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

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

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)
Observed SRF interface interpreted as the LAB (sLABrfe)

Dramatic lithospheric thinning from 85 km to 55 km

Reasonable???

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

- Geoid anomaly ($n>10$) EGM 2008
- FA anomaly (Smith & Sandwell 97)
- Bouguer anomaly (land + satellite data)
- Elevation (ETOPO2 V9.1)
- Heat Flow
Geophysical observables:

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
Ireland’s thermal regime: LitMod 1D modelling

Data:
Topography: 60 ±20 m
Surface heat flow: 60 ±5 mW/m²

Crustal parameters: (all based on data)
Moho depth: 30 ±2 km
Crustal density: Upper (to 20 km): 2780 ±50 kg/m³
Crustal density: Lower (to 30 km): 3100 ±50 kg/m³
Heat production: 1.00 x 10⁻⁶ W/m³ (0.74-1.38 W/m³)
Thermal cond.: 2.5 ±0.5 W/m/K
Thermal expans.: 2.5x10⁵ ±0.25 K⁻¹
Compressibility: 1.33x10⁻¹¹ ±0.27x10⁻¹¹ Pa⁻¹
# Ireland’s thermal regime: LitMod 1D modelling

**Oxide Chemistry (NCFMAS system):**

<table>
<thead>
<tr>
<th>Description</th>
<th>Depleted</th>
<th>Fertile</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oxides</strong></td>
<td>Inver Average</td>
<td>Average Tecton Peridotite</td>
</tr>
<tr>
<td>SiO2</td>
<td>42.5</td>
<td>44.4</td>
</tr>
<tr>
<td>Al2O3</td>
<td>1.9</td>
<td>2.6</td>
</tr>
<tr>
<td>FeO</td>
<td>8.4</td>
<td>8.2</td>
</tr>
<tr>
<td>MgO</td>
<td>45.8</td>
<td>41.1</td>
</tr>
<tr>
<td>CaO</td>
<td>0.6</td>
<td>2.5</td>
</tr>
<tr>
<td>Na2O</td>
<td>0.05</td>
<td>0.18</td>
</tr>
<tr>
<td>Mg#</td>
<td>90.7</td>
<td>89.9</td>
</tr>
</tbody>
</table>

- 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
### Ireland’s thermal regime: LitMod 1D modelling

#### SHF & Topography from varying LAB:

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

To fit the SHF & topo data, LAB must be between 95 – 120 km
Ireland’s thermal regime: LitMod 2D modelling

1: Upper crust
2: Lower crust
3: Northern Ireland lithospheric mantle
4: Southern Ireland lithospheric mantle
5: Asthenosphere
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

**Three-zone lithosphere:**
*Depleted to S: Fertile to N*

- 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

**Maximum thinning possible of 20 km, from 110 km to 90 km**
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

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

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

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

- Diamondiferous
- Non-diamondiferous
- Unknown (to me!)
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 $\rho$ – quantify it?
Jagersfontein & Gibeon kimberlites

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

FRB = Jagersfontein
KGG = Gibeon

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mg#</th>
<th>Ol (%)</th>
<th>Opx (%)</th>
<th>Cpx (%)</th>
<th>Grt (%)</th>
<th>Sp (%)</th>
<th>P (kbar)</th>
<th>T (°C)</th>
<th>D (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRB983</td>
<td>93.2</td>
<td>68.72</td>
<td>24.50</td>
<td>4.24</td>
<td>0.91</td>
<td>0.32</td>
<td>30.5</td>
<td>760</td>
<td>98</td>
</tr>
<tr>
<td>FRB1007</td>
<td>93.2</td>
<td>70.28</td>
<td>23.84</td>
<td>2.56</td>
<td>1.79</td>
<td>0.32</td>
<td>39.1</td>
<td>881</td>
<td>106</td>
</tr>
<tr>
<td>FRB AV</td>
<td>93.2</td>
<td>69.50</td>
<td>24.17</td>
<td>3.40</td>
<td>1.35</td>
<td>0.32</td>
<td>31.8</td>
<td>782</td>
<td>102</td>
</tr>
<tr>
<td>KGG06</td>
<td>91.19</td>
<td>73</td>
<td>11</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>33.2</td>
<td>926</td>
<td>108</td>
</tr>
<tr>
<td>KGG05</td>
<td>92.30</td>
<td>76</td>
<td>12</td>
<td>4</td>
<td>7</td>
<td>0</td>
<td>33.5</td>
<td>872</td>
<td>109</td>
</tr>
<tr>
<td>KGG AV</td>
<td>91.75</td>
<td>74.5</td>
<td>11.5</td>
<td>6.5</td>
<td>7.5</td>
<td>0</td>
<td>33.35</td>
<td>899</td>
<td>108.5</td>
</tr>
</tbody>
</table>
Theoretical variation of $V_s$ and $\rho$

$V_s$ and $\rho$ both $F(P,T,M_{g\#},\text{Comp},H_2O)$

$\rightarrow$ Derive physical parameters (bulk & shear moduli and electrical conductivity) using lab-derived empirical relationships for individual minerals and combining them using Hashin-Shtrikman bounds

$\rightarrow$ Note: $V_s$ is linearly-dependent on $T$ whereas $\rho$ is exponentially-dependent
Laboratory-derived estimates of Vs and Log(resistivity) at Jagersfontein (FRG) and Gibeon (KGG) at 100 km depth for dry conditions (small polaron conduction)

<table>
<thead>
<tr>
<th>Location</th>
<th>Av. Vs (km/s)</th>
<th>σ</th>
<th>Av. Log_{10}(ρ)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jagersfontein</td>
<td>4.675</td>
<td>0.002</td>
<td>5.21</td>
<td>0.17</td>
</tr>
<tr>
<td>Gibeon</td>
<td>4.611</td>
<td>0.0055</td>
<td>4.36</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Mineral physics predictions:

**JAG:**  
Vs = 4.675  
log(ρ) = 5.21

**GIB:**  
Vs = 4.611  
log(ρ) = 4.36
Mineral physics estimates of Vs and Log(resistivity) at Jagersfontein (FRG) and Gibeon (KGG) at 100 km depth:

<table>
<thead>
<tr>
<th>Location</th>
<th>Av. Vs (km/s)</th>
<th>σ</th>
<th>Av. Log$_{10}$(ρ)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jagersfontein (-29.8°N, +25.4°W)</td>
<td>4.675</td>
<td>0.002</td>
<td>5.21</td>
<td>0.17</td>
</tr>
<tr>
<td>Gibeon (-25.1°N, +17.8°W)</td>
<td>4.611</td>
<td>0.0055</td>
<td>4.36</td>
<td>0.26</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Location</th>
<th>Av. Vs (km/s)</th>
<th>σ</th>
<th>Av. Log$_{10}$(ρ)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jagersfontein (-29.8°N, +25.4°W)</td>
<td>4.70</td>
<td>0.08</td>
<td>3.41</td>
<td>0.205</td>
</tr>
<tr>
<td>Gibeon (-25.1°N, +17.8°W)</td>
<td>4.51</td>
<td>0.075</td>
<td>2.78</td>
<td>0.09</td>
</tr>
</tbody>
</table>

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

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

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

Need to introduce something into upper lithospheric mantle to explain conductivity that is 2 orders of magnitude higher than predicted.
Log(resistivity)-Velocity relationship

Shear Wave Velocity [km/s]

1/Log(Resistivity [Ωm])

JAG dry
JAG wet
GIB
ppm 20 40 60 80 100
Water
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.

$Vs = 5.105 - 1.452/\log(\rho)$  Corr. Coeff.: -0.71

Note almost no $Vs-1/\log(\rho)$ points to left of Dry prediction.
Comparison of derived and predicted Vs models

Vs from Rho ➔ (with 1.5 deg smoothing)

← Vs from Fishwick
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)
$1 / \log(\rho) - VsF1.5d @ 100 \text{ km}: \text{ Clustering}$

$Vs = 5.105 - 1.452 / \log(\rho)$  Corr. Coeff.: -0.71

Note almost no $Vs-1 / \log(\rho)$ points to left of Dry prediction

2D histogram shows clustering
$1/\log(Rho)$ - $VsF1.5d \, @ \, 100 \, km$: Cluster analysis

5 clusters (Dunn statistic)

- dry
- 200 wt ppm
- 40 wt ppm

$Vs$ velocity [km/s]

$1/\log($resistivity [ohm.m]$)$
Cluster map
Cluster 1: High velocity/variable resistivity: cold, variably wet (variably depleted?) Kaapvaal Craton
Cluster 2: High velocity/low resistivity: cold, very wet (=not very depleted?), Central Botswana
Cluster 3: Moderate velocity/low resistivity: warmer, very dry (=depleted?) Angola Craton
Cluster 4: Low velocity/Very low resistivity: warm, very wet (=fertile?), Rehoboth Terrain
Cluster 5: Low velocity/Moderate resistivity: warm, dryer (somewhat depleted?) Damara Belt
$1/\log(\rho) - V_s F1.5d @ 100 \text{ km: Water}$

Moving along x-axis is increasing water content

$V_s = 5.105 - 1.452/\log(\rho)$  Corr. Coeff.: -0.71

95% conf.

dry

200 wt ppm

95% conf.

40 wt ppm

Water

4.8

4.7

4.6

4.5

4.4

0.1

0.2

0.3

0.4

0.5

0.6

1/\log\text{(resistivity [ohm.m])}
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

Profile KIM-NAM – 2-D Electrical Resistivity Model

- **Vertical exaggeration = 1.0**

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

- **Kimberlite Cr/Ca–in–garnet maximum pressure estimates**

- **From: Muller et al., 2009, Lithos**

From Muller et al., 2009, Lithos
Electrical resistivity structure from prior work

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

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

Fullea et al., 2011
JGR
1. Understand the implications of “LAB” depths in recent S-wave Receiver Function (SRF) models.

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

Vs versus Depth
Surface wave studies

- 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
   - Magnetotelluric (MT) data
   - Surface heat-flow measurements
   - 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.

<table>
<thead>
<tr>
<th></th>
<th>1. Average Kaapvaal Harzburgite *</th>
<th>2. Average Kaapvaal Low-T Lherzolite *</th>
<th>3. Average Kaapvaal High-T Lherzolite *</th>
<th>4. Primitive Upper Mantle †</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>45.90</td>
<td>46.50</td>
<td>44.40</td>
<td>45.00</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.30</td>
<td>1.40</td>
<td>1.75</td>
<td>4.50</td>
</tr>
<tr>
<td>FeO</td>
<td>6.00</td>
<td>6.60</td>
<td>8.10</td>
<td>8.10</td>
</tr>
<tr>
<td>MgO</td>
<td>45.50</td>
<td>43.80</td>
<td>43.40</td>
<td>37.80</td>
</tr>
<tr>
<td>CaO</td>
<td>0.50</td>
<td>0.86</td>
<td>1.27</td>
<td>3.60</td>
</tr>
<tr>
<td>Mg#</td>
<td>93.10</td>
<td>92.20</td>
<td>90.50</td>
<td>89.30</td>
</tr>
</tbody>
</table>

* 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/m²

**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

**Models examined in subsequent slides**

- Harz. (Moho-160km +)
- Low-T Lherz. (Moho-160km +)
- High-T Lherz. (Moho-160km +)
- Harz. (Moho-160km), High-T Lherz (160 km +)
- Low-T Lherz. (Moho-120km), Harz. (120-160 km), High-T Lherz. (160 km +)
• 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.
• 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.

Model M2

• 240 km thick lithosphere
• 3 chemical layers
• Preferred model
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 $61 \, \mu W/m^3$, elevation 4850m.

**Wet** lithospheric and sub-lithospheric mantle:

Different distribution of water content in mantle with linear decrease to: 150 km

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

*Graphs showing resistivity and phase change with depth and period.*
Conclusions

• Seismology primarily sensitive to \([P, T, \text{Comp}]\)

• Electrical resistivity primarily sensitive to \([T, \text{H}_2\text{O}]\)

• 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