Sub-Ice Thermal Regime, Volcanogenic Processes and Terrane Assembly in Antarctica Using Magnetotellurics

Phil Wannamaker, Graham Hill, Virginie Maris, John Stodt, Yasuo Ogawa, Michal Kordy
Univ. of Utah, Univ. of Canterbury, Tokyo Inst. of Technology

U.S. National Science Foundation, U.S. Department of Energy, Royal Society of New Zealand
Bedrock Topography, Antarctica
Fretwell et al (2013)

Subduction/Backarc Rifting and Continental Growth

Kenneth A. Bevis © 2014
Hansen et al. (2014)

Seismic tomography models from new arrays (Polenet, Tamnnet, Tamseis, Gamseis)

Heezel et al. (2016)

Shen et al. (2017)
**Motivations:**
- Rifting one of 3 main modes of mountain building, volcanism.
- General goal to examine well-expressed modes worldwide.
- Rift regimes contain resources, host earthquakes.
- Understand transition between stretching and stable margins.
- What supports high mountains?, what controls decay of elevation?
- Compare to well-known Great Basin margins.
- How do CO$_2$-dominated phonolitic rift volcanoes differ from H$_2$O-dominated subduction volcanoes?
- What are the differentiation and staging regions for phonolites?

**Approaches:**
- Must understand the third dimension (depth): geophysics.
- Seismology has had limited success: coverage, sources.
- Physical property of electrical conductivity reflects melt, fluids, hydration.
- Magnetotelluric (MT) method: broadband global EM source.
- Need to adapt traditional land method to polar ice sheets.
Source Fields for the Magnetotelluric Method

Regional and Global Lightning Activity for $f > 1$ Hz
Solar Wind-Magnetospheric Interactions for $f < 1$ Hz
\[ E = \mathbf{Z} \mathbf{H} \]
\[ \rho_{xy} = \frac{1}{\omega \mu_0} |Z_{xy}|^2 \]
\[ \varphi_{xy} = \arg(Z_{xy}) \]
\[ \delta \approx 503 \sqrt{\rho T} \]
\[ \int_{-\infty}^{\infty} E_s \cdot dl = 0 \]
MT Recording Components
For Polar Deployment

\[ E = \frac{Z}{H} \]
\[ \rho_{XY} = \frac{1}{\omega \mu_0} |Z_{XY}|^2 \]
\[ \varphi_{XY} = \arg(Z_{XY}) \]
\[ \delta \approx 503 \sqrt{\rho T} \]
\[ \int_{-\infty}^{\infty} E_s \cdot dl = 0 \]
MT Recording Components
For Polar Deployment

\[ \mathbf{E} \approx \mathbf{Z} \mathbf{H} \]

\[ \rho_{XY} = \frac{1}{\omega \mu_0 |Z_{XY}|^2} \]

\[ \varphi_{XY} = \text{arg}(Z_{XY}) \]

\[ \delta \approx 503 \sqrt{\rho T} \]

\[ \int_{-\infty}^{\infty} E_S \cdot dl = 0 \]
Hypotheses for TAM Uplift
(Wannamaker et al., 2017, Nat Comms)
S Klamath Mtns – Great Basin – Colorado Plateau MT

Approx. coincident with COCORP, PASSCAL seismic profiling

Hammond and Thatcher (2004)
Multiscale Magmatic/Hydrothermal Connections
Grand Canyon Hydrol. Model
(Crossey and Karlstrom, 2012)

Klamath - S Modoc - Great Basin - Colorado Plateau

MT Transect (~40 N lat.)
3D MT Inversion of Using Deformable Edge Finite Element Algorithm (Kordy, Wannamaker, et al., 2016, GJI)

Objective: \[ W_\lambda(m) = \{(d - F[m])^T C_\Omega^{-1}(d - F[m]) + \lambda \{(m - m_0)^T C_m^{-1}(m - m_0)\} \]

NL Step: \[ m_{k+1} - m_k = \left\{ J_k^T C_m^{-1} J_k + \lambda C_m^{-1} \right\}^{-1} \left\{ J_k^T C_m^{-1}(d_k - F[m_k]) - \lambda C_m^{-1}(m_k - m_0) \right\} \]

Stabilized Iterative Earth Resistivity Voxel Estimation (Tarantola, 1987)

NL Step Recast to Data-Space Formulation (Parker, 1994)

Can Invert for Impedance Static Distortions (Avdeeva et al., 2015)

Direct Matrix Solutions Used Throughout (Metis, Pardiso, Plasma)

Parallelized on Large RAM, Single-Box Workstations

Discrete Finite Element Simulation

EM Field (Maxwell) Equations And Deformed Finite Element

\[ \nabla \times E = -i\omega \mu H \quad \nabla \times H = \sigma E \]

\[ \nabla \times \nabla \times E = -i\omega \mu \nabla \times H = j \left\{ \nabla \times E \right\} \]

\[ E = \sum_{i=1}^{N} z_i N_i \quad H = \frac{\nabla \times E}{i \omega} \]
Hypotheses for TAM Uplift

(Wannamaker et al., 2017, Nat Comms)
Absolute Shear Wave Speeds
Southern Transantarctic Mountains
(Shen et al., 2017)
Upper Mantle NAMs Hydration
Rift Necking and Thermal Focus

Fisher et al., 2015, SciAdv

Subglacial Lake Whillans
heat flux 285 ± 80 mW/m²

Fisher et al, 2015, SciAdv

Rift Necking and Thermal Focus
Cyanobacterial O production and oC-Sd sequestration
Des Marais (1994)

C-S concentration in starved basins
Sandberg and Gutschick (1983)
oC-Sd sequestration

Des Marais et al. (1992)

oC-Sd global primary production

Mod from Southwick (2014)

Mod from Schulz and Cannon (2007)

Wunderman et al. (2018)
Graphite-sulfide textures in crustal-scale conductors

Luque et al. (AJS, 1998)

Fluid remobilized graphite

Jones et al. (JGG, 1997)

Sulfide Stringers

Graphite-sulfide textures in crustal-scale conductors
Goodge and Finn (2010): Crustal Architecture and Aeromagnetics

Luque et al. (AJS, 1998)
Fluid remobilized graphite

Jones et al. (JGG, 1997)
Sulfide Stringers

Graphite-sulfide textures in crustal-scale conductors
West Antarctic Rift System and Terror Magmatism (Faccenna et al., 2008; Storti et al., 2008)

Mount Erebus Magma Source and Staging (Iacovino et al., 2015, after Oppenheimer, 2008)

Discovery Accommodation Zone (Wilson, 1999)
Mount Erebus, Ross Island


Blondel et al (2018)
Mt Erebus MT Field Campaign: NSF/USAP and RSNZ/AntNZ

Mount Erebus Magma Source and Staging (Iacovino et al, 2015, after Oppenheimer, 2008)
Mt Erebus MT Inversion Finite Element Mesh: ~1.4M cells
Mount Erebus MT Inversion
Resistivity Plan Sections:

- General clay alteration blanket at shallow levels.

- Clear visibility of magmatic conduit and upper chamber by 5 km depth.

- Migration of magmatic structure westward along apparent controlling E-W trend.

- Movement of magmatic plumbing southward from lower middle crust and deeper.
Mount Erebus MT Inversion Section Views from East to West

Mount Erebus MT Inversion Section Views from North to South
Mount Erebus MT Inversion Plan and Section Views

Schematic Mount Erebus magmatic plumbing (Oppenheimer et al., 2008). Note “Nozzle” interpreted at 4 kbar for periodic basanite replenishment.
Broader Impacts:
Thermal regimes understanding, input to ice stability models
Advances in exploration technology for other polar regions
Potential to evaluate geothermal resources for base power

Prominent place of Antarctica in the public imagination
Promotes international scientific and logistical cooperation
Support for new professionals and underrepresented groups
The End!