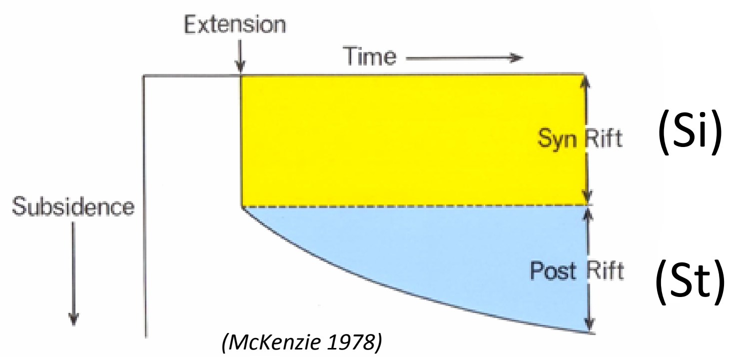
•Determine waterloaded subsidence from Flexural backstripping

•Peralic coals observed at the base of syn-rift indicate zero bathymetry at 0Ma

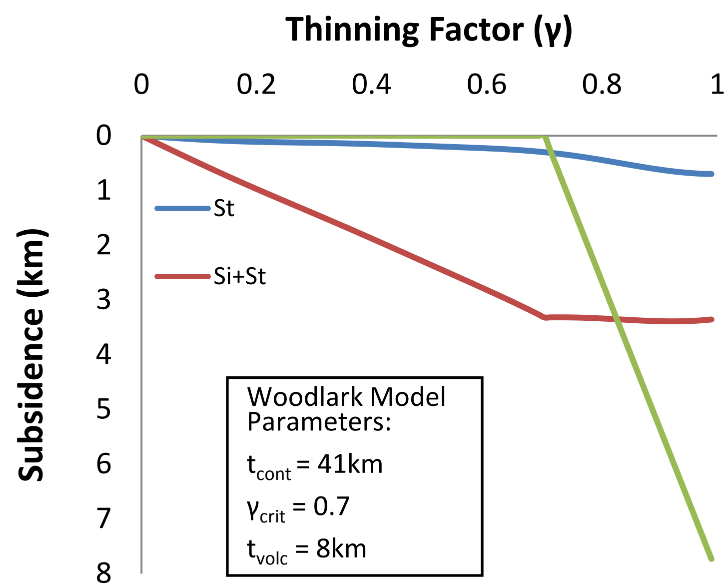
•Flexurally backstripped bathymetry gives water loaded subsidence

•Water loaded subsidence used to predict lithosphere thinning factors using a 1D McKenzie extension model incorporating volcanic addition

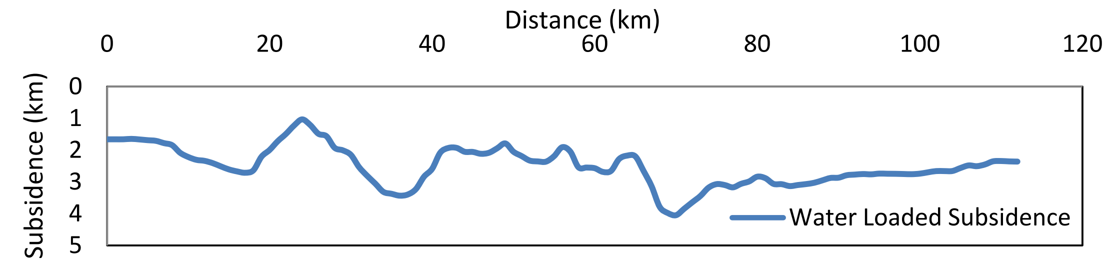


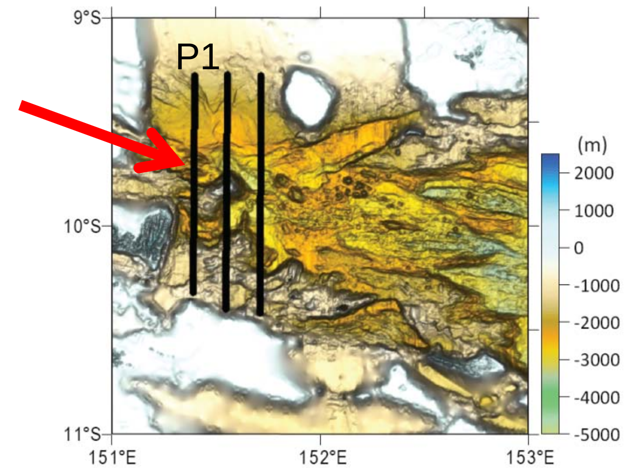


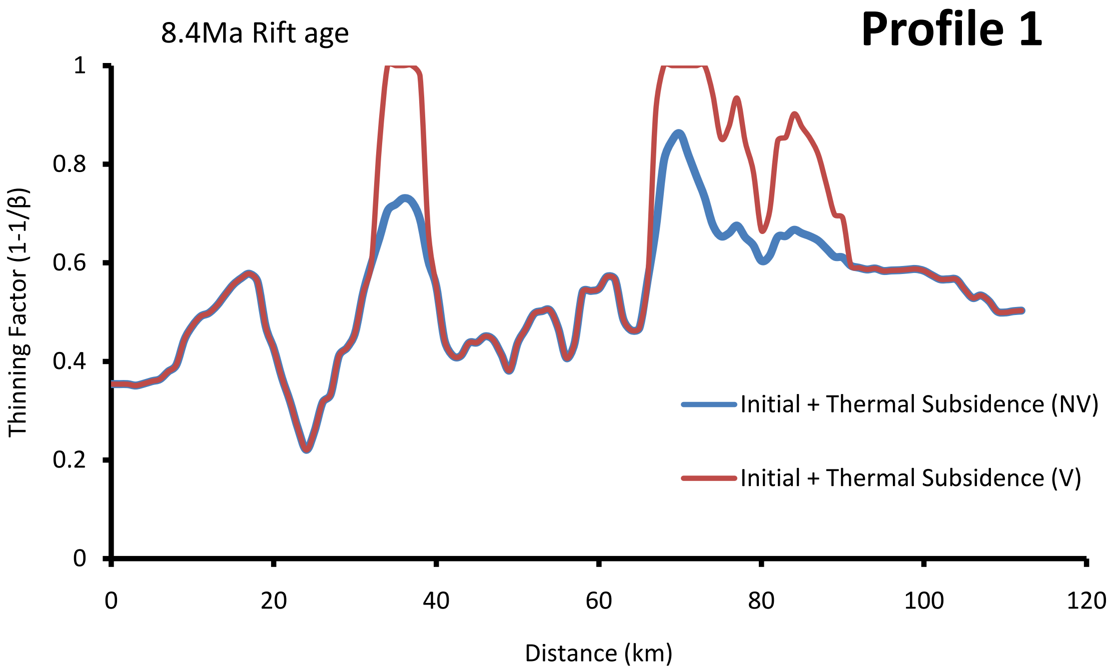
Syn-rift and Post-rift subsidence history
from McKenzie pure shear model



Stretching & Thinning of Continental Lithosphere

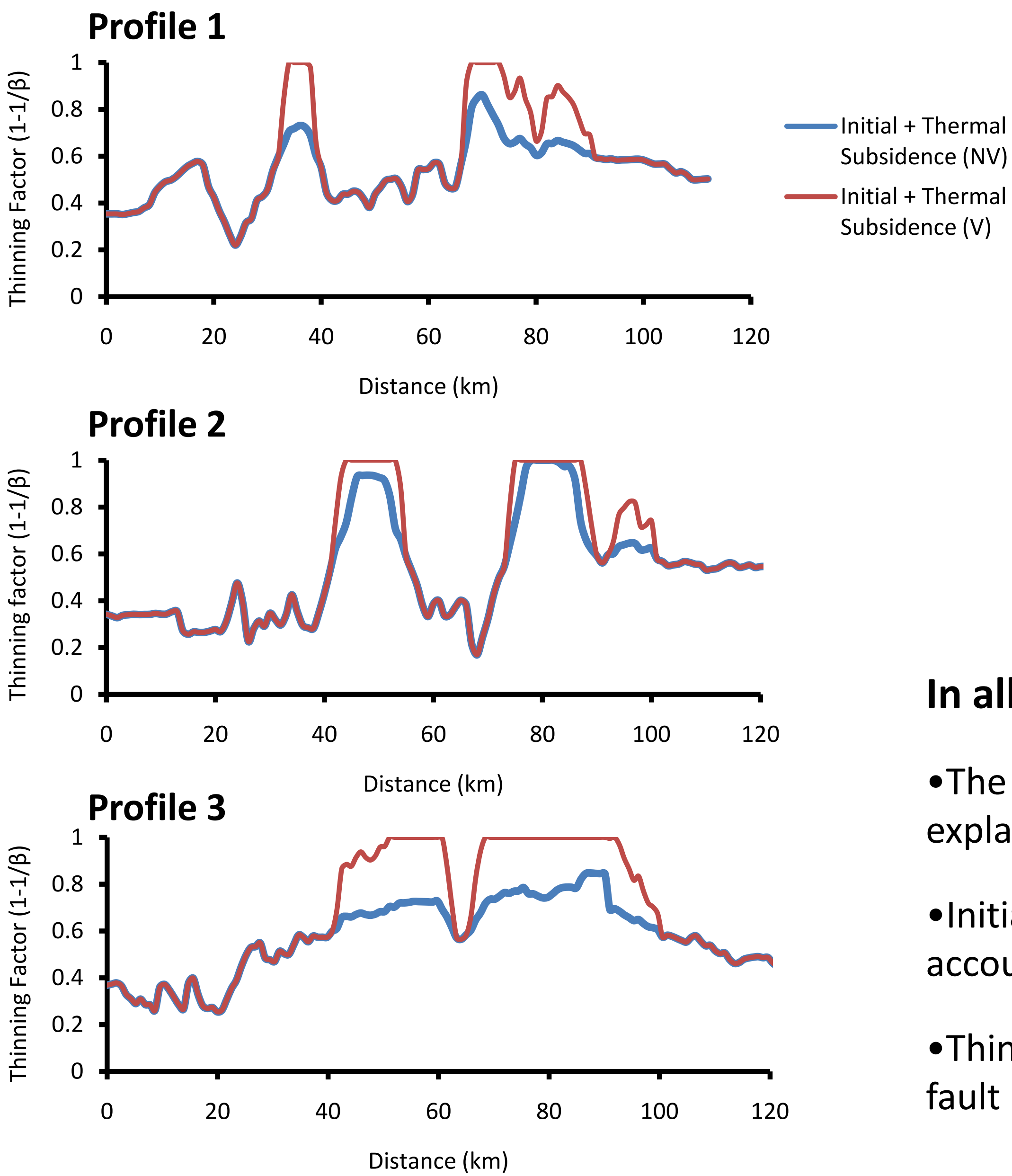


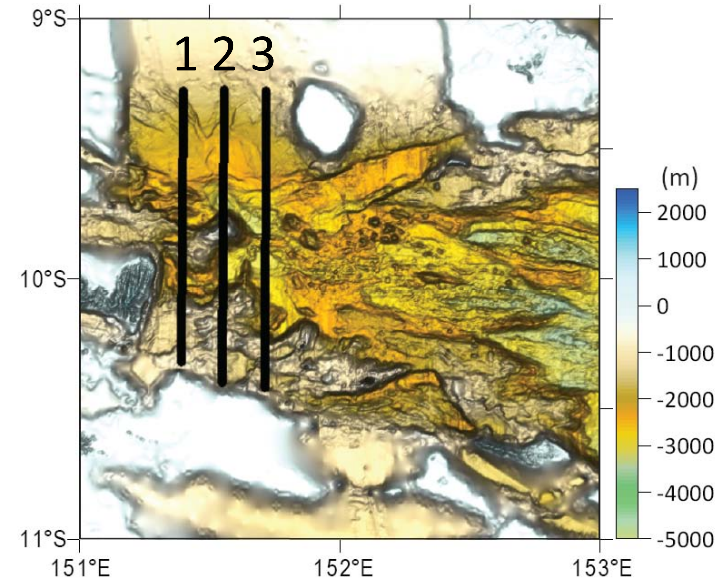




- Water loaded subsidence cannot be explained by thermal subsidence alone
- Need crustal thinning + thermal subsidence

Stretching & Thinning of Continental Lithosphere





In all 3 profiles:

- The water loaded subsidence cannot be explained by thermal subsidence alone
- Initial plus thermal subsidence is needed to account for the water loaded subsidence
- Thinning factor spikes are an artifact of fault bounded topography

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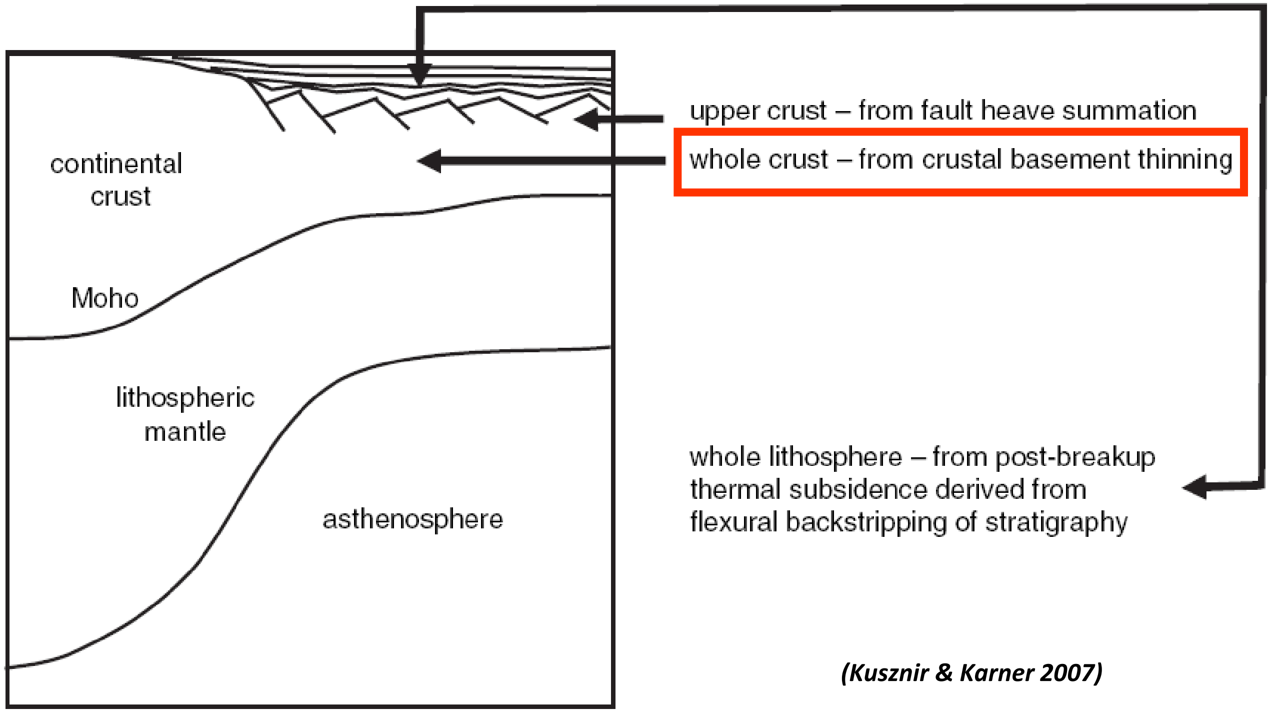
Stretching & Thinning of Continental Lithosphere

Measure at 3 levels:

- Upper crust
- Whole crust
- Whole Lithosphere



(Kusznir & Karner 2007)

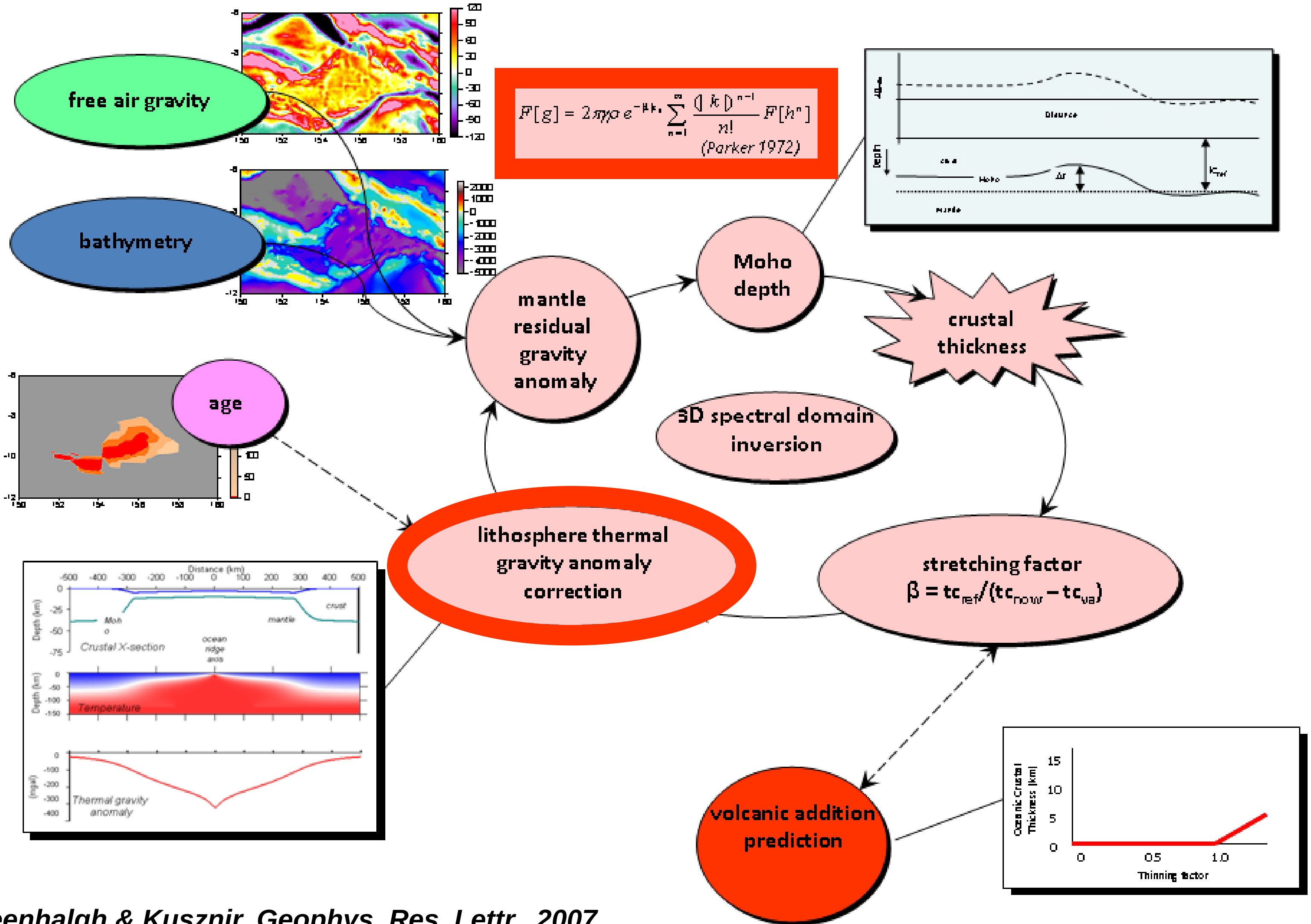
Stretching Factor

- β = Final length/Initial Length

Thinning Factor

- γ = 1-1/β

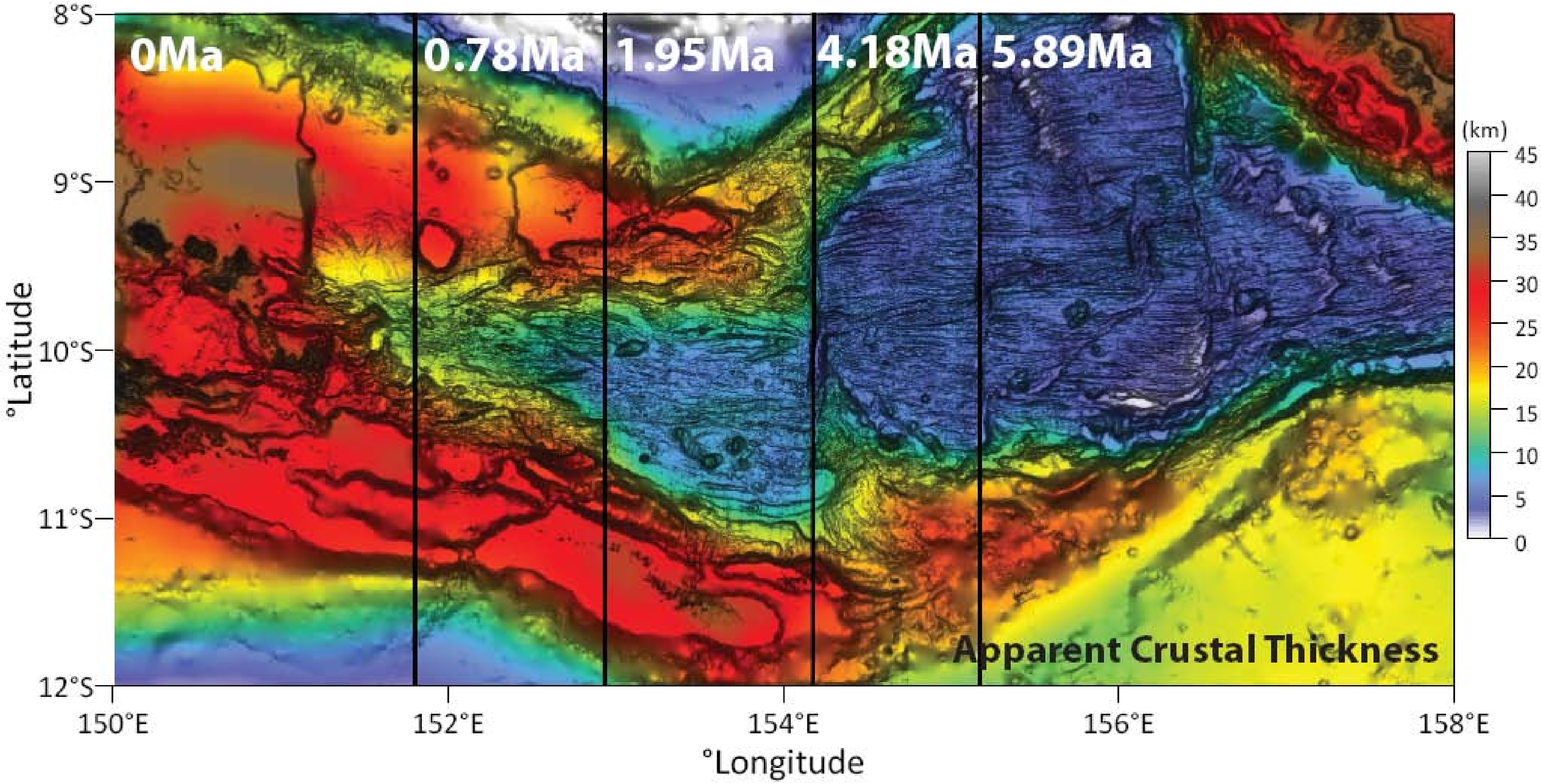
Crustal Thickness, Thinning Factors & OCT Location from Gravity Inversion



Greenhalgh & Kusznir, Geophys. Res. Lettr., 2007
Chappell & Kusznir, Geophys. J. Int., 2008
Alvey, Gaina, Kusznir & Torsvik, EPSL, 2008

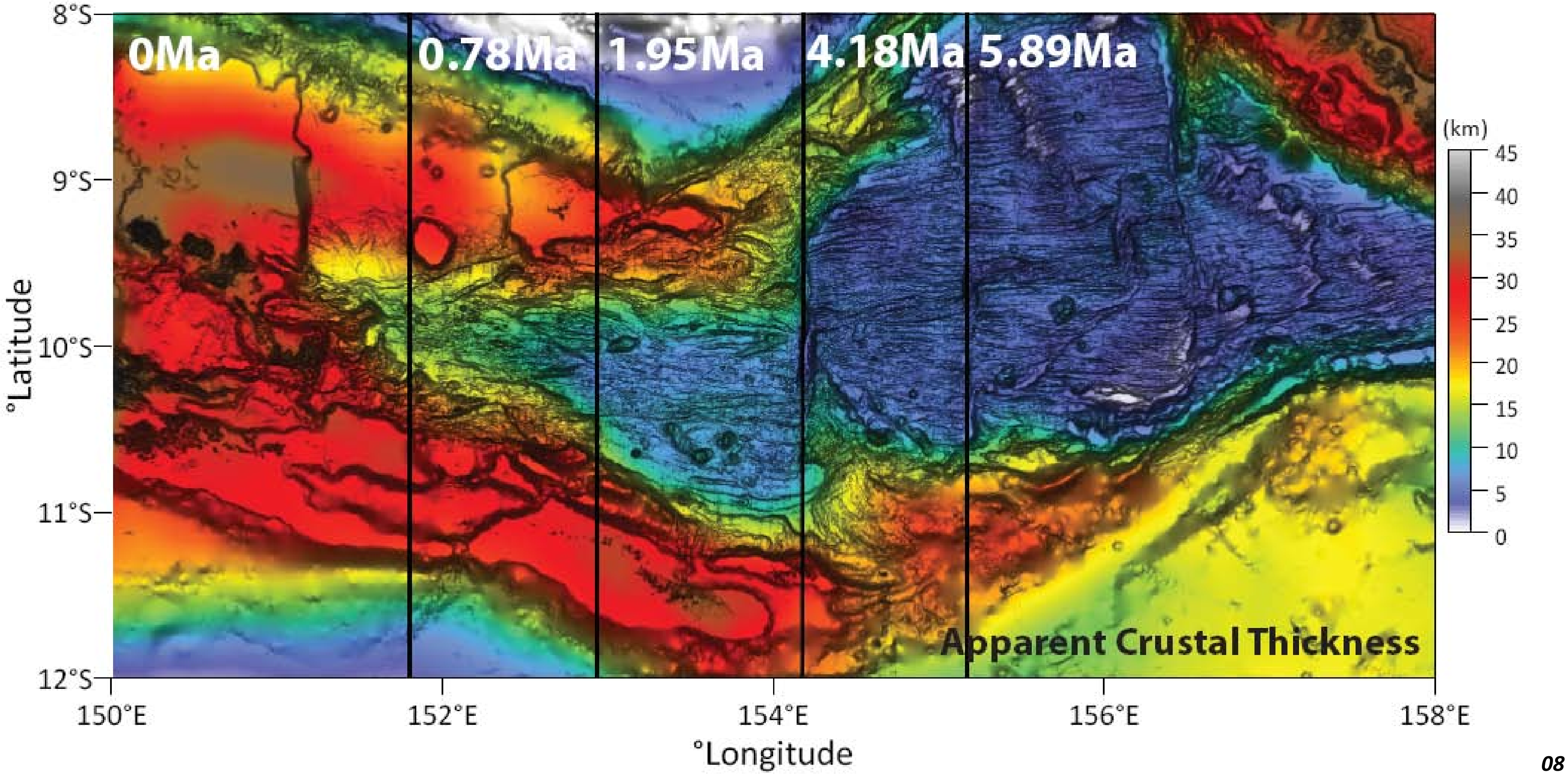
Crustal Thickness from Gravity Inversion

- Crustal reference thickness = 41 km
- Calibrated against Moho depth estimates from seismology & isostasy (Zelt *et al*. 2001, Martinez *et al*. 1999)
- No sediments
- Low pass Butterworth filter (100km)



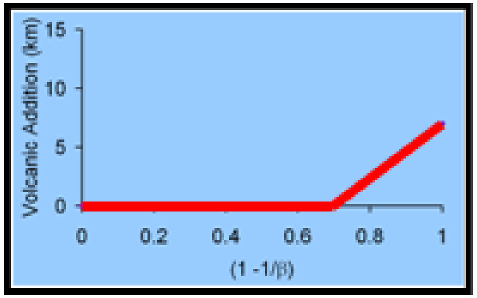
Crustal Thickness from Gravity Inversion

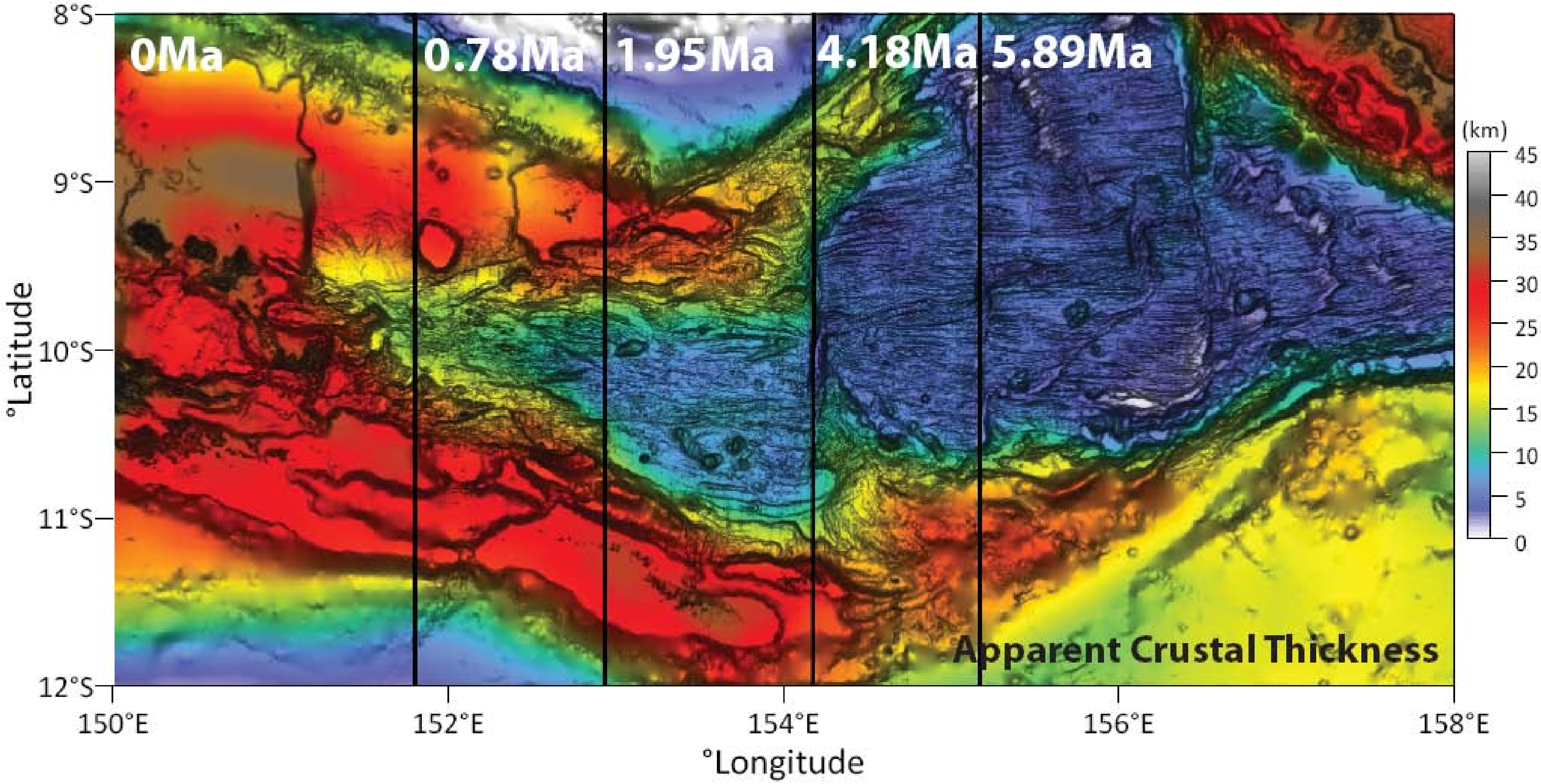
- Gravity inversion requires breakup age
- Sea-floor spreading is propagating westwards
- Breakup age migration deduced from magnetic anomalies
- Ocean isochrons 60% of breakup age only used
- Provides isochron independent OCT location



Crustal Thickness from Gravity Inversion

- “Normal” volcanic addition
    - γ_{crit} = 0.7
    - ct_{ocean} = 8 km





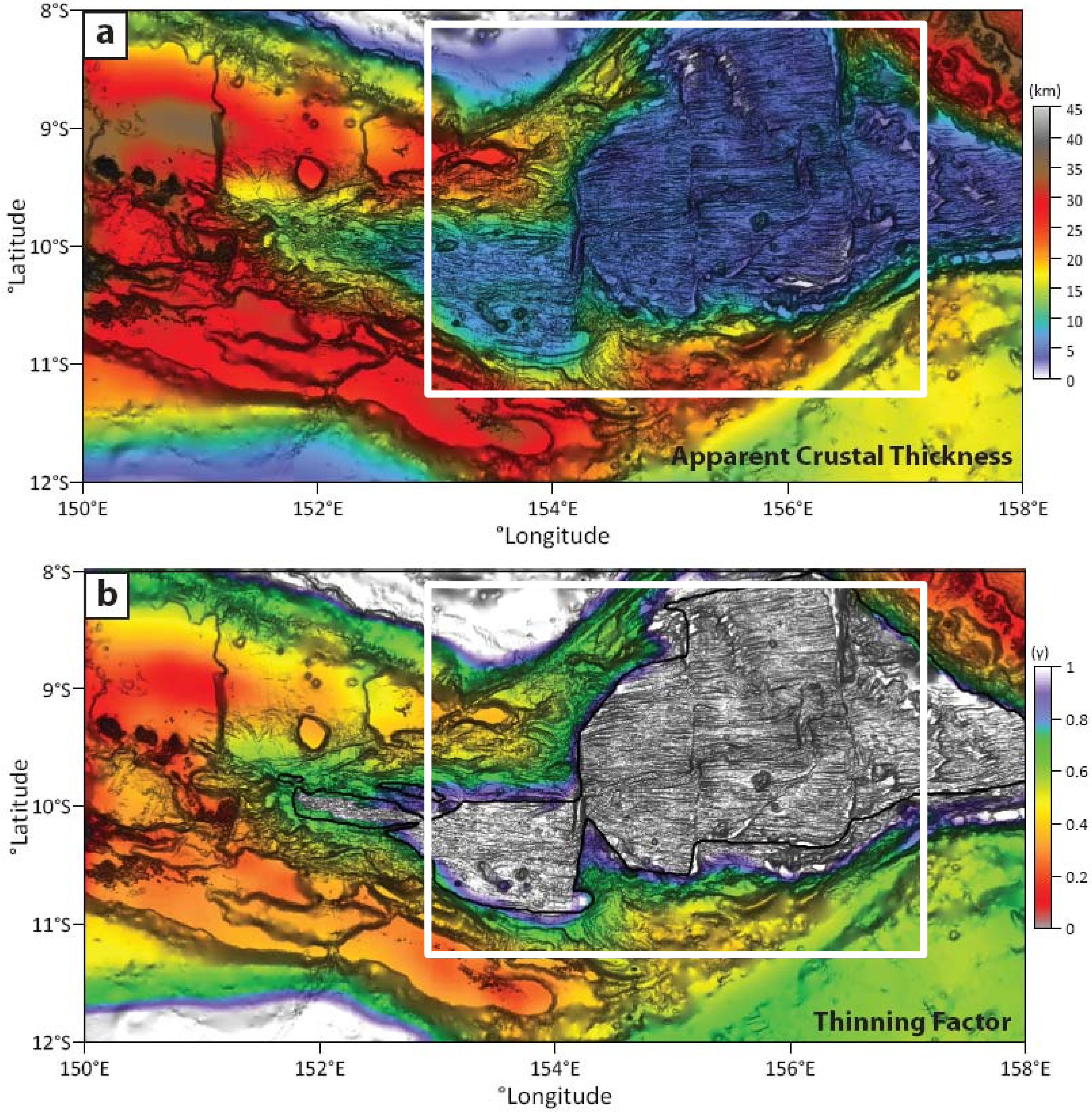
Woodlark Basin - Crustal Thickness from Gravity Inversion

- Eastern basin has characteristics of a normal volcanic addition breakup: ~ 6 km thick oceanic crust

- Crustal thickness in Western Basin is ~ 7-8 km: slightly thicker than in east.

- At propagating tip East of Moresby Seamount, crustal thicknesses of 8-14 km predicted.

- Is this thinned continental crust or oceanic crust?



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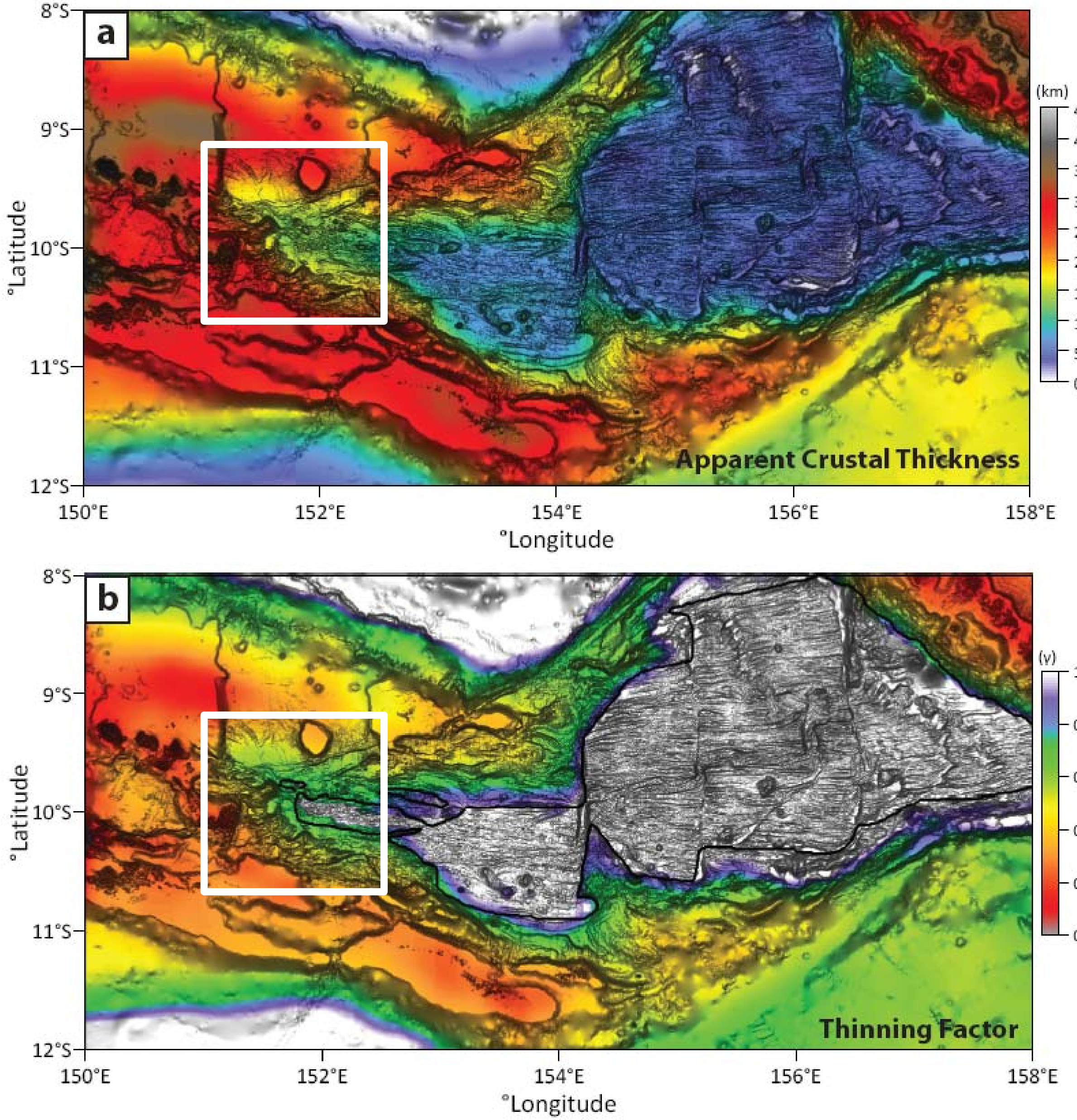
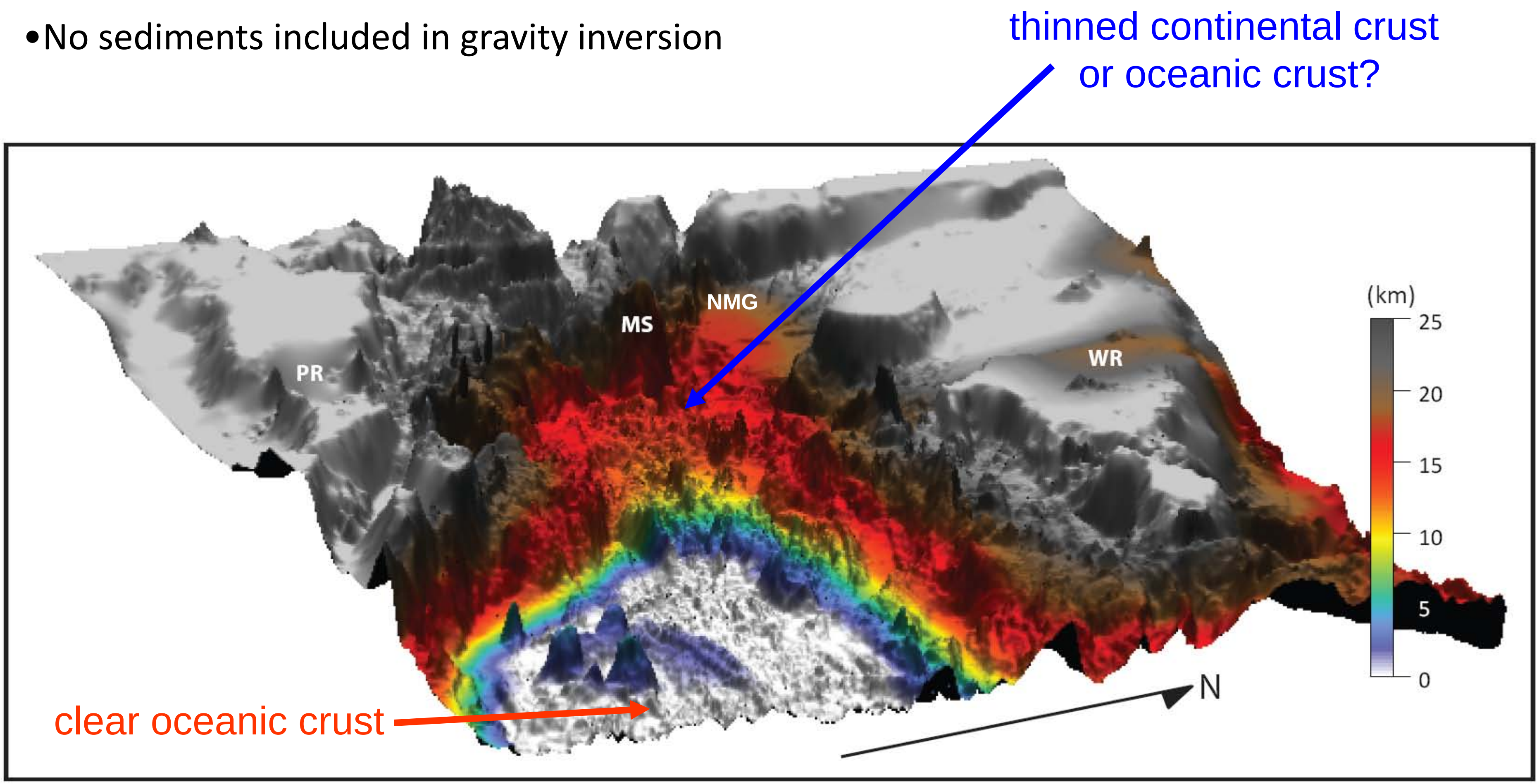


Woodlark Basin - Crustal Thickness from Gravity Inversion

Residual Thickness of Continental Crust

- Volcanic addition - γ_{crit} = 0.7, ct_{ocean} = 7 km
- No sediments included in gravity inversion



View of Western Basin looking towards Moresby Sea-mount

Woodlark Basin - Crustal Thickness from Gravity Inversion

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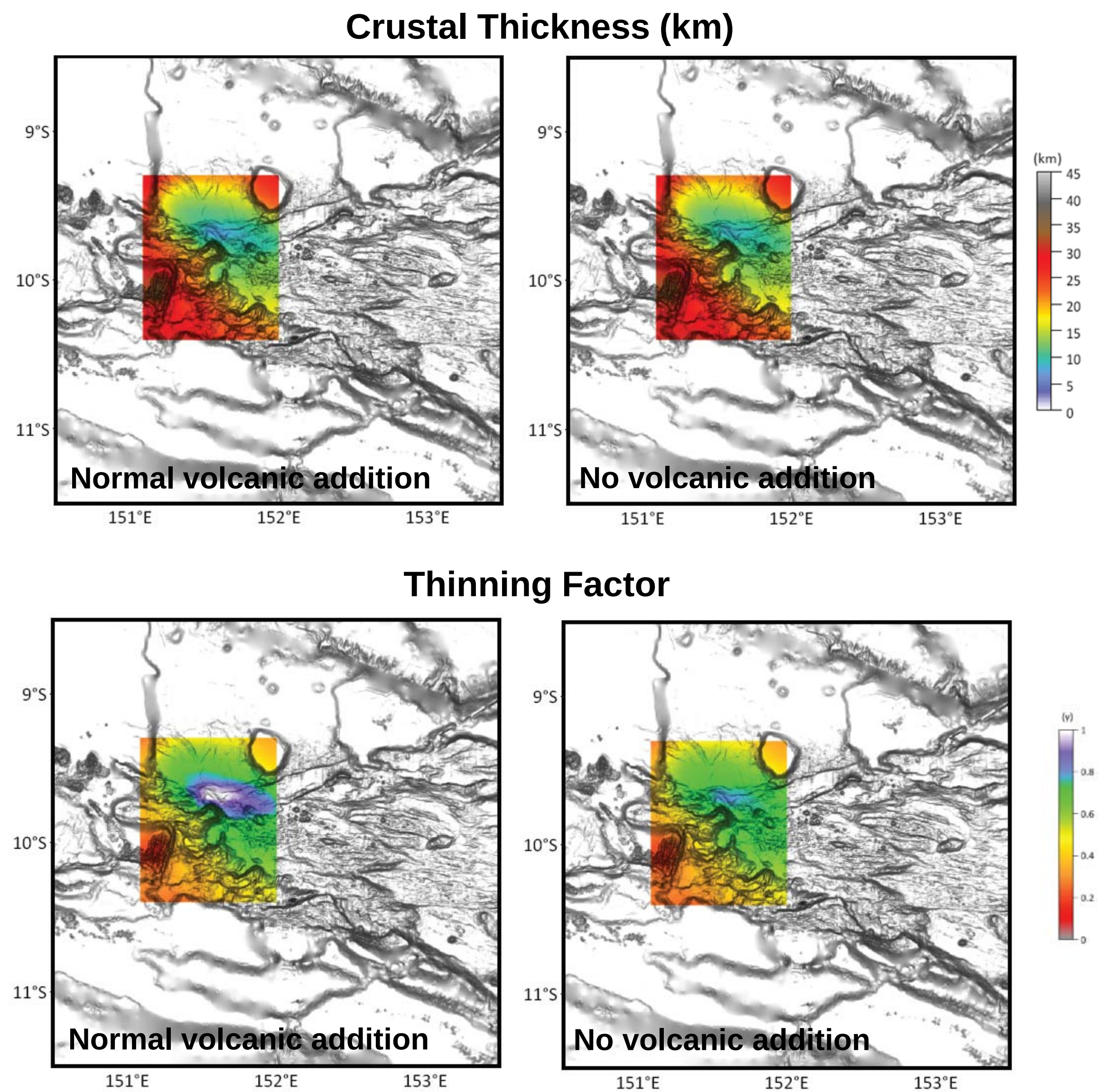
  ~ 6 km thick oceanic crust

- Crustal thickness in Western Basin is ~ 7-8 km: slightly thicker than in east.

- At propagating tip East of Moresby Seamount, crustal thicknesses of 8-14 km predicted.

- Is this thinned continental crust or oceanic crust?

- Include sediments



With Sediments from MCS

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Woodlark Basin - Crustal Thickness from Gravity Inversion

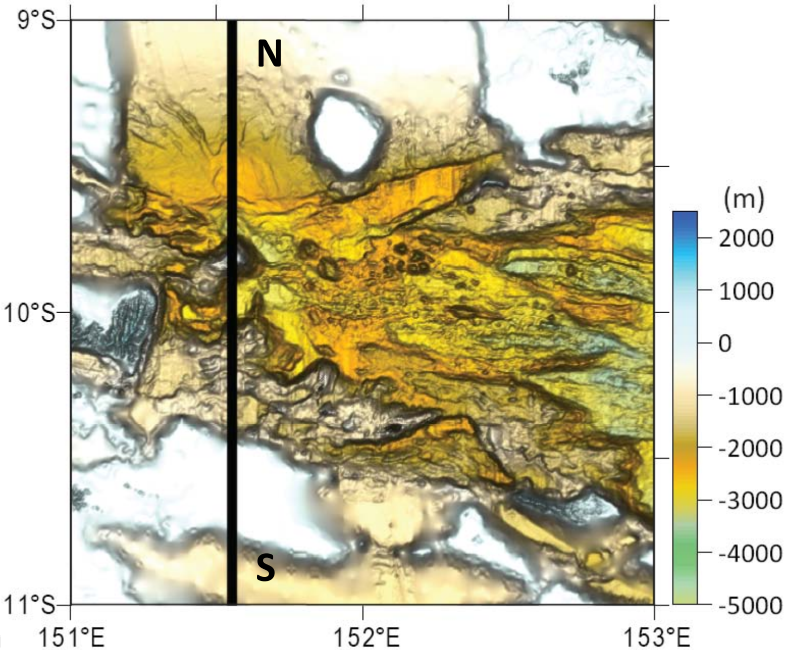
Cross Section - Moresby Seamount

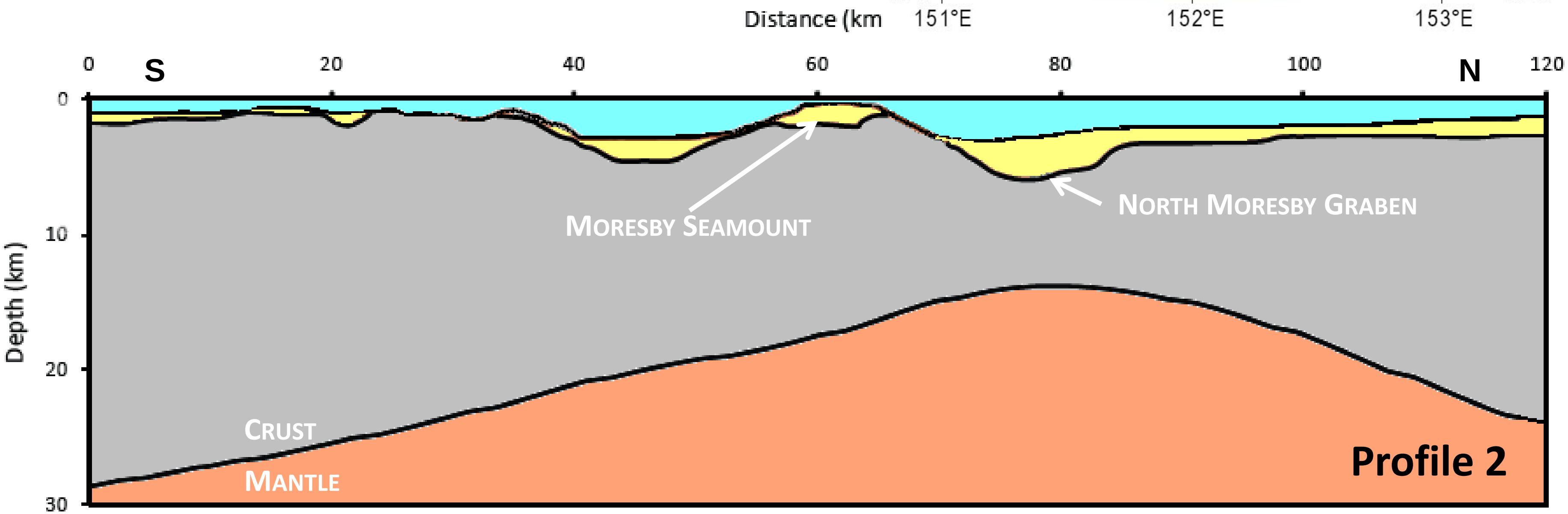
•Sediments from MCS included.

•Well data suggests if there is any volcanism in this area, then it is not reaching the surface.

•Gravity inversion assumes no volcanic addition.

•Thinning of continental crust is highest in the North Moresby Graben - possibly the propagating tip of seafloor spreading.





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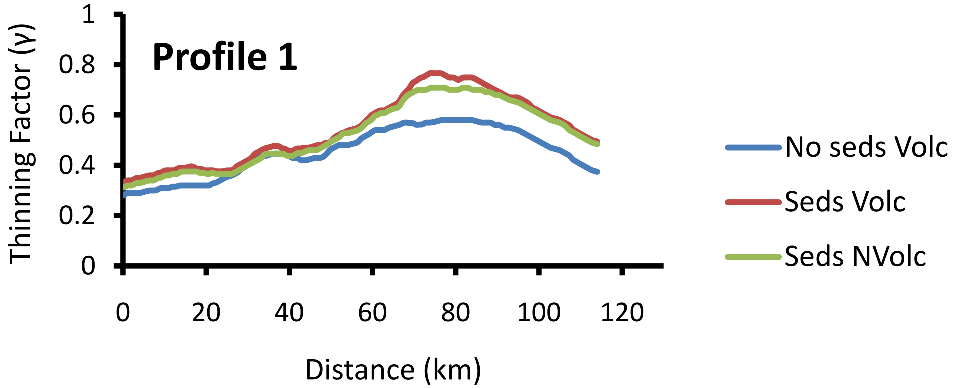
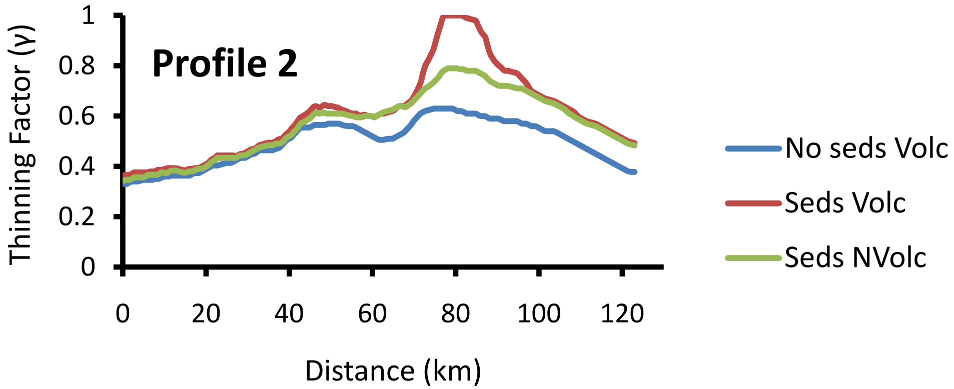
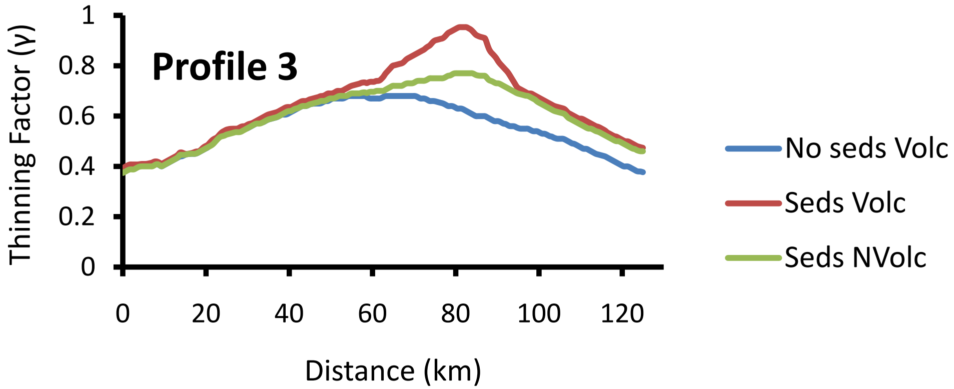
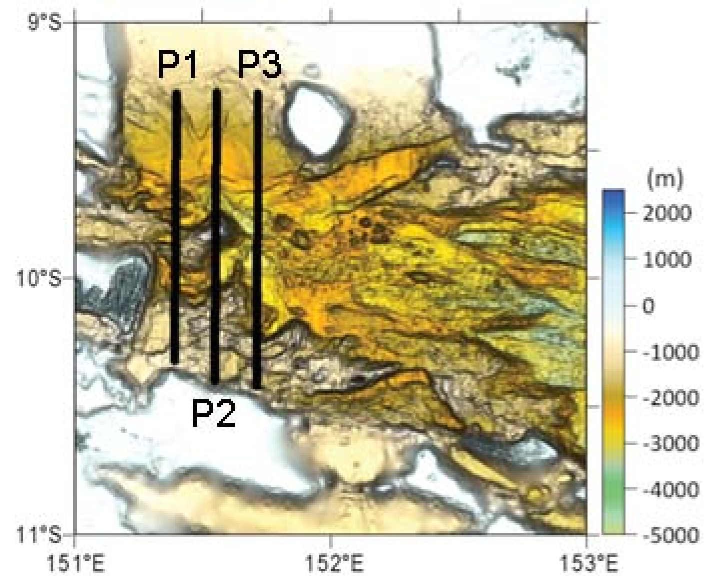
Woodlark Basin – Thinning factors from Gravity Inversion









- No volcanic addition preferred
- Max thinning factor = 0.7 - 0.8
- Thinning factor increases eastwards

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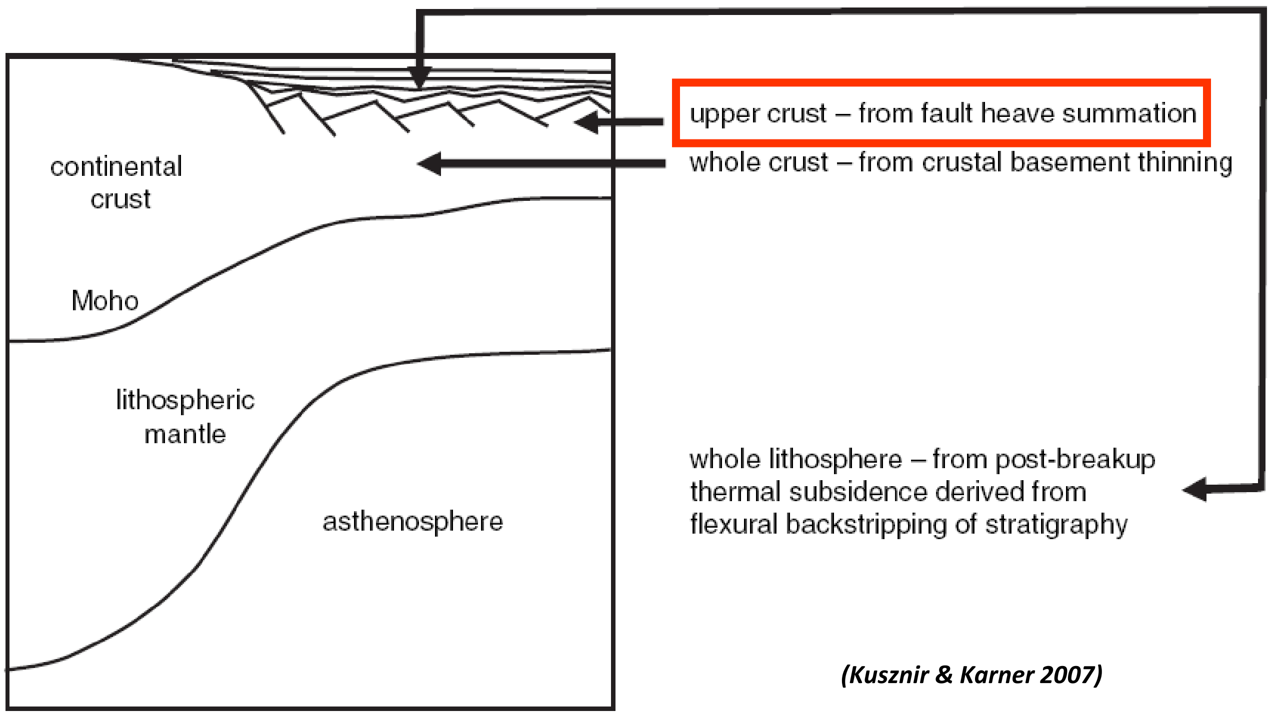
Stretching & Thinning of Continental Lithosphere

Measure at 3 levels:

- Upper crust
- Whole crust
- Whole Lithosphere



(Kusznir & Karner 2007)

Stretching Factor

- β = Final length/Initial Length

Thinning Factor

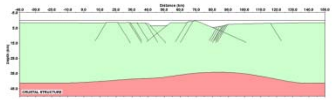
- $\gamma = 1-1/\beta$

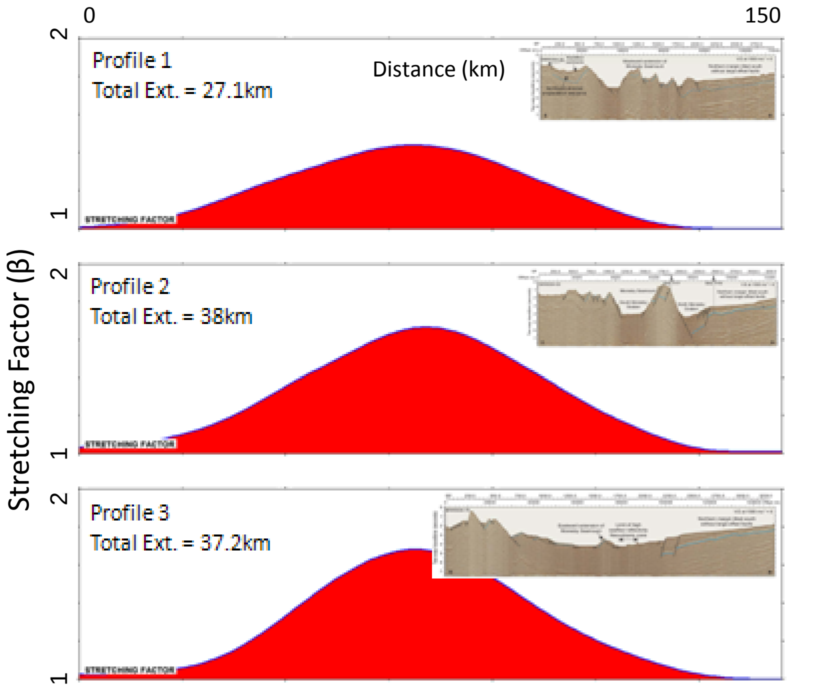
Stretching & Thinning of Upper Continental Crust

Use 2 techniques of determining upper crustal fault extension

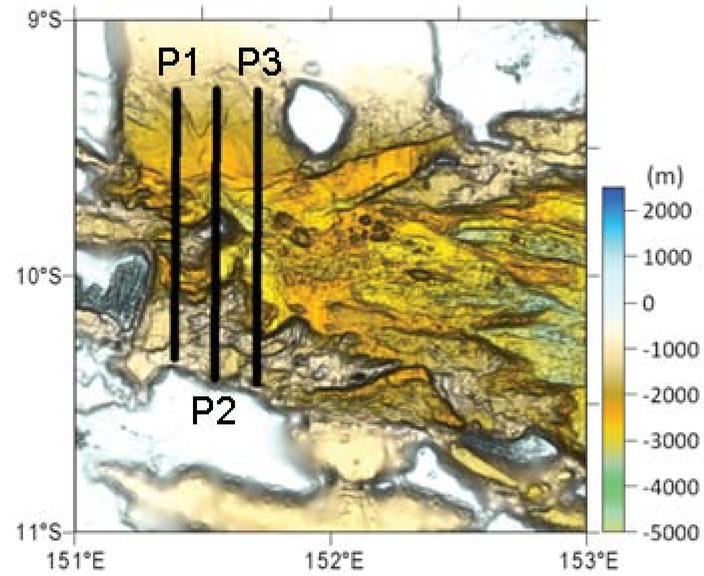
•fault heave summation

•forward syn-rift modelling





Seismic profiles from Goodliffe & Taylor 2006



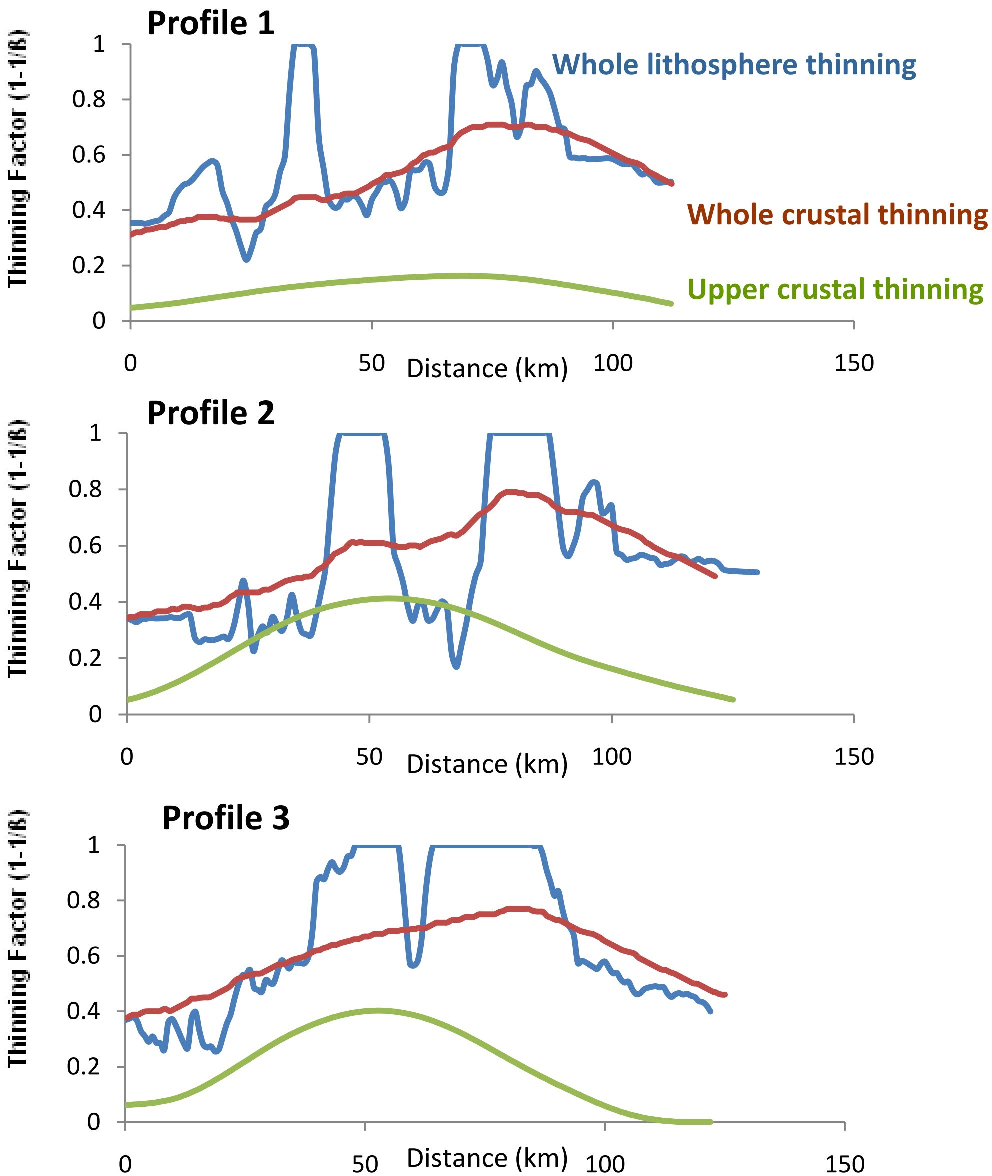
Profile Number	Extension from fault heave summation	Extension from forward modelling of fault systems
1	15.8km	27.1km
2	37.7km	38.0km
3	37.7km	37.2km

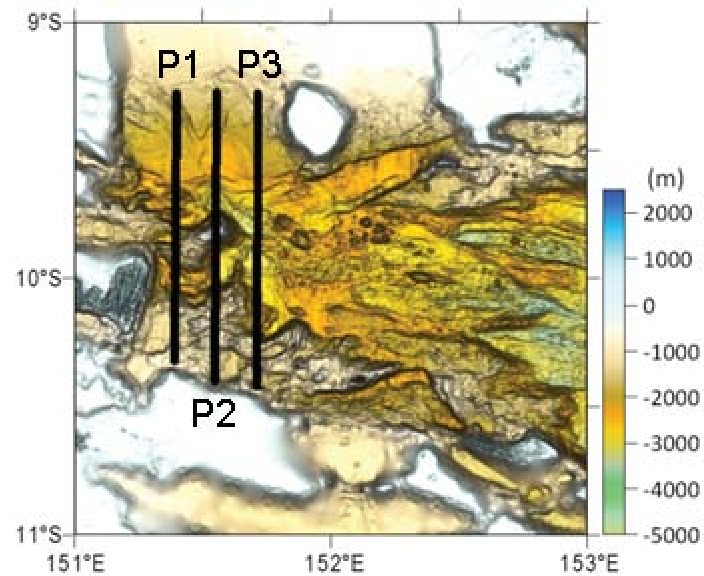
•Extension in the upper crust increases eastwards towards propagating tip of sea-floor spreading

•Estimates agree with Goodliffe & Kington.

Stretching & Thinning of Continental Lithosphere

Comparison of whole lithosphere, whole crustal and upper crustal thinning factors



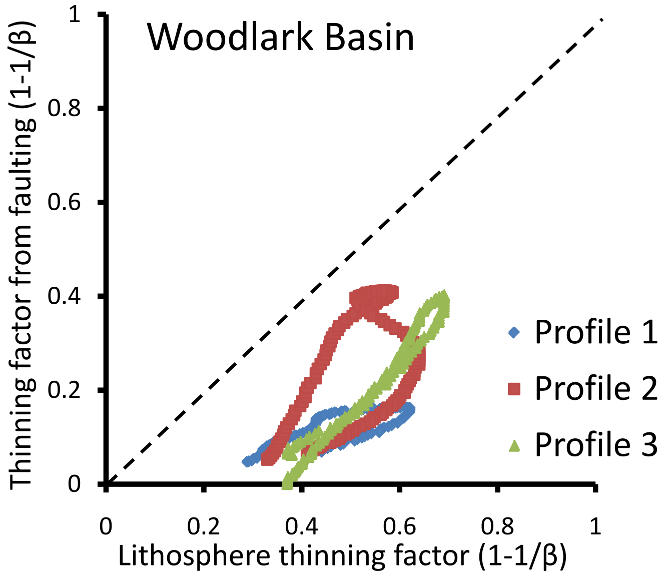


- Whole lithosphere and continental crustal thinning factors both exceed upper crustal thinning factors

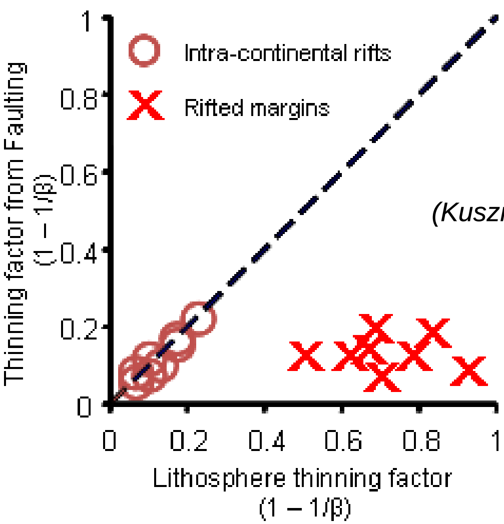
- Depth Dependent Lithosphere Stretching and Thinning

Depth Dependent Lithosphere Stretching & Thinning

- Propagating tip of Woodlark Basin



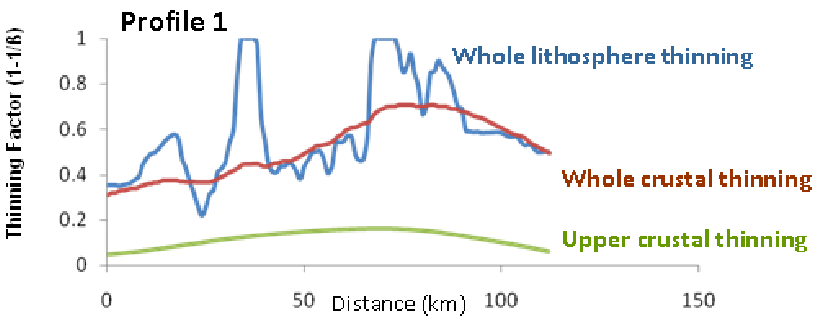
- Comparison with other rifted margins



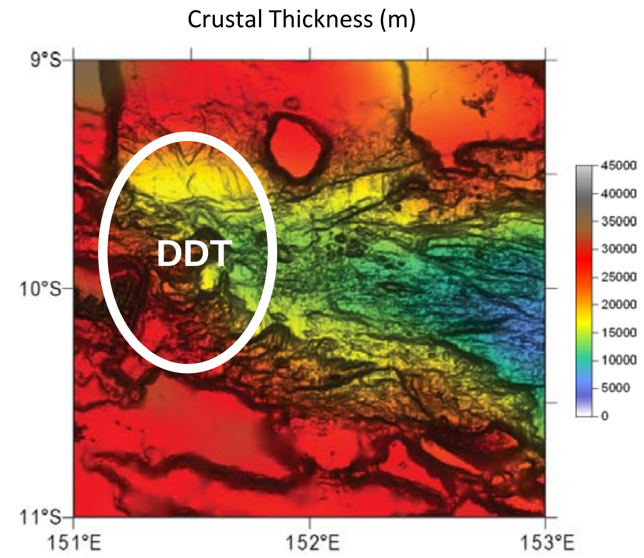
(Kusznir & Karner 2005)

Summary

- Thinning factors for the 3 profiles around the Moresby Seamount show depth dependent lithosphere thinning is occurring at the propagating tip of seafloor spreading



- Is the region east of the Moresby Seamount underlain by oceanic crust or thin continental crust?



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Collaborators – Alan Roberts, Robert Hooper, Garry Karner +

References

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