CRUSTAL VISCOSITY AND ITS CONTROL ON VOLCANIC GROUND DEFORMATION PATTERNS

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**Viscoelasticity**

How are ground deformation patterns modified by a temperature-dependent viscosity distribution?

Does the choice of ambient thermal regime change the predicted ground deformation patterns?

Observed deformation field is a function of:
- Source processes involved
- Surrounding crustal structure
- Rheological response

Shallow or long-lived magmatic systems induce elevated thermal regimes
- Invalidates elastic assumption?
- Time-dependent rheological effects?
- Thermomechanical strain partitioning?

Compare popular viscoelastic configurations, Maxwell and SLS, in an overpressure-driven thermomechanical deformation model
Taupō volcano, New Zealand, is a large silicic caldera complex in the Taupō Volcanic Zone

- Two caldera-forming events; 1.8 ka Taupō (VEI 7) and 26.5 ka Oruanui (VEI 8) eruptions
- Region of high surface heat flow, resulting from volcanism and rifting

High heat flow assumed to reflect elevated temperatures at depth, long-lived magmatic system residing in thermally-primed crust

We model a hypothetical deformation episode, based on inferences of the 1.8 ka Taupō eruption (e.g. Ellis et al, 2007)
Consider 3 thermomechanical set-ups, with a magmatic temperature of 1123 K (850 °C)

- "Lin30" – 30 K/km linear geotherm, with no additional constraints
- "Lin40" – 40 K/km linear geotherm, with no additional constraints
- "BDTZ" – Temperature constraints for basal and mid-crust, producing a ramped geotherm

Models produce near-identical viscosity profiles above the modelled reservoir

Compare against “expected” viscoelastic responses seen in isoviscous models (e.g. Head et al., 2019)

- "Iso17" – $10^{17}$ Pa s for whole model-space
- "Iso18" – $10^{18}$ Pa s for whole model-space
Differences in Vertical Deformation

- **Maxwell** → expected to produce linear deformation (Head et al., 2019)
  - Inconsistent deformation response in thermomechanical set-ups
  - Produces uplift at large distances from source

- **SLS** → consistent viscosity-dependent rate-decreasing deformation (Head et al., 2019)
  - Rate of deformation is viscosity-dependent
  - Thermomechanical models attain ~30-40% more displacement than the elastic model
  - *Why do the thermomechanical models differ?*
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SLS rheology captures a range of *deformation timescales*, due to viscosity structure
- Viscous effects not limited to long-term

BDTZ model attains ~10% more uplift than standard 30 K/km gradient model
- *Deformation partitioning* due to local viscosity structure – *reduces overpressure* requirements?

Maxwell rheology is a *viscoelastic fluid*
- Viscosity gradients allow crustal material to “flow” in response to imposed overpressures
- Produces inconsistent deformation patterns
  Raises questions about *applicability* of this rheology to “solid” deformation studies

Local viscosity structure for each of the thermomechanical set-ups, with contours showing $10^{17}$, $10^{18}$, $10^{19}$, $10^{20}$ Pa s
Appendix

COMSOL Multiphysics® → forward models of ground deformation

• Full 3D geometry with **topography, crustal heterogeneity** from 3D seismic tomography (Eberhart-Phillips et al., 2010)
• Steady-state temperature field from **thermal constraints**, calculate **temperature-dependent viscosity** using Arrhenius formulation (e.g. Del Negro et al., 2009; Gregg et al., 2012; Hickey et al., 2016)
  \[ \eta_{TD} = A_D \exp \left( \frac{E_A}{RT} \right) \]
• \( A_D = 1 \times 10^9 \text{ Pa s} \); \( E_A = 1.3 \times 10^5 \text{ kJ/mol} \)

Modelling a hypothetical deformation episode, source characteristics based on inferences of the **1.8 ka Taupō eruption** (e.g. Ellis et al, 2007)

• **Oblate spheroid** geometry, horizontal radius of **3.4 km** and vertical radius of **0.7 km**
• Centred at **depth** of **6 km**
• Magmatic temperature of **850 °C**
• BDTZ model basal temperature of **950 °C**, mid-crustal temperature of **550 °C** (Stagpoole et al., 2013)
• Overpressure of **10 MPa**
REFERENCES


