



**GEOHERMAL EXPLORATION BEST PRACTICES:
A GUIDE TO RESOURCE DATA COLLECTION, ANALYSIS, AND
PRESENTATION FOR GEOHERMAL PROJECTS**



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Founded in 1973, GeothermEx is a U.S. corporation that specializes exclusively in providing consulting services in the exploration, development, assessment, operation, and valuation of geothermal energy. GeothermEx has participated in geothermal projects in 56 countries, supporting the development of 7,000 MW of geothermal power and US\$12 billion in project finance. GeothermEx was acquired by Schlumberger in 2010. For more information, visit www.geothermex.com.

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The GeothermalCenter (GZB) is a joined research establishment of science and economy with a close link to administration and politics. With its broad anchorage the GZB provides a competence and information center to the public in regard to all Queries concerning the utilization and extraction of geothermal energy. For more information, visit <http://www.geothermie-zentrum.de/en.html>.

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1.0

PURPOSE AND STRUCTURE OF THE GUIDE

1.1 GEOTHERMAL EXPLORATION BEST PRACTICES

Exploration best practices for any natural resource commodity should aim to reduce the resource risk prior to significant capital investment, for a fraction of the cost of the planned investment. For geothermal energy, the high risks cost of proving the resource is one of the key barriers facing the industry. This guide lays out best practices for geothermal exploration to assist geothermal developers and their contractors to address these risks in a cost-sensitive manner, raising project quality. Companies that can demonstrate that their project has followed such best practices will find it easier to access finance. In the same way, this guide will be of use to financiers of geothermal projects, assisting the assessment of projects to ensure project risks have been addressed.

A test of best practice for geothermal exploration is the degree to which each principal resource risk element is addressed. Principal resource risks for geothermal energy are temperature (or enthalpy) and depth of the resource, as well as output and sustainability of flow from producing wells. Each component of a geothermal exploration program should be clearly designed to address one or more of these risks, and each risk component should be addressed in some manner. By the completion of the Exploration Phase, a developer should be able to provide potential financiers with at least a qualified (if not quantified) estimate of the uncertainty associated with forecasting thermal energy production.

Formal ‘Geothermal Reporting Codes’ now exist in at least two countries—Australia and Canada. These Codes expound the principles of transparency, materiality, and accountability with respect to the presentation of geothermal exploration results and estimates of future geothermal power generation. Exploration best practices should, at the very least, emulate these principles if not fully comply with one of the Codes. All relevant exploration results should be clearly and fully presented. A competent, qualified, and experienced person should accept responsibility for the interpretations.

1.2 OUTLINE

This guide provides potential developers with an outline of the various methodologies and strategies employed in the exploration for geothermal resources for power generation. It does this within the context of the typical geothermal development process from preliminary surveying through to power plant development.

This first chapter provides an introduction to the topic and the scope of the report.

Chapter 2 provides an overview of the typical sequence of phases in any geothermal exploration and development program. This guide follows a seven phase process, in line with ESMAP’s Geothermal Handbook (2012). Others in the sector may describe a three or five phase process, but the core elements of each are the same.

Chapter 3 focuses on the Exploration Phase and provides a detailed breakdown of the methodologies and data that should be collected to minimize resource risk prior to presentation to funding entities.

Chapter 4 discusses the various facets of risk relating to geothermal development, including resource risk and financial risk.

Chapter 5 presents a summary of funding models that have been successfully employed for geothermal development in various countries around the World, and which may be investigated elsewhere.

A series of appendices provide greater detail on the exploration methodologies and techniques. The guide can be utilized both as a tool for working through a project, and as an illustration of the geothermal development process.

1.3 EXCLUSIONS

This guide specifically addresses the typical development pathway for hydrothermal geothermal resources. It may not be wholly applicable to exploration for low temperature geothermal resources, 'Enhanced (or Engineered) Geothermal Systems' (EGS, or 'Hot Dry Rock'), or other less conventional or unconventional geothermal developments.

This guide does not address policy, regulatory, and planning frameworks and, as such, is of limited use to governments, development banks or other international funding agencies in designing programs to promote investment in geothermal energy. The recently released ESMAP Geothermal Handbook (2012), which can be considered a companion document to this guide, addresses these areas of interest.

1.4 RELEVANT LITERATURE

A very large body of literature now exists relating to geothermal development. A comprehensive database of published papers can be accessed through the website of the International Geothermal Association (www.geothermal-energy.org) or its member organizations. Overview publications that may provide useful background reading are listed in the box below.

- **Planning and Finance:** - World Bank: ESMAP Geothermal Handbook: Planning and Financing Power Generation: Technical Report 002/12. Available at www.esmap.org/Geothermal_Handbook
- **Geothermal Generation:** - World Geothermal Congress: World Geothermal Generation in 2010 – R. Bertani; in Proceeding from WGC 2010. Available at www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0008.pdf
- **Risk:** - Deloitte 2008 Geothermal Risk Mitigation. Department of Energy/Office of Energy Efficiency and Renewable Energy Program. February 15. Available at www1.eere.energy.gov/geothermal/pdfs/geothermal_risk_mitigation.pdf
- **Environmental:** – IFC/World Bank 2007: Environmental Health and Safety Guidelines for Geothermal Power Generation. Available at <http://tinyurl.com/ck4jeqo>
- **Project Costs:** - New Zealand Geothermal Association: Assessment of Current Costs of Geothermal Power Generation in New Zealand (2007 basis). Available at http://grsj.gr.jp/iga/iga-files/NZ_gpp_cost_estimate_2007basis.pdf
- **Reporting Codes:** - Australian Geothermal Energy Association: Australian Code for Reporting of Exploration Results, Geothermal Resources and Geothermal Reserves, Second Edition (2010). Available at http://www.agea.org.au/media/docs/the_geothermal_reporting_code_ed_2.pdf

2.0

THE PROCESS OF GEOTHERMAL DEVELOPMENT

2.1 INTRODUCTION

This chapter describes the typical process of assessing and developing geothermal power projects. It must be appreciated, however, that every geothermal project is unique, defined by its local geological and market conditions: No two geothermal projects follow exactly the same development path. Therefore, the methodologies, techniques, and project timeline for any geothermal project will be unique to that one resource or project and processes.

Historically, many of the early geothermal projects were developed in a non-systematic manner. There were no clear guidelines for the geothermal development process. The first time geothermal power was harnessed for electricity production was in Italy in the early part of the part of the 20th century using shallow steam from an area where surface discharges were clearly evident. In New Zealand in the 1950's, the Wairakei developments were initially justified on the basis of very high surface heat flows and many surface features (geysers and altered hot ground).

There was no best practice guide at this time. It is only with experience that the stages or phases of how to develop a geothermal resource have become more clearly defined. Even today there are differences in methodologies and techniques between different countries and different agencies.

This guide generally follows a seven phase process of developing geothermal projects, in line with the ESMAP Geothermal Handbook (2012):

1. Preliminary survey
2. Exploration
3. Test drilling
4. Project review and planning
5. Field development
6. Power plant construction
7. Commissioning and operation

Others may use a three phase (exploration, development, and operation) or a five phase (reconnaissance exploration, pre-feasibility, feasibility, detailed design and construction, and operation) process, but the underlying activities will be the same.

The primary focus of this guide is on the Preliminary Survey and Exploration Phases of project development.

Critical resource data and analyses generated during all phases of geothermal development are integrated into continually evolving conceptual models of the resource, which are constantly tested and improved with each new data set. The following sections describe the various phases of a typical geothermal project.

2.2 PHASE 1 – PRELIMINARY SURVEY

The Preliminary Survey Phase involves a work program to assess the already available evidence for geothermal potential within a specific area (perhaps a country, a territory, or an island). The initial surveying may be regional or national and essentially involves a literature review of geological, hydrological or hot spring/thermal data, drilling data, anecdotal information from local populations, and remote sensing data from satellites, if available.

Example:

Most countries have existing data bases of geological and hydrological data. These have usually been gathered for other purposes but may very well be useful for guiding early geothermal surveying and exploration. The potential explorer/developer should make every effort to collect and analyze these data prior to designing and planning an additional exploration program. Remote sensing, in particular, is now playing a more significant role in preliminary surveying for geothermal resources.

Information should also be gathered on access issues during the Preliminary Survey Phase. What are the national, regional, and/or local regulations that might allow or restrict access for exploration activities? Restricted areas might include National Parks, cultural sites, geological hazards, urban areas, areas of unique flora or fauna, or others. Land use issues are also of importance. Could a geothermal development live harmoniously with other existing or possible land uses? It is critical that potential conflicts be identified and assessed at an early stage in a geothermal project, prior to committing to what might be an expensive exploration program. Different countries will have different requirements.

Examples:

In Japan, the majority of identified high temperature geothermal resources are located within or adjacent to National Parks, where access for exploration has, until recently, been forbidden.

In Indonesia, over 50% of known high temperature geothermal resources are located within or adjacent to protected forests or National Parks.

In New Zealand, almost half of the identified geothermal resources are in protected areas where development is limited or forbidden.

In Turkey, no very hard rules or regulations currently exist regarding geothermal exploitation. A Protected Area Special Committee has been established by the Turkish Government that decides if it is appropriate to drill a geothermal well in a protected area. Access for exploration in National Parks is controlled and limited.

The Preliminary Survey Phase should also include an assessment of key environmental issues or factors that might impact or be impacted by a geothermal development. As with any power plant development, geothermal power has its own unique social and environmental impacts and risks that require awareness and management. Making contact with all stakeholders at the early stages of investigation is critical if the developer is to identify potential sociological or environmental roadblocks that may need to be addressed during the project.

Example:

Surface water and groundwater quality and water allocations are becoming major issues worldwide. It is critical to understand the impacts that geothermal developments will have on groundwater availability and quality in the local context.

Necessary infrastructure such as roads, water, power supplies, and availability of equipment must also be considered at an early stage. If roads and bridges have to be constructed in what is frequently steep or mountainous terrain, then the rate of progress for both surface exploration and subsequent drilling may be delayed.

If the project area has a history of mineral and/or water resource exploration then this may provide very useful background or perhaps subsurface information.

The developer also needs to understand the processes for obtaining and retaining legal rights to the geothermal resource throughout the geothermal project. Regulatory issues relevant to obtaining access, land rights for the early stages of work and for subsequent development, power supply agreements and so on, should be understood. Geothermal resources may be either publicly or privately owned. Payments may be required to secure leases or to obtain options to develop the resource if the detailed exploration is successful. Some countries legislate geothermal rights under mining laws; others consider them as water rights, while many countries still have no legal framework for geothermal development. Geothermal permitting processes may be fast or very slow. It is critical that these issues be well understood from the outset.

All the factors mentioned above can significantly impact the time and cost required to move through the various phases of project development. Based on this review, the first question to be answered is:

Does the area of interest (country, region, or island) have a geological setting or features that may indicate the presence of an exploitable geothermal resource?

If the answer is yes, then the assessment can move to the second question, which 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?

In summary, basic background information for the preliminary survey covers:

- the power market and possible power purchase agreements (PPA) or feed in tariff
- infrastructure issues (roads, water, communication, transmission)
- resource ownership issues (in some countries geothermal permits are handled under mining law while elsewhere it may be considered a water right, handled under specific geothermal legislation, or a relevant legal framework might not yet exist)
- environmental and social issues
- institutional and regulatory frameworks
- issues relating to political and financial stability and
- information from available literature on the resource itself, including geological, hydrological or hot spring/thermal data and historic exploration data, potentially from wells drilled in the areas of interest

All these factors need to be considered in order to identify possible barriers to development or potential roadblocks that might derail or slow down a development program. Based on this review and assessment, a developer may decide to proceed to the Exploration Phase. This will require the developer to design and cost an exploration program (Phase 2). It may also be necessary to obtain finance and/or partners to share the risks and expense of the exploration program. There may be several potential sites to investigate, which could effectively spread the risk but involve higher expenditure.

Engagement of experienced geothermal consultants at the Preliminary Survey Phase is one of the keys to identifying and thoroughly assessing relevant background information and designing an effective forward exploration program.

The time required for Phase 1 will depend on a range of factors. It may be as short as several months but if there are many potential sites to investigate and if the environmental approvals and permitting processes are complex and finance is difficult to secure, then it may take one year or longer.

2.3 PHASE 2 – EXPLORATION

The purpose of the exploration program is to cost-effectively minimize risks related to resource temperature, depth, productivity, and sustainability prior to appraisal drilling. Exploration may start off looking at a regional level and, as more data is gleaned, focuses down to a more localized analysis. Exploration typically begins with gathering data from existing nearby wells and other surface manifestations, and goes on to surface and sub-surface surveying using geological, geochemical, and geophysical methods. Environmental studies at this phase establish key background (or baseline) information. Some countries require detailed environmental impact statements as an early component of any exploration program.

In order to make the exploration program cost effective while reducing risk, the survey design will initially focus on simpler (cheaper) methods, and become progressively more complex and costly as early results warrant more detailed efforts and project risks reduce.

Surveying techniques used in this phase may typically include:

SURFACE STUDIES	GEOCHEMICAL SURVEYING	GEOPHYSICAL SURVEYING
<ul style="list-style-type: none"> Gathering local knowledge Locating active geothermal surface features Assessing surface geology 	<ul style="list-style-type: none"> Geothermometry Electrical conductivity pH Flow rate of fluids from active features Soil sampling 	<ul style="list-style-type: none"> Gravity Electrical resistivity Magnetotelluric Temperature gradient drilling 2D & 3D Seismics

A decision to move to temperature gradient (or slim hole) drilling (defined and discussed later) may be recommended after the geological, geochemical and geophysical surveys have been completed. The collaborative data set obtained by using these techniques reduces risk prior to committing to drilling.

For most projects, the decision to mobilize and contract drilling equipment is a significant financial commitment. For this reason, as much information as possible is obtained about the resource prior to this decision by using the surface geoscience techniques to reduce risks prior to committing to drilling. If the data obtained from the surface geoscience studies are extremely encouraging (with high confidence) then it may be justified to move directly to Phase 4 (Project Review). However in most cases the surface geoscience studies will not provide sufficient confidence around potential temperature, depth, productivity, and sustainability to move to the review phase, and temperature gradient drilling can provide a cost-effective approach to risk mitigation by obtaining additional subsurface information.

By the end of Phase 2, sufficient exploration data should have been collected and analyzed to select sites and targets for the first few deep exploration wells. The developer should have a good understanding of the risks remaining around resource temperature and size, depth, permeability, productivity and sustainability, and these risks will have been reduced to a level to justify deep drilling. A preliminary estimate of the magnitude of the resource (expressed in terms of the potentially recoverable thermal energy or thermal power) should also be possible at this stage. Initial conceptual and numerical models can be developed.

Figure 2.1 shows a relatively fast track preliminary survey and exploration timeline. If however, any barriers are encountered during the program, if the geological setting is complex, or if the interpretation of geoscience results remains ambiguous, then the timeline might stretch to two years or longer.

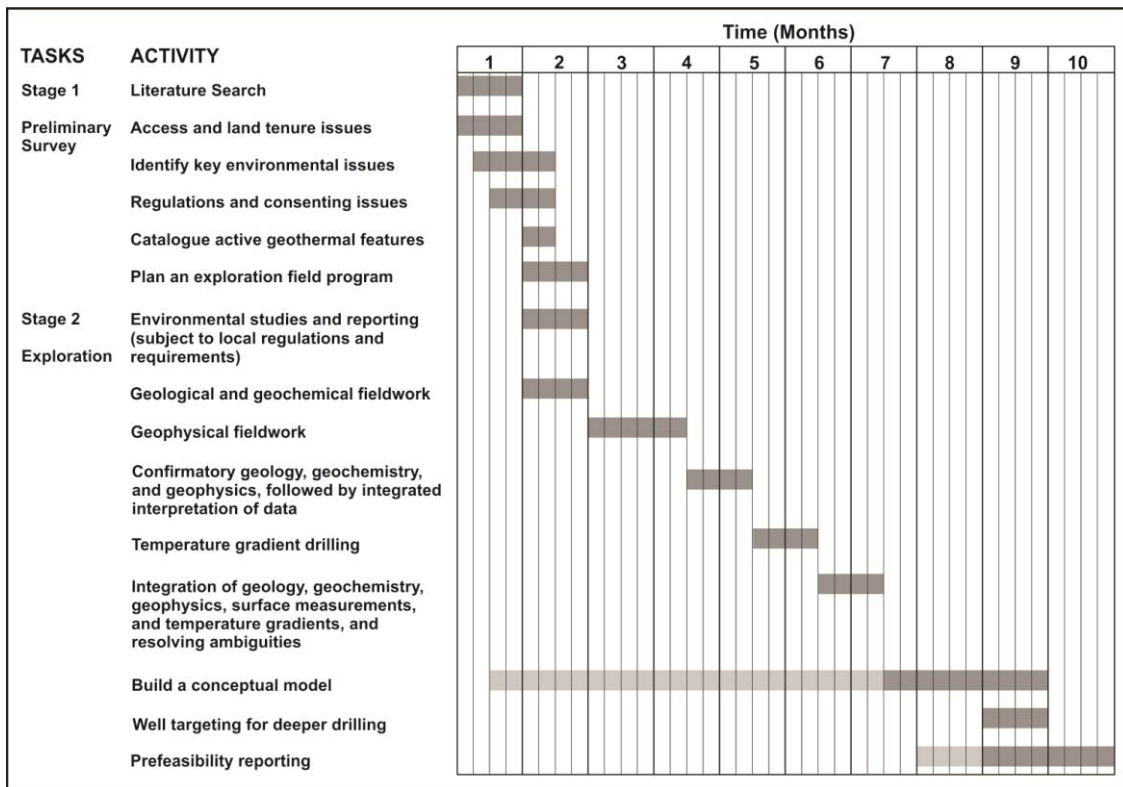


Figure 2.1: Timeline for a well planned and effective surveying and exploration work program in a relatively straightforward geothermal project

A minimum of one successful production well must have been drilled before preparing a pre-feasibility study for a geothermal investment. This requirement is considered to be very important for understanding the system and for development of an acceptable resource model. The private sector places significant importance on the existence of geothermal production wells to justify investments.

2.3.1 Conceptual Modeling

During the exploration phase, a conceptual model of the resource is prepared. This model will be refined as more data is gathered. A conceptual model 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 geological and tectonic information to allow a first pass estimate of resource distribution, temperature, and size. It is used to target deep, full-diameter wells toward lithologic units and/or structures with the highest probability of delivering commercial rates of geothermal fluids. While it is expected that the initial conceptual model may be crude or incomplete, it is important to have an initial model that can be refined and improved as drilling proceeds and more data becomes available. Additional discussion on development of the conceptual model is presented in Section 3 and Appendix A1.

2.3.2 Numerical Modeling

Once a conceptual model consistent with all available data has been constructed, it can form the framework of a numerical model for forecasting the future performance of the reservoir. Once there are some production data to be matched, numerical modeling is used to test the validity of the conceptual model, to estimate the impact that geothermal exploitation will have on the resource, and hence possible degradation of the reservoir and power output.

Numerical modeling is undertaken in three phases:

1. initial state modeling;
2. history matching; and
3. Forecasting future reservoir behavior.

2.3.3 Non-Technical Data Compilation

Having developed a conceptual model and undertaken some numerical modeling, the developer will have a preliminary assessment of the reservoir capacity and will be at a decision point – whether or not to proceed with the project. This is the time to update or confirm current information relating to:

- the power market and possible power purchase agreements
- infrastructure issues (roads, water, communication, transmission)
- resource ownership issues
- environmental and social issues
- institutional and regulatory frameworks
- issues relating to political and financial stability

2.3.4 Prefeasibility Study

The final stage of the Exploration Phase is the assessment of all the technical and non-technical data prior to committing to test drilling. This is a very significant milestone since proceeding to Phase 3 involves major financial commitments to the project. This is a time when resource risk is still high and the expenditure curve is steep (see Chapter 4).

2.4 PHASE 3 – TEST DRILLING

The first full-diameter exploratory wells are drilled during this phase. There is usually a delay while funding is obtained for drilling. Drilling the first wells in any project represents the period of highest risk.

Typically, at least two but more often three, deep wells are drilled to demonstrate the feasibility of commercial production and injection. More wells may be required, depending on the size of the project to be developed and the success in finding a viable geothermal resource with the first series of wells. Drilling, logging and testing significantly improve the understanding of the resource, enabling:

- refinement of the estimate of the heat resource;
- determination of the average well productivity (thus laying out the scope of future drilling);
- selection of the well sites, targets, well path and design for the remaining production and injection wells; and
- development of a preliminary design for the power plant and gathering system.

Upon completion of the test drilling phase, the project moves towards full feasibility.

Example:

In Turkey, at the time of considering bids for geothermal concessions for electricity generation from geothermal fields by the General Directorate of Mineral Research and Exploration (MTA), geological, hydrogeological, geochemical, and geophysical studies must have been satisfactorily carried out as well as evidence of at least one geothermal production well confirming that the geothermal resource exists.

2.5 PHASE 4 – PROJECT REVIEW AND FEASIBILITY

Once the resource has been discovered and confirmed by the first few deep wells, the project risks are substantially reduced and an accurate feasibility report can be prepared.

The resource information permits the developer to update and refine its numerical reservoir model, size the planned development, and secure power purchase agreements on which financial models can be built. Such models, including risk analysis, are required for the developer to be able to obtain the necessary finance to move the project through to development.

The feasibility report is written to provide both the developer and potential financiers with confidence in the viability of the project. The types of data collected, and the recommended method of presenting these data, are outlined in Chapter 3 and Appendix A2.

The feasibility report typically contains the following elements:

- location and design of drilling pads and other civil works (roads, preparation of power plant site, etc.);
- design of development wells;
- specification of drilling targets for remaining production and reinjection wells;
- forecasts of performance from the numerical reservoir model;
- the power plant design;
- the transmission access plan;
- construction budget and costs for all of the above;
- the terms of the power purchase agreement; budget and revenue projections.

Based on the feasibility study and funding availability, a decision is made to develop or not to develop the project. All aspects of a feasibility report need to be updated as the project progresses and more information on the resources characteristics becomes available.

2.6 PHASE 5 – FIELD DEVELOPMENT

The project now proceeds to the Field Development Phase with the drilling of a sufficient number of deep production and reinjection wells to support the proposed power production. Good well targeting is critical to ensure successful wells. Having a sound appreciation of the geological framework and the specific formations and/or structures that provide adequate permeability is critical to designing the wells, their targets, and therefore the drilling programs to be followed. This requires input from the geoscience team, led by geologists and drilling engineers, who draw on information gained during previous phases of project development. In parallel with the drilling, work starts on the steam gathering system to convey the resource from the wells to the power plant.

For large projects, once the resource has been proven through several initial deep wells, it is common practice to have two or more drilling rigs operating in order to shorten the development time and bring revenue from generation as soon as possible. It is rarely possible to predict with great confidence the outputs of wells prior to drilling. The success rate of geothermal drilling varies around the world, but a recent analysis of global geothermal well success done by IFC suggests rates improve from 50% in the test wells, up to 70-80% for production wells. Achieving these success rates depends strongly on the quality of prior exploratory work and the validity of the conceptual model. In areas where many similar geothermal fields have already been developed the success rate may be higher.

For an average well of 2 km depth, a drilling time of 40 to 50 days (24 hour operation) is not unusual. The developer therefore has to define the number of production wells that will be required and the time needed to complete such drilling (including an allowance for some unsuccessful wells). In addition, re-injection wells are

required to return the geothermal fluid to the reservoir, to reduce resource depletion. The ratio of reinjection to production wells ranges from as low as 1:4 in high enthalpy resources to as high as 1:1 in lower enthalpy resources. The actual number required will depend on the enthalpy of the production fluid, the fluid-steam ratio, and the power plant technology. The location and depths of reinjection wells is another key decision based on the conceptual and numerical models, which are continuously updated as new well information becomes available.

The well drilling program requires careful integration of a range of supplies (rigs, casing, drill rods, drilling chemicals, drilling mud etc) and any well completion should be followed by well testing and perhaps tracer testing to assess both production and subsurface conditions. This enables the conceptual model to be continuously updated and refined, and any previous interpretations to be tested. The numerical model also is updated. 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. Once the resource is confirmed, the risks of the project are significantly reduced and debt financing becomes available on commercial terms. Such finance is usually not available until a Power Purchase Agreement has been signed, and the design and contracting of the power plant construction has been committed.

Any delays in drilling programs can seriously impact the timelines for completing the project. Timing may be critical for meeting deadlines in Power Purchase Agreements and for generating revenue for investment returns.

2.7 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.

2.8 PHASE 7 – COMMISSIONING AND OPERATION

At this point, the operational phase begins. Since 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 and reinjection wells may be needed to make up for any decline in productivity or adjustment of the reinjection strategy as the resource responds to exploitation.

3.0

GUIDELINES FOR PRESENTATION OF EXPLORATION DATA TO FUNDING ENTITIES

3.1 INTRODUCTION

This chapter provides the geothermal developer with guidelines for what information and data should typically be assembled during geothermal exploration, and how this information should be presented to potential financiers. It provides examples of 'good outcomes' for each data type. Note that these 'good outcomes' are subjective. They may vary from one geothermal project to the next depending on the geological setting, type of reservoir and generation method, and should be considered as suggestions rather than rigid prescriptions. Appendix A2 contains details of how exploration data are typically acquired in geothermal projects.

3.2 PRELIMINARY INFORMATION

An early task for any developer is to determine what the land tenure and geothermal permitting regulations are in the jurisdiction of interest. In addition, public awareness issues must be surveyed and addressed. Different jurisdictions variously cover geothermal development under mining law, water law, specific geothermal legislation, or have no existing legal framework for geothermal exploration and development. In some countries the granting of geothermal permits is handled by federal agencies, while elsewhere this is the domain of state or regional agencies. Obtaining some form of secure tenure or options over prospective land is an essential first step in any geothermal program.

The developer must determine the local perceptions towards geothermal development. In some countries, indigenous people consider geothermal features to have religious significance. For example, planned developments in Hawaii, Greece, and Peru received hostile responses to development proposals on religious grounds. Identifying any such concerns is an essential component of early geothermal investigations. Local people should be made aware of the impacts, positive and negative, of any geothermal development. Public meetings and surveys should be undertaken to determine pre-existing public attitudes towards development and to provide information in response.

This background information should be compiled and presented in such a manner as to illustrate that the developer understands local requirements and perceptions towards geothermal development. An exploration license should be presented, along with evidence that development rights will be obtained for any geothermal resource that may subsequently be discovered.

3.3 ENVIRONMENTAL IMPACT AND RESOURCE PROTECTION

A thorough understanding of the local regulations for environmental protection is an essential early step for any geothermal development. Although geothermal development is frequently acknowledged as an attractive option for power generation, it must be appreciated that a development of any kind has impacts on the environment and land use.

Example:

In New Zealand, all geothermal resources are classified under one of three categories:

1. Open for major development
2. Open for limited development
3. Protected

New Zealand law does not permit the development of resources in the protected category.

Resources are generally protected because their public value in their natural state is considered greater than the public value of geothermal power. This public value might be due to cultural, environmental, historical or tourism attributes. Resources in close proximity to urban areas may also be protected. In Japan, the majority of known geothermal resources lie within or adjacent to National Parks and many have been fully protected until recently. In Indonesia, some reports indicate that up to 70% of known geothermal resources are in protected forests.

Even where development is allowed, an Environmental Impact Statement (EIS) may be a pre-requisite to embarking on a surveying or exploration program. Any such EIS should be presented in full to a potential financier.

Example:

In Turkey, geothermal power plants with capacity over 5 MWe must prepare an Environmental Impact Assessment (EIA) report. For plants having less than 5 MWe capacity, there is no need to prepare Environmental Impact Assessments but investors have to apply to receive a certificate which confirms that they are exempted from this requirement.

3.4 COLLECTION OF BASELINE DATA

Baseline environmental data, which essentially defines the starting conditions of any development, should be collected as early as possible. In many countries, resource consents impose strict conditions relating to any potential impact of a geothermal project. For example, consents may specify minimal or no impact on other existing land uses. This might cover such impacts as subsidence, air quality, surface geothermal features, groundwater quality, visual amenity, and seismic activity. Collection of baseline data related to such requirements may take significant time. For example, it might require many months of monitoring to define baseline seismicity characteristics or variability of discharge from active geothermal features. It is important for the developer to identify environmental parameters that might be sensitive and address these early in the project.

Baseline data can be presented as maps, charts, graphs, tables, databases, or in other formats as appropriate for reporting, consensus-building, and in pursuit of financing.

3.5 LITERATURE REVIEW

An early step in evaluating a geothermal resource is to find and assess any existing data and previous research pertaining to the project area. In many cases, previous studies offer insights into the geological setting through hydrology, geochemistry, geophysics, or other surveys.

A thorough literature review by experienced geothermal specialists can save the developer significant time, effort, and expense in the Exploration Phase of the project. Such a review may uncover essential baseline environmental data. Historical data can also provide a useful contrast to developer-generated data, enabling the developer to assess the quality and consistency of new data against previously collected information.

A literature review can be performed partly on-line, but a thorough search should also include visits to local government agencies, universities and other institutions where public documents relevant to the project might be

held. The literature review should focus on uncovering articles, reports, maps, databases and figures concerning the geology, geothermal setting, and cultural / environmental aspects of the project area.

Where relevant prior data of useful quality exist, these data should be compiled and reviewed to identify gaps in coverage or quality. This information should be used to formulate plans for additional surveying and exploration. Ongoing exploration efforts can then be focused on addressing the gaps or augmenting information where needed.

A bibliography and library of relevant papers, reports, and data sets should be created. Copies of the most important documents (those with direct relevance to the field) might be presented to potential financiers, but the developer should also prepare a summary document of any previous efforts in geothermal exploration and should use any available (and non-proprietary) previous data as part of the analytical process.

Examples of data sources to be sought and collated include:

- Academic publications from both local and foreign universities and research programs;
- Data, results and/or reports from previous lease-holders including mining tenements or previous exploration campaigns for minerals or oil and gas;
- Reports and documents from relevant agencies of the national government;
- Provincial reports and documents from relevant agencies;
- Municipal reports and documents from relevant agencies;
- Data and information found through internet searches; and
- Maps pertaining to geology, infrastructure, and lease boundaries.

Example:

In Turkey, background geological, hydrogeological, geochemical, and geophysical information about the known geothermal fields, can be searched and bought from the General Directorate of Mineral Research and Exploration and in Universities.

Data compilation is an integral part of the project at any stage, including the initial literature search and review. Geo-referenced digital databases (e.g., locations and characteristics of geothermal manifestations, topography, roads, other infrastructure, geology, geochemistry, geophysics, etc.) should be created whenever possible for ease of analysis and presentation, with data compiled by means of summaries, databases, spreadsheets, maps and figures, depending on the nature of the data. Short narratives (e. g., geologic setting, tectonic history, development history, etc.) suffice where tabular compilation is inappropriate.

This process is greatly facilitated by geospatial programs that can generate maps and other graphics from underlying databases, allowing data from different sources to be overlain on a single map at the same scale. Collated maps should be clearly labeled with sufficient information (on the map itself, in the legend or key, in the form of the figure title, or other obvious location) for the map to stand alone without any further explanatory text. This comment applies to any maps or figures prepared at any phase of the project.

Existing reports and databases in many parts of the world might be in a different language to that of the developer or potential financiers. Where large databases exist, translation costs can be significant and time consuming. However, translation of reports and data will generally provide sufficient value to warrant the additional cost. Many of the international geothermal consultants and funding agencies, for example, require information to be provided in English.

A good outcome upon completion of the literature and published data review is to have high confidence that all relevant data and maps have been identified, collated, and assessed for inclusion in the conceptual model of the resource.

This step is critical to avoid duplication of effort and therefore enabling the developer to apply surveying or exploration funds most judiciously. It is best practice to have a geo-referenced database of information within the geothermal prospect and lease boundaries following this step.

3.6 SATELLITE IMAGERY

More and more data from satellite and airborne sensors are becoming readily available. A range of these data can be applied to geothermal exploration. Examples include satellite or aircraft-based infrared scans, and thermal data acquired by Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors on-board Landsat-5 and Landsat-7 satellites. Data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), launched in 1999 as part of NASA's 'Earth Observing System', is increasingly being applied on a global scale to identify surface geothermal features.

It may be appropriate to develop a Geographic Information System (GIS) database (or equivalent) of potential geothermal sites based on aerial photos and satellite data. The technique may be especially useful in difficult terrain where ground access is difficult. Note, however, that confirmation of thermal anomalies always requires on-ground verification and assessment of their potential.

Relevant remote sensing data can be downloaded into GIS software for integration with data compiled from surface surveys to produce detailed maps for each project area.

3.7 ACTIVE GEOTHERMAL FEATURES

Active geothermal features are proof of an existing geothermal system on some scale, although not proof of a system suitable for power generation. The first step in field exploration is to locate and characterize all existing geothermal features within the project area and within a relevant distance of the project area (Figure 3.1). A conservative rule of thumb is to record hot (>50°C) features within 10 km and warm (>25°C) features within 5 km of the project area.

Active geothermal features include any or all of the following:

- hot/warm springs and seeps (hot = >50°C, warm = >25°C)
- mineral springs (with conductivity exceeding one standard deviation or more above the background)
- fumaroles
- solfataras
- hot/warm wells (including geothermal or groundwater wells)
- gas seeps

The location and names of all the geothermal features, as well as the mapped extents of surrounding geothermal deposits, should be compiled on a single map for each project area consistent with geological and tectonic settings. The remaining data, including temperature, electrical conductivity, pH, and flow rate, should be compiled into tables that correspond directly to what is shown on the map. These two sets of documents should encompass as much of the above listed information as can be obtained. Ideally, all of these data would be geo-referenced, allowing for easy integration with other project data. Logs and testing results from hot/warm wells should be presented and discussed on a well-by-well basis, and down-hole summary plots should be created summarizing all the available information for each well.

A good outcome following analysis of the active geothermal features would be an estimate of the rate of geothermal fluid movement through the system, and an idea of the extent and general geometry of the geothermal resource.



Figure 3.1: Field mapping at a hydrothermal eruption crater, New Zealand (GNS Science, New Zealand).

3.8 GEOLOGY

A thorough understanding of the geology of the project area and how it fits into the surrounding regional geological and tectonic setting is crucial to understanding a given geothermal system. Once data has been gathered from available literature, geological studies (including field work) can be carried out both at a regional and a local level in the Exploration Phase. Initial geological studies are focused on understanding the overall geology of the project area and identifying the most promising areas for more detailed exploration. Later, efforts are focused on the most promising areas with the specific goal of understanding the permeability pathways that bring thermal fluids from their deep source to shallower parts of the system, where they can be economically exploited for geothermal power production.

Geological data for the project area should be presented in the form of geological maps, structural maps, stratigraphic columns, and cross sections for the project areas. Alternatively, a three-dimensional geological model can be developed using specialized modeling and visualization software. However the data are collated, they should address lithology, stratigraphy, hydrothermal mineralization, geological structure, tectonics, and sense of movement on faults. The geological history of the area should be summarized in a separate document, including a description of the local stratigraphy, the lithological units expected during drilling, and a summary of the types, locations, and nature of geological structures.

A good outcome from the geological analysis is a clear picture of the regional and local geology, stratigraphy, and tectonic structure of the area, as well as identification of uncertainties and data gaps that need to be addressed in subsequent stages of exploration. This information should indicate which units or structures could host a geothermal reservoir, and forms the basis for subsequent conceptual and numerical models.

3.9 GEOCHEMISTRY

Geochemistry can be an extremely useful tool in the exploration for high enthalpy geothermal resources. Sampling (Figure 3.2), analysis, and calculation of chemical geothermometry can provide estimates of potential

resource temperature. Interpretation of geochemical data can be very useful during the Exploration Phase to develop an understanding of the temperatures and extent of the geothermal reservoir and to ascertain whether the resource is sufficiently well developed and hot enough to be utilized for geothermal electrical generation. Geochemical studies focus on understanding the geothermal fluid sources and flow paths and assessing potential operational issues that will come with development, such as wellbore scaling, corrosion, and concentrations of non-condensable gases. Regional CO₂ gas surveys, which are a recent advancement in geochemical evaluation to be done during the regional exploration stage, are becoming increasingly popular to supplement geothermometry techniques, because elevated CO₂ at the surface may indicate the presence of permeable faults or the extent of an active geothermal system.



Figure 3.2: Geochemical sampling at a thermal pool, New Zealand (GNS Science, New Zealand).

Fluid and gas geochemical data are presented on maps, tables, drawings, and plots for the project area. Accompanying reports should explain the inferences and conclusions drawn from the data. Inferences and conclusions may include parameters such as:

1. estimated resource temperature at depth;
2. the genesis (origin) of the resource;
3. the locations of different aquifers or reservoirs in two and three dimensions;
4. mixing between aquifers;
5. sources of recharge to the geothermal system;
6. pathways of discharge from the geothermal system; and
7. the potential for corrosion and/or scaling of the geothermal fluids.

The following should be provided as a minimum for each project area, if appropriate data are available:

- A map of sample locations showing the local or assigned names of the geothermal features from which the samples were taken.

- A table summarizing the fluid geochemistry of the sampled geothermal features, keyed to the map. This table should include:
 - field parameters, including location, temperature, EC, pH, flow rate, gas bubbles, odors, precipitates (detailed in Appendix A2)
 - geochemical analyses of the following at minimum 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 (measured in diluted sample, corrected to native concentration). In addition Sr, Rb, Mn, F^- , ^{18}O , and D stable isotopes in water and ^{18}O in dissolved SO_4^{2-} are extremely useful. The table should also include the ion balance of each sample and/or other evidence of quality control on the analyses undertaken.
- A table summarizing the gas geochemistry of the sampled geothermal features, keyed to the map. This table should include:
 - field parameters, including location, temperature, flow rate, odors
 - geochemical analyses of the following at minimum NH_3 , H_2S , CO_2 , CH_4 , H_2 , N_2 , Ar, He, SO_2 , HCl, HF, O_2 . In addition, $^3\text{He}/^4\text{He}$, $^{40}\text{Ar}/^{36}\text{Ar}$, noble gas ratios, and stable isotopes in steam condensate can be very valuable in assessing the geochemistry of the system. The table should also include the standard deviation of each sample and/or other evidence of quality control on the analyses undertaken.
 - Total flux and makeup of non-condensable gases for any well in production.
- A table showing the results of the geothermometry calculations. This table should include all of the following geothermometers that can be calculated for a given sample: silica (Quartz, Chalcedony, and Amorphous Glass), cation (Na-K-Ca, Na-K-Ca-Mg, Na/K, K-Mg) and sulfate water isotope (^{18}O).
- In addition, graphs of the geochemical data should be provided, including, but not limited to:
 - Piper diagrams
 - Potassium concentration versus Sodium concentration: K(mg/L) vs. Na(mg/L)
 - Delta Deuterium versus Delta ^{18}O (δD vs $\delta^{18}\text{O}$)
 - A ternary plot of the major anions ($\text{SO}_4\text{-HCO}_3\text{-Cl}$)
 - A ternary plot of sodium, potassium and magnesium, including scales for the Na/K and K-Mg geothermometers
 - Sodium potassium calcium geothermometer temperature versus chloride concentration
 - Temperature of the sodium potassium calcium geothermometer versus temperature of the potassium over magnesium geothermometer: Temp NaKCa ($^{\circ}\text{C}$) vs. Temp K/Mg ($^{\circ}\text{C}$)
 - Discharge temperature versus chloride concentration, Temp ($^{\circ}\text{C}$) vs. Cl (mg/L)
 - A ternary plot of nitrogen, carbon dioxide and argon (N_2 , $\text{CO}_2/100$, $100*\text{Ar}$)
 - 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)

Contour maps showing the sample points and their values are appropriate to depict soil survey data, as well as tables including the locations, values, and characteristics of the sample points.

A good outcome of the geochemistry studies would be an indication of temperature distribution within the geothermal system, a maximum temperature range for the resource, and a fluid-mixing model and, as with geologic studies, the identification of uncertainties and data gaps that need to be addressed in the following stages of exploration.

3.10 GEOPHYSICS

Geophysical surveys are indispensable tools in geothermal exploration (Figure 3.3). They help constrain our understanding of stratigraphy, structure and heat flow. Identifying which geophysical technique might be most appropriate and cost effective in any specific exploration program requires input from experienced geothermal scientists.



Figure 3.3: Electrical resistivity survey (Western GECO).

There are many types of geophysical surveys that can be carried out. They include gravity surveys, temperature gradient drilling (also referred to as heat flow surveys), electrical and electromagnetic resistivity surveys (particularly magneto-telluric (MT), but there are also several others), and 2D and 3D seismic techniques. In some geological settings, seismic reflection surveys can provide valuable information about the depth to lithologic units, reservoir rocks and the faults that offset them, but the value of the additional data might not always justify the cost of running the survey and therefore geophysical surveys should be soundly planned and carried out.

Example:

In Turkey, over the past two to three years, magnetotelluric (MT) and seismic surveys have been recognized to be amongst the most useful geophysical studies, since greater emphasis has been placed on deep exploration for geothermal resources.

Geophysical data collection points should be presented on maps with license boundaries and cross section lines clearly labeled. Maps should be provided as geo-referenced digital files or have a grid overlain on them that allows for easy geo-referencing (including UTM coordinates or latitude-longitude, with appropriate projection and datum information). In addition, cross section views should be provided as appropriate for the data sets, including orientations that are parallel and perpendicular to the regional geological structural trends.

Gravity data should be presented as contour maps of complete Bouguer and residual gravity, with the appropriate reduction densities indicated. Two- or three-dimensional models fitting the data should be provided in the form of maps and cross sections that show the measured and calculated results.

Resistivity data should be presented in a similar way, with contour maps of resistivity or conductivity at a particular elevation/depth, or iso-resistivity contour maps showing the elevation of a particular resistivity or conductivity value. Cross sections showing resistivity distributions are ideally presented along the same profiles as presented for gravity data.

Before presentation, seismic data requires more detailed processing and interpretation than either resistivity or gravity data. An important element of seismic interpretation is the development of a seismic velocity model based on known or inferred geological conditions. This velocity model may be well or poorly constrained, depending primarily on the presence or absence of deep wells in the area to which the seismic data may be 'tied'. The interpreted results are most commonly presented as cross sections, with 'two-way-travel-time' converted to depth using the seismic velocity model. Interpreted sections typically show the most important seismic reflectors and faults as solid colored lines on top of the actual processed data. Seismic cross sections should be presented both with and without these features highlighted, enabling the reviewer to assess the quality of the reflections and the interpretation provided. The seismic contractor should provide a report giving the details of data acquisition, processing, and interpretation.

Temperature gradient (or heat flow) drill holes are typically less than 500 meters (m) deep and have a relatively 'slim' diameter [up to 6 inches (in), or 15 centimeters (cm)] as compared to production wells. Such slim holes may be drilled with relatively small drill rigs, commonly truck mounted, as are typically used throughout the world for mineral exploration or groundwater drilling. The use of a truck mounted drill rig for temperature gradient drilling is important from a cost perspective.

Being able to mobilize small, locally available drill rigs may enable critically valuable subsurface data to be obtained at relatively low cost to justify moving to the review phase and continuing the project. If such rigs are not available locally, then high mobilization costs and time may significantly impact the rate of progress.

The primary objective of such drilling is to obtain temperature gradient information which will improve the confidence around temperature and depth predictions. Secondary objectives might be to ground-truth geophysical survey data or to obtain additional geochemical data. Slim-hole drilling may be especially useful to resolve ambiguities in the interpretations of geoscientific surveys, especially in areas where temperature data are missing due to the absence of sufficient exploration wells, e.g. from hydrocarbon exploration. Subsurface data gathered from the drilling will assist in developing a more robust conceptual model (see Section 2.4.1).

For temperature gradient drilling, at a minimum all temperature vs. depth data should be presented graphically, with a legend listing the dates that each profile (temperature log) was made. These data are most typically presented on separate charts for each hole. In all cases, the data should demonstrate that final, stabilized temperatures have been reached. If temperature alone was recorded, then the temperature gradient in the deeper part of each hole can be estimated and used to predict temperatures at depths beyond the maximum well depth. Best practice includes collecting thermal conductivity data for the intersected rocks. Such data allow the temperature logs to be translated into conductive heat flow logs to: delineate conductive zones from zones of convection; identify zones that are transferring heat through convection; quantify the conductive flux of thermal energy through the area; and allow more accurate extrapolation of temperature to greater depth (so long as the bottom of the hole is in a conductive zone).

Temperature data can be presented on maps at specific depths or elevations by contouring temperatures, temperature gradients, or heat flow values, and on cross sections that include the shallow geology and may show how temperature gradient and heat flow changes with depth (owing to the variation in the thermal conductivities or movement of heat through convection).

Each geophysical survey should be carried out soundly and the acquired data should be interpreted by an experienced operator with deep insight in the region's tectonics and geology.

The acquired and interpreted data should be summarized in a document setting out the survey parameters, analytical methods, results, and interpretations. A separate summary document might compile the salient data and results for all geophysical surveys.

Good outcomes of geophysical investigations include, but are not limited to; an indication of the temperature distribution both horizontally and vertically, improved knowledge of the geological structure and stratigraphy, and indications of fluid migration pathways and reservoir boundaries.

3.11 CONCEPTUAL MODEL

All exploration data should be integrated into a conceptual model of the geothermal system under investigation. This model must respect and be consistent with all known information. The model needs to be of sufficient detail to allow a first pass estimate of resource temperature and size and, in later stages of development, is used to target deep, full-diameter wells toward particular lithological units and/or structures that are judged most likely to deliver commercial rates of geothermal fluid.

A geo-referenced database is the most efficient way to integrate all of the geo-spatial data. This facilitates the development of maps at uniform scales (changing that scale as needed) and overlaying different data to investigate inter-relationships. If a GIS-based approach is not possible, then each data set should be presented at the same scale to facilitate a manual or visual overlay.

In addition, the subsurface dimensions of the conceptual model should be illustrated with cross sections and drawings. Cross sections should be created at the same scale as the maps, preferably with a 1:1 relationship between horizontal and vertical scales. Drawings may be free form (particularly if a concept is illustrated rather than data presented). All diagrams should include a preliminary estimate of the subsurface temperature distribution (estimated isotherms) and some indication of fluid flow directions, even if these are only approximate.

Existing well site(s) and proposed drilling target(s) can be presented on diagrams of the conceptual model, but should be accompanied by a narrative description of the rationale for selecting the proposed target(s). This rationale will naturally refer to the conceptual model, which forms the primary basis for well targeting. However non-geological factors might also affect decisions about particular well sites. For example, the number of sites that can be occupied by a large drilling rig may be limited by terrain or access restrictions, or certain areas may be off limits for environmental reasons. Deviated (directional) drilling may be preferred. Any non-geological rationale of this kind must be clearly discussed when presenting well sites and drilling targets.

A good conceptual model provides clear evidence that the developer has considered and integrated all available data. Nothing in the conceptual model should contradict data presented elsewhere, unless a clear rationale is provided. The conceptual model will demonstrate a justifiable understanding of the geology, temperature, and fluid pathways within the geothermal system. By utilizing the conceptual model, the developer can select drilling sites that maximize the chances for a successful well based on all current data. Figures 3.4 to 3.6 illustrate various types of conceptual models, including a conceptual map, cross-section, and 3D visualization, respectively.

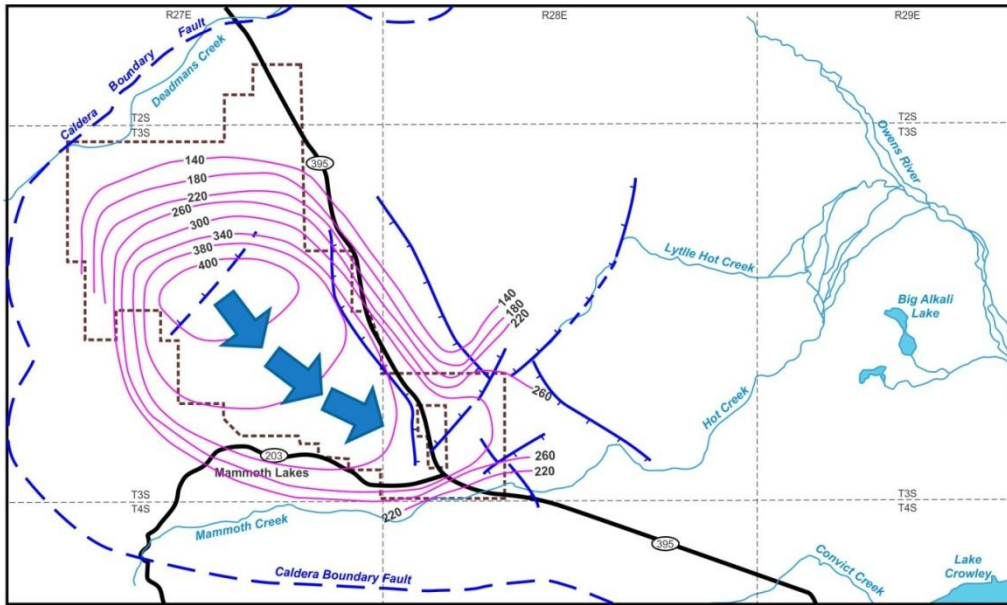


Figure 3.4: Example of a conceptual model map (GeothermEx, Inc.; redrawn by GNS Science, New Zealand).

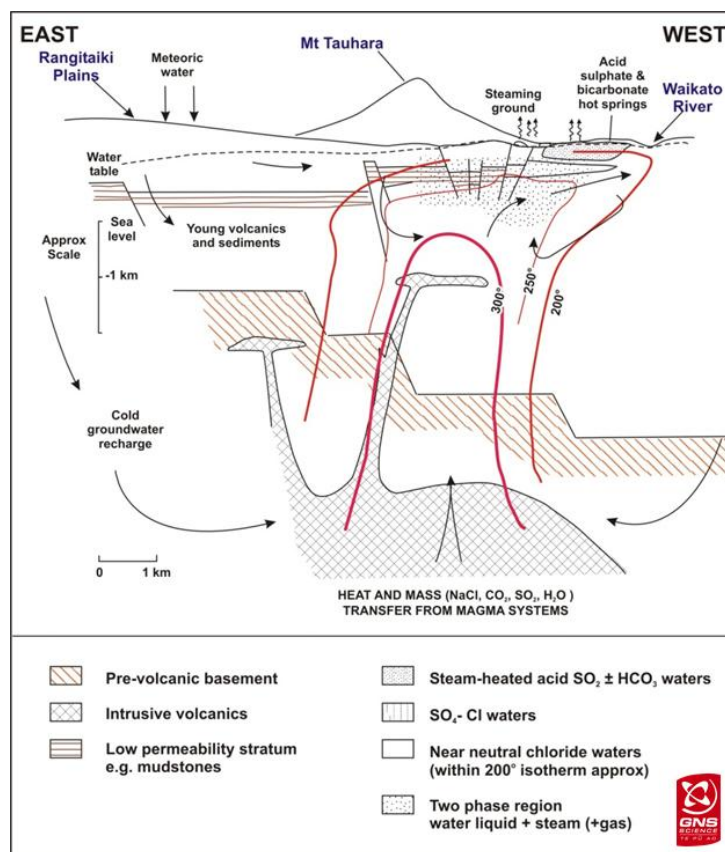


Figure 3.5: Example of a simple schematic cross-section through a geothermal system (GNS Science, New Zealand).

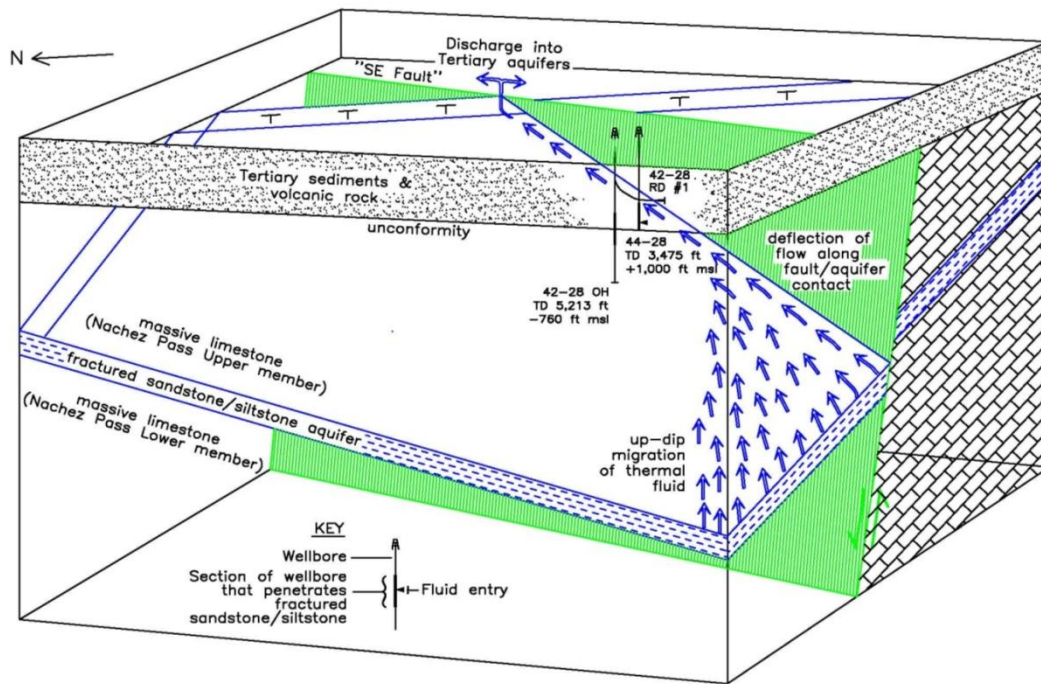


Figure 3.6: Example of a 3D conceptual block-model (GeothermEx, Inc.).

3.12 NUMERICAL MODELING

Once a suitable conceptual model has been constructed, it can form the basis of a numerical model. Numerical modeling is used to characterize in a quantitative way the physical processes at work within a geothermal system. These are primarily fluid and heat flow processes, controlled by temperature and/or pressure gradients and permeability pathways. A numerical model can test the validity of the conceptual model to explain the observed distribution of temperature and flow paths. It can then forecast the future performance of the reservoir under conditions of exploitation (production and injection). This is used to estimate the impact that geothermal exploitation will have on the resource, and hence possible degradation of the reservoir and power output.

The development and use of a numerical model involves a number of stages, from initial state modeling to history matching and then forecasts under a number of selected scenarios to predict the future behavior of the reservoir under various levels of production.

3.13 NON-TECHNICAL DATA COMPILATION

Following development of a conceptual and numerical model, the developer will have a preliminary assessment of the reservoir capacity and will be at a decision point – whether or not to proceed with the project. This is the time to update or confirm current information important to project success. This may be particularly relevant if prices, costs, public attitudes, and/or institutional frameworks may have changed over the time interval since these topics were first studied, including:

- the power market and possible PPA's;
- infrastructure issues (roads, water, communication, transmission);
- resource ownership issues;
- environmental and social issues;
- institutional and regulatory frameworks; and
- issues relating to political and financial stability.

All these topics should be discussed in a comprehensive document in which any potential barriers to development are identified and resolved.

3.14 FINANCIAL JUSTIFICATION TO PROCEED TO PHASE 4 (TEST DRILLING)

The aim of all preceding steps in the feasibility study is to evaluate the resource for the viability of power production, mitigate financial risk associated with development, and build a business case for funding support from private, public, or institutional bodies to proceed with the project. The data assembled from the technical and non-technical studies and surveys are brought together and incorporated into a financial model to predict returns on investment and to justify the next phase—the high expense of deep drilling.

4.0 RISK

4.1 INTRODUCTION

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 be observed or characterized without relatively large expenditures for drilling. The long time period typically required to move a project from preliminary exploration through to development is another factor to consider. Historically, many large (50 MWe or larger) geothermal projects have taken close to 10 years to develop. This is a long time to 'tie up' capital for an investment with modest profit potential, with the added disincentive of high resource risk in the early phases of the project.

Many of the risks in geothermal projects are identical to those faced for any grid-connected power project. But additional factors, as discussed below, impact investors' willingness to accept the level of risk associated with geothermal projects and hence the availability of project funding.

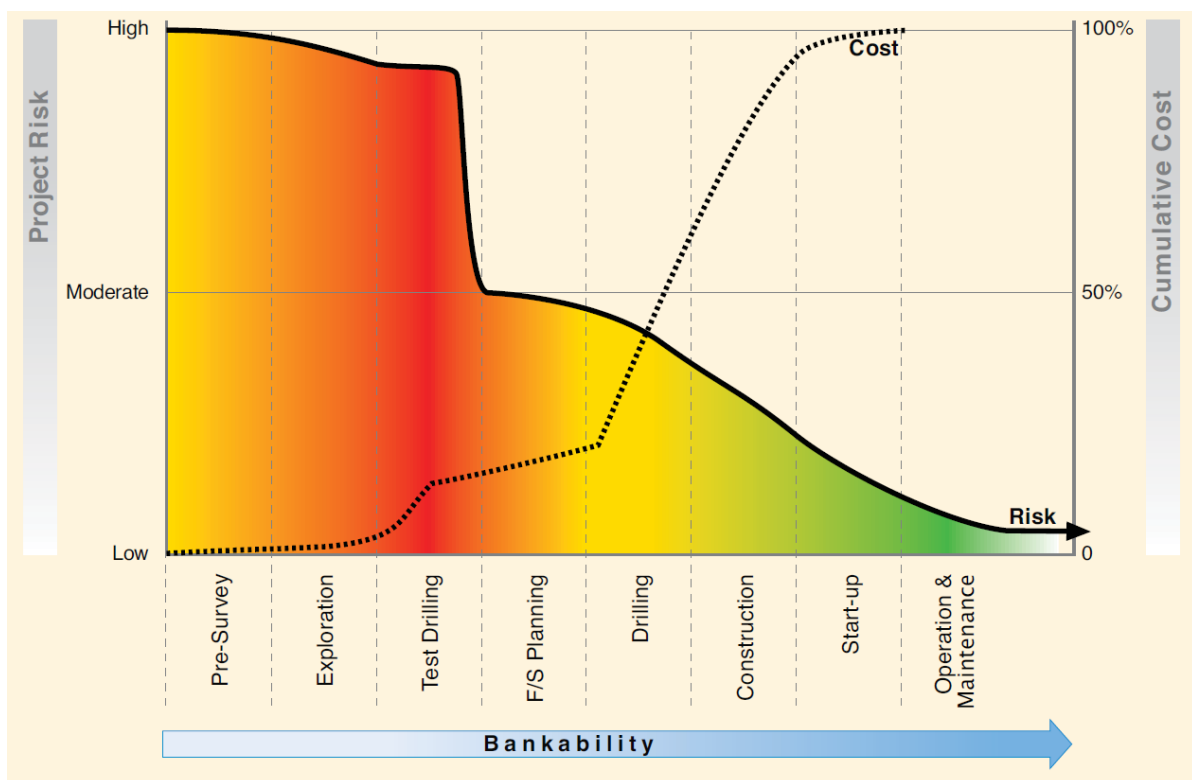


Figure 4.1: Typical risk profile for a geothermal project vs. time (ESMAP World Bank Geothermal Handbook 2012).

As can be seen from Figure 4.1, the risk profile is greatest during the Preliminary Surveying and Exploration Phases, but in that part of the project the expenditures are relatively low. Moving forward to the test drilling phase requires an accelerated level of expenditure while there is still a high level of uncertainty (i.e. risk). This step in expenditure is frequently the stumbling block or hurdle to the project progressing further.

Numerous aid agencies and governments around the world have recognized this step as a barrier to development. Risk mitigation funds have been established in some jurisdictions to assist projects through this phase.

Funding is only committed to the test drilling phase of project development if the financier believes there is a reasonable probability of making an adequate financial 'return on investment' (ROI). The expected ROI is usually expressed in terms of a percentage of the committed capital per annum. Risk mitigation funds improve the predicted ROI by either reducing the amount of capital invested by the financier (i.e., a grant scheme). However, maximum ROI is only achieved if wells produce at or above their predicted outputs, and this result relies on high quality exploration methods and interpretation.

4.2 EXPLORATION RISK

The quality of exploration work prior to drilling is a critical factor for maximizing the probability of achieving the required ROI for a financier. Geothermal exploration essentially involves the application of a number of geological, geochemical, and geophysical techniques. The aim is to apply the most appropriate techniques to minimize risk associated with ascertaining resource temperature, depth, productivity, and sustainability in the specific circumstances of each project. Selecting appropriate techniques at the correct phases of an exploration program is important for optimal efficiency. Experienced interpretation of data collected with these geoscience techniques enables a geothermal geoscience team to develop an initial conceptual model of the geothermal system. No single exploration technique provides the key to a successful conceptual model, and ultimately no conceptual model can be confirmed except by temperature gradient and test drilling.

The best possible exploration risk mitigation is achieved through the correct sequential selection of a combination of various techniques followed by experienced interpretation, as discussed in Sections 2 Section 3, and Appendix A1.

4.3 TEST DRILLING RISK

The objective of test drilling is to confirm the viability (i.e., quality) of the resource, and therefore, of the conceptual model that has been developed during the preceding phases of exploration. Key variables that test drilling aims to confirm include temperature, permeability, flow potential and fluid chemistry, as well as the location, areal extent and depth of the resource.

There are significant risks associated with drilling activities. These risks are a function of the drilling conditions, which range from logistical (e.g., location of the drill pad and timely availability of equipment and services) to technical (e.g., borehole rock type that must be drilled through to reach the reservoir, borehole competency and pressure conditions during drilling, and the experience and expertise of both the developer and the drilling contractor). Intended drilling depth and the length of inclined or deviated wells are key parameters in determining the cost of a drilling program. If target depths are shallow, then it may be possible to obtain information sufficient to prove the resource using a relatively small, truck mounted drill rig. If the target is deep then a larger drilling rig will be needed as will better roads and support services; therefore, the levels of expenditure will be higher.

The number of test wells will vary from project to project, with a minimum of two to three wells typical for both resource confirmation and financing purposes. It is uncommon but possible that one well may be sufficiently successful to enable the project to move to the Project Review Phase. Conversely, a project may require more than three wells (to confirm the extent of the resource) to justify moving to Project Review.

Developers should outline the drilling program with illustrations such as a decision-logic diagram displaying the probabilities, to support choices of alternatives based on results obtained during the drilling and testing of each well.

4.4 RESOURCE SUSTAINABILITY

Geothermal power plants are built as long-term infrastructure, typically with design lives of 30 years or more. The geothermal resource must provide geothermal fluid consistently and reliably to the plant during this timeframe. Resource degradation risks, especially in two phase systems, during this period include:

- higher-than-anticipated declines in production rates;
- premature cooling (either from injection water breakthrough or from incursion of cool groundwater); and
- adverse chemical effects such as increases in non-condensable (NCG) gas levels, or changes in reservoir conditions leading to scaling, etc.).

Because of declines in well productivity, it is common that “make-up” wells will be needed over the lifespan of a geothermal power project to maintain generation rates at or near pre-decline levels. The cost of drilling make-up wells should be included in the project financial model.

Degradation risks can occur at various times during the exploitation history, but early indications can typically be detected during exploration or the first few years of production. Implementation of a proper reservoir monitoring program, combined with a properly calibrated numerical model, is essential tools for understanding and avoiding or remedying resource degradation.

5.0

FINANCING GEOTHERMAL PROJECTS

5.1 INTRODUCTION

Chapters 1 and 2 described the various phases involved in geothermal projects. Chapter 3 proposed minimum levels of reporting requirements. Chapter 4 outlined the different elements of risk at the various phases of geothermal development. This chapter presents a range of alternatives funding strategies for geothermal development, which are largely drawn from ESMAP's Geothermal Handbook (2012), where more information is available.

Many governments and international funding agencies now offer some level of financial support or risk mitigation funding to encourage geothermal development. Countries differ in their financial regulations and laws, however, so the proportions of public versus private financing that may be appropriate for one country may not be relevant for another. The requirements for financing in developing countries may be very different to those in developed countries. A range of financial models that have been successfully applied in different countries is discussed in Section 5.3.

Historically, governments have undertaken the earliest phases of geothermal surveying and exploration in those countries that now have established geothermal industries. These governments saw the benefits of geothermal as a valuable indigenous energy source. Major developments therefore took place in developed countries that were sufficiently well governed and funded to commit public funds and manpower to the high-risk early phases of geothermal projects. Examples include New Zealand, Japan, Mexico, Iceland, and Italy.

Example: There are 2 models for the geothermal power plant investments in Turkey:

Model 1: The geothermal fields and well(s) Licenses are leased (US\$6.5 Million – US\$109 Million) from MTA (General Directorate of Mineral Research and Exploration) for 30 years (+10 years). Considerable geological, hydrogeological, geochemical, and geophysical studies have been done by MTA with up to four wells drilled by MTA in individual fields. The Turkish private sector developer leases these geothermal fields and wells and develops the fields, drilling additional wells where and when appropriate to guarantee a return on the investment. In this model there is no investment cooperation between the Government and the private sector.

Model 2: The Turkish private sector can apply to the local governments for a geothermal field exploration license (3 years + 1 year). On receiving the exploration license, geological, hydrogeological, geochemical, and geophysical studies and well drilling have to be carried out by the private sector. Once the geothermal field is proven, the private sector starts the development with the terms of the power plant operating license being for 30 years + 10 years. In this model the total risk belongs to the private sector. Several geothermal plants in Turkey have been developed under this mode. Also in this model, there is no investment cooperation between Government and the private sector.

The rules of EMRA (T.R. Energy Market Regulation Authority), stipulate that after receiving the license until commissioning, there is maximum period of 60 months. This duration could be extended under some conditions, but the Turkish private sector has shortened this duration to about 30 months. During this time period, field development, well drilling, plant procurement, plant construction, and commissioning must occur. The Turkish private sector is fast and successful in this regard.

There are two ways to sell the geothermal electricity produced in Turkey. The developer can sell the power on the open market or, the developer may benefit from the government incentives which apply to renewable energies in Turkey. In such a case, the price is fixed. While under the open market the price is floating.

In developing countries which may lack the required financial and skilled human resources, a combination of public and private funding may be required along with significant support from both national and international funding agencies (includes bilateral and multilateral funding and climate investment funds). This support and funding may come through grants, loans or risk mitigation strategies (Section 5.4). Development in the Philippines, Indonesia, and Kenya are examples where such partnerships have been successful.

In many countries, the financing of early surveying and exploration may be best achieved through private sector or equity partnerships). Through these partnerships, risk can be spread and shared across a number of partners or agencies. Once a field has been sufficiently proven (i.e., 'de-risked') and is under development, project and construction financing comes into play.

The World Bank's ESMAP 'Geothermal Handbook: Planning and Financing Power Generation' (2012) provides a useful overview of the various models and sources for geothermal financing. Table 5.1, which is modified from the Handbook, is a useful summary of financing options that may be appropriate.

Table 5.1 – Summary of funding options for the various stages of geothermal projects.

EARLY STAGE	MIDDLE STAGE	DEVELOPMENT (LATE) STAGE
Preliminary surveying, exploration and exploration drilling	Resource Confirmation, production + reinjection drilling and feasibility studies	Power Plant engineering and purchase, construction and commissioning
High Risk	Medium Risk	Low Risk
Balance sheet financing by developer	Balance sheet financing by developer	Construction debt or long term debt from commercial agencies
Private equity but high premiums due to high risk	Public equity issuance or loan guarantees by Government	Long term debt from International Funding Institutions
Government incentives (various options)	Long term debt or guarantees by international funding agencies	Partial risk guarantee instruments from commercial agencies
Concessional funds (international donors)	Export credit agency finance	Export credit agency finance

During the funding acquisition process, a developer must synthesize the results of exploratory efforts within a document or series of documents to support their application for funding from a government or funding agency. The information and data provided should be effectively communicated along with the interpretation of the data and a clear indication of data gaps in the conceptual model. Well prepared funding applications are essential for the government or funding agencies to evaluate the potential of the project. To assist the developer with preparing a funding application, this document contains:

- a data checklist for geothermal well productivity insurance applications (Appendix A3); and
- an example table of contents for a resource report (Appendix A4).

These resources should be used as guidelines when preparing applications for funding.

5.2 PRIVATE SECTOR FUNDING

Private sector financing at the Exploration Phase typically requires a high premium (ROI) to offset the exploration risks. Due to the high risks associated with geothermal drilling, debt financing is not commercially available for exploration activities. Therefore, equity investors are the primary source of private funding for geothermal exploration, beyond government subsidies. Private equity investors are likely to require relatively high rates of return on their invested capital. A required return on equity of 20 to 30 percent per year is not unusual.

Equity investors may bring more than just money to the project. Under a Joint Venture or Equity Partnership, a second firm may invest money and/or expertise in exploration and early-stage drilling in exchange for a certain level of equity in the project. An equity partnership can spread risk, as well as create a broader financial base to fund exploration of the geothermal resource. This can also provide an opportunity to leverage experience from different groups. For example, a financial group could collaborate with an exploration group with each partner bringing a particular expertise to the project. This type of equity partnership can potentially lower costs if it reduces the need for external auditors or consultants. Later in a geothermal project, equity partnerships are less attractive financing options as the costs are high relative to other financing options, due to the higher returns required.

5.3 PUBLIC SECTOR FUNDING

Due to the high risks and costs associated with geothermal exploration, it is often difficult to attract sufficient funds from private sector equity investors. Therefore, the public sector usually plays an important role in financing exploration. This can take various forms, from exploration being entirely carried out by public institutions to grant subsidies.

5.4 POSSIBLE SOURCES OF FUNDING SUPPORT TO REDUCE RISK

At the completion of the Exploration Phase of the project, resource risk remains relatively high. It is at this stage that funding support from governments or international agencies may provide the greatest value. Without such support, it may be very difficult (or costly) to obtain funding elsewhere. Government funding may encourage co-investment from private or institutional funding agencies. Risk sharing agreements between the public and private sectors can facilitate the funding of the test drilling phase by both sharing costs and limiting the financial losses that may be incurred if the resources are found to be inadequate for the target market. Spreading risk over a portfolio of projects is another strategy for minimizing financial risk.

5.5 SUCCESSFUL BUSINESS MODELS

There are a number of possible business models for financing the sequence of phases for geothermal projects. The different models vary in the proportions of contributions from the public and private sectors at each phase. Some countries have favored funding early phases entirely from public funds. Examples include Kenya, Ethiopia, and Costa Rica. The maturity of the geothermal sector in other countries has allowed those countries to transition to entirely privately funded developments.

For the majority of developments, however, the most common practice is to have a significant component of public funding for the early exploration activities and then to involve private sector funding, or public-private-partnerships, once the exploration and test drilling has been completed successfully. In some countries, the mix of public and private participation may change with changes in the political climate, maturity of the geothermal sector, or other factors. For example, in Kenya the current move is towards more private sector involvement.

Figures 5.1 and 5.2, taken from the ESMAP Geothermal Handbook (2012), summarize the range of public versus private funding models applied to geothermal projects over many years worldwide.

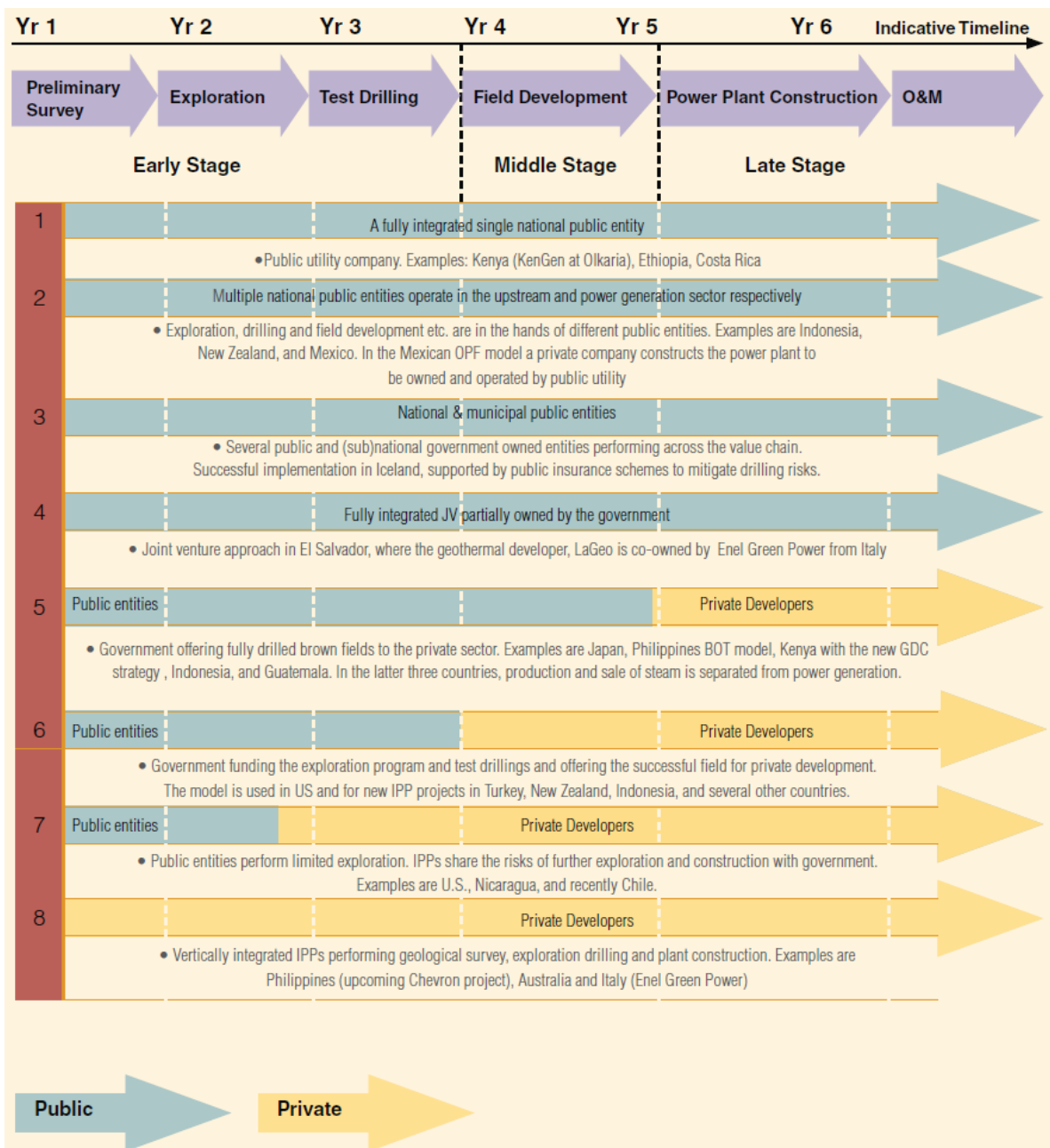


Figure 5.1: The range of business models previously used in successful international geothermal developments (Extracted from the ESMAP Geothermal Handbook 2012).

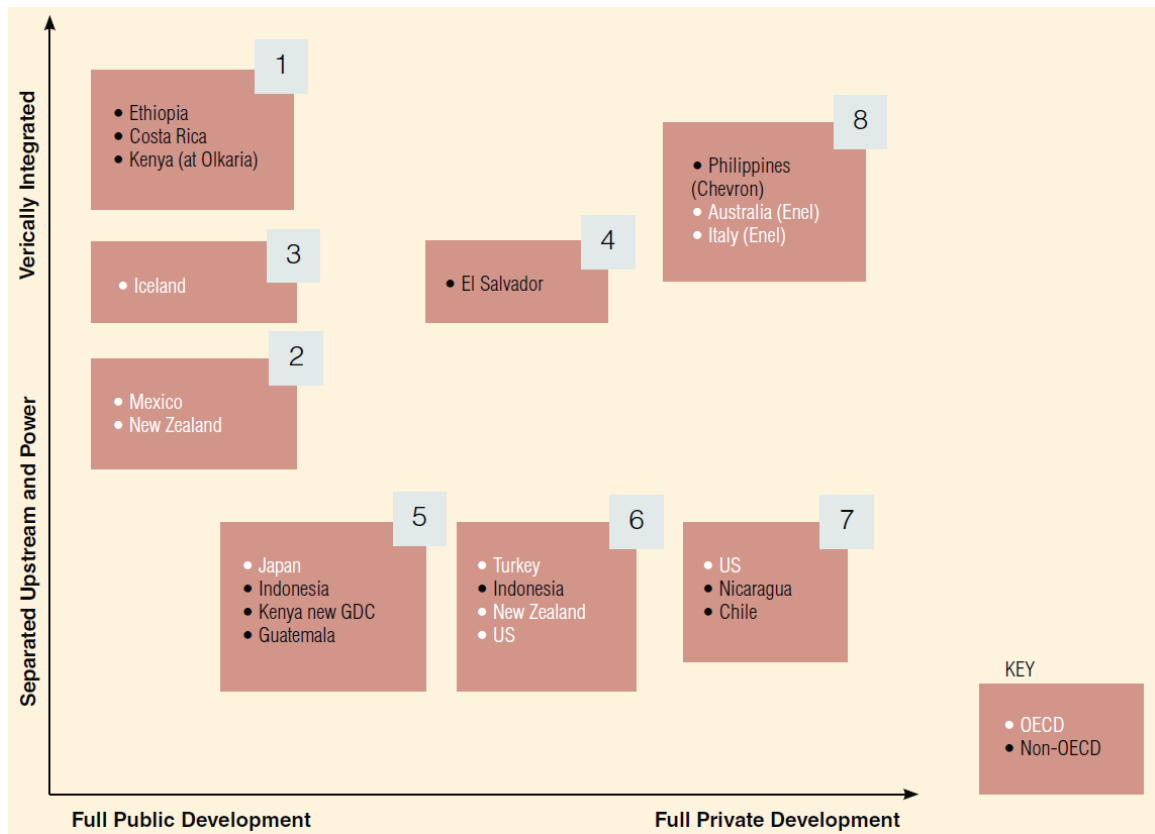


Figure 5.2: Presents information on public/private partnerships, with the model numbers defined in Figure 5.1 shown in pale blue (Extracted from the ESMAP Geothermal Handbook, 2012).

APPENDIX A1: DETAILS OF PROJECT STAGES

A1.1 INTRODUCTION

Throughout the course of a geothermal development project, data are collected and applied to expand the current understanding of the field. Different geothermal fields evolve differently; therefore there is no single way to move through each development phase. This appendix is intended as a guide to the types of data typically collected at each phase. It is not a rigid prescription.

A1.2 PHASES OF GEOTHERMAL DEVELOPMENT

Each geothermal project is different, and the exact steps to be taken at any stage in a given project are dependent on specific conditions. However, geothermal projects generally go through the same overall process of exploration, development, and operation, and pass through the following seven phases:

- Preliminary survey;
- Exploration;
- Test drilling;
- Project review and planning;
- Field development;
- Power plant construction; and
- Commissioning and operation.

Each of these phases is described herein, including what data are typically collected in each phase.

A1.3 PHASE 1 – PRELIMINARY SURVEY

During this phase, data are collected to begin the process of defining the resource.

A1.3.1 Literature Search

The first step is the literature search and review. This helps focus the target for specific data collection. For example, if a base geologic map is found in the literature search, the next step would be to perform detailed mapping of the geology in the target area. It is key at this phase to determine all the known information regarding the field to avoid duplicating analyses and to plan exploration to fill data gaps in what is known about the resource. Data gathered in this phase typically includes:

A) MAPS

- a) Topographic map(s) showing geothermal license area(s)
- b) Map(s) showing areas licensed to others around subject license area(s)
- c) Map(s) of easements or other rights of use
- d) Map(s) of land use restrictions
- e) Other maps

B) RESOURCE DATA FROM AVAILABLE LITERATURE

- 1) Active Geothermal Features

- 2) Geological Data
- 3) Geochemical Data
- 4) Geophysical Data
- 5) Subsurface Temperature Data from existing wells

A1.3.2 Non-Resource Data Collection

It is also necessary during this phase to consider the non-resource aspects of the field. The geothermal project area should be clearly identified and it is necessary to verify that the developer has the legal right to carry out exploration activities in that area. Issues related to access to the project area and land use restrictions should be identified, investigated, and discussed.

A developer will need to demonstrate legal access to the resource, typically in the form of a geothermal exploration license obtained at the national or provincial level. Licenses establish the developer's legal right to conduct exploration activities in and around the project area, and should be presented when requested. The coordinates of the license boundaries should be provided for verification, along with maps showing the boundaries of the license areas. In addition, topographic maps of the area, with the geothermal license areas belonging to the project developer clearly marked, should be provided. Ideally, these maps would also show areas in the vicinity that are licensed to other developers, particularly for lands immediately adjacent to the applicant's license(s).

Access issues for the project area should be investigated. Are there any access restrictions, such as certain roads or properties that cannot be crossed or which have limited access, or is access unrestricted? In addition, are there any land use restrictions on the project area? These might consist of environmental restrictions, such as the presence of a nearby park or protected area, as well as prior use restrictions such as the presence of residences or agriculture in the project area. It should be clear from the surveying which areas (if any) are 'off limits' for development, either because of access or other restrictions.

Documents and maps detailing easements or other rights of use should be provided, as well as documents and maps detailing any land-use restrictions in the area. These restrictions may arise owing to prior use of the land, environmental or cultural reasons.

Information should also be provided about the selected drilling company, including its equipment and experience in similar projects. Information may be needed about the project company, including ownership, management, financial structures, the experience of personnel with respect to similar projects, or other commercial issues relevant to the project.

A1.4 PHASE 2 – EXPLORATION SURVEY

At the beginning of the Exploration Phase, it is most common to do broad-scale analyses to identify the big picture of the resource before going in to more detail in areas showing the most promise.

A1.4.1 Regional Resource Exploration

During the early stages of exploration, data are collected to begin the process of defining the resource. The work undertaken in this phase includes geological data collection and analysis, geochemical data collection and analysis, and geophysical surveys. For some areas a lot of relevant data may already exist. If this is the case, then many of the surveying tasks will be to resample or verify the quality of the earlier work.

A1.4.2 Localized Resource Evaluation

At the end of the regional exploration stage, the available exploration data are evaluated to determine whether the presence of a commercial resource is indicated or not. If the data are encouraging, the project moves into a localized exploration stage, during which the exploration becomes focused on the most favorable resource areas. By the end of the Exploration Phase, sufficient exploration data have been collected and analyzed to enable the selection of sites and targets for the first few deep exploration wells. A preliminary estimate of the magnitude of the resource (expressed in terms of the potentially recoverable heat in place) is also made during this phase.

The same type of data collected during regional exploration may be collected during localized exploration. The difference between the two stages is the level of detail of the data analyses—regional exploration is done at a broad scale, localized is more focused. Temperature gradient drilling may also be undertaken at this stage. The significant costs required for temperature gradient drilling usually means this is one of the last activities conducted during the Exploration Phase, and the decision to do so is based on a pre-feasibility report that gathers all other resource data to assess the likelihood of finding a viable geothermal resource. A preliminary conceptual model will be developed for this pre-feasibility report, and will be updated based on data gathered from drilling activities. By the end of the localized surveying, the following data and information may be collected:

A) RESOURCE DATA

1) Active Geothermal Features

- a) Location (Lat/Long or UTM)
- b) Temperature (°C)
- c) EC ($\mu\text{S}/\text{cm}$)
- d) pH
- e) Flow rate (l/s or kg/sec)
- f) Presence of gas bubbles and their compositions
- g) Presence of odors (sulfur or other odors)
- h) Presence of precipitates in the fluids
- i) Detailed local map(s) of area(s) with thermal features clearly labeled

2) Geological Data

- a) Geologic map(s) of license area(s)
- b) Geologic cross sections from license area(s)
- c) Summary descriptions of stratigraphy and lithology with stratigraphic columns
- d) Summary descriptions of regional and local structure with accompanying maps
- e) Identification and characterization of potential reservoir unit(s)
- f) Presence of mineralization associated with hydrothermal systems

3) Geochemical Data

- a) Location, name, and characteristics of sampling points
- b) Temperature (°C), pH, EC ($\mu\text{S}/\text{cm}$), and flow rate (approximate) at time of sampling
- c) Sample preservation method(s) used
- d) Chemical analyses of collected samples
- e) Name of laboratory that provided analysis

- f) Calcite inhibition treatment information (if sample is from producing well)
 - g) Names, descriptions and locations of scale or mineral deposits
 - h) Geothermometry estimates
 - i) Interpretations and/or plots of geochemical data
 - j) Reference data of neighboring wells and projects (if available)
- 4) Geophysical Data
- a) Gravity surveys
 - b) Electrical resistivity (MT)
 - c) Seismic surveys (2D and 3D)
 - d) Heat flow/temperature gradient surveys
 - e) Geomagnetic surveys
 - f) Other surveys
- 5) Subsurface Temperature Data
- a) Raw temperature from logs
 - b) Flowing temperature from hot springs or wells
 - c) Maps of temperature contours at various depths
 - d) Cross sections showing temperature distribution
- 6) Conceptual Model that incorporates all of the above

A1.4.3 Conceptual model

The first step in creating a conceptual model is to integrate all the various data sets gathered during the Preliminary Survey and Exploration Phases, including those found in the literature and newly generated data collected by the developer (i.e., the inventory of active geothermal features, geology, geochemistry, and geophysics). If any data is deliberately excluded, it should be clearly explained why that data was considered to be incorrect, insufficient, or irrelevant. Specific descriptions of necessary data are presented below.

Through this process of data integration, the developer aims to understand and explain the three-dimensional composition of the project area, including its geologic structure, stratigraphy, geophysical properties, locations of thermal features, and geochemical characteristics. The model derived from this data locates the heat source and the possible sources of geothermal fluids, and the nature of the pathways that allow those fluids to move through the system, from the source, through the reservoir, and to the point of discharge. On the basis of this understanding of fluid flow, the conceptual model is used to target wells toward specific subsurface lithologic units and/or structures.

A robust conceptual model of the resource answers the following critical questions, which determine the feasibility of the project and targets locations and depths for full-bore well drilling.

- Is the resource temperature sufficient for power generation?
- What is the subsurface temperature distribution, and how is it affected by fluid flow?
- Are there rock units present at depth with good porosity and permeability? If so, what are they, and what is their orientation and extent?
- What is the likely relationship between the geology and the geothermal features?

- Do the geothermal manifestations appear to be related to one another, suggesting a common source?
- Are the fluids rising along faults?
- If so, is this a shallow phenomenon, or does fault-hosted flow persist to depth?
- Are the fluids flowing within particular stratigraphic units?
- Can these factors be evaluated holistically to identify the probable deep source of thermal fluid?
- Where are the best places and targets to drill, and why?

Presentation of the conceptual model is described in Section 3. Figure A1.1 shows how all the data collected are integrated into the conceptual model, and how the model is constantly refined as more data are acquired.

One important use of the conceptual model, particularly at the early stages of a project, is to estimate the heat resource. This typically involves a volumetric calculation of the heat-in-place in the project area based on a combination of:

- known and assumed temperature distributions;
- estimates of the depth, thickness and porosity of possible reservoir rocks;
- reasonable assumptions about how much of the heat-in-place may be recovered at the wellhead; and
- reasonable assumptions about converting heat to electricity, based on the performance of modern geothermal power plants.

While the presence of a suitably large heat resource does not guarantee the viability of a project, which can only be demonstrated through the drilling, logging and testing of wells, it is a pre-requisite for nearly all geothermal projects.

A1.4.4 Numerical Model

Numerical modeling is undertaken in three phases:

1. initial state modeling;
2. history matching; and
3. forecasting of future reservoir behavior.

Initial State Modeling

The initial state model describes the reservoir in the pre-exploration or natural state. An initial state model is created because geothermal systems evolve over geologic time, with the thermodynamic and hydrodynamic conditions in the system attaining a dynamic equilibrium. The rate of change in the natural system is very small relative to the changes induced by exploitation. Hence, for all practical purposes, undeveloped geothermal systems are considered to be in a quasi-steady state. Modeling of the natural or initial state of the reservoir has the following objectives:

- Verification that the permeability distribution used in the model is reasonable, both within and outside the areas of the model where measured data are available;
- Verification that assumptions regarding the location and strengths of heat and mass inflows and outflows are reasonable, both conceptually and mathematically; and
- Formation of a stable starting point for use in matching available production/injection data and for considering future development scenarios.

The initial-state model is based on a conceptual model of the geothermal system, which is derived from geological, hydrological, geophysical, geochemical, and reservoir engineering data. The most important set of data used in the initial-state simulation is the subsurface temperature distribution. Correct interpretation of the temperature data can not only provide significant insight into how the geothermal fluid is moving through the system, but can also help define the permeability distribution and boundary conditions. The initial state modeling process is illustrated in Figure A1.2 below.

History Matching

As shown in Figure A1.3, history matching is based either on well testing or actual well field operation. Early in the project, before start-up, it is common to test multiple wells simultaneously to understand how the reservoir will behave during routine production. Several production and injection wells are used during such tests, and pressures are monitored in the field. Such data provide an important means of further calibrating a numerical reservoir model. Routine production and injection data can be similarly used, once the field is fully operational. The calibration of the numerical model is improved in that a second data set—how the resource responds to production—becomes available for matching by the numerical model.

Periodically thereafter, the numerical model will continue to be improved as more data become available. Such a model is a critical resource management tool that becomes more accurate over time, improving predictions of field performance and long-term field viability

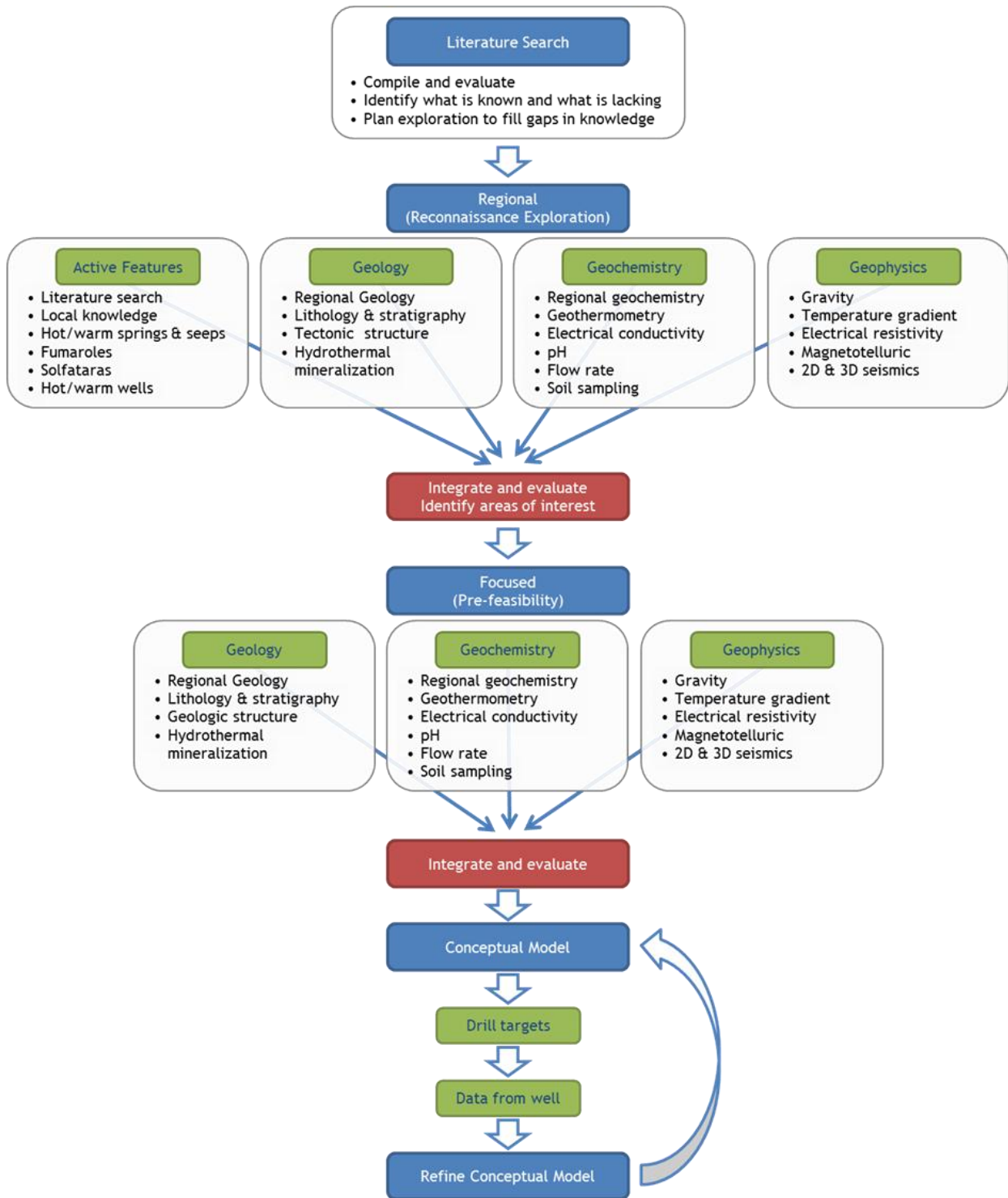


Figure A1.1: Flow chart showing project stages with typical data acquired and integrated into the conceptual model (GeothermEx, Inc).

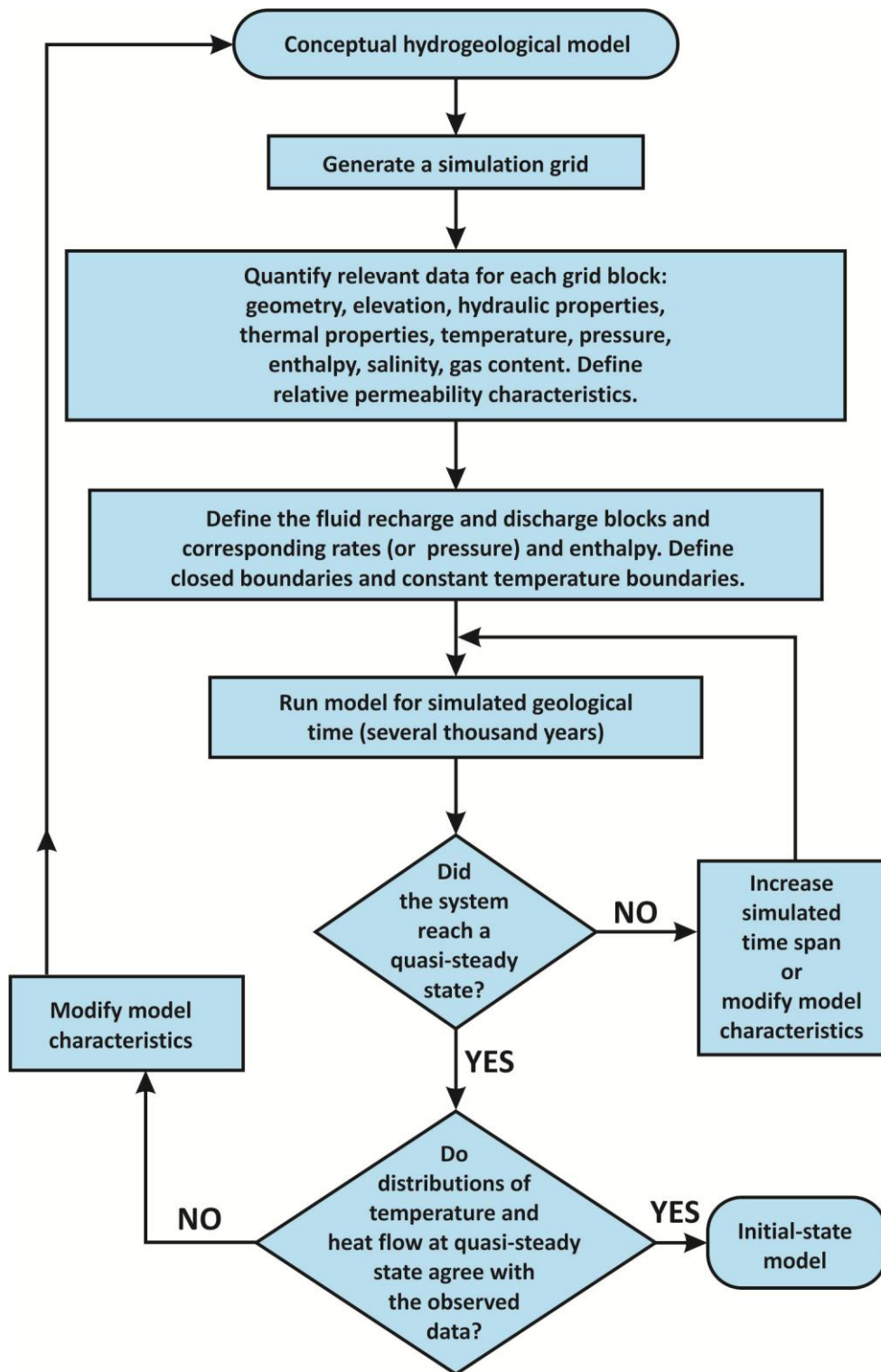


Figure A1.2 : Flow chart of the initial-state modeling process (GeothermEx, Inc.).

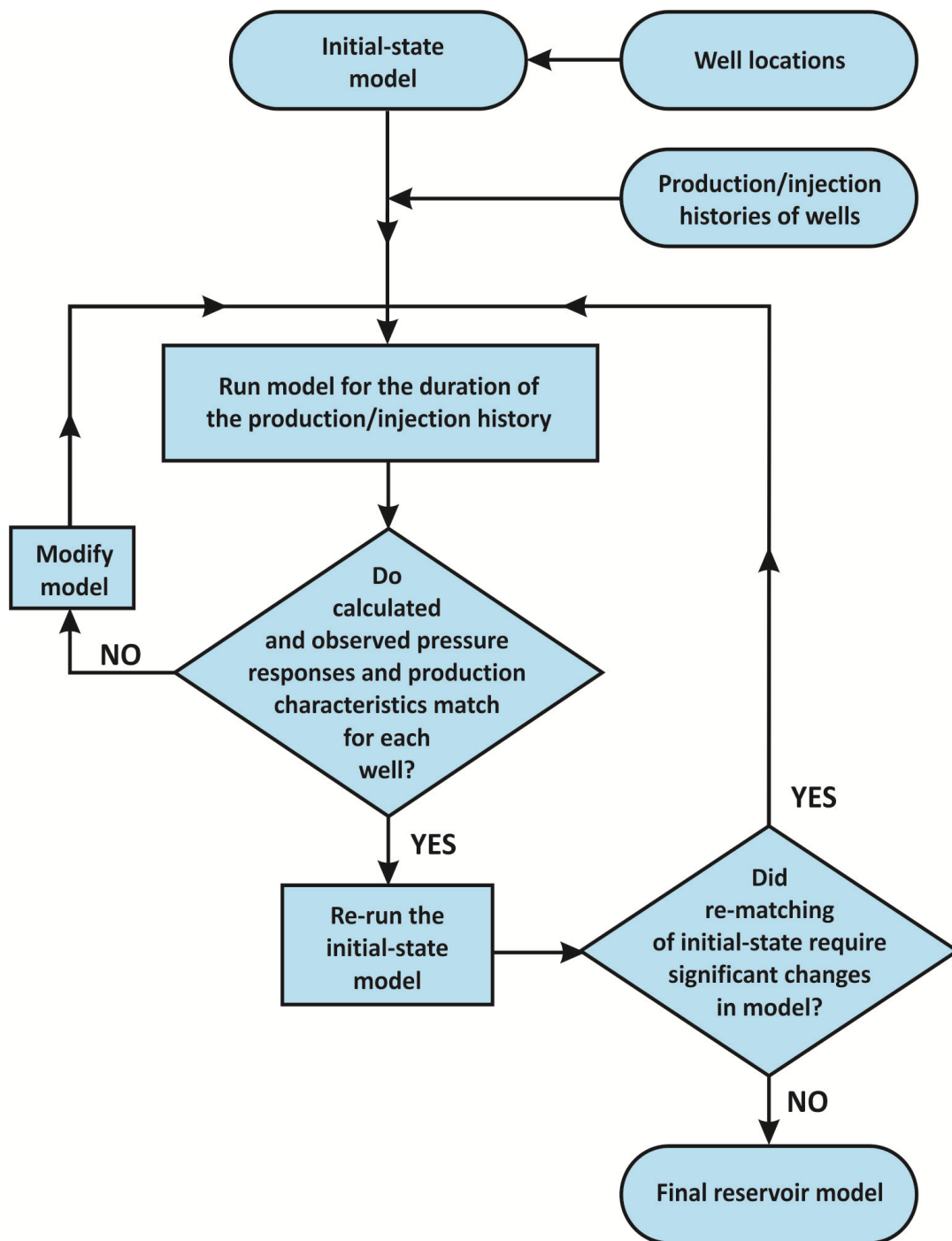


Figure A1.3 : Flow chart of the history matching process (GeothermEx, Inc.).

A1.5 PHASE 3 – TEST WELL DRILLING

Moving forward from the pre-feasibility report requires drilling of the first full-diameter exploratory wells. Typically, at least two deep wells are drilled to demonstrate the feasibility of commercial production and injection, and sometimes more, depending on the size of the project to be developed and the success in finding a viable geothermal resource with the first series of wells (i.e. the drilling success rate). In areas where a significant amount of data from previous wells is available, there could be no need for test wells. Drilling, logging and testing significantly improve the understanding of the resource, enabling:

- refinement of the estimate of the heat resource;

- determination of the average well productivity (thus laying out the scope of future drilling);
- selection of the well sites and targets for the remaining production and injection wells; and
- development of a preliminary design for the power plant and gathering system.

A1.6 PHASE 4 – PROJECT REVIEW AND PLANNING

Once the resource has been discovered and confirmed by the first few deep wells, the project risks are substantially reduced and a more accurate feasibility report can be prepared.

The resource information permits the developer to size the planned development and secure PPA's on which financial models can be built. Such models, including risk analysis enables the developer to obtain the require finance to move the project through to development.

The feasibility report is designed to develop confidence in the viability of the project, facilitating project financing. The types of data collected and the recommended method for presenting this data are outlined in Appendix A2. The feasibility report includes the following elements:

- location and design of drilling pads and other civil works (roads, preparation of power plant site, etc.);
- design of development wells;
- specification of drilling targets;
- the power plant design;
- the transmission access plan;
- construction budgets for all of the above;
- the terms of the power sales agreement; and
- budget and revenue projections.

The feasibility report is designed to develop confidence in the viability of the project, facilitating project financing.

A1.7 PHASE 5 – FIELD DEVELOPMENT

Following the Project Review Phase is the Field Development Phase, which continues with the drilling and testing of the production and injection wells required to initially supply the plant (with some excess capacity).

Data and information gathered or provided to project partners during this Phase in the project may include:

A) INFORMATION ABOUT DRILLING RIGS AND DRILLING SUPERVISION

- 1) Detailed specifications of drilling rigs used or planned
- 2) Drilling company's experience and track record of geothermal wells
- 3) Drilling programs for wells already drilled and those to be drilled
- 4) List and qualifications for sub-contractors for specialized services
- 5) CVs of drilling managers and their senior support staff
- 6) Information regarding geothermal experience of drilling crew

B) RESULTS OF DRILLING, LOGGING AND TESTING

- 1) Drilling records, times, and costs

- 2) Resource data analysis
- 3) Integration of resource data into the updated conceptual model
- 4) Possible measures for the improvement of thermal output and stimulation of the well(s)

C) INFORMATION ON COMMERCIAL ASPECTS OF THE PROJECT

- 1) Plan for electricity sales and retail or wholesale distribution
- 2) Description of project structure
- 3) Forward-looking financial projections including contingencies for miscellaneous costs during drilling and possible costs for improvement / stimulation
- 4) Description and value of the assets or equipment to be insured

D) INFORMATION ABOUT THE PROJECT DEVELOPER'S COMPANY

- 1) Basic company information (type, structure, ownership, finances, related companies, etc.)
- 2) Experience of senior management with drilling and natural resource development
- 3) Organization and management structure
- 4) Professional technical staff and their experience
- 5) Number and type of support staff

A1.8 PHASE 6 – POWER PLANT CONSTRUCTION

In this period the civil works required for steam collection system and power station are completed. The final design, procuring and constructing of the power plant and transmission lines are undertaken during this phase. Well testing may also continue at this time.

A1.9 PHASE 7 – COMMISSIONING AND OPERATION

Upon completion of construction, the Commissioning and Operation Phase begins. Since the fuel supply for the project has already been developed (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 and ensure the reliable delivery of geothermal power.

APPENDIX A2: GEOTHERMAL RESOURCE DATA COLLECTION

A2.1 ACTIVE GEOTHERMAL FEATURES

For each active geothermal feature, the following parameters should be carefully measured and recorded:

- Location in UTM with zone or Latitude and Longitude. In both cases the projection and datum information should be clearly indicated (*e.g.*, WGS 84, ED 1950, etc.)
- Temperature in degrees Celsius (°C)
- Electrical Conductivity (EC) which is also known as Specific Conductivity (SC) in microsiemens ($\mu\text{S}/\text{cm}$)
- pH
- Flow rate in liters per second (l/s) or kilograms per second (kg/s). Estimates are sufficient; this measurement does not need to be exact, only accurate to within an order of magnitude.
- Presence of gas bubbles
- Presence of odors (sulfur, or other odors)
- Presence of precipitates in the fluids
- Presence and extent (mapped if possible) of deposits associated with the active geothermal manifestations such as sinter, travertine, bleaching/alteration, and/or silicification of surrounding or underlying deposits.

In addition to the above parameters, the overall number of manifestations should be recorded (particularly for springs > 50°C and wells > 80°C), and their areal extent and the cumulative flow rate of all the manifestations in each given area. If this information is available from previously published studies, it should be re-checked, as geothermal systems are dynamic and can evolve over relatively short periods of time (years or less). It is important to document current conditions, although historical data are also useful.

In the case of hot/warm wells, additional information should be recorded if available:

- Purpose (objectives) of the well spud date (the date drilling started)
- completion date (the date the hole was completed)
- total depth (bottom hole depth, both depth drilled and true vertical depth)
- drilling history (daily drilling reports and/or summaries of the drilling conditions)
- drilling results (temperature and flow rate upon completion of the hole)
- bottom hole temperature
- temperature and outputs of long term discharges under different wellhead pressures
- Well completion data
 - casing diameter as well as the depth of the hanger and the depth of the casing shoe (there may be multiple casing strings, in which case the information for each one should be recorded).
 - liner diameter as well as the depth of the hanger and the depth of the bottom of the liner (there may be multiple liners, in which case the information for each one should be recorded)
 - nature of any open interval (open hole, gravel pack etc.).
- Geologic logs (mud logs, core logs)

- Geophysical logs (temperature pressure spinner logs, resistivity logs (FMI))
- Well test results
- Other tables

This information can be very helpful in determining which lithologic units and/or structures are associated with the production of hot water. The locations of active geothermal features can be shown on a map, such as in Figure A2.1.

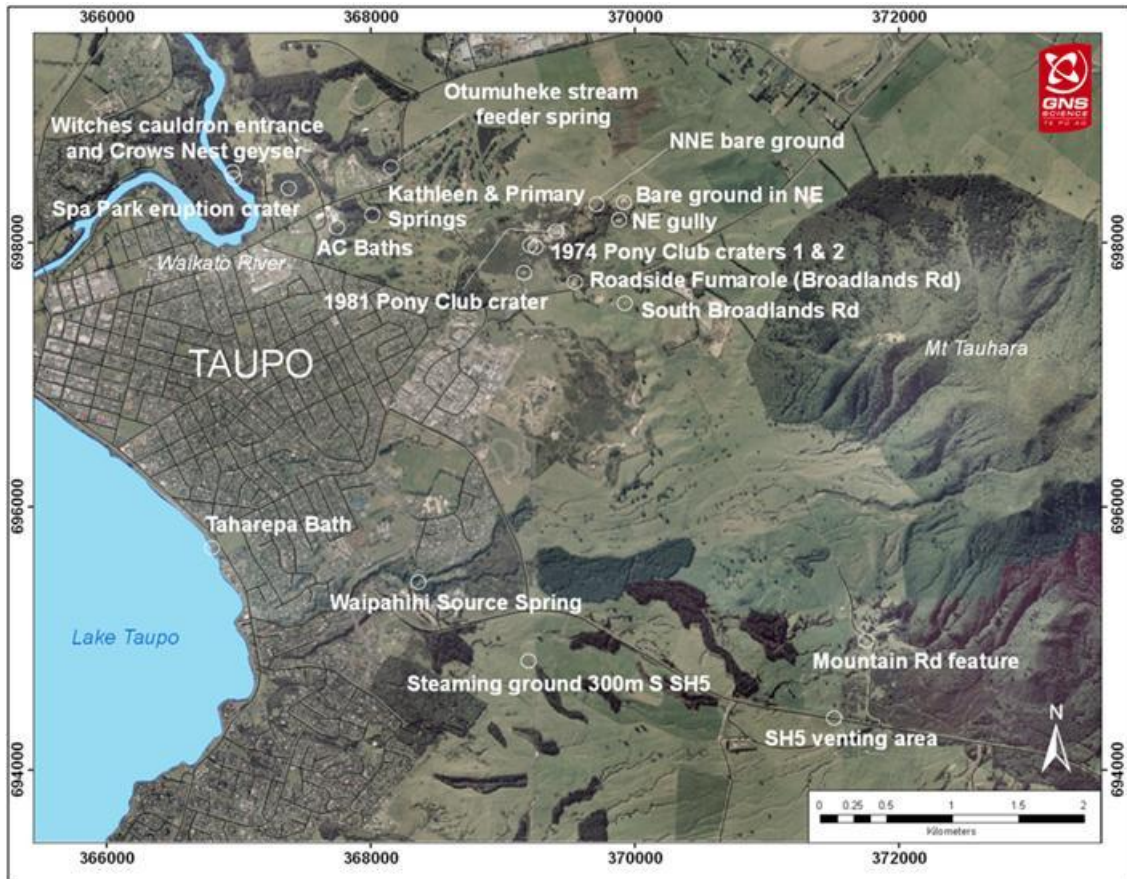


Figure A2.1: Example map of active geothermal features (GNS Science, New Zealand).

A2.2 GEOLOGY

During the literature review, the developer assesses the state of geologic mapping for the area in question. Once the existing maps have been located and examined, the following steps should be undertaken to evaluate and supplement existing mapping.

Assess the accuracy and suitability of existing maps and cross sections by comparing them to field observations. If the quality of existing mapping is sufficient, but cross sections have not been constructed for the project area, this should be done. If the quality of existing mapping and/or cross sections is insufficient, new geologic mapping should be undertaken. In either case, multiple cross sections should be constructed through the project area to present and evaluate the three dimensional subsurface structure.

In many cases, a developer finds that the existing geologic mapping is of good quality, but there is a need for additional mapping that focuses on areas and issues of particular relevance to geothermal exploration, including those discussed below. An example of a geological map from the geothermally active Taupo Volcanic Zone in New Zealand is shown in Figure A2.2.

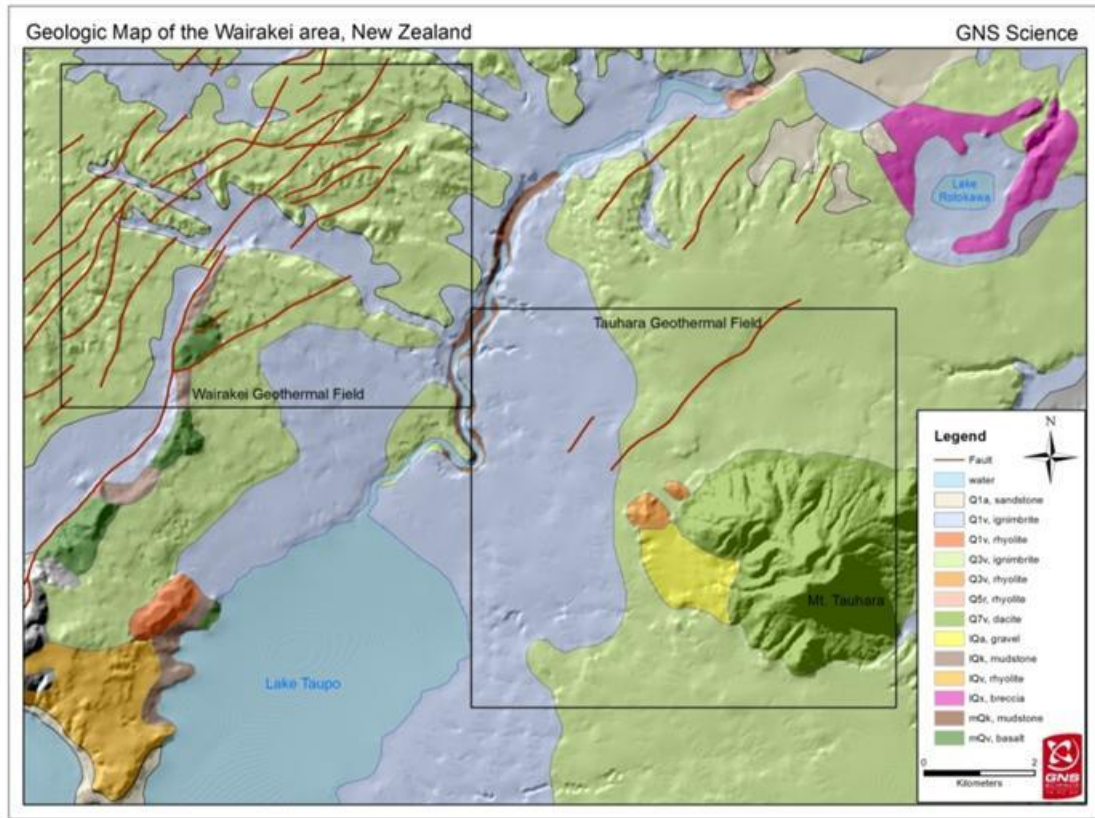


Figure A2.2: Example of a geologic map (GNS Science, New Zealand).

Heat Source

The possible heat sources for the system should be identified or inferred, providing the concept about the driving mechanism for the geothermal system. The heat source may be associated with active volcanism or regional high heat flow. Felsic volcanism is often associated with shallow magma chambers that can be a heat source for geothermal systems, whereas mafic volcanism tends to be sourced from deeper magma chambers that are less likely to drive a geothermal system. The most interesting igneous rocks will be of Miocene (12 my) or younger age, as they are most likely to be associated with magma chambers that still retain significant heat. In Turkey, there is some significant young volcanism in the eastern parts of the country. Despite this the major focus of geothermal development in Turkey is currently in Western Anatolia, where regional heat flows are known to be high.

Geothermal Manifestations

As discussed above, geothermal manifestations are direct indicators of hot water flowing in the subsurface and therefore need special attention when preparing maps. Areas that lack active geothermal manifestations, but show evidence of their earlier presence are also of extreme interest. It is common, particularly in heavily populated or agricultural areas, for water tables to have lowered over time. This can result in active geothermal manifestations drying up, even though there is still an active system below at depth. Indicators of areas of former hot spring activity include hot spring deposits (sinter, travertine, etc.), bleached or hydrothermally altered areas, and silica cementing of shallow deposits, all of which indicate that hot water has passed through the area.

Certain types of mineralization are often associated with hydrothermal systems, such as sulfur (S), mercury (Hg), gold (Au), silver (Ag), and antimony (Sb). Because circulating geothermal fluids concentrate these minerals into economically attractive deposits, the presence of such deposits can indicate the potential existence of a geothermal system, and therefore should be mapped. However, there are limitations to the use of mineral

deposits. While concentrations of these minerals are sometimes associated with active geothermal systems, most such deposits are associated with long extinct geothermal systems that, while providing potentially attractive mining targets, do not currently have active geothermal systems associated with them.

In addition to concentrating certain economic minerals, geothermal fluids break down the rocks through which they are passing, changing their minerals. The most common result of this water-rock interaction is the formation of clays as a product of hydrothermal alteration. Sometimes colorful, other times bleached white, these clay alteration zones are one of the most prominent indicators of a geothermal system. However, as with the mineral deposits described above, these alteration zones may be the result of ancient rather than current activity. In some geothermal areas, the careful mapping of alteration types and patterns provides insight about the history of thermal activity in an area.

Lithology and Stratigraphy

Certain lithologies have greater potential to be reservoir rocks. These are lithologies with high primary and/or secondary permeability, such as sandstone, limestone, quartzite, marble, gneiss, lava flows, and other brittle rock units that can sustain fractures when deformed. Permeability is almost always a limiting factor in geothermal projects, therefore identifying units which are likely to sustain permeability is of high importance when targeting wells.

It is also important to identify potential capping rocks (aquitards and aquicludes). These are units with low primary and secondary permeability such as clay, silt, shale, schist, and other rock types that tend to have plastic (rather than brittle) deformation. The distribution of low permeability and high permeability rocks define fluid flow pathways, resulting in a geothermal reservoir of a particular size or shape.

Understanding the stratigraphic sequence in the area will permit a better understanding of the distribution of various lithologies. In areas with major normal faulting, exposures in the hills and mountains may provide clues to what lies beneath the subsurface in the adjacent valley. Drilling data from any deep wells in the region should also be evaluated to confirm the stratigraphic sequence, to the extent that such data are available. The construction of stratigraphic columns from drill hole data from the Wairakei Geothermal Field in New Zealand is illustrated in Figure A2.3.

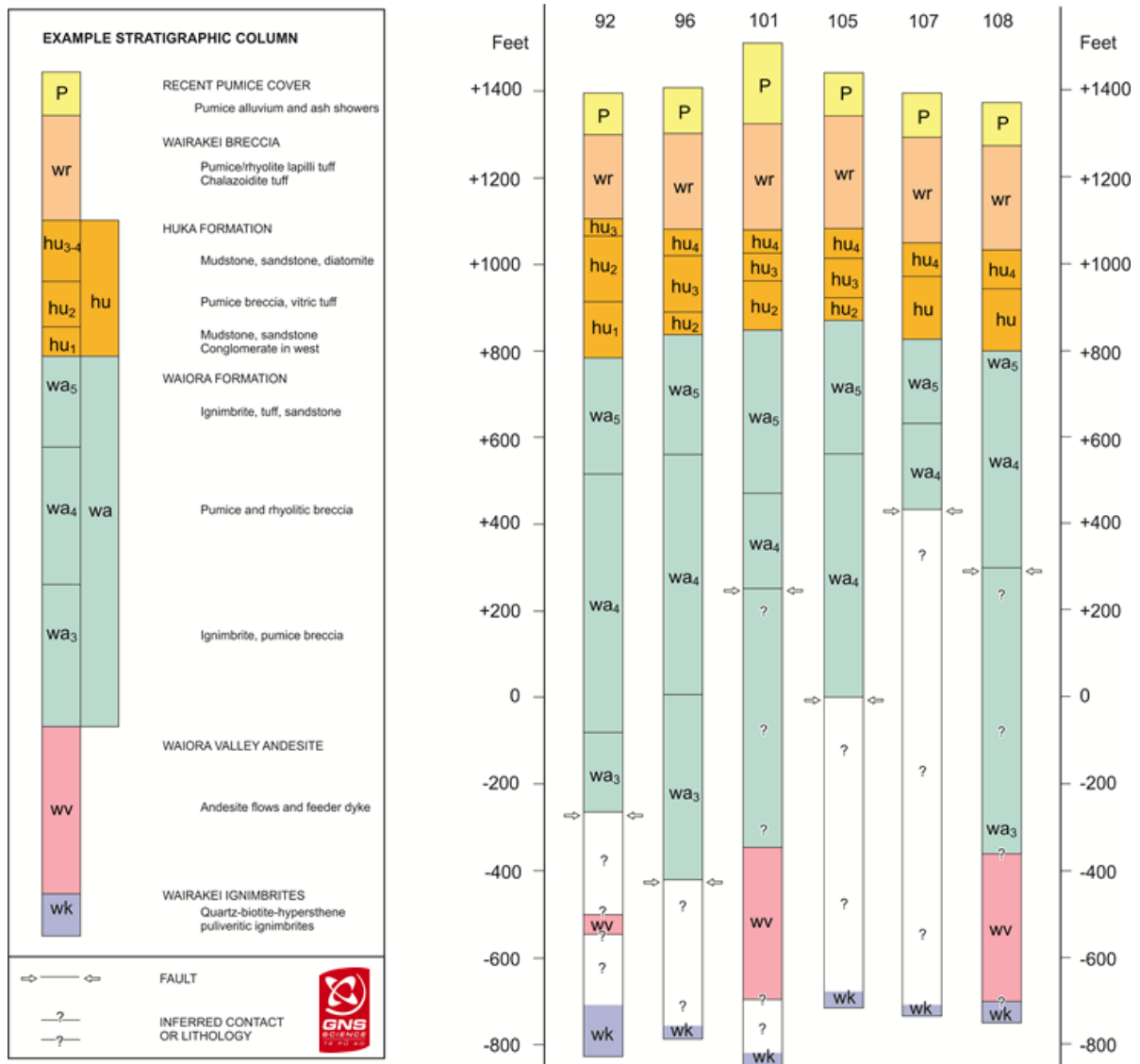


Figure A2.3: Example of a stratigraphic column, and comparison between wells (GNS Science, New Zealand).

Geologic and Tectonic Structure

Analysis of regional geologic structure enables an understanding of the geological context of the project area. Of particular interest are large scale extensional features such as grabens and metamorphic core complexes, or any other structural features that result in or are the result of crustal thinning. In addition, the location, orientation, and distribution of regional deep fault zones are important, as these faults can play many roles in a geothermal system, from fluid conduits to barriers to fluid flow as well as creating or enhancing secondary permeability.

Local geologic structure is of paramount importance in any geothermal project. Geothermal systems are often associated with structural highs and in many cases dipping units may transmit geothermal fluids from depth across significant distances (*i.e.*, the source or reservoir is laterally offset from the surface manifestations). Understanding the depth, orientation, and thickness of potential reservoir units and lower-permeability units is essential to developing a comprehensive conceptual model. Of equal importance is understanding the locations, orientations, and sense of slip along both regional structures (*e.g.*, graben-bounding faults) and local structures (*e.g.*, cross-cutting faults).

Two-Dimensional (2D) Cross-Sections

Two-dimensional (2D) geologic cross-sections (as shown in Figure A2.4) illustrate the basic stratigraphic and structural framework of a particular prospect.

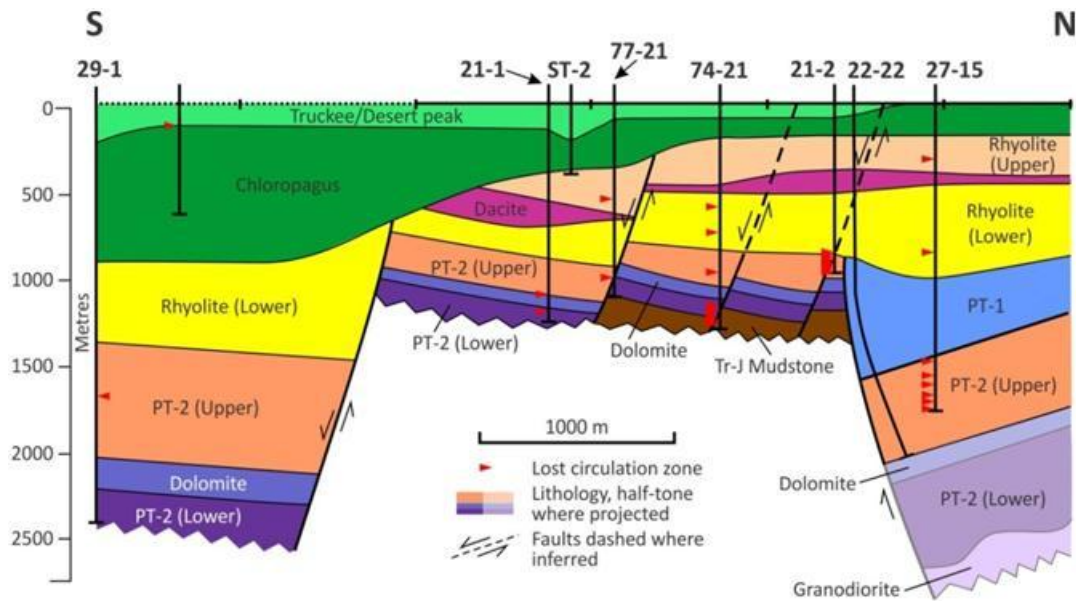


Figure A2.4: Example of 2D geologic cross section (GeothermEx, Inc.).

Three-Dimensional (3D) Models

When drill hole information is available, all structural and stratigraphic information can be integrated into a 3D model as illustrated in Figure A2.5. These 3D models are proving to be extremely useful for well targeting and structural and stratigraphic visualization.

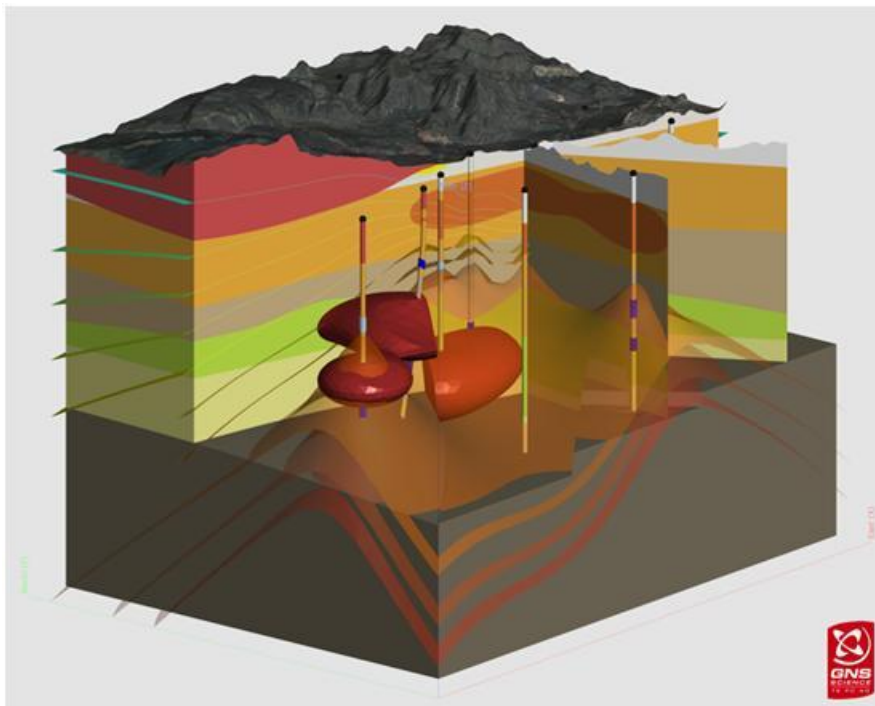


Figure A2.5: Example of 3D geologic cross section (GNS Science, New Zealand).

A2.3 GEOCHEMISTRY

Fluid and Gas Sampling

Once geothermal manifestations have been identified, located, and characterized, geochemical samples should be taken of representative fluids, steam, and/or gases. When numerous geothermal manifestations exist in an area, those with the highest temperatures and electrical conductivities should be given priority for sampling (if all cannot be sampled). If there are multiple features with comparable temperatures and electrical conductivity (EC) values, the features with the highest flow rates are the most important for sampling. If field measurements of temperature and conductivity (and chloride content, which is sometimes measured in the field) suggest that the manifestations may be mixtures of hotter and colder water bodies, a range of samples should be selected to assist in understanding how the thermal fluid is mixing with other water components.

In the case where no thermal manifestations have been located in the area, springs or wells with elevated EC levels, gas bubbles, unusual odors, or tastes should be sampled. These attributes are sometimes the result of an input of thermal fluids, although not in all cases. EC can vary with geologic terrain. Therefore, an appropriate method for determining what constitutes an “elevated” EC level is to measure numerous non-thermal water sources in the area to establish an average “baseline” EC for the area. Any spring that has an EC one standard deviation or more above the average would be considered to have an elevated EC level.

The physical and chemical characteristics of the geothermal feature being sampled should be recorded as described in Section A2.1. If the characteristics, location, temperature, etc. of the geothermal feature have been recorded prior to the geochemical sampling the following characteristics of the sampled geothermal features should be measured and recorded again at the time of sampling:

- Location in UTM with zone or Latitude and Longitude. In both cases, the projection and datum information should be clearly indicated (*e.g.*, WGS 84, ED 1950, etc.)
- Temperature in degrees Celsius (°C)
- Electrical Conductivity (EC) which is also known as Specific Conductivity (SC) in microsiemens ($\mu\text{S}/\text{cm}$)
- pH
- Flow rate in liters per second (l/s) or kilograms per second (kg/s), estimates are sufficient, this measurement does not need to be exact, only accurate to an order of magnitude.
- Presence of gas bubbles
- Presence of odors (sulfur, or other odors)
- Presence of precipitates in the fluid

The sampled fluids should be properly preserved and analyzed for silica, cations, anions, and isotopes in water and sulfate. Analysis of the geochemistry of the thermal fluids should be carried out by a laboratory with experience in analyzing geothermal fluids. There are a number of concerns specific to the analysis of geothermal fluids that other laboratories (*e.g.*, those that specialize in analyzing typical groundwater) may not appreciate or understand, potentially leading to poor analyses.

The completed analyses should be compiled into a spreadsheet or database. Silica, cation, and isotope geothermometers should be calculated and added to a table where they can be compared to each other. Geothermometers respond to cooling at different rates and are affected differently by various rock types and other reservoir conditions; therefore it is necessary to calculate the geothermometers as a suite, within their geologic context, in order to properly estimate potential resource temperatures. Chemical parameters should be plotted against each other in a variety of plots to assess the characteristics of the geothermal fluids. The

following figures (Figures A2.6 to A2.12) illustrate the way in which geochemical data is used to develop mixing models, identify end members, and follow the evolution of fluid compositions in a geothermal system.

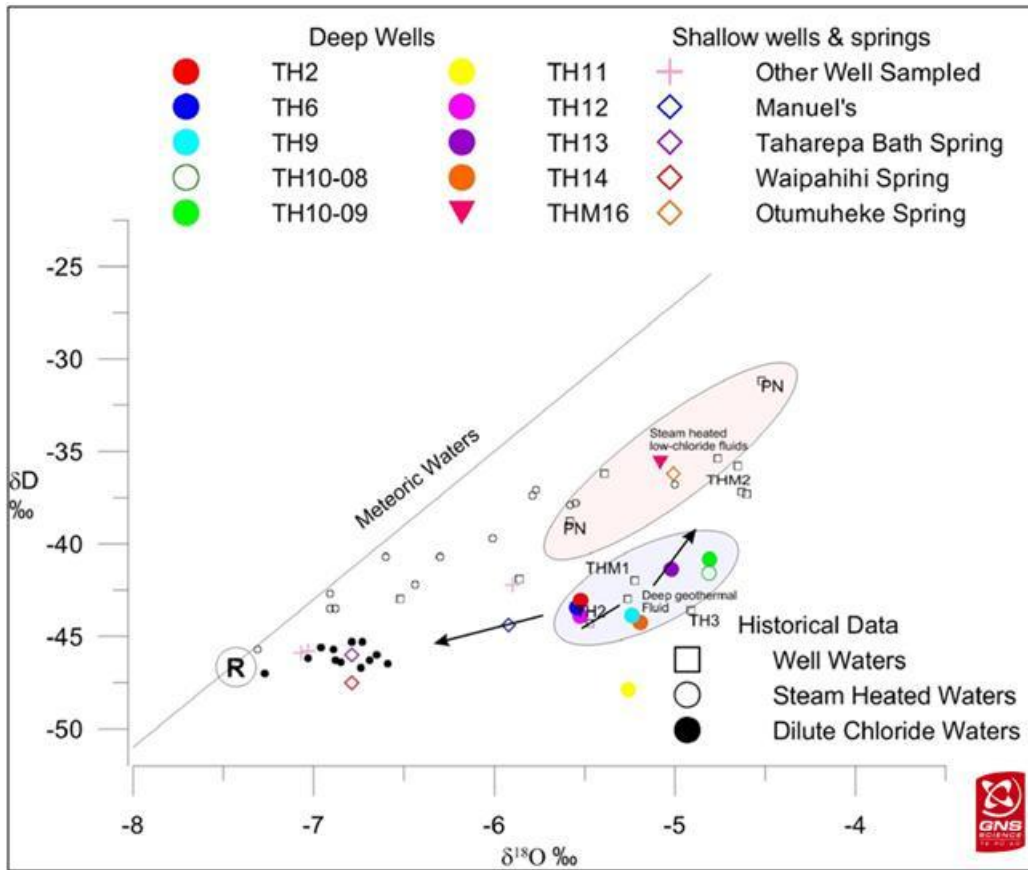


Figure A2.6: Example plot of fluid stable isotope data (GNS Science, New Zealand).

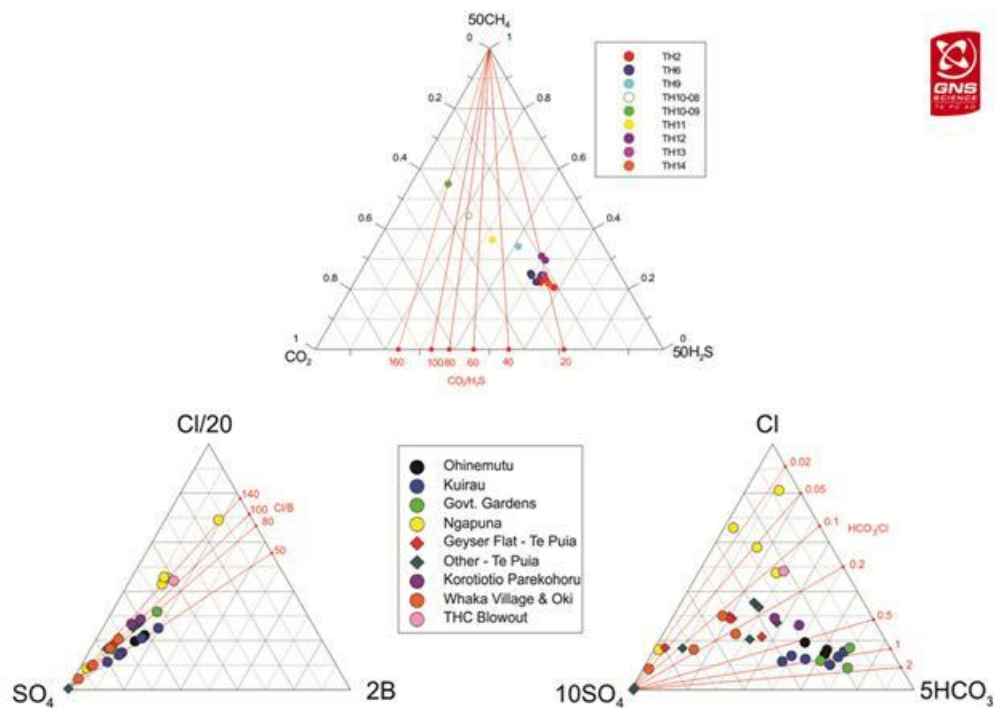


Figure A2.7: Examples of various plots of fluid geochemistry (GNS Science, New Zealand).

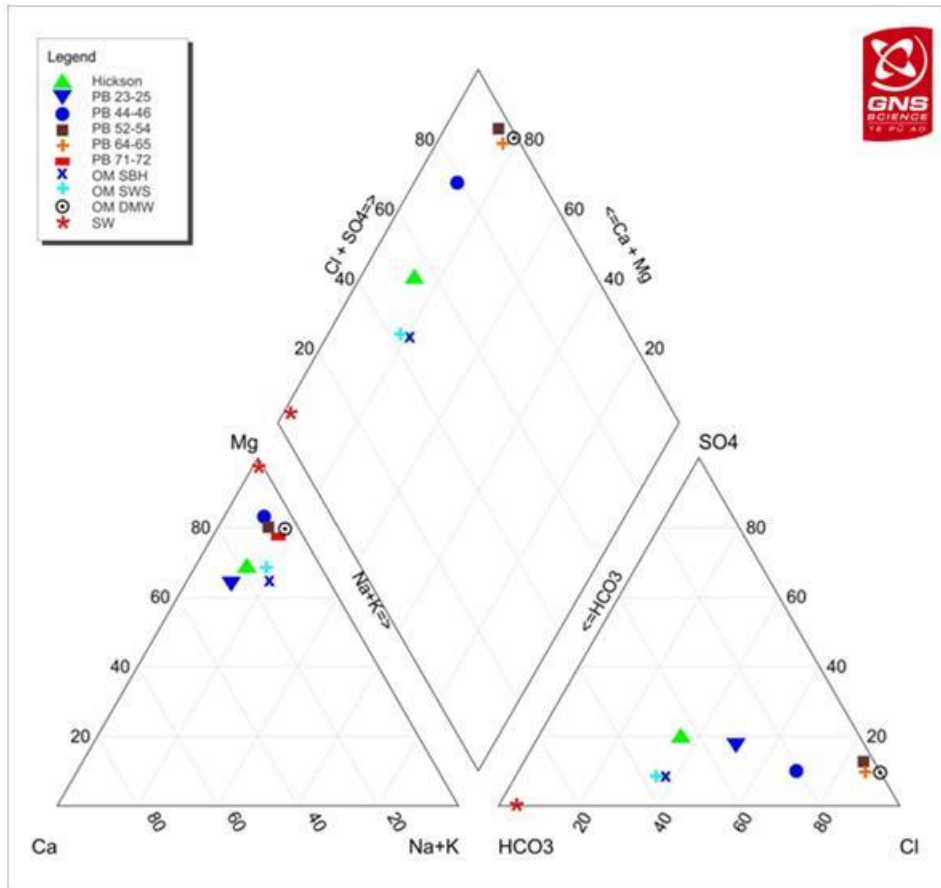


Figure A2.8: Example of a piper diagram (GNS Science, New Zealand).

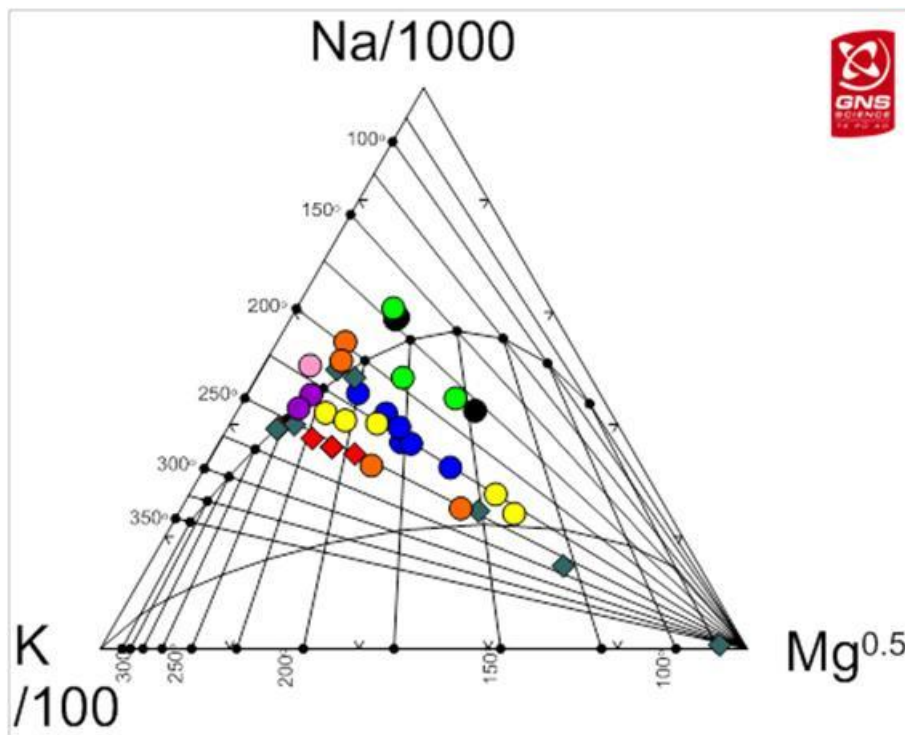


Figure A2.9: Example of geothermometer comparison (GNS Science, New Zealand).

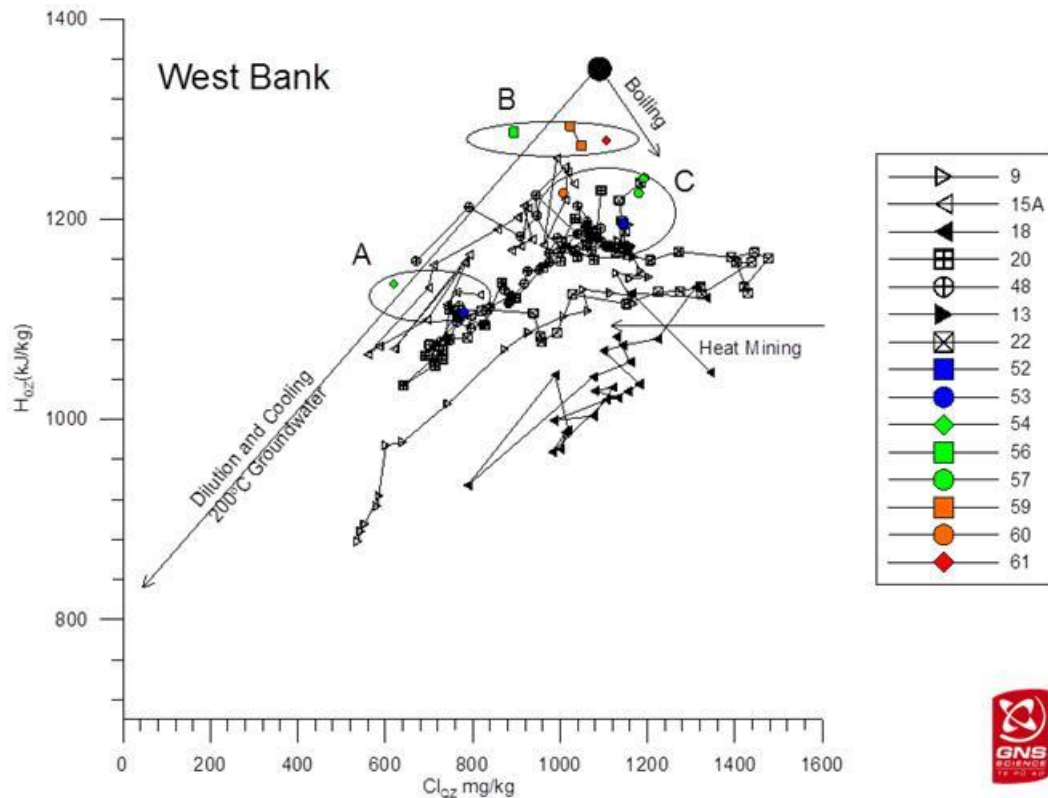


Figure A2.10: Example of an Enthalpy vs. Cl plot (GNS Science, New Zealand).

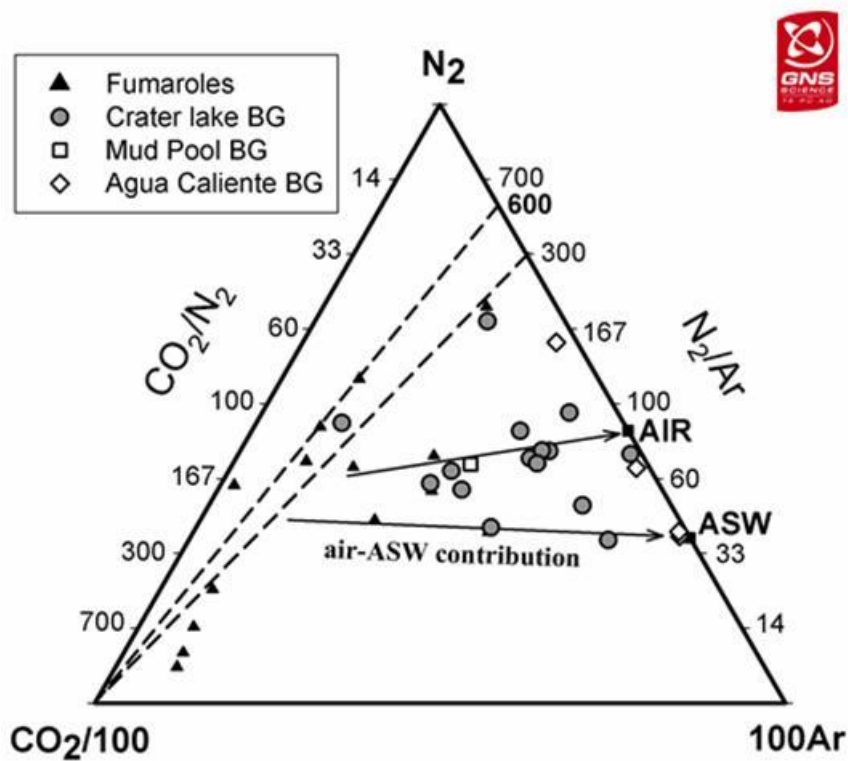


Figure A2.11: Graph showing Ar, CO₂ and N₂ in the gases of various thermal features (GNS Science, New Zealand).

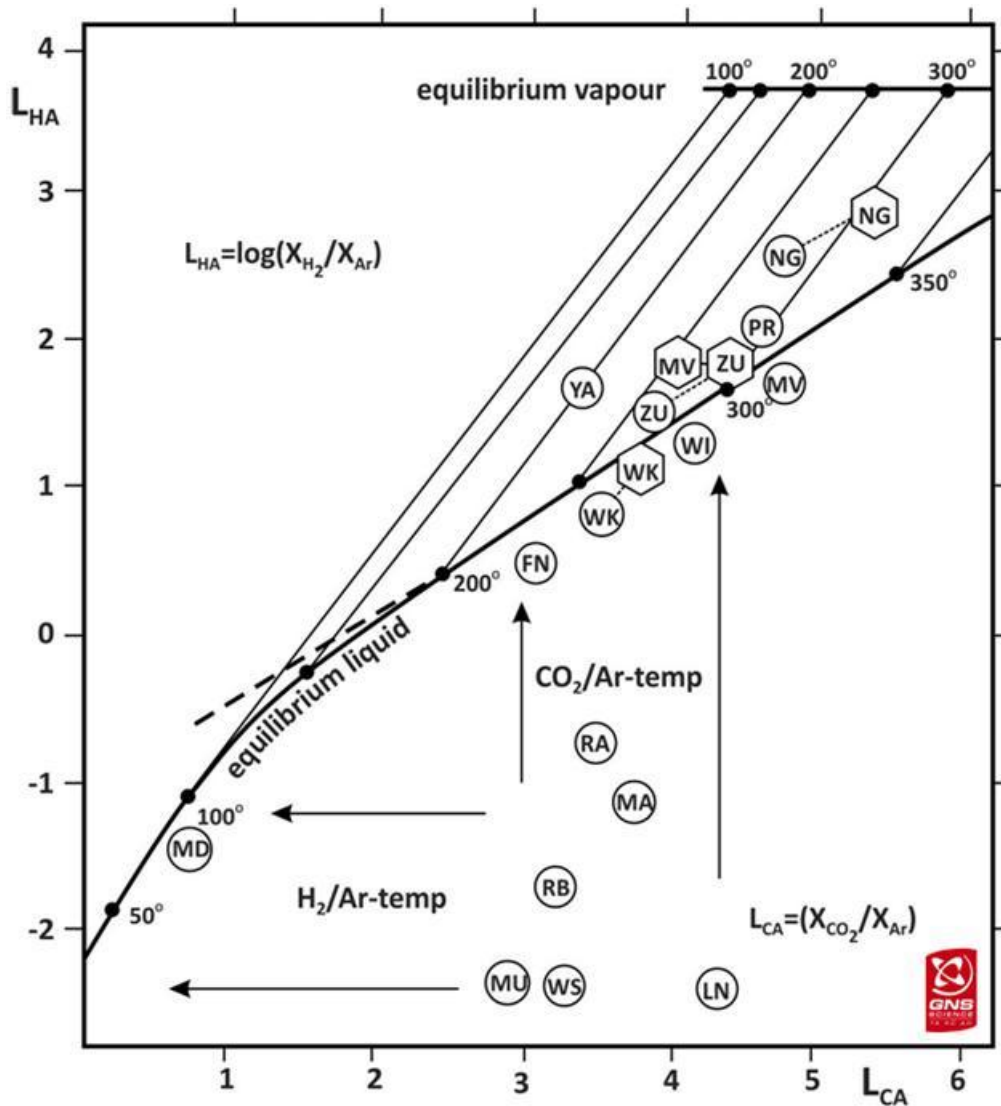


Figure A2.12: Example of a Giggenbach gas ratio grid (GNS Science, New Zealand).

Soil Sampling

Another commonly used geochemical exploration technique is to survey for carbon dioxide (CO₂) soil flux and/or mercury (Hg) in soil. Geothermal systems contain non-condensable gases, the principal component of which is CO₂, and often have elevated levels of Hg. Therefore, soil sampling surveys are designed to locate anomalously high concentrations of CO₂ and/or Hg that could indicate a potential geothermal system at depth.

Increased CO₂ flux occurs near many active geothermal manifestations, and CO₂ flux can suggest a geothermal system at depth. CO₂ soil flux surveys are done with a portable meter that measures the active flux of CO₂ through the soil. While CO₂ soil flux surveys can show the presence of active geothermal manifestations and structures such as faults that may be conducting geothermally-derived gases toward the surface, these surveys rarely provide significant geologic or geochemical insight. However, they can often confirm the results of other methods (notably geologic mapping), and they are reasonably cost-effective.

Mercury surveys are performed by taking small soil samples and analyzing them in a portable mercury detector. While this method can resolve very small differences in mercury concentration, there are many other sources of mercury aside from active geothermal systems which tend to cloud the results. Extinct hydrothermal systems can still have mercury associated with them millions of years after activity has ceased. In addition, there are numerous anthropogenic sources, such as improper disposal of mercury bearing items (thermometers,

refrigerators, etc.), and industrial processes such as manufacturing or mining that lead to the disposal of fluids with elevated mercury. To the extent that the history of a site is known, this may help in the interpretation of soil Hg survey data.

A2.4 GEOPHYSICS

Gravity Surveys

Gravity surveys are relatively simple to implement, and measure the bulk density of the rock sequence beneath the project site. Starting with reasonable assumptions about the thickness and density of different subsurface rock units, gravity data are modeled in an iterative way to arrive at the best match between the observed data and the calculated result from the gravity model. Figure A2.13 is a map of gravity data, and Figure A2.14 depicts the interpretation of the data. This process helps to assess the stratigraphy and structure of the subsurface. Gravity data are commonly integrated with the geologic mapping to provide better insight into the three-dimensional distribution of rock units and the overall geologic structure of the area. Gravity surveys can be applied at both the regional scale and at a more localized level during the Exploration Phase to better understand the structure of the more promising areas. Gravity is a cost-effective technique and fundamental technique used in exploring many types of natural resources, including geothermal exploration. Sometimes magnetic data are collected during the same survey, requiring the use of a magnetometer as well as a gravity meter. While magnetic surveys are less important than gravity data, they can sometimes yield additional insights into stratigraphy and structure.

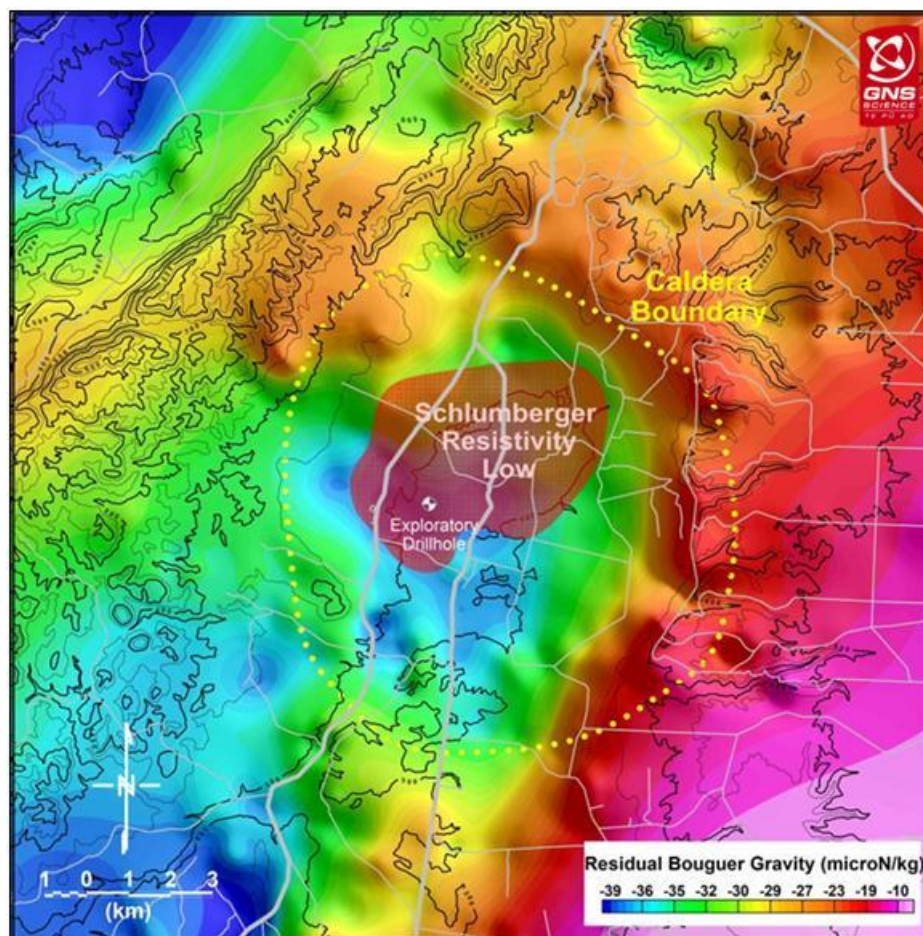


Figure A2.13: Example of gravity data (GNS Science, New Zealand).

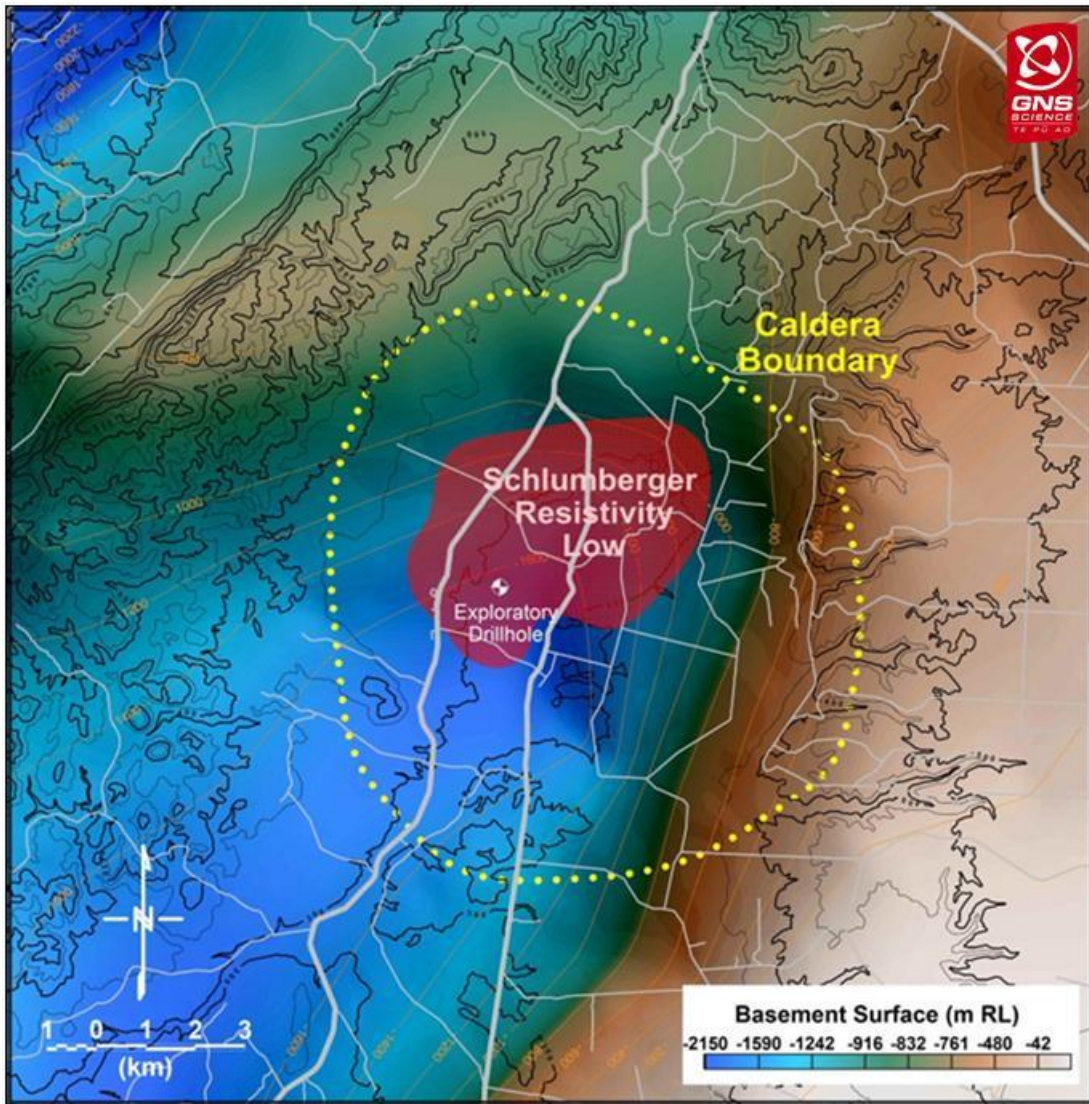


Figure A2.14: Example of gravity data interpretation (GNS Science, New Zealand).

Temperature Gradient Drilling

Although commonly considered as a drilling method rather than a geophysical method, temperature gradient (TG) drilling is undertaken to directly measure subsurface temperature, which is a geophysical property. Since it measures the quantity being sought (heat), TG drilling is one of the most valuable geophysical techniques used in geothermal exploration. It is often possible to drill TG holes with a water well rig, which cost far less to mobilize and operate than larger rigs (which are used for deep slim holes or full diameter wells). This makes temperature gradient drilling a very cost-effective exploration technique in geothermal projects.

TG drilling is most commonly applied towards the end of the Exploration Phase, focusing on areas deemed to be the most promising based on earlier exploration and analysis, enabling an evaluation of the variation in temperature gradient across an area. As with other geophysical methods, interpretation of TG data informs our understanding about the depth and attitude of possible reservoir rocks, and, most importantly, the estimated reservoir temperature (Figure A2.15). In this sense, TG drilling is an excellent complement to chemical geothermometry, which estimates the temperature at the deep fluid source, but is unable to say at what depth that fluid might be found. TG drilling also helps elucidate geologic structure, like the other geophysical methods discussed above.

TG drilling often uses a truck-mounted or other small rotary rig that can quickly drill wells to depths that rarely exceed about 200 m. Such holes are typically completed within a matter of days. In some cases, deeper TG holes are drilled (to depths as great as 500 or 600 m), and in some cases, they may encounter a geothermal resource. Deeper TG holes are sometimes drilled using two rigs: a rotary rig to drill the “top hole” and a coring rig to drill the deeper section. This two-rig method can shorten the drilling program and save costs. Further, although rock cuttings are logged and described, the collection of core data from the reservoir itself and even from the interval above the reservoir provides valuable information for the conceptual model.

TG holes drilled with a rotary rig are typically completed with inner tubing that is capped on the bottom and has been back filled with gravel or cuttings in the annular space between the tubing and the wellbore walls. TG holes drilled with a coring rig typically leave the coring rods in the hole (this forms the well’s “casing”). Both completions keep the hole open for logging while reducing the potential for flow into or out of the well, which means that the temperature measured inside the tubing reflects the actual formation temperatures of the penetrated rock, rather than being an artifact of internal flow. To the extent that internal flow within the casing does occur, this needs to be considered when TG data are interpreted. Because the drilling process disturbs natural temperatures, a series of “heat-up” temperature logs (perhaps about 3 or 4 over the course of several wells) are run to establish the final stabilized temperature; these stabilized data are used for analysis.

Occasionally, a TG well will encounter a shallow geothermal resource. In this case, there are opportunities to collect additional information that are useful for understanding the system. For example, it may be possible to collect fluid samples by briefly flowing or bailing the well. If the drilling permit does not allow such activities, it may be possible to conduct a short injection test of the well. Injection test data, together with the stabilized temperature profile, can be used to estimate the productivity of a full-diameter well drilled into similar conditions.

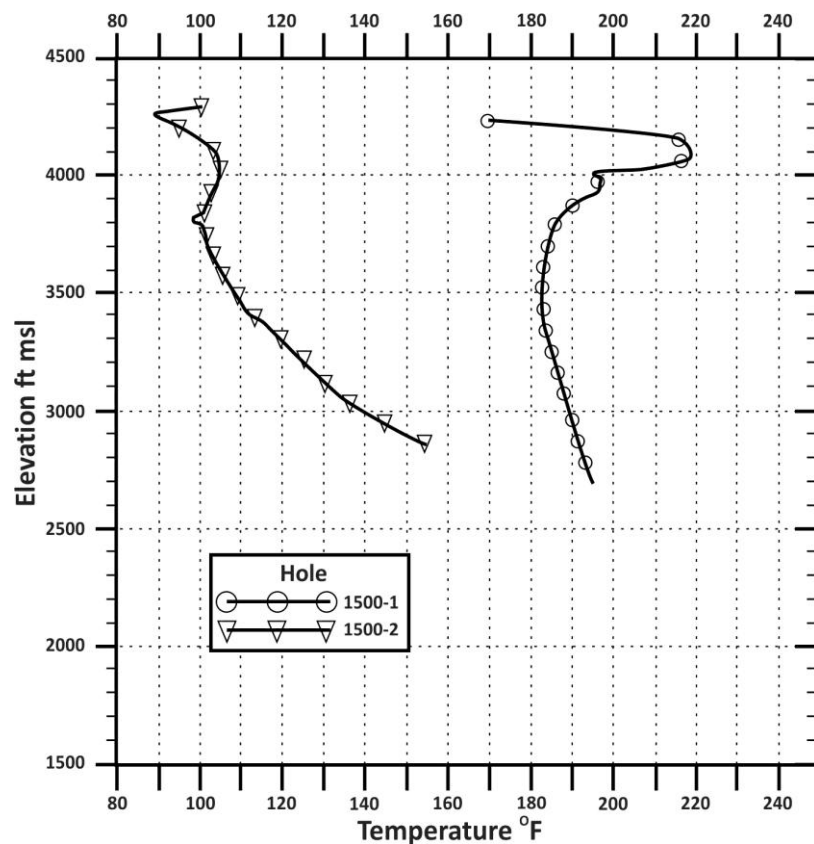


Figure A2.15: Example of temperature gradient well logs.

Temperature Contour Maps and Cross-Sections

Information about formation temperatures from drill hole data can be plotted as temperature contour maps (Figure A2.16), or overlain on geologic cross-sections (Figure A2.17). Such diagrams can provide useful information for future well targeting.

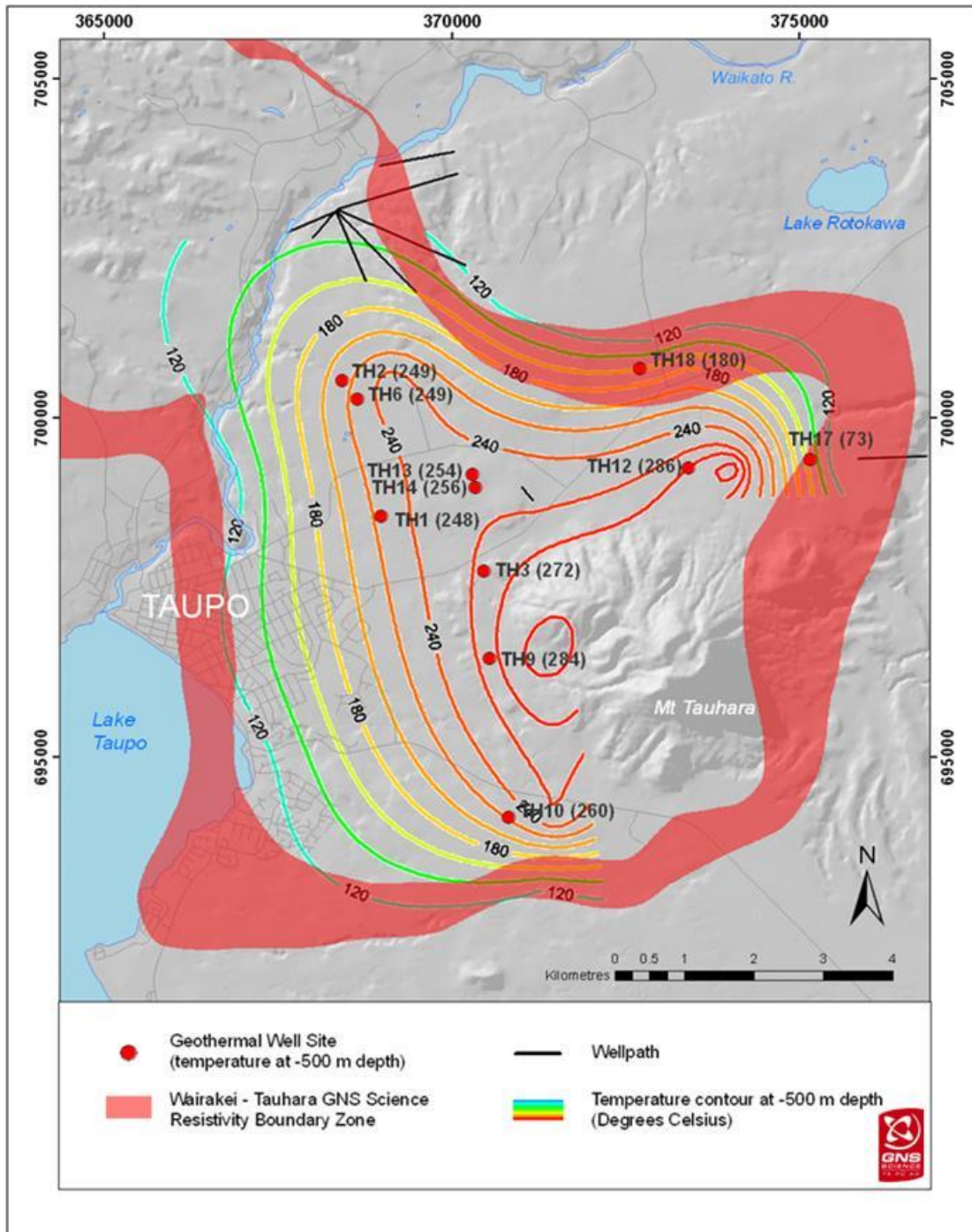


Figure A2.16: Example of temperature contour map (GNS Science, New Zealand).

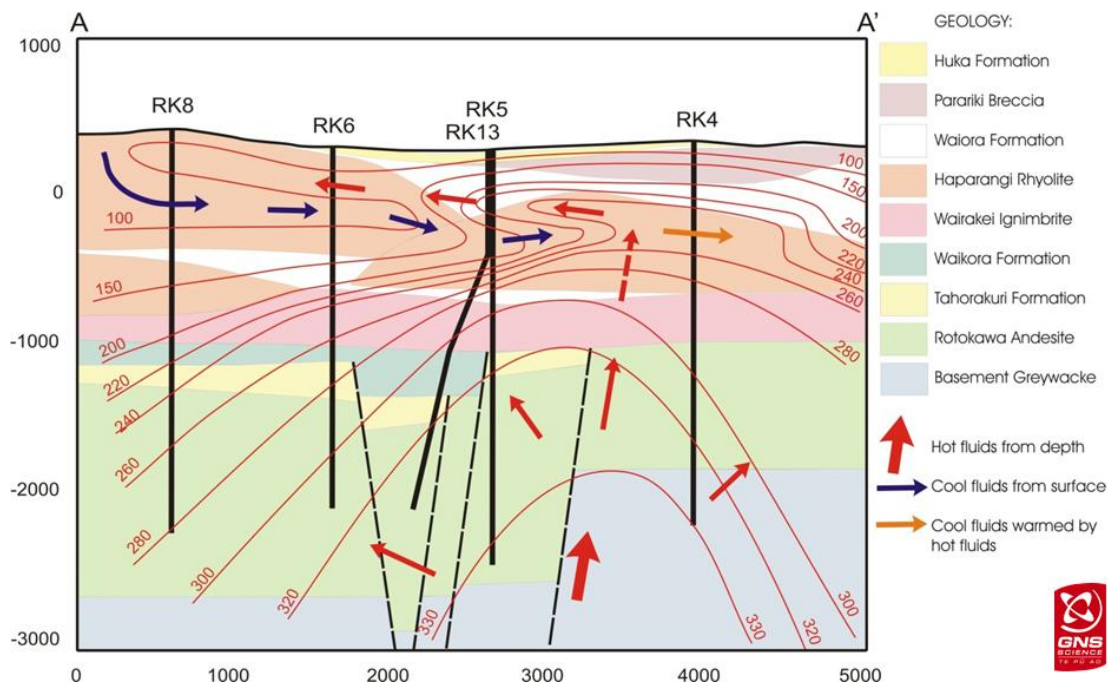


Figure A2.17: Example of a combined geologic and temperature cross section (GNS Science, New Zealand).

Electrical Resistivity Surveys

A commonly used geophysical technique in geothermal exploration, electrical resistivity surveys can be extremely valuable as an exploration tool, but have some important limitations. There are numerous resistivity methods available, including vertical electric soundings (VES or “Schlumberger soundings”), DC resistivity surveys, time-domain electric magnetic (TDEM) surveys, magneto-telluric (MT) surveys, and controlled-source audio-magneto-telluric (CSAMT) surveys. At present, MT is probably the most common technique used in most geothermal fields, as it can measure rock resistivity (or conductivity) to deep levels (a few km, which is significantly greater than for most other methods).

Electrical resistivity methods were first applied in volcanic terrains that host high-enthalpy geothermal reservoirs (with temperatures exceeding 200°C. In such reservoirs, a “cap” of hydrothermally altered clays is present above the reservoir. Resistivity surveys can help to image this clay alteration cap as a zone of low resistivity, with the higher resistivity reservoir lying below the cap. Lower temperature systems such as those common in Turkey tend not to have well developed clay alteration caps. In these cases, resistivity surveys can offer insight into regional stratigraphy and geologic structure, depending on the lithologies present.

Resistivity surveys can be performed at a regional scale; in these cases, the station spacing may be on the order of a few per km². It is usually more cost effective to identify a prospective area with other methods, and then conduct a detailed resistivity survey in that area, with perhaps as many as 10-15 stations per km². That said, conditions sometimes call for the application of a relatively detailed resistivity survey to help define an attractive area. This was the case in at least one project where a geothermal resource was expected to be present, but environmental issues severely restricted access to the resource. The areas where geothermal development could occur were therefore surveyed in detail. These resistivity data were interpreted together with other information (most importantly, temperature gradient data) to help identify locations for deep, full-diameter wells. The combination of resistivity surveys and TG wells has been used as a basis for targeting full-diameter “step-out” wells in a new portion of operating geothermal fields. As with nearly everything described in this guide, it is emphasized that electrical resistivity data should be evaluated in the context of other data and information. Figure A2.18 presents an MT resistivity map based on ~1 km grid spacing within the Taupo Volcanic Zone in an area where at least 10 active geothermal systems are located. The data can also be presented in three-

dimensional (3D) models as shown in Figure A2.19. These sophisticated models are proving invaluable for successful well targeting.

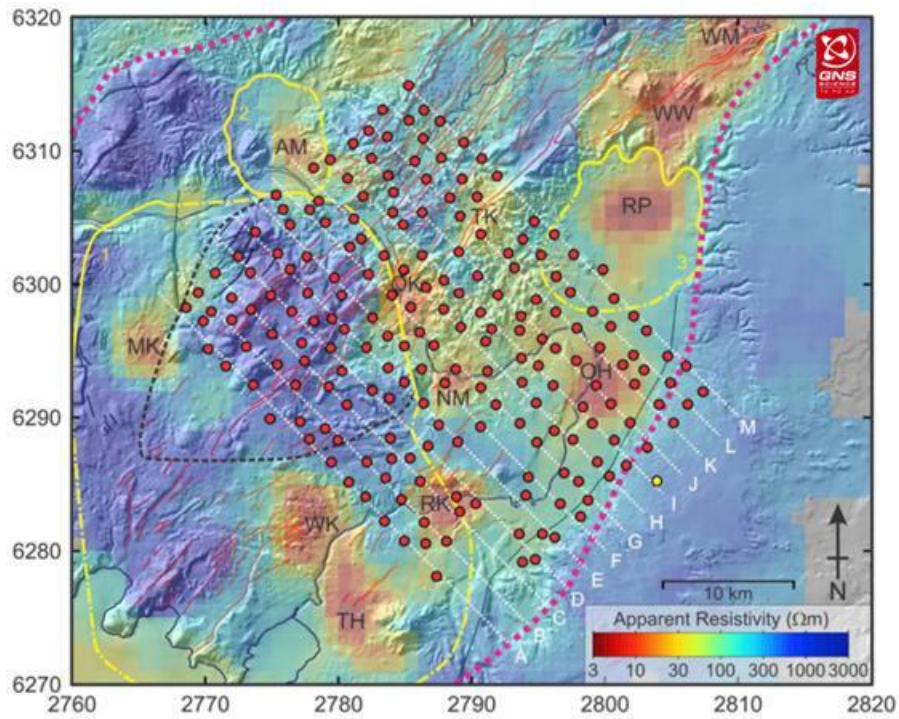


Figure A2.18: Example of MT resistivity map (GNS Science, New Zealand).

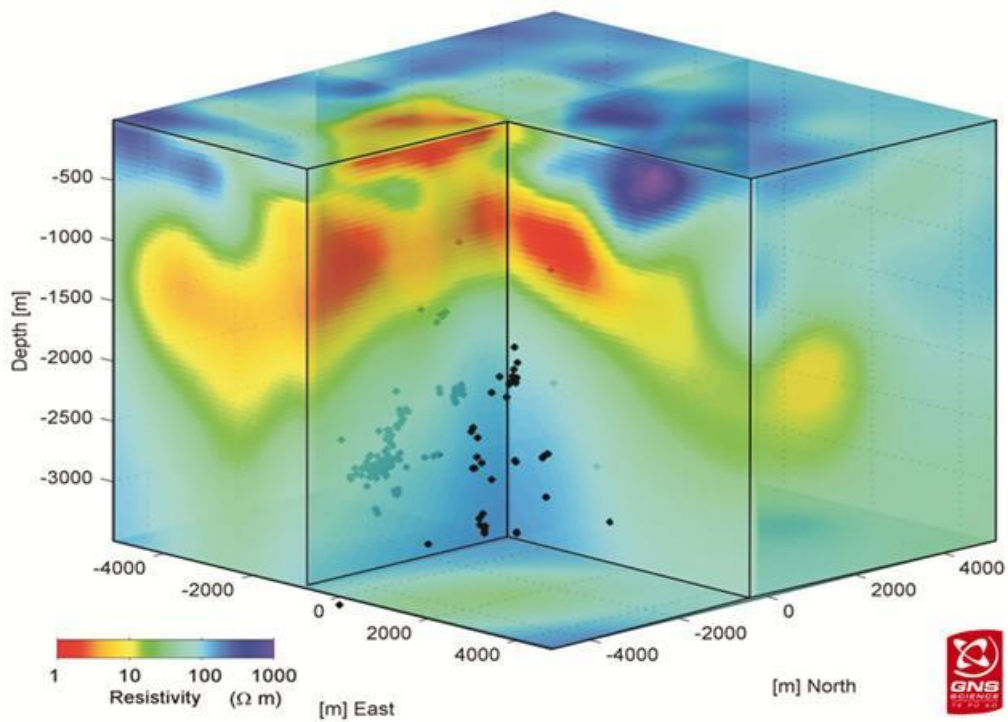


Figure A2.19: Example of 3D MT resistivity cross section (GNS Science, New Zealand).

Seismic Reflection

While seismic reflection is possibly the most commonly used geophysical technique in oil and gas exploration, it is not often used in geothermal exploration. One reason is the cost of the method relative to the value of the resource (hydrocarbons have far more value per unit of measure than geothermal fluids). A second reason is that oil and gas deposits tend to be hosted in well stratified sedimentary sequences that offer many reflecting horizons. Faults are seen in the data at locations where these reflectors are offset. With some well control (most oil and gas fields have some wells) seismic reflection data can be effective at mapping out a particular stratigraphic horizon. Low and medium enthalpy geothermal systems come very often along with sedimentary layers or karstic formations. 2D-seismic reflection can identify faults and extensive structures (Figure A2.20). 3D-seismic reflection represents the most sophisticated type to identify certain sedimentary facies and the most promising drilling targets.

High enthalpy geothermal systems tend to be hosted in deformed metamorphic and volcanic rocks that are characterized by less lateral continuity, which results in seismic data sets that are difficult to interpret. To the extent that geothermal reservoirs are hosted in poorly stratified rocks (such as in volcanic areas), or have no wells to provide the needed control, seismic reflection offers more ambiguous (and therefore less useful) results. Thick, near-surface volcanic deposits (particularly pyroclastic units) tend to attenuate the seismic energy, limiting the ability to obtain coherent reflections from deeper horizons.

This technique would be used during the Exploration Phase to help assess the structure and stratigraphy of the most promising areas. If the data quality is sufficient and if enough is known about the stratigraphic section being imaged, seismic reflection data can be used to make inferences about permeability variations. Because of its high cost, however, the application of reflection seismic methods in geothermal exploration and development tends to be limited to areas where both geologic and economic conditions support its use. Figure A2.21 shows a seismic section with a proposed borehole track. Figure A2.22 is a conceptual geological model based on seismic data.

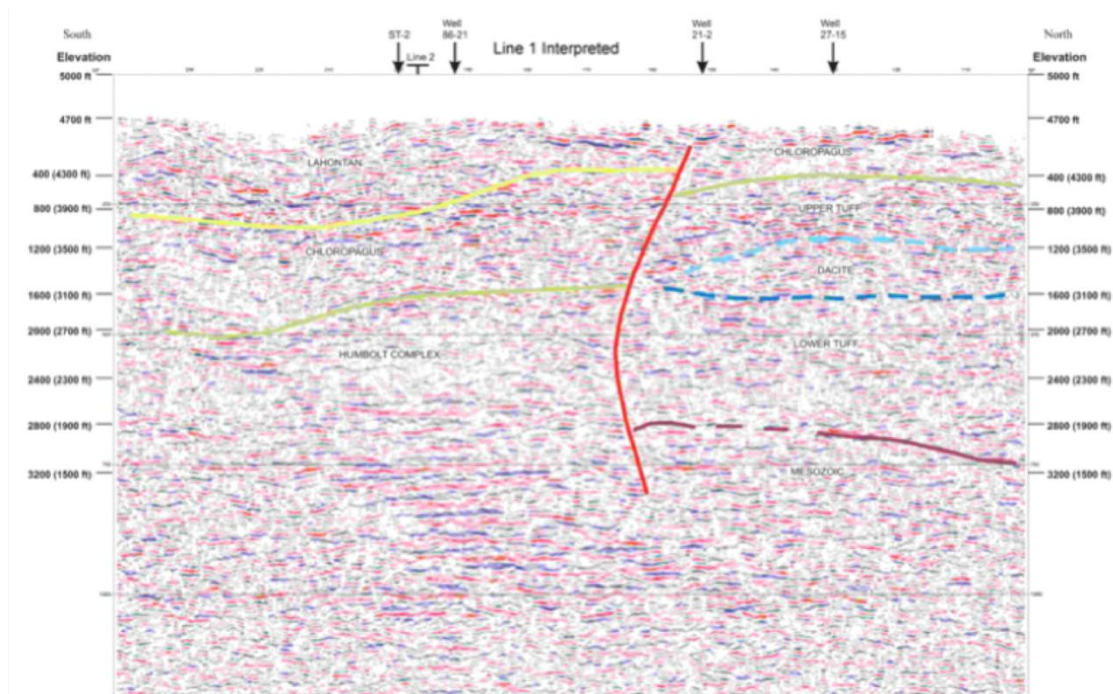


Figure A2.20: Example of seismic section.

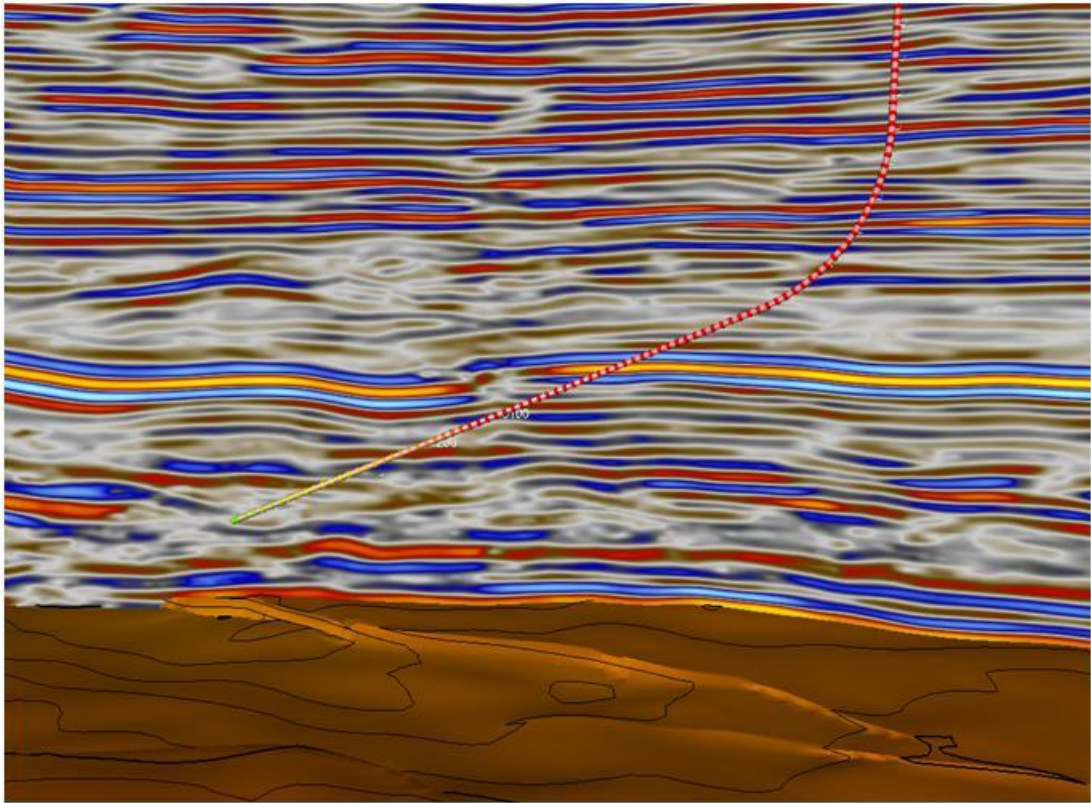


Figure A2.21: Example of seismic section with planned borehole (Erdwärme Bayern GmbH & Co. KG-).

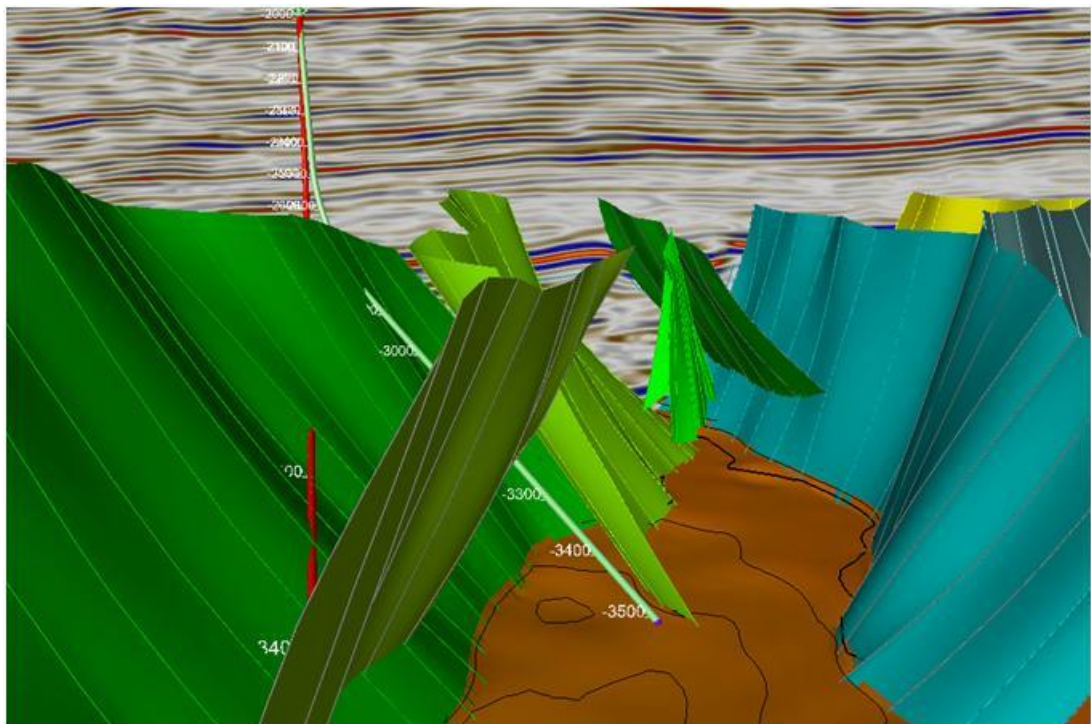


Figure A2.22: Example of seismic section with geological interpretation (Erdwärme Bayern GmbH & Co. KG-).

APPENDIX A3: DATA CHECKLIST FOR PROJECT REVIEW AND EXPLORATION RISK INSURANCE APPLICATIONS

A) LICENSE INFORMATION AND MAPS

- 1) License Information
 - a) Coordinates of license boundaries*
 - b) Copies of actual license(s)*
- 2) Maps
 - a) Topographic map(s) showing geothermal license area(s)* and planned drill locations
 - b) Map(s) showing areas licensed to others around subject license area(s) including surrounding wells
 - c) Map(s) of easements or other rights of use
 - d) Map(s) of land use restrictions*
 - e) Other maps

B) RESOURCE DATA

- 1) Active Geothermal Features
 - a) Location (Lat Long or UTM)~
 - b) Temperature (°C)~
 - c) EC ($\mu\text{S}/\text{cm}$)~
 - d) pH~
 - e) Flow rate (l/s)~ or kg/sec
 - f) Presence of gas bubbles~ and their types
 - g) Presence of odors (sulfur or other odors)
 - h) Presence of precipitates in the fluids
 - i) Detailed local map(s) of area(s) with thermal features clearly labeled~
 - j) Well specific information~
 - (1) Drilling period
 - (2) Total depth
 - (3) Drilling results
 - (4) Bottom hole temperature
 - (5) Well Completion Data
 - (6) Geologic logs for wells drilled
 - (7) Geophysical logs for wells drilled (GR, TPS, Resistivity, CBL, etc)
 - (8) Results of well tests and discharge history
 - (9) Other Tables
- 2) Geological Data
 - a) Geologic map(s) of license area(s)*
 - b) Geologic cross sections from license area(s)*
 - c) Summary descriptions of stratigraphy and lithology with stratigraphic columns

- d) Summary descriptions of regional and local structure with accompanying geologic and tectonic maps
 - e) Identification and characterization of potential reservoir unit(s)*
 - f) Presence of mineralization associated with hydrothermal systems
 - g) Detailed geological report by an approved engineering consultant
 - h) Target formation (lithology, depth of top reservoir, thickness, porosity, permeability)
- 3) Geochemical Data
- a) Location, name, and characteristics of sampling points~
 - b) Temperature (°C), pH, EC (μS) , and flow rate (approximate) at time of sampling~
 - c) Sample preservation method(s) used
 - d) Chemical analyses of collected samples~
 - e) Name of laboratory that provided analysis
 - f) Calcite inhibition treatment information (if sample is from producing well)
 - g) Names, descriptions and locations of scale or mineral deposits
 - h) Geothermometry estimates~
 - i) Interpretations and/or plots of geochemical data~
- 4) Geophysical Data
- a) Gravity surveys~
 - b) Electrical resistivity (MT)~
 - c) Seismic surveys~
 - d) Vertical electrical sounding (VES)
 - e) Remote sensing
 - f) Heat flow/temperature gradient surveys~
 - g) Other surveys
- 5) Subsurface Temperature Data
- a) Raw temperature from logs~
 - b) Flowing temperature from hot springs or wells~
 - c) Maps of temperature contours at various depths~
 - d) Cross sections showing temperature distribution~
- 6) Conceptual Model
- a) Maps and cross-sections with various data overlain*
 - b) Source concept and fluid flow direction(s)*
 - c) Rationale for new well locations*
 - d) Heat resource estimate
 - e) Power utilization concept: heat/electricity; flash/binary

- f) Geological model as a result of the exploration work
- g) Dynamic, hydrogeological model
- 7) Drilling, Logging and Testing Data
 - a) Well locations, well paths and subsurface drilling targets*
 - b) Well design(s) and cost estimate(s)*
 - c) Drilling program(s)* (number and position of wells, well design, bit sizes, casing/liner specifications, setting depths, well completion, DLS, deviation, MD and TVD depths etc.)
 - d) Planned stimulation methods and measures
 - e) Loss mitigation: possible alternatives (e.g. sidetracks, fracturing, acidizing etc.)
 - f) Reference data of nearby and / or similar wells
 - g) Expected output parameters (thermal, draw down, flow rate, temperature)
 - h) Well logging program (s)*
 - i) Well testing program (s)*

C) INFORMATION ABOUT DRILLING RIGS AND DRILLING SUPERVISION*

- 1) Drilling company including references
- 2) Detailed specifications and photographs of drilling rigs used or planned
- 3) Drilling programs for wells already drilled and those to be drilled
- 4) List and qualifications for sub-contractors for specialized services
- 5) CVs of drilling managers, supervisors, company men
- 6) Detailed specifications and photographs of drilling rigs used or planned
- 7) Drilling programs for wells already drilled and those to be drilled
- 8) List and qualifications for sub-contractors for specialized services
- 9) CVs of drilling managers
- 10) Information regarding geothermal experience of drilling crew

D) ENVIRONMENTAL REGULATORY INFORMATION*

- 1) Determination of requirement for EIA
- 2) Documentation of environmental clearance and other permits required
- 3) Copy of Conservation Areas Survey Report defining environmental stipulations
- 4) Copies of annual exploration and/or operation activity reports submitted to the SPA
- 5) Developer's plans to convert from Exploration License to Production License

E) INFORMATION ON COMMERCIAL ASPECTS OF THE PROJECT~

- 1) Plan for electricity sales and retail or wholesale distribution
- 2) Description of project structure
- 3) Forward-looking financial projections
- 4) Description and value of the assets or equipment to be insured

F) INFORMATION ABOUT THE PROJECT DEVELOPER'S COMPANY*

- 1) Information about the insured company
- 2) Basic company information (type, structure, ownership, finances, related companies, etc.)
- 3) Experience of senior management with drilling and natural resource development
- 4) Organization and management structure
- 5) Professional technical staff and their experience
- 6) Number, type and experience of support staff
- 7) Geology and Engineering Company (incl. CV & references)

* denotes necessary data/information

~ denotes data/information that would be preferred

In an ideal scenario, all of the * and ~ data would be provided, as well as additional data from this list

APPENDIX A4: EXAMPLE TABLE OF CONTENTS FOR RESOURCE REVIEW REPORT

The following table of contents is an example of a detailed resource report. Not all geothermal fields will have this much data available, therefore many reports will not be this extensive. However, this provides an example with all data types collected and analyzed.

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