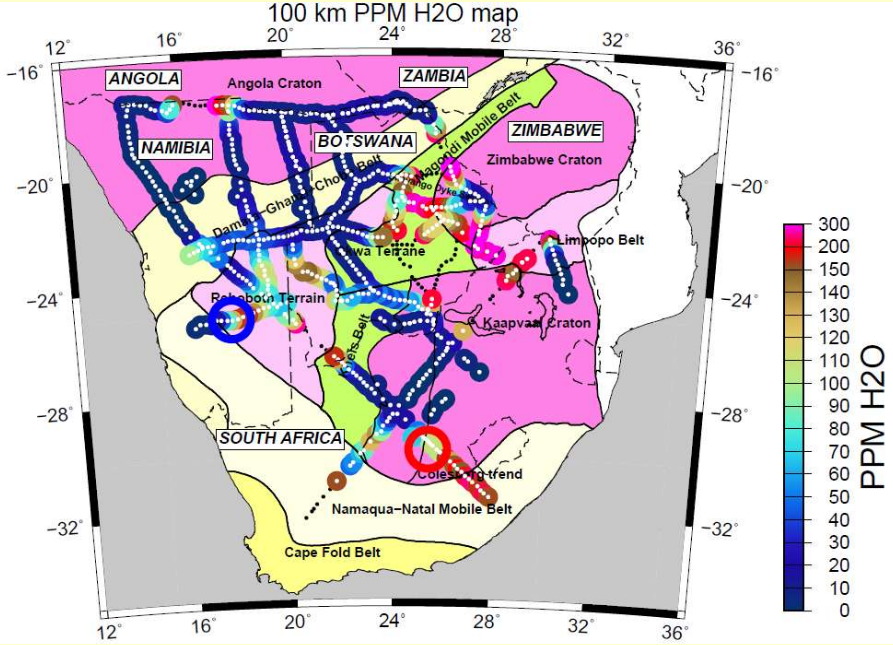
Insights into the Continental Lithosphere from Electromagnetic Studies combined with Other Geoscientific Data: A plea for embracing holistic modelling that satisfies all available data



Alan G. Jones (DIAS)

**With a huge amount of help from many, many colleagues, including:
The SAMTEX Team, all Canadian MT workers for the last 30 years, Stewart Fishwick, Juan Carlos Afonso, Javier Fullea, Jan Vozar, Sergei Lebedev**

**Presented at Workshop on "Structure and Dynamics of the Lithosphere/Asthenosphere System",
College de France, Paris, 19-20 November, 2013**

COLLÈGE DE FRANCE
1530
Teaching research in the making

Take-home message

We must STOP looking only at one type of data!!!

A change in velocity or electrical conductivity or thermal conductivity or density has effects on most of the others

Undertake modelling of your data taking into account the constraints from other data in a quantitative formal manner

We have far more data than we use – for example topography, geoid, heat flow is available almost everywhere

Also, check your data – if it seems unreasonable, there is probably something wrong with your data or your interpretation!

Example from Ireland


Available online at www.sciencedirect.com

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Earth and Planetary Science Letters 255 (2007) 32–40

EPSL

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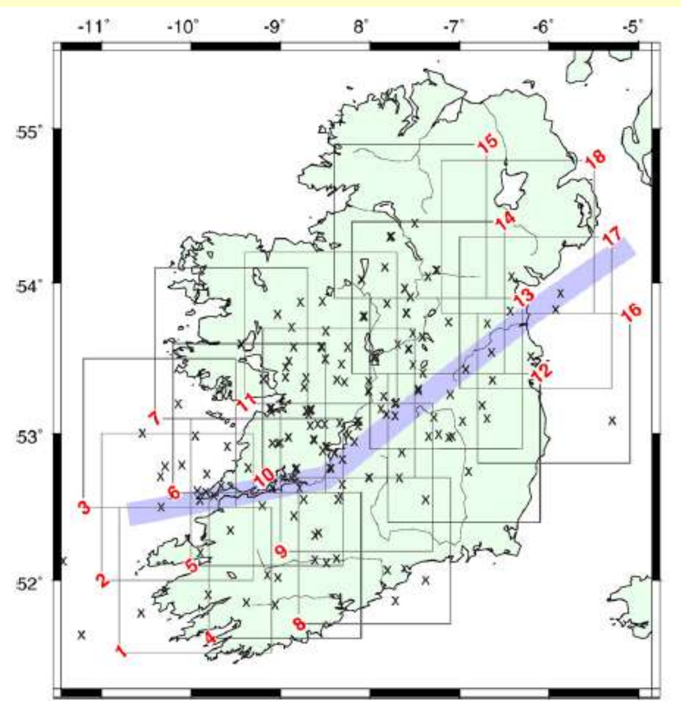
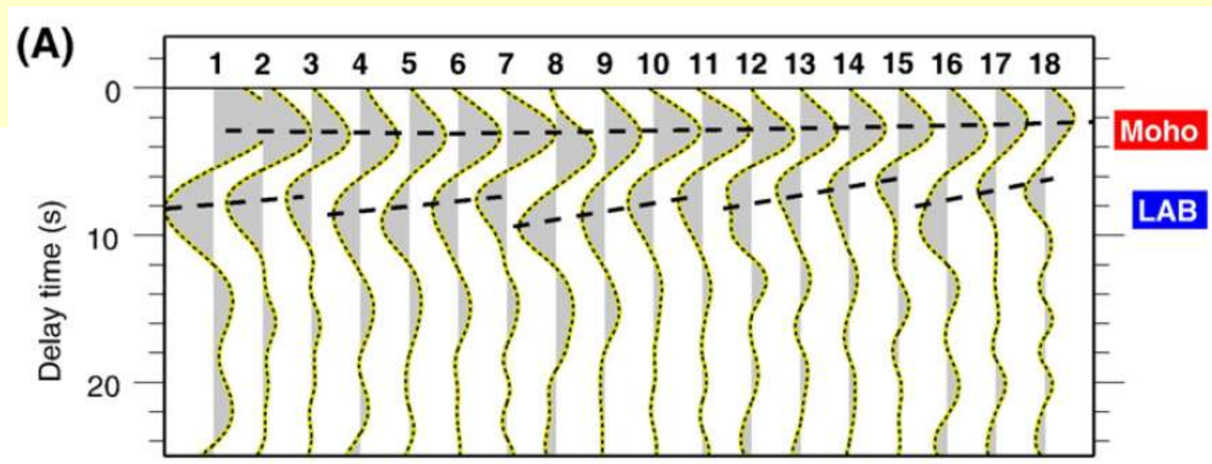
Proto-Iceland plume caused thinning of Irish lithosphere

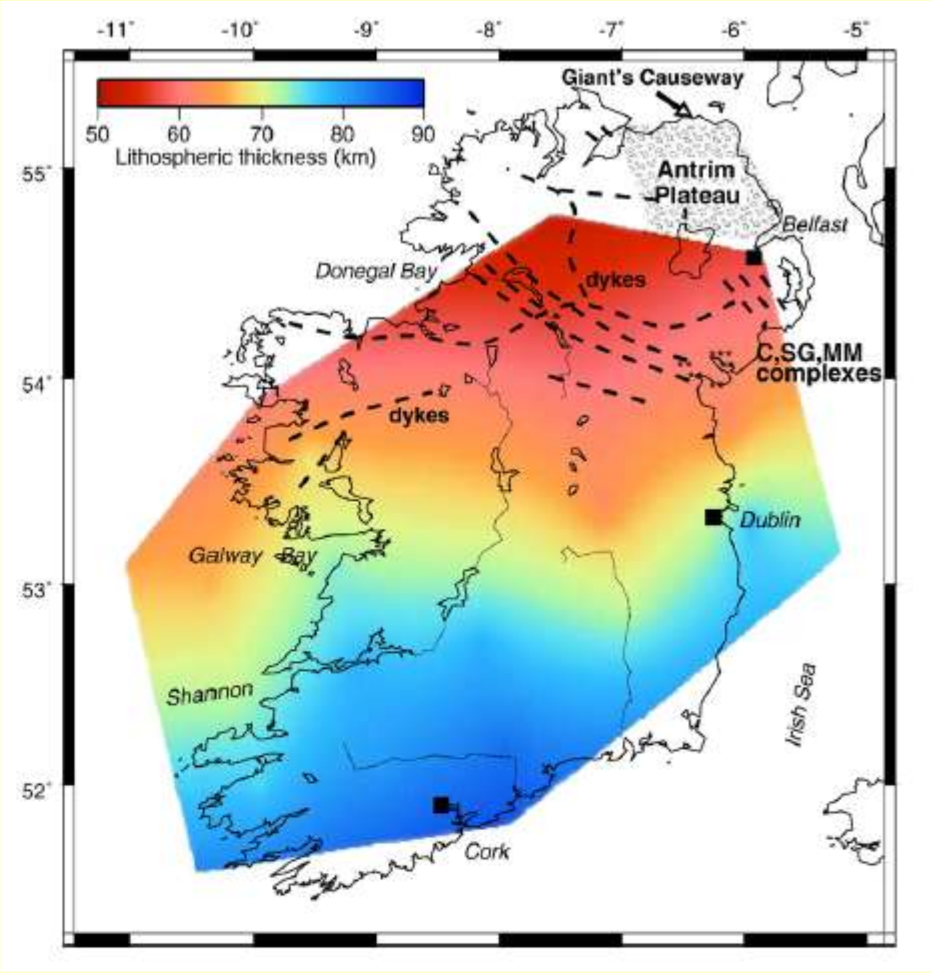
Michael Landes [a,*], J.R.R. Ritter [a], P.W. Readman [b]





S Receiver Functions from stations in Ireland going from SouthWest (1) to NorthEast (18)

Example from Ireland

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Proto-Iceland plume caused thinning of Irish lithosphere

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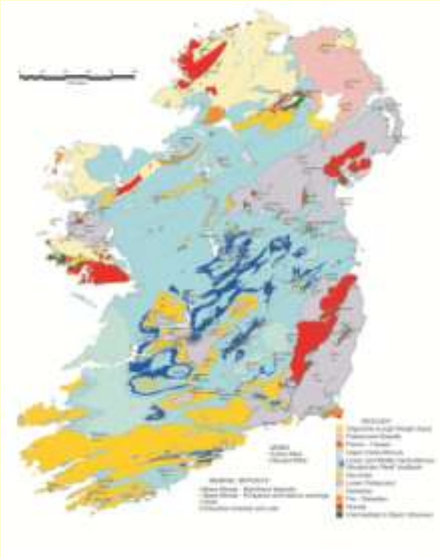
Observed SRF interface interpreted as the LAB (sLABrf)

Dramatic lithospheric thinning from 85 km to 55 km

Reasonable???

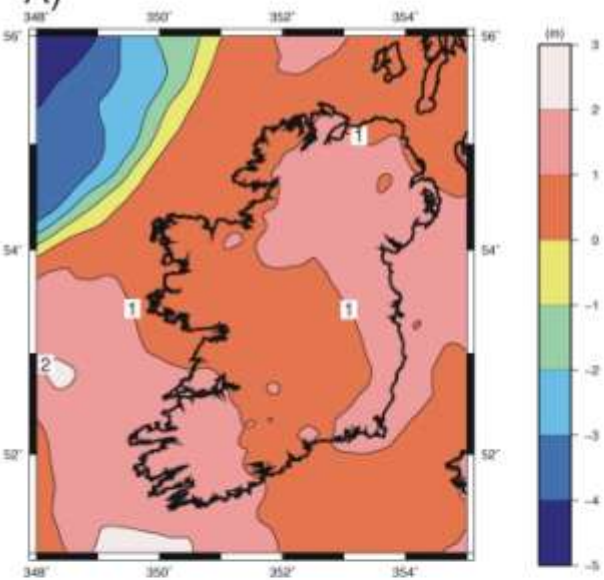
Other data: Heat flow, Topography, Gravity, Geoid, Moho (+MT)

Geophysical observables:

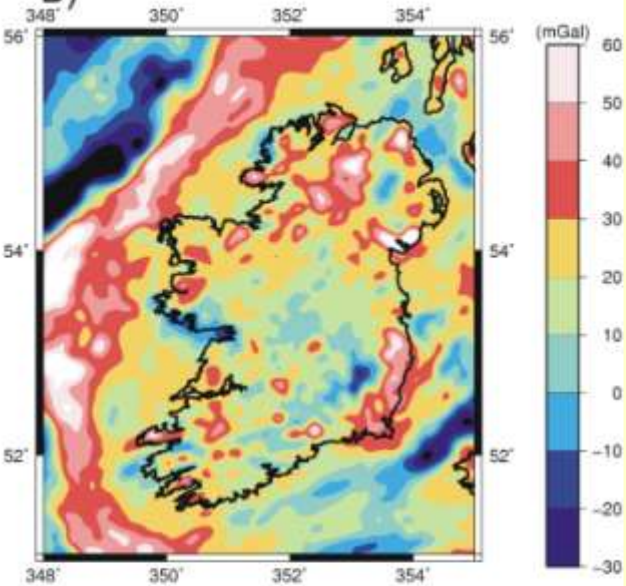


Geological map of of Ireland. (courtesy GSNI and GSI).

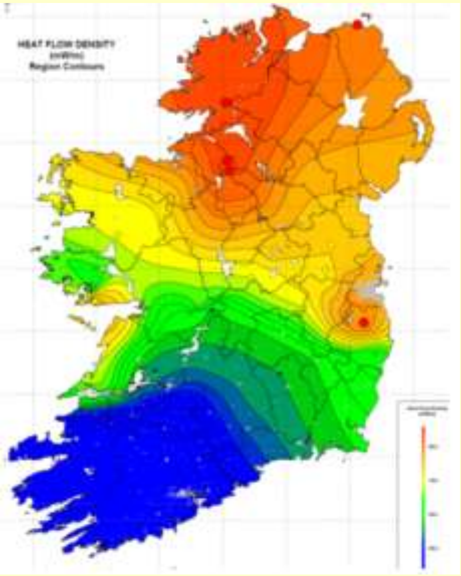
A) **Geoid anomaly (n>10) EGM 2008**



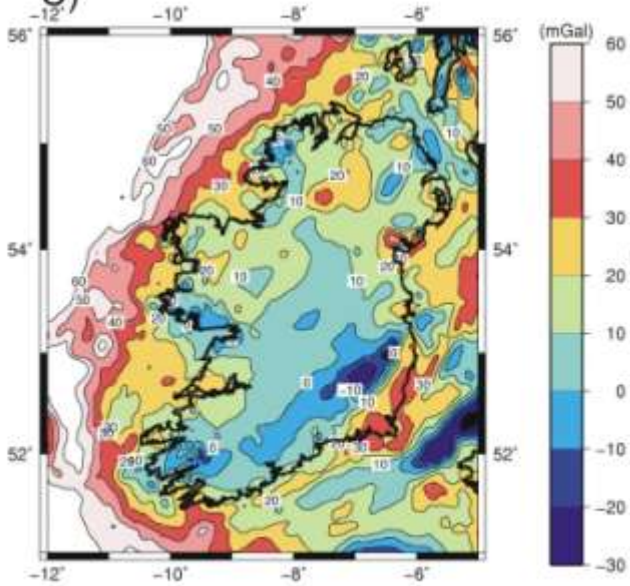
B) **FA anomaly (Smith & Sandwell 97)**



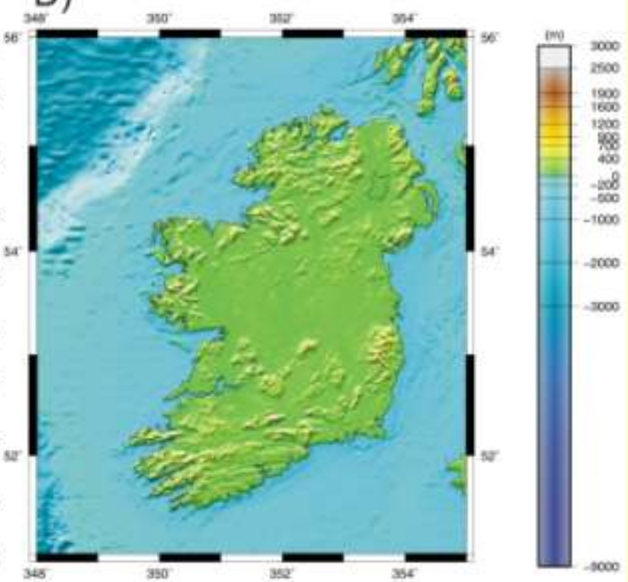
Heat Flow



C) **Bouguer anomaly (land + satellite data)**

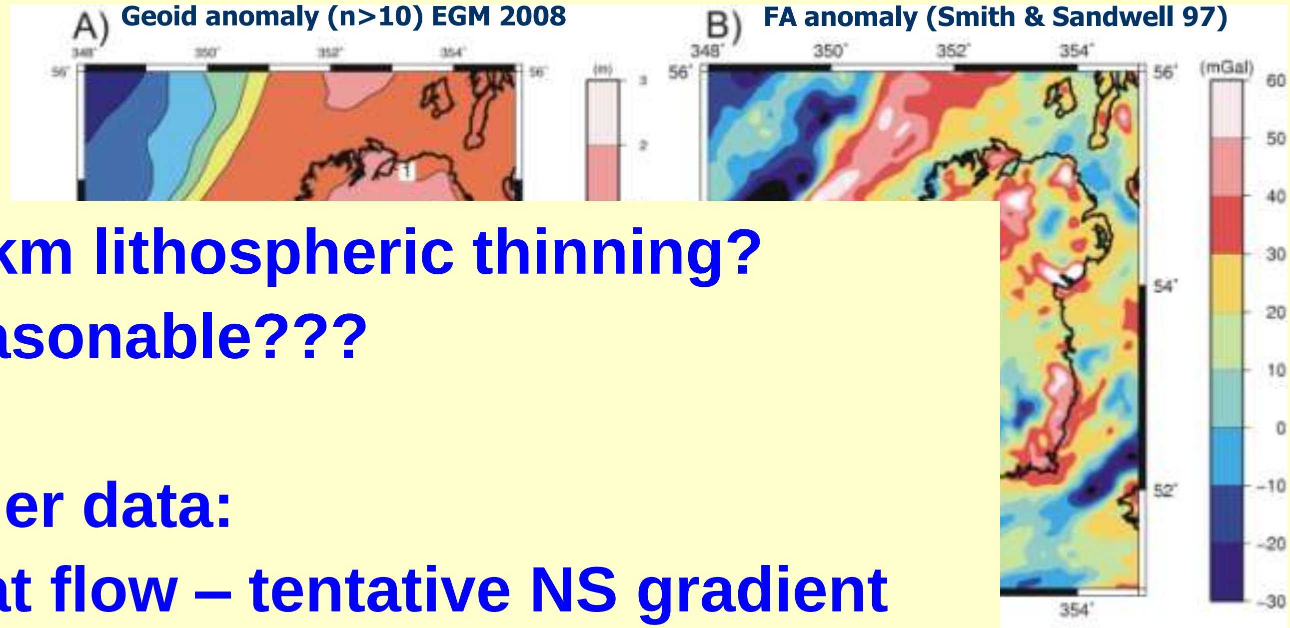


D) **Elevation (ETOPO2 V9.1)**



Geophysical observables:

Geological map of of Ireland. (courtesy GSNI and GSI)



30 km lithospheric thinning? Reasonable???

Other data:

Heat flow – tentative NS gradient

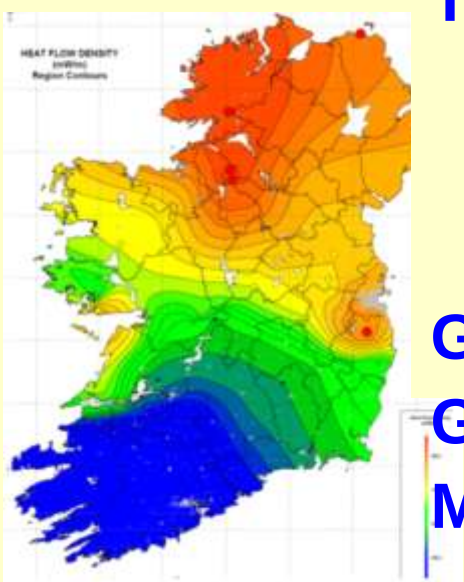
Topography – flat (minor depression in the middle of Ireland)

Gravity - flat

Geoid - flat

Moho - flat

Heat Flow



Ireland's thermal regime: LitMod 1D modelling

Data:

Topography:	**60 ±20 m**
Surface heat flow:	**60 ±5 mW/m^2**

Crustal parameters: ***(all based on data)***

Moho depth:	**30 ±2 km**	
Crustal density:	**Upper (to 20 km):**	**2780 ±50 kg/m^3**
	Lower (to 30 km):	**3100 ±50 kg/m^3**
Heat production:	**1.00 x 10^{-6} W/m^3 (0.74-1.38 W/m^3)**	
Thermal cond.:	**2.5 ±0.5 W/m/K**	
Thermal expans.:	**2.5x10^5 ±0.25 K^{-1}**	
Compressibility:	**1.33x10^{-11} ±0.27x10^{-11} Pa^{-1}**	

Ireland's thermal regime: LitMod 1D modelling

Oxide Chemistry (NCFMAS system):

Inver: Mantle xenoliths from Inver, Northern Ireland
Av Tecton Perid.: Average of young lithosphere
Av. Spinel Perid.: Average lithosphere <80 km
Av. Garnet Perid.: Average lithosphere >80 km
PUM: Primitive Upper Mantle

Description	Depleted → Fertile				
Oxides	Inver Average	Average Tecton Peridotite	Average Spinel Peridotite	Average Tecton Garnet Peridotite	Primitive Upper Mantle
SiO2	42.5	44.4	44.0	45.0	45.0
Al2O3	1.9	2.6	2.3	3.9	4.5
FeO	8.4	8.2	8.4	8.1	8.1
MgO	45.8	41.1	41.4	38.7	37.8
CaO	0.6	2.5	2.2	3.2	3.6
Na2O	0.05	0.18	0.24	0.28	0.36
Mg#	90.7	89.9	89.8	89.5	89.3

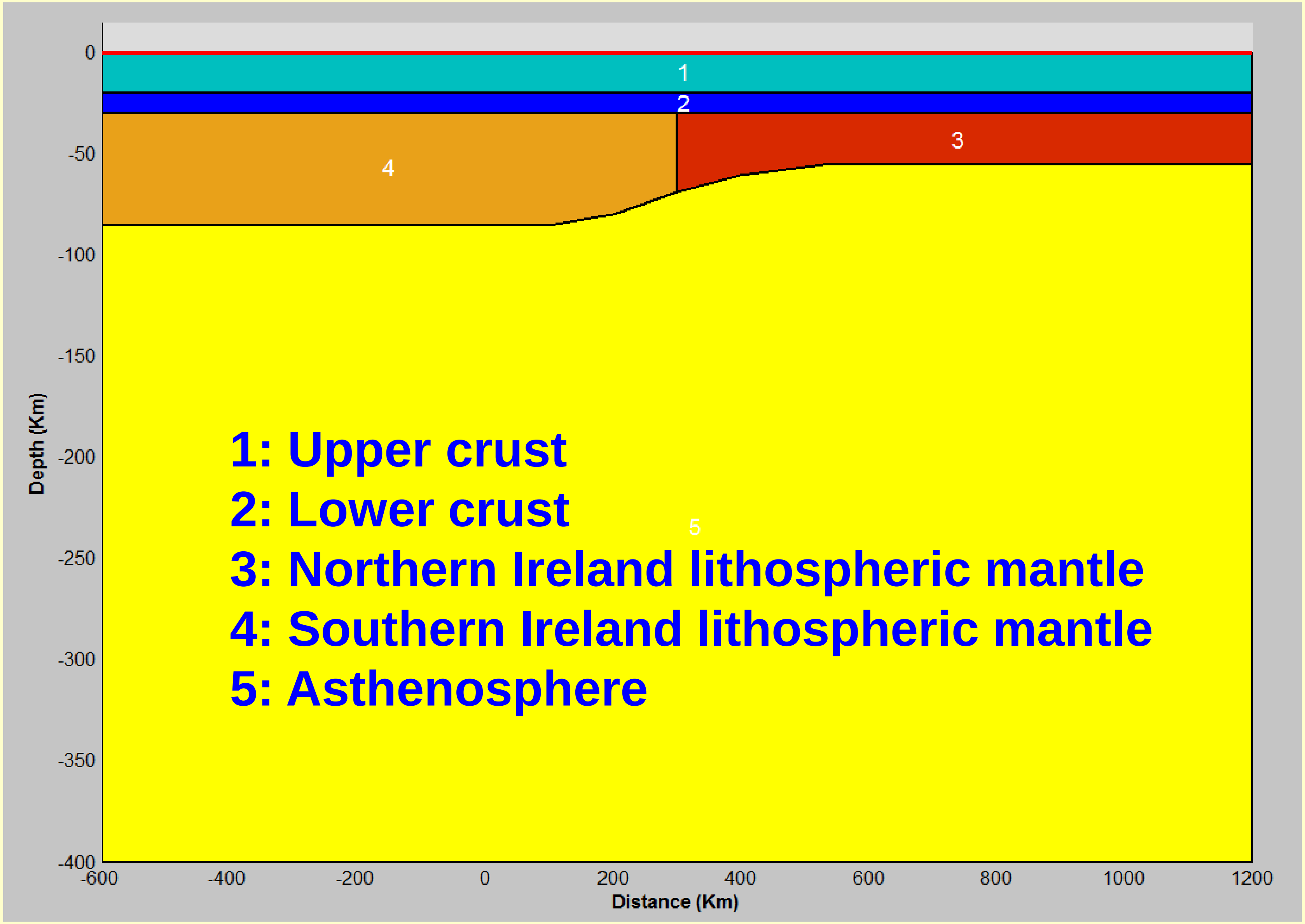
Ireland's thermal regime: LitMod 1D modelling

SHF & Topography from varying LAB:

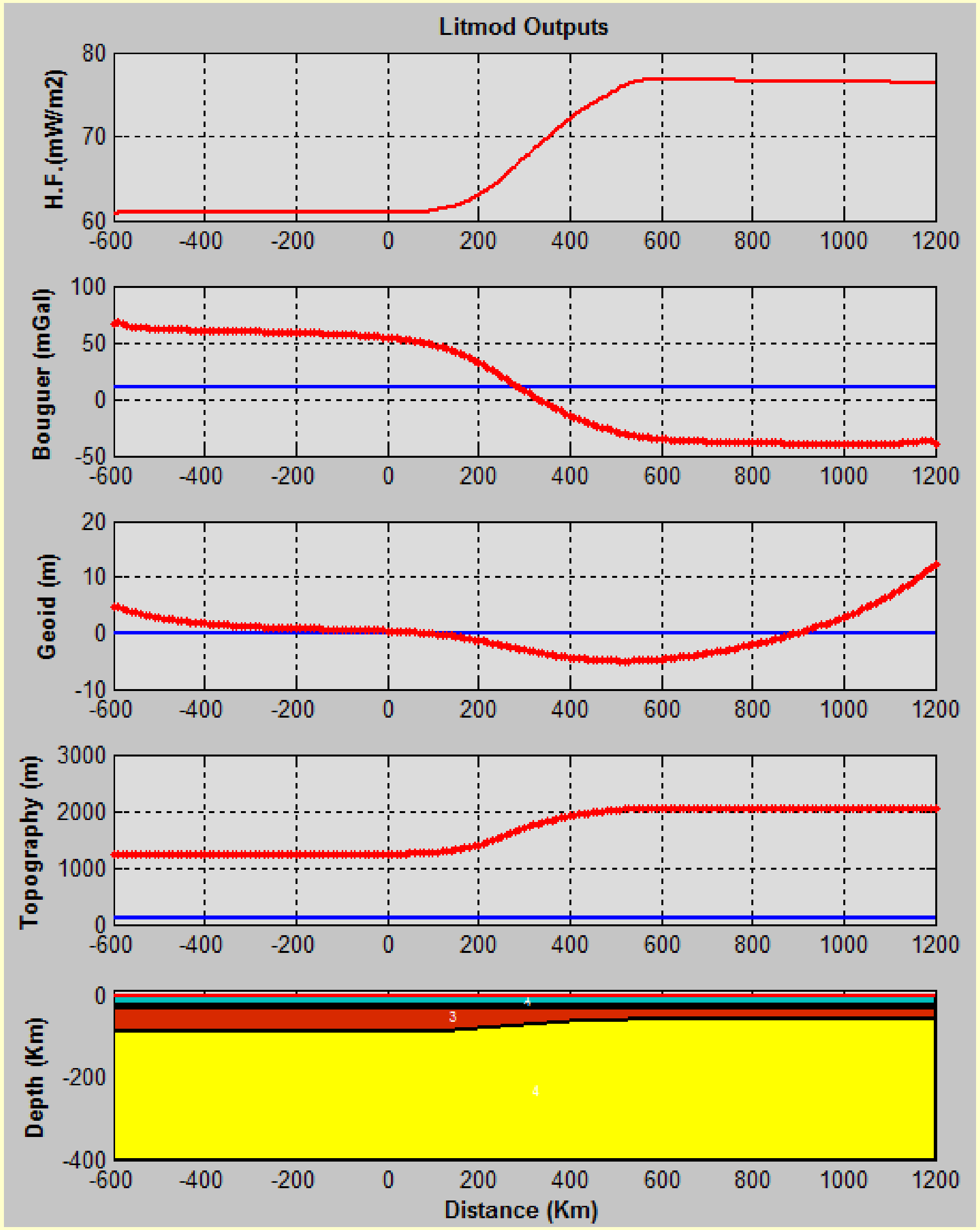
Depth (km)	Heat Flow	Topography (m)				
		Inver Average	Average Tecton Peridotite	Average Spinel Peridotite	Average Tecton Garnet Peridotite*	Primitive Upper Mantle
60	71	1350	1300	1350		1200
70	67	1050	1050	1050		950
80	64	800	600	800		500
90	61	550	330		500	160
95	60	-	190		-	0
100	59	350	65		230	
105	58		-100		100	
110	57	160	-280		-100	
115	56	60	-460			
120	56	-53				

➔ **To fit the SHF & topo data, LAB *must* be between 95 – 120 km**

Ireland's thermal regime: LitMod 2D modelling



Ireland's thermal regime: LitMod 2D modelling



Uniform lithosphere

→**Increase in HF**

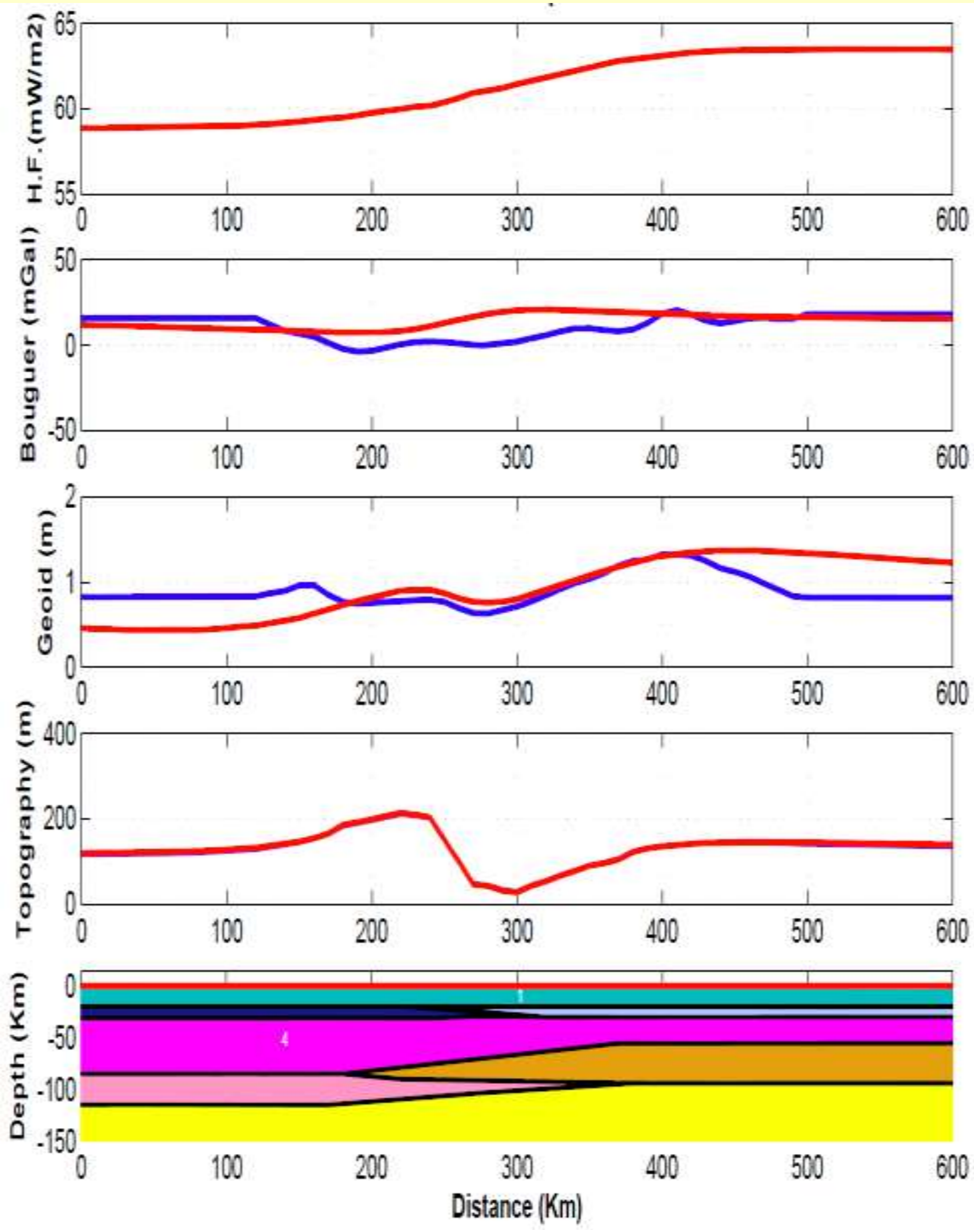
→**Decrease in Bouger by 100 mGal**

→**Geoid anomaly of 6 m**

→**Topographic increase of almost 1000 m from S to N**

Thinned lithosphere, from 85 km to 55 km, yields ↑

Ireland's thermal regime: LitMod 2D modelling



<u>Three-zone lithosphere: Depleted to S: Fertile to N</u>

Upper lithosphere to 55 km in N and 85 km in S

→ Gives a chemical (=physical) discontinuity

Fertile lower lithosphere to the north

Depleted lower lithosphere to the south

<u>Maximum thinning possible of 20 km, from 110 km to 90 km</u>

Ireland's thermal regime: Depth to LAB

Need to know the depth to the lithosphere-asthenosphere boundary in order to quantify contribution from the mantle

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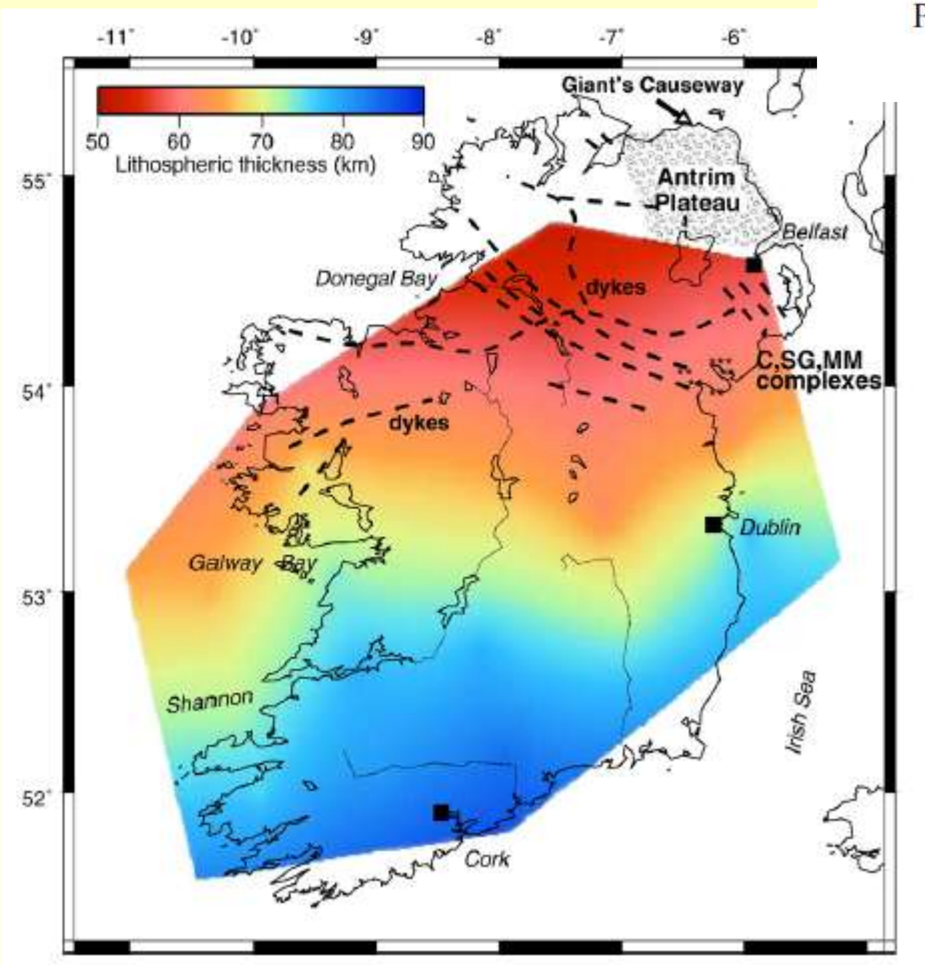


This "LAB" map is nonsense!

Although it explains a tentative S-N gradient in heat flow, it would also invoke S-N changes in:

-Topography

- Geoid

- Gravity

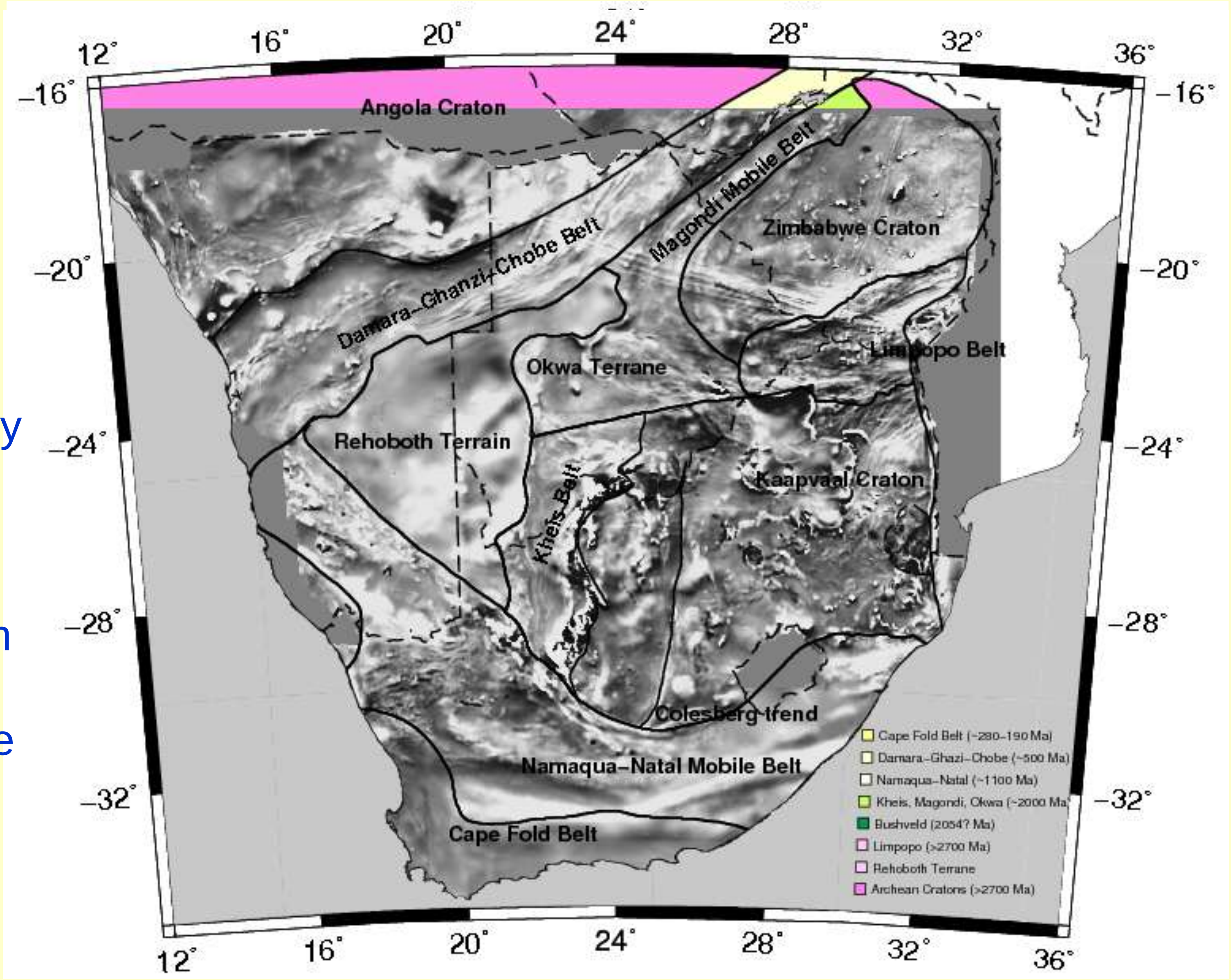
None are seen!!!

Interpretation driven by observed sRFs and S-N SHF variation

Southern Africa: Tectonic map

Tectonic map from Sue Webb (Wits)

Based on exposed geology in South Africa and Zimbabwe, but based on magnetic map in Namibia and Botswana where there is thick cover

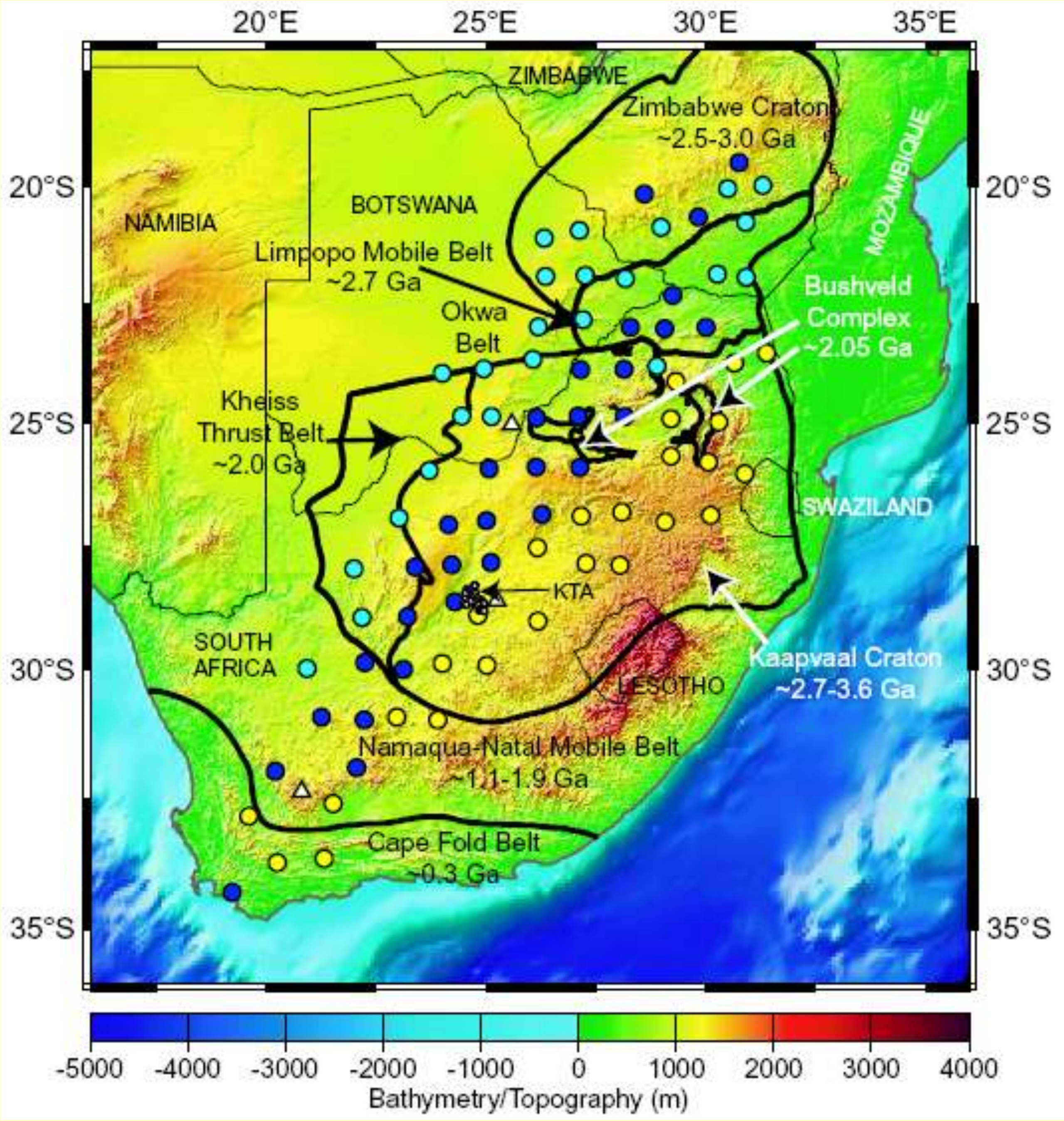


SASE

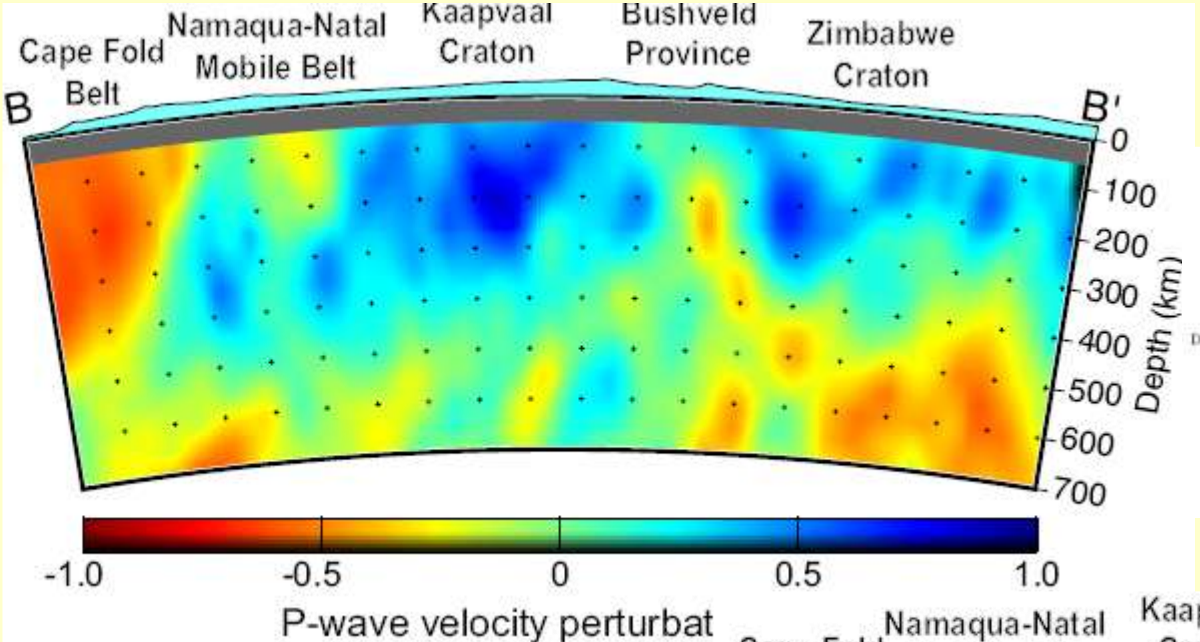
Southern African Seismic Experiment

2 year deployment at central (dark blue) stations

1 year only at other stations



Body wave tomographic models



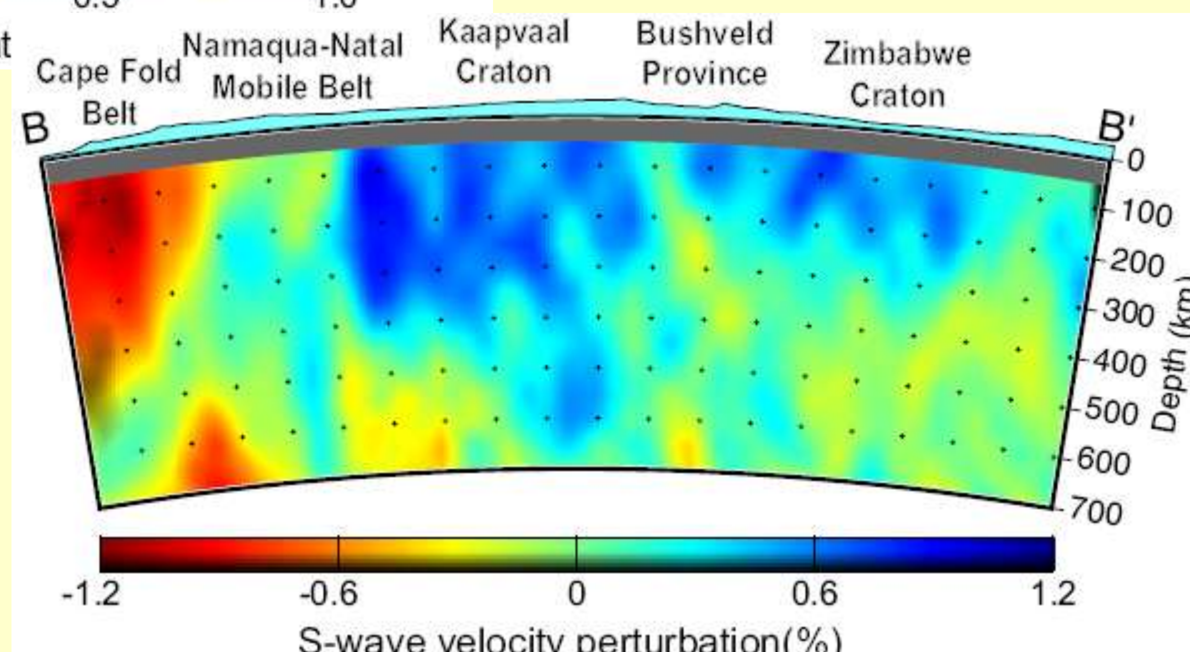
Mantle seismic structure beneath the Kaapvaal and Zimbabwe Cratons

Matthew J. Fouch
Department of Geological Sciences, Arizona State University, Tempe, AZ 85287, USA
e-mail: fouch@asu.edu

David E. James and John C. VanDecar
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA
e-mail: james@dtm.ciw.edu;vandecar@dtm.ciw.edu

Suzan van der Lee
Department of Geological Sciences, Northwestern University, Evanston, IL 60208, USA
e-mail: susan@earth.northwestern.edu

Kaapvaal Seismic Group
URL: http://www.ciw.edu/kaapvaal

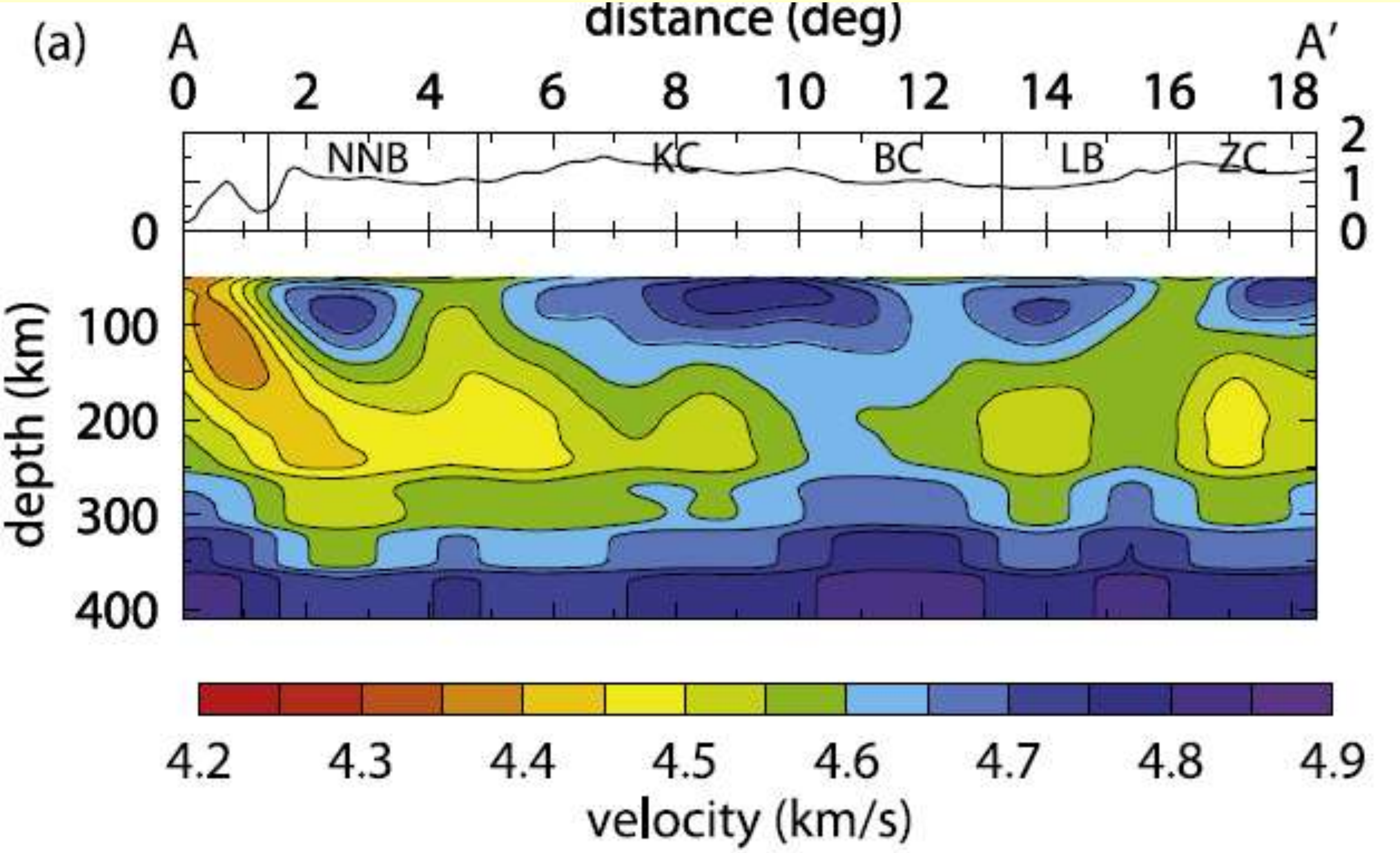


Very thick (>300 km) lithospheres in both P and S

Petrologists have a problem with this!

Rayleigh wave tomographic model

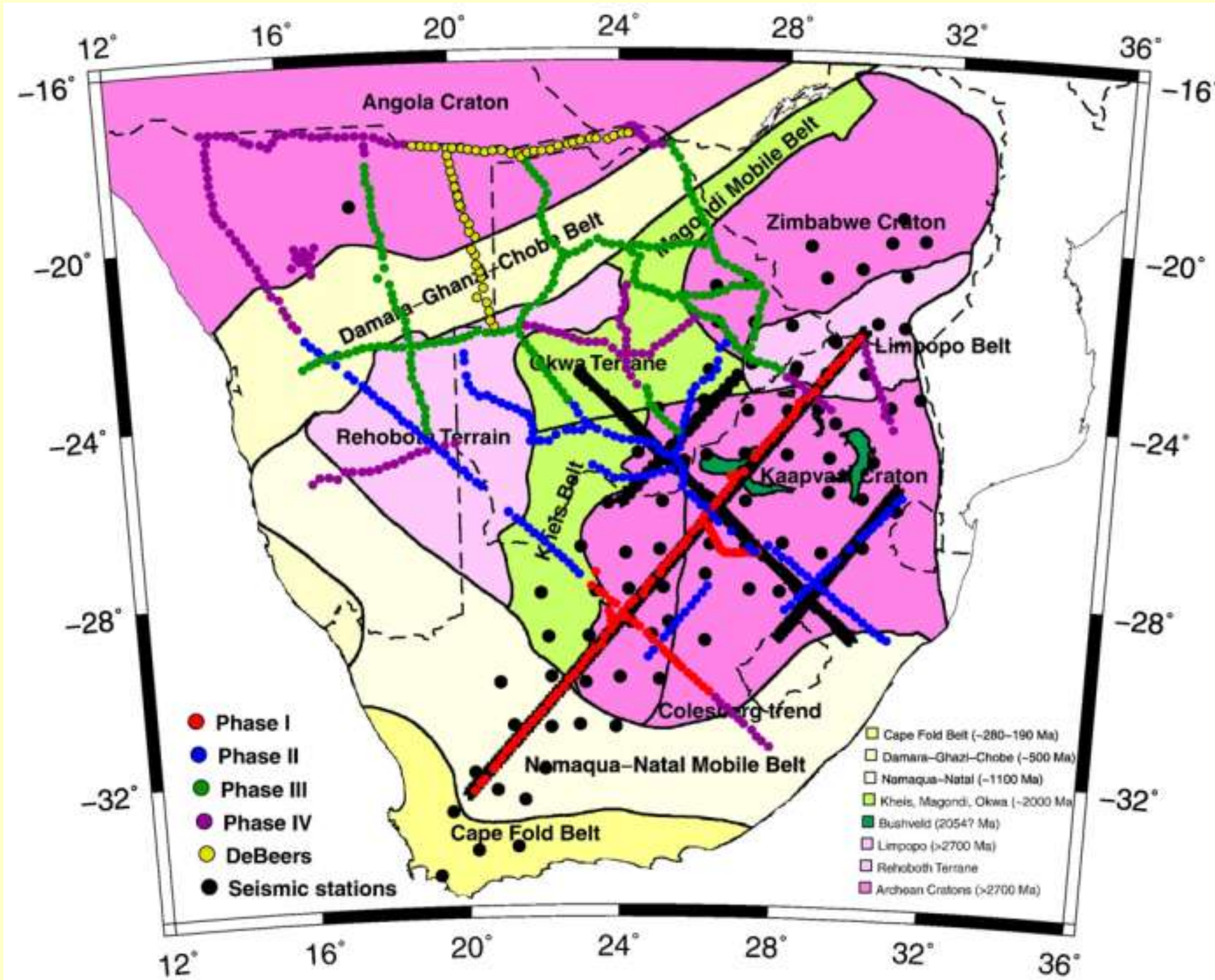
LI AND BURKE: 3-D SHEAR WAVE MODEL OF SOUTHERN AFRICA



SAMTEX: Southern African MT Expt.

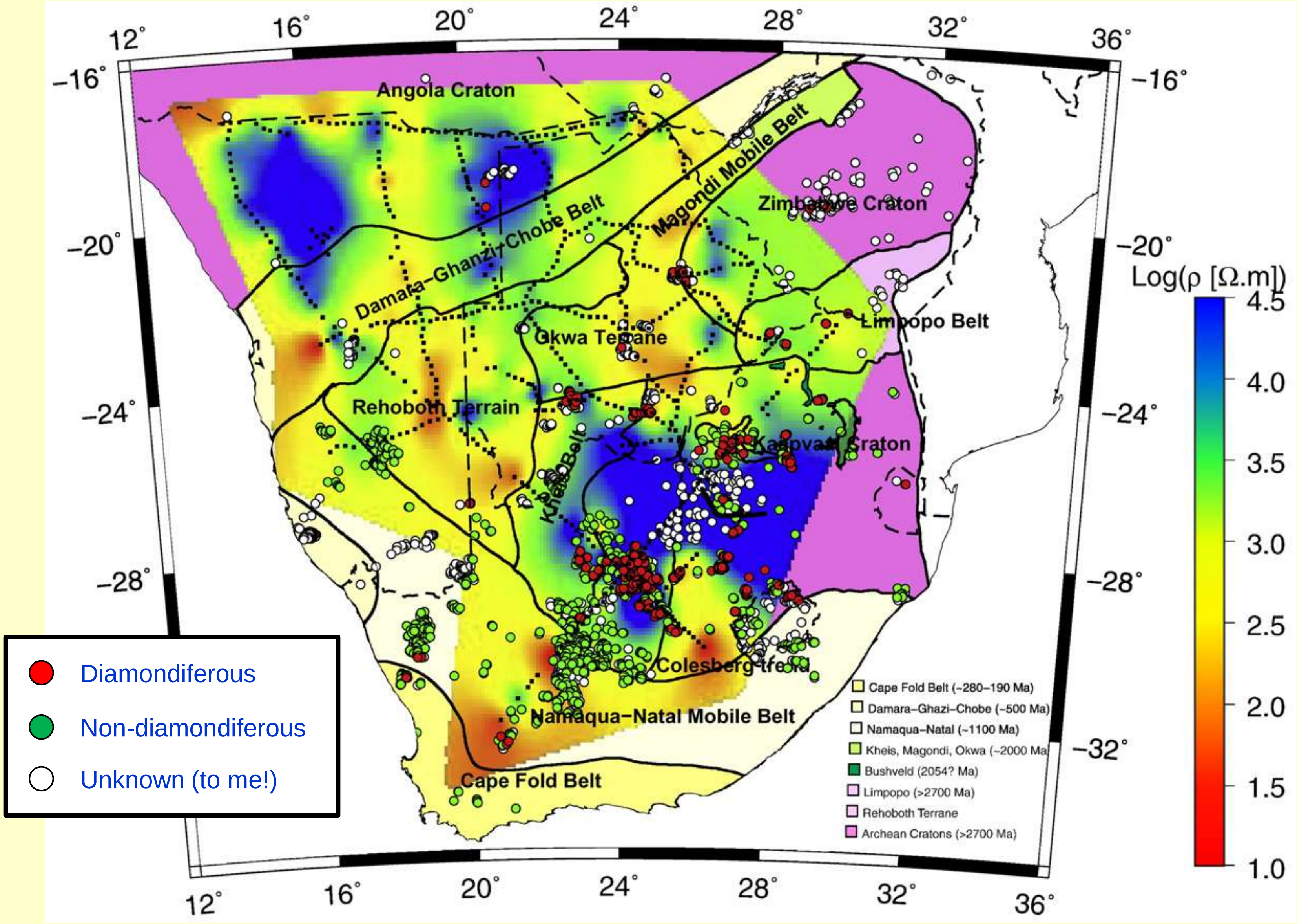
Four phases of SAMTEX covers South Africa and southern Botswana as SASE, but also covers northern Botswana and Namibia *(terra incognita)*

Total of >750 MT sites in an area >1M sq.km.



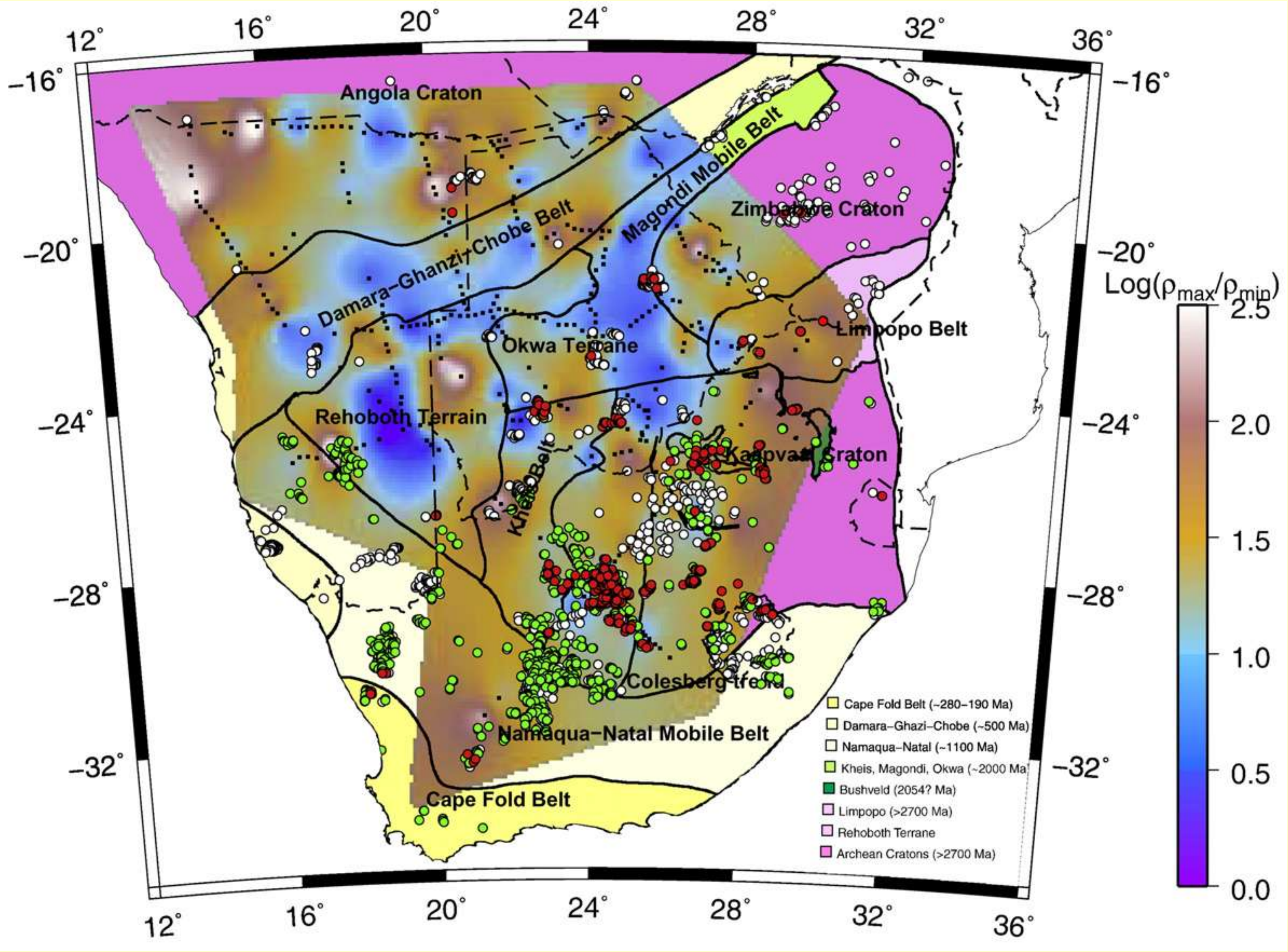
Resistivity map – 200 km (RhoMAX)

Correlation with diamondiferous and non-diamondiferous kimberlites



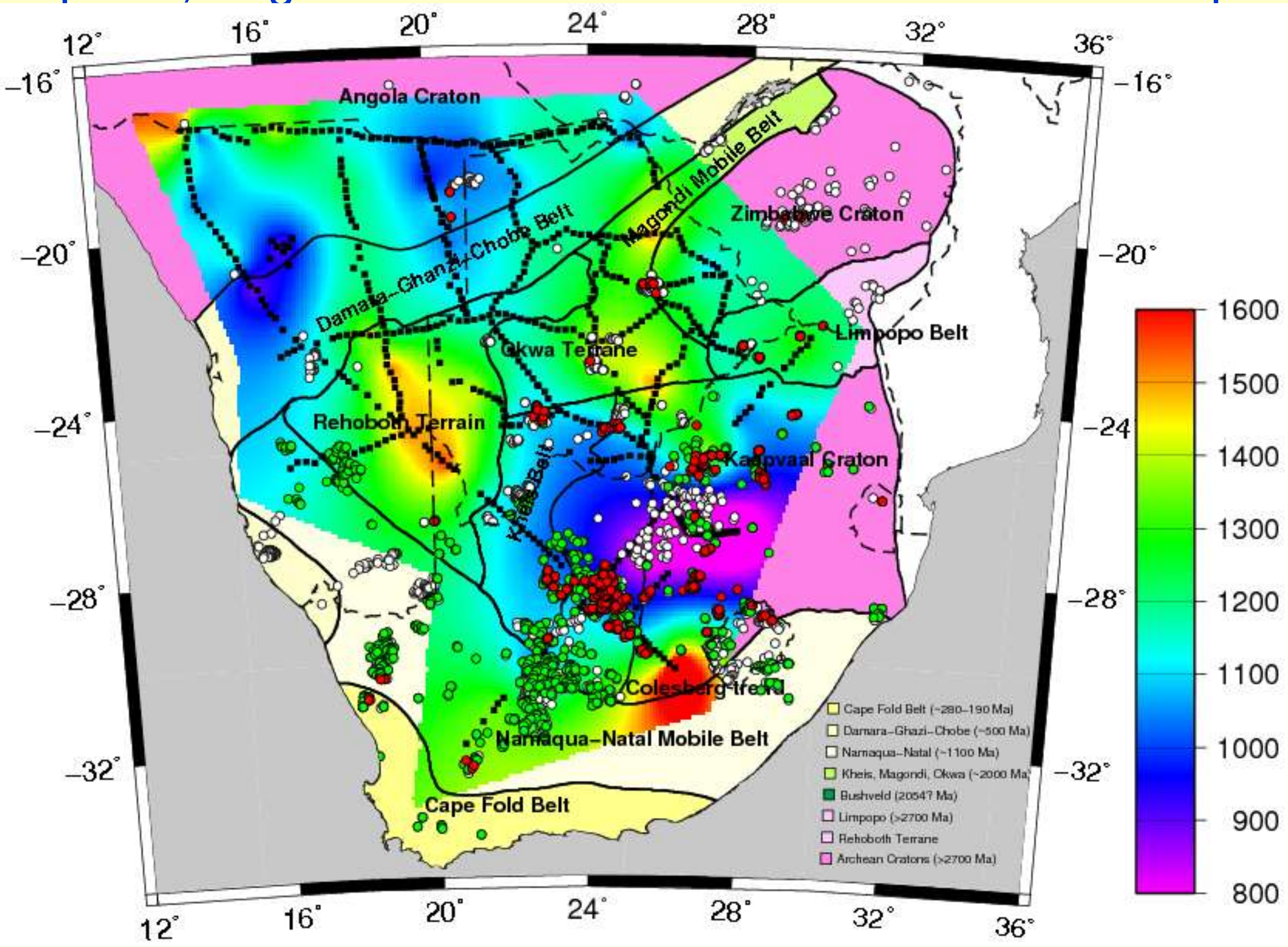
Resistivity anisotropy map – 200 km

Correlation with diamondiferous and non-diamondiferous kimberlites



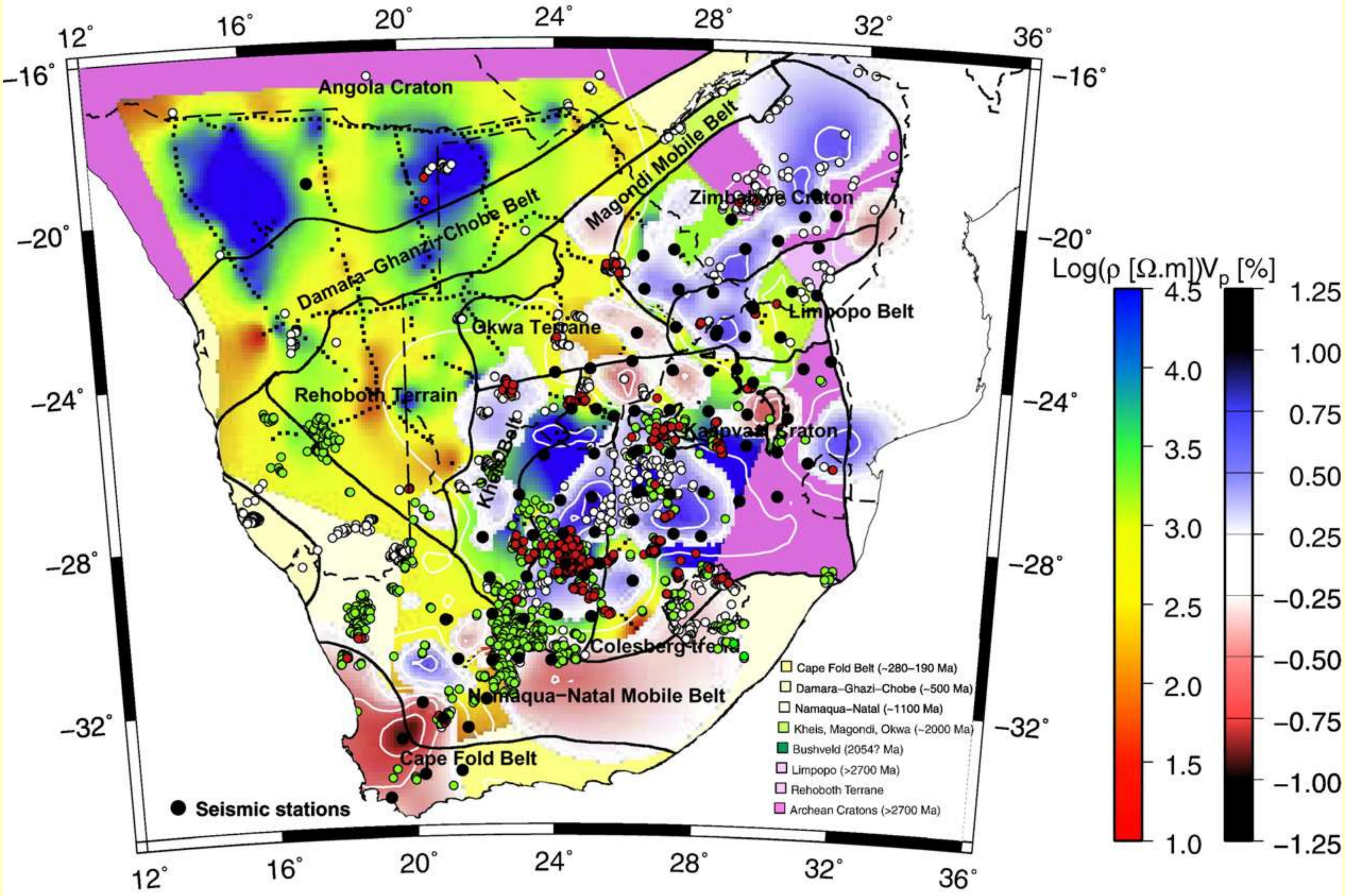
Temperature map – 200 km

Kaapvaal, Angola and Zimbabwe cratons show coldest part



Resistivity cf. Vp map – 200 km

Qualitative correlation between Vs and ρ – quantify it?

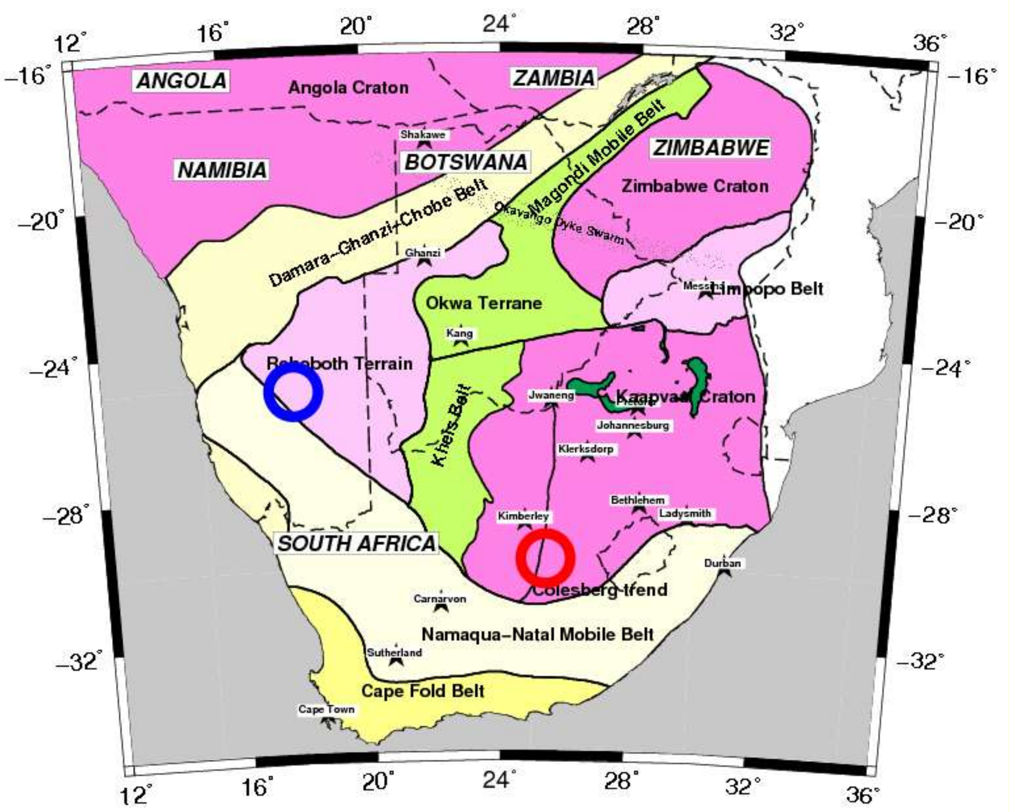


Jagersfontein & Gibeon kimberlites

Detailed xenolith information about Jagersfontein (red – on craton) and Gibeon (blue – off craton)

FRB = Jagersfontein

KGG = Gibeon



Sample	Mg#	Ol (%)	Opx (%)	Cpx (%)	Gt (%)	Sp (%)	P (kbar)	T (°C)	D (km)
FRB983	93.2	68.72	24.50	4.24	0.91	0.32	30.5	760	98
FRB1007	93.2	70.28	23.84	2.56	1.79	0.32	33.1	804	106
FRB AV	**93.2**	**69.50**	**24.17**	**3.40**	**1.35**	**0.32**	**31.8**	**782**	**102**
KGG06	91.19	73	11	9	8	0	33.2	926	108
KGG65	92.30	76	12	4	7	0	33.5	872	109
KGG AV	**91.75**	**74.5**	**11.5**	**6.5**	**7.5**	**0**	**33.35**	**899**	**108.5**

Theoretical variation of Vs and ρ

Vs and ρ both F(P,T,Mg#,Comp,H2O)

- →Derive physical parameters (bulk & shear moduli and electrical conductivity) using lab-derived empirical relationships for individual minerals and combining them using Hashin-Shtrikman bounds
- → Note: Vs is linearly-dependent on T whereas r is exponentialy-dependent

Lithos 109 (2009) 131–143

Contents lists available at ScienceDirect

Lithos

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Velocity–conductivity relationships for mantle mineral assemblages in Archean cratonic lithosphere based on a review of laboratory data and Hashin–Shtrikman extremal bounds

Alan G. Jones [a,*], Rob L. Evans [b], David W. Eaton [c]

Log(resistivity) & Velocity @ JAG & GIB

Laboratory-derived estimates of Vs and Log(resistivity) at Jagersfontein (FRG) and Gibeon (KGG) at 100 km depth for dry conditions (small polaron conduction)

Location	Av. Vs (km/s)	σ	Av. $Log_{10}(\rho)$	σ
Jagersfontein (-29.8°N, +25.4°W)	4.675	0.002	5.21	0.17
Gibeon (-25.1°N, +17.8°W)	4.611	0.0055	4.36	0.26

Mineral physics predictions:

JAG: **Vs = 4.675** **log(ρ) = 5.21**

GIB: **Vs = 4.611** **log(ρ) = 4.36**

Log(resistivity) & Velocity @ JAG & GIB

Mineral physics estimates of Vs and Log(resistivity) at Jagersfontein (FRG) and Gibeon (KGG) at 100 km depth:

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Observations of Vs and Log(resistivity) at Jagersfontein (FRG) and Gibeon (KGG) at 100 km depth (100 km spatial averaging applied):

Location	Av. Vs (km/s)	σ	Av. $Log_{10}(\rho)$	σ
Jagersfontein (-29.8°N, +25.4°W)	4.70	0.08	3.41	0.205
Gibeon (-25.1°N, +17.8°W)	4.51	0.075	2.78	0.09

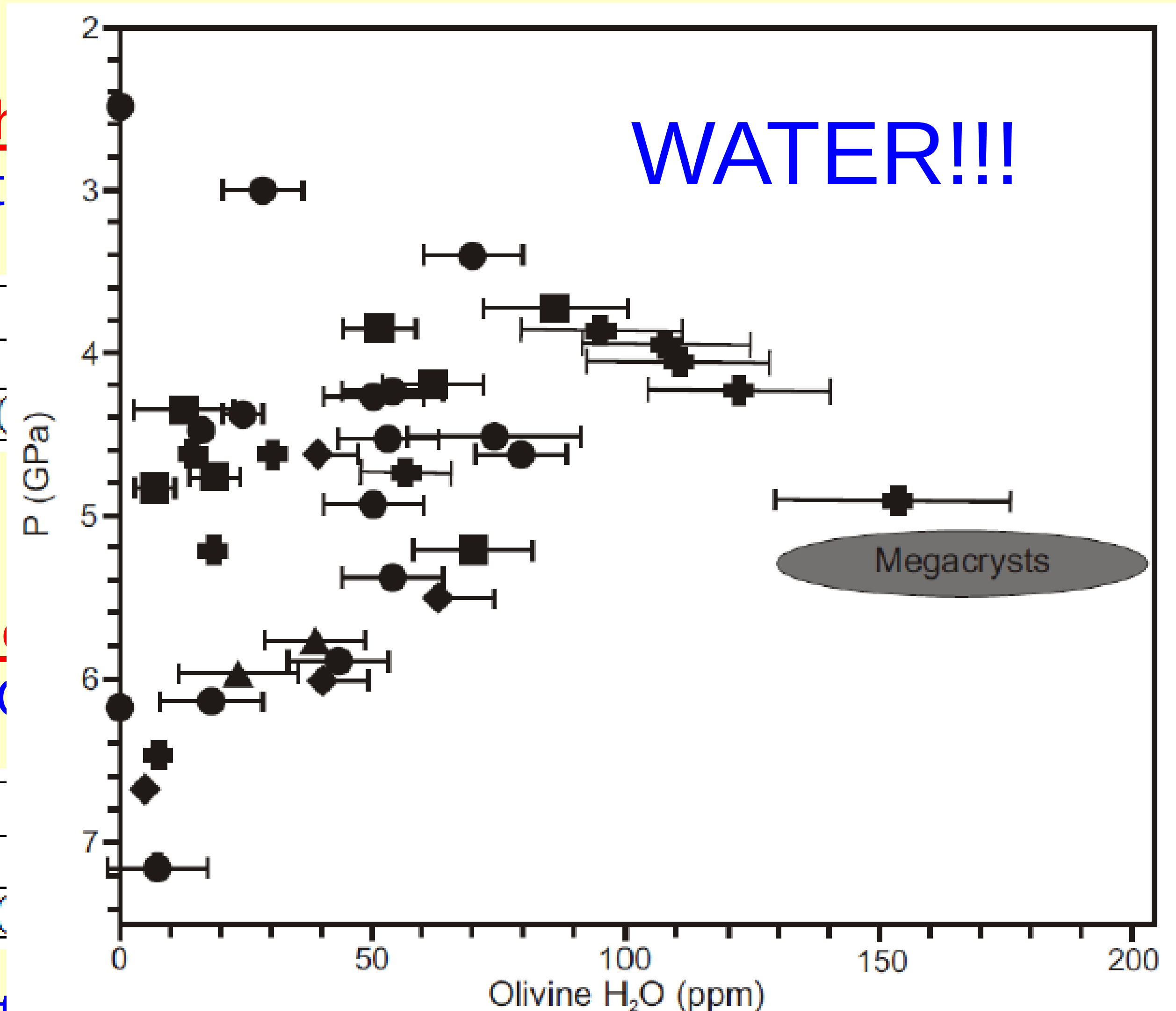
Need to introduce something into upper lithospheric mantle to explain conductivity that is 2 orders of magnitude higher than predicted

Log(resistivity) & Velocity @ JAG & GIB

Mineral ph

Jagersfont

Location		)	σ
Jagersfontein			0.17
Gibeon	(		0.26



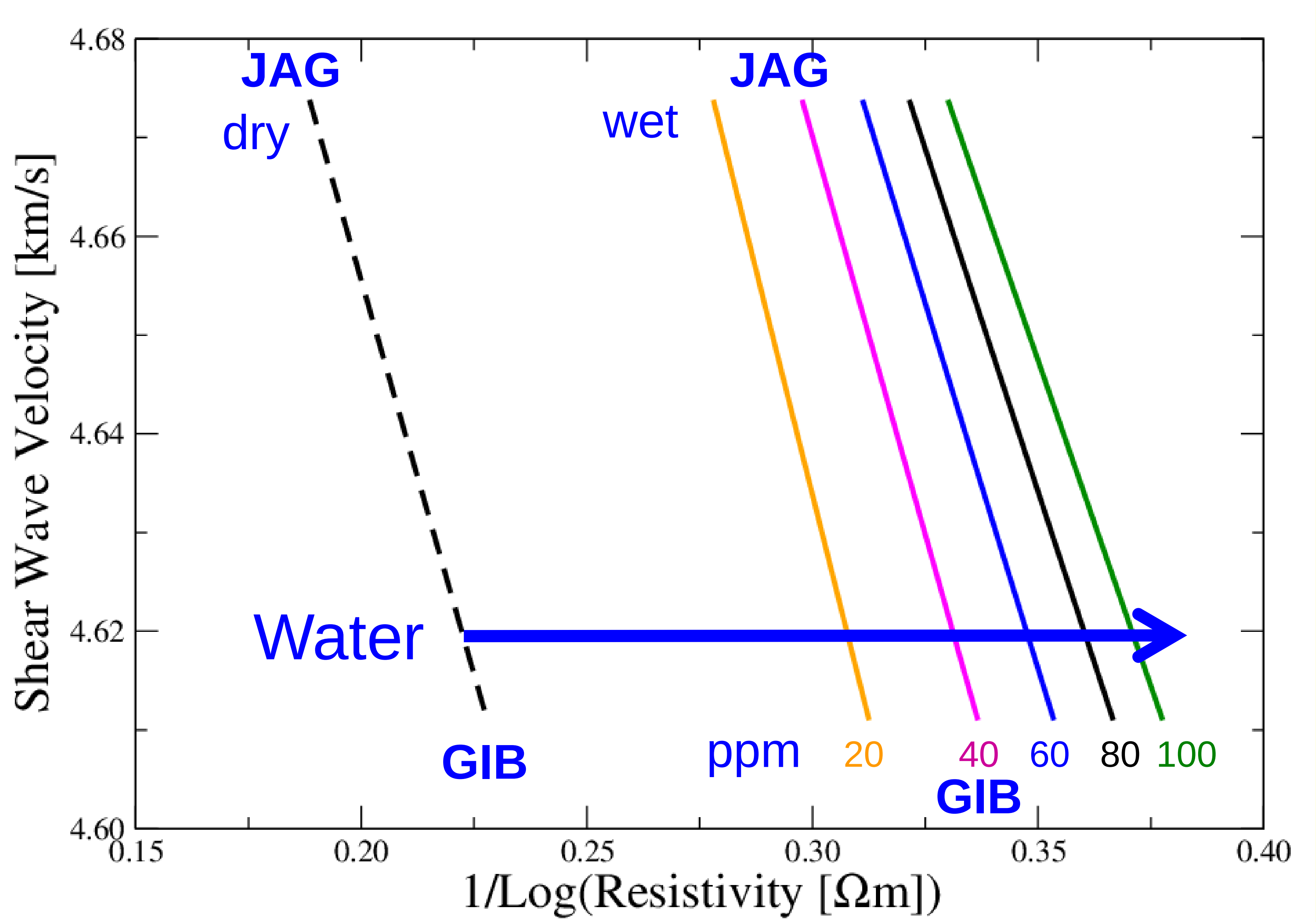
Observati RG) and

Gibeon (K applied):

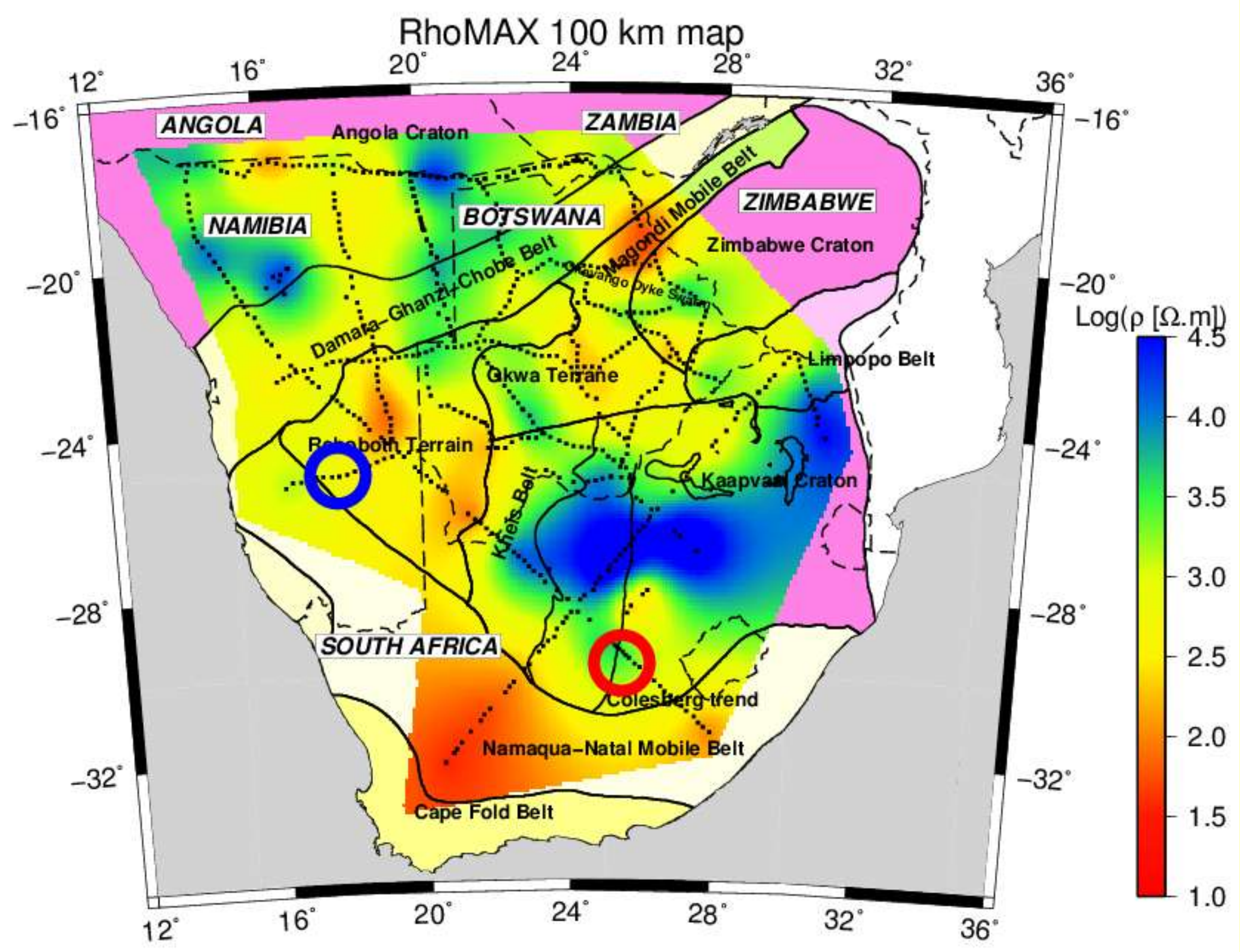
Location		)	σ
Jagersfontein			0.205
Gibeon	(		0.09

Need to int… something … to explain conductivity that is 2 orders of magnitude higher than predicted

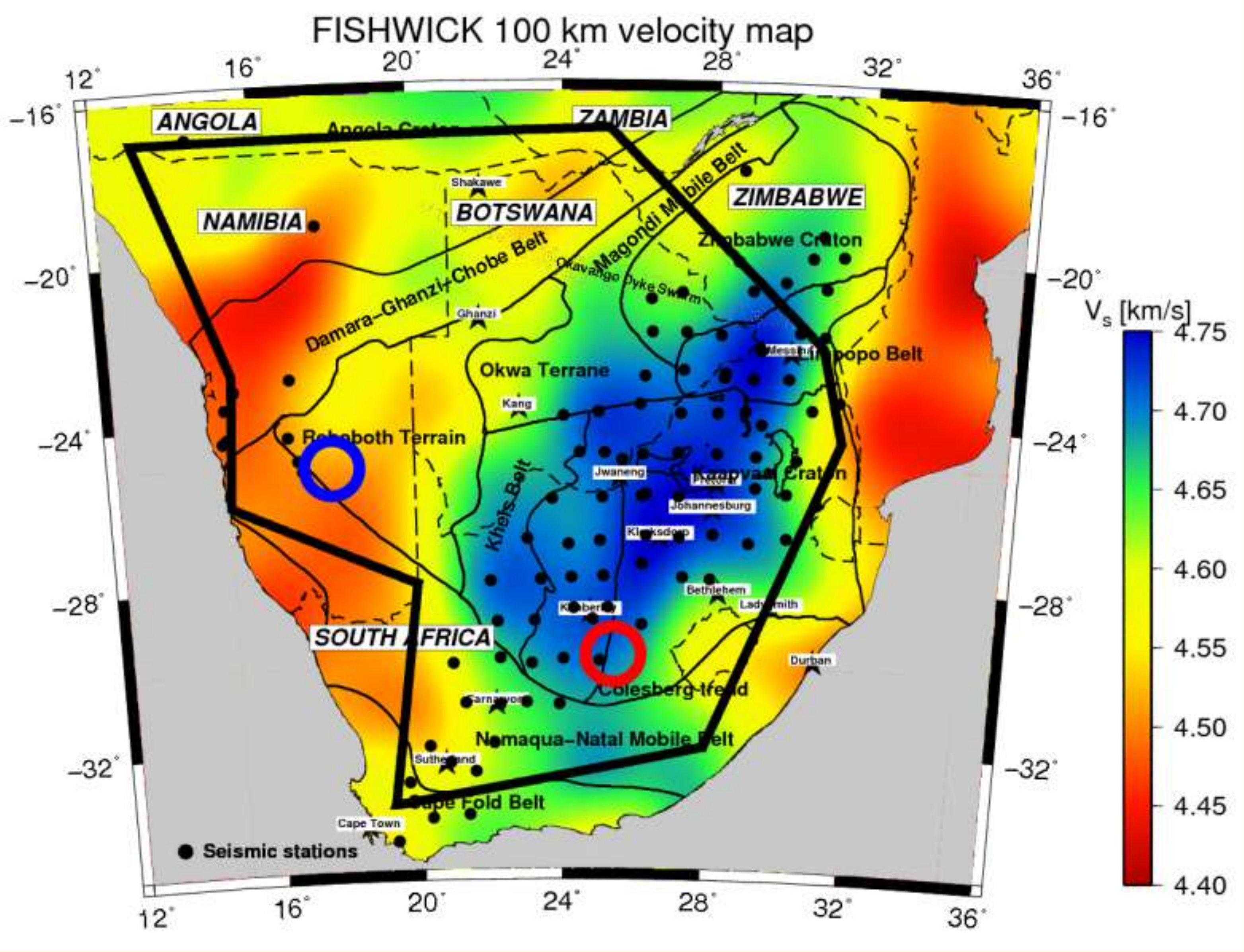
Log(resistivity)-Velocity relationship



Resistivity at 100 km (RhoMAX)

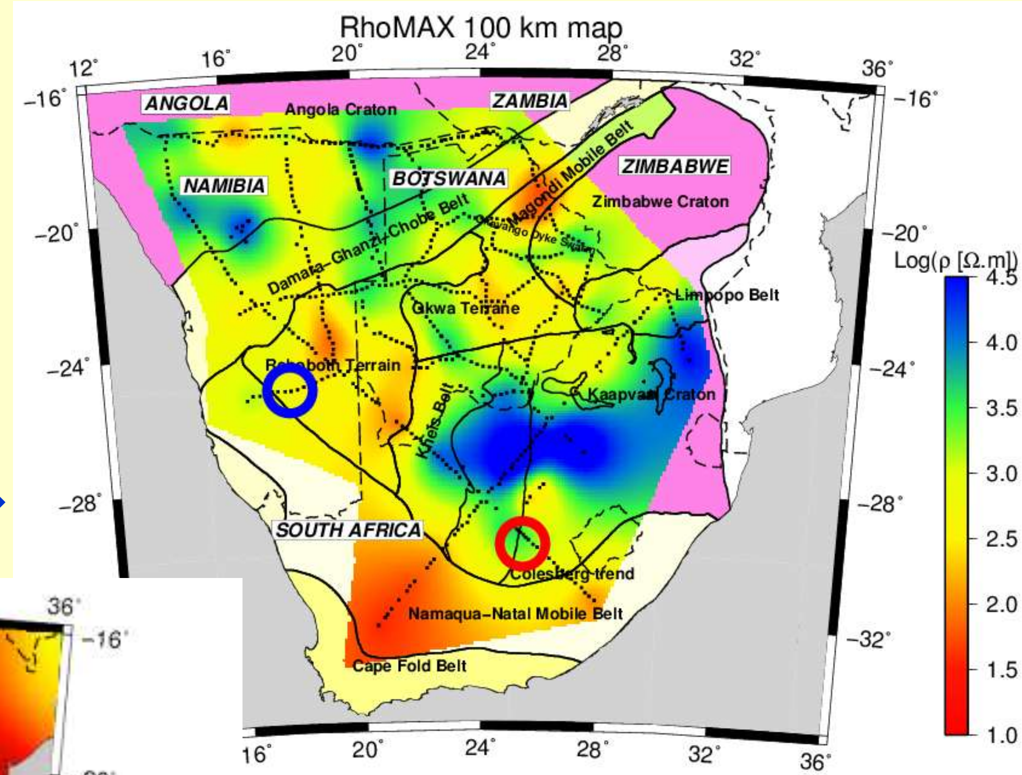


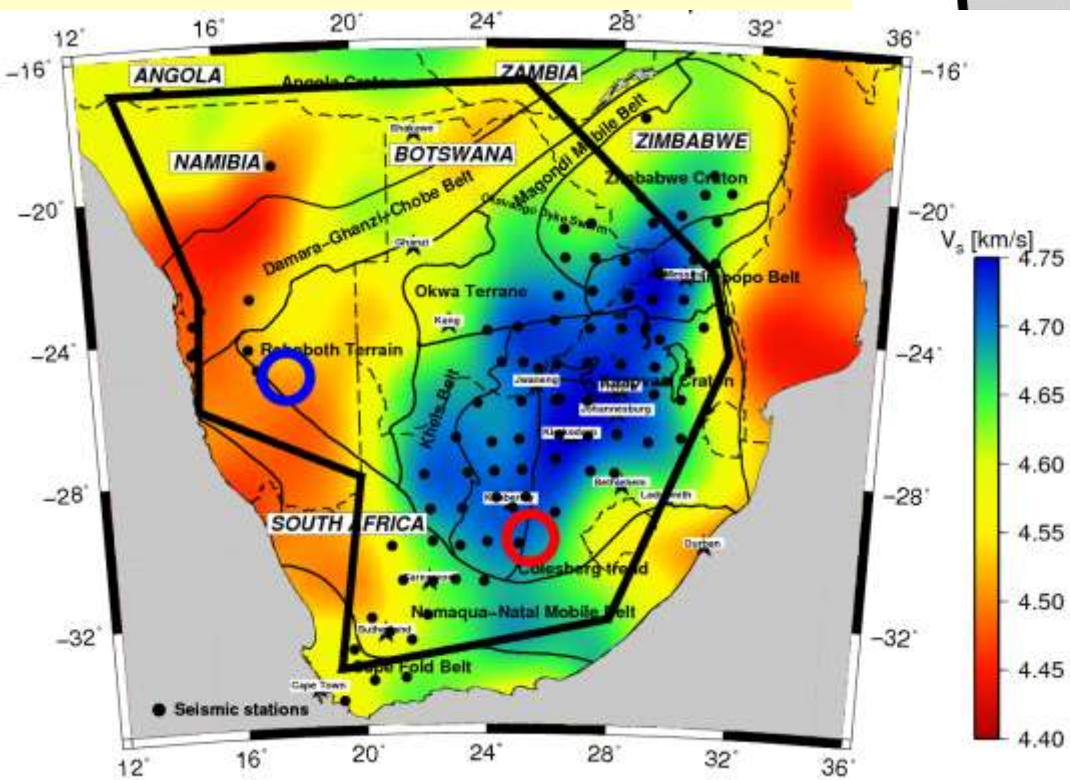
Velocity model VsF1.5d at 100 km



Comparison of velocity and resistivity models at 100 km

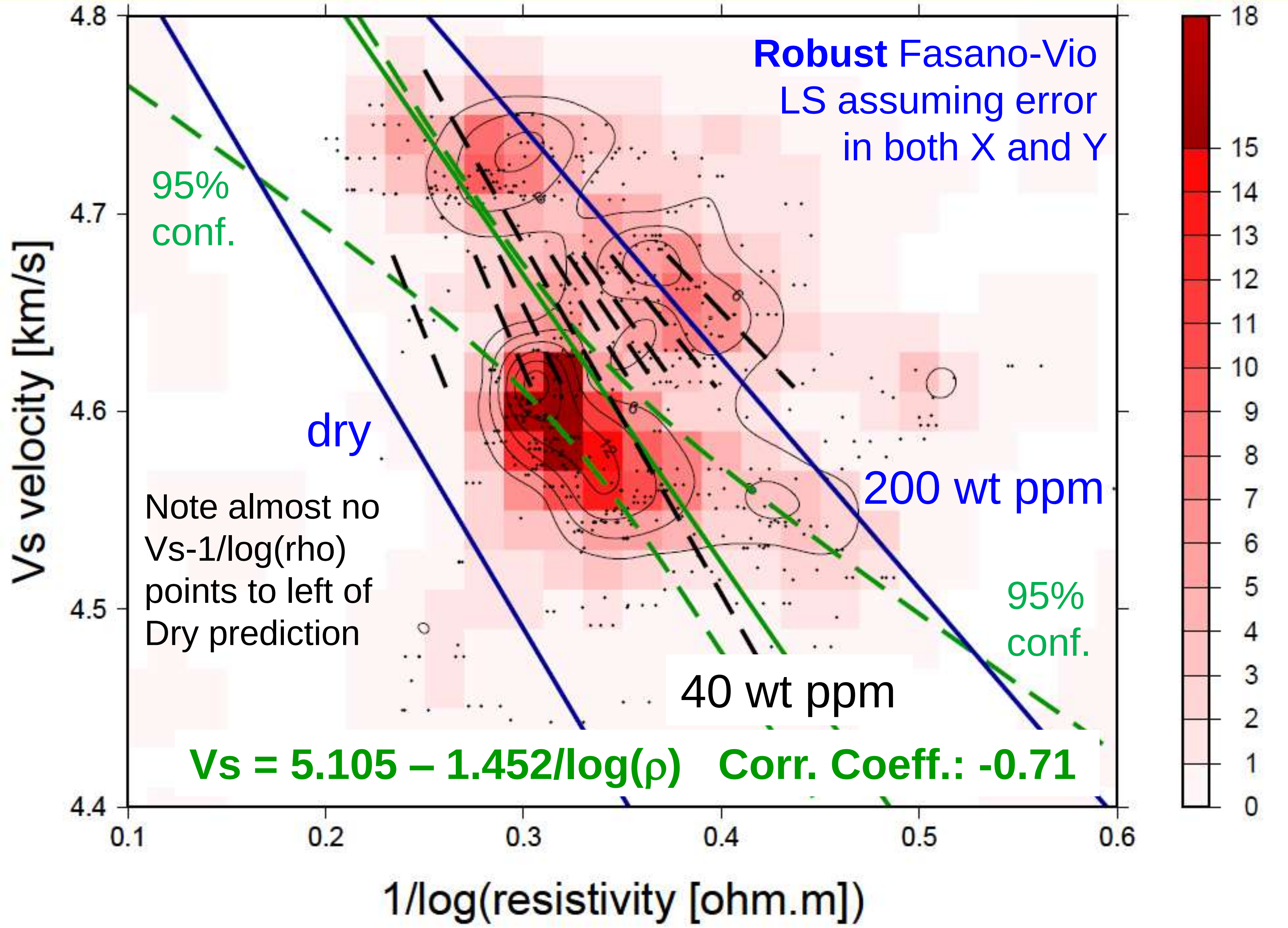
SAMTEX →





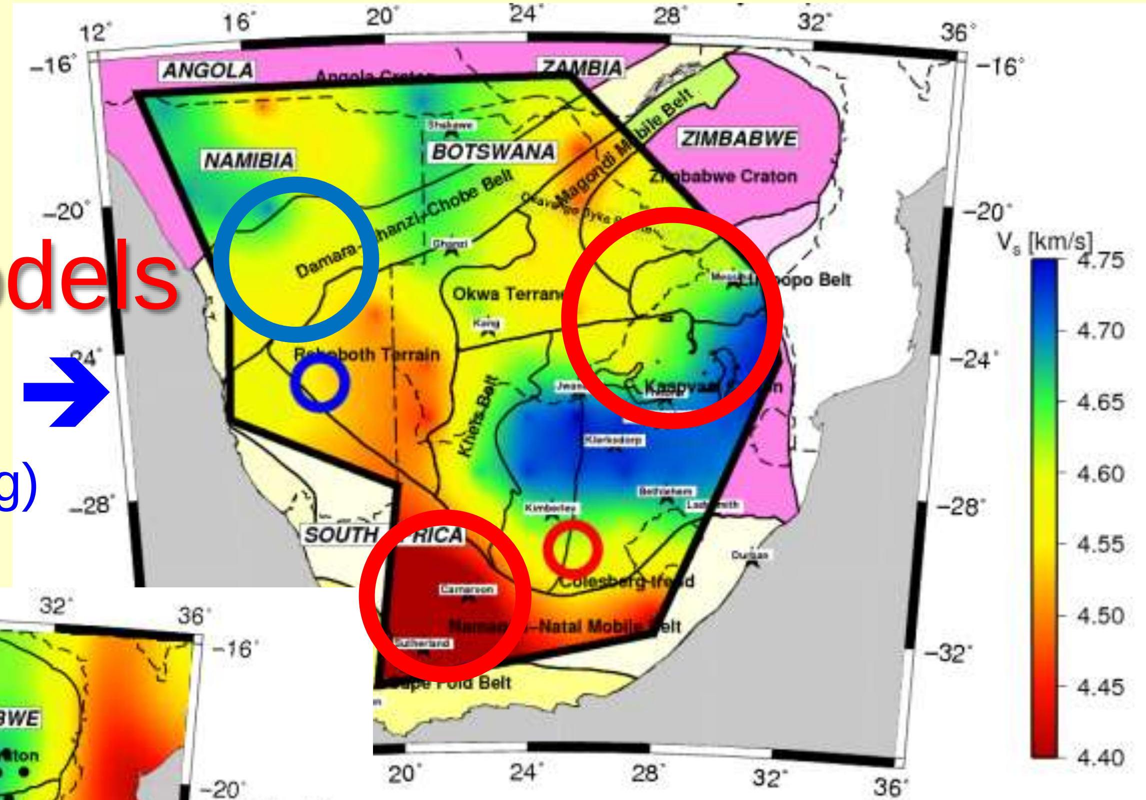
← Fishwick

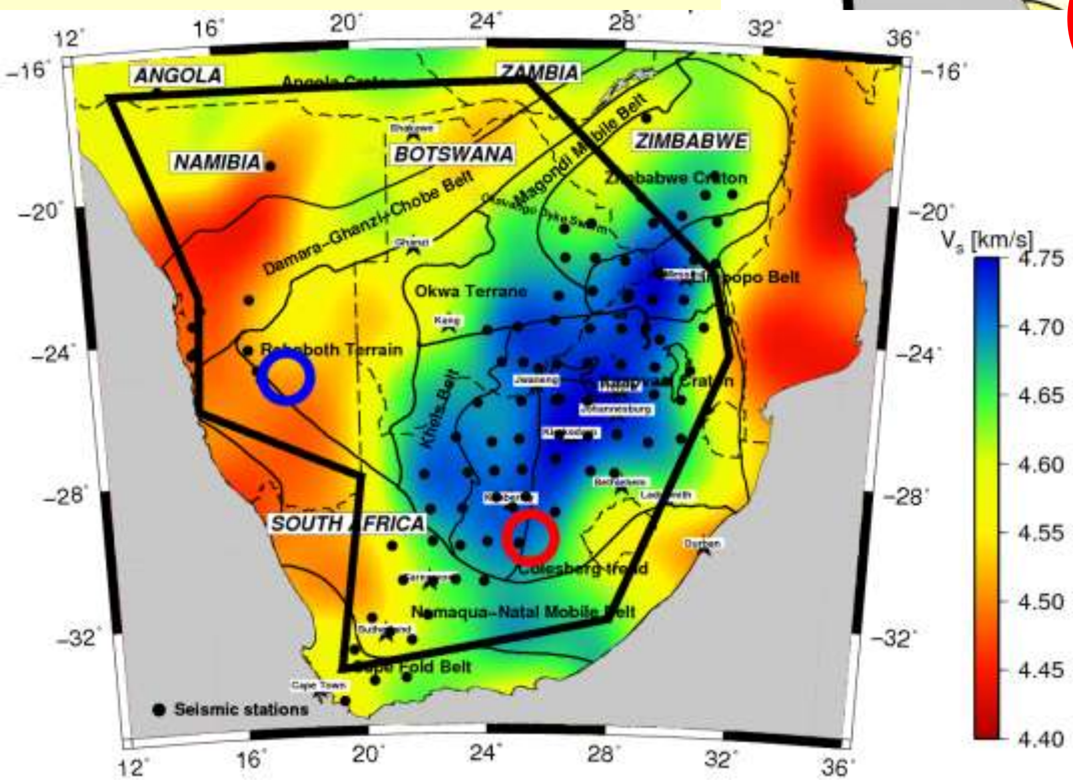
1/log(Rho)-VsF1.5d @ 100 km: Robust reg.



Comparison of derived and predicted Vs models

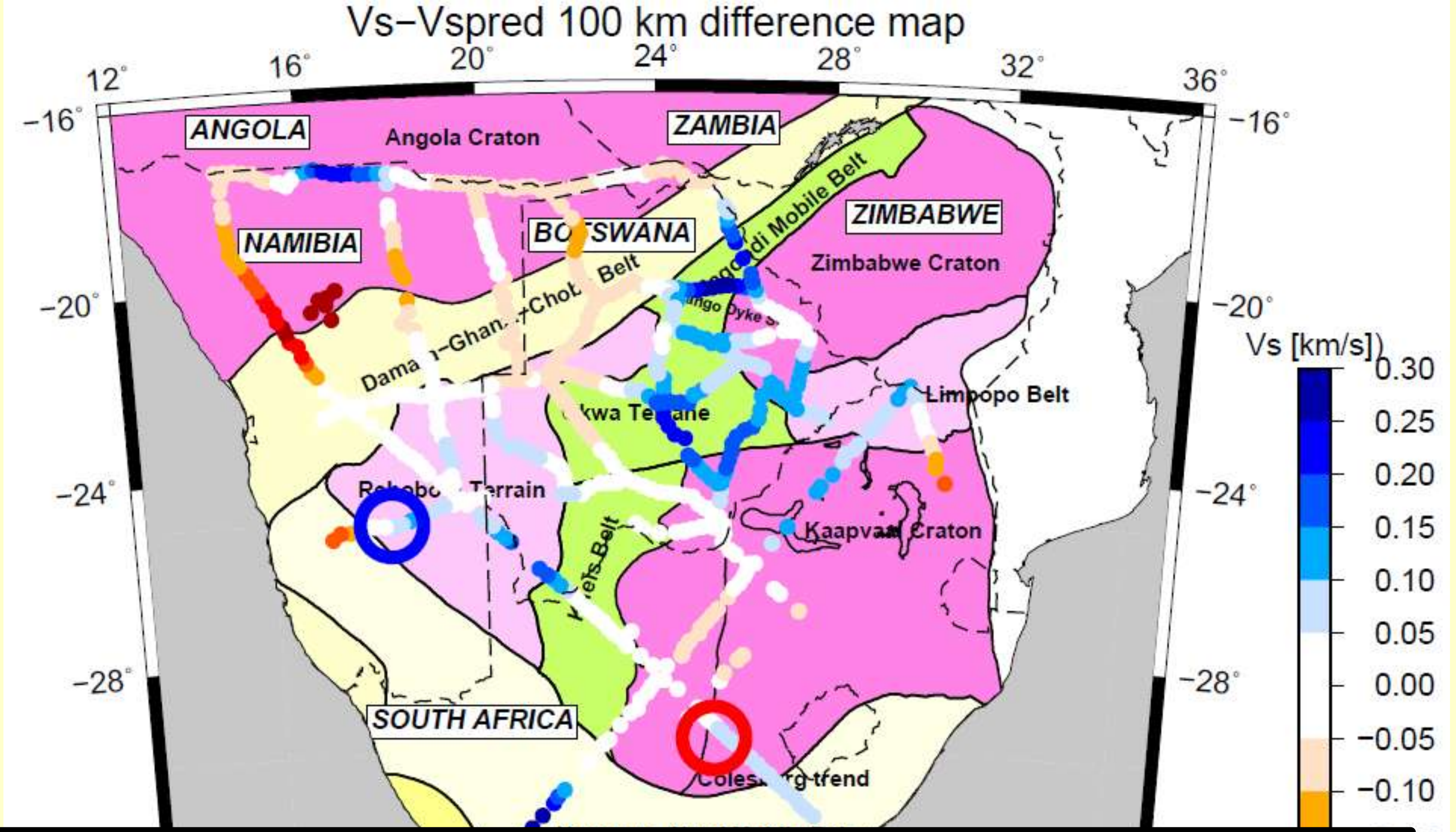
Vs from Rho →
(with 1.5 deg smoothing)





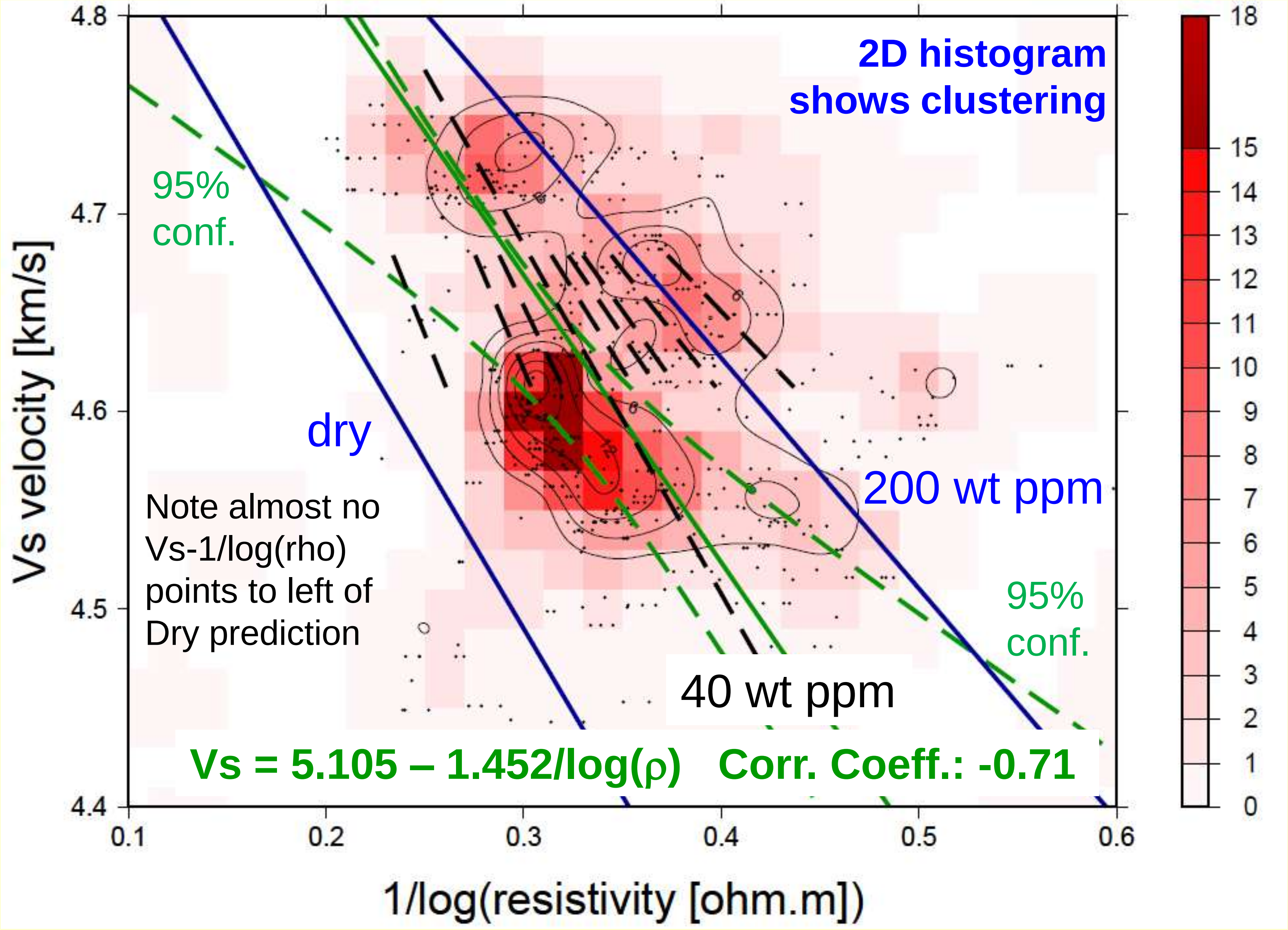
← Vs from Fishwick

Difference map: Vs – Vs_{pred} (100 km)

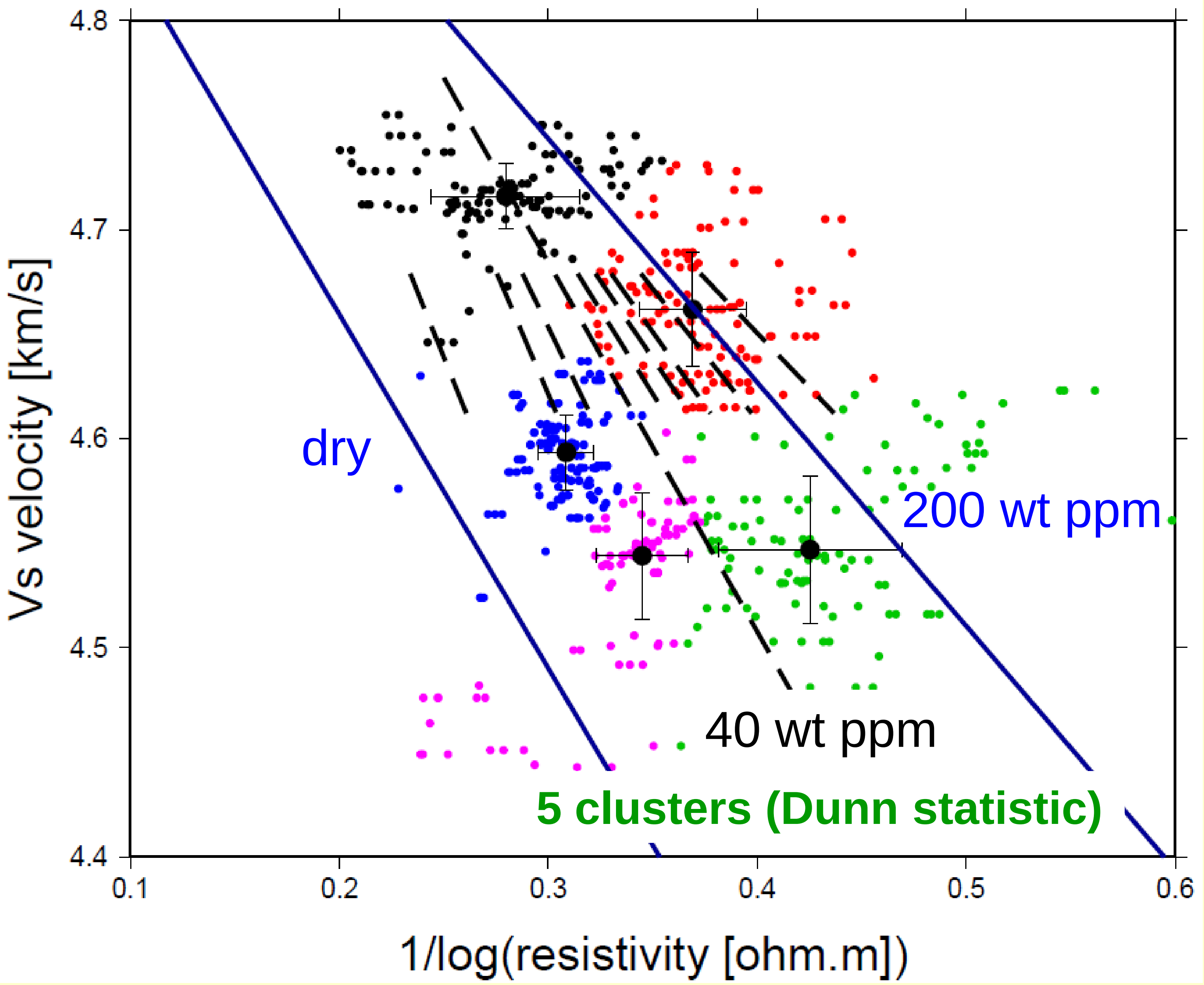


Electrical resistivity can predict shear wave velocity to within error (0.1 km/s) for over 80% of Southern Africa!!! (Over 90% of cratonic regions)

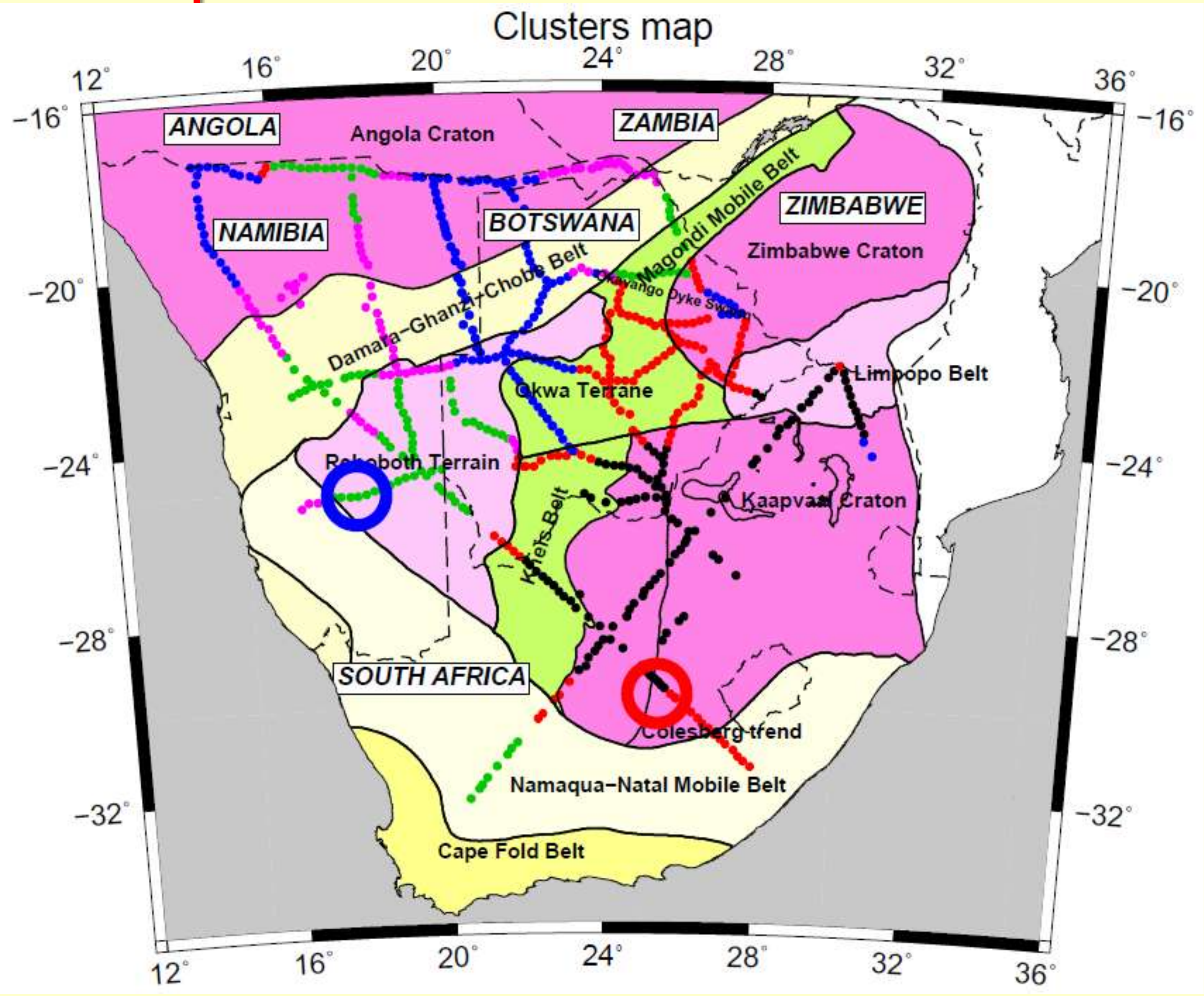
1/log(Rho)-VsF1.5d @ 100 km: Clustering



1/log(Rho)-VsF1.5d @ 100 km: Cluster analysis



Cluster map

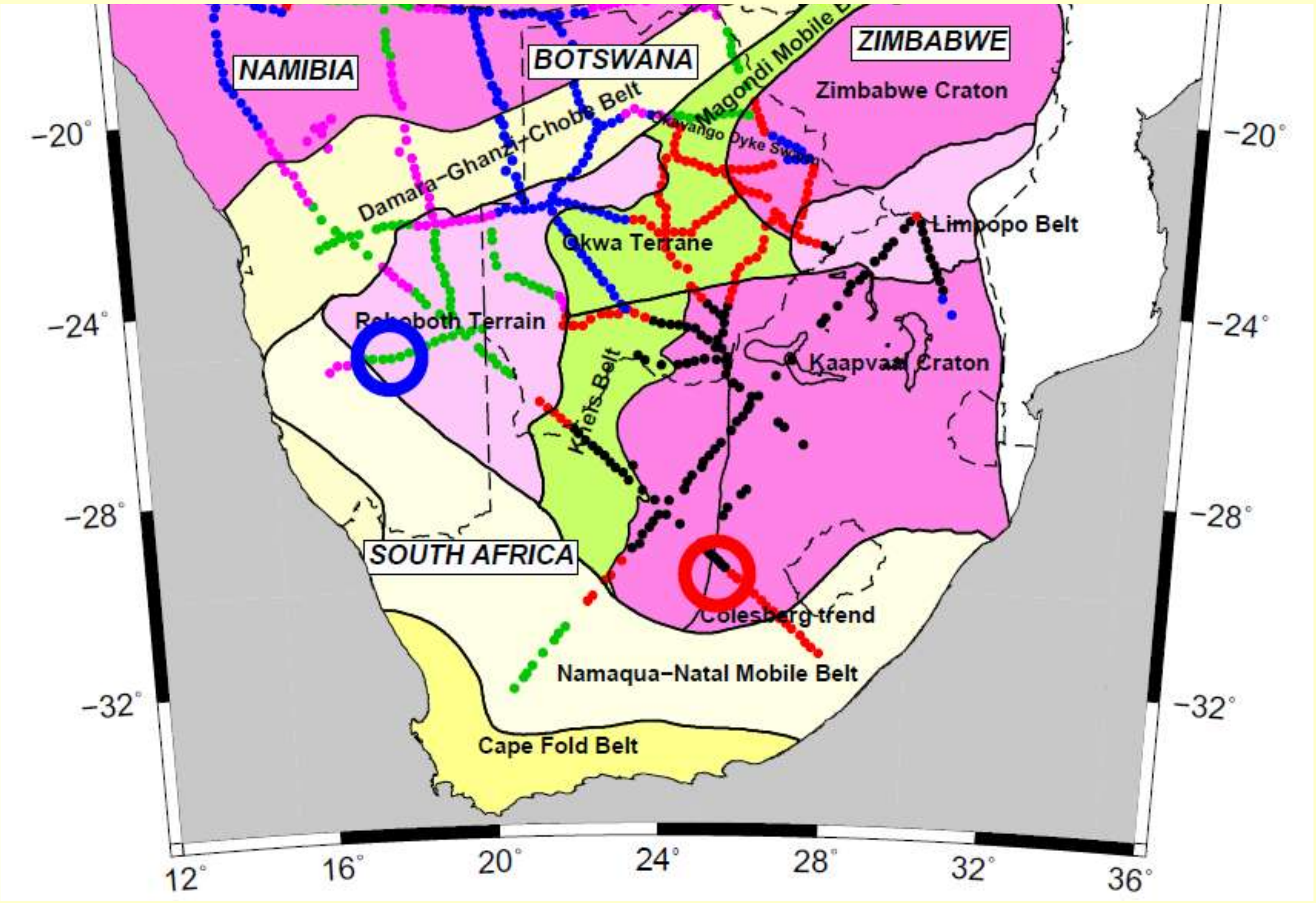


Clusters map
12°
16°
20°
24°
28°
32°
36°
−16°
−20°
−24°
−28°
−32°
ANGOLA
Angola Craton
ZAMBIA
NAMIBIA
BOTSWANA
ZIMBABWE
Zimbabwe Craton
Magondi Mobile Belt
Damara−Ghanzi−Chobe Belt
Okavango Dyke Swarm
Limpopo Belt
Okwa Terrane
Rehoboth Terrain
Kheis Belt
Kaapvaal Craton
SOUTH AFRICA
Colesberg trend
Namaqua−Natal Mobile Belt
Cape Fold Belt

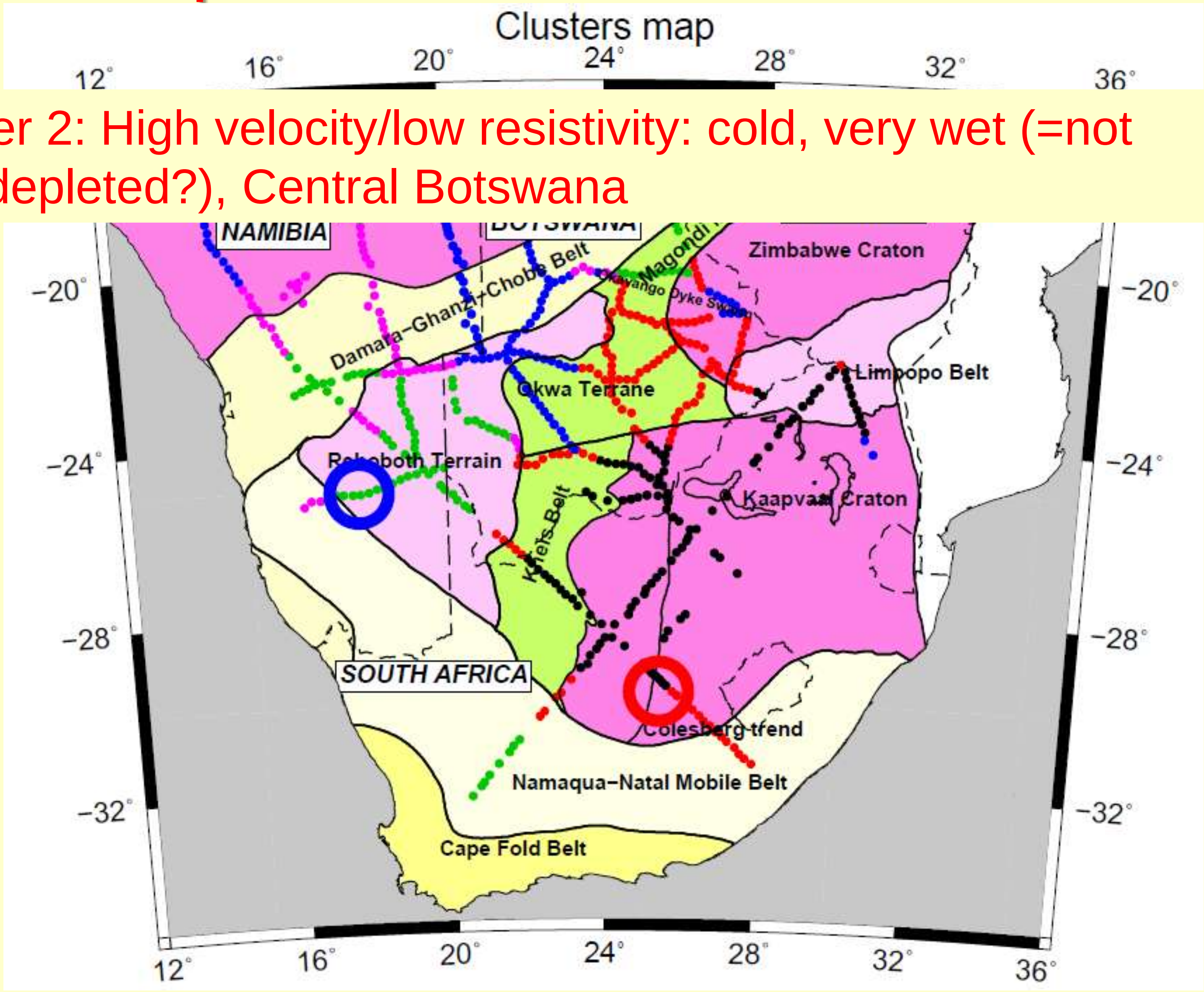
Cluster map

Clusters map

Cluster 1: High velocity/variable resistivity: cold, variably wet (variably depleted?) Kaapvaal Craton

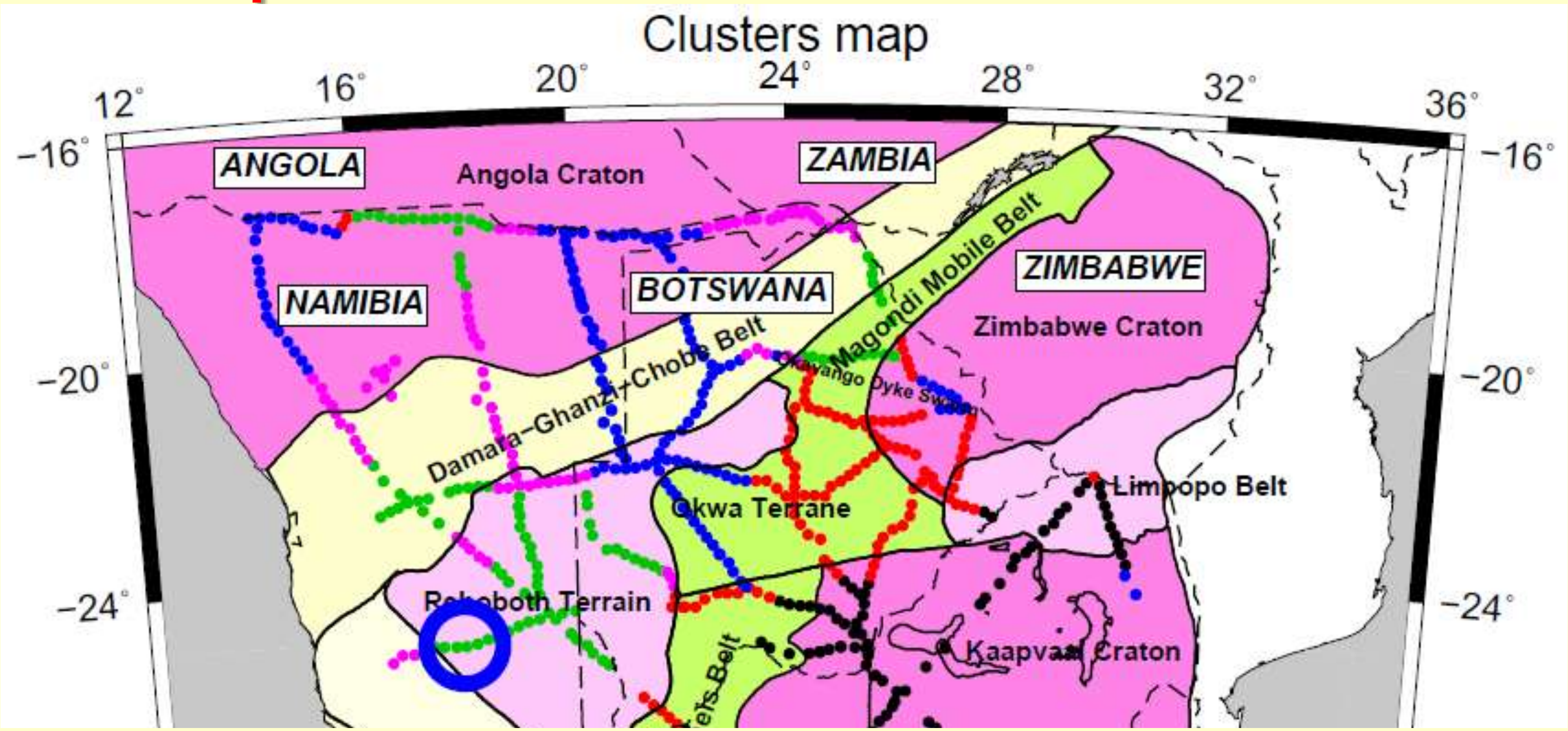


Cluster map

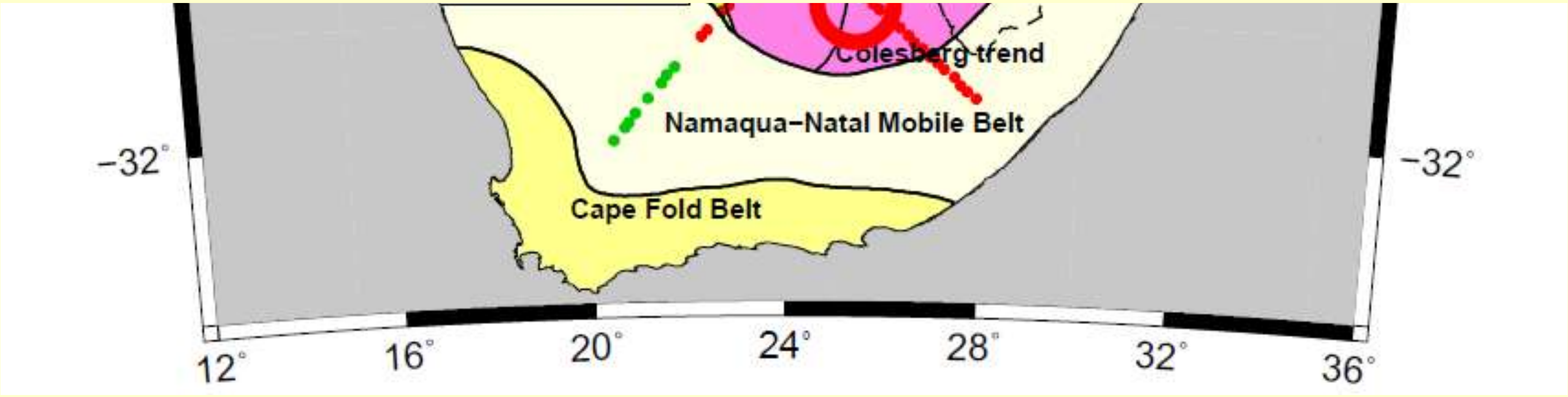


Cluster 2: High velocity/low resistivity: cold, very wet (=not very depleted?), Central Botswana

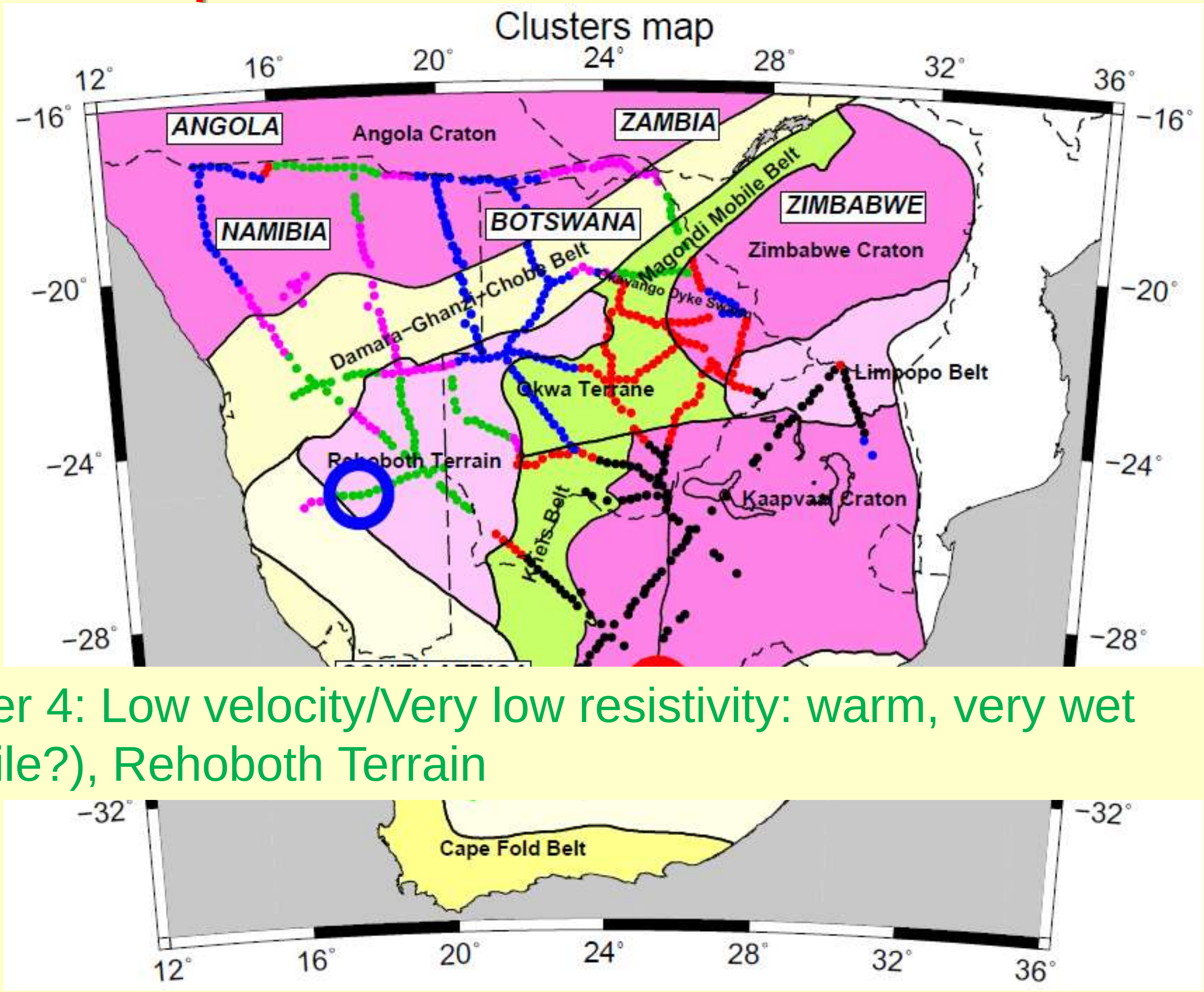
Cluster map



Cluster 3: Moderate velocity/low resistivity: warmer, very dry (=depleted?) Angola Craton

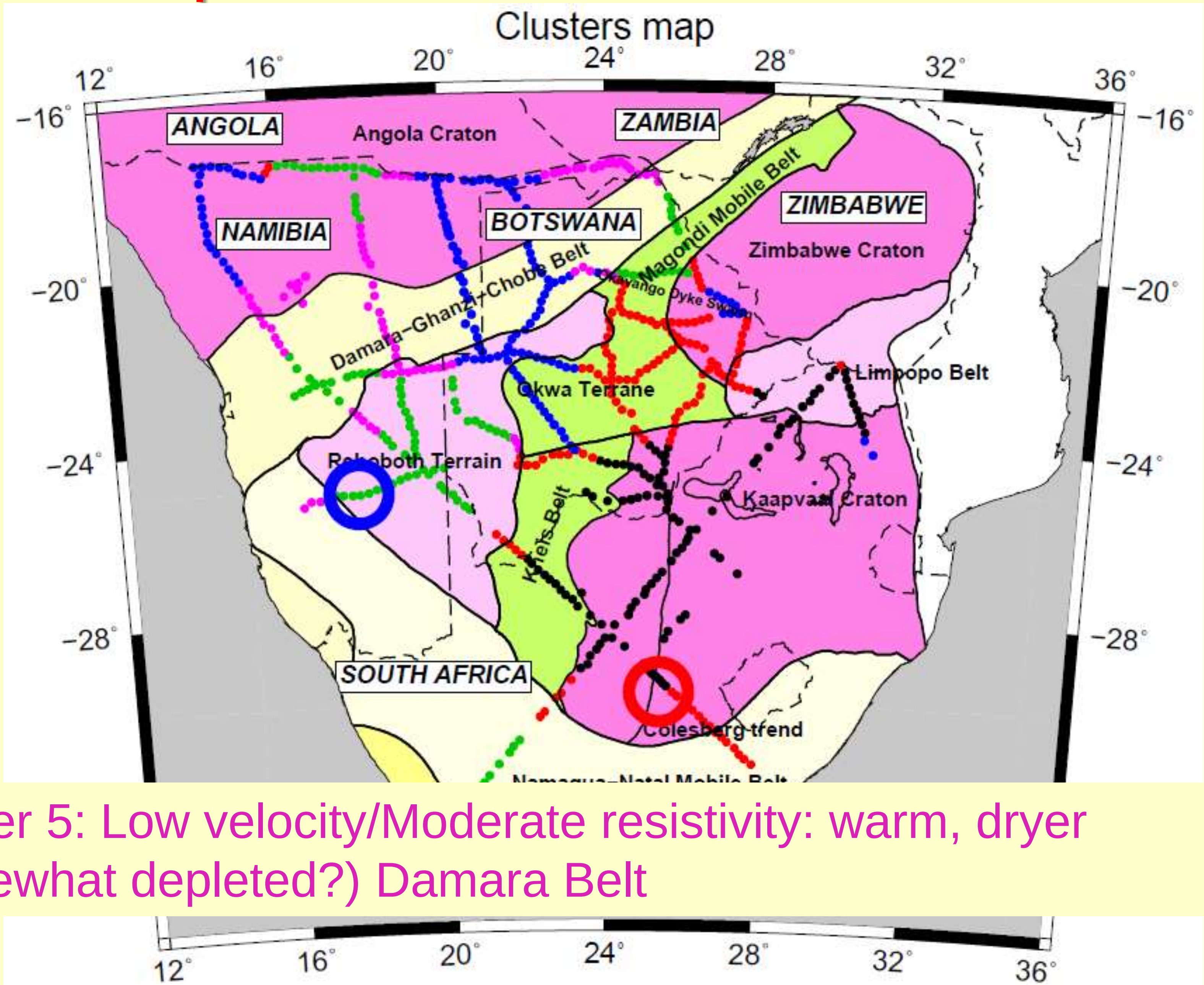


Cluster map



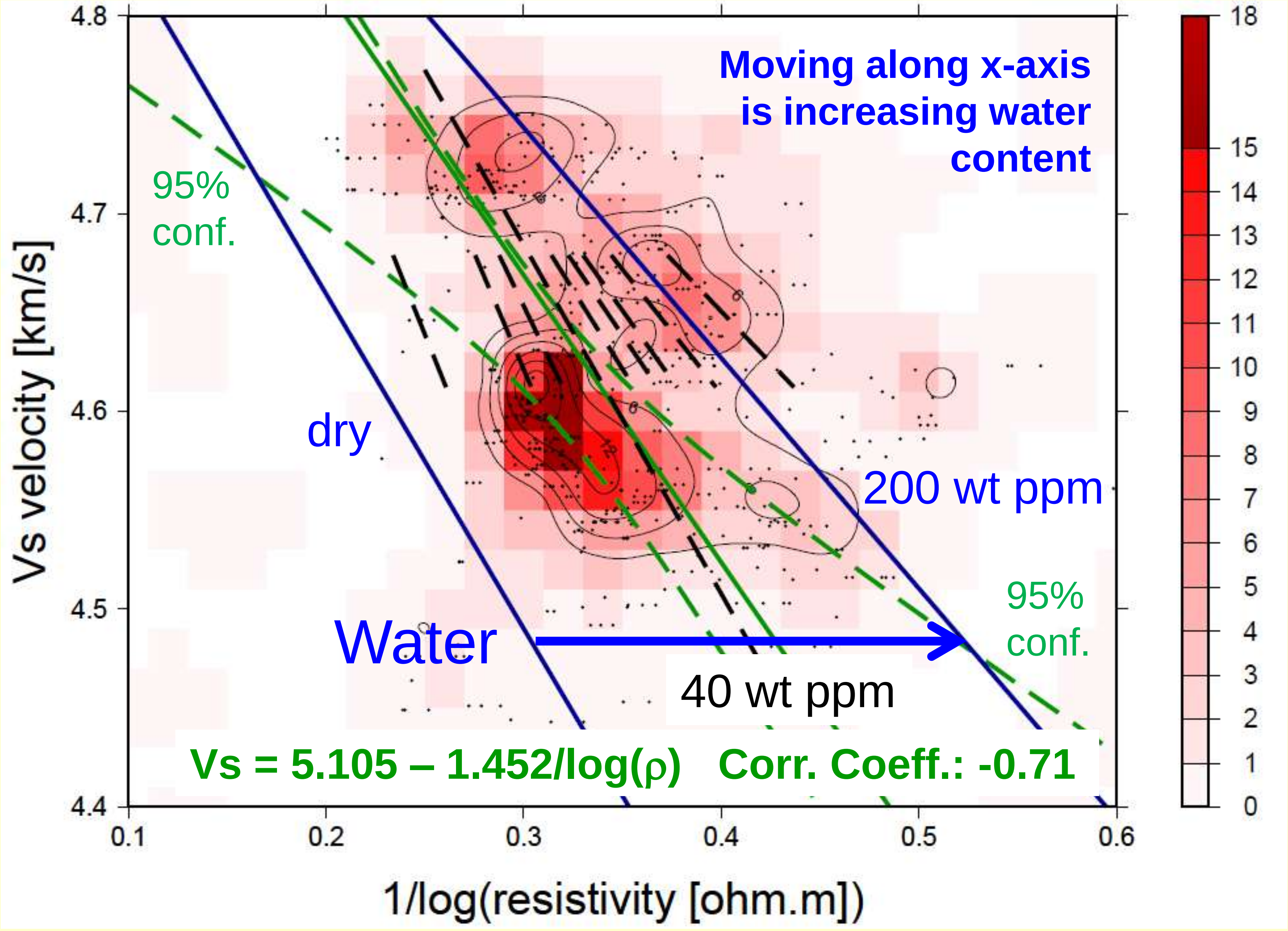
Cluster 4: Low velocity/Very low resistivity: warm, very wet (=fertile?), Rehoboth Terrain

Cluster map

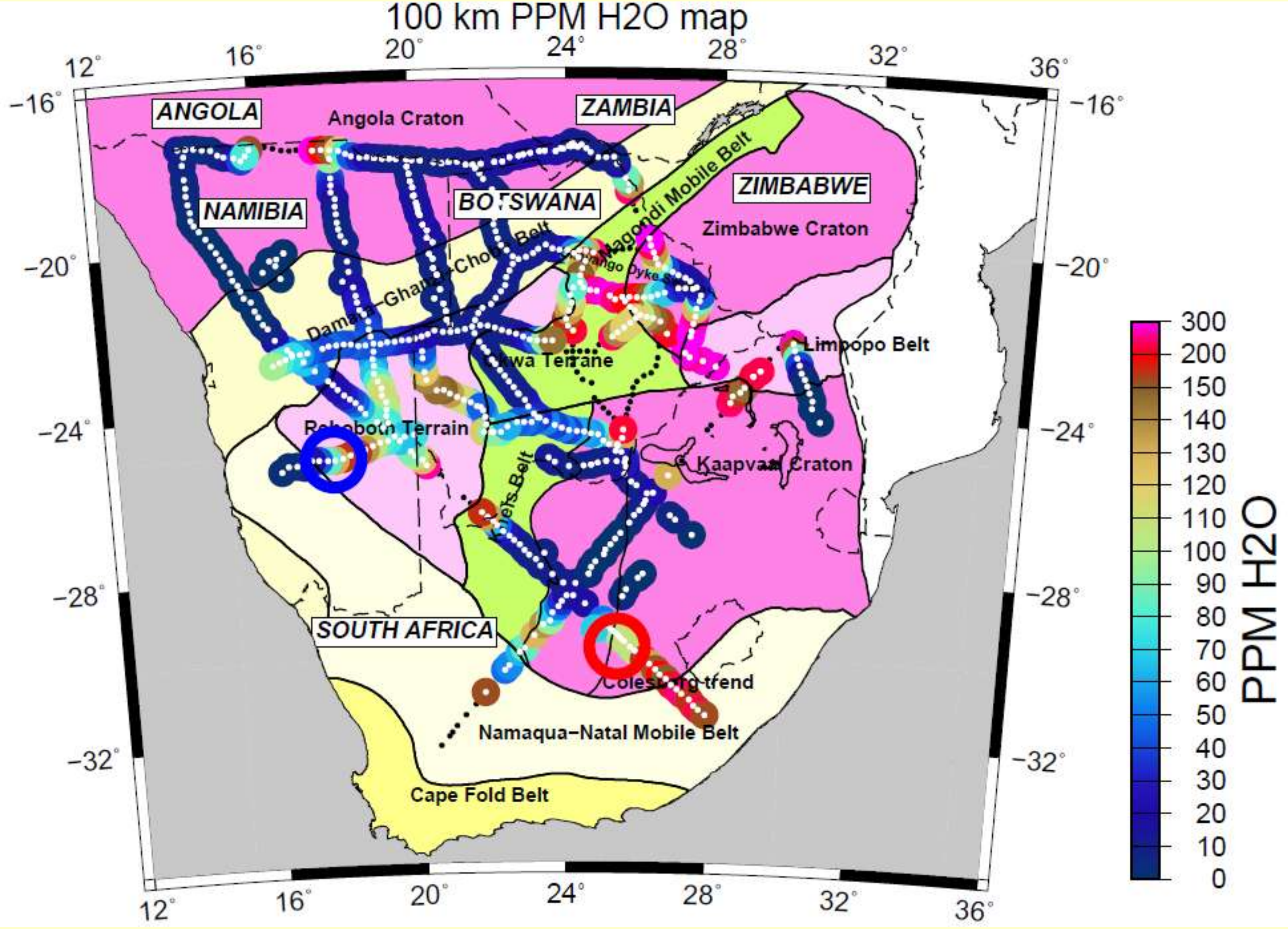


Cluster 5: Low velocity/Moderate resistivity: warm, dryer (somewhat depleted?) Damara Belt

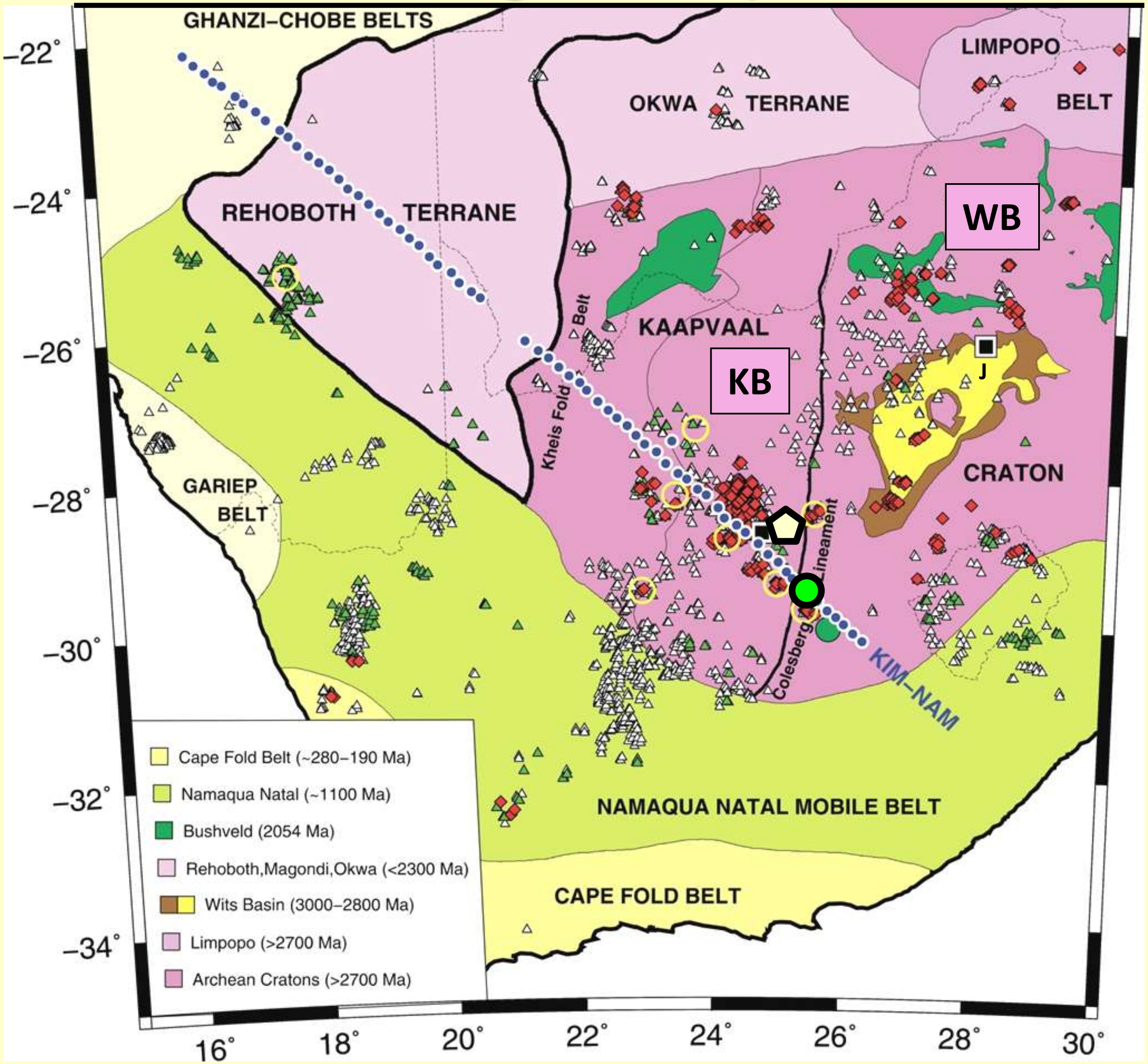
1/log(Rho)-VsF1.5d @ 100 km: Water



Water map @ 100 km (wt ppm in Olivine)



Tectonic setting – Kaapvaal Craton



Late Proterozoic

Mesoproterozoic

Early Proterozoic

Archaean

MT SITES

MT KIM015

Seismic station BOSA

KIMBERLITES

Diamondiferous

Non-diamondiferous

Unknown

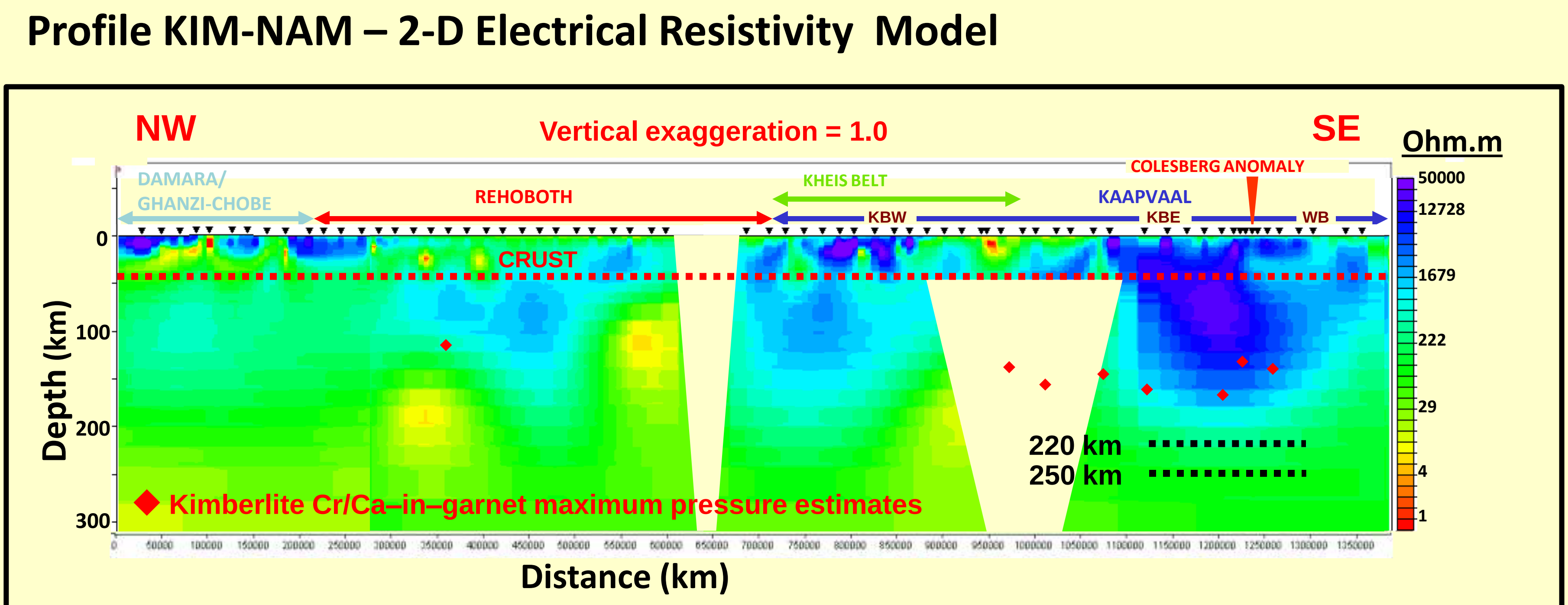
Garnet Cr/Ca data

KB = KIMBERLEY BLOCK

WB = WITWATERSRAND BLOCK

Digital terrane boundaries courtesy S. Webb, University of the Witwatersrand, Johannesburg.

Electrical resistivity structure from prior work

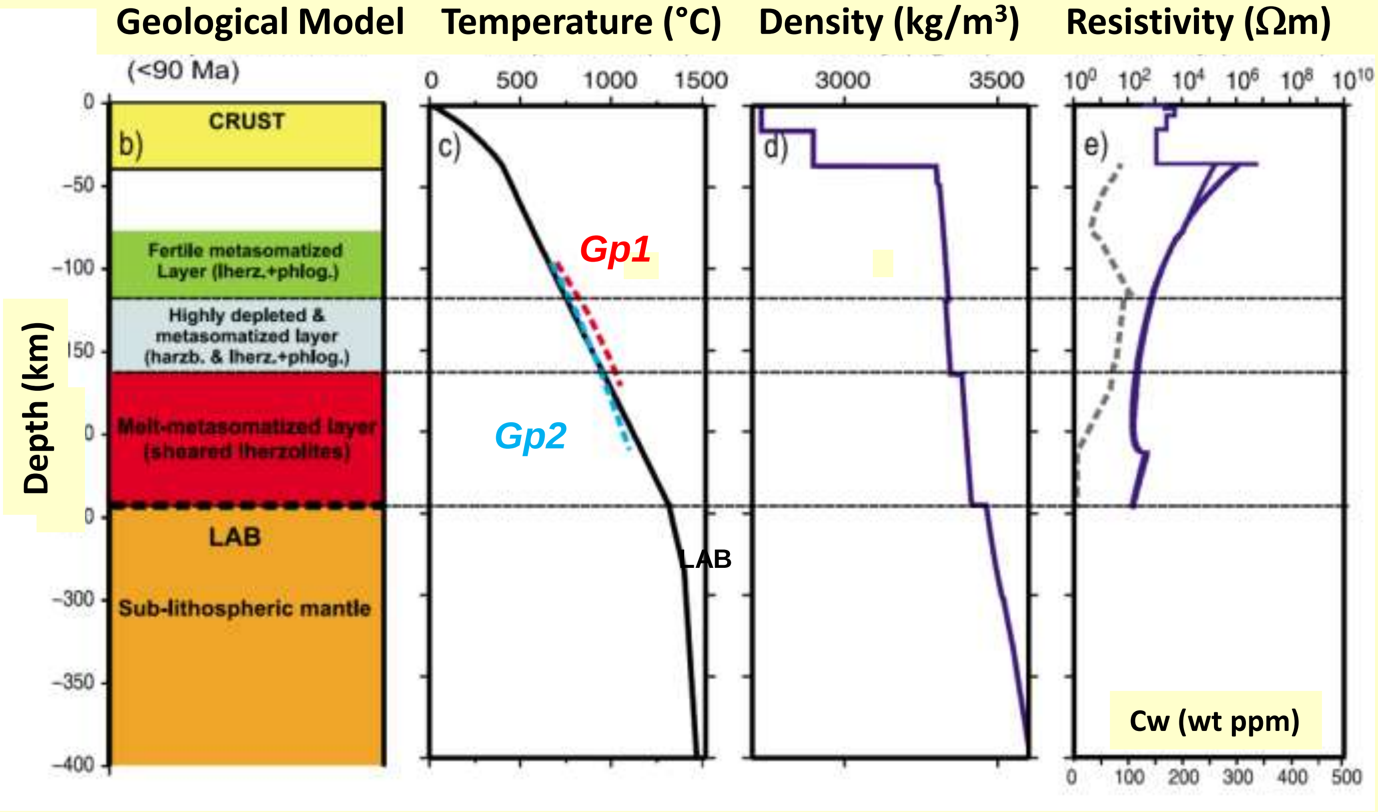


From: Muller et al., 2009, Lithos

- **eLAB depth: not shallower than 220 km**

Electrical resistivity structure from prior work

Self-consistent 1-D MT modelling at site KIM015 using LitMod code



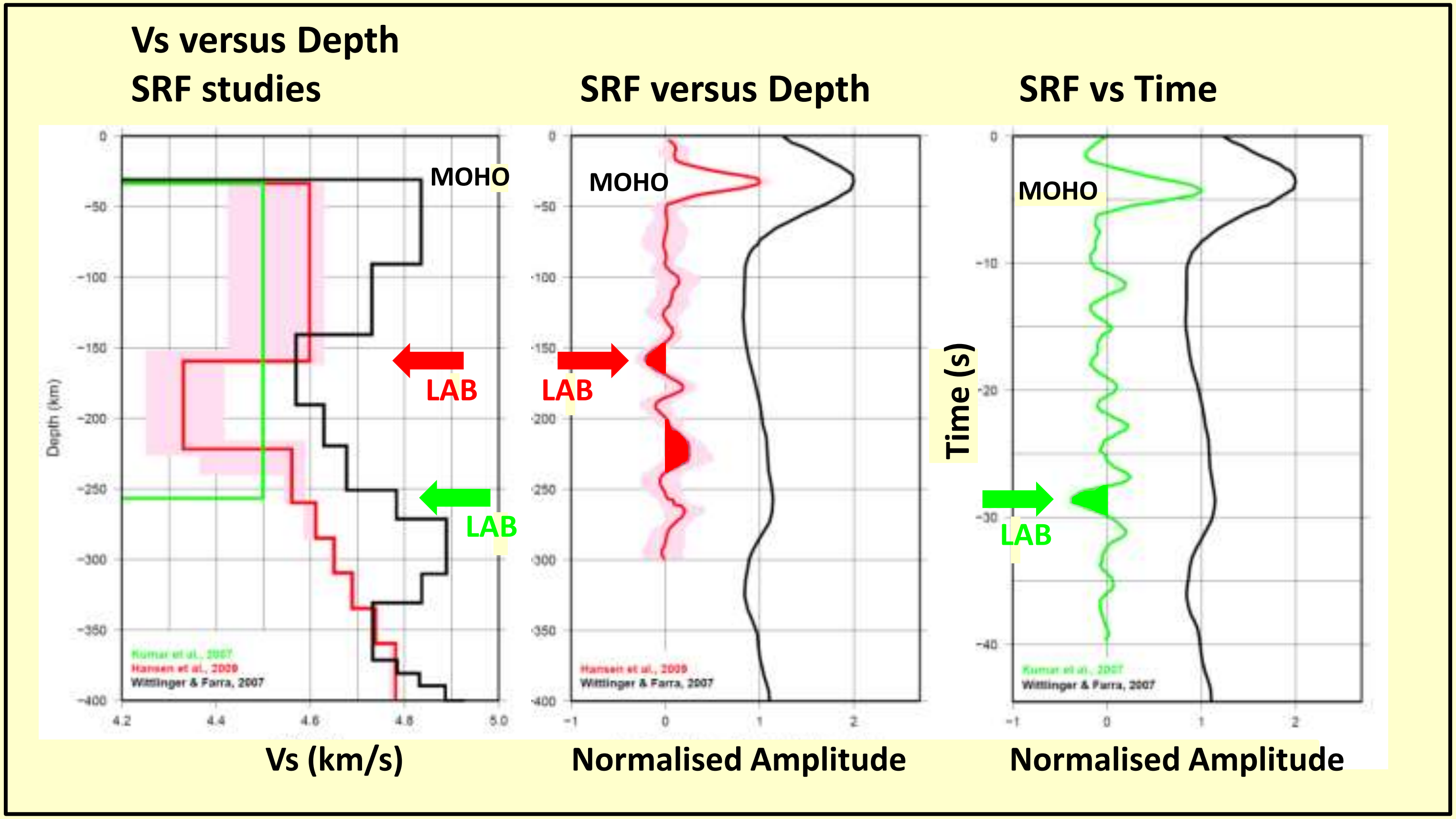
Fullea et al., 2011 JGR

- **eLAB depth: 240 km (depths up to 260 km acceptable)**
- **Lower lithospheric-mantle is dry**

sLABrf – results from previous SRF studies

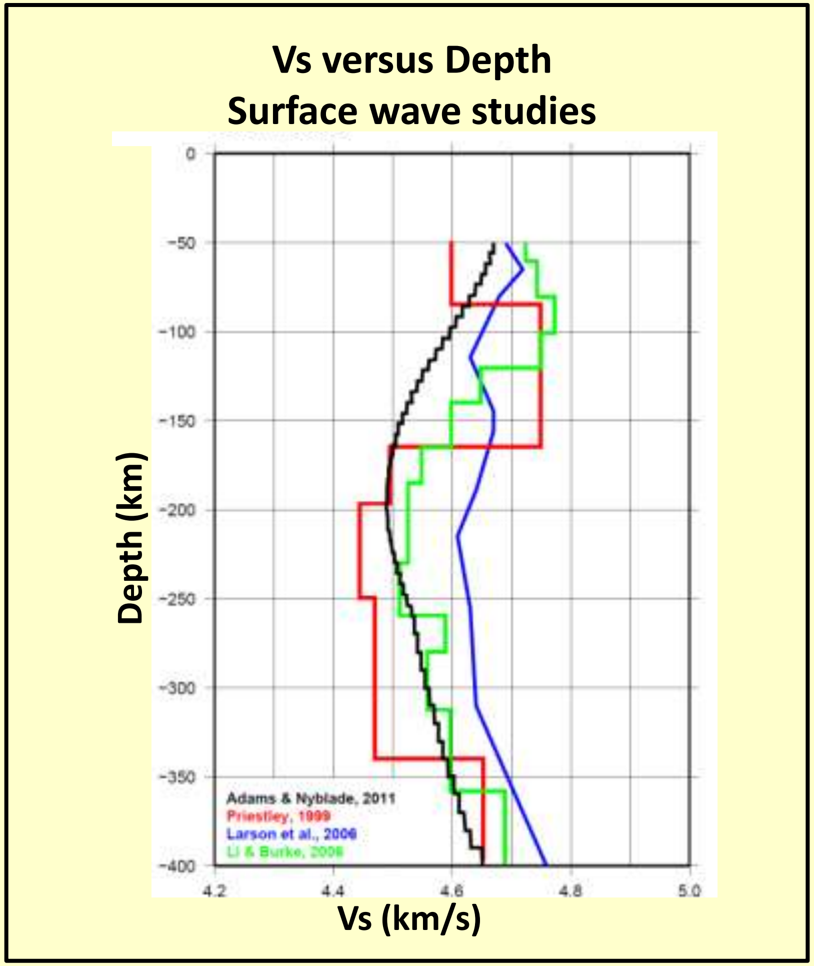
1. Understand the implications of “LAB” depths in recent S-wave Receiver Function (SRF) models.
   Wittlinger & Farra (2007)   Hansen et al. (2009)   Kumar et al. (2007)

2. Where is the base of the depleted lithospheric-mantle and where is the base of the conductive geotherm in these seismic models?



sLABsw – results from selected SW studies

1. Understand the implications of “LAB” depths in previous surface wave (SW) models.
2. Where is the base of the depleted lithospheric-mantle and where is the base of the conductive geotherm in these seismic models?



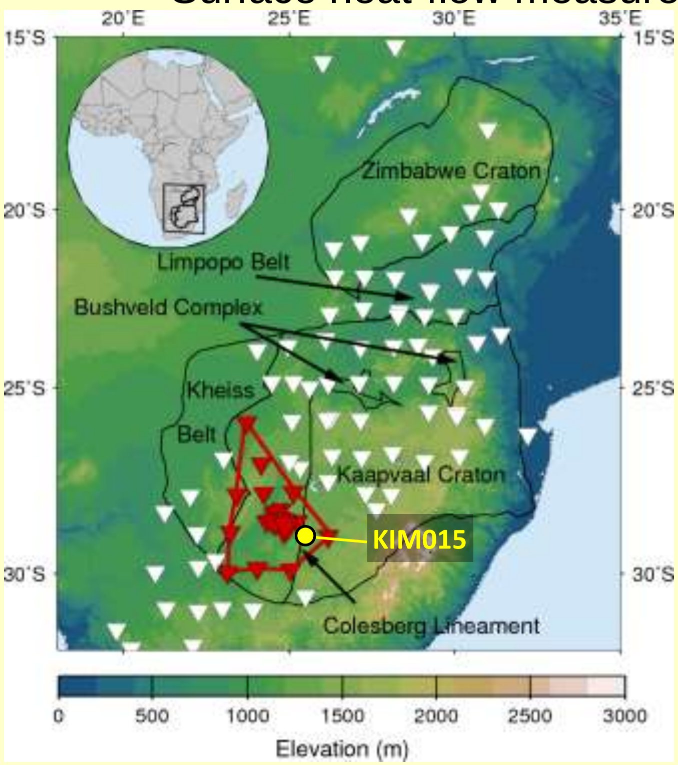
Adams & Nyblade (2011)
Priestly (1999)
Larson et al. (2006)
Li & Burke (2006)

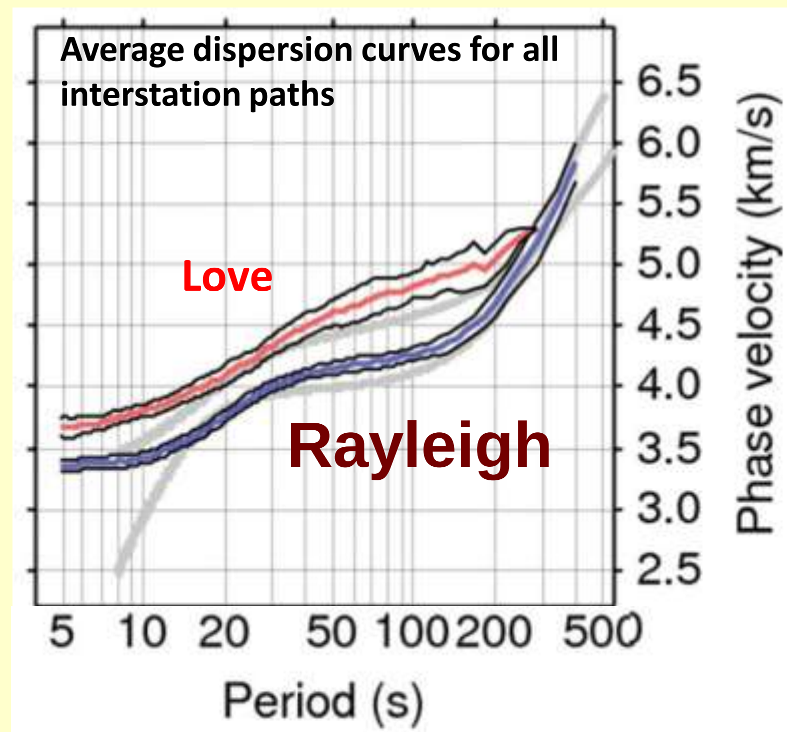
Objectives

To derive models of the chemical and thermal state of the lithospheric-mantle that ***self-consistently*** satisfy:

1. Xenolith constraints on mantle composition
2. Geophysical observables:

Surface wave (SW) dispersion data
Surface heat-flow measurements
Magnetotelluric (MT) data
Surface elevation





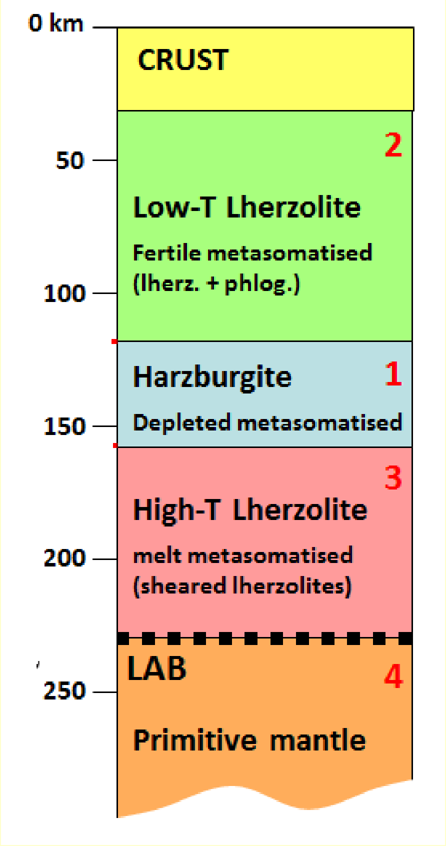
Data from: Adam and Lebedev (2012), GJI

LitMod modelling – mantle chemistry

- **Assigned chemical compositions for 3 representative average Kaapvaal lithospheric-mantle rock types and for primitive upper mantle.**

	1. Average Kaapvaal Harzburgite *	2. Average Kaapvaal Low-T Lherzolite *	3. Average Kaapvaal High-T Lherzolite *	4. Primitive Upper Mantle †
SiO_2	45.90	46.50	44.40	45.00
Al_2O_3	1.30	1.40	1.75	4.50
FeO	6.00	6.60	8.10	8.10
MgO	45.50	43.80	43.40	37.80
CaO	0.50	0.86	1.27	3.60
Mg#	93.10	92.20	90.50	89.30

**Afonso et al., 2008.*
†McDonough and Sun, 1995.

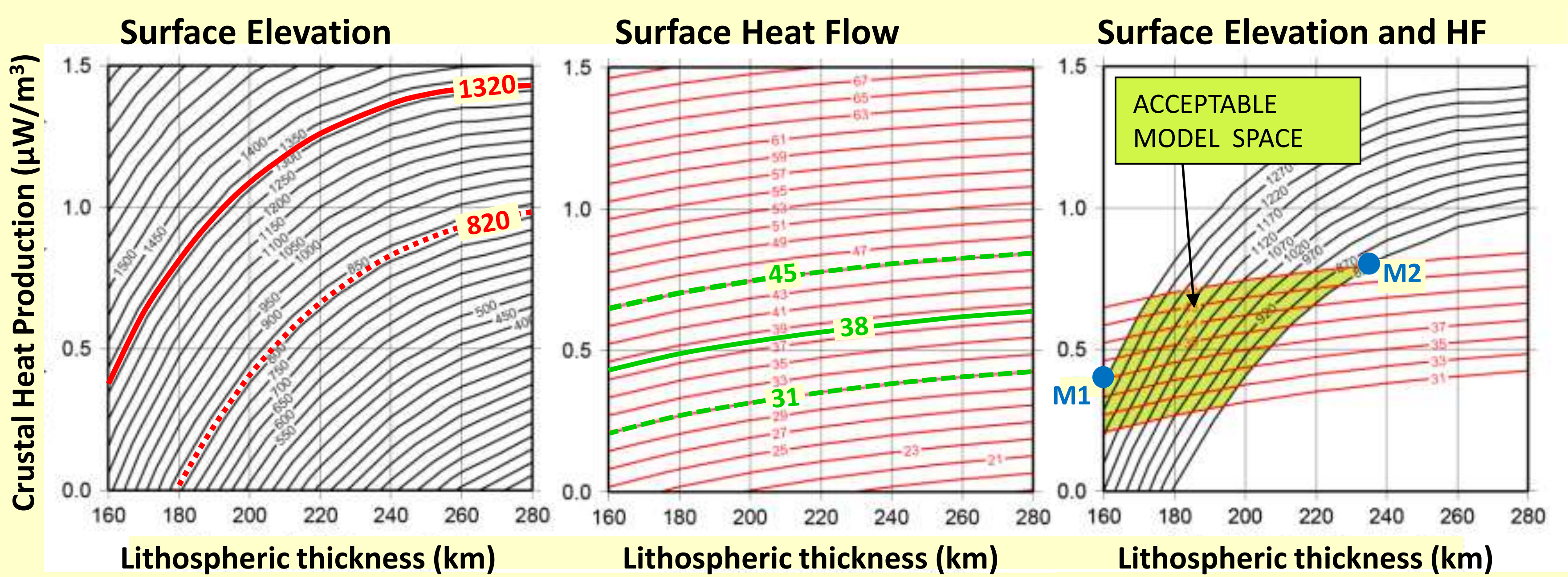


SHF and elevation vs crustal HP and lithospheric thickness

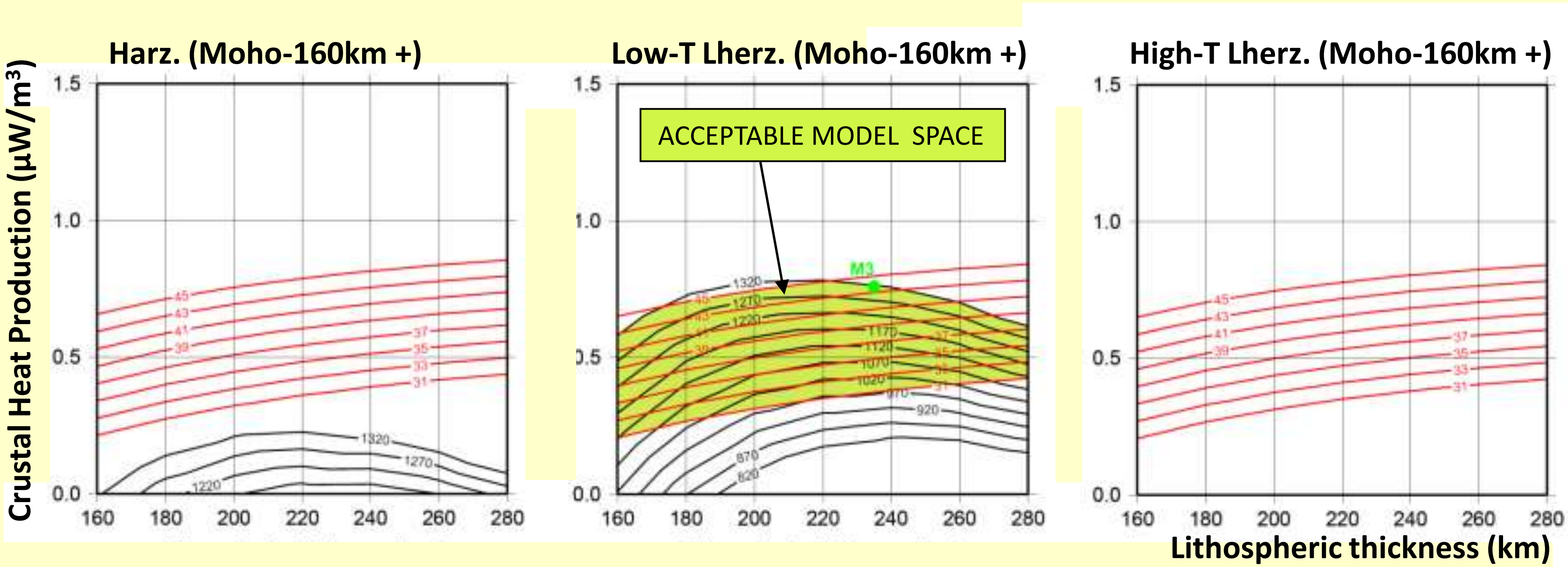
Data: Surface Elevation: 1320 m (up to 500 m dynamic topography)
Surface Heat Flow: 38 ±7 mW/m^2

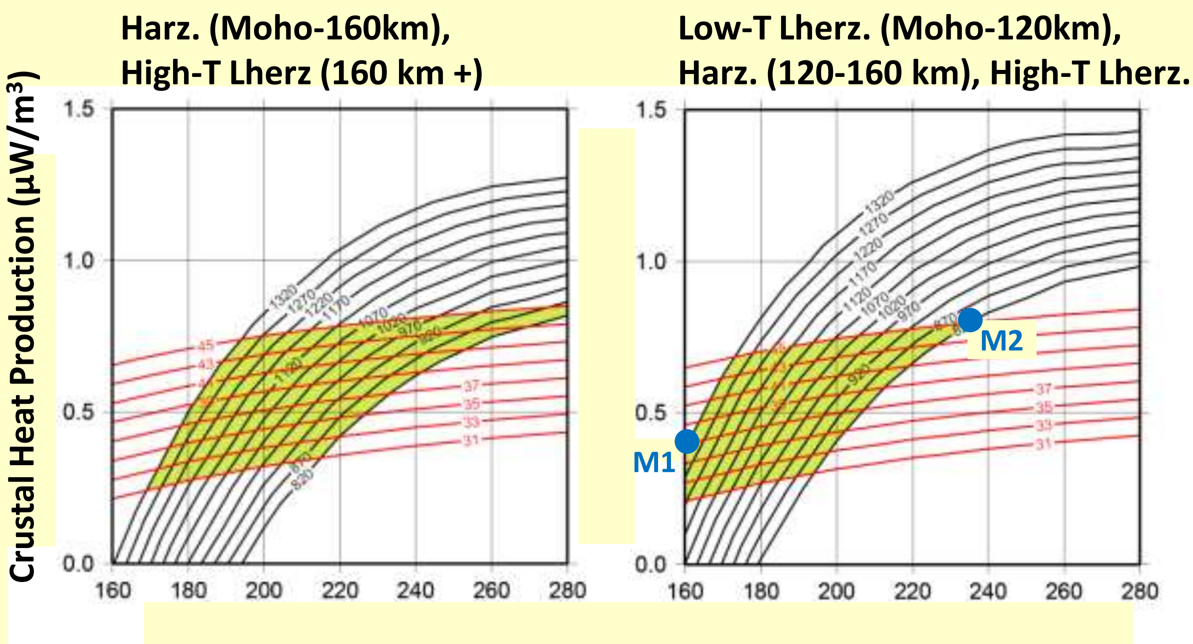
Models: M1: 160 km LAB M2: 236 km LAB

THREE-LAYER LITHOSPHERIC-MANTLE MODEL
Low-T Lherz. (Moho-120km), Harz. (120-160 km), High-T Lherz. (160 km +)



SHF and elevation vs crustal HP and lithospheric thickness

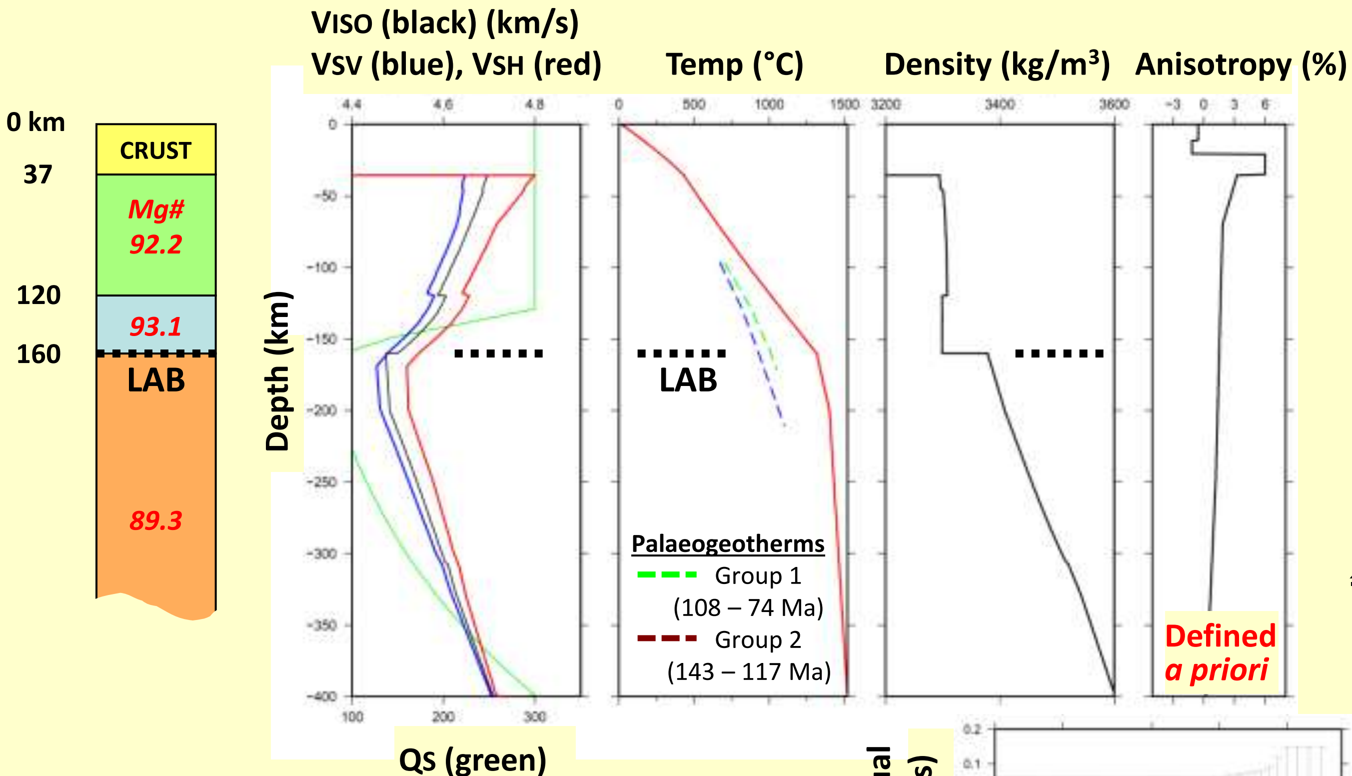




M1 & M2
Models examined in subsequent slides

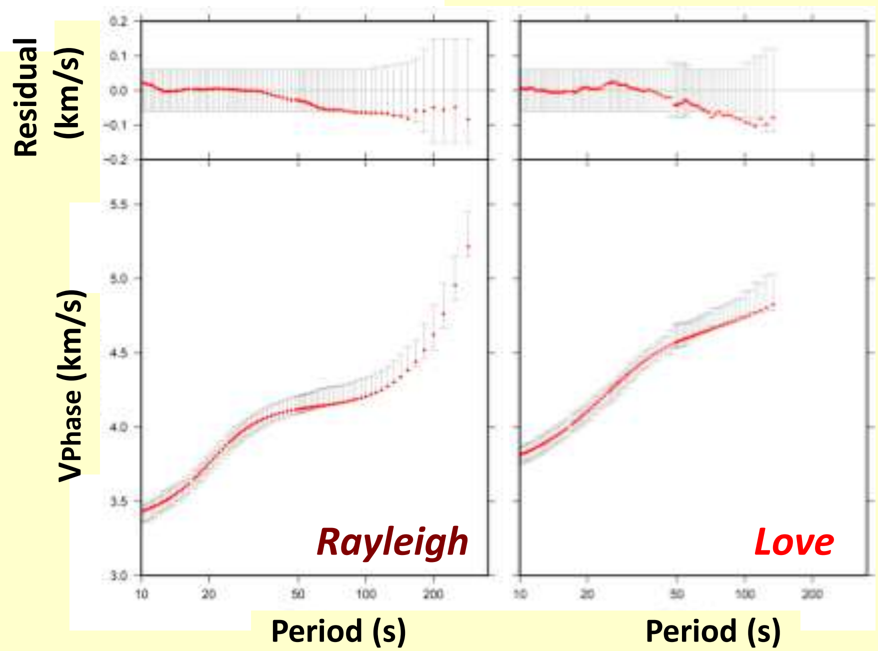
Model M1

- **160 km thick lithosphere**

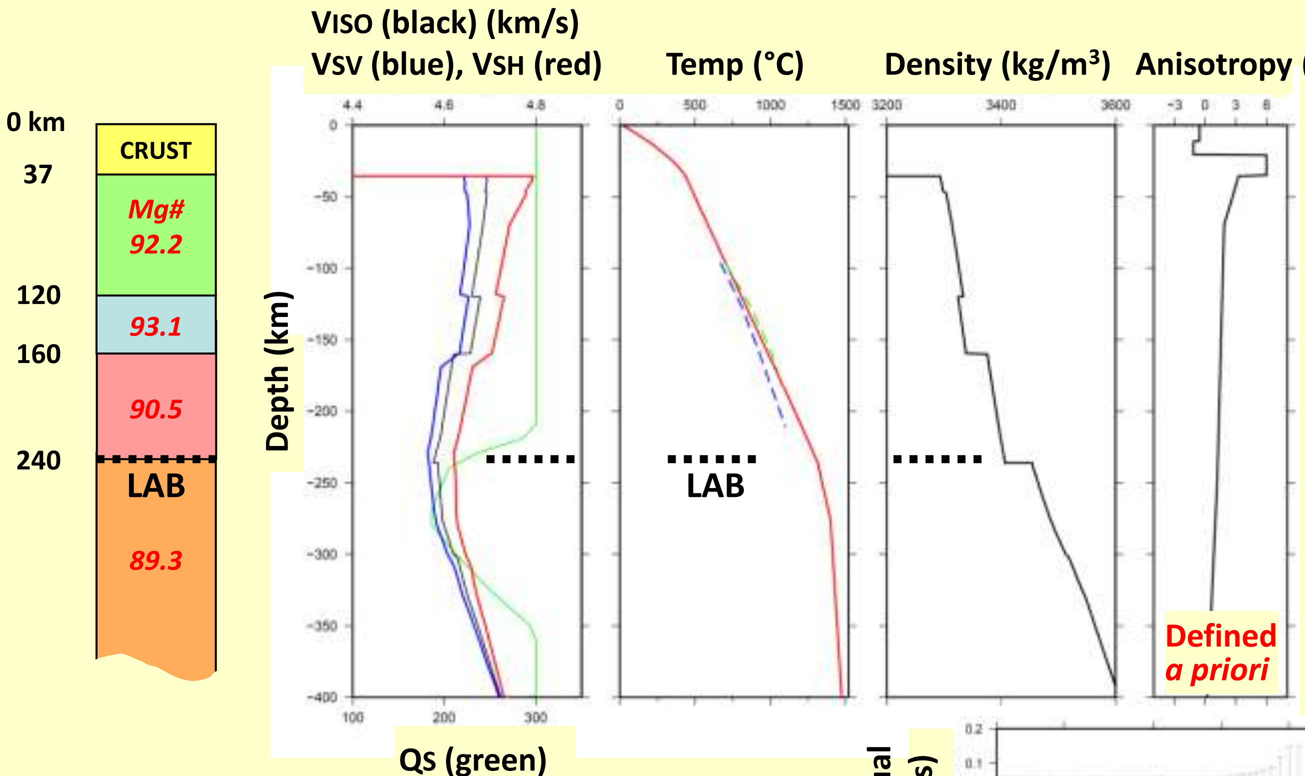


Xenolith palaeogeotherms
From: Griffin et al., 2003, Lithos

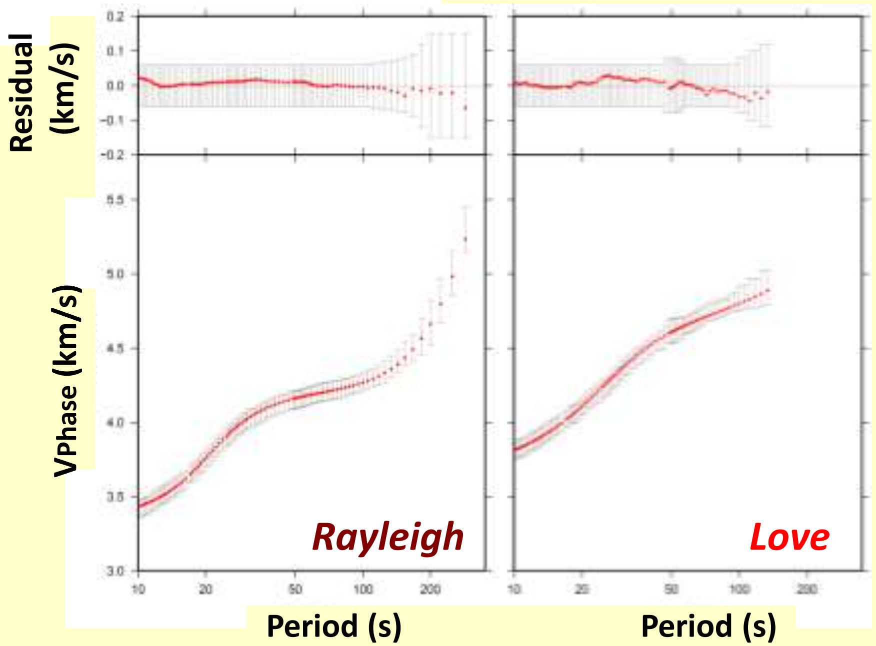
- Does **not** match SW dispersion data.
- Model does **not** fit 1-D MT response at site KIM015.
- Does **not** match either Gp I or Gp II palaeogeotherms.



Model M2

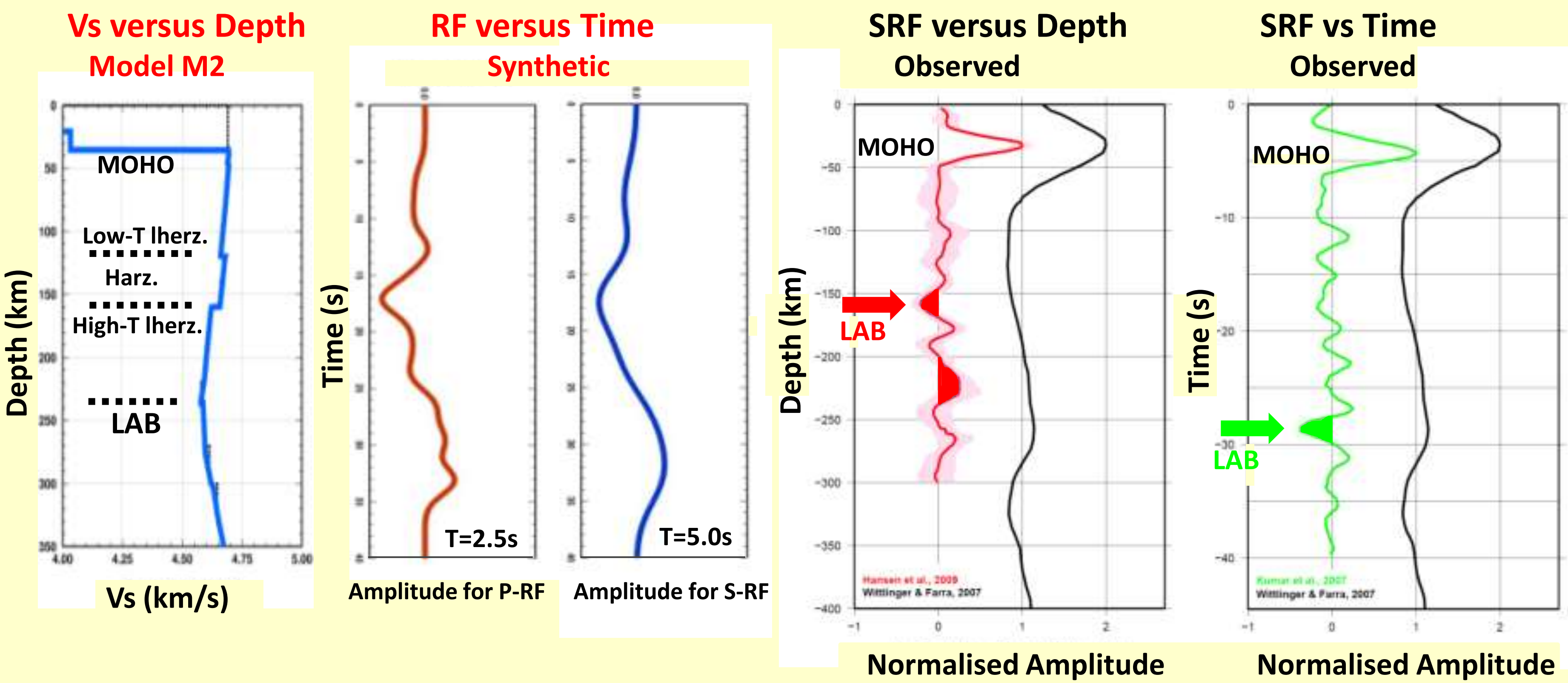


- 240 km thick lithosphere
- 3 chemical layers
- Preferred model



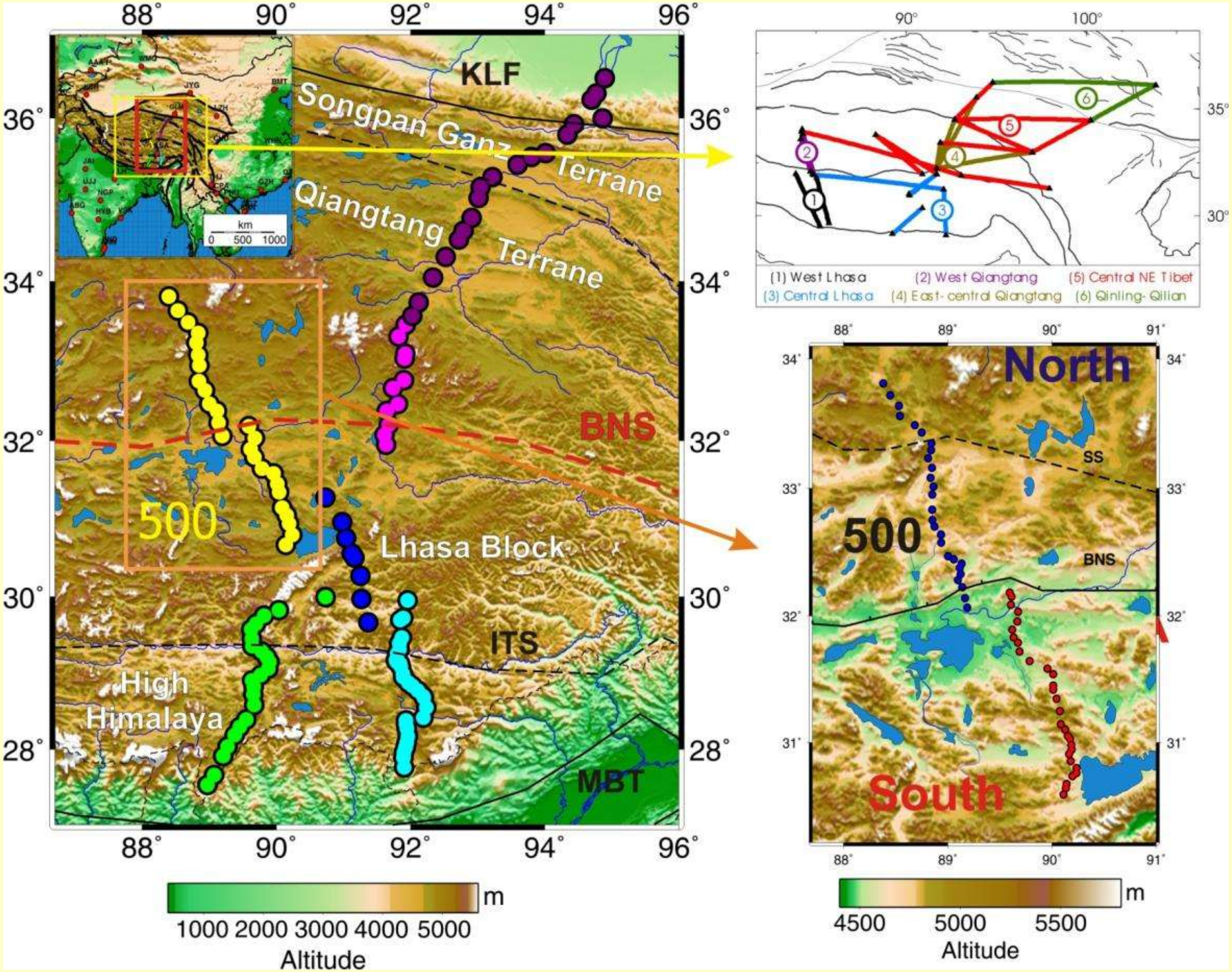
- Matches SW dispersion data well.
- Model fits 1-D MT response at site KIM015.
- Matches more recent Gp I palaeogeotherms.
- Chemical boundary at 160 km depth may account for SRF event at this depth.

Synthetic SRFs



➔ Infer that the **chemical transition at 160 km depth** – depleted harzburgite to (refertilised) high-T lherzolite – in our preferred model **accounts for observed SRF conversion event** at this depth.

Application to Southern & Central Tibet



LitMod1D inversion

Thermodynamically-consistent petrophysical-geophysical based 1D inverse modelling of data from southern (Lhasa terrane) and central (Qiangtang terrane) Tibet

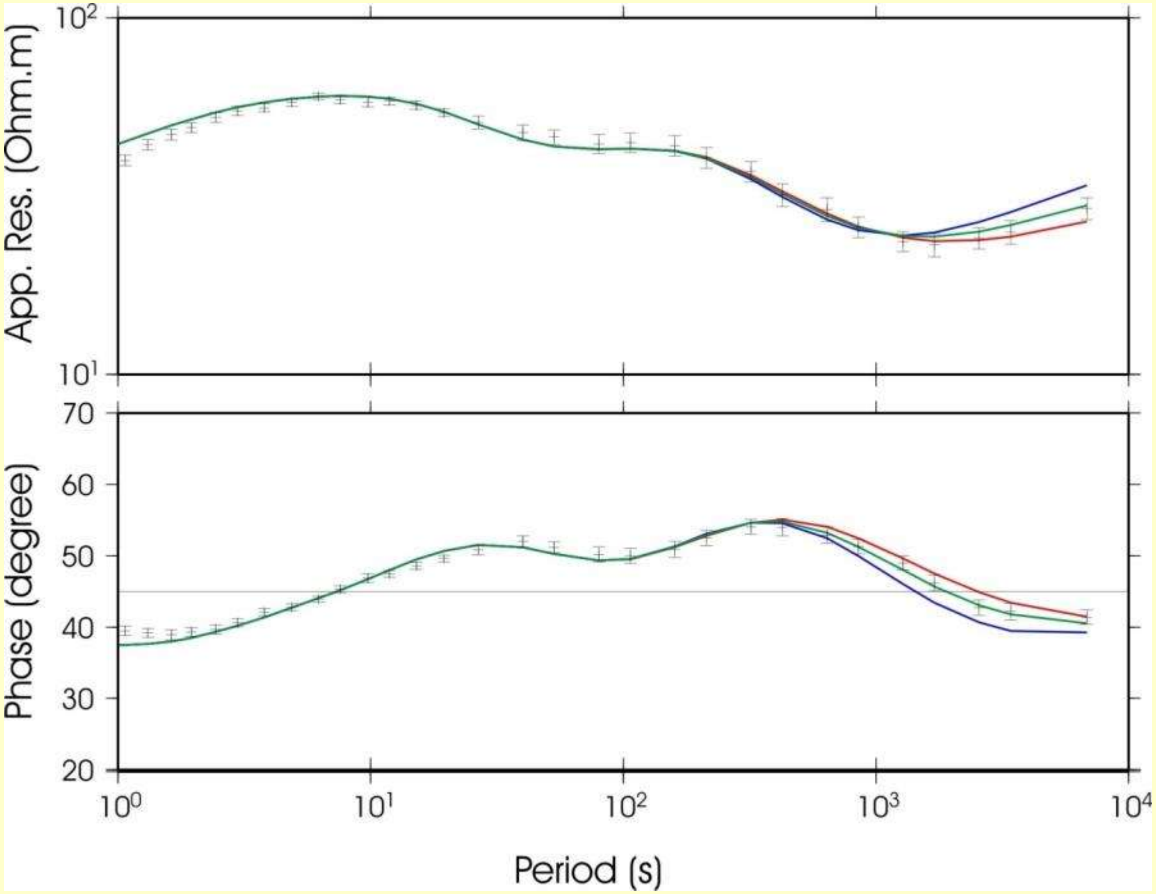
Data:

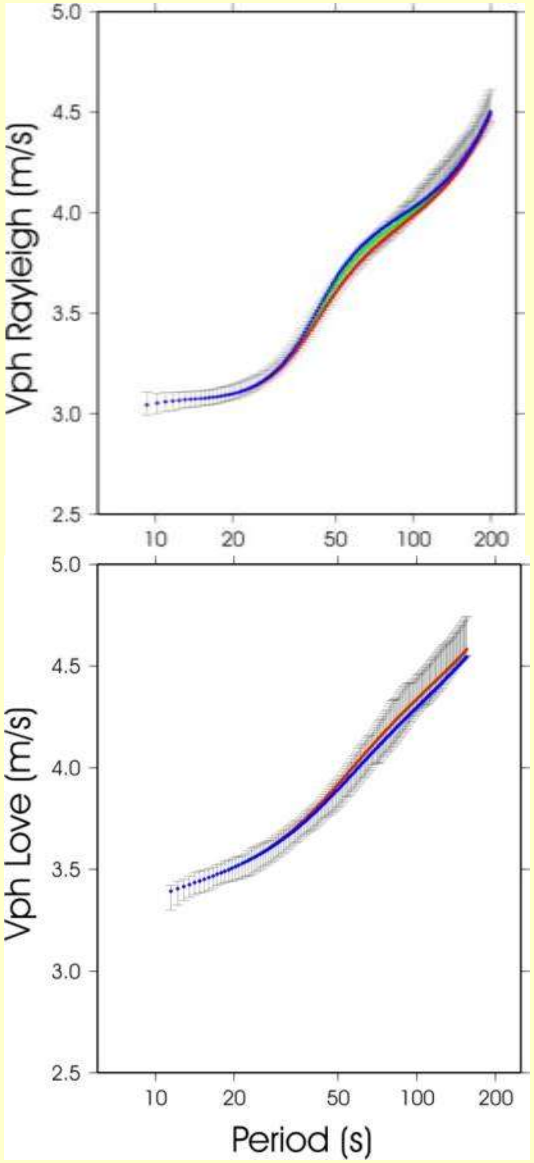
- MT data from two representative deep-penetrating 1D sites in Qiangtang Terrane and Lhasa blocks
- Surface wave dispersion curves from paths within the two blocks
- Heat flow
- Topography

Qiangtang Terrane

Calculated values: surface heat flow 67μW/m³, elevation 4920m.
LAB in depths:

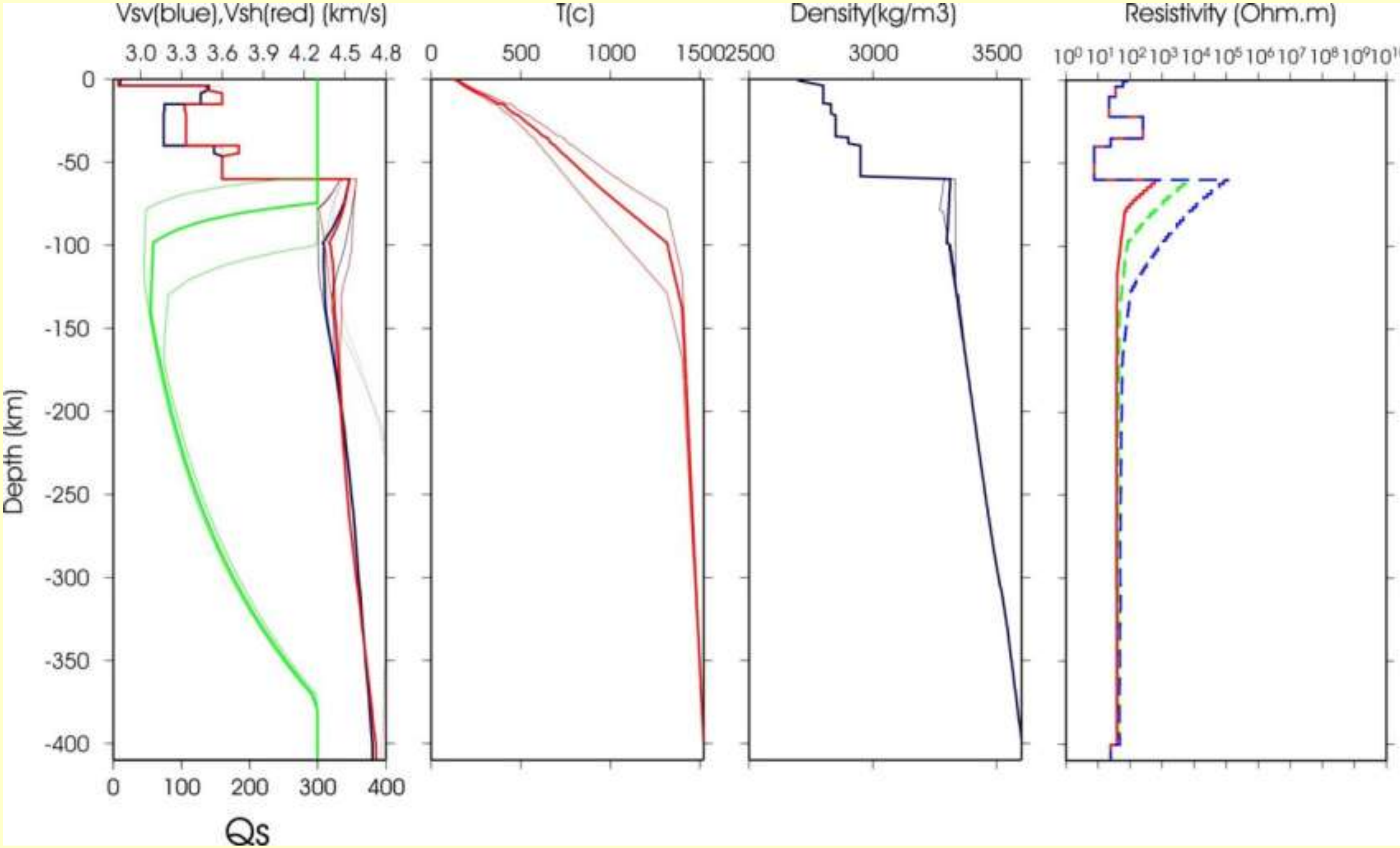
- 80 km
- **100 km**
- 120 km





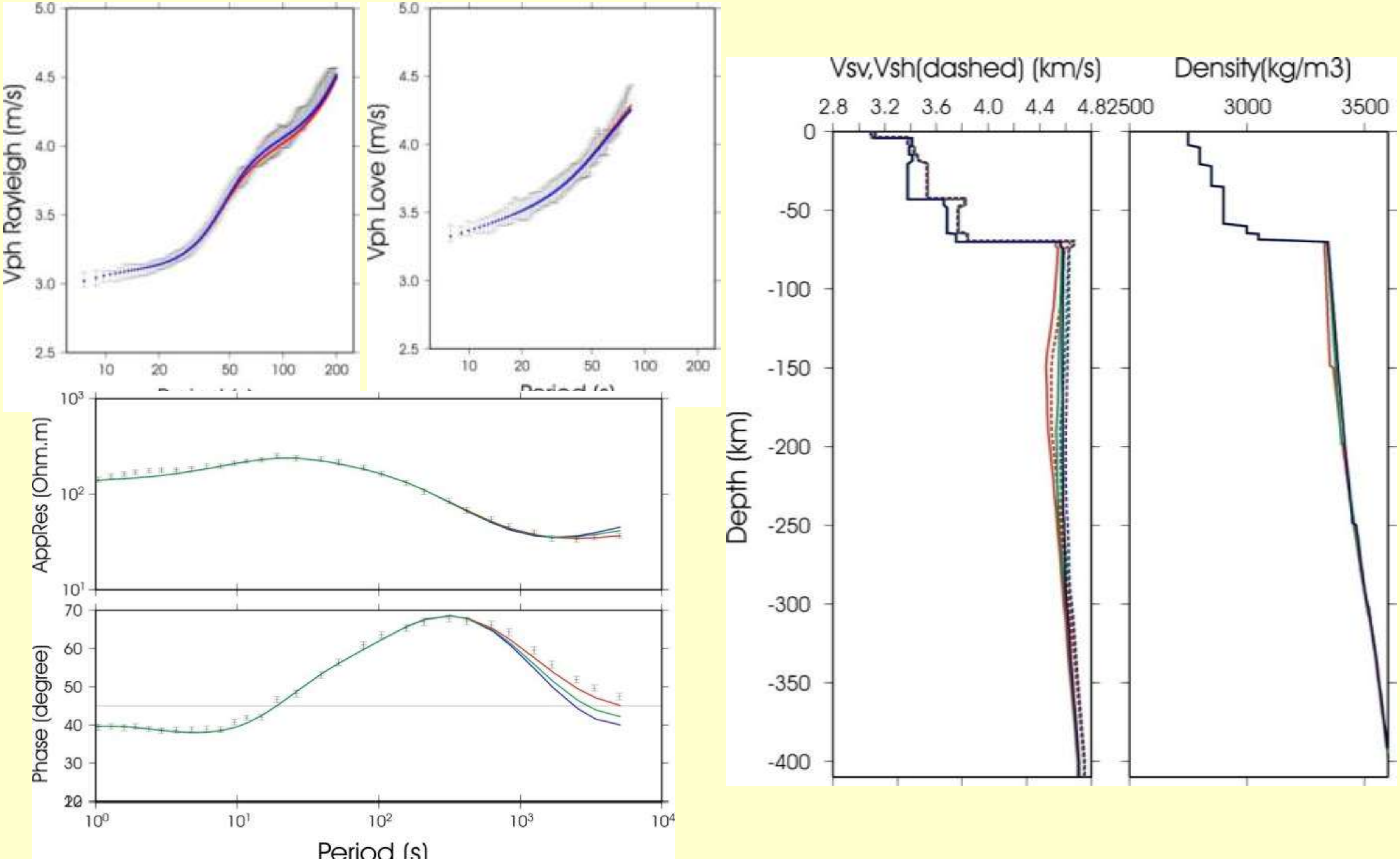
Qiangtang Terrane

Dry lithosphere. Densities of the crust, heat production, thermal conductivity (Jimenez-Munt et al, 2008; Christensen and Mooney, 1995). LAB in depths: 80 km, 100 km, 120 km.
Upper and lower bounds are displayed by thinner lines



Lhasa Terrane

Dry lithosphere, densities of crust, heat production, thermal conductivity (Jimenez-Munt et al, 2008 & Hetenyi et al., 2007) LAB in depths: 150 km 200 km 250 km

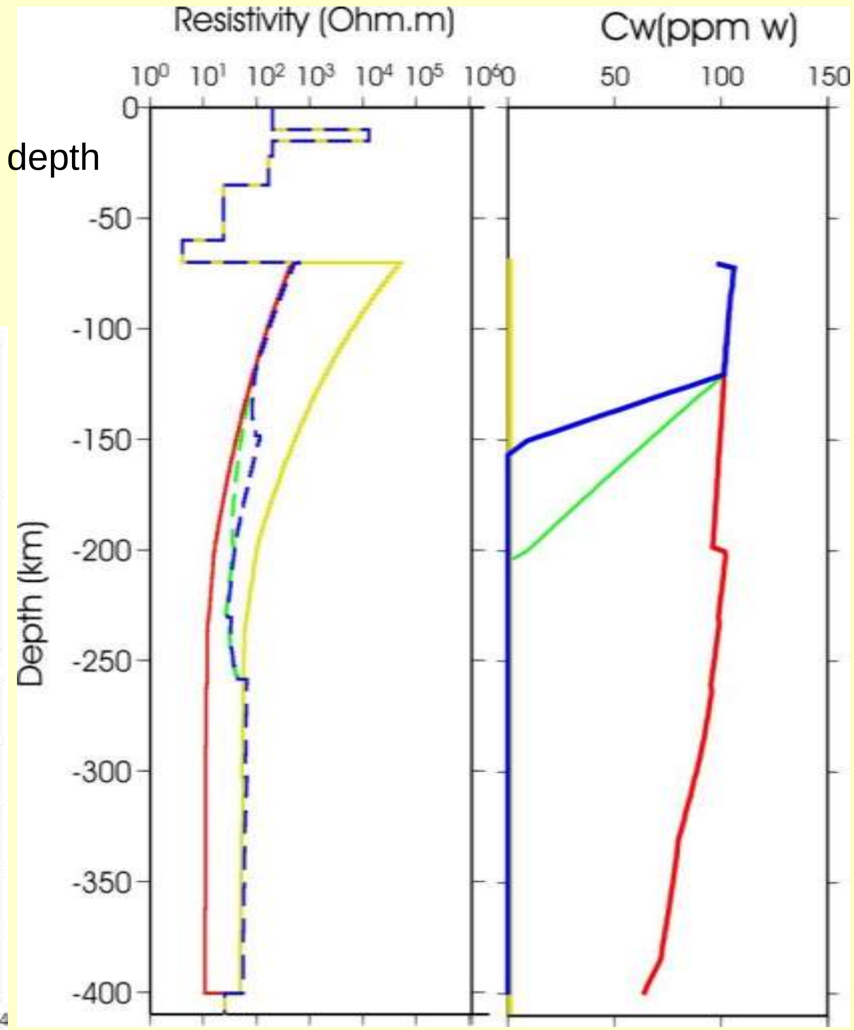


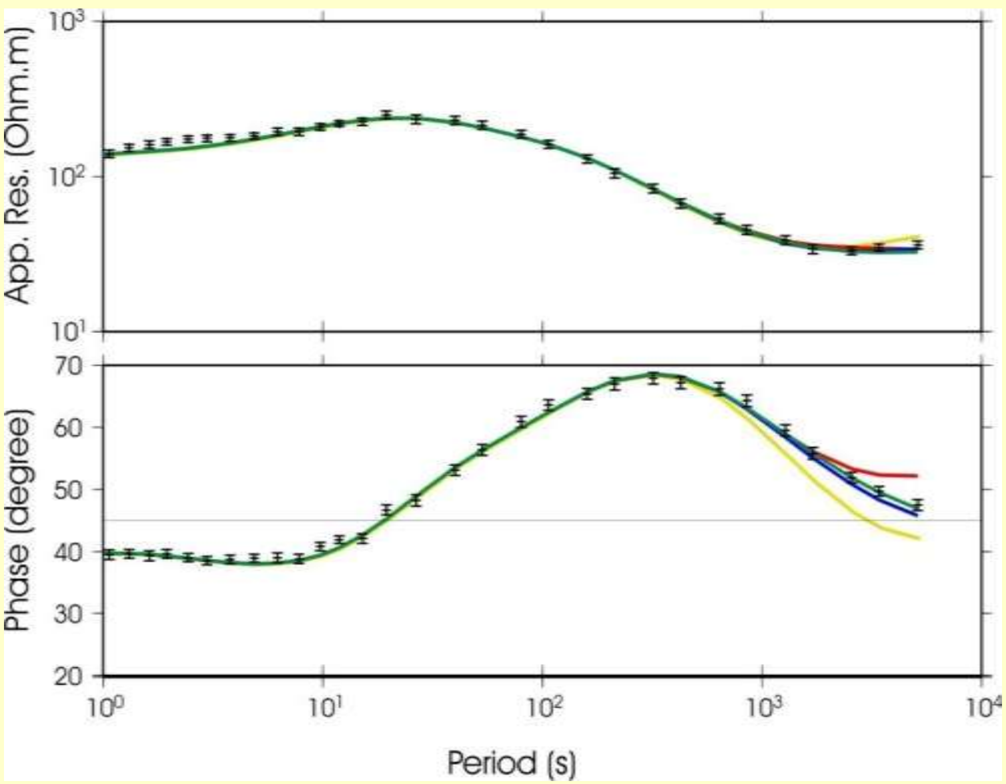
Lhasa Terrane

Calculated values: surface heat flow 61 μW/m³, elevation 4850m.
Wet lithospheric and sub-lithospheric mantle: —
Different distribution of water content in mantle with linear decrease to: — **150 km**
— **200 km**

Dry lithospheric and sub-lithospheric mantle (for the LAB in depth 200 km): —

Bulk water content in the mantle





Conclusions

- **Seismology primarily sensitive to [P,T,Comp]**
- **Electrical resistivity primarily sensitive to [T,H2O]**
- **Taken together estimates of temperature and water content can be made**
- **Topography significantly constrains lithospheric thickness – but have to have exquisite knowledge of crustal parameters**
- **Lithospheric mantle appears to be wetter in the upper part and dry in the lowermost part**

Take-home message

We must STOP looking only at one type of data!!!

A change in velocity or electrical conductivity or thermal conductivity or density has effects on most of the others

Undertake modelling of your data taking into account the constraints from other data in a quantitative formal manner

We have far more data than we use – for example topography, geoid, heat flow is available almost everywhere

Also, check your data – if it seems unreasonable, there is probably something wrong with your data or your interpretation!

Best approach to use is one that models all if the data, is thermodynamically self-consistent, and is based on petrology and geophysics