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GEOTHERMAL GEOPHYSICS AND RESOURCE ASSESSMENT

Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

USC 12-Mar-2015

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Geothermal Geophysics Questions

Integrate geophysics with geochemistry and geology in a consistent geothermal conceptual model to answer:

1. Does a conventional geothermal reservoir exist?
2. If it exists, how big is it?
3. What is the uncertainty (and risk)?
4. What is the lowest cost well targeting strategy to discover, then prove, and then develop the resource?

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How Do Geothermal Assessments Fail?

- Data Uncertainty
  - Acquisition noise always create some uncertainty
  - As a natural source method, MT is particularly susceptible to the spread of electrical noise
- Inversion (Imaging) Uncertainty
  - Reliability of inversion is limited to range of data for which inversion assumptions are valid. 1D vs 2D vs 3D
  - Inversions are sensitive to data noise, and inversions with more "D" are more difficult to realistically constrain
- Conceptual Interpretation Uncertainty
  - Inconsistency with other types of data and model constraints
  - Ambiguous correlation with resource properties

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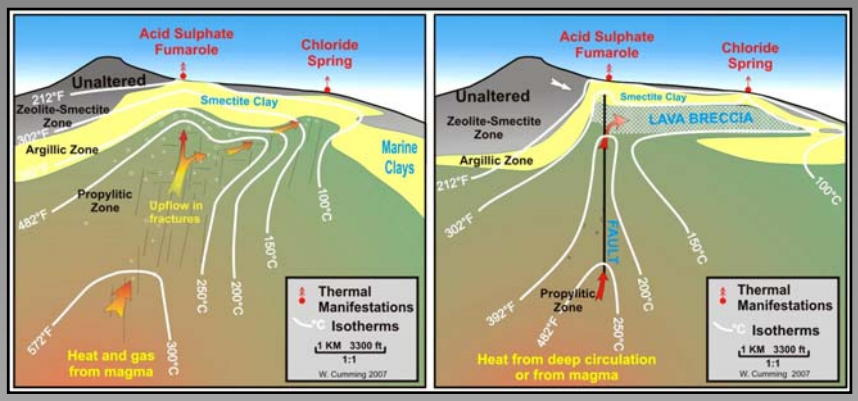
Generic Geothermal Conceptual Model Elements

Distributed Permeability Upflow Small Outflow

Single Fault Zone Upflow Large Shallow Outflow



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Outline

1. Exploration geophysics types, objectives, and strategies
2. Elements of geothermal conceptual models
3. Steps in exploring and building a geothermal conceptual model in a volcano-hosted prospect using MT resistivity integrated with geochemistry, structure, geology, etc
4. Well targeting and resource capacity risk assessment
5. Uncertainty Common pitfalls in and challenges in MT interpretation
6. Microearthquake applications to geothermal development

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Geothermal Geoscience Conceptual Context

Basic physics of permeable geothermal reservoirs (non-EGS)

- Geothermal reservoirs lose energy to surface through any rock by heat conduction and through leaky rocks by buoyant advection of hot fluid
- In proportion to stored energy, a geothermal reservoir emits energy at a rate orders of magnitude higher than O&G reservoirs
- The geothermal emphasis on "seeps" does not indicate primitive technology relative to O&G but a difference in resource physics

Implications for geothermal exploration strategy

- Permeable hot geothermal reservoirs must "leak" heat upward, and so "hidden" systems without near-surface manifestations are "special"
- Most cost-effective reduction of geothermal resource risk is usually to demonstrate permeability and temperature using water chemistry, if not from springs then from shallow wells

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Geochemistry and Resistivity Methods Dominate Exploration For Permeable Geothermal Reservoirs

Why?

- All commercial geothermal systems leak hot water or heat to surface or near-surface
- For leaky systems, geochemistry cost-effectively indicates
  - Likelihood of economic temperature?
  - Significant permeability at that temperature?
- Resistivity detects the clay cap, cost-effectively answering
  - What is the geometry of the reservoir top?
  - How big might the reservoir be?
  - What well casing design is optimum?

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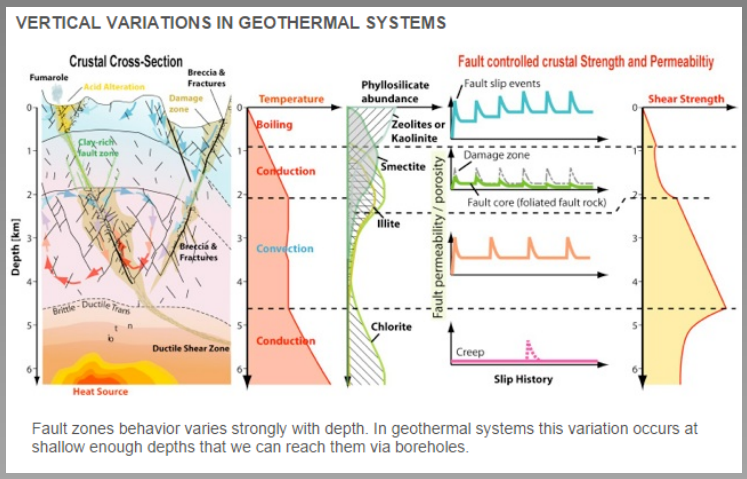
Geothermal Permeability

Davatzes et al (2010) and Lutz et al. (2010)



Fault zones behavior varies strongly with depth. In geothermal systems this variation occurs at shallow enough depths that we can reach them via boreholes.

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Smectite Clay Interpretation Model for Resistivity in a Geothermal Context

- Hydrated smectite alteration is created over almost all geothermal systems due to gas loss from hot water
- Hydrated smectite causes low bulk permeability
- Hydrated smectite causes the lowest resistivity detected in all commercial geothermal systems.
- Archie's Law is for clay-free rock. Assumption that low resistivity implies high temperature is incorrect in a geothermal context
- Smectite is temperature sensitive, converting to illite clay at higher temperatures and is complete near 200-250°C
- Low resistivity correlates with low permeability "cap" over high resistivity, high permeability, high temperature reservoir

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Surface Geophysics for Exploration

Infer geothermal resource characteristics for well targeting and resource capacity estimation by remotely constraining rock properties such as:

- **Resistivity:** using MT, TDEM, VES, CSAMT, HEM
- **Density:** using gravity and seismic
- **Magnetic susceptibility:** using magnetic field
- **Natural electrical potential (V):** using SP
- **Fractures and stress:** using MEQ and active seismic
- **Seismic velocity:** using active seismic and MEQ
- **Seismic impedance:** using reflection seismic

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Surface Geophysical Techniques For Conventional Geothermal Targets

Common (sometimes justified) assumptions

Standard:	**MT** (TEM for statics is not standard)
Case by case:	**T-MT, AMT, CSAMT, TEM, VES, DC-T, HEM, TGH Gravity, SP, Active Seismic, Microearthquake Aeromagnetics, Precision Ground Magnetics**
Development:	**Microgravity, Microearthquake, Subsidence**
Research:	**Many claims are still unverified 1) Reflection / Refraction Seismic, 2) deep TGH 3) MEQ imaging, 4) d-SP, 5) deep MT**
Legacy:	**Dipole-Dipole, Roving Dipole**
Suspect:	**Seismic Noise, Low Res Ground Magnetics Plausible methods with weak technical support**

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Geothermal Decision Making

How will resource decisions be informed?

- Anomaly hunting – target data
- Anomaly compilation – target compiled data
- Conceptual models – target a range of conceptual models consistent with data and uncertainty

How will risky resource decisions be made?

- Leader relies on technical sales or preferred Oracles
  - Monte Carlo probabilistic assessment based on plausible population distributions for resource
- Team assessments using Bayesian confidence based on conceptual models representative of uncertainty

Anomaly Hunting

- Rationale
  - Works by analogy
- Pitfalls
  - Conceptual relevance to new targets not considered, just outcomes
  - Other data not conceptually integrated
  - Not directly tested by wells
    - Drill a 5 ohm-m anomaly and it remains 5 ohm-m
- Remedy
  - Use for early and low cost decisions

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Conceptual Models

- Rationale
  - Decisions based on analogous experience
  - Conceptual differences considered
  - Directly tested by wells
- Pitfalls
  - Who can integrate geophysics, geochemistry, geology, reservoir engineering …
  - Multiple models require risk assessment
- Proposed Remedy
  - Training on building conceptual models and assessing risk using case histories

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Geothermal Conceptual Model Elements

- Hydrology, especially deep water table but also perched aquifers
- Isotherm pattern consistent with pressure and permeability
- Heat Source
- Deep benign hot buoyant upflow in fractures
- Formations and alteration favorable to open space fracture permeability (and often primary permeability at shallower depths)
- Smectite Clay Cap (commonly combined cap, rarely, non-smectite cap, very rarely for commercial systems, uncapped)
- Faults creating permeable zones, flow barriers and field boundaries
- Reservoir temperature outflow with buoyant flow updip below clay cap (in liquid systems)
- Sub-commercial outflow with buoyant flow updip below clay cap (in liquid systems)
- Cold meteoric water flow down-dip into reservoir

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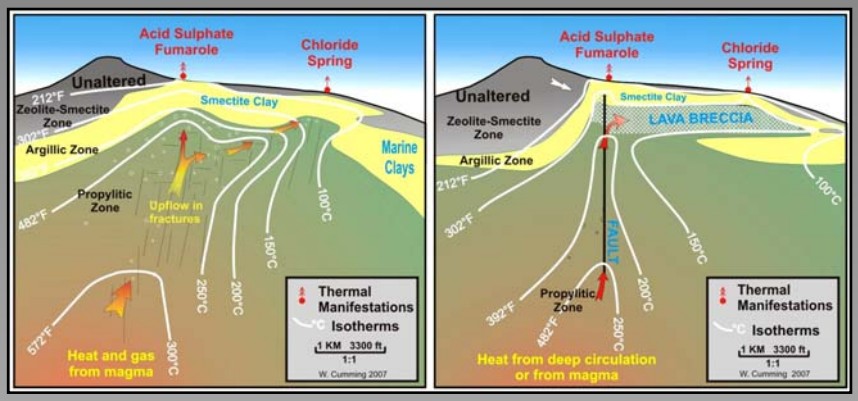

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Geothermal Conceptual Model Isotherm Properties

- Isotherms define the permeable reservoir
- Isotherms are constrained by hydrothermodynamics:
  - Water table defines pressure and maximum temperature distribution
  - Temperature < hydrostatic boiling point
  - Hot upflow and outflow by buoyancy in permeable zones
  - Cold influx by hydrostatic gravity flow in permeable zones with colder or higher elevation source and aquifer connection
  - Conduction where permeability low
  - Very high temperature gradients require permeable high and low temperature zones on each side of an impermeable zone
  - No isolated hot or cold zones (cross-sections use arrow heads/tails)

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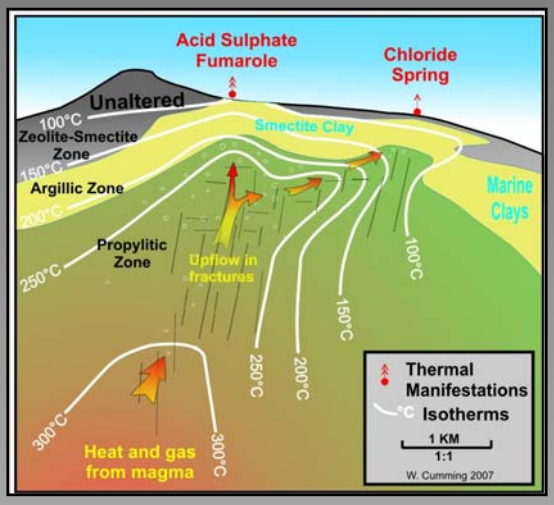
"Standard" Geoscience Plan >200°C Geothermal Exploration

- Gas and fluid geochemistry for existence and conceptual target
- MT to map base of clay "cap"
- Maybe TEM for MT statics
- Geology, alteration and structure for context
- Shallow hydrology for context



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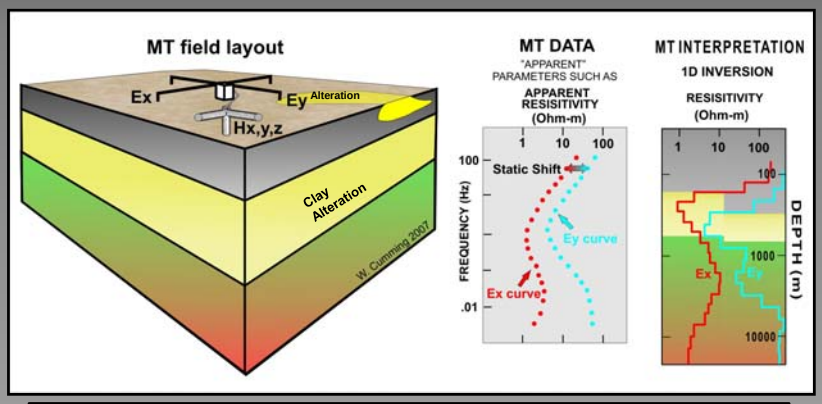
MT Method



- 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

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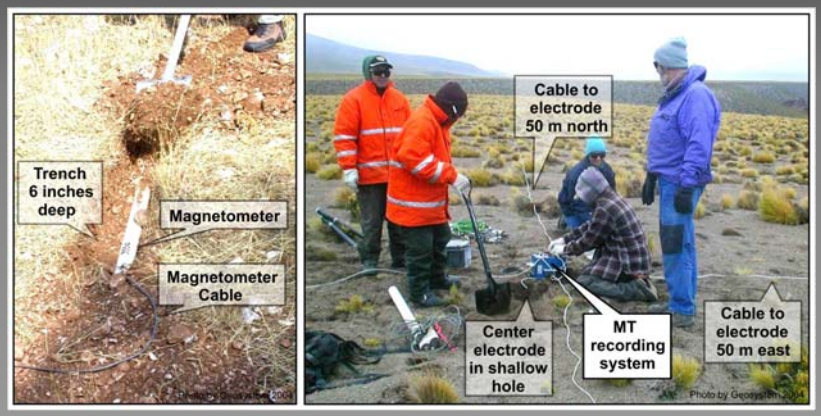

- Ex, Ey 2 dipoles ~100 m
- Hx, Hy, Hz 3 magnetometers
- Horizontal magnetometers buried in shallow trenches
- Equipment portable
- >8 hours so one station/day
- Two stations record at once to provide "remote reference " noise reduction

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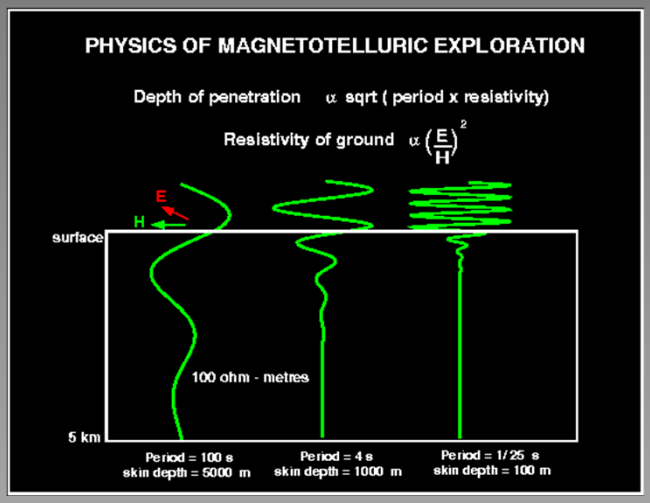
MT Depth of Penetration



Geophys.washington.edu

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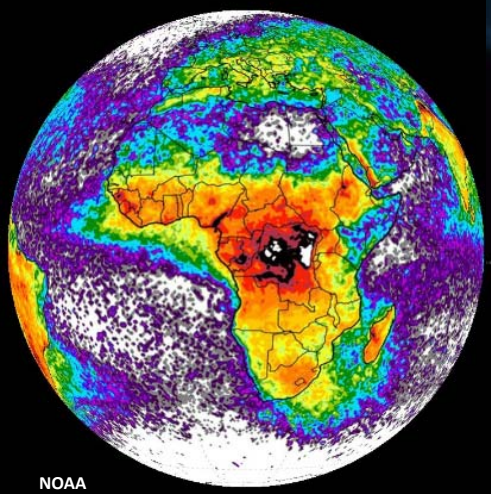
MT Signal Source > 1 Hz



NOAA

NOAA

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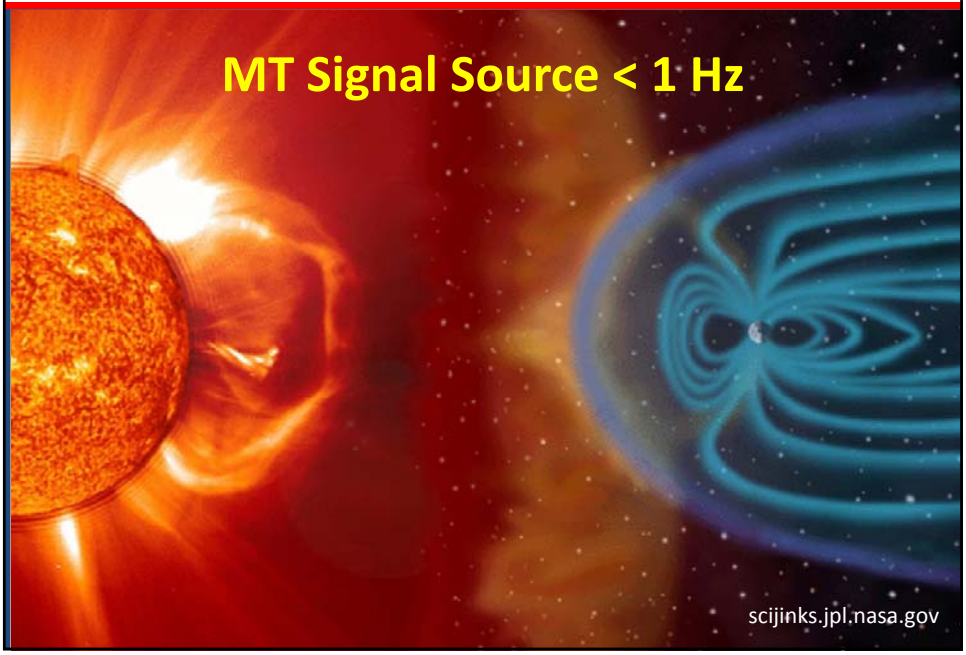
MT Signal Source < 1 Hz



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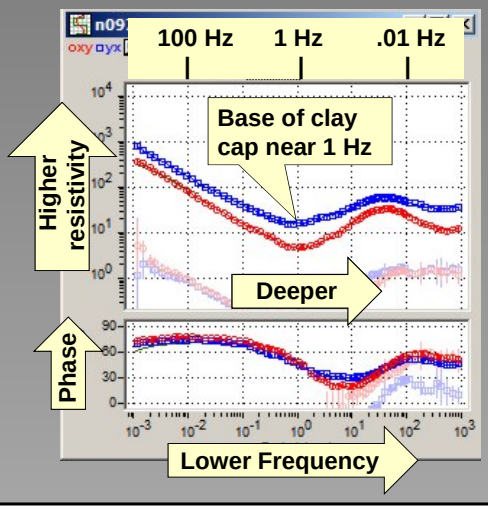
Standard MT Plot
Apparent Resistivity and Phase Spectra



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MT Inversion: 1D, 2D and 3D

- 1D inversion of MT average of both modes (curves) is widely used for quality assurance
- 1D Occam smooth inversion of the MT TE-mode can be truncated to depth where 1D is valid
  - where valid, often more realistic than 2D or 3D inversion
- 2D profile is OK if the geology is 2D
  - 2D inversion limitations are commonly misunderstood
- 3D can be effective if data coverage is appropriate and noise is carefully edited

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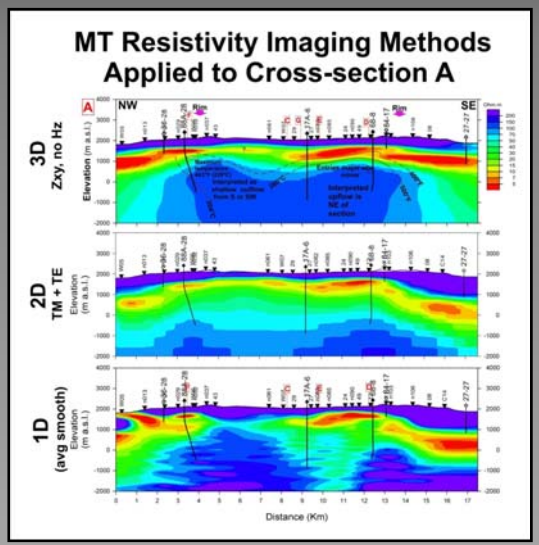
Glass Mountain Geothermal Field

1D vs 2D vs 3D MT Inversions

- 3D inversion resolves base of cap but resistivity in reservoir is almost uniform
- 2D inversion is not oriented at right angles to local strike. It resolves similar pattern but with less amplitude.
- 1D inversions stitched into a profile based on invariant mode of MT fits 3D except at NW end of profile.



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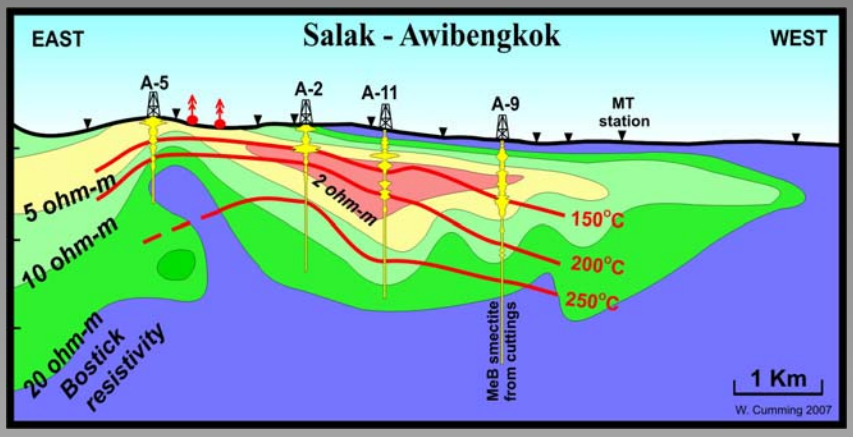
Salak Geothermal Field MT Cross-section

MT Resistivity with MeB Smectite & Isotherms from Wells



from: Gunderson, Cumming, Astra and Harvey (2000)

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Using Geophysics to Build a Geothermal Resource Conceptual Model

High Temperature Volcanic Case

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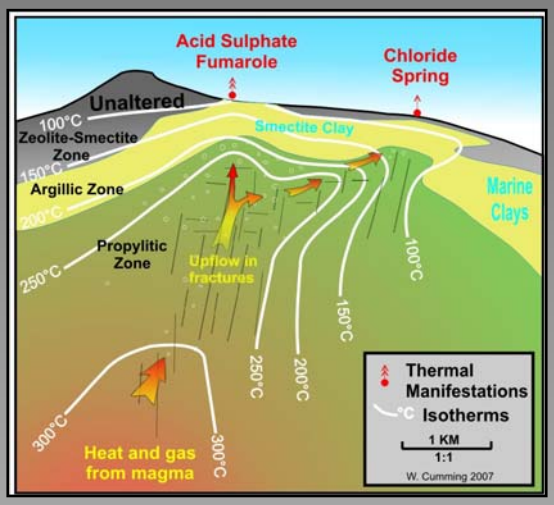
"Basic" Geoscience Plan For Volcanic Geothermal Prospect

- Gas and fluid geochemistry for existence, temperature and conceptual target
- MT to map base of smectite clay "cap"
- Maybe TEM for MT statics
- Geology, alteration and structure for context
- Shallow hydrology for context



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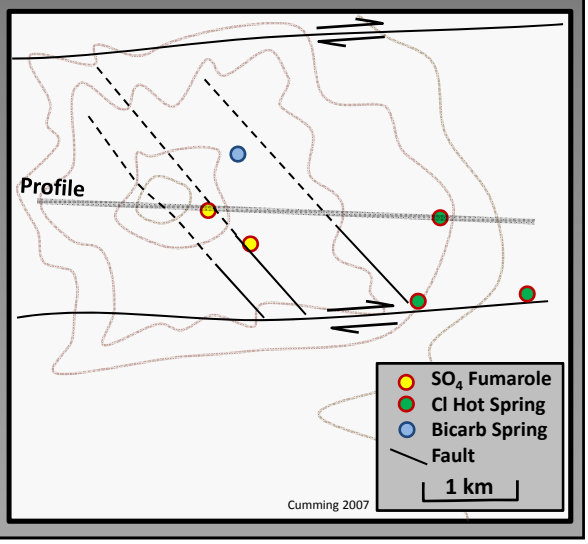
Geothermal Conceptual Model Map

- To illustrate conceptual model after recon stage, map shows topography, thermal features, geochemistry, geology, structures.
- Strike slip faults are often barriers to flow, even when adjacent structures and formations have enhanced permeability.



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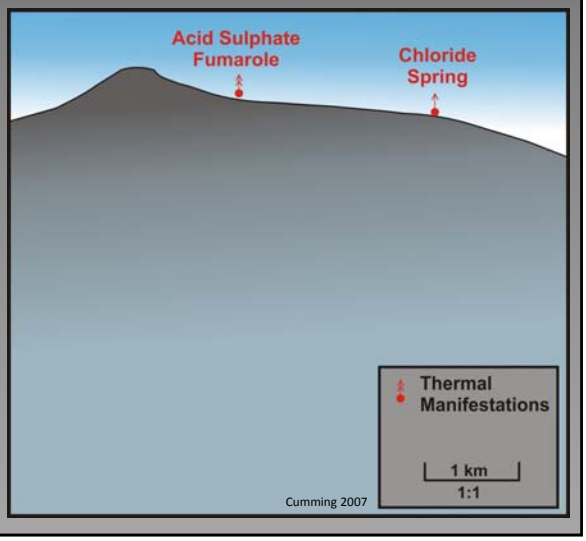
Start Geothermal Exploration Process

- Cross-section illustrates data and conceptual elements developed from geoscience "plan"
- Geochemistry - gas sampled at fumarole and water from hot springs
- Geology – small volcano, minor alteration near fumarole and spring



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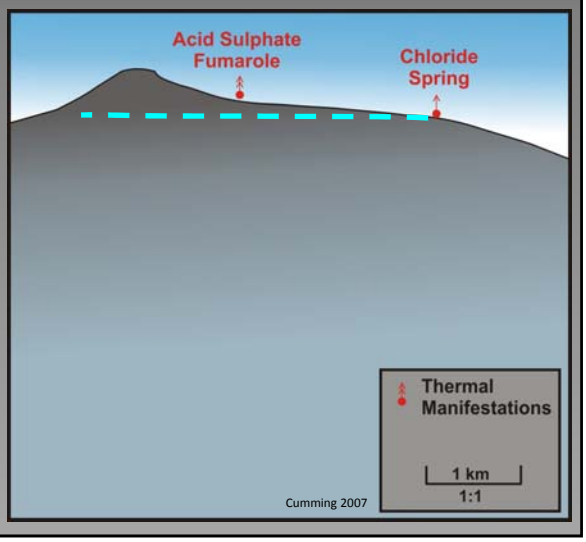
Geothermal Prospect Water Table

- Elevation to highest chloride spring provides estimate of minimum top of liquid pressure gradient in reservoir



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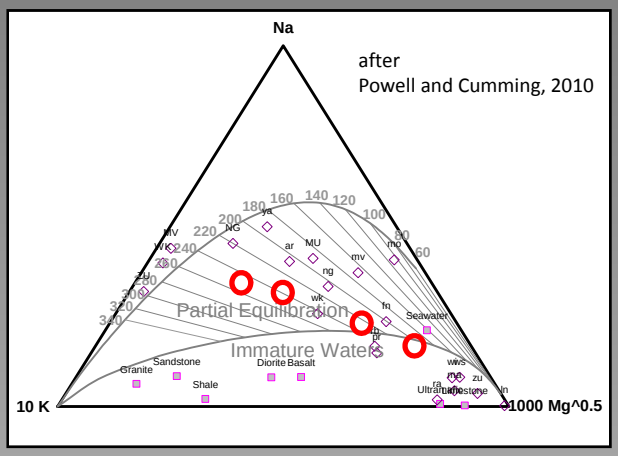
Exploration Cation Geochemistry

"Giggenbach" Na-K-Mg Ternary



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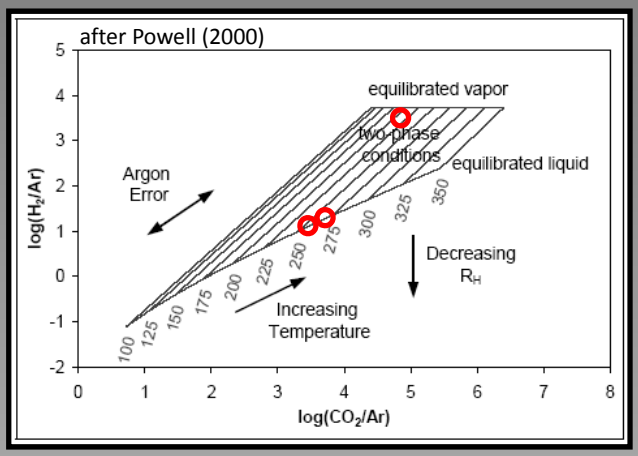
Exploration Gas Geochemistry

H_2Ar-CO_2Ar Gas Ratio Geothermometer



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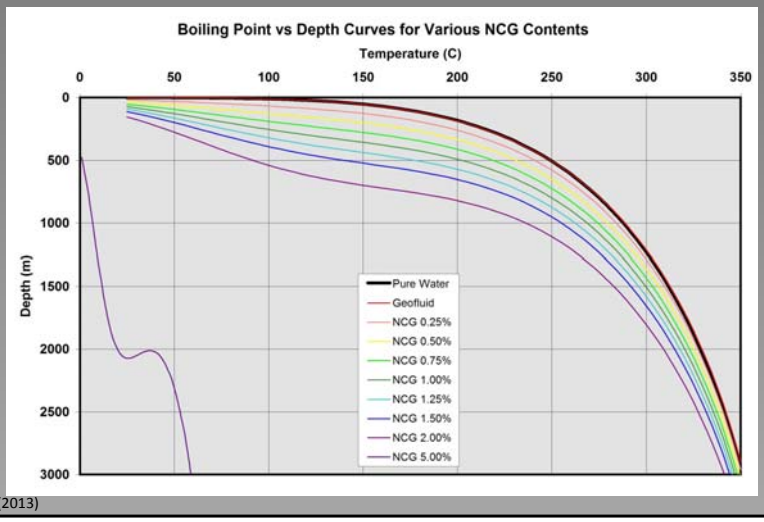
Geothermal Conceptual Model
Hydrostatic Boiling Point For Depth



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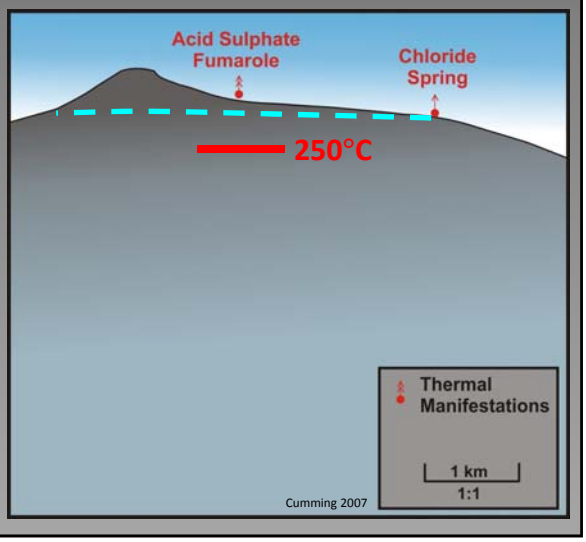
Geothermal Prospect Isotherm

- Elevation to highest chloride spring provides estimate of minimum top of liquid pressure gradient in reservoir
- Gas and water chemistry suggests water at 250°C at top of reservoir with thin steam zone at 220°C
- Boiling point curve indicates shallowest depth to 250°C is 500 m below water table



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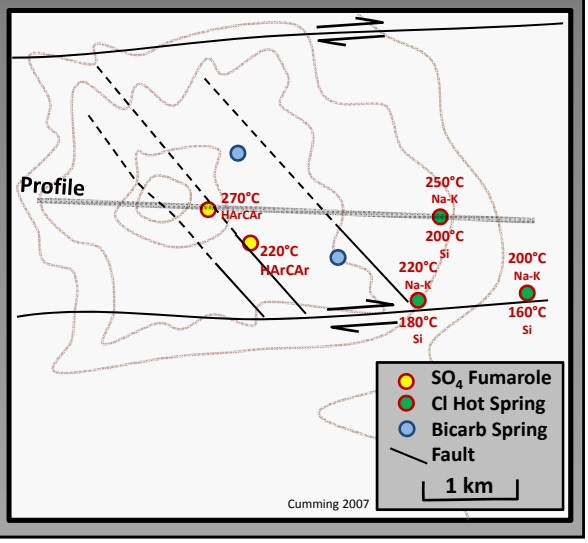
Geothermal Conceptual Model Map

- Update conceptual model after gas and water geochemistry are available
- Ground truth lineaments
- Faults that meet surface in a brittle permeable formation and do not leak gas or hot fluid more likely host shallow cold water down, not hot up.



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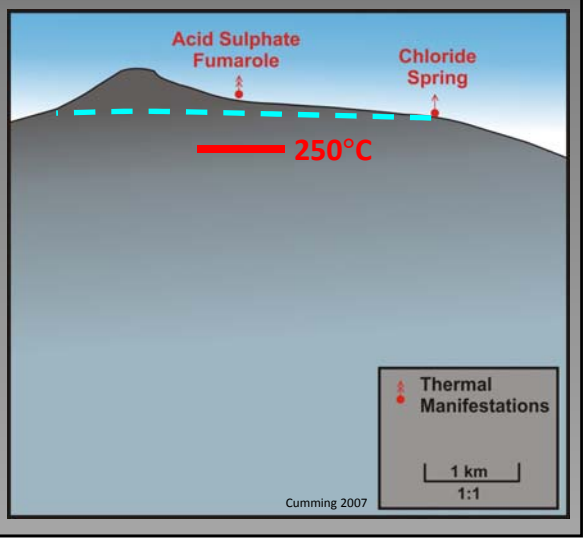
Expected Base of Clay and MT Plan

- From geothermometry and water table, base of clay ~500 m at fumarole
- Base of clay >1000 m at volcano margin/basin
- MT stations spaced closer together than the expected depth to the base of the clay cap
- Maybe TDEM to correct MT static distortion
- For thinner cap, VES or CSAMT is lower cost



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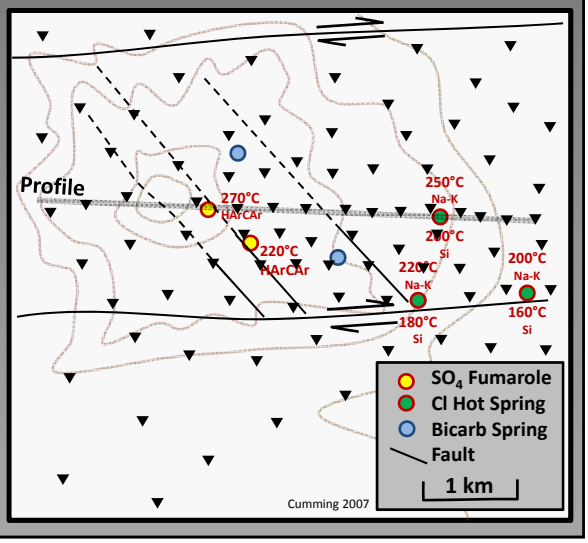
Geothermal MT Survey Plan Map

- MT stations spaced 300 to 700 m apart, mostly closer together than the expected depth to the base of the clay cap
- Avoid small peaks



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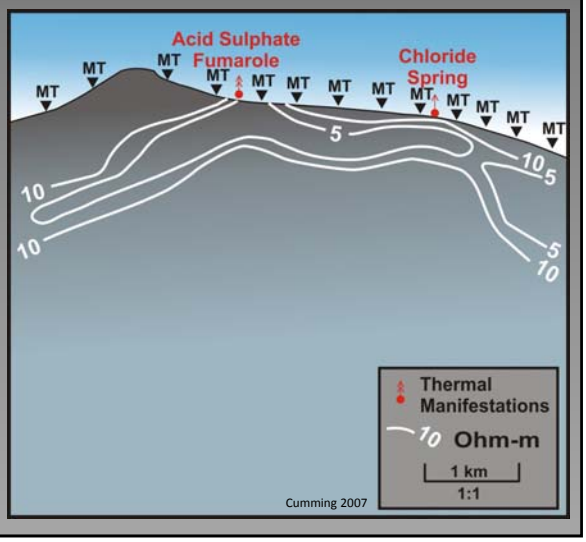
MT Survey and Resistivity Pattern

- MT resolves low resistivity pattern corresponding to smectite clay



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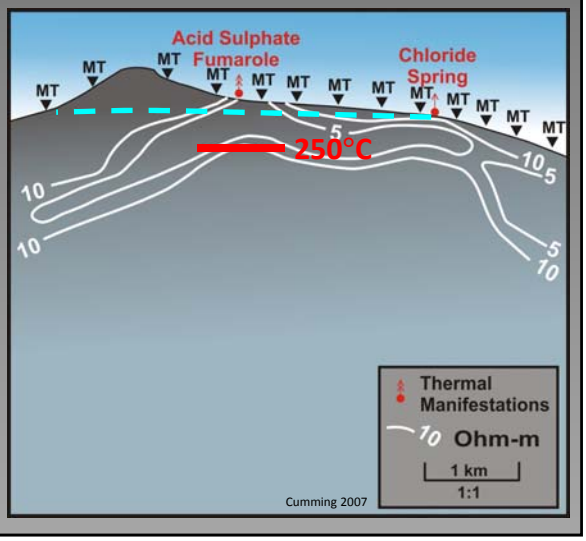
Geothermal Resistivity Pattern

- Resistivity lower than 10 ohm-m shallower than 2000 m depth is reliably interpreted as clay cap.
- Temperature interpreted from geochemistry, not directly from resistivity
- Clay cap and isotherm interpretation based on resistivity cross-sections
- Maps include resistivity slices, conductance, and elevation of base of clay



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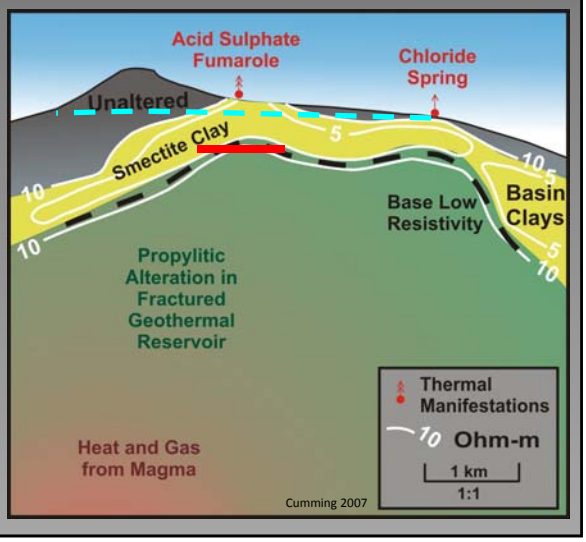
Base of Conductor/Clay Cap

- Specific correlation of resistivity with base of clay depends on alteration history of field, salinity, primary rock properties, and resolution MT
- Base of smectite clay usually initially inferred from resistivity gradient at base of conductor and expected depth of reservoir temperaure



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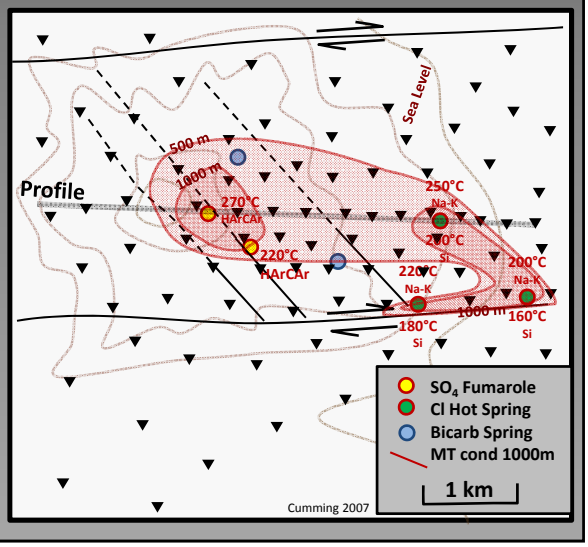
Geothermal BoC Elevation Map

- Map of MT BoC = Base of Conductor (or Base of smectite Clay)
- Locally high sometimes over upflow, almost always over outflow



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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Conceptual Model Isotherm Properties

- Isotherms define the permeable reservoir
- Isotherms are constrained by hydrothermodynamics:
  - Water table defines pressure and maximum temperature distribution
  - Temperature < hydrostatic boiling point
  - Hot upflow and outflow by buoyancy in permeable zones
  - Cold influx by hydrostatic gravity flow in permeable zones with colder or higher elevation source and aquifer connection
  - Conduction where permeability low
  - Very high temperature gradients require permeable high and low temperature zones on each side of an impermeable zone
  - No isolated hot or cold zones (cross-sections use arrow heads/tails)

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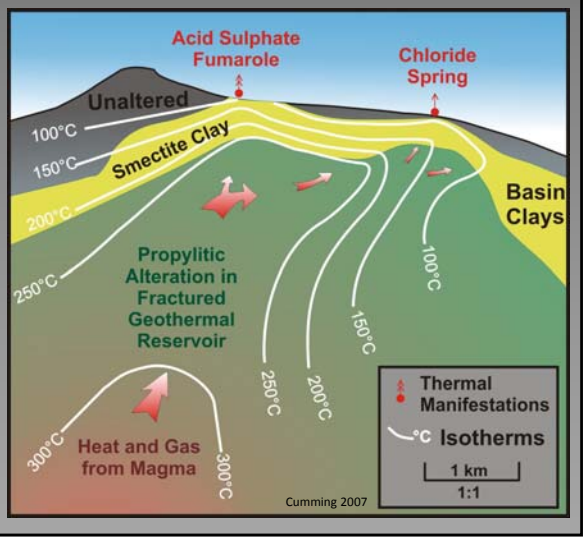
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Conceptual Model

- Build conceptual model consistent with geochemistry, resistivity, thermodynamics, hydrology, etc
- Top of reservoir conforms to base of low resistivity clay cap
- Isotherms crowded together in clay cap that separates cool meteoric flow above cap from hot reservoir below cap



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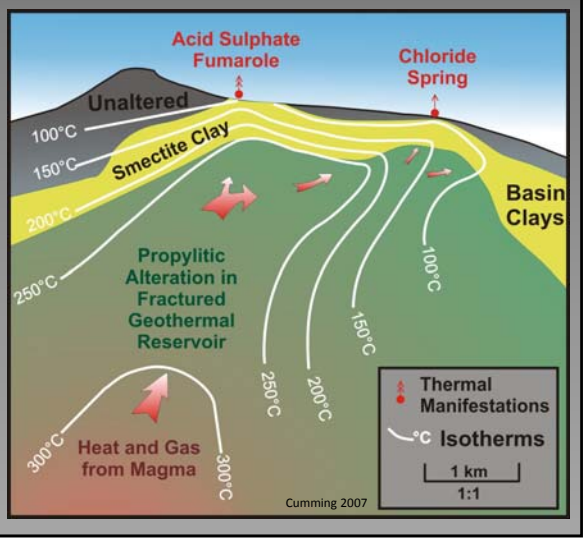
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Conceptual Model Upflow/Outflow

- Upflow vs Reservoir Outflow vs Outflow < $T_{minimum}$ based on geochemistry, clay geometry, geology, structure and analogs
- e.g. outflow extent from chloride spring long memory Na-K-Mg and short memory Si geothermometry
- Important to reservoir area and MWe capacity



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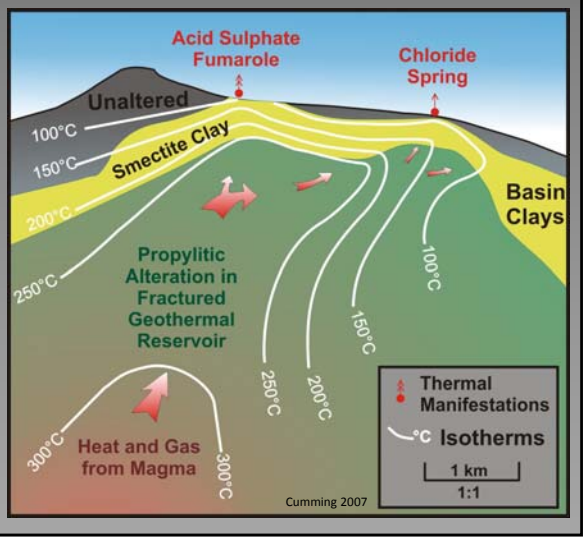
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Deep Geothermal Conceptual Model

- Deeper reservoir isotherm pattern inferred from shallow geometry, long memory geothermometers and analogous reservoirs
- Basalt magma at <4 km depth constrains 350°C and reservoir base.
- Most heat sources poorly connected and uncertain so treated as boundary condition



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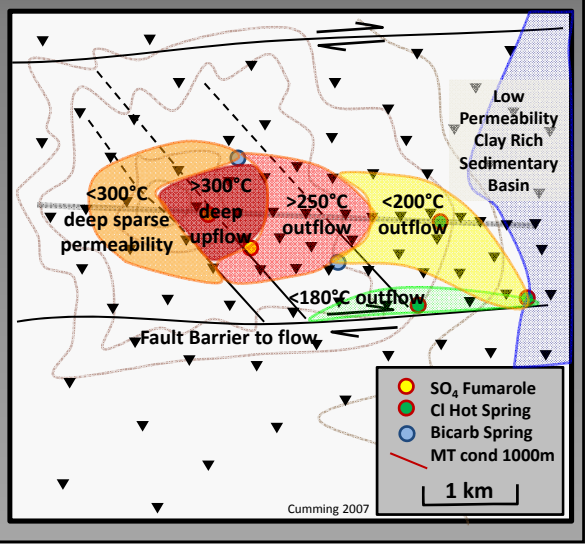
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Conceptual Elements Map

- Elements of the conceptual resource model are outlined based on geochemistry and MT resistivity indications of the pattern of hydrothermal clay alteration and sedimentary clay deposition in the context of the geology and structure.



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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Well Targeting Decision Table

- Choose conceptually independent targets
- Decision table compares constraints on target concept and risk
  - Evidence for high deliverability well
  - Evidence for targets being too tight or cool

Candidate locations testing conceptually different targets

Indicators	A	B	C	D	E	F
Geochemistry						
MT Geometry						
MT Resistivity						
What Else?						
Conceptual Risk						
Summary						

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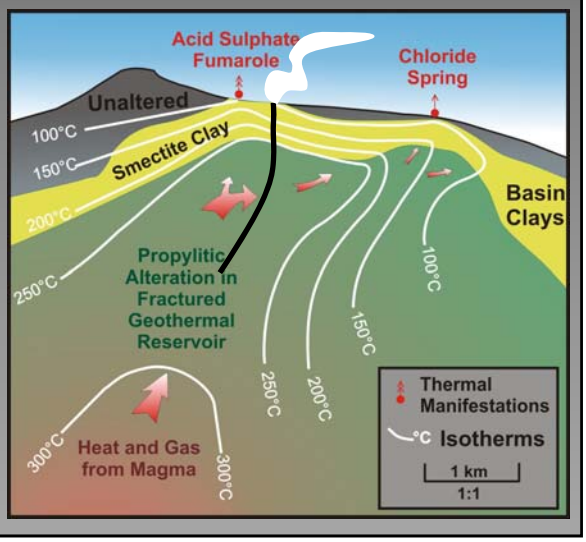
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Well Targeting

- Target highest geothermometry fumarole with neutral chemistry
- Target upflow apex in thinned base of clay cap
- Target particularly low resistivity in thinned clay cap
- Directional well across structure associated with acid-sulfate alteration.



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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

How Do Assessments Fail?

- Data Uncertainty
  - Acquisition noise always create some uncertainty
  - As a natural source method, MT is particularly susceptible to the spread of electrical noise in Indonesia
- Inversion (Imaging) Uncertainty
  - Reliability of inversion is limited to range of data for which inversion assumptions are valid. 1D vs 2D vs 3D
  - Inversions are sensitive to data noise, and inversions with more "D" are more difficult to realistically constrain
- Conceptual Interpretation Uncertainty
  - Inconsistency with implications of other types of data and model constraints
  - Ambiguous correlation with resource properties

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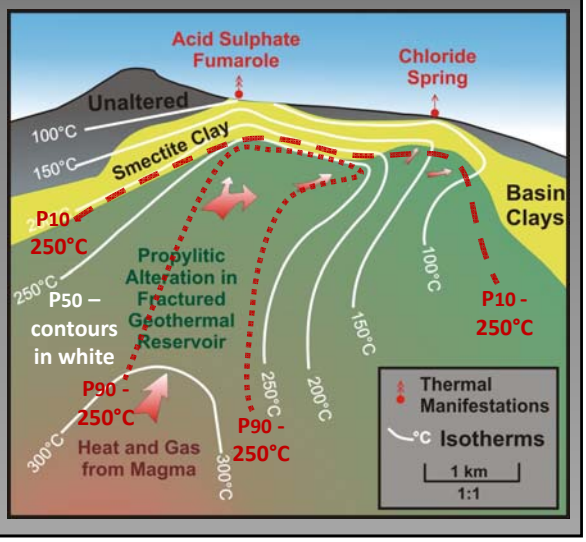
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Resource Capacity Uncertainty

- Consider conceptual and data uncertainty to build representative range of resource models at 10% 50% and 90% confidence
- Fit MT cross-sections, thermal manifestations, alteration, structure, geology, etc to build area outlines
- Adjust sections/maps to fit outlined areas to lognormal distribution



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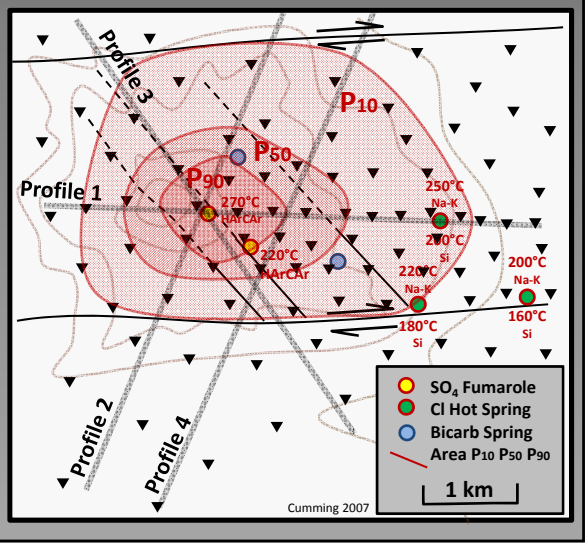
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Resource Area Estimate

- Areas at 10, 50 and 90% confidence levels are outlined by referring to several cross-sections, each of which has three conceptual models sketched.
- P10 (optimistic, large)
  P50 (median)
  P90 (pessimistic, small)
  resource areas are adjusted to fit a lognormal distribution.



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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Monte Carlo Heat-In-Place Method Geothermal Resource Capacity

- Australian Geothermal Resource Reporting Code
- Canadian Geothermal Resource Reporting Code
  - Developed to support investment by finance companies relying on experts
  - Requires exclusive use of Monte Carlo Heat-in-Place
  - Explicitly rejects use of 1) Analogy, 2) Power Density
  - Encouraged $billions of short term investment in long term speculative resources like Australian EGS
  - Supported worldwide geothermal investment bubble

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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Monte Carlo Heat-In-Place Method Geothermal Resource Capacity

- Malcolm Grant (2015, WGC)
  - Attempts to codify the process have been spectacularly unsuccessful, as shown by the example of the Australian Code which is biased high, sometimes by a large multiple. Attempts to compensate by using Monte Carlo methods have been at times comical failures.

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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Monte Carlo Heat-In-Place Method Geothermal Resource Capacity

Group 1 Parameters (high uncertainty):

- Reservoir Area (km2)
- Reservoir Thickness (m)
- Reservoir Temperature (°C)
- Thermal Recovery Factor (%)
- Reservoir Depth For Drilling Cost (m)

Group 2 Parameters (low uncertainty):

- Volumetric Heat Capacity (kJ/m3-K)
- Rejection Temperature (°C)
- Conversion Efficiency (%)
- Plant or Project Life (years)
- Plant Load Factor (%)

Garg and Combs (2010, Stanford)

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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Power Density Method Geothermal Resource Capacity

Two Constrained Capacity Parameters:

- Reservoir Area (km^2) based on MT, alteration etc.
- Power Density (MWe/km^2) constrained by fields with analogous reservoir temperature, extraction technology, and geologic indications of reservoir thickness and permeability

Depth from MT for drilling cost

Power Density compiles:

- Reservoir Temperature (°C)
- Thermal Recovery Factor (%)
- Reservoir Thickness (m)

and

- Low uncertainty Group 2 Parameters

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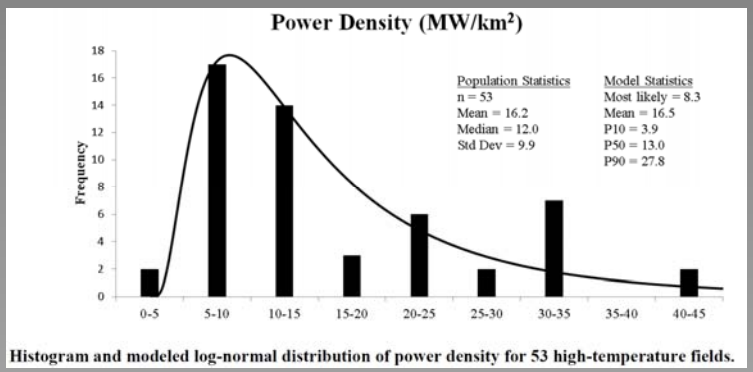
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Resource Capacity Distribution

Power density roughly fits a lognormal / power law distribution



Histogram and modeled log-normal distribution of power density for 53 high-temperature fields.

Wilmarth and Stimac, 2014

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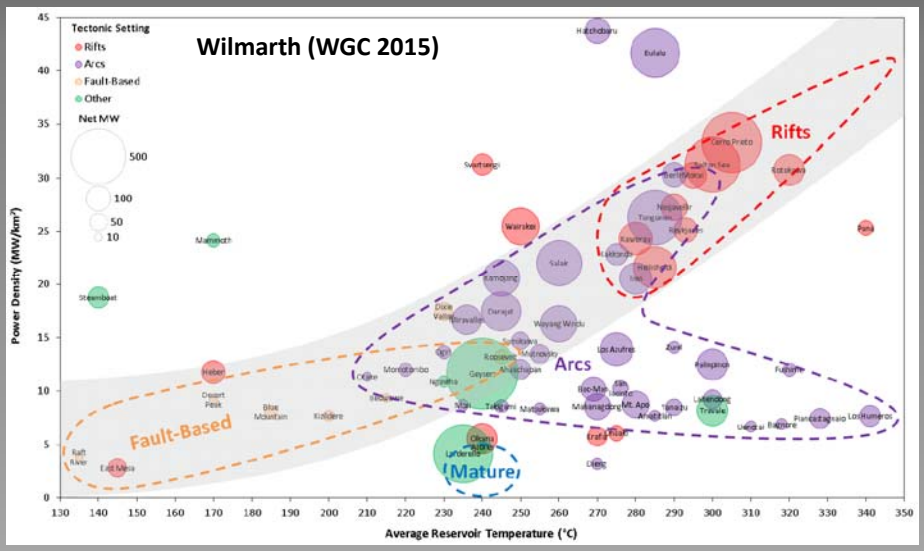
Geothermal Resource Power Density



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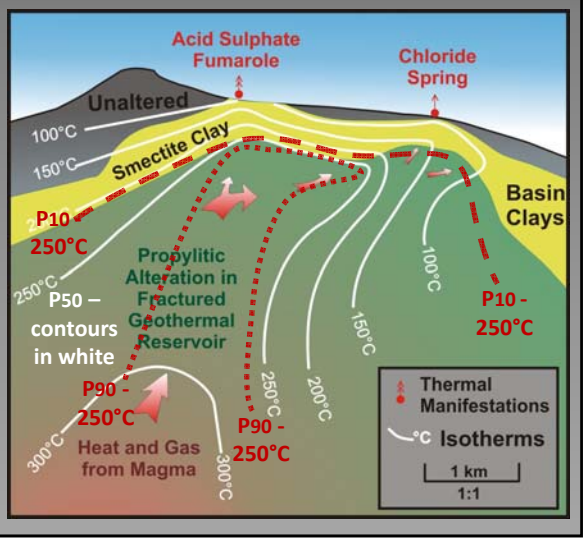

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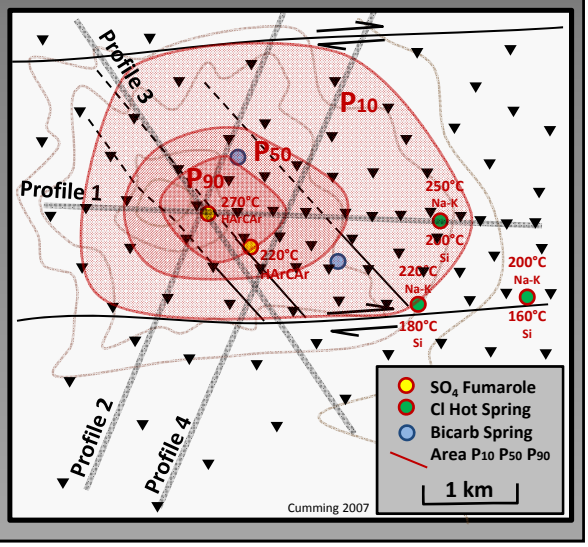

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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Power Density Method Geothermal Resource Capacity

- Estimate P10, P50 and P90 for Area in km² and Power Density in MW/km²
- Capacity computation using P10, P50 and P90 and lognormal distributions:
  Cumming (2013) Geothermal resource capacity assessment spreadsheet.
  Free GPU license with acknowledgement

EXLORATION: Is it there?

Assuming a likely exploration and drilling program, what is the likelihood of demonstrating that at least one well is commercial with 90% confidence

	Confidence in temperature.		Confidence in permeability. Commercial mDarcy		Confidence in chemistry. Not corrosive or scaling		Probability of exploration success
	PTemperature		Ppermeability		Pchemistry		POSexpl
Exploration Confidence	0.85	*	0.65	*	0.95	=	0.52

APPRAISAL AND DEVELOPMENT: Assuming it's there, how big is it?

Cumulative confidence of representative optimistic case = 10% That is, the optimistic case is assumed to be P10

Temperature range of permeable reservoir area from resource conceptual model. This should be consistent with assumed power density distribution.

Startup average production temperature for P10 reserves = 280 °C 250 °C = minimum temperature of P90 reservoir

Nu and Sigma are the mean and variance in log units required for specifying lognormal distributions in tools like @RISK

Representative Cases		P99	P90	Pessimistic P90	Middle P50	Optimistic P10	P10	P01	Mean	nu	sigma
Area > 250°C	(km²)	0.4	1.0	1.0	3.2	10.0	10.0	25.6	4.7	1.15129	0.89836
Power Density 250 to 280 °C	(MWe/km²)	7	12	10	15	24	24	34	16	2.74032	0.34157
MWe Capacity		5	14	14	49	168	168	458	78	3.89161	0.96110

EXPECTED POWER CAPACITY RESERVES (based on analogous reservoirs used to assess confidence in power density and area)

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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Decision Table To Rank Information

- Decision table compares influence of data type or analysis type on elements of capacity estimate
- Enter in cells the specific contribution and relative weight of each data type for each element of the capacity assessment
- Rank cost-effectiveness using (overall weight)*(cost of data type)

	Resource Capacity Elements				Valuation	
Indicators	POS_{expl}	P_{90}	P_{50}	P_{10}	Weight	Cost
Gas Geochemistry						
MT Geometry						
Imaging of Alteration						
Structure						
Conceptual Model 1						
Etc						

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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Exploration of Volcanoes
Top Data Priorities For Decision Risk Analysis

Base Maps	Digital high resolution satellite 50 cm color images georectified and integrated with an SRTM DEM. In some areas, Google Earth is adequate. Digital topographic maps with culture at resolution better than 1:50000 All images and maps should be in UTM projection with datum specified
Old Boreholes	Temperature logs, water/gas, cuttings descriptions, cuttings clay analyses
Geochemistry	Water chemistry of all hot springs and water wells and gas chemistry of all fumaroles, acid-sulfate features and boiling springs
Active Alteration	Based on visual review of <50 cm color images, identify candidate features and ground check for alteration type and surface temperature
MT (+-TEM)	Remote reference robust MT from .01-300 Hz, better .001-10000 Hz QA using D+ editing, 1D Occam inversion AVG, likely 3D inversion Add TEM if likely to detect top of conductor at <30% cost increment
Geology	Standard exploration geology: volcanic history, expected reservoir rock, formation map, heat source, exposed brittle rocks like rhyolite dome as cold water source, basin structure, sediments, hydrothermal processes, alteration mapping (not just active alteration detection), eruption breccias, etc.
Structure	Map lineaments, ground check geometry and rate, review evidence of extension. Implications for permeability of the interaction of structure with reservoir leakage, vertical stress, formation properties, alteration, irregularity, etc.
MEQ	Microearthquake monitoring for >3 months to detect magma below active basalt shield or for hazard assessment of an active andesite volcano (<4 to >100 Hz)
GPS + DEM	GPS makes other methods more cost-effective if quality is controlled. Check datum and coordinate quality. Use DEM or dGPS for elevation.

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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

What Goes Wrong?

- Data Uncertainty
  - Acquisition noise always create some uncertainty
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- Inversion (Imaging) Uncertainty
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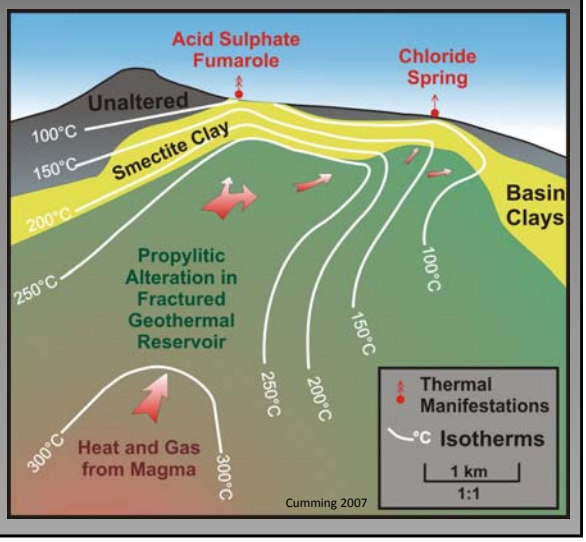
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Conceptual Model Uncertainty

- Deeper reservoir isotherm pattern inferred from shallow geometry, long memory geothermometers and analogous reservoirs
- Uncertainty in inference of isotherm pattern increases if clay cap differs from analysts' case history experience



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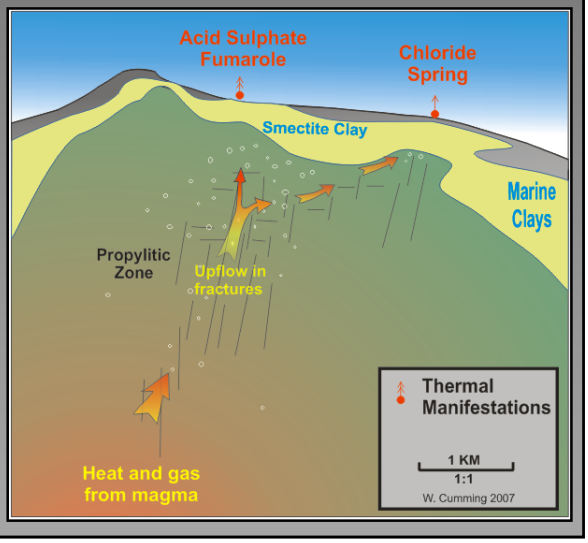
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Conceptual Model 2

- Base of clay cap from < 10 ohm-m resistivity follows topography
- Top of apparent propylitic alteration 700 m above water table



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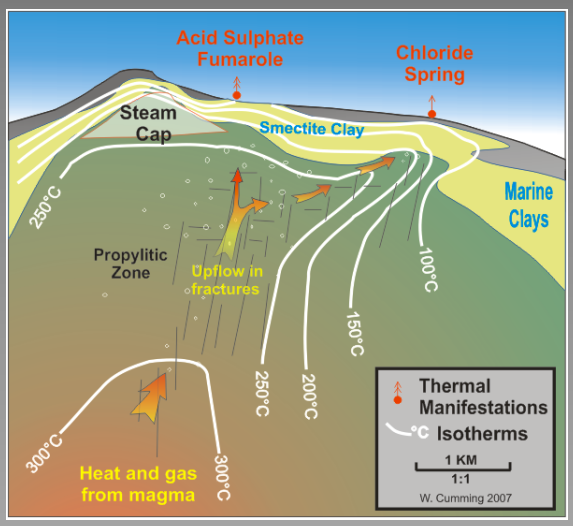
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Conceptual Model

- Base of clay cap from < 10 ohm-m resistivity follows topography
- Top of apparent propylitic alteration 700 m above water table
- Zone between water table and base of the clay cap commonly interpreted as steam cap



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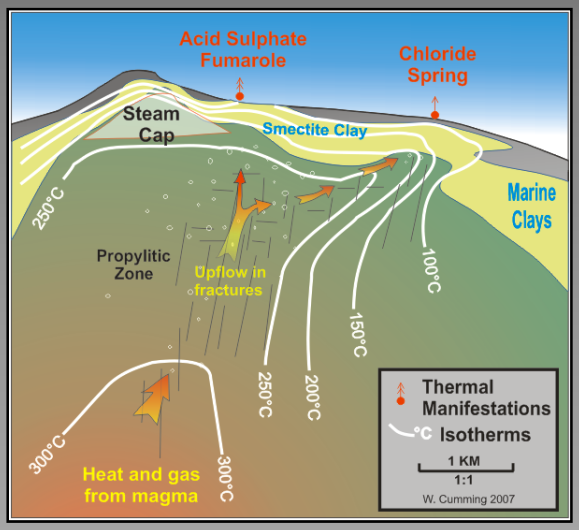
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Conceptual Model

- Base of clay cap from < 10 ohm-m resistivity follows topography
- Top of apparent propylitic alteration 700 m above water table
- Zone between water table and base of the clay cap commonly interpreted as steam
- Pressure at top of steam zone exceeds frac pressure but no leakage



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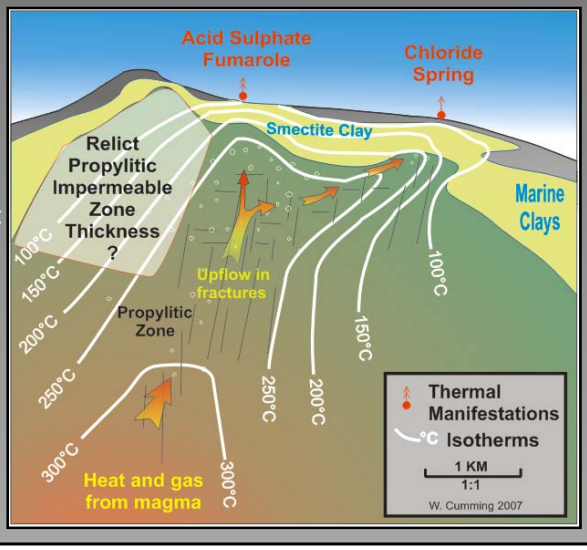
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Conceptual Model

- Commonly observed model consistent with lack of leakage
- Top of apparent propylitic alteration 700 m above water table but relict (cold) and low permeability
- Reservoir smaller
- Look for surface exposure of chlorite in deep drainages to confirm



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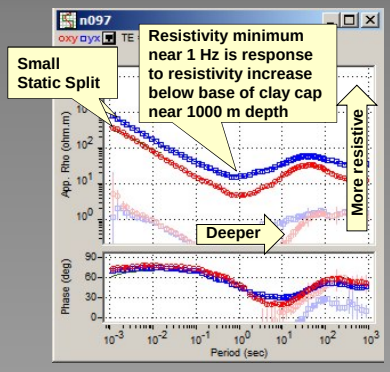
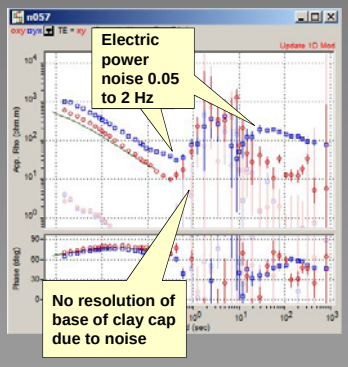
GOOD/BAD MT DATA



- 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

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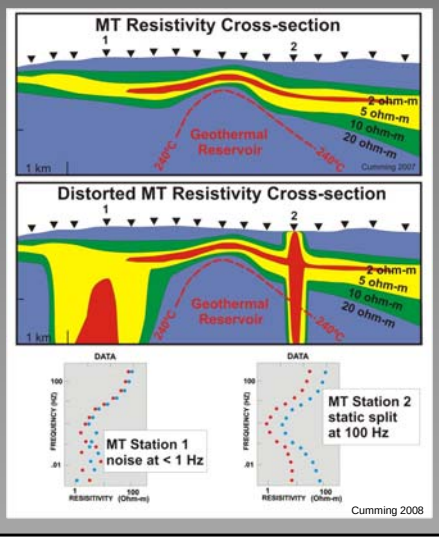
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal MT Interpretation Pitfalls

- MT cross-section without distortion shows typical geothermal low resistivity cap in volcanic tuffs
- Deep low resistivity zone (red) below Station 1 misinterpreted as reservoir
- Vertical low resistivity contours below Station 2 misinterpreted as fault
- MT imaging of resistivity distorted by:
  - noise near station 1
  - static at station 2



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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Deep Low Resistivity Zones Below Base of Geothermal Clay Cap

- **Smectite clay alteration**
  - The temperature reversal below a reservoir outflow sometimes hosts low resistivity clay. The deeper low resistivity zone is a limit, not a target.
- **Basaltic magma**
  - The basalt-hosted Krafla and Puna fields are the best understood magma zones that can be imaged using MT (and earthquakes).
  - This reservoir element is both a constraint on the 350°C reservoir and a zone to be cautiously approached by drilling.
- **Acid volcanic aquifers**
  - Although Kawah Bodas, Patuha and Krafla include acid core zones imaged as low resistivity, the MT resolution of these acid zones is questionable.
- **Graphitic/Pelitic schist in Paleozoic metamorphosed sediments**
  - Graphitic schist is very low resistivity and low permeability unless silicified.
- **MT imaging artifacts**
  - Deep low resistivity zones often prove to be imaging artifacts, especially when they are associated with steeply dipping high amplitude resistivity contrasts.

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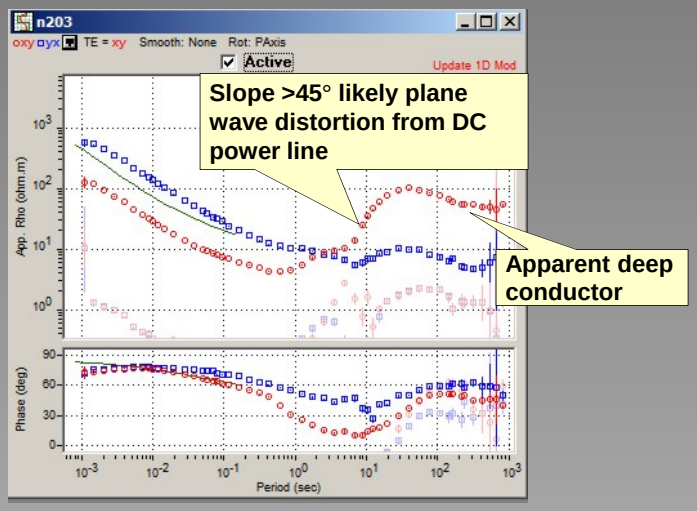
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Non-Plane Wave Distortion



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

Apparent deep conductor

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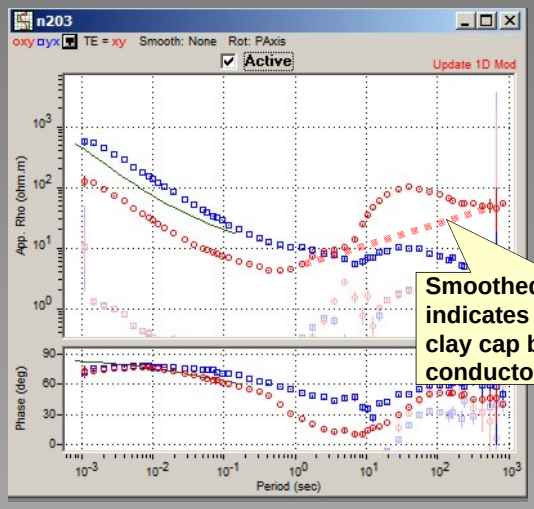
Non-Plane Wave Distortion



Smoothed resistivity trend indicates increase below clay cap but no deep conductor

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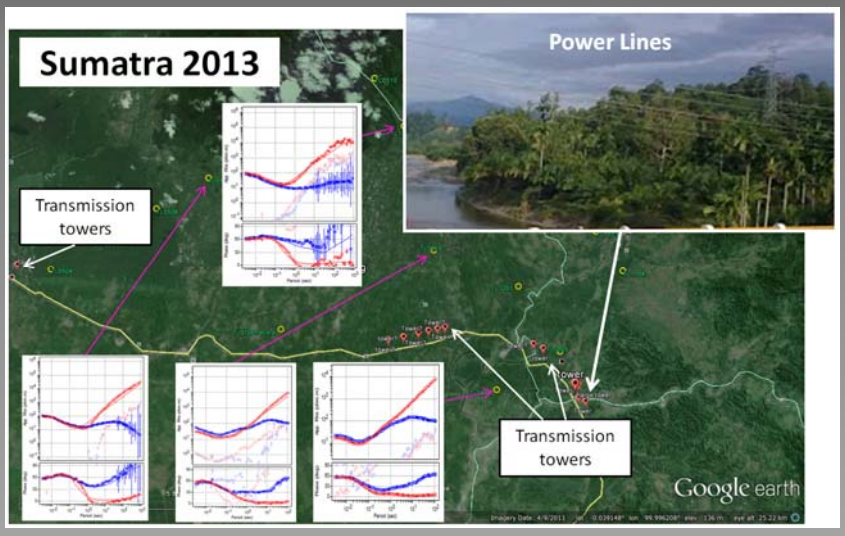

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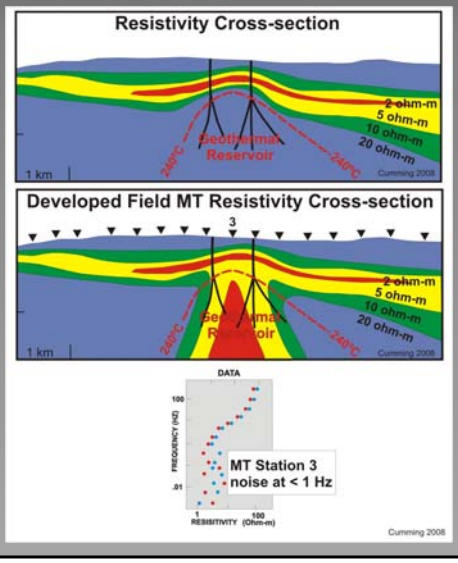
MT Pitfalls in Geothermal Development

- MT cross-section without distortion shows classic geothermal cap geometry
- Deep low resistivity zone (red) below wells interpreted as reservoir
- MT imaging of resistivity distorted by:
  - noise near station 3 related to power line



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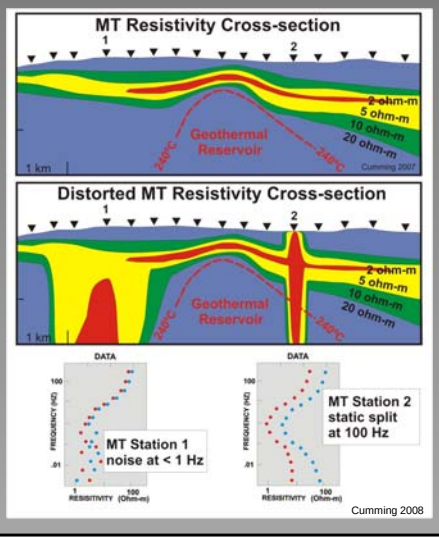
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal MT Interpretation Pitfalls

- MT cross-section without distortion shows typical geothermal low resistivity cap in volcanic tuffs
- Deep low resistivity zone (red) below Station 1 misinterpreted as reservoir
- Vertical low resistivity contours below Station 2 misinterpreted as fault
- MT imaging of resistivity distorted by:
  - noise near station 1
  - static at station 2



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Geothermal Geophsyics Case Histories

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Ngatamariki Geothermal Field

Conceptual model based on MT:

- Conventional low resistivity correlation with smectite and low permeability
- Urzua (2007) interpreted P_{90} upflow to south, P_{10} upflow close to current model
- Shallow "Huka" lake beds cap intermediate aquifer
- Deeper clay cap
- Deep cap less well resolved to south below 180°C outflow in "silicified aquifer"

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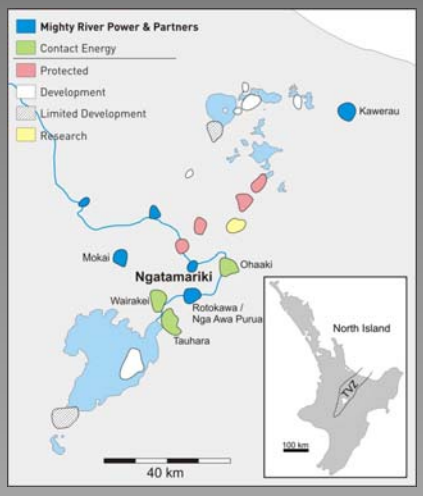
Ngatamariki Field Location

- Ngatamariki about 20 km northeast of Wairakei and just north of Rotokawa Geothermal Field
- Geothermal resource in the Taupo Volcanic Zone
- Initial geothermal exploration and 4 wells drilled by the New Zealand government in the 1980s
- Currently operated by Mighty River Power



Boseley et al., 2010

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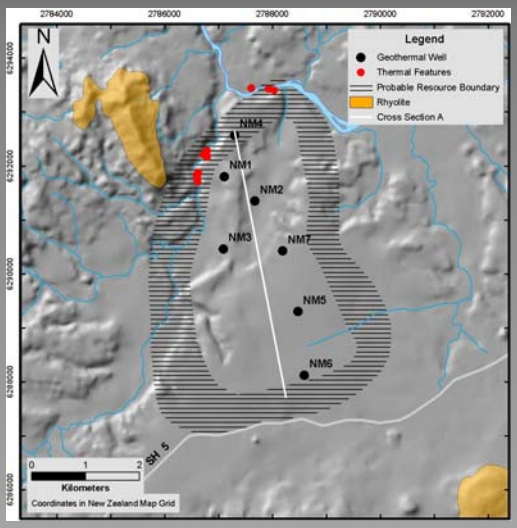
Ngatamariki Field Map

- Wells NM1 to NM4 were drilled in the 1980s.
- Three productive at 275°C but field was interpreted to be small based on shallow resistivity pattern.
- As a thesis project on MT supported by Mighty River Project, Luis Urzua predicted an extension >3 km to the south of NM3
- NM5 and NM6 confirmed much of this hypothesis



Boseley et al., 2010

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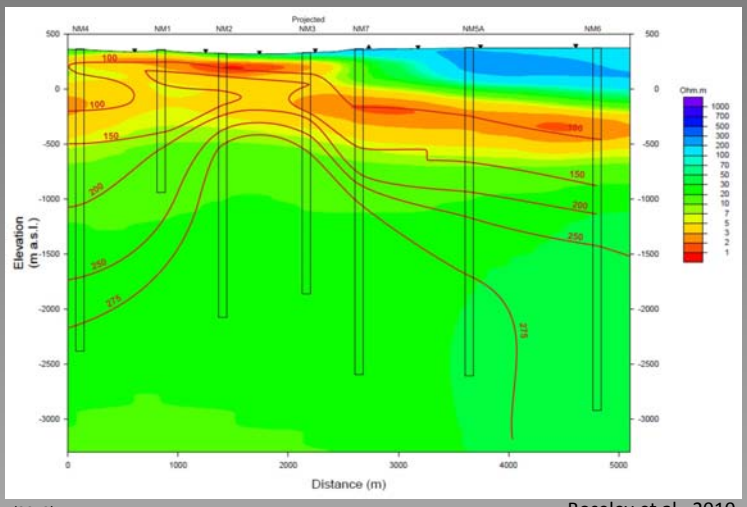
Ngatamariki Cross-section 3D MT Resistivity With Isotherms



Boseley et al., 2010

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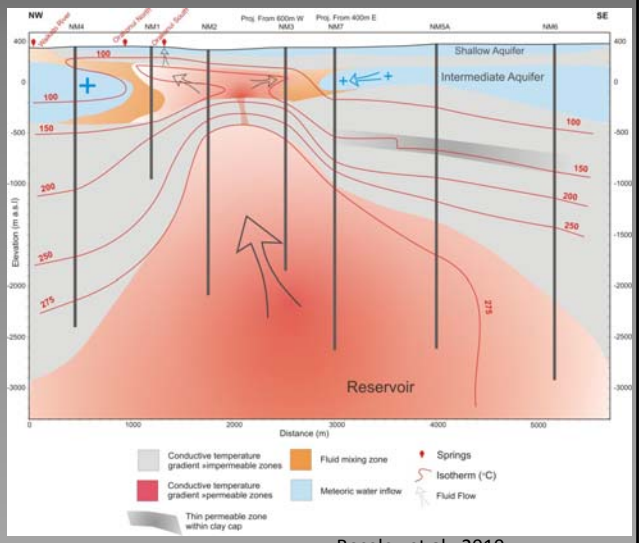
Ngatamariki Aquifer Interpretation

- Resistivity cross-sections fit the wells and constrained the unusually large number of elements in the hot and cold aquifer systems shown at right.
- The elements include upflow, deep outflow, constricted hot leak to intermediate aquifer, hot and cold sections of the intermediate aquifer and a surface aquifer.
- The conceptual model includes all of the barriers to flow.



Boseley et al., 2010

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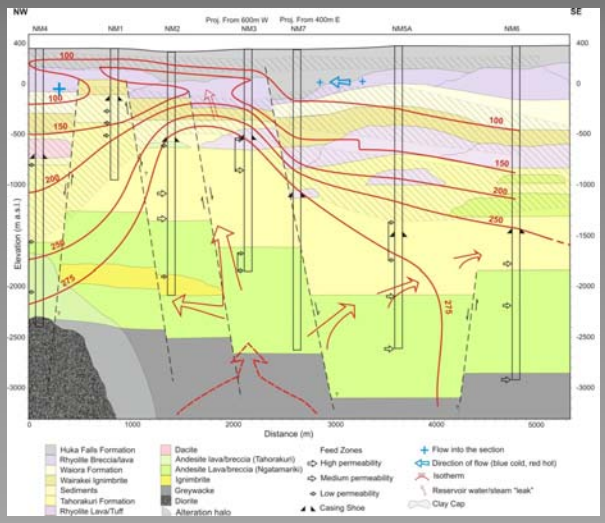
Ngatamariki Conceptual Cross-section

- The geological model illustrates the controls on the flow patterns
- Deep local upflow at >280°C in fractured greywacke
- Shallower than 1000 m, the upflow encounters formation permeability in rhyolite lava.
- Rhyolite lavas also host cold cross-flows
- Impermeable sediments partially isolate cold cross-flows from outflows



Boseley et al., 2010

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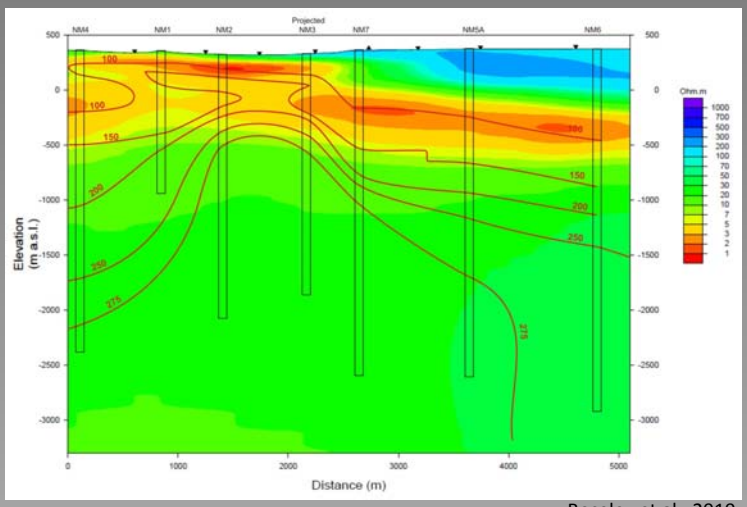
Ngatamariki Cross-section 3D MT Resistivity



Boseley et al., 2010

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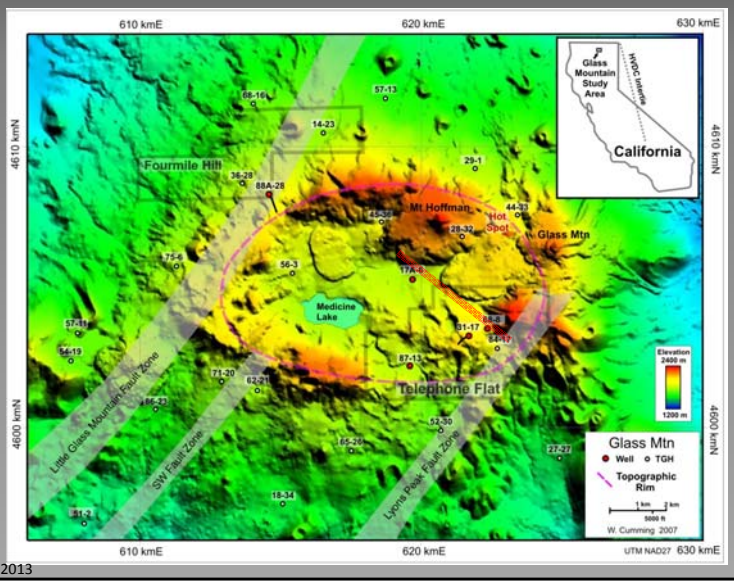
Glass Mountain Geothermal Field



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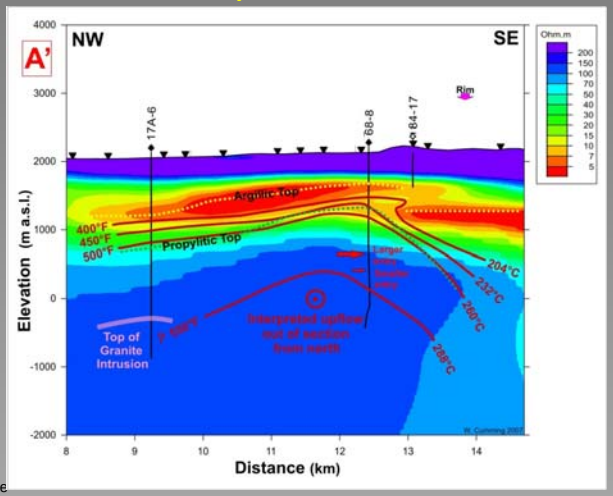
Glass Mountain Geothermal Field
MT Cross-section
MT Resistivity with isotherms from Wells



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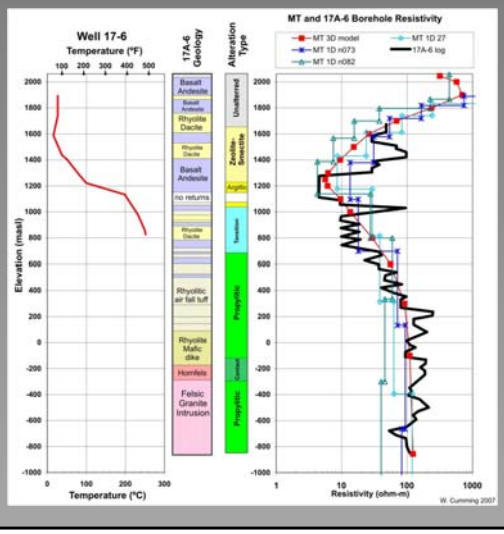
Glass Mountain Geothermal Field
MT Resistivity and Well 17A-6



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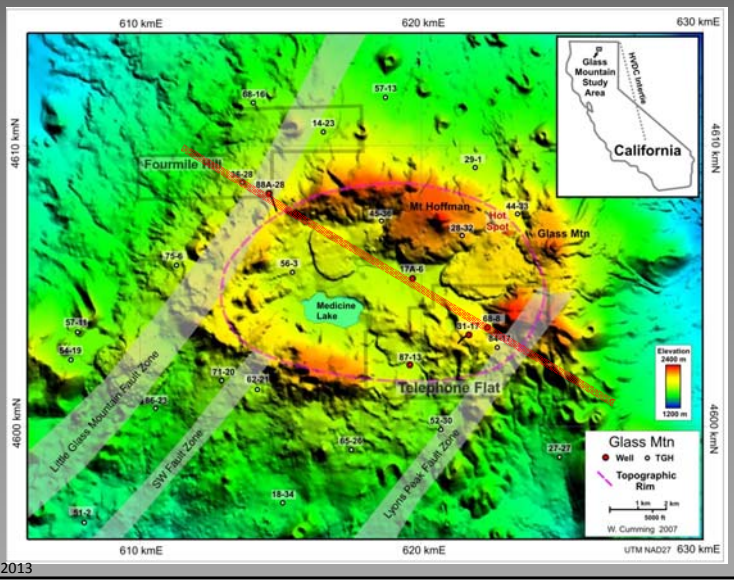
Glass Mountain Geothermal Field



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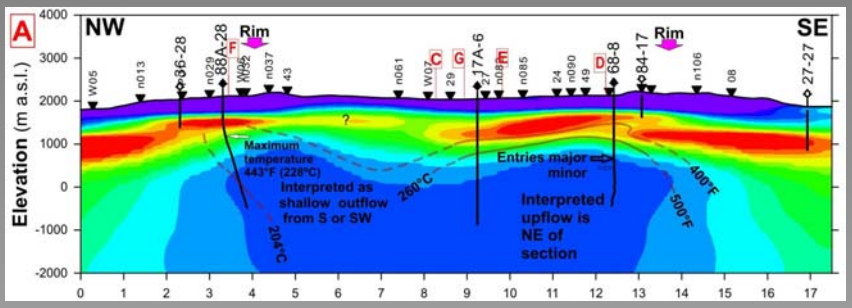
Glass Mountain Geothermal Field
MT Cross-section

MT Resistivity with isotherms from Wells



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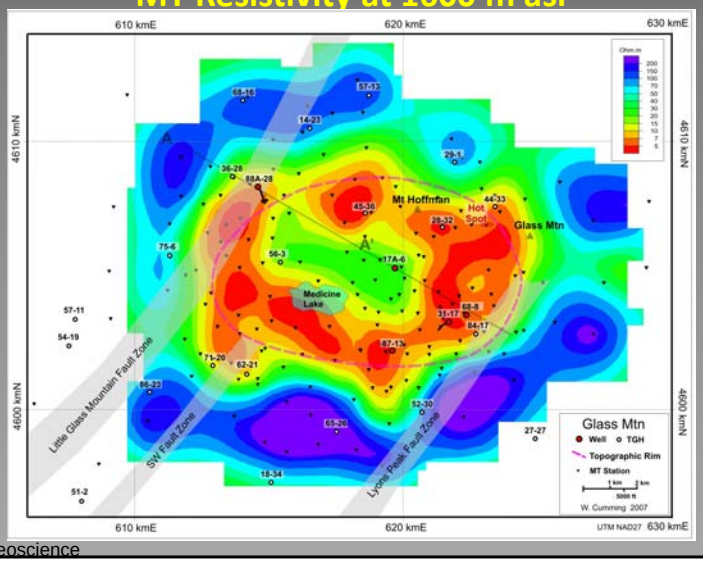
Glass Mountain Geothermal Field
MT Resistivity at 1600 m asl



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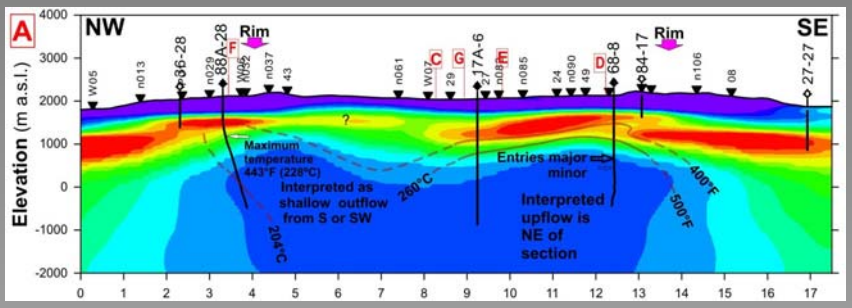
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Glass Mountain Geothermal Field
MT Cross-section

MT Resistivity with isotherms from Wells



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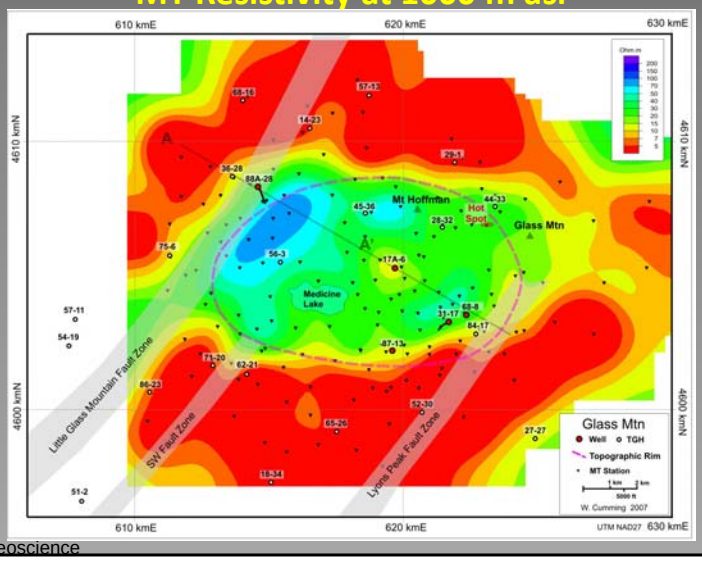
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Glass Mountain Geothermal Field
MT Resistivity at 1000 m asl



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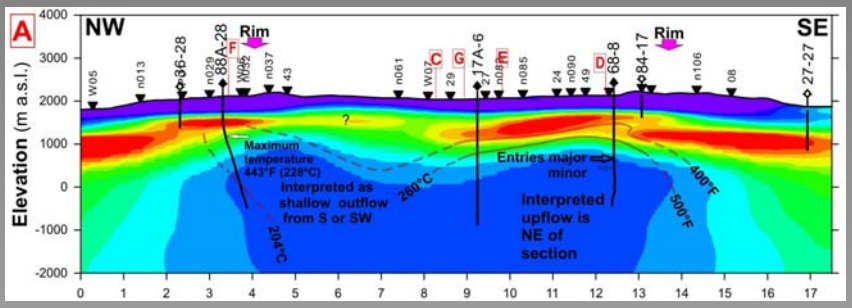
Glass Mountain Geothermal Field
MT Cross-section

MT Resistivity with isotherms from Wells



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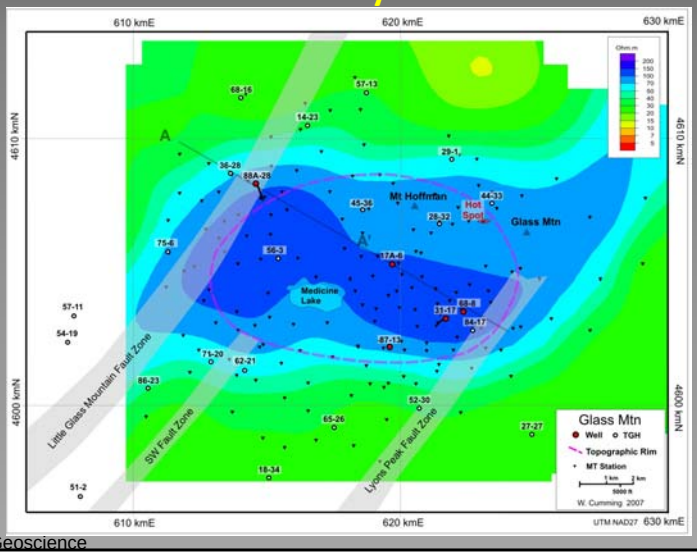
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Glass Mountain Geothermal Field
MT Resistivity at 0 m asl



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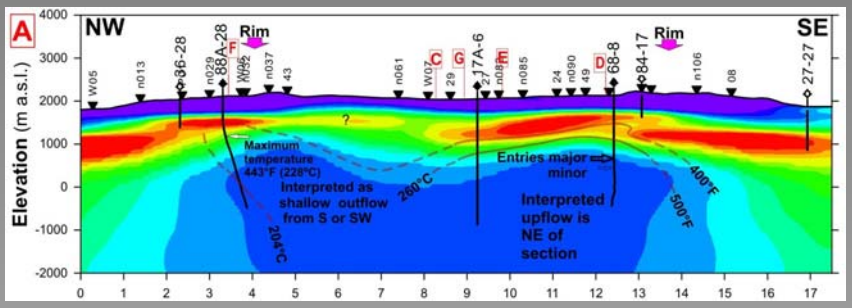
Glass Mountain Geothermal Field
MT Cross-section

MT Resistivity with isotherms from Wells



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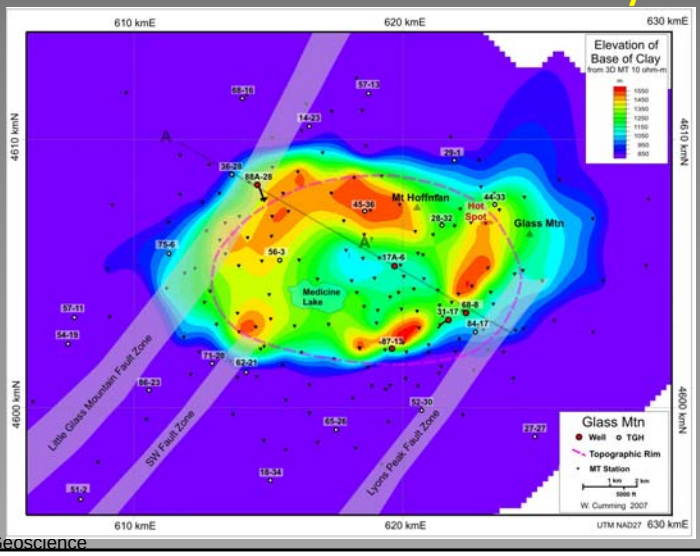
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Glass Mountain Geothermal Field
3D MT Elevation of Base of Low Resistivity Zone



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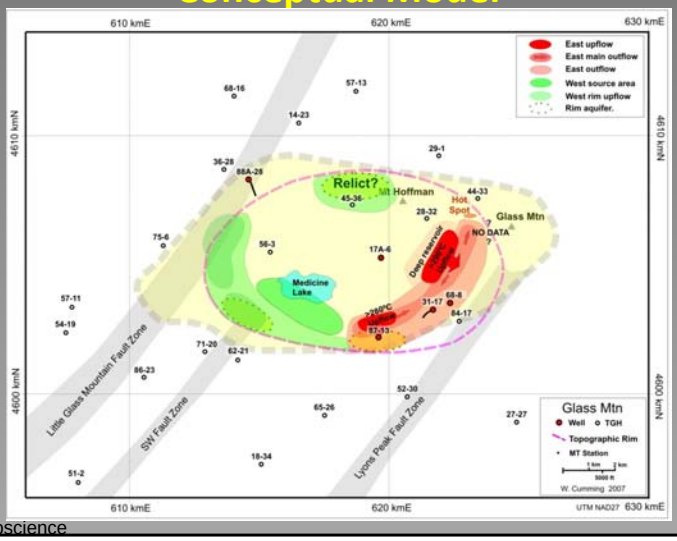
Glass Mountain Geothermal Field

Conceptual Model



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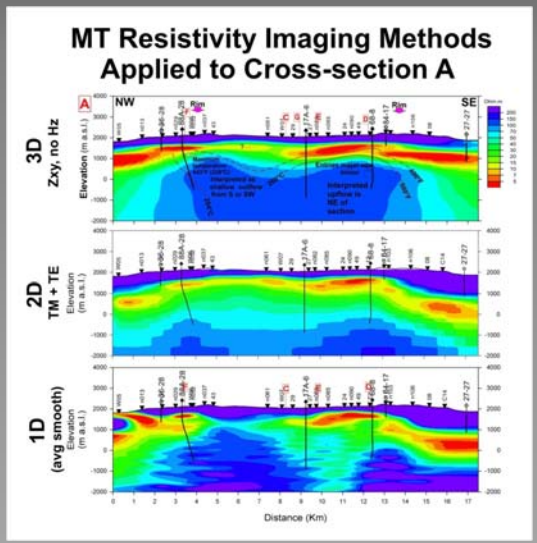
Glass Mountain Geothermal Field



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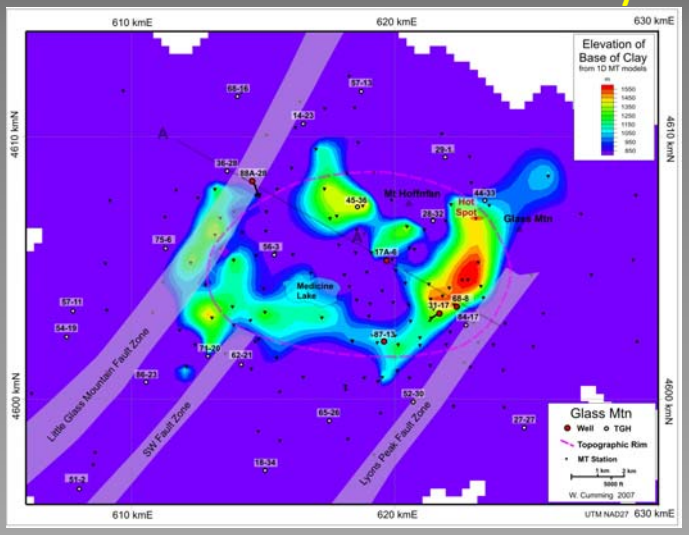
Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Glass Mountain Geothermal Field

1D MT Elevation of Base of Low Resistivity Zone



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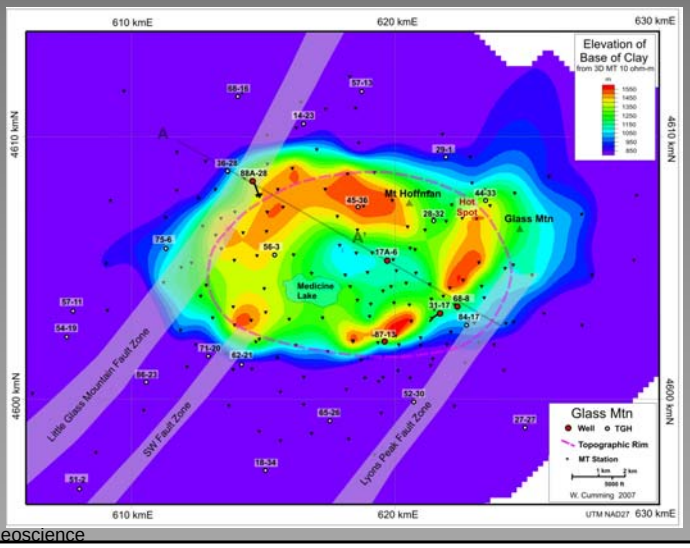
Glass Mountain Geothermal Field

3D MT Elevation of Base of Low Resistivity Zone



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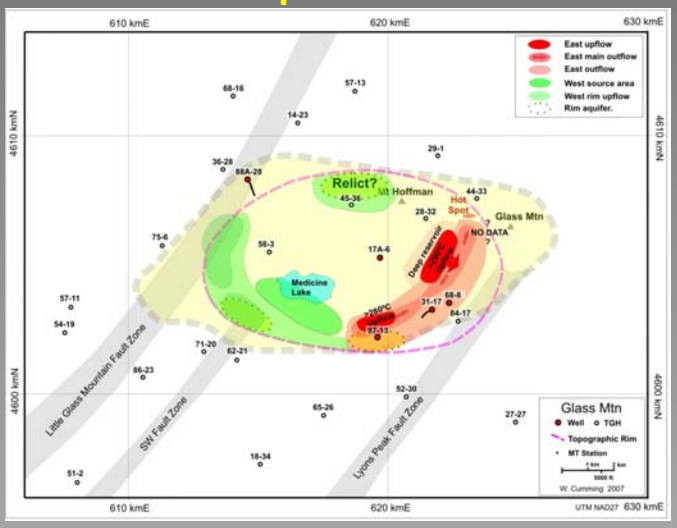
Glass Mountain Geothermal Field
Conceptual Model



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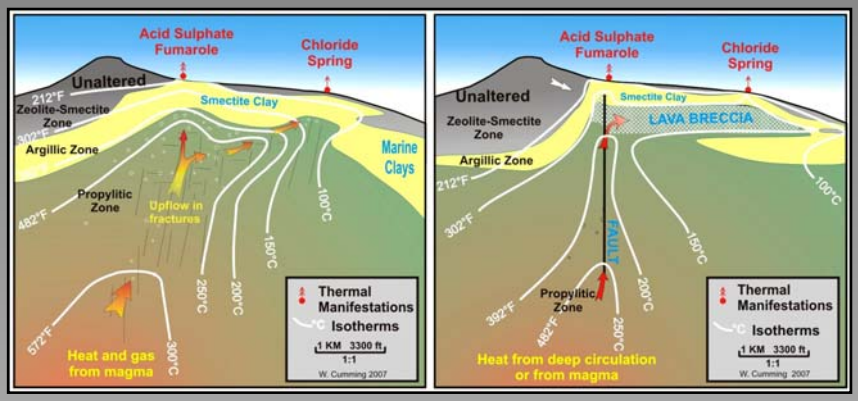
Geothermal Conceptual Models

Distributed Permeability Upflow
Small Outflow

Single Fault Zone Upflow
Large Shallow Outflow



Cumming (2013)

106

MEQ Applications To Geothermal Resource Management

- Exploration
  - Magma imaging below basalt-hosted reservoirs
  - Volcanic hazard assessment
  - Research (e.g. S-wave splitting tomography)
- Development
  - Base of reservoir
  - Injection tracking
  - Reservoir permeability barriers
  - Lateral extent of long term compaction due to reservoir pressure change
  - Management of induced seismicity
  - Permeable zone targeting and avoidance
  - Research (e.g. tomographic imaging of % steam)

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Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

Geothermal Induced Seismicity Mechanisms

Most induced earthquakes are triggered by stress change related to:

- Hydro-Frac for EGS (but not commercial geothermal)
- Temperature decrease related to injection
- Compaction related to production pressure drawdown
- Compaction related to temperature contraction
- Transient pressure change (e.g. field shut-in)
- Pressure increase due to injection

MEQ Applications To Geothermal Resource Management

- Please check the paper

Sewell, S. M., Cumming, W., Bardsley, C.J., Winick, J., Quinao, J., Wallis, I.C., Sherburn, S., Bourguignon, S., Bannister, S. (2015) Interpretation of Microseismicity at the Rotokawa Geothermal Field, 2008 to 2012. Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015.

CUMMING GEOSCIENCE
GEOTHERMAL GEOPHYSICS AND RESOURCE ASSESSMENT

Geophysical Applications to Geothermal Resource Assessment and Their Uncertainty

USC 12-Mar-2015

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