Western EARS
Geothermal Geophysics Context
Mar-2016

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Geothermal Resource Assessment Requires Consistent Geoscience Context

Context Issues Worldwide

• Sumatra and Philippines - arc andesite volcanics **BUT** oblique subduction so many fields at step-overs in strike-slip faults, **NOT** at big volcanoes **AND** most mapped faults boundaries **NOT** targets

• Eastern EARS – trachyte and phonolite do not alter to smectite, modifying capping concept and MT resistivity interpretation

Context Issues in Western EARS

• Growing Consensus: Volcanics from deep magma with little shallow residence. Heating regional not localized

• Growing Consensus: High CO₂ gas flux and deep structure

• Incomplete: Basin structure and localization of permeability

• Incomplete: Hydrology and permeability (+geochemistry, structure)

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Kibiro Geophysics
Mar-2016

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Geophysical Data Types and Results

- Reflection seismic illustrates structures in Lake Albert Basin adjacent to Kibiro that may source the hot water
  - GIS and time-depth requested
- MT constrains 2D resistivity pattern consistent with upflow from sedimentary basin into shallow tabular onshore aquifer
- TEM follow up for shallow sediments and static MT
- Airborne gravity data available only from structural map which has been very helpful (but incomplete)
- Aeromagnetic survey detected intrusions younger than Proterozoic that provided important initial support for basin structure but too ambiguous in timing to infer heating

Cumming (2016)
Kibiro Seismic Cross-section

- Reflection seismic surveys acquired for petroleum exploration – 2D covers the offshore area near Kibiro.
- Profiles approach to within 500 m of shore.
- Conceptualization important but lack seismic trace locations to make specific correlations.

From Karpe et al (2012)
Seismic Structure of Albertine Basin

- Basin structure (red is high, blue is low) constrained by reflection seismic, gravity and aeromagnetic data
- Kibiro is located off structural highs and so was not covered with 3D seismic
- Sediments within structural blocks are dipping along strike more than across strike
- Details of structure and permeability unclear at Kibiro

From Karpe et al (2012)
Oil Trap Type Conceptual Cross-section

Tullow (2007)
Kibiro Geophysics

Kibiro Seismic Cross-section

2D line HLA03-053 NW – SE

Cumming (2013)
Kibiro Geophysics

Kibiro Seismic Cross-section

2D line HLA03-055 NW – SE

Cumming (2013)
Seismic Structure of Albertine Basin

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From Karpe et al (2012)
Kibiro Seismic Cross-section

2D line HLA03-014 SW - NE

Cumming (2013)
Seismic Structure of Albertine Basin

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From Karpe et al (2012)
Kibiro Seismic Cross-section

2D line HLA03-014 SW - NE

Cumming (2013)
Lake Albert 3D Seismic Cross-section
Seismic Structure of Albertine Basin

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From Karpe et al (2012)
• TEM detected mostly high resistivity with local low resistivity
• Conclusion based on gradient well results was that resistivity might indicate mineral resource targets
Kibiro 2015 MT Data Quality

- Static distortion of the MT at Kibiro is usually minor
- Noise limits use of data below 10 s period, deeper than 20 km
Kibiro 2015 MT Cross-section

- MT resistivity at 1 Hz shows low resistivity clay rich sediments in yellow-red to NW and high resistivity Pre-Cambrian crystalline rocks in green-blue to SE
Kibiro 2015 MT Cross-section

- MT 2D resistivity from Profile 2 through the Kibiro chloride hot springs.
- Low resistivity sediments are yellow-red, high resistivity Pre-Cambrian is blue.
- Green is ambiguous
- Because the aperture is limited, the profile resolution below -200 m is less reliable
Oil Trap Type Conceptual Cross-section

Tullow (2007)
Kibiro Land Gravity

- Gravity matches change in density from crystalline rocks to sediments but has insufficient scale to constrain a model.
- Variations in gravity over Pre-Cambrian related to local soil and sediment accumulation.
- Airborne gravity would help constrain offshore structure at Kibiro.
Airborne Gravity for Oil Exploration

- Gravity matches change in density from crystalline rocks to sediments
- Published map stops just northeast of Kibiro

Tullow (2007)
Kibiro Geophysics Review

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Ngozi-Songwe Geophysics
Mar-2016

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2015-2016 Geophysical Program

- 28 BGR MT and 32 TEM stations at Ngozi noisy and interpretations uncertain, so revised
- 96 TGDC-GDC MT-TEM less noisy and more extensive, resolving resistivity pattern at Songwe rift and Ngozi volcano
- TEM for MT static correction and reprocess BGR
- Gravity profiles along most easy access across graben at Songwe, Ngozi Volcano and regional structures
- Aeromagnetic data used to confirm structural continuity
- Ground magnetic data being acquired

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Ngozi-Songwe Geophysics

Ngozi-Songwe MT Survey

• MT stations around Ngozi Volcano, access limited at crater
• MT stations in profiles across graben at Songwe
Ngozi BGR and GDC MT

BGR (27)

GDC (96)

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MT Method

- Ex, Ey 2 dipoles ~100 m
- Hx, Hy, Hz 3 magnetometers
- EM signal from sun and lightening
- Solar signal sometimes low

- 1 Hz is about 1 km deep
- Shallow features like surface alteration result in different resistivity on Ex and Ey dipole. This is called static distortion
MT Depth of Penetration

PHYSICS OF MAGNETOTELLURIC EXPLORATION

Depth of penetration \( \propto \sqrt{\text{period} \times \text{resistivity}} \)

Resistivity of ground \( \propto \left( \frac{E}{H} \right)^2 \)

- Surface
- 100 ohm - metres
- 5 km

Period = 100 s
Skin depth = 5000 m

Period = 4 s
Skin depth = 1000 m

Period = 1/25 s
Skin depth = 100 m

Geophys.washington.edu
MT Signal Source > 1 Hz
MT Signal Source < 1 Hz
Standard MT Plot
Apparent Resistivity and Phase Spectra

• Basic MT display is apparent resistivity and phase versus frequency
• These must be “inverted” to rock resistivity versus depth (1D) or rock resistivity versus X-Y-Z (3D)
• At volcanic targets with a base of clay cap near 1000 m depth, xy and/or yx apparent resistivity is lowest near 1 Hz
• Phase and Apparent Resistivity are related and a mutual quality check
• Phase should usually vary like 1/slope of the apparent resistivity curve
• Mutual smooth constraints (like D+) are used to assess reliability

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GOOD/BAD MT DATA

- Almost perfect MT data
- Base of the clay resolved
- MT demonstrates that a clay cap exists to >300 m depth
- Poor MT near 1 Hz implies base of the clay not resolved

- Resistivity minimum near 1 Hz is response to resistivity increase below base of clay cap near 1000 m depth
- Electric power noise 0.05 to 2 Hz
- No resolution of base of clay cap due to noise

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Good/Bad MT From GIS/Google Earth

- Good MT Site
- Bad MT Site

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Solving MT Equations With Remote Reference

Gamble et al. (1979)

- Impedance tensor

\[ E_x(\omega) = Z_{xx}(\omega) H_x(\omega) + Z_{xy}(\omega) H_y(\omega), \]
and

\[ E_y(\omega) = Z_{yx}(\omega) H_x(\omega) + Z_{yy}(\omega) H_y(\omega). \]

- Impedance from cross-powers

\[ Z_{xy} = \frac{(E_x H_y^* H_x H_x^* - E_x H_x^* H_x H_y^*)}{D}, \]
\[ Z_{yx} = \frac{(E_y H_x^* H_y H_y^* - E_y H_y^* H_y H_x^*)}{D}, \]
where

\[ D = H_x H_x^* H_y H_y^* - H_x H_y^* H_y H_x^*. \]

Subscript "r" is remote reference
MT Time Series Processing
Without and With Remote Reference

Without remote reference
Biased to low resistivity from 0.1 to 10 Hz due to magnetic noise

With local remote reference
Data very good, especially at 1 Hz

Unsworth et al. (2007, Geophysics)
MT Static Distortion

- Ex, Ey 2 dipoles ~100 m
- Hx, Hy, Hz 3 magnetometers
- EM signal from sun and lightening
- Solar signal sometimes low

- 1 Hz is about 1 km deep
- Shallow features like surface alteration result in different resistivity on Ex and Ey dipole. This is called static distortion
TDEM / TEM

- Pulse current in outer loop, measure signal in inner loop from “smoke rings” of current induced by magnetic field.
- TDEM depth often < 300 m, << MT
- No electrodes so no static distortion
- Focused so less 2D/3D distortion
- Noisy data or no signal is sometimes misinterpreted
TEM Signal

- Quality assurance using voltage signal from detector
- Conductor causes voltage to decline more slowly.
- If no conductor, voltage declines to noise floor
- Data at later times is commonly incompletely edited, causing the noise after 10 msec to create a false low resistivity zone.
- Noise level separately recorded to help resolve this problem

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Non-Plane Wave Distortion

Sumatra 2013

Transmission towers

Power Lines

Transmission towers

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Non-Plane Wave (Near Field) Distortion

- CSAMT points with near field notch and 45 degree branch characteristic of near-field distortion

- MT with likely plane wave distortion at <0.1 Hz
Ngozi-BGR and GDC MT

BGR (max 27)

GDC (max 43)
Non-Plane Wave Distortion

Slope >45° likely plane wave distortion from DC power line

Apparent deep conductor
Non-Plane Wave Distortion

Smoothed resistivity trend indicates increase below clay cap but no deep conductor.
CSIMT (Coherent Source Interference MT)
Guðni Rosenkjær, UBC (26-Feb-2016)
Research on use of the coherent power line noise as a signal

- Resistivity model with 4 ohm-m geothermal clay cap base at 700 m with magma at 9000 km
- Station 1500 m distance from power line
- Demonstrates serious distortion by power line at most signal/noise ratios
CSIMT Noise as Signal

Guðni Rosenkjær, UBC (26-Feb-2016)

Research on use of the coherent power line noise as a signal

- Resistivity model with 4 ohm-m geothermal clay cap base at 700 m with magma at 9000 km
- Station 5000 m distance
- Demonstrates use of noise as signal for shallow cap at 5000 m distance with most signal/noise ratios
Non-Plane Wave Distortion

Songwe

Cement Plant

4 km

©Cumming (2013)
Non-Plane Wave Distortion

Mbeya

Power Line

2 km
Ngozi-Songwe MT Survey

- MT conductance to 1000 m depth consistent with Songwe gravity
- MT conductor shows clay enclosing Ngozi Volcano, except to east
Ngozi MT Interpretation

- Cross-section 1 through Songwe to Ngozi
- Base of hydrothermal alteration locally 1000 m deep

km

(vertial exaggeration 4:1)
Ngozi MT Interpretation

- Cross-section 1 through hot spring closest to Ngozi
- Base of hydrothermal alteration locally 1000 m deep
- Pattern consistent with distinct aquifers

km

(vertical exaggeration 1:1)
Songwe MT Interpretation

- Cross-section SO1 through hot spring with highest geothermometry
- Low-resistivity, clay-rich shallow volcanoclastics dip up from NE to SE consistent with half-graben
- Pattern consistent with upflow below low resistivity cap

km
(vertical exaggeration 1:1)
Ngozi-Songwe Regional Gravity Data

- Usangu basin (Marobhe, 1989) for regional
- Awaiting regional data sets more relevant to Ngozi and Songwe (archiving issues)
Gravity at Ngozi is not diagnostic, except with regional trend.

At Songwe, gravity consistent with half graben dipping down to NE.

Integrate with regional and fit to Songwe MT cross-sections.
Ngozi-Songwe Gravity Data

- Depth to metamorphic basement in rift probably not feasible
- Need georectified gravity map with data points and preferably gravity principal facts
Ngozi-Songwe Aeromagnetic Data

- Countrywide aeromagnetic survey from early 80’s
  - Line spacing – 1 km
  - Flight height – 120 m
- Of interest for structural implications
- Low relief northwest of Ngozi ambiguous since no shallow sulfate alteration
- Depth to metamorphic basement in rift probably not feasible

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2015-2016 Geophysical Program

• Low resistivity surrounding Ngozi Volcano consistent with apparently isolated chloride hydrology
• Some conduction or leakage to bicarbonate springs
• Gravity and MT consistent with Songwe half-graben
• MT consistent with upflow anywhere from graben center to vertical below springs
• Aeromagnetic data confirms structural continuity but interpretation in terms of sulfate alteration ambiguous
• Deep BGR TEM conductor disappears with revised editing
• Conceptual model review next week
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