Geothermal Exploration Best Practices: Overview

Geothermics 2025-2026

Outline

- Introducing the Best Practices Guide - Colin
- Project Precursors - Ann
- Phase 1: Preliminary Survey - Colin
- Phase 2: Detailed Exploration - Ann
- Phase 3: Test Drilling - Both
- Phase 4: Project Review and Feasibility - Both
- Phase 5: Field Development - Ann
- Phases 6 & 7: Construction, Commissioning and Operation – Colin
- Risk Overview - Colin

Introducing the Geothermal Exploration Best Practices Guide - its Purpose

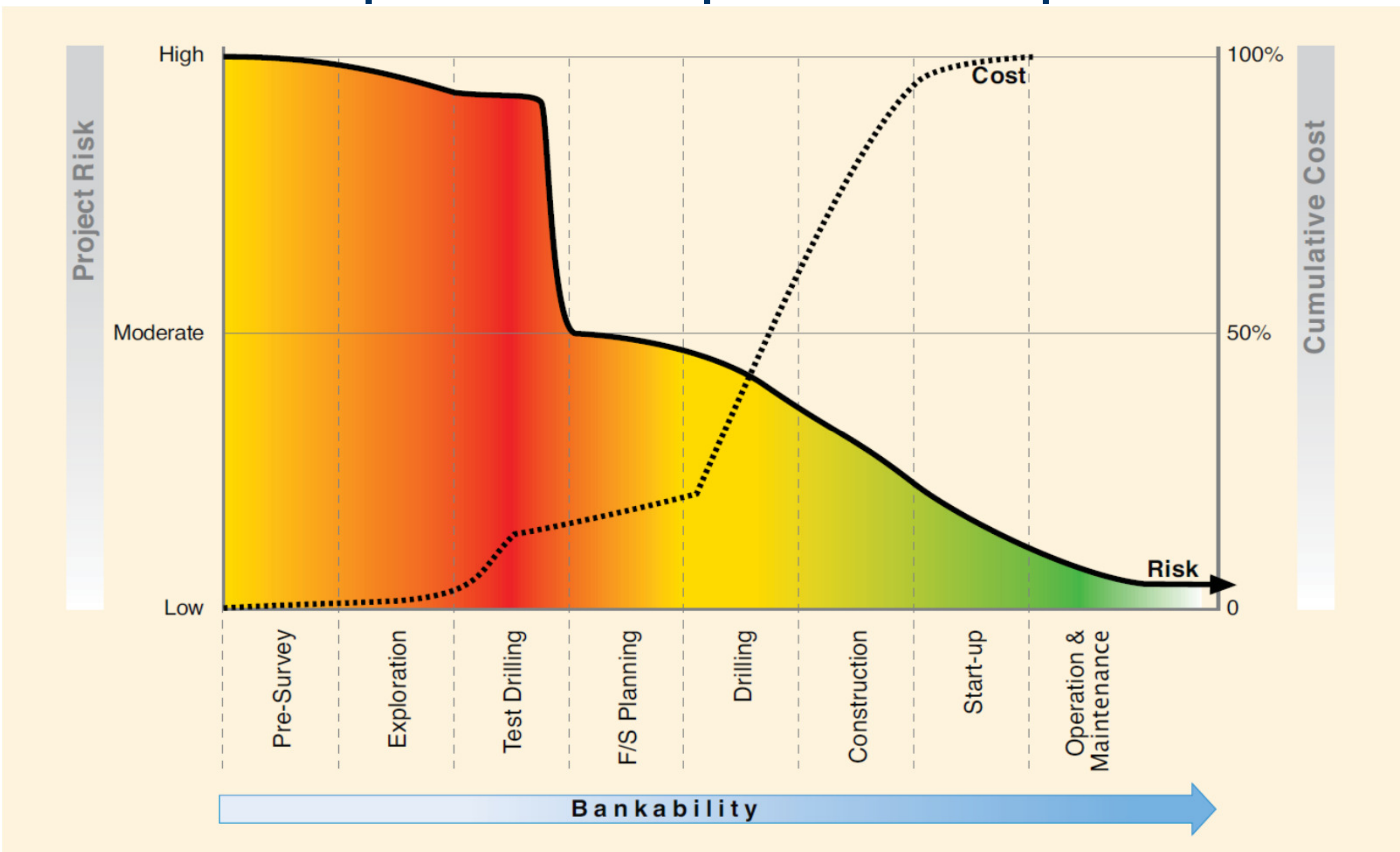
Exploration for any natural resource should aim to reduce risk for investment by carrying out exploration in an efficient and cost effective way

Development of geothermal requires high levels of investment

These investments are considered high risk because the risk is only reduced once deep wells have been drilled to prove the resource

Having a Best Practice Guide enables developers to undertake effective exploration; reduce risk and thereby attract investment

This risk profile for geothermal project (ESMAP WB Geothermal Handbook 2012) illustrates why accelerated growth in costs requires best practice exploration



The Motivation, Authors and Reviewers

The concept for the Guide was initiated by IFC

The original draft by GeothermEx Inc (USA)

In late 2012 reviewed through Service Company of IGA (International Geothermal Association)

Restructured and reviewed and then endorsed by numerous agencies listed below

-The Board of IGA

- Munich IRE

- IFC

- GZB (Germany)

- GeothermEx

- World Bank Officers

- Global Environmental Facility

- GNS Science (New Zealand)

The seven phases of a geothermal program

Preliminary survey (reconnaissance)

Exploration and pre-feasibility

Test drilling

Project review, feasibility and planning

Field development

Power plant construction

Commissioning and operation

Project Precursors

including . . .

Capable and experienced technical team

Adequate finances

Power purchase agreement

Understanding of the regulatory environment

Environmental and Social Impact Assessment

The Team

. . . . . in house or hired

Geoscience

GIS / Cartography

Contracting / Negotiations

Logistics / Procurement

Drilling, Logging, Testing

Construction

Power Production

Operations & Maintenance

IFC Performance Standards on Environmental and Social Sustainability

Performance Standard 1: Assessment and Management of Environmental and Social Risks and Impacts – requirements include:

1. Established policies, objectives and principles for evaluation and mitigation
2. ESIA covering wellfield, power plant and transmission corridor
3. Consideration of cumulative impacts of proposed and existing projects
4. Operational procedures, emergency procedures, communications plan and mitigation plan(s) in place
5. Organizational structure with defined roles and responsibilities for monitoring, compliance, mitigation and communication
6. Periodic review to monitor and measure the effectiveness of the management program
7. Stakeholder engagement plan / information dissemination procedures

Other IFC/WB Performance Standards

2. Labor and Working Conditions – developer to provide summaries of its labor force and labor management practices, including occupational health and safety plans
3. Resource Efficiency and Pollution Prevention – ESIA to address this at WB standard levels, or provide a justification for not doing so. Water consumption minimized; water resources protected
4. Community Health, Safety and Security – ESIA to include analysis and mitigation of risks to local community, and describe security plans
5. Land Acquisition and Voluntary Resettlement – land acquisition plan to describe any land issues, and acknowledge and compensate displaced people
6. Biodiversity Conservation and Sustainable Management of Living Natural Resources – consider in ESIA; awareness of habitat
7. Cultural Heritage – "chance finds" procedure in place

Phase 1: Preliminary Survey

Assess available evidence for geothermal potential in the area of interest

Reconnaissance may be regional or national

Involves a literature review of geological, hydrological or hot spring and/or drilling data

Obtain anecdotal information from local people

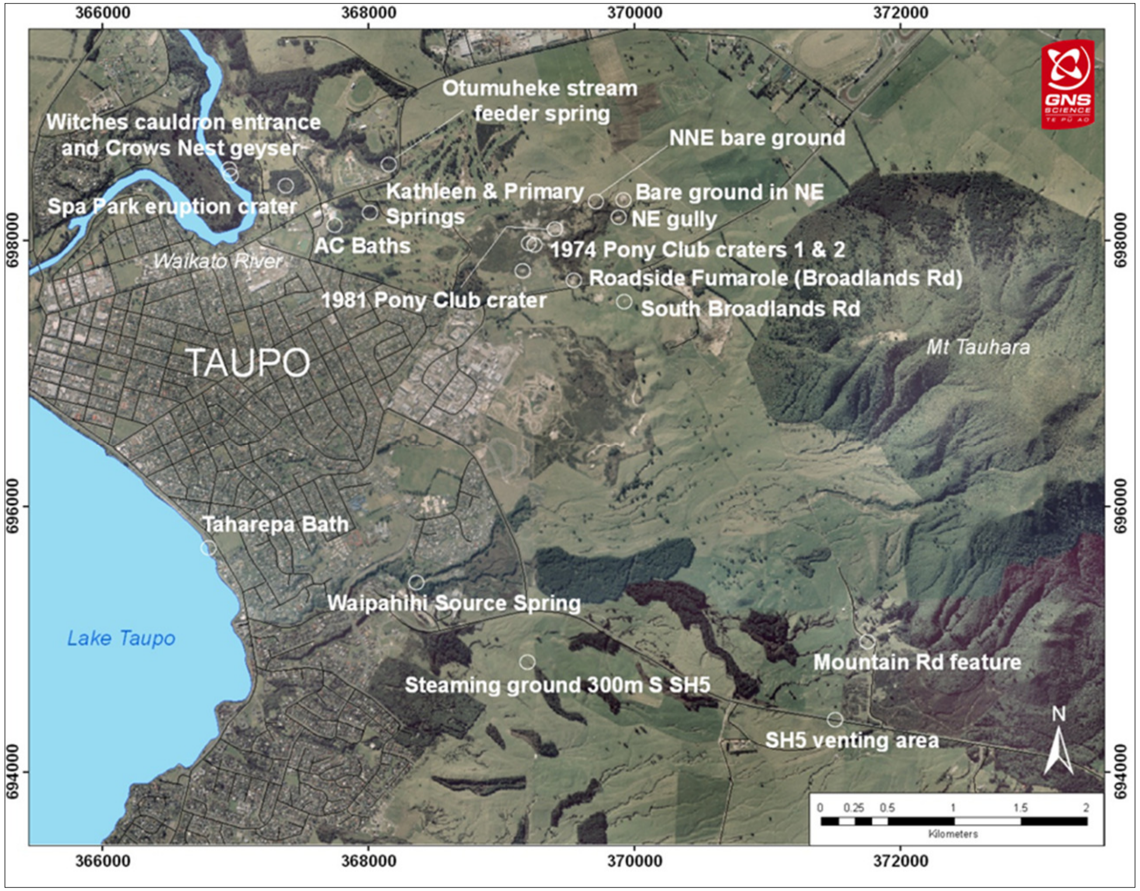
Analyse remote sensing data from satellites

Review available mineral exploration data

Review rules/regulations for geothermal development

Review environmental requirements and issues

Prepare map of thermal features



Non-technical data collection

Land access issues

Identify national, regional, and/or local regulations that might allow or restrict access for exploration activities (such as national parks, cultural sites, geological hazards, urban areas, areas of unique flora/fauna

Identify land use issues. Could a geothermal development live in harmony with existing or possible future land uses?

Evaluate Infrastructure requirements

Assess required infrastructure such as roads, water and power supplies

Availability of equipment for civil works and subsequent drilling

If roads and bridges have to be constructed in what is frequently steep or mountainous terrain, then this may impact the time needed for both surface exploration and subsequent drilling

Seasonal factors may limit field season and access for drilling and construction etc

Investigate

The power market and possible power purchase agreements (PPA) or potential for feed in tariffs

Identify competing resources for base load supply?

resource ownership issues (in some countries geothermal permits are handled under mining law while elsewhere it may be considered a water right or handled under specific geothermal legislation)

institutional and regulatory frameworks

political and financial stability

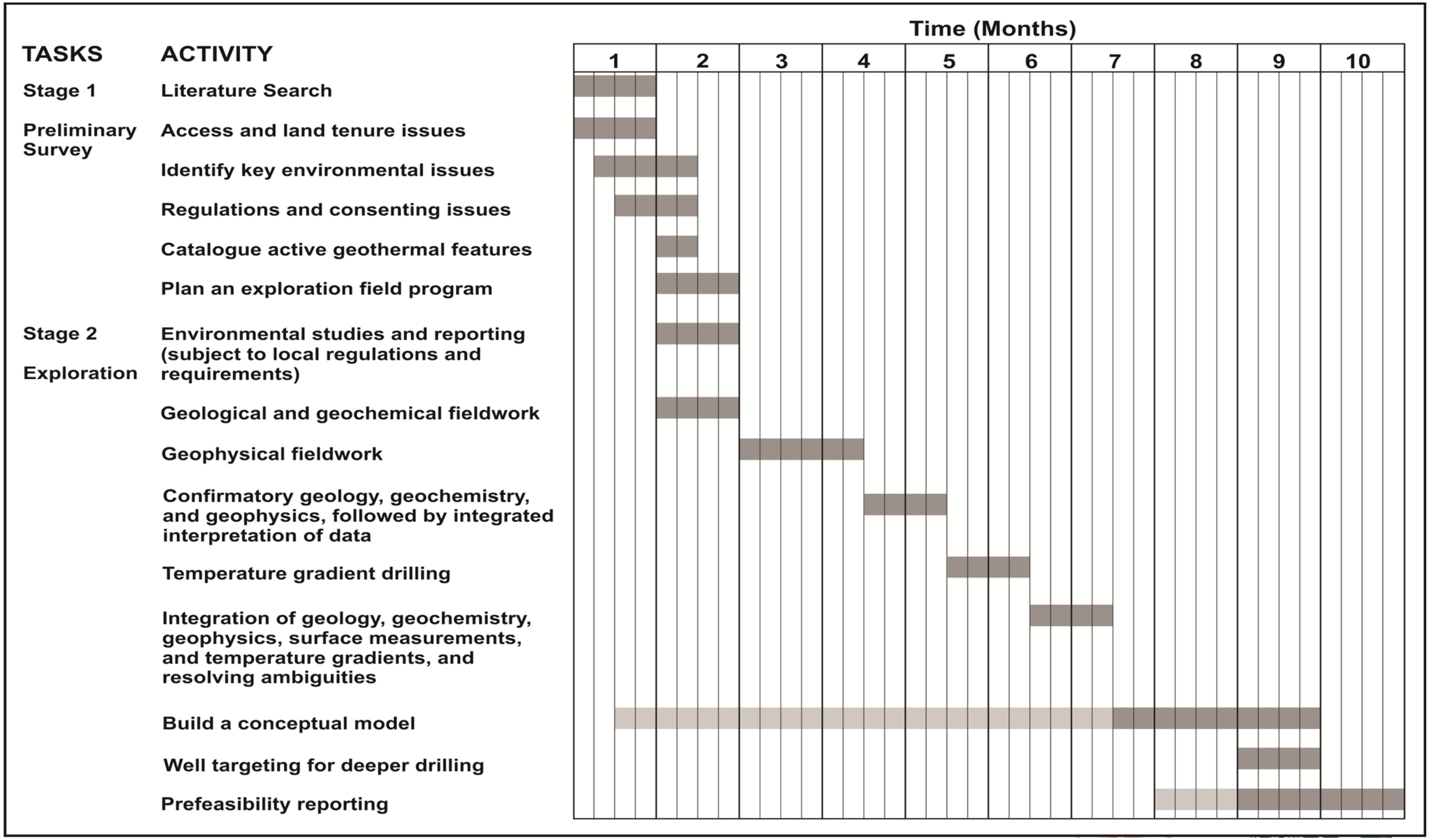
Consultant Role in the Phase 1 Reconnaissance and Interpretive Report

Prepare detailed geological maps

Analyse waters and gases

Interpret all geological, geophysical and geochemical data

Prepare the reconnaissance report which could include prioritisation of prospects and recommendations for a Phase 2 programme


Time (Months)
1
2
3
4
5
6
7
8
9
10
TASKS
ACTIVITY
Stage 1
Literature Search
Preliminary Survey
Access and land tenure issues
Identify key environmental issues
Regulations and consenting issues
Catalogue active geothermal features
Plan an exploration field program
Stage 2
Exploration
Environmental studies and reporting (subject to local regulations and requirements)
Geological and geochemical fieldwork
Geophysical fieldwork
Confirmatory geology, geochemistry, and geophysics, followed by integrated interpretation of data
Temperature gradient drilling
Integration of geology, geochemistry, geophysics, surface measurements, and temperature gradients, and resolving ambiguities
Build a conceptual model
Well targeting for deeper drilling
Prefeasibility reporting

Decision point at the end of Phase 1

Does the area of interest have a geological setting or features that may indicate the presence of an exploitable geothermal resource?

If the answer is yes, then the second question is:

If suitable indications of geothermal potential exist, is it possible to obtain concessions over the most promising areas and, if they become productive, how would geothermal power fit with the existing energy infrastructure?

Phase 2: Exploration

Typically –

Geologic mapping

Geochemistry

Geophysics

Temperature gradient drilling

To test resource concept(s)

To constrain the resource model

To delineate the reservoir

To determine where to drill, and why

Geology – provides the basic framework

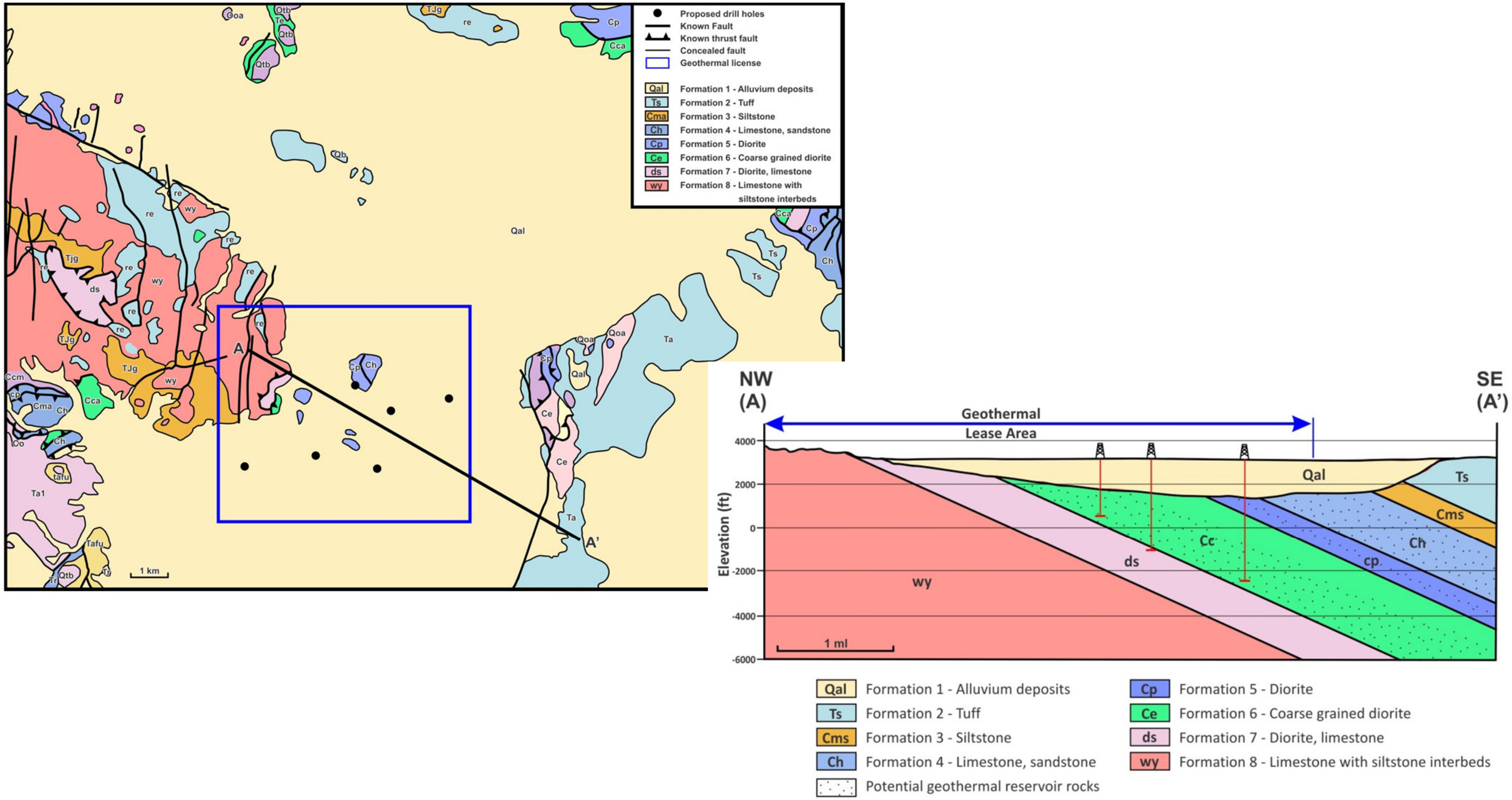
Essential to understanding the geothermal system

- What is controlling fluid flow?
- What do we have to drill through to reach the reservoir?

Mapping reveals . . .

- Potential reservoir units and capping units
- Stratigraphy
- Structure
  - Faults offsetting reservoir rock units
  - Fractured zones of enhanced permeability
- Mineralization / Alteration
  - Past and present centers of hydrothermal activity

Geologic Maps and Cross-Sections – Choose & Conceptualize Well Targets



Outcomes of Geologic Mapping & Interpretation

A clear picture of the regional and local geology, stratigraphy, and tectonic structure of the area

Identification of uncertainties and data gaps that need to be addressed in subsequent stages of exploration

An indication of which units or structures could host a geothermal reservoir

A basis for conceptual and numerical models

Geochemistry – an Extremely Useful Tool

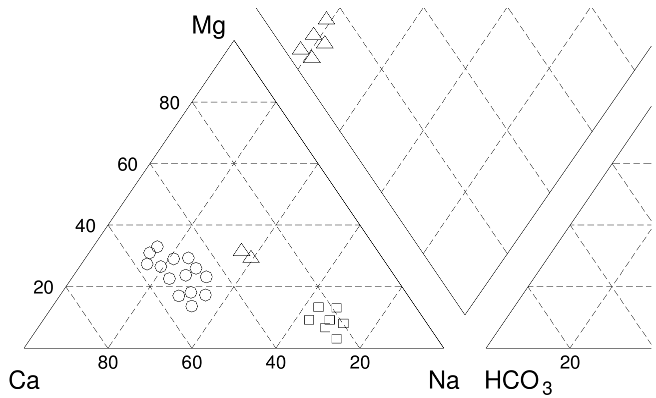
- Estimate potential resource temperature
- Identify "parent" source
- Evaluate mixing
- Understand fluid flow
- Identify operational issues

Geochemistry – Basics of Data Collection

- Map of sample locations
- Data table for liquid geochemistry, including
  - Field parameters (location, temperature, conductivity, pH, flow rate, etc
  - Analyses of Na, K, Ca, Mg, Li, Cl, B, SO_4^{2-}, NH_3, TDS, pH, Alkalinity as HCO_3 and CO_3 and total alkalinity as HCO_3, and SiO_2
  - Also Sr, Rb, Mn, F-, ^{18}O and D stable isotopes in water and ^{18}O in dissolved SO_4^{2-}
  - Ion balance or other indication of quality control on analyses
- Data table for gas geochemistry
  - Field parameters (location, temperature, flow rate, odors)
  - Geochemical analyses of NH_3, H_2S, CO_2, CH_4, H_2, N_2, Ar, He, SO_2, HCl, HF, O_2
  - Also preferably $^3He/^4He$, $^{40}Ar/^{36}Ar$, noble gas ratios, and stable isotopes in steam condensate
  - Standard deviation of each sample and/or other evidence of quality control on the analyses

Geochemistry – Basics of Data Evaluation and Presentation

- Table of geothermometry calculations
  - silica (Quartz, Chalcedony, and Amorphous Glass), cation (Na-K-Ca, Na-K-Ca-Mg, Na/K, K-Mg) and sulfate water isotope (^{18}O)
- Graphs of data, including
  - Piper diagrams
  - K vs Na
  - δD vs $\delta^{18}O$
  - Ternary plot of major anions SO_4-HCO_3-Cl
  - Ternary plot of Na, K and Mg
  - Na-K-Ca geothermometer temperature vs Cl
  - Temp NaKCa(°C) vs Temp K/Mg(°C)
  - Discharge temperature (°C) vs Cl
  - Gas ternary plot (N_2, CO_2/100, 100*Ar)
  - Giggenbach Gas Ratio Grids (H_2/Ar vs. CO_2/Ar, H_2/Ar vs. T, CH_4/ CO_2 vs. CO/ CO_2, CO/ CO_2 vs H_2/Ar)

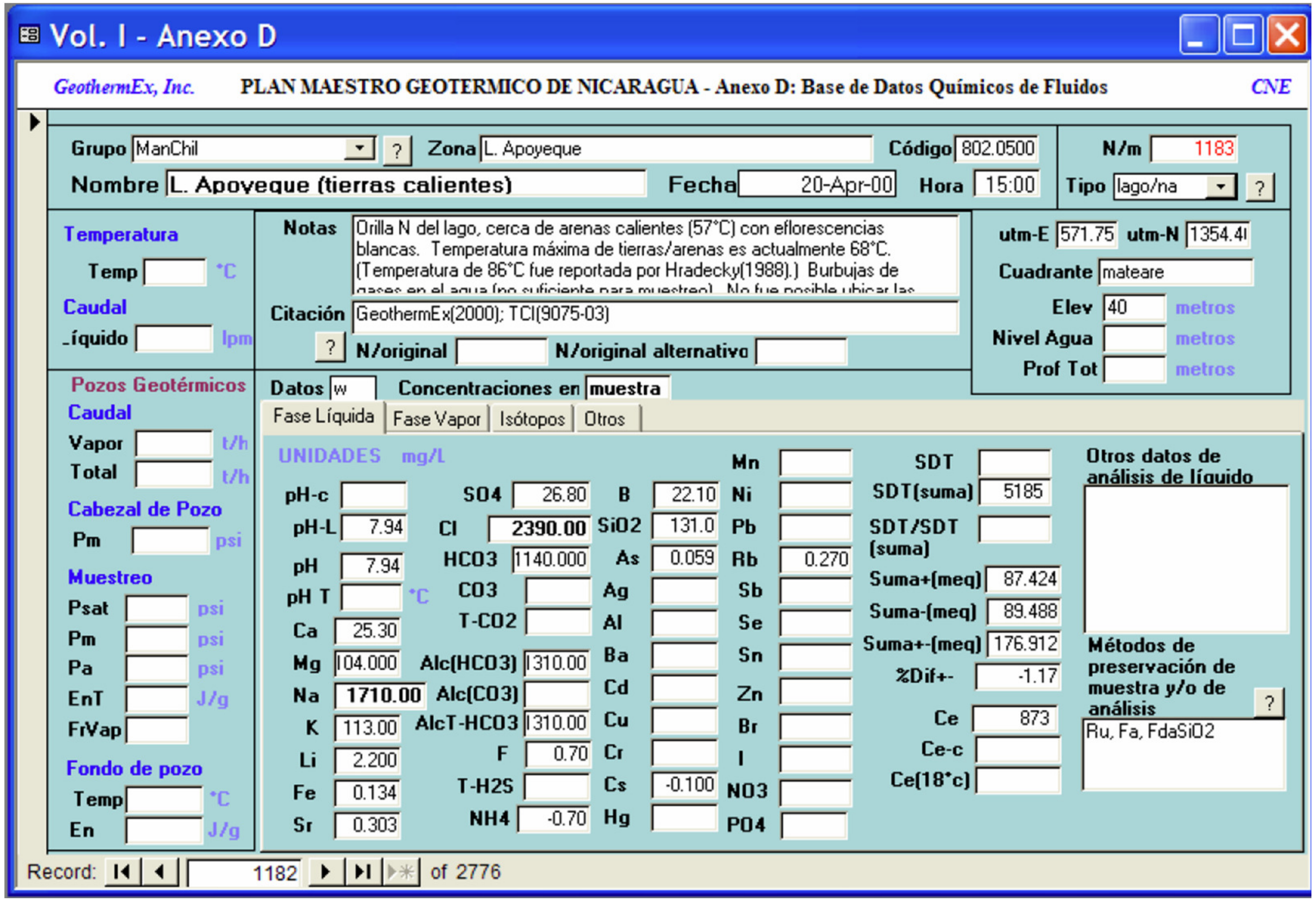


- Data presentation on maps (contour maps of soil gases, etc.)

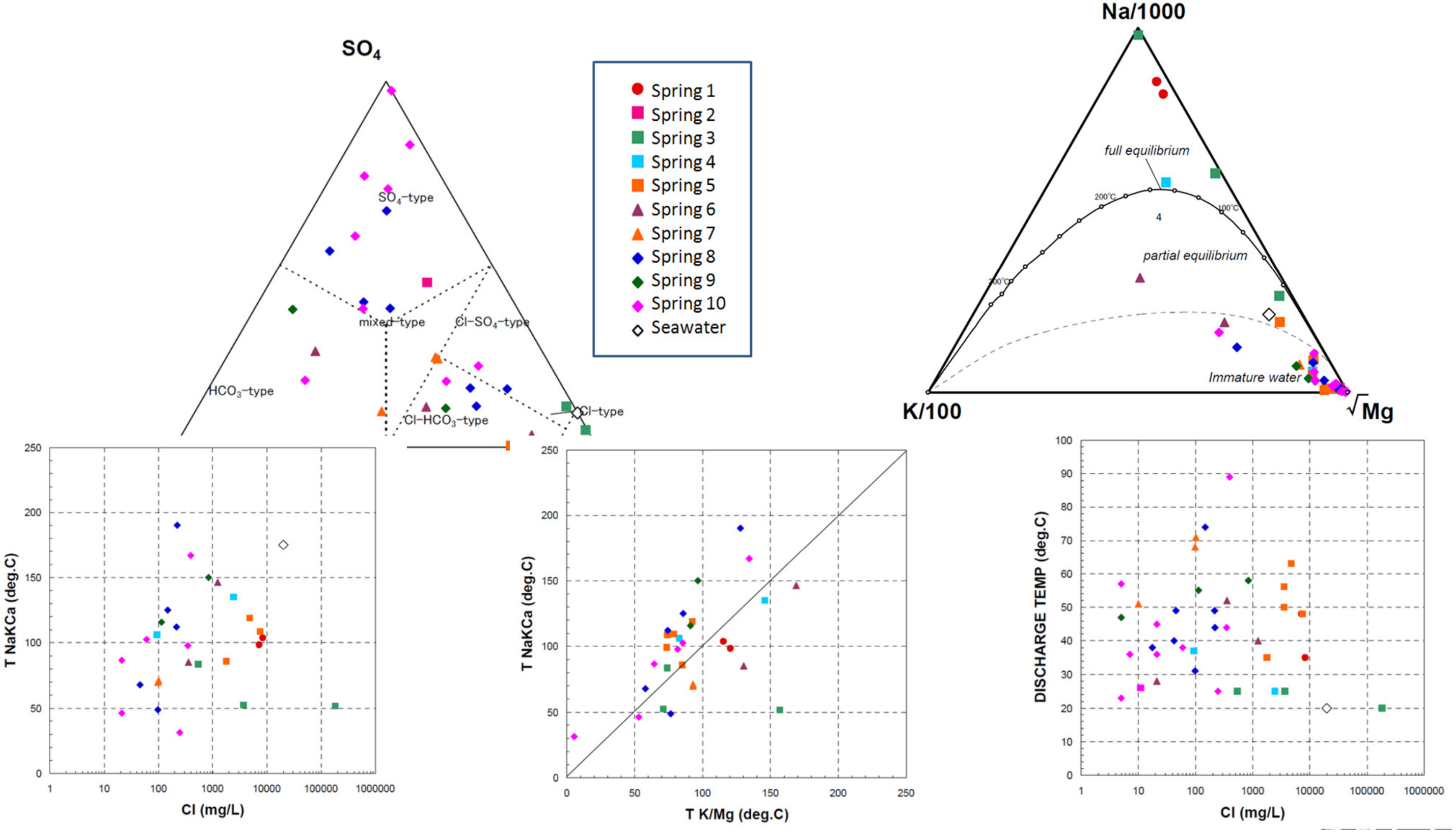
Geochemistry Requires Good Data Organization

Chemical data should be compiled into databases or spreadsheets

This aids in organizing the data and facilitates plotting and interpretation



Solutes: what's dissolved in the fluids?



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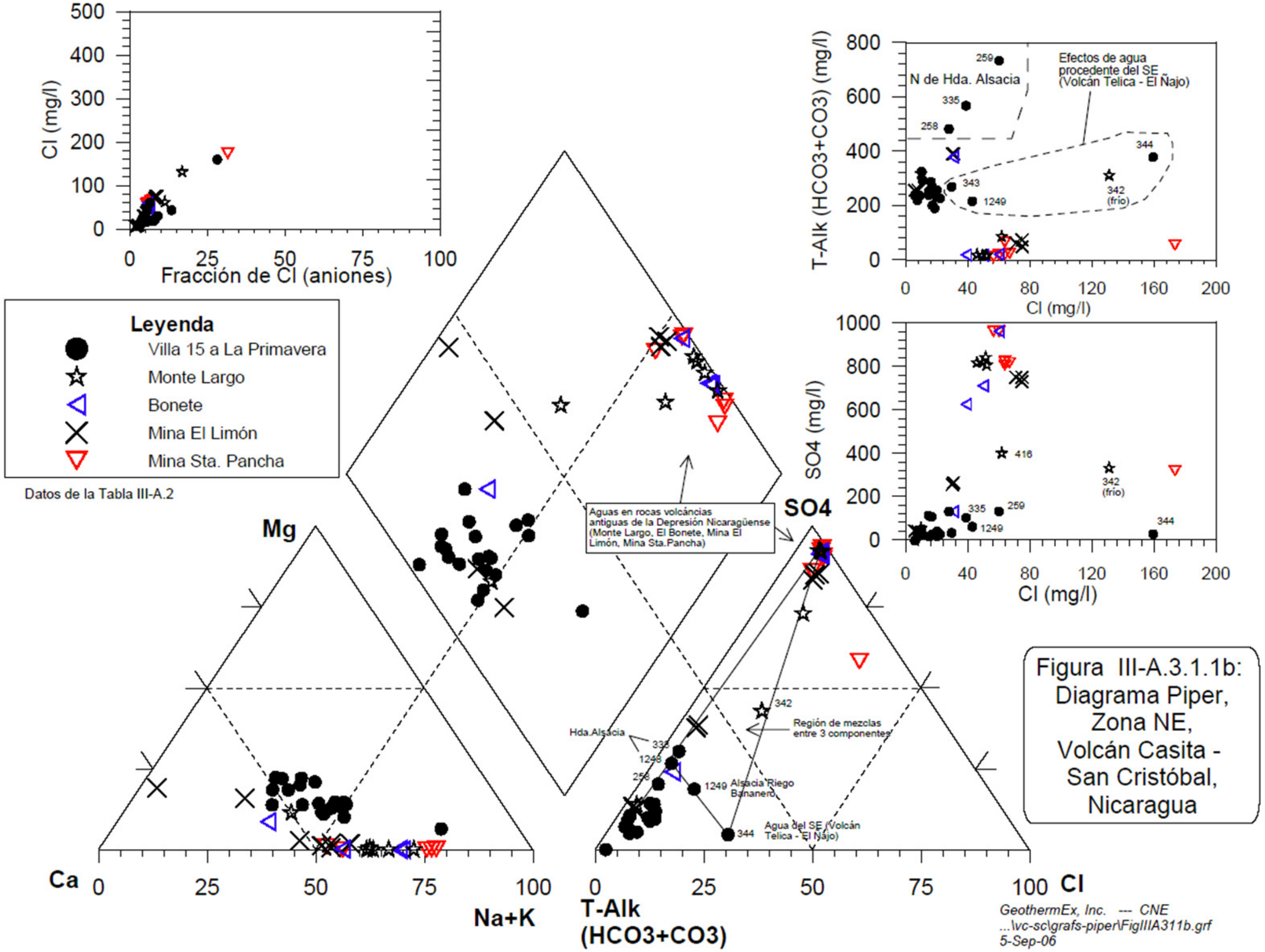
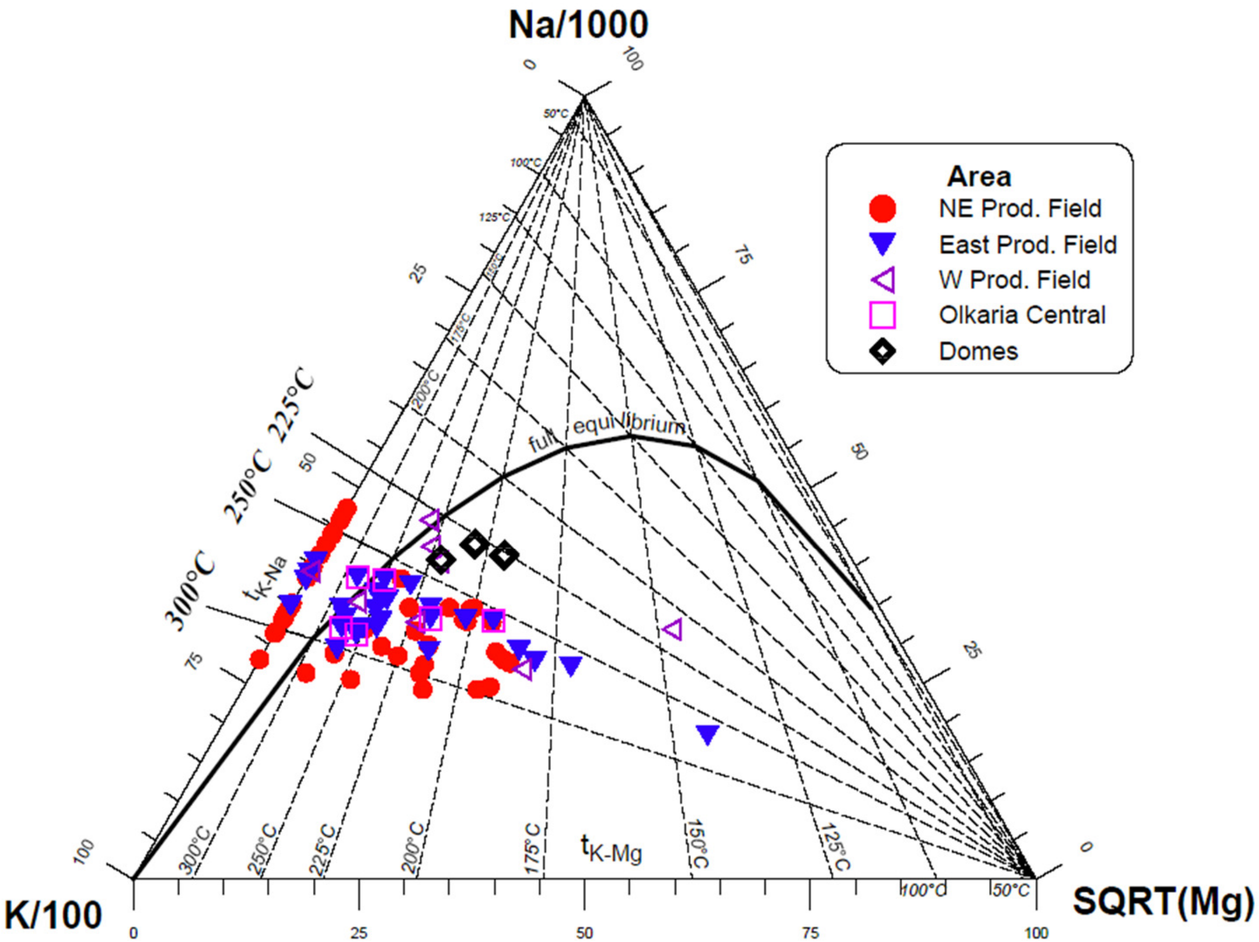


Figura III-A.3.1.1b: Diagrama Piper, Zona NE, Volcán Casita - San Cristóbal, Nicaragua

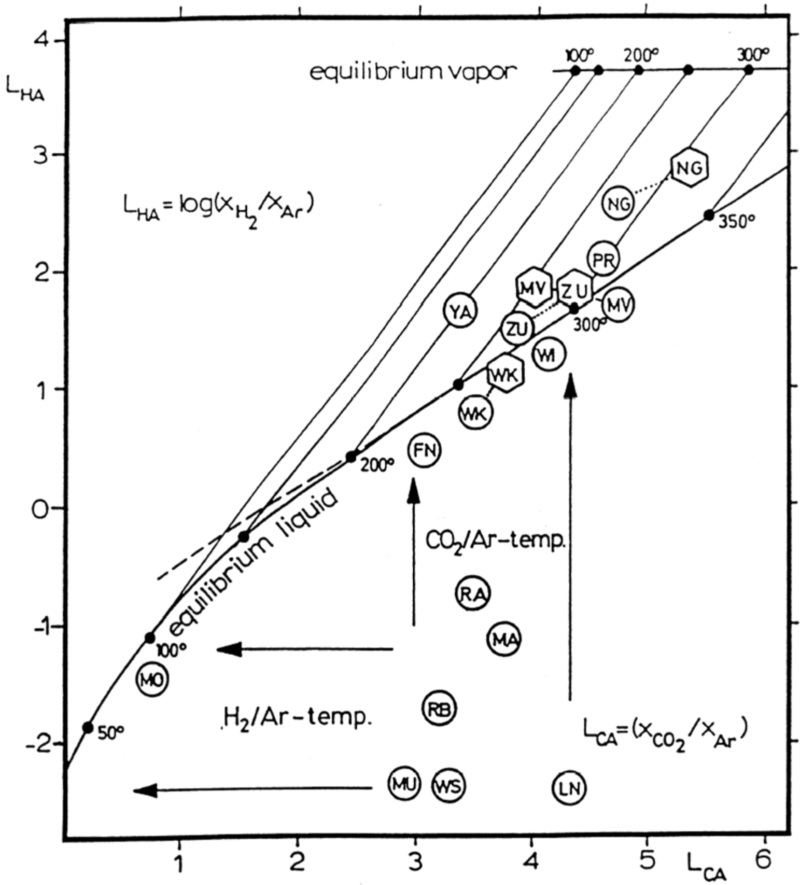
Geochemistry

Some simultaneous temperature-dependent relationships can be represented on graphs

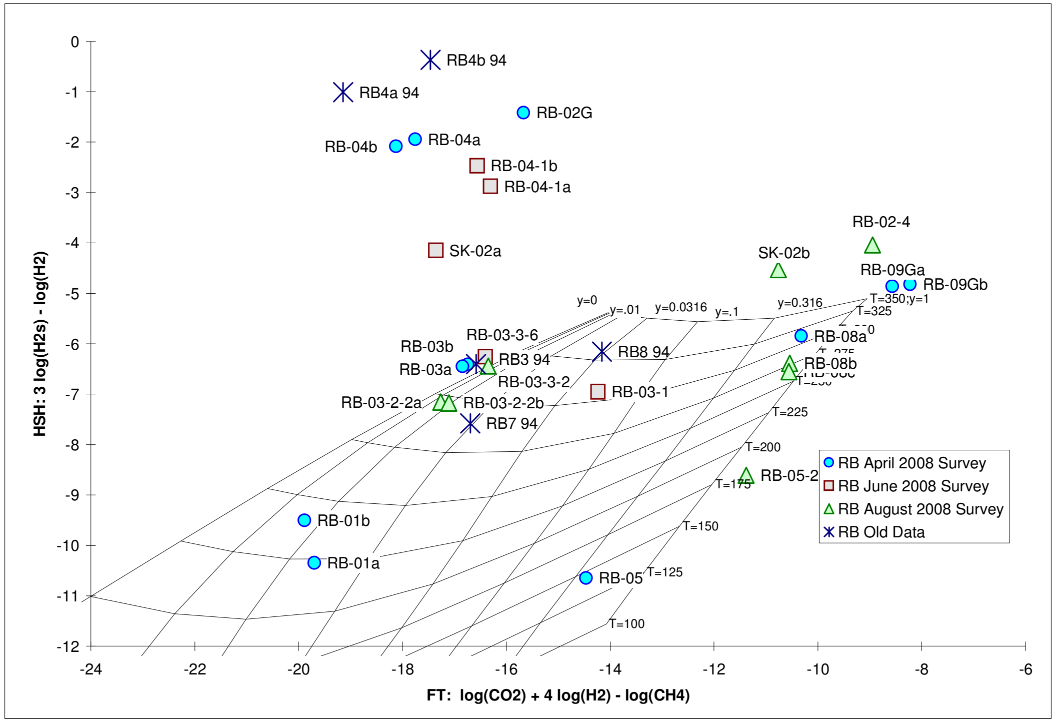


Graph showing relative concentrations of Na, K and Mg, and the Na-K (Giggenbach) and K-Mg (Giggenbach) geothermometers, in selected waters of the Olkaria geothermal system

Gas Geochemistry



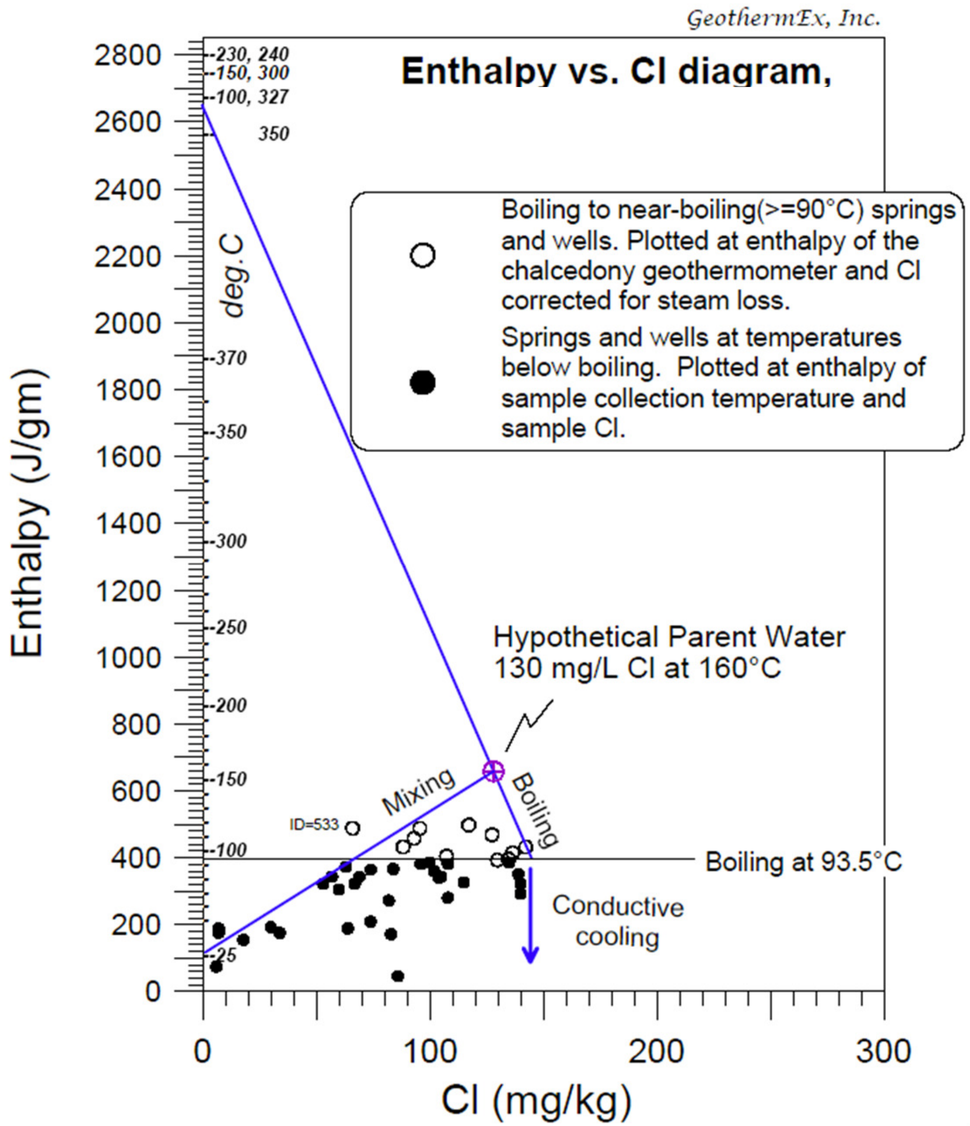
Giggenbach Gas Ratio Grid



D'Amore Grid

Including several different gas geothermometers

Geochemical Mixing Models

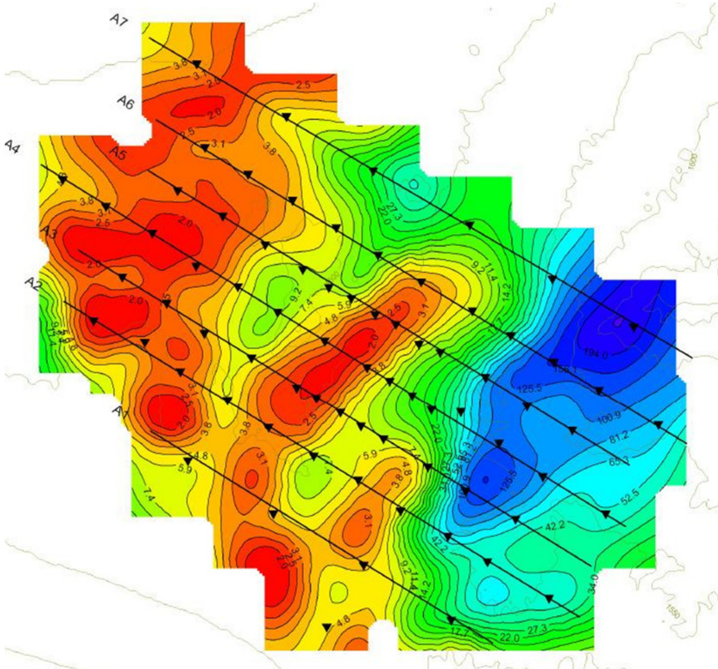


Geochemistry Program – Desire Outcomes

- Temperature distribution within the system
- Maximum temperature range for the resource
- Fluid mixing model
- An indication of operational issues that may occur (scaling, corrosion, high non-condensable gases)
- Identification of uncertainties and data gaps that require additional work to resolve

Geophysics to Look Deeper

- Gravity
  - Useful for assessing subsurface structure
  - Simple and cost effective
- Electrical resistivity (MT)
  - Useful for imaging clay alteration caps and assessing structure
  - Relatively expensive
- Seismic reflection
  - Useful for assessing subsurface structure and stratigraphy
  - Relatively expensive
- Temperature gradient drilling
  - The only direct measurement of subsurface temperature distribution
  - Cost effective



Geophysics alone is not enough . . . . .

Geophysics must be assessed in the context of the geology

A geophysical exploration program should be designed to test a concept and/or answer a question

- Temperature gradient drilling is the only direct measure of a subsurface property.
- Other geophysical methods are indirect measurements whose interpretation depends heavily on the geology of the study area.
- There are a number of geologic possibilities that can result in a low resistivity body, a gravity high, or a seismic reflector.
- The question is: “What exactly is being imaged?”
- The evolving conceptual model helps answer this question.

Geophysics at Different Scales

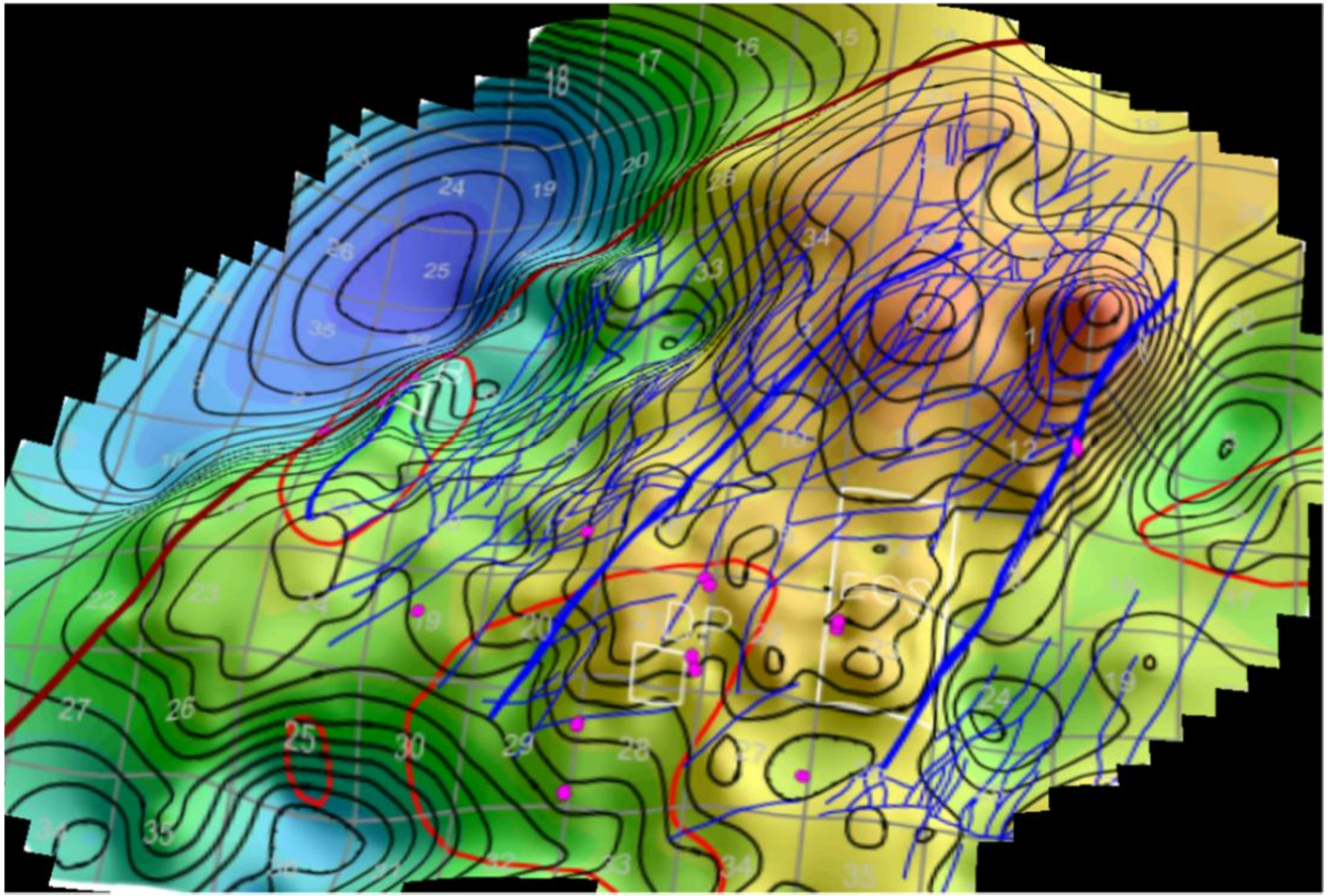
Regional

- Gravity (low cost, relatively quick, useful for assessing regional basement structure)
- Temperature gradient drilling (regional drilling used successfully to locate geothermal resources in NV)

Focused

- MT (relatively expensive, most cost effective if focused on most attractive areas)
- Temperature gradient drilling (only direct measurement of heat, invaluable for determining subsurface temperature distribution).
- Seismic reflection (can be useful for determining subsurface structure, depending on rock types present)

Example of Gravity Data



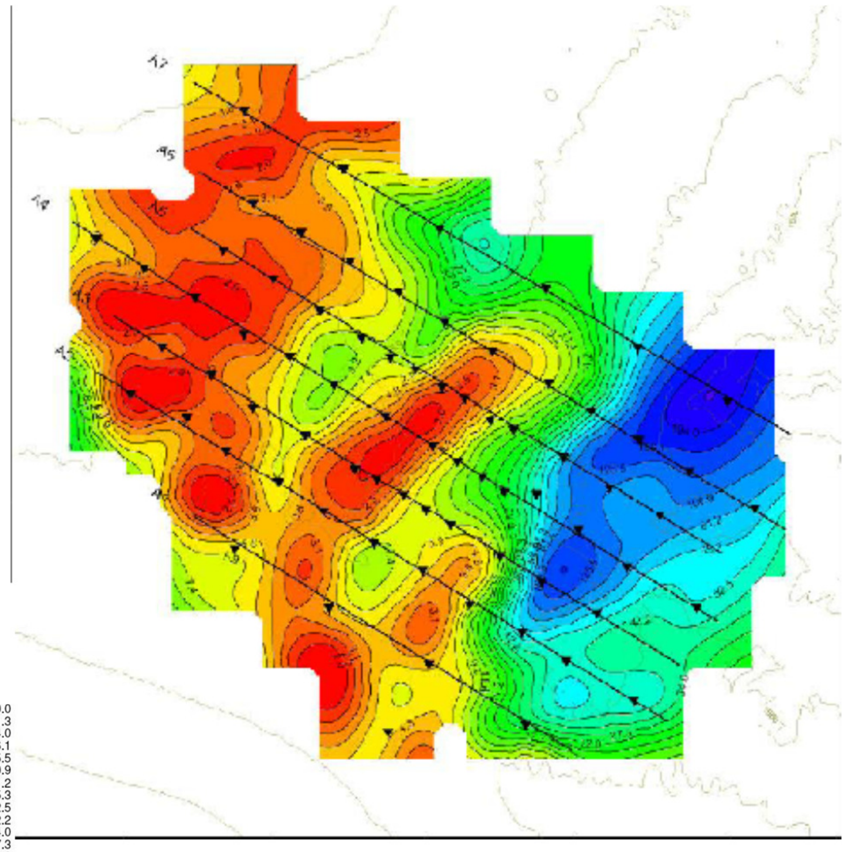
Electrical Resistivity Surveys (MT)

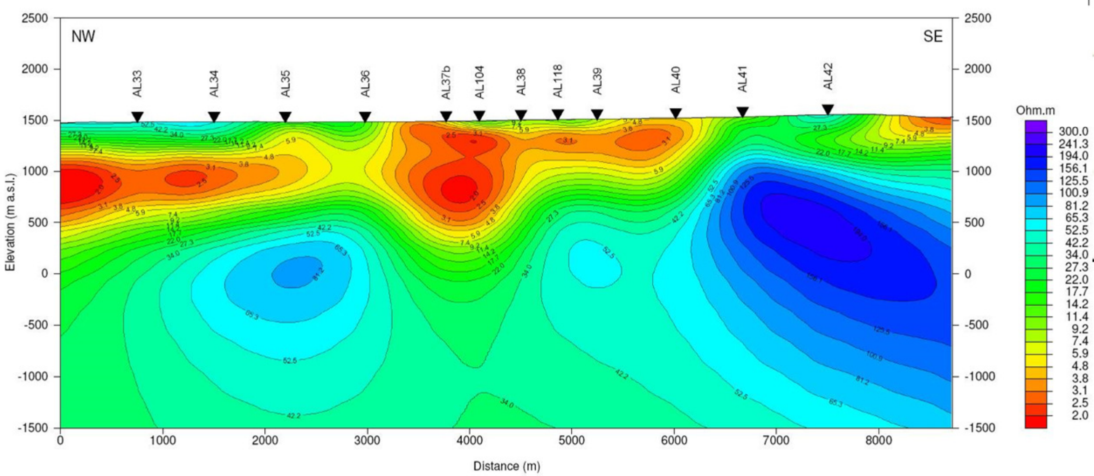
What is being imaged?

A low-permeability, clay-rich cap rock?

Fine-grained basin sediments?

Something else?

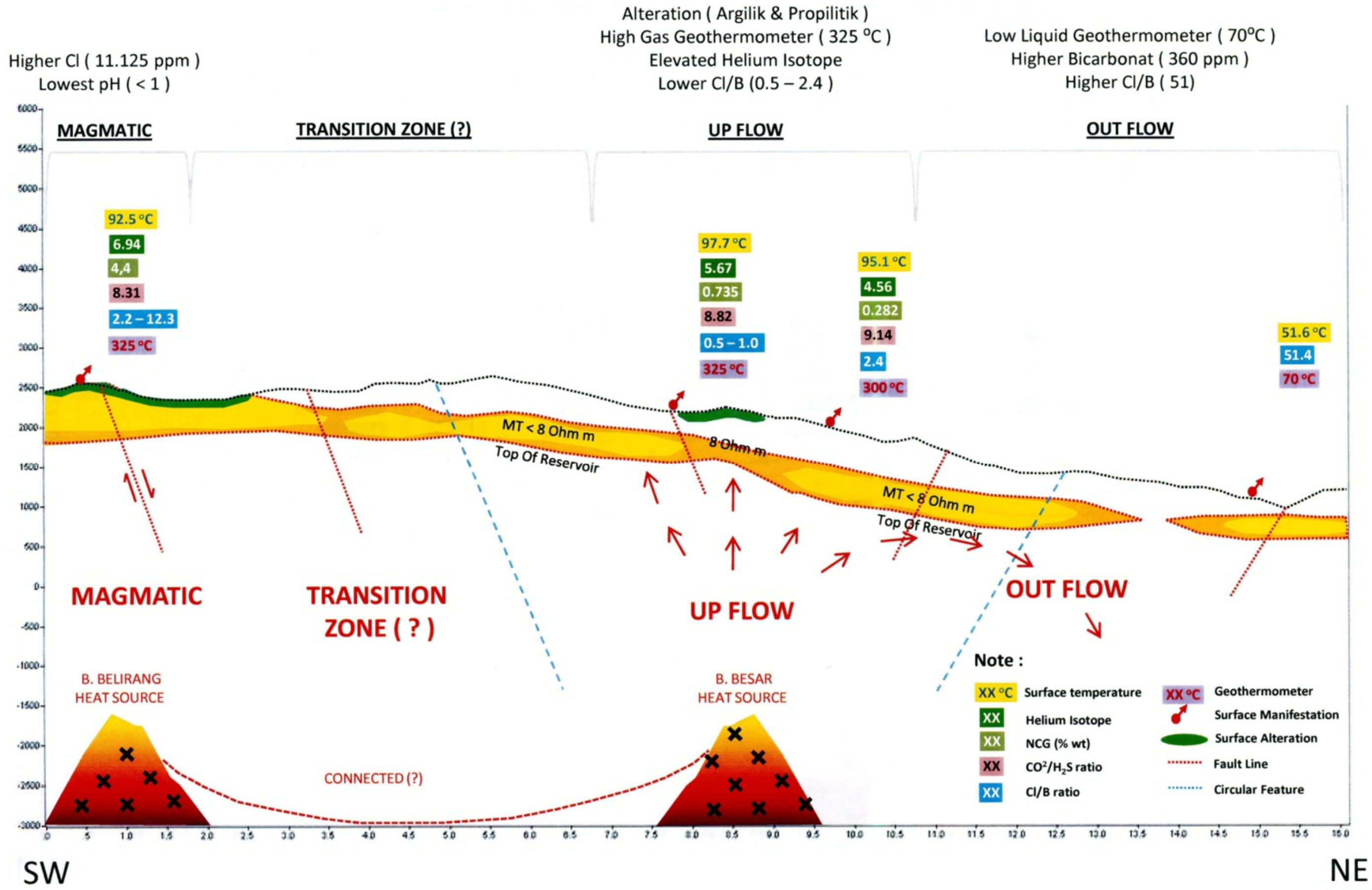




Electrical Resistivity Surveys (MT)

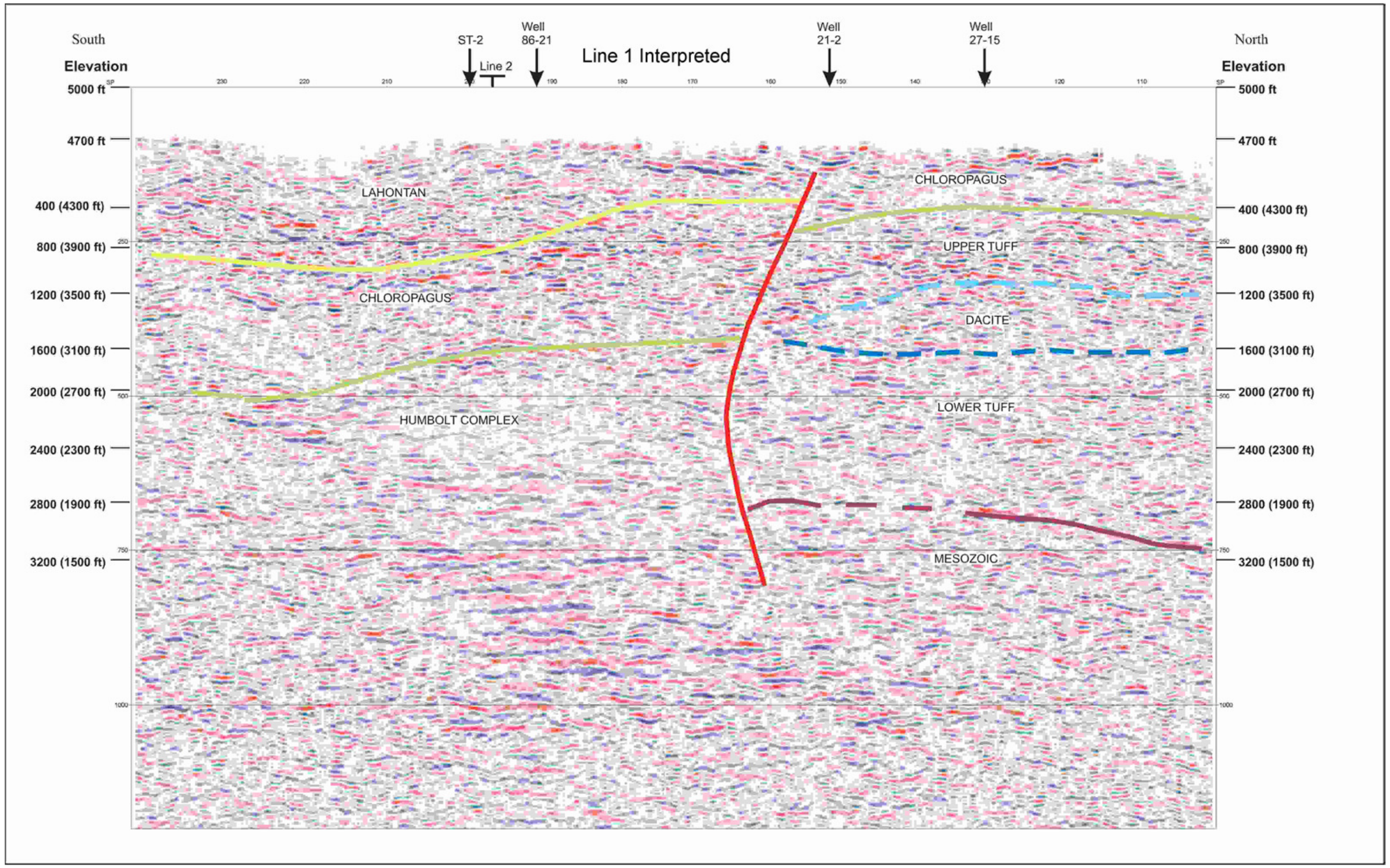
Resistivity methods work best in high temperature magmatic systems

Resistivity also works best in combination with other data, particularly geochemistry



Seismic Reflection

- Facilitates interpretation of structure and stratigraphy in layered, laterally continuous sequences
- Beginning to be used more in geothermal, especially in non-volcanic systems
- Advanced processing techniques yield information about porosity and permeability

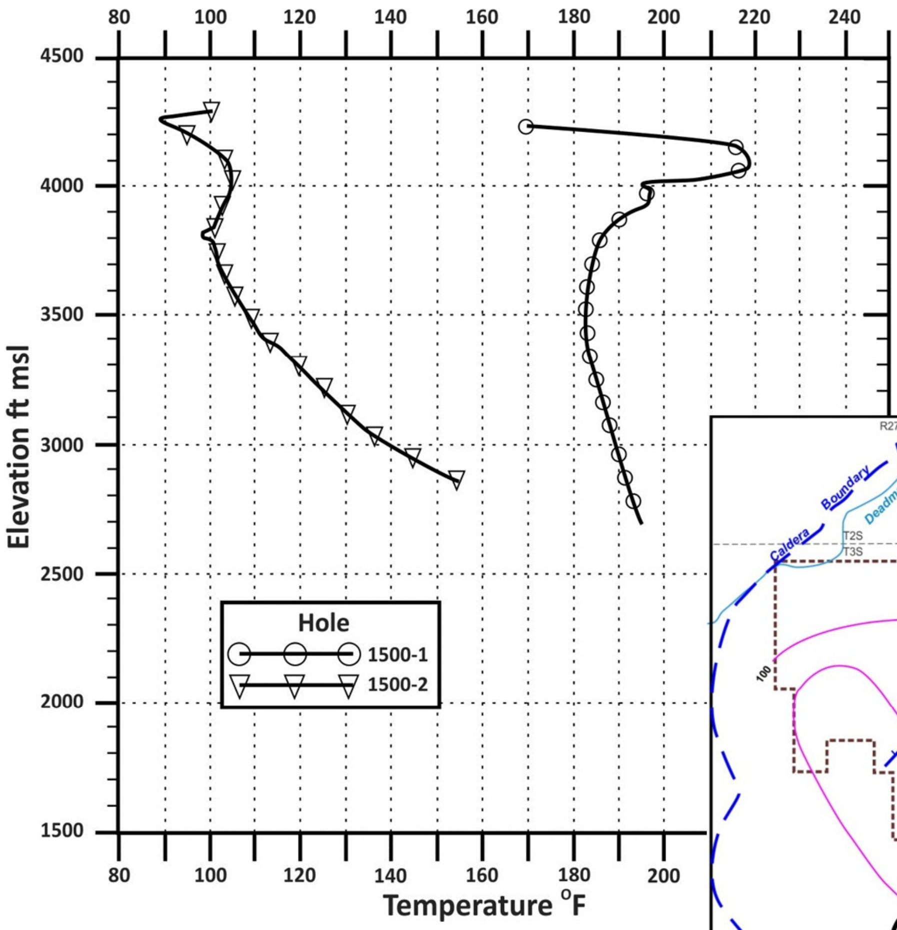


Temperature Gradient Drilling

A direct indication of what we really want to know: how fluid is moving at shallow and intermediate levels

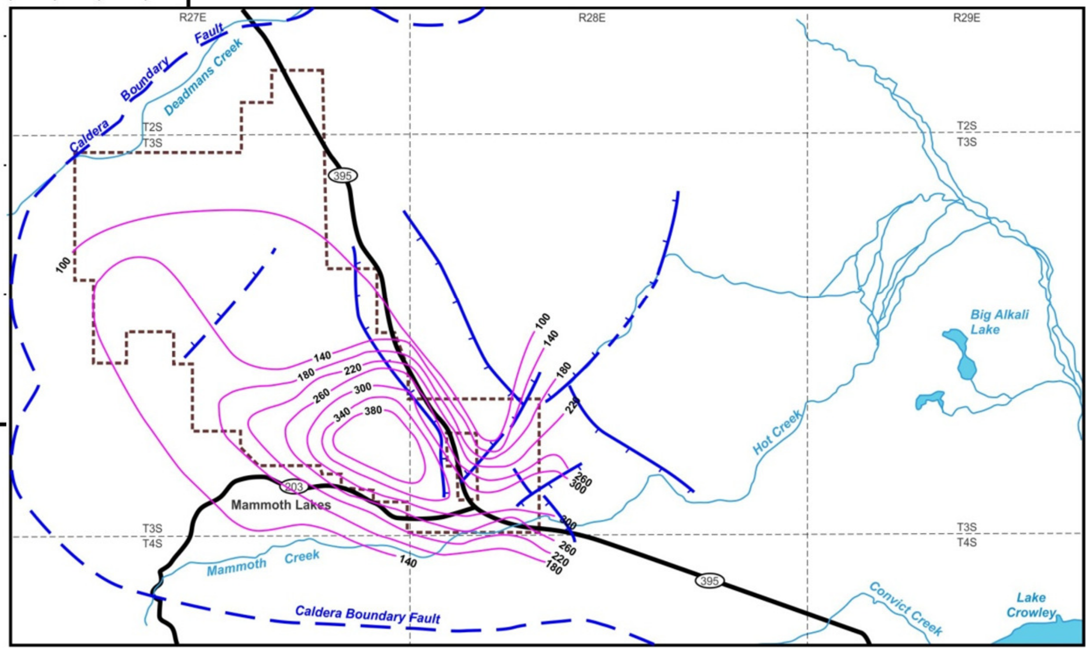
The shallow-intermediate temperature field helps define the geometry of the reservoir

Temperature Gradient Drilling



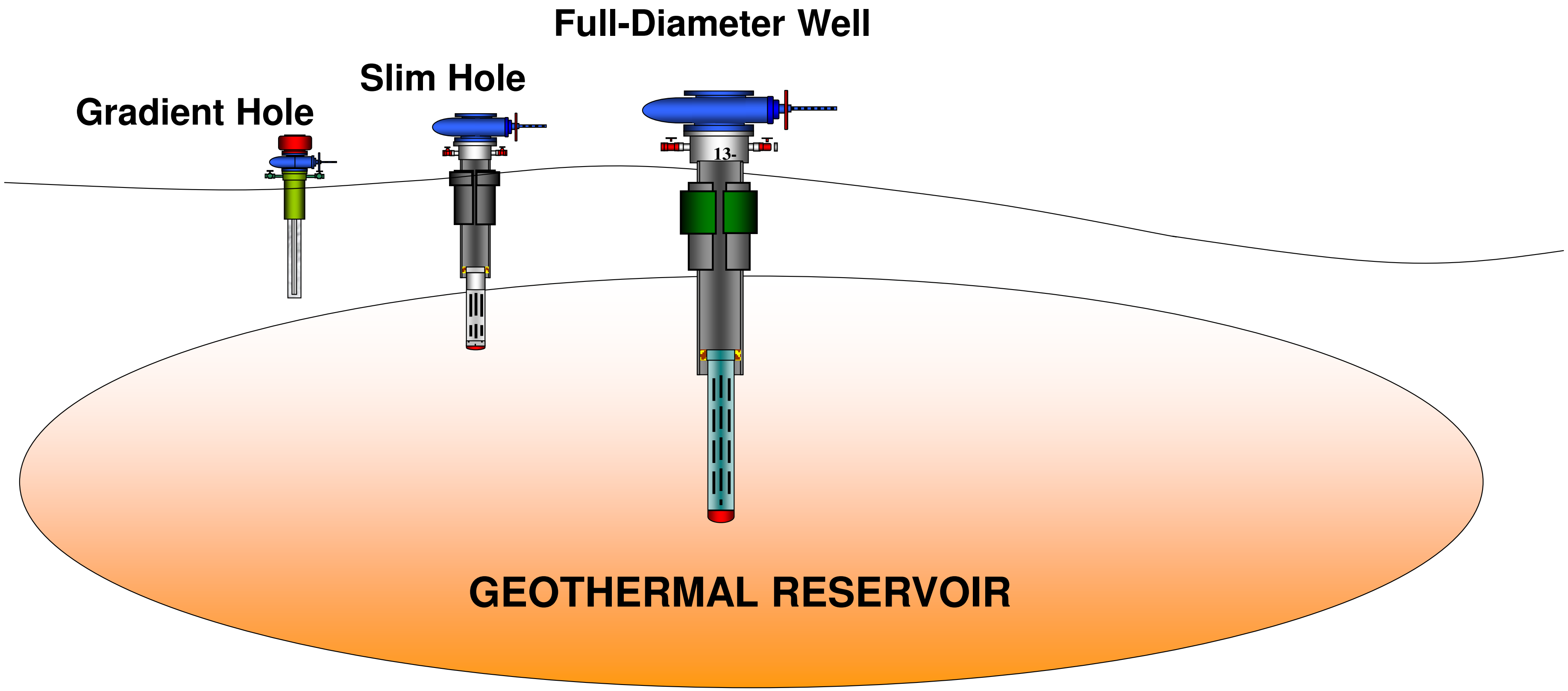
The shape of each profile reveals much

Multiple holes start to show a useful pattern



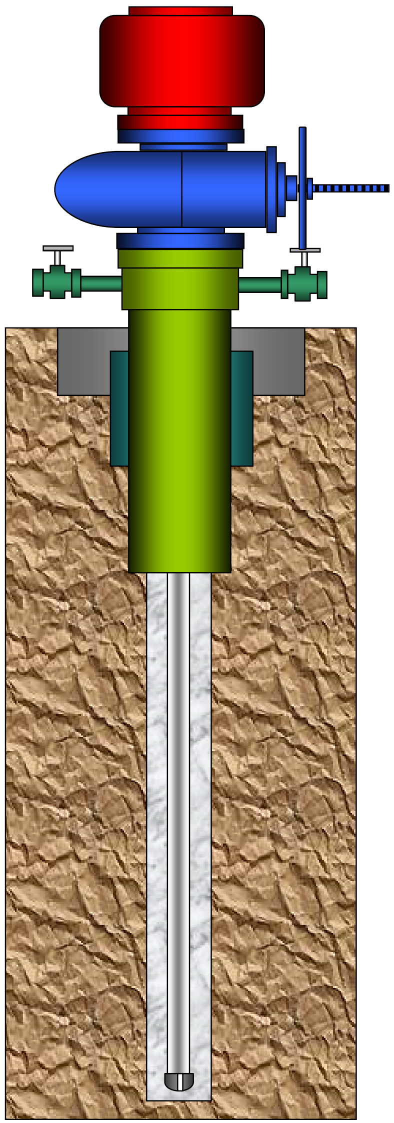
Phase 3: Test Drilling

The "reach" of different well types



Temperature Gradient Well

Facilitating Geothermal Resource Quantification



A rapid, high value exploration tool

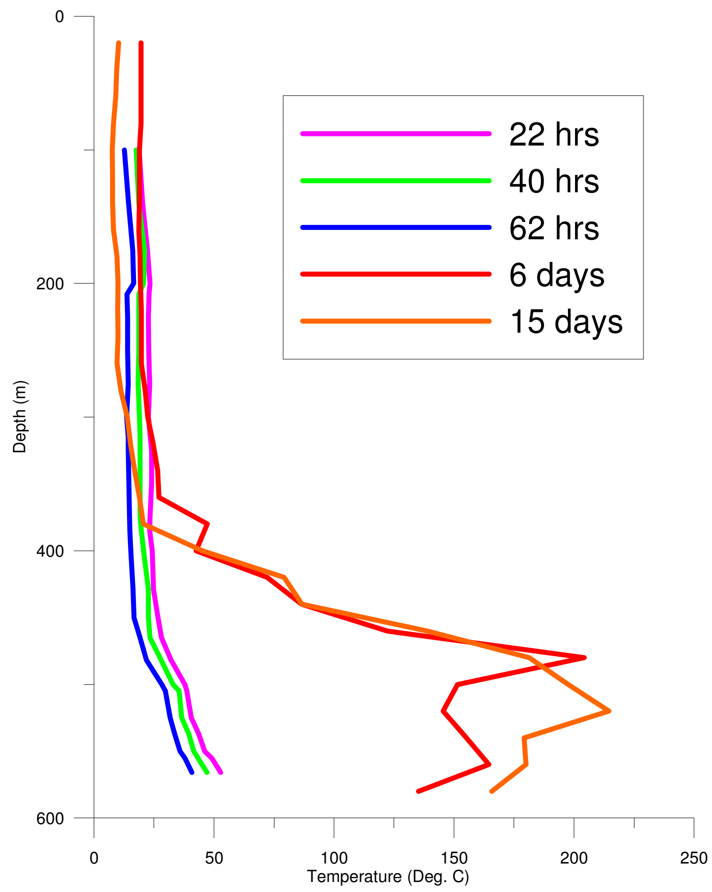
Directly measures the quantity sought **- HEAT -**

Rapidly permitted and drilled

Defines resource footprint

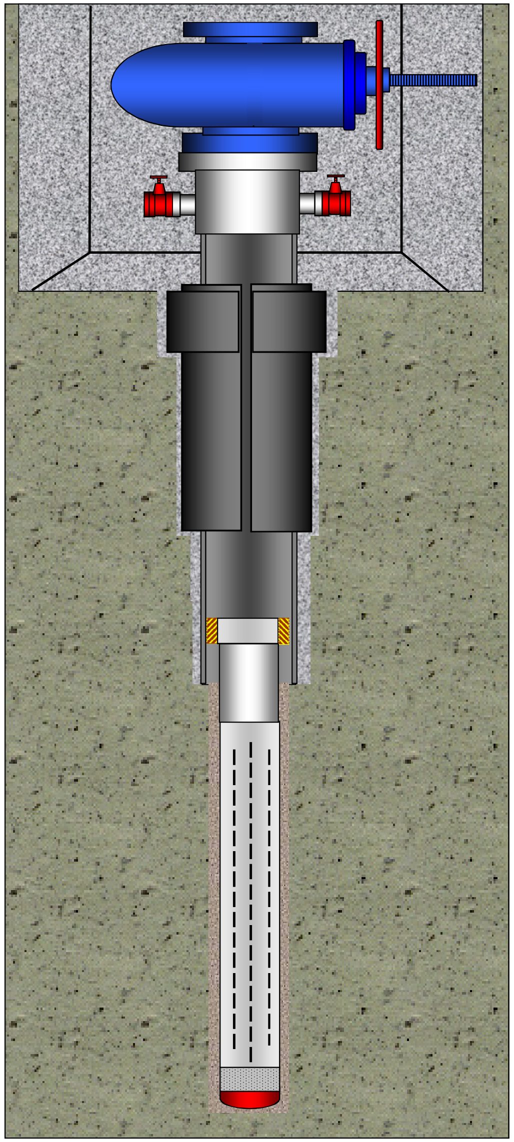
Enables temperature extrapolations

Delineates of near-surface temperature distribution and geothermal fluid flow patterns

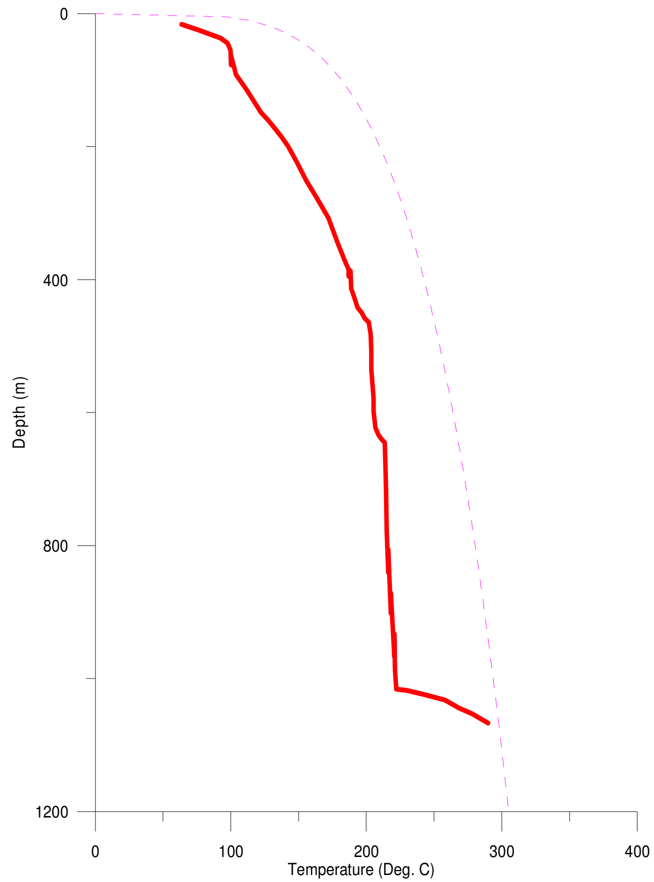


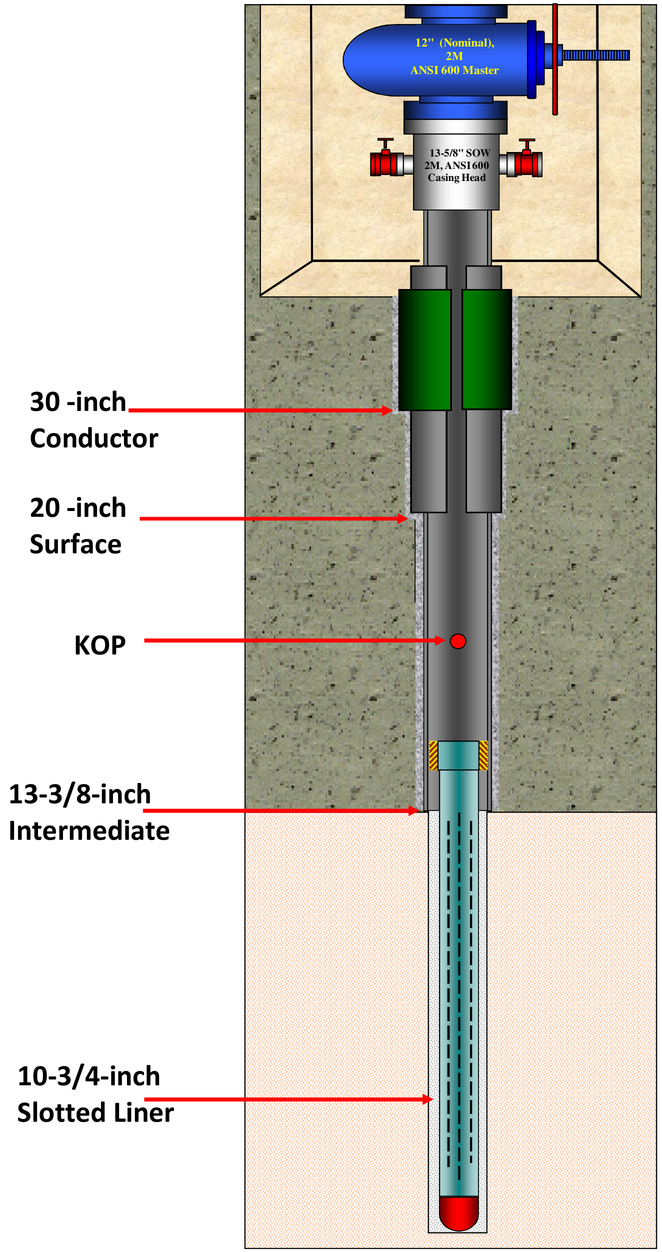
Geothermal Slim Hole

Reaching and Measuring the Reservoir at Lower Cost



- An intermediate step in the drilling campaign
- Enables reservoir testing and chemical sampling
- Provides reservoir proof
- Provides direct knowledge of drilling conditions in and around the reservoir zone
- Valuable for downhole monitoring during operations





Full-Diameter Geothermal Wells

Demonstrating Availability at the Wellhead
Defining Critical Reservoir Parameters

Resource discovery, confirmation, characterization and quantification

Defining production and injection zones / regions

Critical input to power cycle selection and plant design

Temperature Gradient Drilling

Obtain as much resource information using the surface geoscience techniques to build conceptual models in order better target wells

Decision to mobilize and contract drilling equipment is a significant financial commitment

Locally available drilling equipment should be sought . Truck-mounted or perhaps helicopter –lifted rigs may minimize mobilization costs.

Well design may require specialist input.

Conceptual Models

A conceptual model of the resource is prepared during the exploration phase which is progressively updated as more data is gathered.

This is a representation of the current best understanding of a geothermal system, consistent with all known data and information.

The model needs to contain sufficient data to allow a first pass estimate of resource size and temperature

It is used to target temperature gradient wells and when further refined – to target deep, full-diameter wells

New Zealand's Convective Hydrothermal Systems

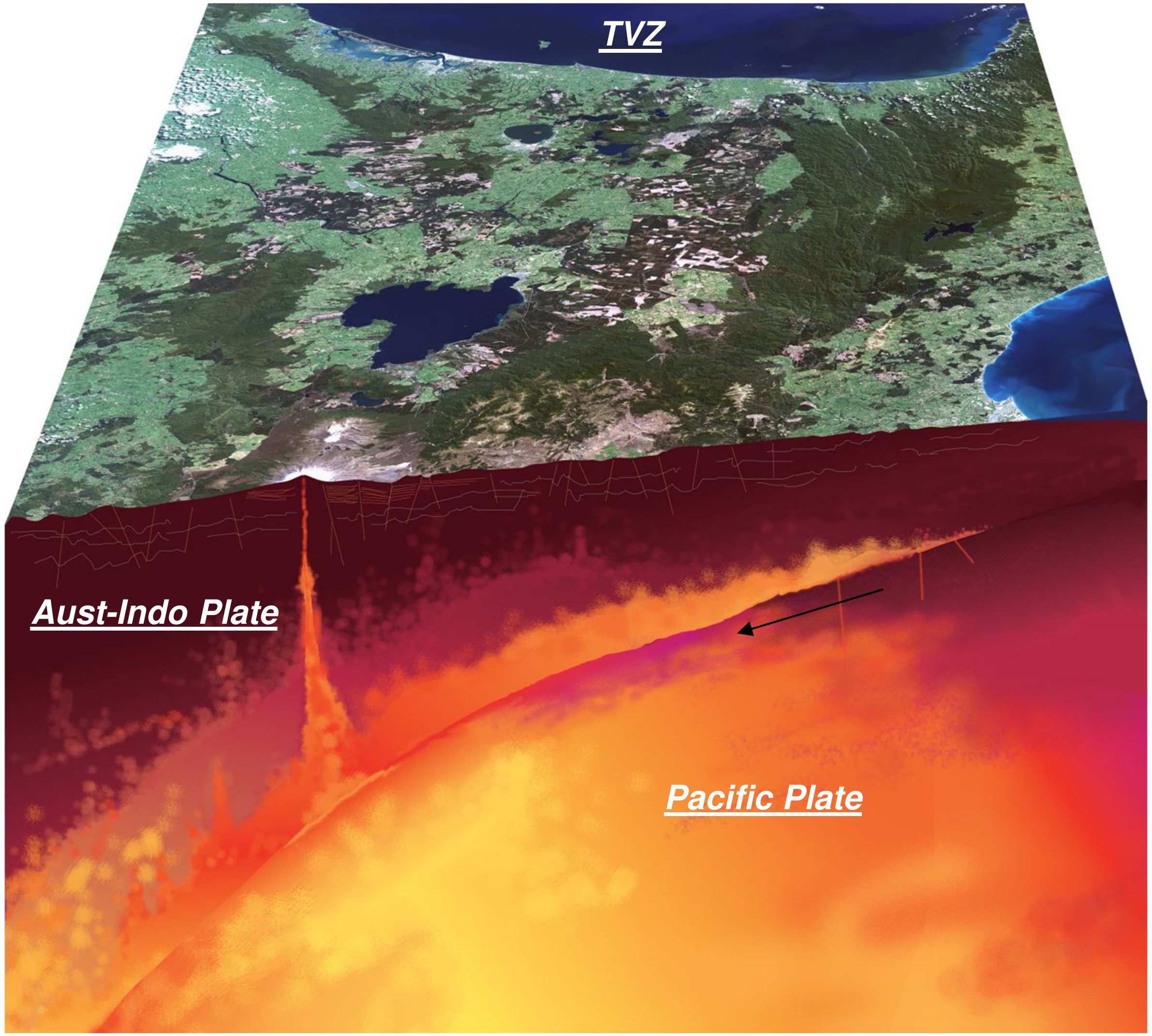
Taupo Volcanic Zone (TVZ) is a vast Natural Energy Source

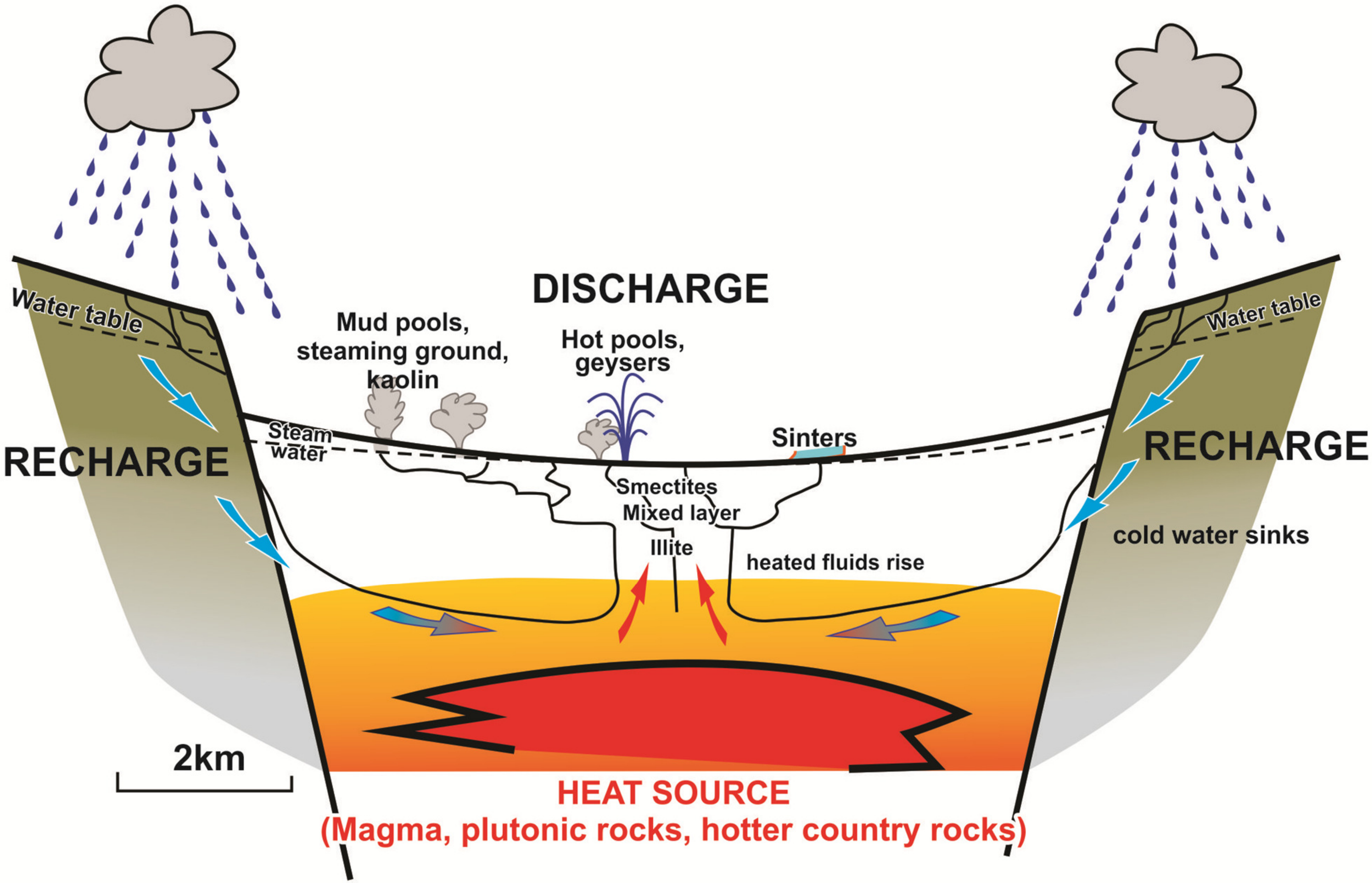
Unproductive

Developed
(conventional geo-thermal to 2500 m : 1500 MWe potential)

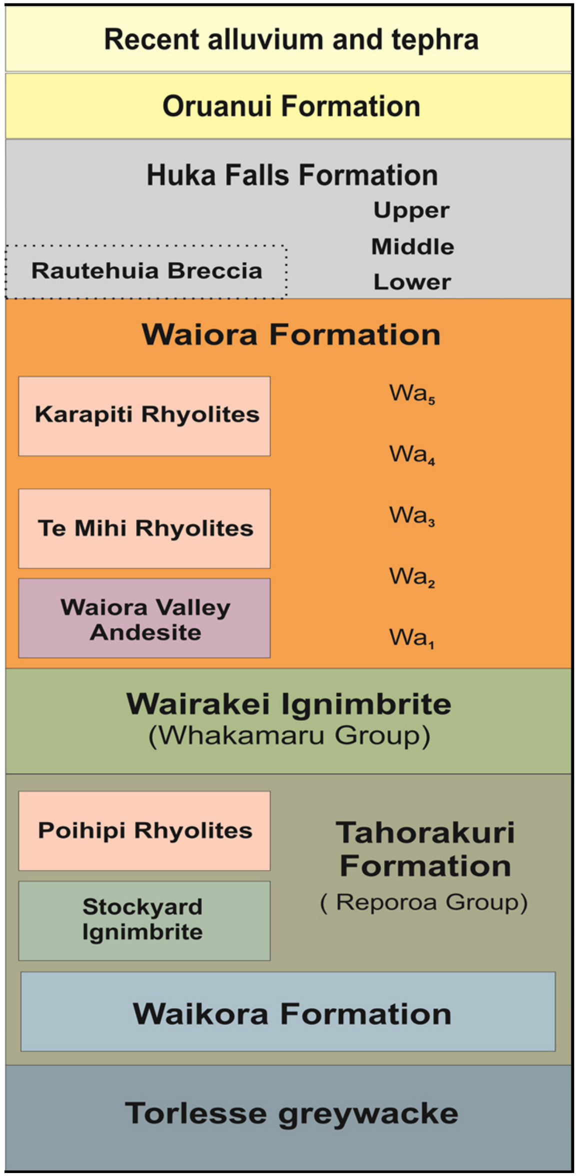
Deep Potential

- recent drilling using large rigs to 3000 m
- Temp. increases with depth, whilst permeability decrease.

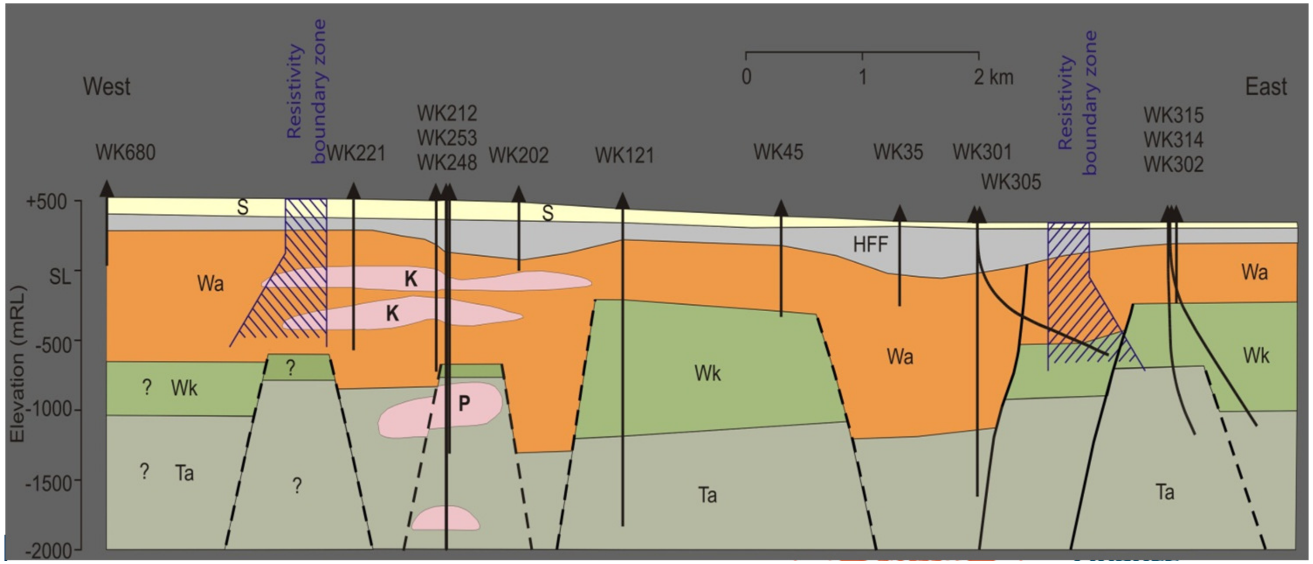



DISCHARGE
Mud pools,
steaming ground,
kaolin
Hot pools,
geysers
Water table
Water table
Steam
water
Sinters
RECHARGE
RECHARGE
Smectites
Mixed layer
Illite
heated fluids rise
cold water sinks
2km
HEAT SOURCE
(Magma, plutonic rocks, hotter country rocks)

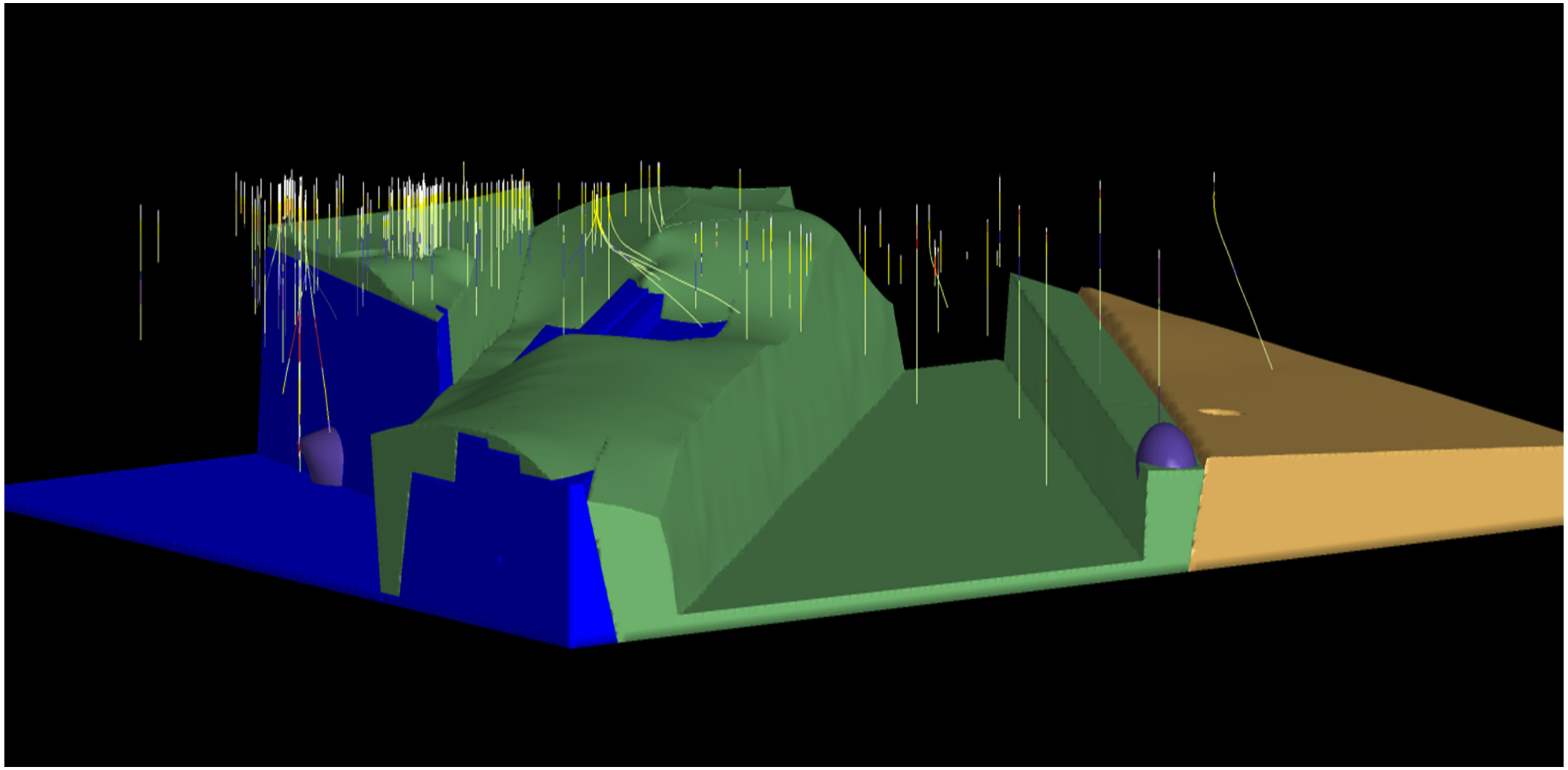
TVZ Stratigraphy



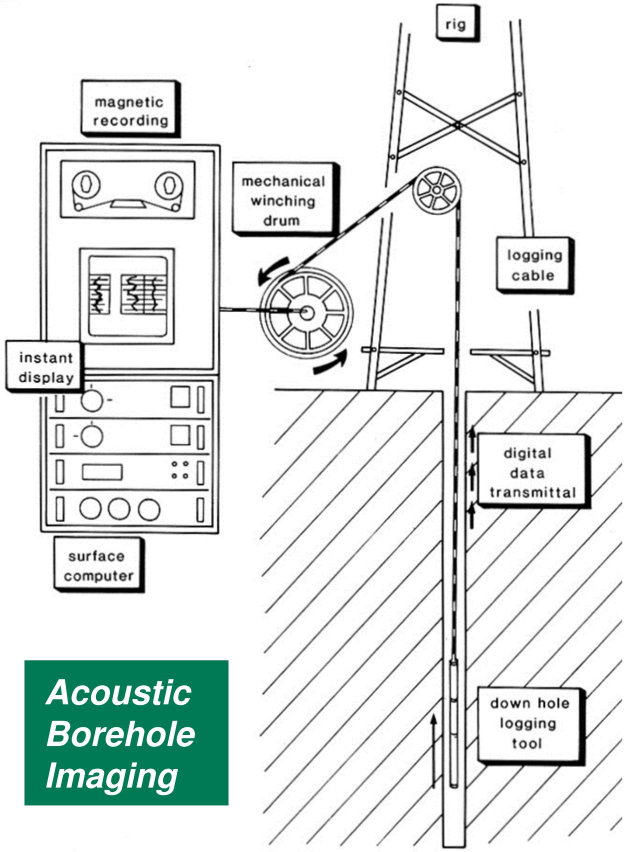
- NE-SW trending fault-controlled volcano-tectonic depression
- Filled by Quaternary volcanic rocks and sediments
- Active normal and extensional faulting
- High crustal heat flow
  - results in high temperature geothermal

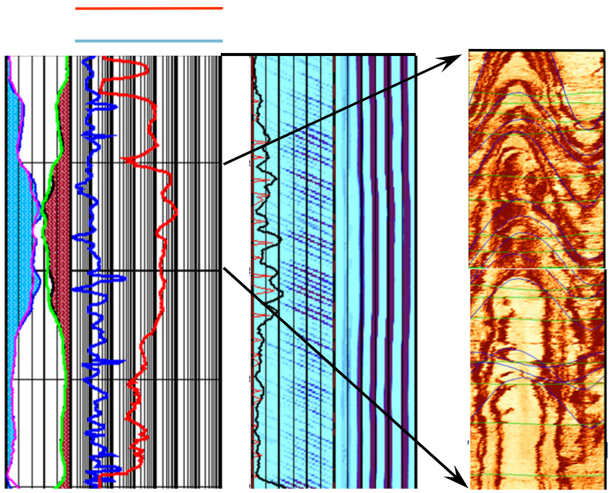


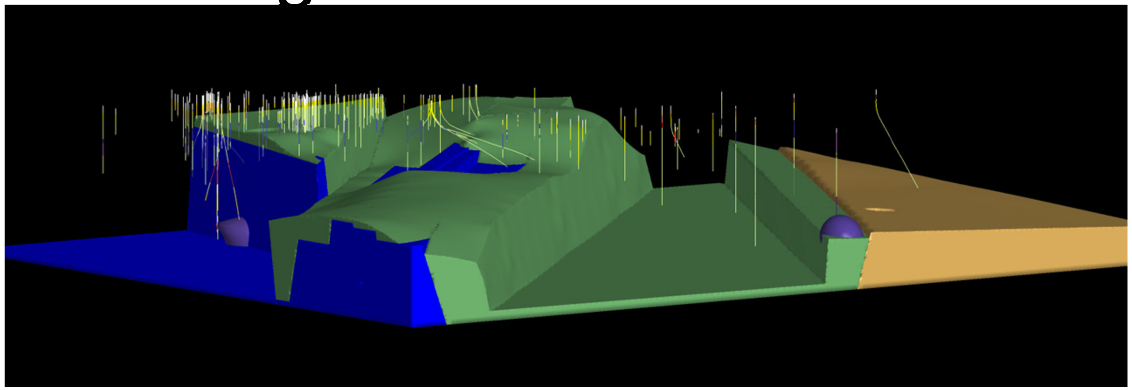
Conceptual Model - Wairakei Geothermal Field

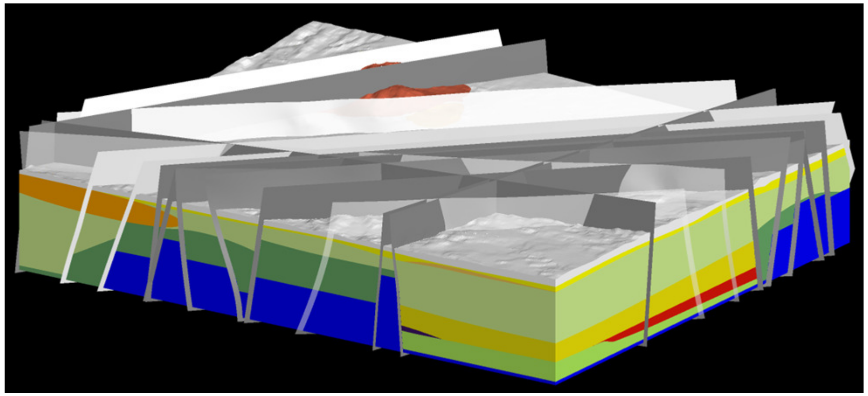


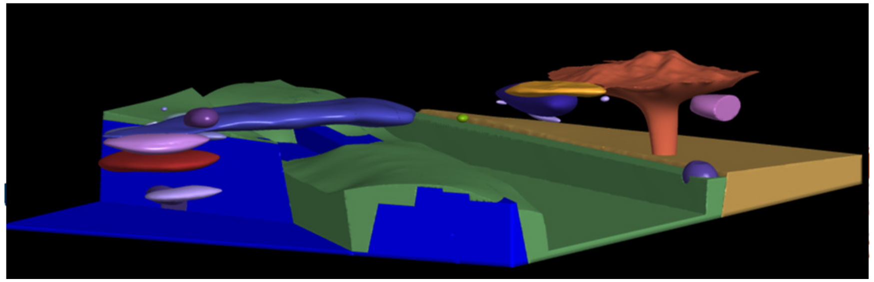
Acoustic Borehole Imaging & 3D modelling



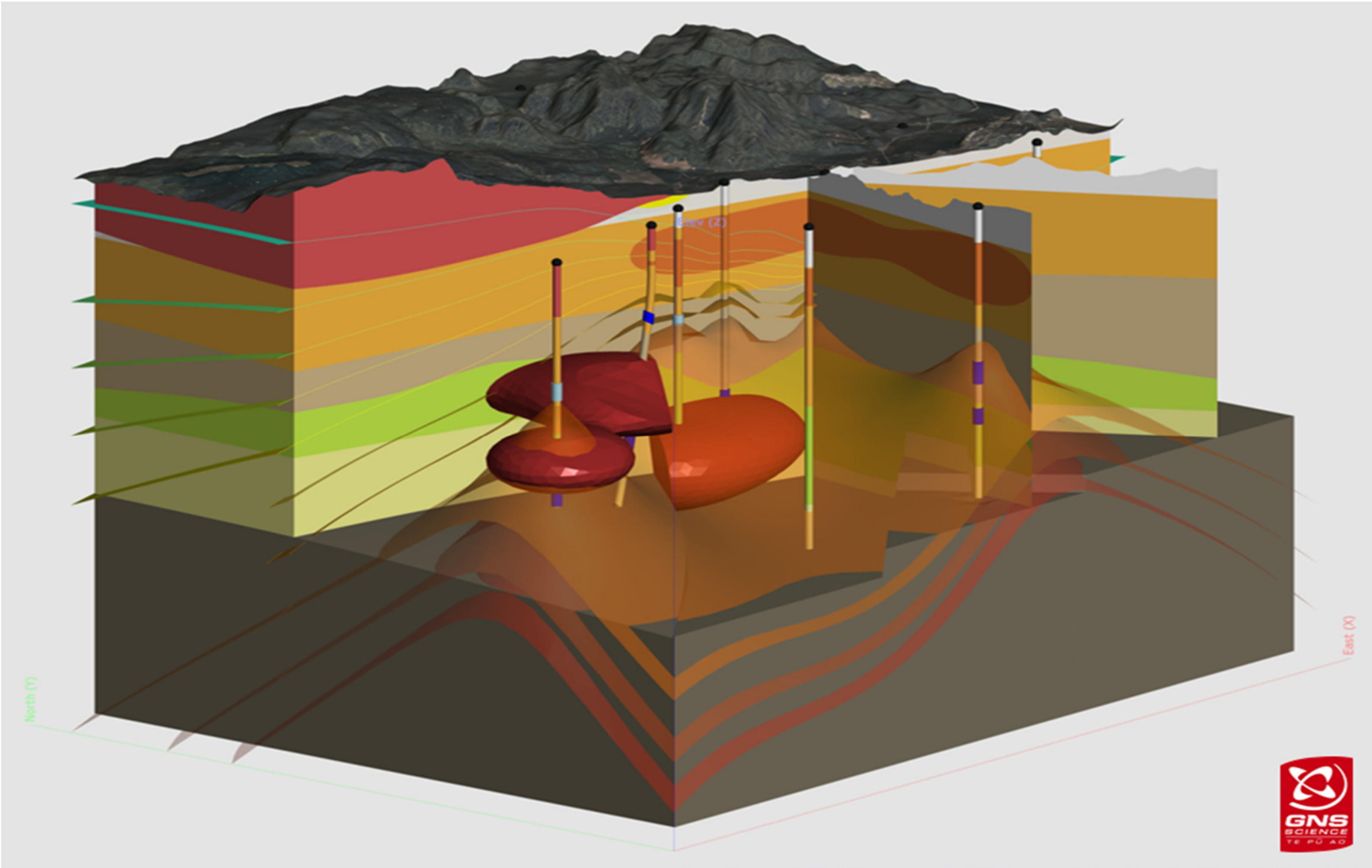








Level of sophistication in model builds with additional well data



4 Basic Resource Requirements for a Successful Geothermal Project

1. **An adequate heat resource**

   Exceeding a certain temperate, at drillable depths

2. **Commercially productive wells (and good injectors)**

   Heat + permeability together, plus reservoir storage

3. **No excessive operational problems**

   Most are manageable, at a cost

4. **A strategy to avoid undue resource degradation**

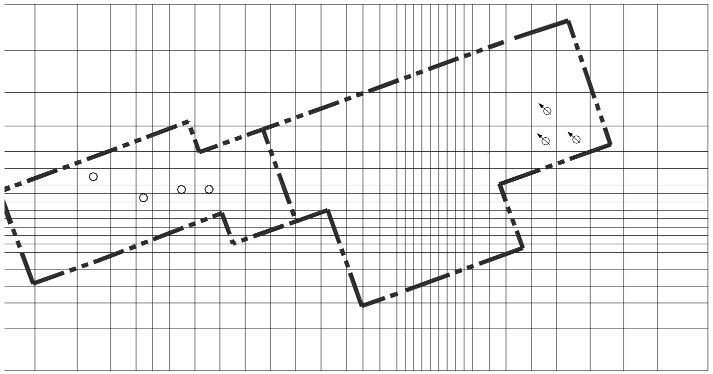
   Monitoring, evaluation, optimization

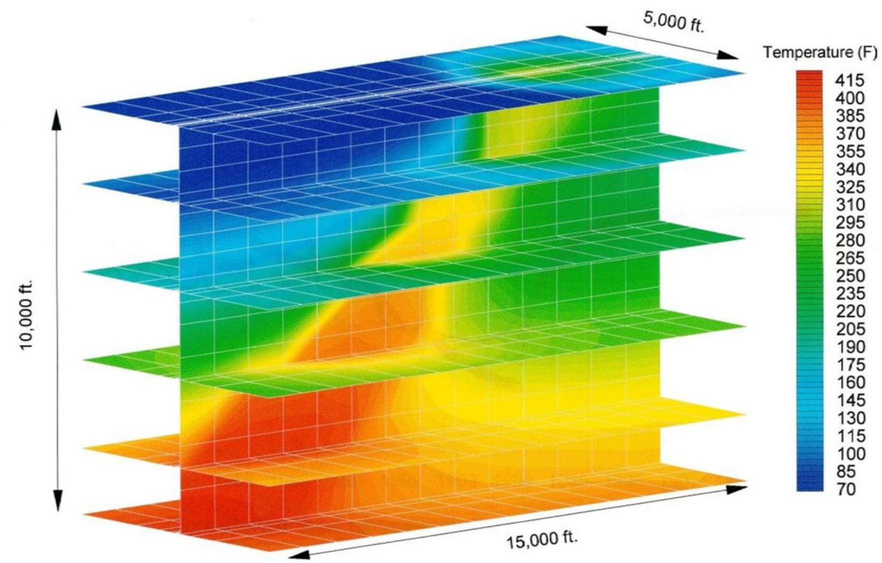
These are pre-requisites for a project, but do not guarantee feasibility

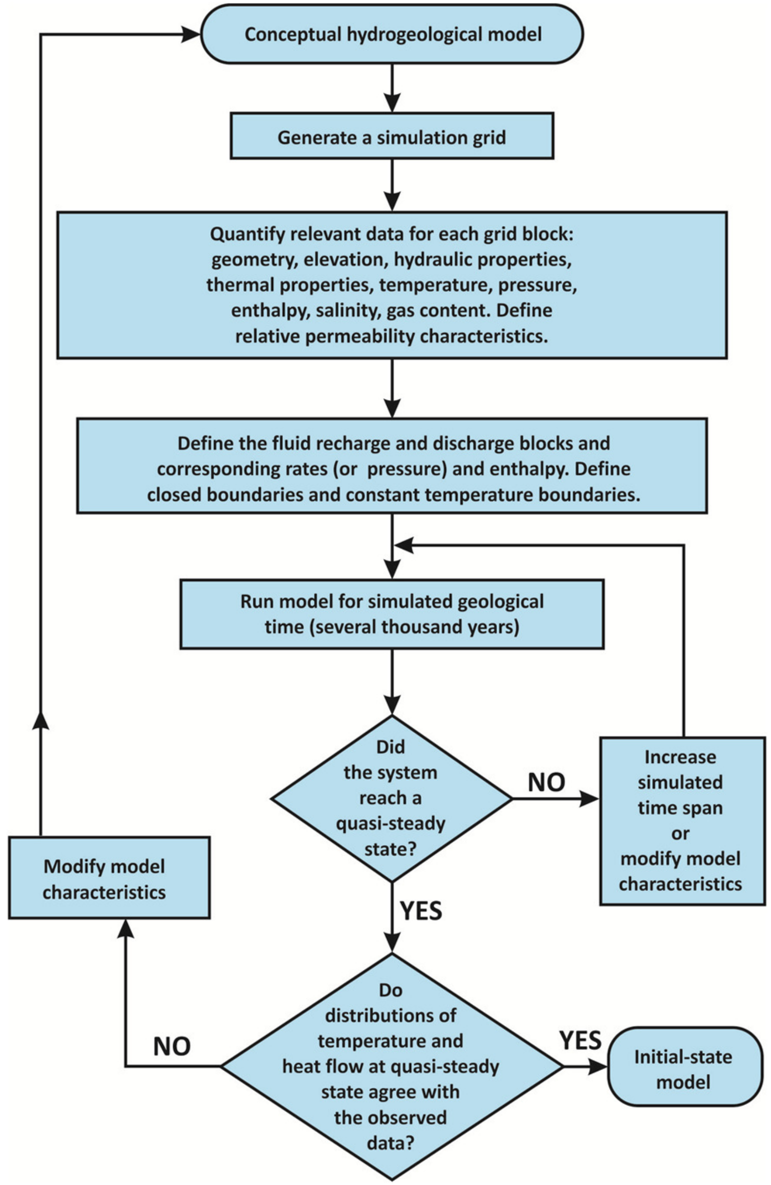
How is Feasibility Demonstrated?

- Exploration and analysis has led to resource discovery
- Confirmation wells have been drilled to delineate the resource
- Conceptual model is well developed and robust (confirmed by drilling)
- There is more than adequate heat-in-place to support the proposed development
- Wells have been tested and produced fluids have been sampled
- Fluid chemistry issues are minimal or manageable
- There is a plan, rationale, budget and timetable for drilling the remaining wells
- An initial injection strategy has been proposed
- A quantitative (typically numerical} model has been developed
- The power cycle has been determined and a basic power plant design has been developed
- The transmission interconnect process is clear, and the power price is known
- All costs have been estimated and a cash flow model has been developed
- An independent feasibility report has been written by a qualified entity

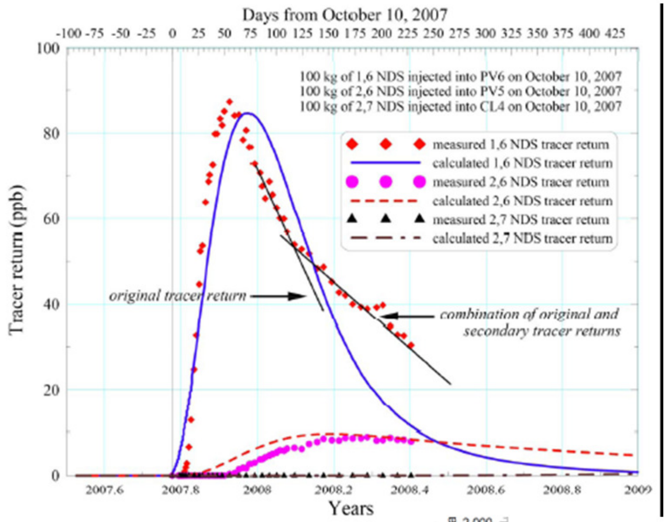
Numerical Modeling: Initial State







Numerical Modeling: History Matching



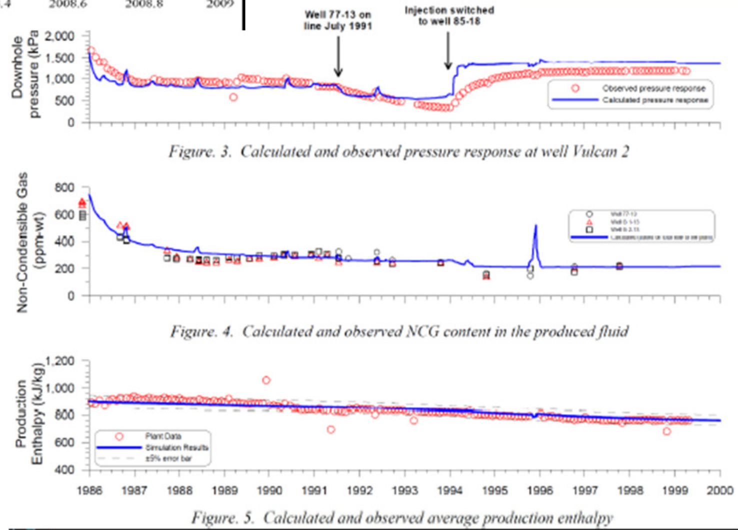
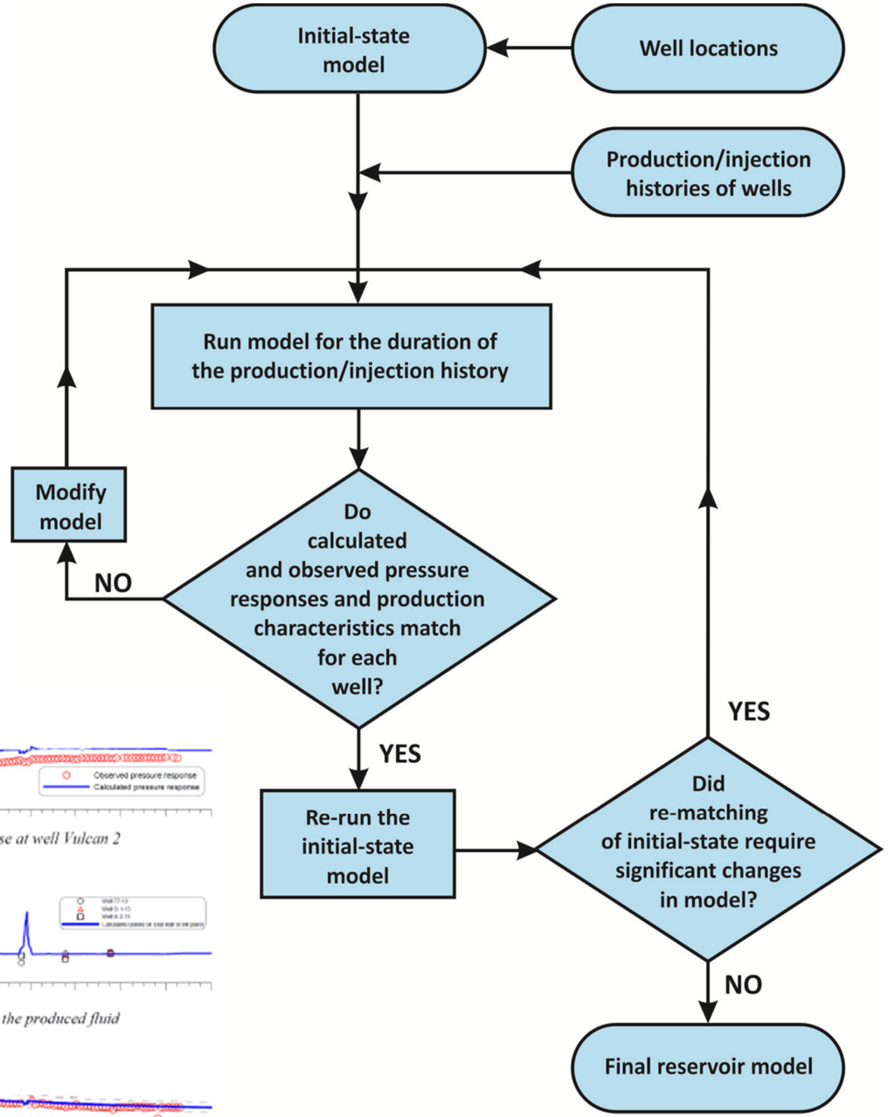


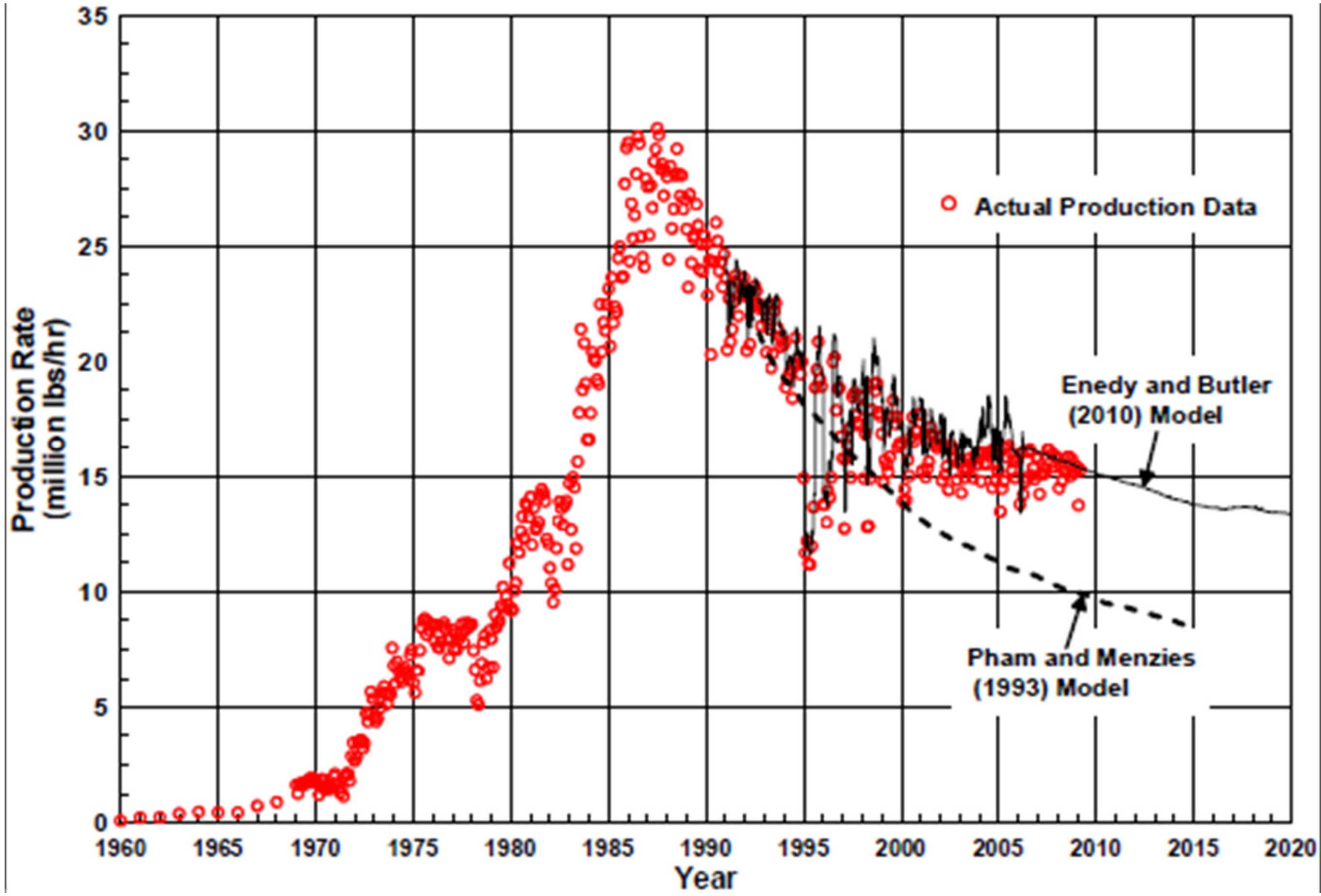
Figure. 3. Calculated and observed pressure response at well Vulcan 2

Figure. 4. Calculated and observed NCG content in the produced fluid

Figure. 5. Calculated and observed average production enthalpy



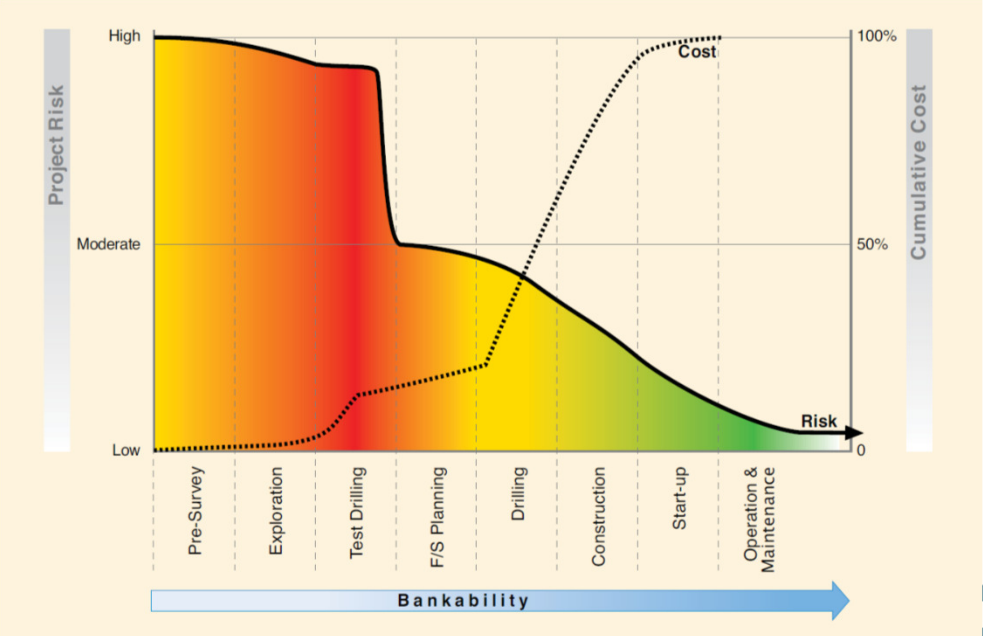
Numerical Modeling: Forecasting



PHASE 4 Feasibility study

This involves the assessment of all the technical and non-technical data prior to committing to development. This very significant milestone lead to the major financial commitments to the project.

The feasibility study evaluates the resource for the viability of power production, mitigation of financial risk associated with development, and builds a business case for funding support from private, public, or institutional bodies. All data (technical and non-technical studies) are built in a financial model to predict returns on investment and to justify the next phase—the expense of deep drilling



Phase 5: Field Development

- Through the feasibility process:
  - drilling conditions are known
  - the locations and targets of the remaining wells are known
  - the technical and economic viability of the project has been demonstrated
  - risks have been reduced significantly
  - the investors have invested
- The wellfield build-out is “routine” as it does not carry the high risk associated with initial drilling
- In large projects with short timelines, multiple rigs may be brought in at this stage

PHASE 5 Field Development

The well drilling program and its management requires careful integration of a range of supplies (rigs, casing, drill rods, drilling chemicals, drilling mud etc) to ensure there are no dleays which can prove costly

Some excess production capacity should be included in the planning and allowed for in the operating costs. A realistic decline rate for geothermal wells should be taken into account.

While drilling is being carried out, the developer also needs to secure finance for power plant construction.

PHASE 6 – POWER PLANT CONSTRUCTION

The completion of the steam gathering system is coordinated with any necessary civil works and infrastructure to allow the power plant to be constructed along with further testing of the wells. Power plants are often constructed using EPC contracts.

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PHASE 7 – COMMISSIONING AND OPERATION

The fuel supply for the project has already been fully provided (by drilling)

The main focus is to optimize the production and injection scheme to enable the most efficient energy recovery and utilization

This helps to minimize operational costs, maximize investment returns, and ensure the reliable delivery of geothermal power

New production/reinjection wells may be needed for any decline in productivity or adjustment of the reinjection strategy

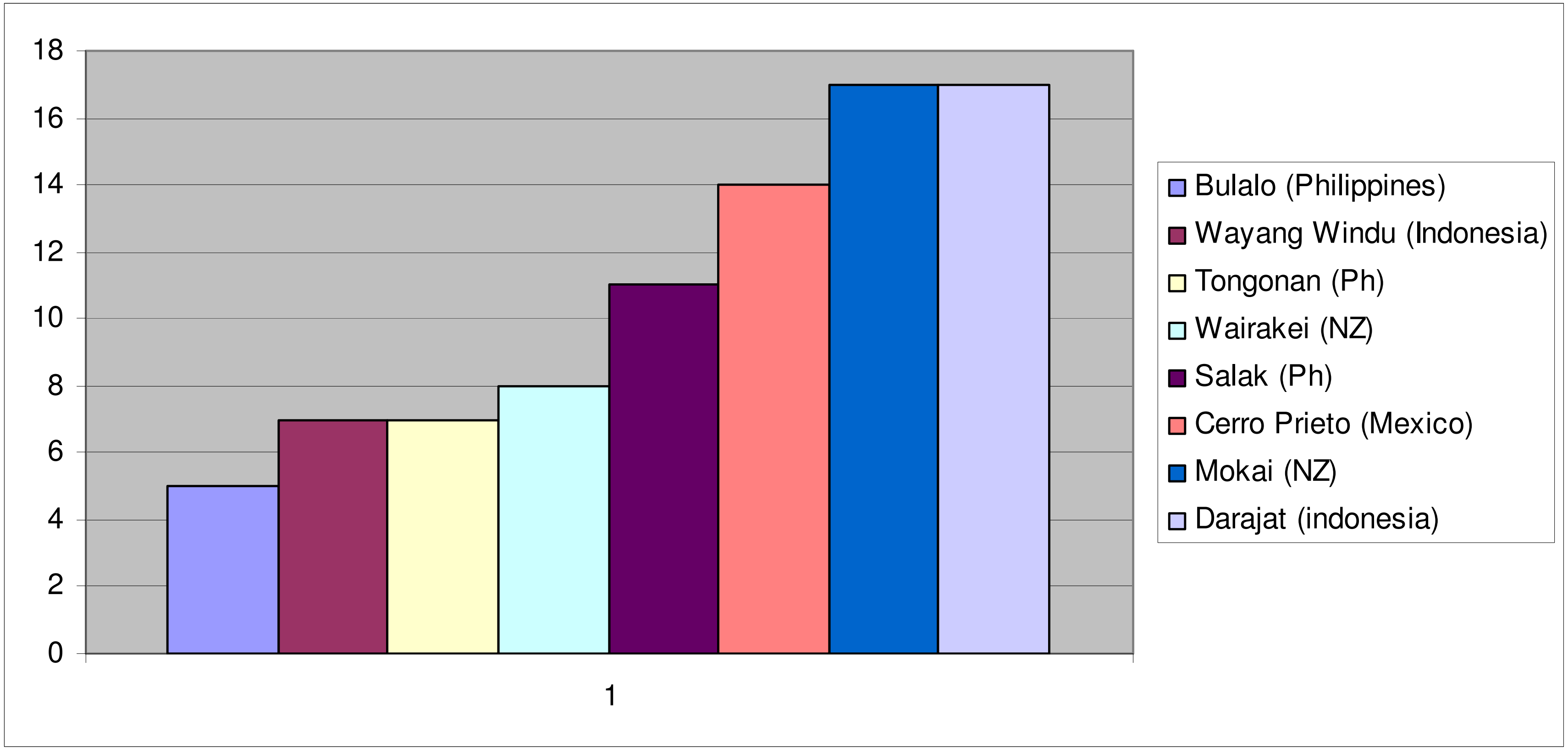
Summary on Risk

Geothermal exploration and development is an acknowledged high-risk investment .

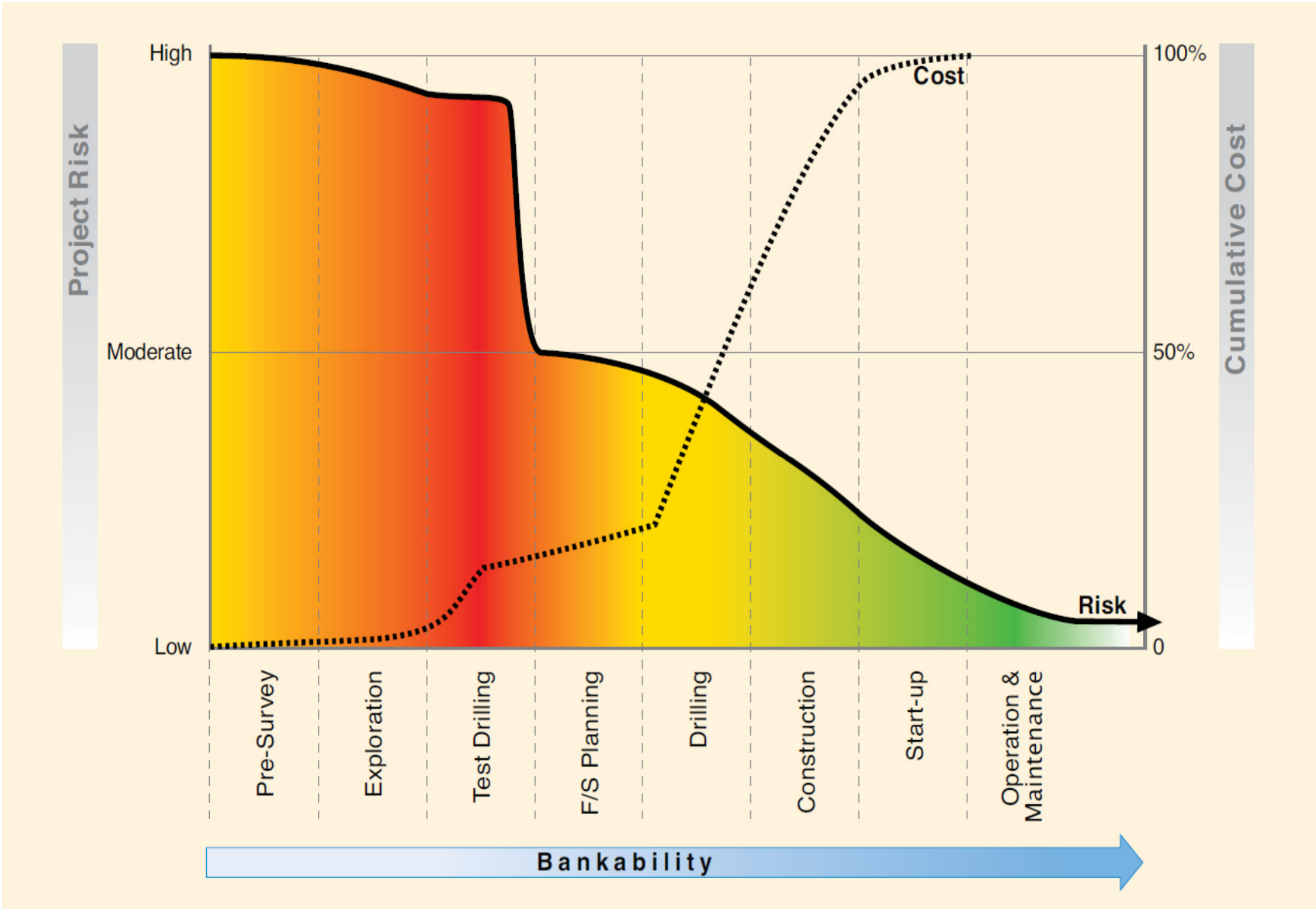
The risk in geothermal development is the uncertainty associated with a natural resource that cannot readily characterized without large expenditures for drilling.

The long time period typically required to move a project from preliminary exploration to development is another factor to consider

Actual time taken to move large geothermal projects from conception to commissioning



Typical risk profile for a geothermal project with time (ESMAP World Bank Geothermal Handbook)



Exploration Risk

The quality of the exploration is a key factor. The best possible exploration risk mitigation is achieved by the correct sequential selection of a combination of scientific techniques followed by experienced interpretation

Drilling Risk

The aim of test drilling is to confirm the viability (i.e. quality) of the resource.

Key variables include temperature, permeability, flow potential and fluid chemistry, location, extent and depth of the resource.

Minimising drilling risk requires quality unambiguous scientific data on which to build good models select good well targets, suitable quality drilling equipment and sound drilling practices and management.

Resource Sustainability Risk

Resource degradation risks include:

-higher-than-anticipated declines in production

-premature cooling (either from injection water breakthrough or from incursion of groundwater)

-adverse chemical effects such as increases in non-condensable (NCG) gas levels, or changes in reservoir conditions leading to scaling, etc.

Mitigation of resource risk includes quality design and management of resource operating systems, sound numerical models and regular monitoring of key issues