BEST PRACTICES GUIDE FOR GEOTHERMAL EXPLORATION

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Prepared by

IGA
International Geothermal Association

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About this Guide

This edition of the Best Practices Guide for Geothermal Exploration has been written under the direction of the IGA Service GmbH. The Guide builds on an earlier exploration guide (Geothermal Exploration Best Practices: A Guide to Resource Data Collection, Analysis, and Presentation for Geothermal Projects, IGA Services GmbH, 2013) prepared by IGA Service GmbH, the owner of this publication. The work is managed by IFC, using funds from the Global Environmental Facility.

The senior editor of the 2nd edition is Dr. Colin Harvey, assisted by Dr. Graeme Beardsmore. Contributions are by Dr. Colin Harvey, Harvey Consultants Ltd., New Zealand; Graeme Beardsmore, Hot Dry Rocks Pty Ltd., Australia; Dr. Inga Moeck, University of Alberta, Canada; and Dr. Horst Rüter and Stefan Bauer, HarbourDom GmbH, Germany. The Guide was reviewed externally by Tom Harding-Newman, Magnus Gehringer, and Patrick Avato of IFC; Dr. Christopher Richard, BCS Incorporated supporting the U.S. Department of Energy; Joel L. Renner, Idaho National Laboratory, retired; Dr. Patrick Dobson, Lawrence Berkeley National Laboratory ; Edward Knight of Arup, Turkey; Matthias Tönnis, Munich Re; Prof. Umran Serpen, Istanbul Technical University; Dr. Ladislaus Rybach, GEOWATT AG and ETH Zurich; Dr. Kasumi Yasukawa, National Institute of Advanced Industrial Science and Technology, Japan; Dr. Orhan Mertoglu and Nilgun Basarir of the Turkish Geothermal Association.

About IGA Service GmbH and the International Geothermal Association

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TABLE OF CONTENTS

1. PURPOSE AND STRUCTURE OF THE GUIDE 11
1.1. Geothermal Exploration Best Practices........ 13
1.2. Standard Protocols for Estimating and Reporting Geothermal Potential 13
1.3. Outline of the Guide 14
1.4. Exclusions 15
1.5. Risk 16
1.5.1. Introduction........ 16
1.5.2. Risk Reduction through Exploration 17
1.5.3. Risk Reduction through Test Drilling 18
1.5.4. Resource Sustainability Risk........ 19
1.6. Relevant Literature 19

2. CATALOG OF GEOTHERMAL PLAY TYPES........ 21
2.1. Introduction........ 23
2.2. The Geothermal Play: Definition and Concept 24
2.3. Geological Perspective on Geothermal Play Types 25
2.4. Convection-Dominated Play Types 27
2.4.1. CV1a: Magmatic Play Type, Active or Recent Magmatic Intrusion 28
2.4.2. CV1b: Magmatic Play Type, Extinct Magmatic Intrusion........ 29
2.4.3. CV2: Extensional Domain Play Type........ 31
2.5. Conduction-Dominated Play Types 32
2.5.1. CD1: Intracratonic Basin Type........ 33
2.5.2. CD2: Orogenic Belt Type........ 34
2.5.3. CD3: Basement Type 35
2.5.4. Geothermal Exploration........ 35

3. PROCESS OF GEOTHERMAL DEVELOPMENT 37
3.1. Introduction........ 39
3.2. Phase 1: Preliminary Survey 40
3.3. Phase 2: Exploration 42
3.3.1. Conceptual Model 45
3.3.2. Non-Technical Data Compilation 45
3.3.3. Pre-feasibility Study........ 45
3.4. Phase 3: Test Drilling........ 46
3.4.1. Updating the Conceptual Model 47
3.4.2. Numerical Modeling........ 47
3.5. Phase 4: Project Review and Feasibility 47
3.6. Phase 5: Field Development 48
3.7. Phase 6: Power Plant Construction........ 49
3.8. Phase 7: Commissioning........ 50
3.9. Phase 8: Operation 50

4. DATA COLLECTION AND EXPLORATION METHODS 51
4.1. Introduction........ 53
4.2. Phase 1: Preliminary Survey 54
4.2.1. Non-Geoscientific Information 54
4.2.2. Environmental Impact and Resource Protection 54
4.2.2.1. Local Requirements 54
4.2.2.2. Baseline Environmental Data 55
4.2.3. Literature Review 55
4.2.4. Satellite Imagery, Aerial Photogrammetry, and LIDAR........ 57

4.2.5. Conclusion of Preliminary Survey ... 57
4.3. Phase 2: Exploration Methods ... 58
4.3.1. Overview ... 58
4.3.2. Geology ... 60
4.3.2.1. Mapping and Identification of Play Type ... 60
4.3.2.2. Heat Source ... 61
4.3.2.3. Hydrothermal Alteration ... 61
4.3.2.4. Mineral Geothermometers ... 62
4.3.2.5. Lithology and Stratigraphy ... 65
4.3.2.6. Geologic and Tectonic Structure ... 66
4.3.2.7. Two-Dimensional (2D) Geologic Cross-Sections ... 66
4.3.2.8. Three-Dimensional (3D) Geologic Models ... 67
4.3.2.9. Geological Hazards ... 67
4.3.3. Geochemistry ... 67
4.3.3.1. Overview ... 67
4.3.3.2. Active Geothermal Features ... 68
4.3.3.3. Fluid and Gas Sampling Procedures ... 70
4.3.3.4. Assumptions and Applications of Chemical Geothermometers ... 71
4.3.3.5. Selection of Appropriate Geothermometers ... 72
4.3.3.6. Use of Triangular Diagrams and Chemical Ratios to Develop Mixing Models ... 73
4.3.3.7. Geochemical Modeling Software ... 77
4.3.3.8. Carbon Dioxide Flux and Soil Sampling ... 77
4.3.3.9. Summary of Geochemical Data ... 78
4.3.4. Geophysics ... 79
4.3.4.1. Gravimetric Surveys ... 80
4.3.4.2. Geomagnetic Surveys ... 84
4.3.4.3. Magnetotelluric Surveys ... 87
4.3.4.4. Controlled Source Electromagnetic Surveys ... 92
4.3.4.5. Electrical Resistivity (Direct Current) ... 94
4.3.4.6. Self-Potential Methods ... 95
4.3.4.7. Seismic Surveys ... 97
4.3.4.8. Ground Temperature Mapping ... 103
4.3.4.9. Heat Flow (or Thermal Gradient) Drilling ... 104
4.3.5. Laboratory Measurements on Shallow Cores, Cutting, and Outcrop Samples ... 108
4.3.6. Stress Field Estimates ... 109
4.4. Conceptual Model ... 113
4.5. Numerical Model ... 117
4.6. Justification to Proceed to Test Drilling (Phase 3) ... 118

5. STRATEGIES FOR GEOTHERMAL EXPLORATION AT MAGMATIC (CV1) PLAYS ... 119
5.1. Introduction ... 121
5.2. Conceptual Models ... 121
5.2.1. Water-dominated Volcano/Pluton-Hosted Systems ... 121
5.2.2. Vapor-Dominated Volcano/Pluton-Hosted Systems ... 123
5.2.3. Graben-Hosted Systems in CV1 Plays ... 125
5.3. Exploration Methods for Geothermal Systems in CV1 Plays ... 126
5.3.1. Satellite Imagery, Aerial Photogrammetry, and LIDAR ... 126
5.3.2. Geology and Mineralogy ... 126
5.3.3. Geochemistry ... 128
5.3.4. Geophysics ... 129
5.3.4.1. Surface Heat Flow ... 130
5.3.4.2. Temperature Gradient Drilling ... 130

5.3.4.3. Seismics 130
5.3.4.4. Resistivity (Excluding Magnetotellurics) 130
5.3.4.5. Magnetotellurics 132
5.3.4.6. Gravity 133
5.3.4.7. Magnetics 133
5.4. Development and Updating the Conceptual Model 133
5.5. Prioritization of Target Areas 134

6. STRATEGIES FOR EXPLORATION IN CONVECTION-DOMINATED EXTENSIONAL DOMAIN (CV2) PLAYS 135
6.1. Introduction 137
6.2. Structural Setting of Extensional Domains 138
6.3. Exploration Methods 140

7. EXPLORATION FOR CONDUCTION-DOMINATED PLAYS 143
7.1. Introduction 145
7.2. Techniques that Reveal Basin Geometry and Composition 145
7.2.1. Existing Geological Information 146
7.2.2. Gravity and Magnetics 146
7.2.3. 2D/3D Reflection Seismic Technologies 146
7.2.4. Structural Geology 147
7.3. Techniques Constraining the Distribution of Temperature 147
7.3.1. Existing Subsurface Temperature Data 148
7.3.2. Heat Flow Drilling 148
7.3.3. Rock Property Measurements 149
7.3.4. Numerical Conductive Heat Flow Modeling 149
7.4. Techniques Reducing Uncertainties in Estimates of Hydrogeological Properties of Reservoir Units 149
7.4.1. Seismic Sequence Stratigraphy for Porosity/Permeability Prediction 150
7.4.2. Diagenesis Investigation 150
7.4.3. Seismic Attributes for Porosity Estimates 151
7.4.4. Magnetotelluric Polarization for Identifying Fractured Rock 151
7.4.5. Seismic Shear Wave Splitting for Identifying Fractured Rock 152
7.4.6. Stress Field Analysis and Geo-mechanical Modeling 152
7.5. Exploration Outcomes 152

8. REQUIREMENTS FOR THE PRE-FEASIBILITY STUDY 153
8.1. Introduction 155
8.2. Preliminary Information 155
8.3. Environmental Impact and Resource Protection 155
8.4. Collection of Baseline Data 156
8.5. Literature Review 156
8.6. Active Geothermal Features 157
8.7. Geology 157
8.8. Geochemistry 158
8.9. Geophysics 158
8.10. Drilling Data 158
8.11. Conceptual Model 159
8.12. The Pre-feasibility Study and Financial Justification to Proceed 159

9. APPENDIX A1: Table of Contents Example for Pre-feasibility Report............. 161

10. Glossary of Terms 165

11. References 179
- 11.1. Chapter 1 179
- 11.2. Chapter 2 180
- 11.3. Chapter 3 184
- 11.4. Chapter 4 185
- 11.5. Chapter 5 190
- 11.6. Chapter 6 192
- 11.7. Chapter 7 193
- 11.8. Chapter 8 194

1. 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 commitment of any significant capital investment. While presenting the framework, information, and guidelines for best practices for geothermal exploration, this Guide will assist geothermal developers, contractors, and investors to address early-stage risks in a cost-sensitive manner and to raise project quality.

Though significant growth in electricity generation from geothermal energy has occurred worldwide in recent years (Bertani, 2010), the high-risk cost of drilling to confirm the existence of a viable geothermal resource remains one of the key challenges facing the industry. However, following best practices in the exploration stage will reduce the uncertainty of the resource's location, size, and productivity characteristics, which in turn will lower the risk during the drilling phase.

This Guide can be used by developers and contractors to identify the most appropriate tools and techniques to define the resource, and by investors to ensure that projects have made all reasonable effort to reduce risks.

A test of best practices 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 transmissivity (or permeability-thickness), which together determine the rate and sustainability of thermal power output from producing wells. Reservoir volume, chemistry, and depth are also important criteria. Each component of a geothermal exploration program should be clearly designed to address one or more of these risk elements, and each risk element should also be addressed in some manner. Through exploration, a developer should aim to provide potential financiers with at least a qualified (and ideally quantified) estimate of the uncertainty associated with forecasting thermal energy production and a sensitivity analysis on potential levels of net power production.

1.2. Standard Protocols for Estimating and Reporting Geothermal Potential

At present, there is no internationally accepted standard protocol to estimate and report the potential of geothermal energy. The major countries harnessing geothermal energy for electric power generation each have their own methodologies and classification schemes to estimate and report potential. Only two countries (Australia and Canada) at this time have adopted formal geothermal reporting codes (see Section 1.6). These codes expound the principles of transparency, materiality, and accountability for presenting geothermal exploration results and estimates of future geothermal power generation. The current standard practice on developed geothermal fields is to calculate field capacities based on numerical simulation, once sufficient data are available. At the time of print, the global geothermal community, through the IGA, is working towards developing standard international protocols for adoption in other parts of the world.

1.3. Outline of the Guide

This Guide provides developers with an outline of various methodologies and strategies employed in the exploration for geothermal resources for power generation. This is done within the context of the typical geothermal development process, recognizing that the most appropriate exploration tools strongly depend on the geological setting of the project.

This first chapter was prepared by Colin Harvey and Graeme Beardsmore. The chapter provides an introduction to the topic and the scope of the Guide.

Chapter 2 was prepared by Inga Moeck. The chapter introduces the concept of geothermal play types and describes the range of geological settings in which potentially exploitable geothermal systems may be present. The geothermal play type is a corollary to play types used in the oil and gas sector and classifies the geological setting of a geothermal resource, which impacts the most suitable approach to exploration.

Chapter 3 was prepared by Colin Harvey. The chapter gives an overview of the typical sequence of phases in any geothermal exploration and development program with reference to various geothermal play types. The Guide divides the geothermal development process into eight phases, in line with ESMAP's Geothermal Handbook (Gehringer and Loksha, 2012). International developers or their consultants may divide the process into a different number of phases, but the core elements of the process are essentially the same in all cases. These are the eight phases:

Phase 1: Preliminary Survey
Phase 2: Exploration (includes temperature gradient drilling)
Phase 3: Test Drilling (deep drilling)
Phase 4: Project Review and Planning
Phase 5: Field Development
Phase 6: Power Plant Construction
Phase 7: Commissioning
Phase 8: Operation

Chapter 4 was prepared by Horst Rüter, Colin Harvey, Graeme Beardsmore, Inga Moeck, and Stefan Bauer. The chapter includes a "tool box" for geothermal exploration and gives a detailed breakdown of the range of methodologies currently used and perhaps appropriate to reduce geothermal resource risk prior to raising funds for the Test Drilling Phase (Phase 3). The list of techniques is extensive, and new methodologies and techniques are continuing to be developed and applied. The developer or the exploration manager should select the most appropriate and cost effective set of methodologies to reduce overall risk.

Only a subset of the tools presented in Chapter 4 would be appropriate for any given project. Understanding which tools are the most appropriate and under which circumstances is the key to carrying out an efficient and effective exploration program. The exact choice is unique to each project, but certain sets of tools are commonly associated with specific play types.

The subsequent chapters present high-level discussions about the most appropriate and commonly used tools for convection-dominated magmatic plays (Chapter 5, prepared by Colin Harvey); convection-dominated extensional domain plays (Chapter 6, prepared by Inga Moeck); and conduction-dominated plays (Chapter 7, prepared by Horst Rüter and Graeme Beardsmore). The discussions focus on geoscientific tools. Non-technical and environmental requirements common to all play types addressed in Chapters 3 and 4 are not considered any further in subsequent chapters.

Chapter 8, prepared by Colin Harvey, lists the data sets that should be assembled by a developer and how they should be combined, both to ensure a comprehensive exploration study and to aid with presenting this to investors.

Appendix A1 provides a table of contents for a typical pre-feasibility report.

1.4. Exclusions

This Guide specifically addresses the first two phases of the typical development pathway to geothermal resources for power generation up to the conclusion of the Exploration Phase. The Guide is intended to present a developer with an appropriate set of exploration tools in order to minimize financial risk in different geological settings prior to raising funds for the Test Drilling Phase. However, the Guide does not discuss geothermal drilling, except in the context of shallow wells for temperature gradient or heat flow measurements. Drilling to reservoir depth is assumed to be part of the Test Drilling Phase and is beyond the scope of this Guide. Moreover, the Guide does not address the range of power generation technologies which may be used.

The advice in this Guide may not be entirely appropriate for the exploration for low-temperature geothermal resources for direct use, ultra-high temperature developments, or other less conventional or unconventional geothermal developments.

The Guide does not address policy, regulatory and planning frameworks, or project economics. As such, the Guide is of limited use to governments, development banks or other international funding agencies for designing programs to promote investments in geothermal energy. The recently released ESMAP Geothermal Handbook (Gehringer and Loksha, 2012), considered a companion document to this Guide, addresses these topics.

1.5. Risk

1.5.1. Introduction

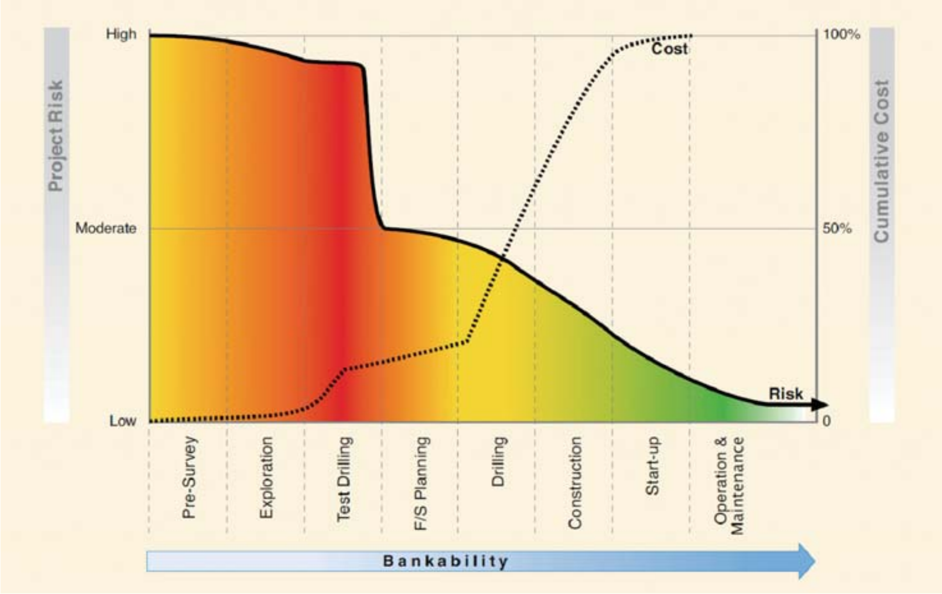
In financial term risk can be defined as “the potential for financial loss.” Financial risk increases proportional to the size of an investment and the uncertainty of making a return on that investment. Geothermal projects are high-risk investments during the early stages of exploration and development (Phillips et al., 2013) because they require significant financial commitments at a stage when uncertainty about the viability of the resource remains high.

At the early stages, the principal component of risk of a geothermal project is the uncertainty associated with a natural resource that cannot be readily observed or characterized without relatively large expenditures for drilling. The long lead times required to develop geothermal projects exacerbate this risk by prolonging the period until financial returns are realized. This high-risk profile makes it difficult to attract financing for early-stage project development.

Figure 1.1 illustrates typical uncertainty and expenditure profiles associated with a geothermal project. The highest financial risk of a geothermal project occurs in the lead-up to the Test Drilling Phase when uncertainty is still high. Although test drilling provides information substantially reducing the uncertainty of the viability of geothermal resource, it does so at significant up-front cost and risk. This high-risk barrier is frequently the stumbling block or hurdle to a project’s further progress (Gehringer and Loksha, 2012).

Figure 1.1. Typical uncertainty and expenditure profiles for a geothermal project.

Source: Gehringer and Loksha, 2012.



The return on investment (ROI) for a project is linked to many factors including the project's capital cost, timeline for development, and price of generated power. At the early stages, however, the potential ROI has to be weighted by the probability that no viable geothermal resource will be discovered. The purpose of exploration is to efficiently and effectively minimize resource uncertainty as much as possible, thereby reducing the cost of capital. The Guide recommends appropriate tools to minimize resource uncertainty prior to test drilling.

Every major grid-connected power project faces significant risks, for example, those related to power price, demand, subsidies, government policy, and environmental and social issues. The exploration and drilling risks of geothermal projects come on top of these other risks and impact the availability of project funding at the early stages.

Numerous aid agencies and governments throughout the world have recognized the risk profile of the Test Drilling Phase as a barrier to geothermal development. Risk mitigation funds have been established in some jurisdictions to assist projects through this phase (Sanyal & Koenig, 1995; Sanyal and Morrow, 2012; Sanyal et al., 2011). Risk mitigation funds decrease financial risk by either reducing the amount of capital invested by the financier (i.e., a grant scheme) or by increasing the ROI to investors over the project's life (e.g., through feed-in tariffs) or by decreasing the uncertainty that the capital will be recovered (i.e., an insurance scheme; Kreuter and Schrage, 2010).

However a project is financed, maximum ROI is only achieved if wells produce at or above their predicted outputs. Maximizing the probability of achieving adequate well productivity relies on high quality exploration methods and interpretation, as outlined in this Guide.

1.5.2. Risk Reduction through Exploration

The quality of exploration work prior to Test Drilling Phase (Phase 3) is a critical factor for reducing well productivity risk. 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 uncertainties associated with estimates of temperature, depth, productivity, and sustainability of the geothermal resource in the specific circumstances of each project.

Selecting appropriate techniques at the correct phases of an exploration program is important for optimal efficiency and maximum risk reduction prior to the Test Drilling Phase (for examples,see Antics & Ungemach, 1995). Experienced interpretation of data collected with these geoscientific techniques enables a geothermal geoscience team to develop a "conceptual model" of the heat source and fluid flow in a geothermal system (Cumming, 2009). No single exploration technique provides the key to a successful conceptual model, and ultimately no conceptual model can be confirmed except through test drilling.

This Guide provides advice on which exploration techniques are most appropriate at different stages and in different geological settings. The most effective risk reduction is achieved by sequentially applying the exploration techniques appropriate for the geological setting, followed by experienced interpretation.

1.5.3. Risk Reduction through Test Drilling

The successful completion of the Test Drilling Phase dramatically reduces the overall uncertainty for the project (Figure 1.1), and investment capital is typically easier to secure at that time. Test drilling confirms (or refutes) the existence of a geothermal reservoir that warrants continued appraisal, thus validating (or refuting) the conceptual model developed during the preceding project phases. Key parameters that test drilling aims to confirm include temperature, transmissivity, flow potential, and fluid chemistry, as well as the location and areal extent and depth of the reservoir (for an example, see Sperber et al., 2010).

The locations for the test wells are determined based on the data gathered during the Exploration Phase (Phase 2). Therefore, carrying out the exploration in line with best practices reduces the risks during the Test Drilling Phase.

Test drilling aims to substantially reduce uncertainties associated with reservoir characteristics, but there are significant risks and costs associated with drilling activities themselves. The risks are a function of the drilling conditions, ranging from logistical considerations such as drill pad location and timely availability of equipment and services, to technical considerations such as the stability of the rock 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. Costs are a function of the drilling location, mobilization costs, the intended drilling depth, well bore diameter, casing depth requirements, and the length of inclined or deviated wells.

If target depths are shallow, then it may be possible to obtain sufficient information to prove the existence of a viable resource, using a relatively small and inexpensive 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 test drilling program should be designed with an aim to reduce uncertainties, associated with the extent, characteristics, and sustainability of the geothermal resource, to a level where significant expenditure can be justified for the Project Review Phase (Phase 4) and subsequent development. To achieve this goal, the optimal number of test wells will vary from project to project. A minimum of two or three wells is a typical compromise between resource appraisal and cost for convection-dominated geothermal plays. However, prudent planning is recommended for additional wells due to the possibility of engineering or logistical failures. A single test well might be optimal for conduction-dominated geothermal plays where drilling costs are greater but reservoir parameters are laterally less variable.

Interesting to note is that a recent review of drilling data for over 2,600 geothermal wells around the world (IFC, 2013) found that the “success” rate for the first well drilled to test a new reservoir was about 50 percent. The average success rate rose to 59 percent over the first five wells, to 74 percent during field development, and averaged 83 percent for wells drilled in operating fields.

Sanyal and Morrow (2012) previously carried out a survey on the majority of the more than 4,000 geothermal wells that had been drilled worldwide. While widely different success rates were encountered during the Exploration Phase, they concluded that improved success rates and faster drilling were almost always achieved in geothermal fields where local knowledge was obtained through experience. All these numbers depend on how the word success is defined with respect to an economic well production rate.

1.5.4. Resource Sustainability Risk

Geothermal power plants are built as long-term infrastructure, typically with a 30-year or more design life. The size of a plant is limited to what can be sustainably developed from the resource. The geothermal resource must consistently and reliably provide geothermal fluid to the plant during its full design lifetime. During this period, resource degradation risks include these factors:

- Faster-than-anticipated decline in pressure or production rate
- Premature cooling (either from injection water breakthrough or from incursion of cool groundwater)
- Adverse chemical effects such as increases in non-condensable gas levels or changes in reservoir conditions leading to scaling (for an example, see Lichti et al.,2005; and Salonga and Lichti, 2005)

The resource can degrade at various times during the exploitation history, but early indications can often be detected from Test Drilling Phase through the first few years of production. Implementation of a robust reservoir-monitoring program, combined with a reliably calibrated reservoir model, is essential for detecting and remedying resource degradation at an early stage (Clearwater et al., 2011). The Exploration Phase is critical in preparing the groundwork for this reservoir model. Baseline data, against which production data can be compared, should be collected during the exploration and test drilling.

1.6. Relevant Literature

A very large body of literature now exists relating to geothermal development. A comprehensive database of papers presented at geothermal conferences can be accessed through several websites, including those of the Geothermal Resources Council, the IGA, and Stanford University. Here is a list of overview publications that may provide useful background reading.

- Planning and finance: Gehringer, M. and Loksha, V. (2012). Geothermal Handbook: Planning and Financing Power Generation. ESMAP / World Bank, Washington, D.C., 150 pp. Available at www.esmap.org.
- 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 Geothermal Risk Mitigation Strategies Report.Department of Energy/ Office of Energy Efficiency and Renewable Energy Program. February 15, 2008. http://www1.eere.energy.gov/geothermal/pdfs/geothermal_risk_mitigation.pdf
- Environment: IFC/World Bank 2007: Environmental Health and Safety Guidelines for Geothermal Power Generation. Retrieved from http://www.ifc.org/sustainability
- Drilling success: IFC Success of Geothermal Wells – A Global Study. International Finance Corporation, member of the World Bank Group, 76 pp. http://www.ifc.org/wps/wcm/connect/7e5eb4804fe24994b118ff23ff966f85/ifc-drilling-success-report-final.pdf?MOD=AJPERES
- Reporting code: Australian Geothermal Reporting Code Committee: Australian Code for Reporting of Exploration Results, Geothermal Resources, and Geothermal Reserves (2nd edition, 2010). http://www.agea.org.au/media/docs/the_geothermal_reporting_code_ed_2.pdf

Reporting code: Canadian Geothermal Energy Association: The Canadian Geothermal Code for Public Reporting (2010). http://www.cangea.ca/geothermal-code-for-public-reporting.html

2. CATALOG OF GEOTHERMAL PLAY TYPES

2.1. Introduction

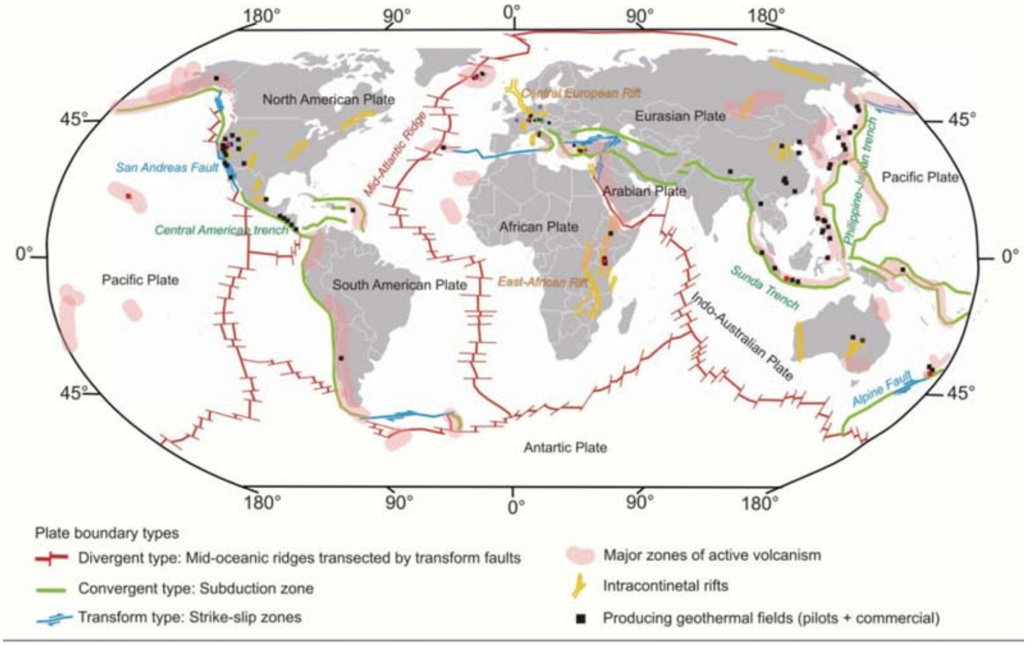
The characteristics of natural geothermal reservoirs cover a wide spectrum in terms of temperature, depth, geometry, geology, and fluid chemistry. It is natural and useful to try to divide this broad spectrum of reservoirs into groups with similar characteristics and development strategies. Many such schemes have previously been published, with groups defined, mainly according to the temperature, thermodynamic properties, or depth of the reservoir. Such schemes are useful to guide decisions on drilling, reservoir engineering, and plant design based on previous experiences with similar reservoirs. They do not, however, help with the design of exploration programs because the reservoir characteristics cannot be known (by definition) until exploration is complete. Exploration strategy is best guided by considering the geological setting of the geothermal system under investigation. To that end, exploration advice in this Guide is based on a catalog of geothermal play types.

The advice presented in this Guide is based on a catalog of geothermal play types representing sets of geological circumstances that may host accumulations of potentially recoverable heat (Moeck, 2014). The term geothermal play type is analogous to the lowest level of the classification scheme for petroleum systems defined by the Petroleum Resources Management System of the Society of Petroleum Engineers (SPE-PRMS, 2007). Petroleum “play types” represent particular stratigraphic or structural geological settings that include all the components necessary for a potentially economic accumulation of petroleum: a source rock, reservoir rock and trap (Allen and Allen, 2005). Translated to geothermal systems, a geothermal play type might be defined as a geological setting that includes a heat source, heat migration pathway, heat/fluid storage capacity, and the potential for economic recovery of the heat.

Understanding and characterizing the geological controls on geothermal systems has been the topic of many ongoing studies, which have focused on different scales, from plate tectonics (e.g. Muffler, 1976; Heiken, 1982), to local tectonics/structural geology (Faulds et al., 2010), to well logs and cores (Leary et al., 2013). The characteristics of individual geothermal systems are a function of site-specific variables such as the nature and depth of the heat source; the dominant heat transfer mechanism; permeability and porosity distribution; rock mechanical properties; fluid/rock chemistry; and fluid recharge rates/sources. The catalog on which this Guide is based defines six broad geothermal play types according to plate tectonic setting, the nature of the heat source (magmatic or non-magmatic), and whether the dominant heat-transfer mechanism is convection or conduction (Figure 2.1). The division of geothermal play types is independent of the subsequent heat recovery strategy. The Guide applies to all geothermal systems, including “engineered (or enhanced) geothermal systems” (EGS), thus recognizing that ongoing technological development and economic subsidies are increasing the range of potentially economic geothermal systems.

Figure 2.1. Plate tectonic setting of installed geothermal systems worldwide[1]

Source: Gehringer and Loksha, 2012.



Geothermal plays with geothermal production projects

CV1a - Magmatic: active or recent magmatism: Taupo (New Zealand), Kamojang (Indonesia), Reykjanes (Iceland), Puna (Hawai/USA)
CV1b - Magmatic: inactive/extinct magmatism: Larderello (Italy), The Geysers (USA)
CV2 - Non-magmatic: Extensional domain type: Bradys (Nevada/USA), Kizildere (Turkey), Soulz-sous-Forets (France)
CD1 - Intracratonic Basin Type: Neustadt-Glewe [heat] (Germany), Paris Basin [heat] (France)
CD2 - Orogenic Belt Type: Unterhaching (Germany), Altheim (Austria)
CD3 - Basement (hot dry rock) Type: Habanero (Australia)

2.2. The Geothermal Play: Definition and Concept

The term play type is commonly used during mineral and petroleum resource exploration processes. A "geothermal play" may be thought of as a conceptual model in the mind of a geologist of how a number of geological factors might generate a recoverable geothermal resource at a specific structural position in a certain geologic setting. The identification of a play is the first step in any project development. The aim of the geothermal play concept is to group similar geological settings that might host exploitable geothermal resources, and to develop site-specific exploration strategies that may lead to resource discovery and estimates of reserves. A geothermal play is defined only on the basis of geological setting, and has no economic implication other than providing a basis for an economic assessment.

The term geothermal play is used by the Australia Geothermal Reporting Code (2010) to qualitatively describe heat accumulations in the earth's crust and is clearly discriminated from terms used to quantify energy potential. The play fairway concept for hydrothermal systems has been defined as a geographic area over which favorable combinations of heat, permeability, and fluid are thought to extend (Phillips et al., 2013). King and Metcalfe (2013) applied the geothermal play concept in their description of rift zones, defining a play as "a repeating set of prospects with common characteristics".

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[1] The abbreviation CV indicates convection is the dominant heat transfer mechanism, while CD indicates conduction is the dominant heat transfer mechanism. Geothermal fields from http://geothermal-powerplant.blogspot.com; www.thinkgeoenergy.com; Zheng and Dong, 2008; Plate tectonic map based on Frisch and Loeschke, 2003.

The general ingredients of a geothermal play are heat source and heat transport, permeability structure (faults, stratigraphy) and the presence of fluid volume and a storage system (porosity, fracture network). The set of geothermal play types adopted for this Guide (Moeck, 2014) synthesizes previous groupings of geothermal systems identified by Rybach (1981) and Hochstein (1988) with play concepts used by the petroleum industry and the above-mentioned recent definitions of geothermal plays. The main division of geothermal play types follows that of Rybach (1981) based on the dominant heat transfer mechanism, namely, convective- and conductive-dominated geothermal plays. Convective geothermal plays can be either magmatic ("hydrothermal systems," ibid.) or fault controlled in extensional domains ("circulation systems," ibid.). Magmatic and extensional domain types are consistent with the opinion of Hochstein (1988), who separated volcanic from non-volcanic systems. The age of a magmatic system, volcanic field, basin, or tectonic cycle is an important geological parameter in defining geothermal plays.

2.3. Geological Perspective on Geothermal Play Types

The plate tectonic setting has a fundamental influence on the types of geothermal plays that might exist in a region. The plate tectonic framework controls the thermal regime, hydrogeological regime, fluid dynamics, fluid chemistry, faults and fractures, stress regime, and lithological sequence (Rybach, 1981; Bogie et al., 2005). The thermal state of the crust at active plate boundaries is typically far more dynamic than intraplate and tectonically quiescent settings.

The broadest division of geothermal play types defined in this Guide is determined by the dominant mode with which heat is transferred from the heat source to the reservoir, consistent with the previous division of Rybach (1981). Generally, naturally occurring heat transfer within geothermal systems is dominated at the system scale by either convection or conduction. In this Guide, we use the word convection to denote all modes of shallow and deep natural groundwater flow. These include thermally driven flow and hydraulic gradient driven flow ("advection" or "heat sweep" as defined by Hochstein et al., 2013), as well as buoyancy driven flow due to different concentrations of salinity. Whether convection or conduction dominates with respect to heat transport depends primarily on the characteristics of the heat source and the distribution of permeability within the host rocks at the system scale (Bogie et al., 2005; Lawless et al., 1995). Important to recognize is that in all instances, however, convection and conduction are end-members of a heat transfer continuum. Conductive intervals always exist in localized parts of a convective regime, while minor convective intervals can sometimes exist within conductive systems, depending on the porosity and permeability structure of the site. For example, gravity-driven convection might occur within a discrete permeable aquifer within a conduction-dominated thermal regime in steep mountainous terrain where the recharge zone is at a higher elevation than the discharge site.

In greenfield exploration, whether heat transport is dominated by convection or conduction might not be initially clear. To predict which mode is likely to dominate, it is important to understand the geological controls on heat transport. For example, fractures often control the transport of fluids (and hence heat), so if the dominant heat transport mode is poorly understood then it may be critical to investigate fracture networks and their relationship to the present-day stress field to determine their ability to channel fluids. This example illustrates the value of the exploration play concept: applying an understanding of the geological controls on geothermal systems for exploration and targeting.

Six geothermal play types are described in the following sections based on the primary delineation of convection-dominated and conduction-dominated heat transport. Convection-dominated plays are further divided into magmatic/plutonic types (i.e., igneous, thermally driven convection) and non-magmatic, fault- and fracture-controlled extensional domain types, referring to the nature of the dominant heat source and tectonic setting. Conduction-dominated plays are further divided according to their dominant permeability control: lithofacies, fractures, or a combination of both.

While each play type lies within a geological continuum and specific geothermal systems can possibly have geological characteristics of more than one play type, Table 2.1shows that currently developed geothermal systems can largely be grouped into three main play categories. It is obvious from these figures that most of the developed geothermal systems in the world can be categorized as convection-dominated magmatic play types. The development of conduction-dominated geothermal plays has predominantly been restricted to Europe (specifically Germany), where the regulatory framework has nurtured their development. Developed extensional domain plays are mainly located in the Basin-and-Range Province in the United States and in Western Turkey.

Table 2.1. Geothermal systems (187) developed worldwide, grouped by play types and regions

Sources: Systems drawn from www.thinkgeoenergy.com; www.geotis.de; Zheng and Dong (2008).

Region Play type	The Americas Eastern Pacific	Asia Pacific	Europe Atlantic Africa
Convection-dominated plays			
Magmatic play type *Geologic controls:* Intrusion of different age, hydrothermal *Geologic setting:* active to extinct volcanic fields (convergent, divergent, transform faults, hot spots, plumes)	46	57	36
Extensional domain type *Geologic controls*: active faults, amagmatic, high porosity, high permeability strata *Geologic settings:* active rifts, metamorphic core complexes, back-arc basins, segmented strike-slip faults	21	4	11
Conduction-dominated plays			
Geologic controls: Faults, fractures, lithofacies, diagenesis *Geologic settings:* sedimentary basins, basement provinces, orogenic belts	0	2	10

2.4. Convection-Dominated Play Types

In convection-dominated geothermal plays, heat is transported efficiently from depth to shallower reservoirs or the surface by the upward movement of fluid along permeable pathways. Laterally extensive, porous high-permeability formations act as the primary reservoirs. Convection-dominated geothermal plays are grouped primarily according to the nature of the heat source.

Convection-dominated geothermal play types (CV1-CV2 in Figure 2.1) include those often referred to as viable or active geothermal systems (Gianelli and Grassi, 2001). They include all known “high-temperature” (greater than 200°C) geothermal reservoirs shallower than 3,000 meters. These invariably lie adjacent to plate tectonic margins or in regions of high tectonic activity (Nukman and Moeck, 2013; Hickman et al., 2004), high volcanic activity (Bogie et al., 2005), young plutonism (less than three million years old), or regions with elevated heat flow due to crustal thinning during the extension of the crust (Faulds et al., 2009, 2010).

Favorable tectonic settings for convection-dominated geothermal play types include magmatic arcs above subduction zones in convergent plate margins (e.g., Indonesian Sunda Arc or Philippine-Japan Arc); divergent zones located within oceanic (e.g., Mid-Atlantic Ridge) or intracontinental settings (e.g., East African Rift or extensional provinces); transform plate margins with strike-slip faults (e.g., San Andreas Fault in California); and intraplate ocean islands formed by hot spot magmatism (e.g., Hawaii). It is possible for different types of convection-dominated plays to lie geographically close to each other where the structural setting varies over short distance scales.

The age of magmatism is an important indicator of the presence of a heat source and heat accumulations. Active and recent magmatism often indicates an excellent underlying heat source (McCoy-West et al., 2011), while inactive or extinct magmatism may be associated with large-scale intrusions of igneous rock (plutons) at greater depth (>5 km depth) with remnant heat and additional heating by radioactive decay in granitic rock. In this, the definitions of McCoy-West et al. (2011) are drawn on the following:

- Active magmatism: volcanism <500 years
- Recent magmatism: volcanism 500-50,000 years
- Inactive or extinct magmatism: volcanism >50,000 years

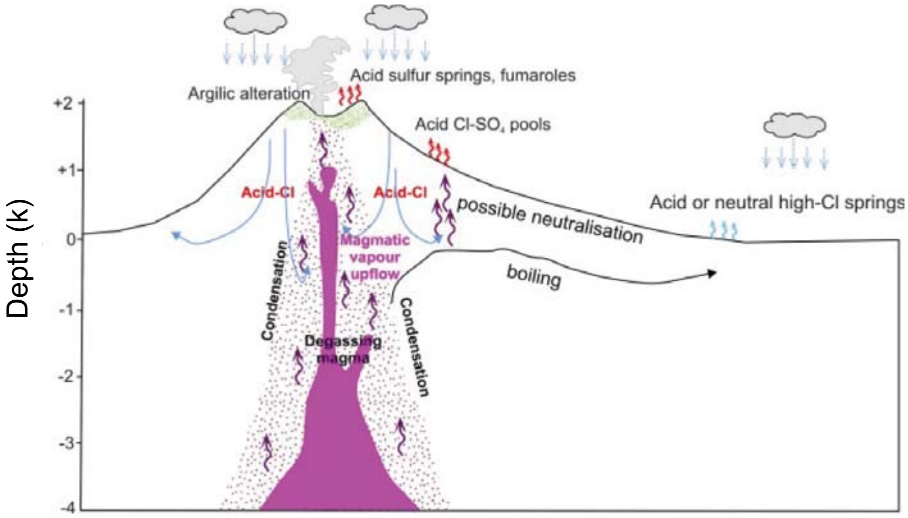
The composition of erupted volcanic material may be an indicator of the potential for an underlying heat source. Many recently active basaltic volcanoes in the Pacific and elsewhere show no evidence of surface thermal features, indicating rapid cooling. It is interesting to note that in basaltic settings where geothermal developments have been successful, subsequent evidence has emerged of shallow magmatic bodies of felsic or intermediate composition that have been created by differentiation, partial melting or partial incorporation of crustal material (Harvey and Harvey, 2010).

2.4.1. CV1a: Magmatic Play Type, Active or Recent Magmatic Intrusion

A relatively shallow magma chamber is the dominant feature in all magmatic geothermal plays. The chamber's parental melts, recharge of basalt, and crystallized melts control fluid chemistry, fluid flow, and the overall geothermal system. A magmatic geothermal play with an active or recent magmatic intrusion (CV1a) is distinguished by a shallow, intense heat source in the form of a young magma chamber (Figure 2.2). Such plays can be identified in regions with active basaltic volcanism at divergent plate margins (e.g., Iceland), basaltic to andesitic volcanism along island arcs (e.g., Java, Indonesia), or recent andesitic to dacitic volcanism (e.g., South American Andes or Japan).

Figure 2.2. Active or recent magmatic play type with eruptive magma chamber.

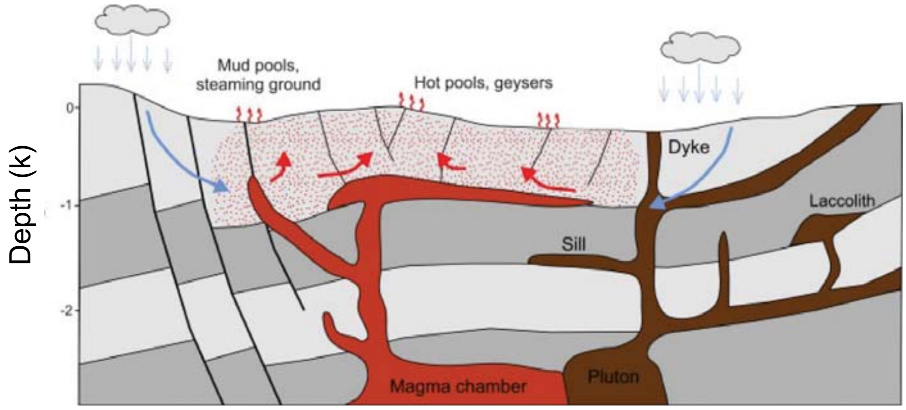
Source: From Moeck, 2014; modified after Williams et al., 2011.



Intrusions of recent (but not active) magmatic bodies underneath or in the vicinity of volcanoes commonly represent prime heat sources for geothermal developments. However, an active magma chamber does not always produce volcanism, especially if magmatism is juvenile or if the magma is siliceous (thus highly viscous and unable to reach the surface). Such magma chambers might also, however, represent heat sources for geothermal developments (Figure 2.3).

Figure 2.3. Active or recent magmatic play type with intrusive magma chamber.

Source: From Moeck, 2014.



Influenced by active faulting, deep rooted magmas can intrude beneath flat terrain with no volcanism. Basaltic intrusions are favorably associated with dilational step-over regions of major transform faults or juvenile rifts as the Imperial Valley (Salton Sea geothermal field, California) along the San Andreas Fault, or its neighboring rift arm at Cerro Prieto (Mexico). In some cases, such settings can lead to the upflow of liquid and the formation of hot springs, fumaroles, boiling mud pools, and other geothermal surface manifestations, as seen in the Taupo Volcanic Zone in New Zealand (Bogie et al., 2005).

Geothermal systems associated with the “CV1a” play type may include an upflow zone and an outflow zone, provided the topography of the volcano supports this zonation (Williams et al., 2011; Giggenbach, 1992; Hochstein, 1988). The outflow is generally modified from the original fluid, and has a lower temperature and higher pH than the upflow due to lateral migration (with associated heat loss) and loss of gases (during boiling) towards the flank of the volcano (Hochstein, 1988). Vertically extensive, low-permeability, clay-rich layers in steep terrain, such as andesitic stratovolcanoes, can cap high temperature reservoirs.

A vapor-dominated zone may develop in regions of a high heat-generating, localized magma body and moderate to high topographic relief. A single circulation system may develop at depth, generating significant liquid through flow at shallower depth and a vapor-dominated zone due to phase separation (Ingebritsen and Sorey, 1988). Steam heated discharge at higher elevation and chloride spring discharge at lower elevation are typical surface manifestations of these vapor-dominated plays. Examples of this play type can be found at several systems in the Philippines including Tongonan (Ingebritsen and Sorey, 1988 and references within).

Ultimately, the placement of the magma chamber relative to the surrounding terrain controls the geometry of the geothermal systemand affects the hydraulic head of steam and brine. Faults can act as seals or conduits, playing a role in forming reservoir compartments or hydrothermal convection, while accommodation zones of faults can sustain enhanced vertical permeability and channel hydrothermal plumes (Rowlands and Sibson, 2004).

2.4.2. CV1b: Magmatic Play Type, Extinct Magmatic Intrusion

A magmatic geothermal play with non-active or extinct magmatic intrusion (CV1b) incorporates a heat source in the form of a pluton consisting of crystalline rock enriched in heat generating elements (Figure 2.4) or a young, crystallized but still cooling, intrusive igneous body (Figure 2.5). Such play types are located where surrounding mountain ranges provide high recharge rates of circulating meteoric[2] water, driving a hydrothermal system with possible vapor partition above the hot rock. They are typically located along continent-continent convergent or transform margins with recent magmatism, such as the southern periphery of the European Alps (e.g., Italy). An example is the Larderello (Italy) geothermal system, which is controlled by the interaction between igneous rocks and faults. The system includes a vapor-dominated layer above a fluid-dominated layer (Bertani et al., 2006). The fluid-dominated layer sits above a granite intrusion emplaced during a Pliocene extensional event (1.3-3.8 million years ago). Melts emplaced during a subsequent Pleistocene magmatic event (0.2-0.3 million years ago) provide the primary heat source, while low-angle normal faults from the Pliocene event control the recharge of meteoric water into the system.

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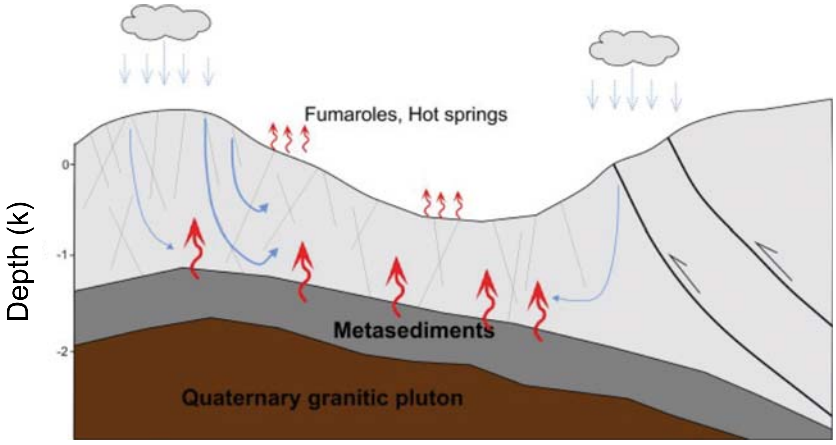
[2] Relating to or denoting water derived from the atmosphere by precipitation or condensation.

A low permeability barrier may act as cap-rock preventing the escape of steam or hot fluids to the surface. The Geysers in California is an example, where a large felsite pluton provides the heat source for a vapor-dominated fluid in a porous metasedimentary reservoir overlying the intrusion (Ingebritsen and Sorey, 1988). The reservoir rock is covered by low permeability serpentinite, mélange and meta-greywacke. There is little or no natural recharge into the reservoir, so treated sewage is injected as a means of enhancing heat recovery (Majer and Peterson, 2007).

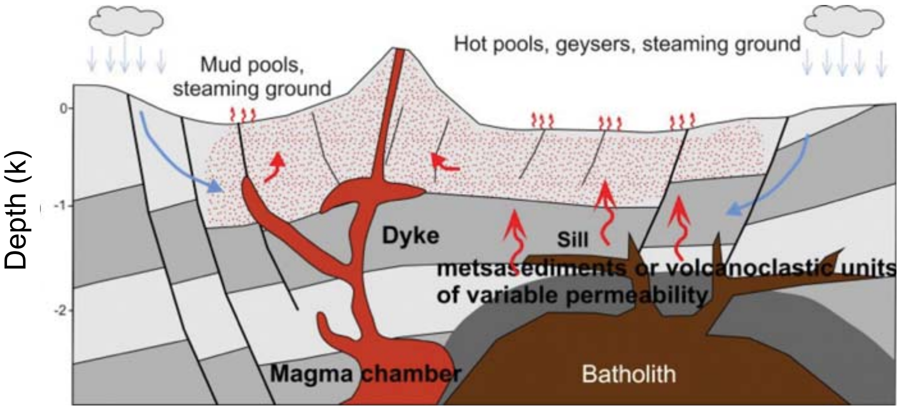
Figure 2.4. Extinct magmatic play types controlled by late Cenozoic to Quaternary plutons or batholiths without associated volcanism.



Larderello and The Geysers are thermally powered by large-scale plutons and support large-scale installations, with nearly 1 GWe of installed capacity at Larderello and 1.52 GWe of installed capacity at The Geysers. Small scale installations at Fang (Thailand) and Chena (Alaska, U.S.A.), however, are also examples of this play type.

This play type can coexist with active or recent magmatism (Figure 2.6)

Figure 2.5. Extinct magmatic play types controlled by late Cenozoic to Quaternary plutons or batholiths with associated volcanism.



2.4.3. CV2: Extensional Domain Play Type

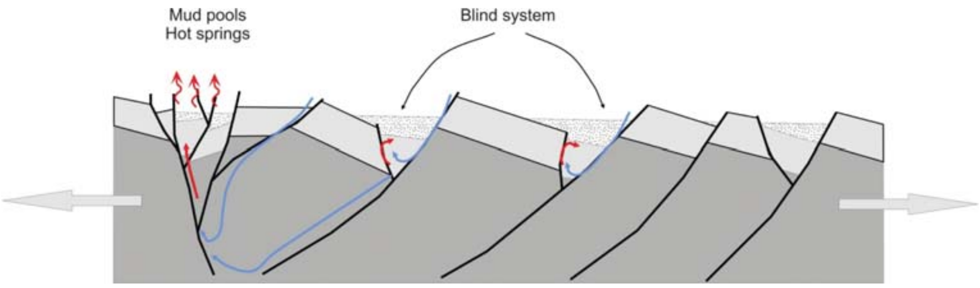
In an extensional domain geothermal play (CV2), the mantle is elevated due to crustal extension and thinning. The elevated mantle provides the principal source of heat for geothermal systems associated with this play type. The resulting high thermal gradients facilitate the heating of meteoric water circulating through deep faults or permeable formations (Figure 2.6). Examples of regions hosting extensional domain geothermal plays include the Great Basin (Western U.S.), Western Turkey, pull-apart basins along the Sumatra Fault Zone, and the East African Rift. Even the Soultz-sous-Forêts engineered geothermal system in France could be categorized as an extensional domain play type because the distribution of heat in the system is controlled by the circulation of fluids along faults and tilted sedimentary beds on an active shoulder of the Upper Rhine Graben (Genter et al., 2010; Kohl et al., 2000).

These non-magmatic play types are either “fault zone controlled” or “fault-leakage controlled” at the system scale. Hydraulic heads and hydrological budgets control the regional groundwater flow systems. In purely fault-controlled play types, meteoric water infiltrates down a shallow fault, circulates and heats through deep-seated faults, and rises along other faults (Reed, 1983). In fault-leakage controlled play types, water circulates through a combination of faults and permeable concealed formations, typically recharging and discharging (if the systems reach the surface) along fault zones. By the judicious interpretation of water chemistry in combination with isotopic analysis (particularly oxygen-deuterium), it may be possible to develop mixing models and identify the end member chemistries of the component fluids (Flynn and Ghusn, 1983).

In general, segmented faults are more favorable for geothermal systems than large faults with large offsets. The local stress regime and its orientation relative to fault geometry has a controlling impact on permeability pathways, with faults oriented perpendicular to the minimum compressive stress direction more likely to be permeable (Barton et al., 1997). Belts of intermeshing, overlapping, or intersecting faults, such as step-over regions, fault terminations and accommodation zones, often provide high permeability pathways through closely spaced, breccia[3]-dominated fracture networks (Faulds et al., 2010). In the Western United States, for example, most known geothermal fields are located at step-over regions or relay ramps (Faulds et al., 2012), while geothermal systems are relatively rare along displacement maxima or on the mid-segments of faults.

Figure 2.6. Extensional domain play type as in the Basin and Range Province (Western U.S.), showing possible fault-controlled fluid flow paths.

Note: Lateral arrows indicate direction of crustal extension.



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[3] Rock consisting of angular fragments of stones cemented by finer calcareous material.

2.5. Conduction-Dominated Play Types

Conduction-dominated geothermal play types (CD1-CD3 in Figure 2.1) include all of what could be called passive geothermal systems due to an absence of fast convective flow of fluids or short-term variations in fluid dynamics. These play types are dominant within passive tectonic plate settings where there has been no significant recent tectonism or magmatism. In these settings, temperature increases steadily (although not necessarily linearly) with depth. Conductively heated geothermal reservoirs with temperatures that might be economically productive are located at greater depth than convectively heated geothermal reservoirs. Economic viability, therefore, is closely linked to the geothermal gradient. Gradients higher than the global average can be found in regions of high heat flow (e.g., due to elevated concentrations of heat generating elements in the crust), or where overlying strata are thermally insulating (Beardsmore and Cull, 2001).

Conduction-dominated geothermal play types can be subdivided according to the natural porosity–permeability ratio within the potential reservoir rock, and the absence or presence of producible natural reservoir fluids. This Guide divides them into Intracratonic Basin Type, Orogenic Belt Type, and Basement Type. Favorable geological settings for conduction-dominated geothermal play types include extensional, divergent margins and grabens, or lithospheric subsidence basins such as the North German Basin (Germany) or the Otway Basin (Australia); foreland basins within orogenic belts, such as the Molasse Basin north of the Alps (Europe) or the Western Canadian Sedimentary Basin east of the Rocky Mountains (Canada); and crystalline basement underlying thermally insulating sediments, such as the Big Lake Suite Granodiorite beneath the Cooper Basin (Australia).

Faults do not naturally channel heat in conduction-dominated play types. However, faults can play an important role as a fluid conduit or barrier during production from geothermal reservoirs associated with these play types, and may cause compartmentalization of the reservoir into separate fault blocks. Greatly influencing reservoir quality are (a) lithofacies, a rock unit formed in a certain depositional environment affecting grain size, pore geometry and mineralogy; (b) diagenesis, the physical and chemical changes occurring during the conversion of sediment to sedimentary rock; and (c) karstification. Hence, evaluating fault and lithofacies characteristics should be primary goals of exploration of these play types.

Conduction-dominated geothermal play types with naturally low permeability reservoirs such as tight sandstones, carbonates, or crystalline rock can only be developed using engineered geothermal systems (EGS) technology. Although EGS techniques might be applied to improve the productivity of any geothermal reservoir, the development of many conduction-dominated geothermal systems strongly depends on them. Through the application of EGS techniques, non-commercial reservoir conditions (e.g., rocks with naturally low permeability or porosity) might be improved, for example, in the Denver Basin (U.S.) in the future. The in situ stress field is a critical parameter for EGS technology because the successful planning and management of large-scale injection and hydraulic stimulation requires knowledge of stress direction and magnitudes (e.g., Moeck, 2012; Moeck and Backers, 2011).

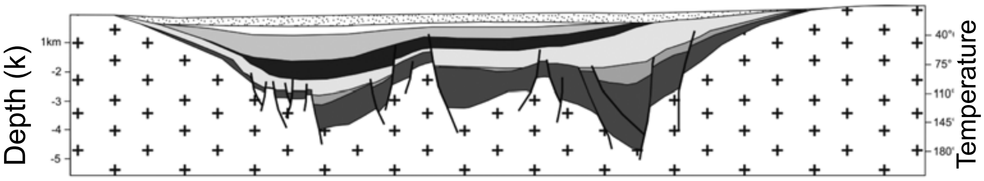
2.5.1. CD1: Intracratonic Basin Type

An intracratonic basin geothermal play (CD1) incorporates a reservoir within a sedimentary sequence laid down in an extensional graben or thermal sag basin (Figure 2.7). Intracratonic basins that originate from lithospheric thinning and subsidence are commonly divided into several troughs or sub-basins (Salley, 2000). The long geological history of intracratonic basins usually produces a sediment fill several kilometers thick that spans a wide range of depositional environments, which may include fluvial siliciclastics, marine carbonates, muds and evaporites (a natural salt or mineral deposit left after the evaporation of a body of water). Lithology, faulting, and diagenesis control the pattern of high and low porosity domains (Wolfgramm et al., 2009; Hartmann and Beaumont, 2000), and are themselves strongly influenced by basin evolution and subsidence rates. Lithology, diagenesis, faults, and the stress field control permeability and its anisotropy.

Potential geothermal reservoirs are located in different basin portions depending on the internal present-day structure of the basin. Formations above salt diapirs might provide suitable geothermal reservoirs for district heating because high thermal conductivity of salt rock causes local positive thermal anomalies in the overburden (Norden and Förster, 2006). Formations in deeper parts of the basin might provide suitable reservoirs for power and heat production, provided they can produce geothermal fluids at a flow rate of about 70 kg/s or more (Tester et al., 2007). In all potential sedimentary reservoirs, primary porosity (affected by deposition through lithofacies or biofacies) and secondary porosity (affected by diagenesis) have a major influence on the fluid storage capacity. Potential reservoir units are terrestrial sedimentary rocks, such as aeolian and fluvial siliciclastic sequences, and shallow to deep marine sediments from carbonate sequences to shale and pelagic clays. Typical fluids are high-chloride brines (referred to as basinal fluids) or hydrogen carbonate (HCO3) rich fluids (referred to as infiltration water).

The geological environment of many sedimentary basins and graben systems is already well known from hydrocarbon exploration. Substantial databases of reflection seismic data and bore hole data such as corrected bottom hole temperature, drill-stem, and petrophysical data, (Leary et al., 2013) can be re-evaluated for geothermal assessment (e.g. Moeck et al., 2009; Anderson, 2013).

Figure 2.7.
Typical configuration of an intracratonic sedimentary basin with several troughs or sub-basins within.

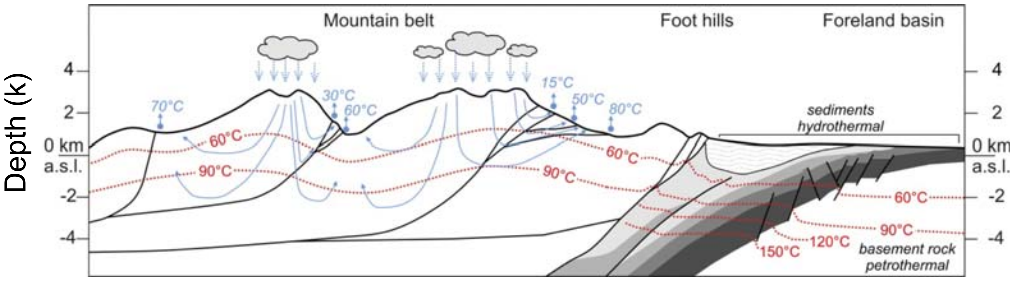


2.5.2. CD2: Orogenic Belt Type

An orogenic belt geothermal play (CD2) incorporates a sedimentary reservoir within a foreland basin or orogenic mountain belt (Fig. 2.8). Sedimentary sequences in foreland basins are influenced by significant crustal subsidence (up to several kilometers) towards the orogen due to the weight of the thickened crust of the orogenic belt and loading of erosional products from the mountain belt on the non-thickened crust. The result of this process is downward bending of the non-thickened lithosphere, forming areas of local extension and normal faulting in an overall compressional plate tectonic setting (Moeck, 2014). The wedge shape of foreland basins results in a progressive deepening of potential aquifer rocks towards the orogen, with an associated increase in temperature. Faults and reef complexes provide prime reservoir targets in carbonate rocks of the Bavarian Molasse Basin (Germany) (Lüschen et al., 2011), while highly permeable and porous sandstone in the Alberta Basin (Canada) provides potential geothermal reservoir targets (Majorowicz and Grasby, 2010).

Within the orogenic mountain belt itself, the conductive thermal regime can be locally disturbed where groundwater infiltration cools the rock mass. Groundwater flow and thermal gradient are both strongly influenced by extreme relief and resulting hydraulic head (Toth, 2009). The great depth and small width of mountain belt valleys result in relatively shallow penetration of recharge water, discharging in valley floors or on shallow valley slopes (Toth, 2009). Conductive thermal gradients can vary from about 15-20°C/km beneath high mountains to about 30-50°C/km beneath deep valleys (Craw et al., 2005; Grasby and Hutcheon, 2001). Figure 2.8illustrates a typical conduction-dominated, locally convectively disturbed, thermal structure in an orogenic zone.

Figure 2.8. Typical conductive thermal structure (red isotherms), groundwater flow paths, and discharge temperatures (blue arrows) in orogenic zones.



Note: The deeper parts of the foreland basin may provide targets for sedimentary geothermal reservoirs.

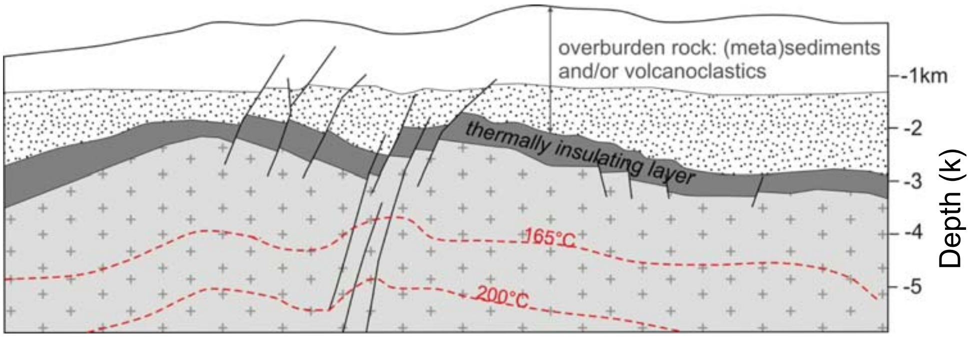
Source: From Moeck, 2014.

2.5.3. CD3: Basement Type

The key features of a basement geothermal play (CD3) are a faulted or fractured crystalline (usually granitic) rock with very low natural porosity and permeability, but storing vast amounts of thermal energy (Figure 2.9). These might also be referred to as petro-thermal or hot dry rock systems. Such low porosity-low permeability rocks underlie large areas of continents but require reservoir development by EGS techniques to allow man-made induced circulation between injector and producer wells using the hot rock mass as a heat exchanger (Cuenot et al., 2008). Fractured crystalline rocks attain potentially economic temperatures through elevated heat flow or thermal insulation in the overburden. Heat flow is likely to be elevated if underlying rocks have elevated radiogenic heat production from heat- producing elements such as potassium, thorium, and uranium.

Since crystalline rocks are generally not natural aquifers, fluids need to be injected both to improve the permeability of the rocks and to “charge” the system with “geothermal fluid” as in the Cooper Basin, Australia (Wyborn, 2010). Mineralogy and crystal size may have major effects on the success of stimulation and the self-propping of induced fractures, critical to maintain fracture permeability after stimulation and shear-offset along a rough fracture surface.

Figure 2.9. Geological controls on temperature in a crystalline rock-basement play type consisting of heat-producing rock covered by thermally insulating layers such as shale and other overburden sediments.



2.5.4. Geothermal Exploration

The division of geothermal play types described above seeks to catalog geothermal systems based on geological differences related to plate tectonic settings. The catalog provides a basis to identify likely geothermal play types at the earliest stage of assessment of the geothermal potential of a region. By doing so, the most appropriate exploration strategies and methods can be selected for the specific geological setting. In a broad sense, exploration for convection-dominated geothermal play types relies on mapping surface geothermal phenomena, geochemical and geophysical data against background geology. Exploration for conduction-dominated plays places greater importance on subsurface rock properties and mapping through 2D/3D geological modeling of geophysical data. Optimal exploration for any geothermal play might require additional techniques such as stress field analysis; geomechanical studies; natural seismicity with seismic risk analysis; or an emphasis on structural geology.

With regard to the relationship between geothermal play types and hydrocarbon plays, conduction-dominated geothermal plays in basin settings (CD1, CD2) may co-exist with hydrocarbon plays. Technology transfer in exploration (as well as fluid recovery methods) may therefore be more straightforward for these play types.

3. PROCESS OF GEOTHERMAL DEVELOPMENT

3.1. Introduction

This chapter describes the typical process of exploration, assessment, and project development for geothermal power projects. However, 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 specific combination of methodologies, techniques, and timelines for any geothermal project will be unique to that one project.

Historically, many of the early geothermal projects were developed in a non-systematic manner. There were no clear guidelines or extensive experience to draw upon for the geothermal development process, while exploration was rudimentary at best. The first time geothermal power was harnessed for electricity production was in Italy in the early part of the 20th century using shallow steam from an area where surface discharges were clearly evident. In New Zealand in the 1950s, the large utility-scale Wairakei developments were initially justified on the basis of very high surface heat flows and the presence of numerous surface features, e.g., geysers and altered hot ground.

Developing an understanding and defining the stages or phases of how to develop a project to extract a geothermal resource has taken time for the geothermal sector to accomplish. Even today, different countries and different agenciesemploy different methodologies and techniques. For example, this Guide introduces the concept of categorizing geothermal systems on the basis of play types (Chapter 2).

The Guide divides the process of developing geothermal projects into eight phases, in line with the ESMAP Geothermal Handbook (Gehringer and Loksha, 2012), as follows:

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

Other consultants and developers may divide the process into a different number of phases (e.g., three phases: exploration, development, and operation; or five: reconnaissance exploration, pre-feasibility, feasibility, detailed design and construction, and operation), but the underlying activities and philosophy are essentially the same. Completion of each phase represents an increase in the developer’s understanding of the geothermal system, a decrease in the overall uncertainty of the project’s financial viability, a project decision point, and (usually) a requirement for significant financial investment.

The following sections introduce the eight phases of a typical geothermal project, with the primary focus of this Guide on Phases 1 and 2: preliminary survey and exploration phases of project development.

3.2. Phase 1: Preliminary Survey

The Preliminary Survey Phase involves a work program to assess the already availableevidence for geothermal potential within a specific area and to identify relevant geothermal play types to guide subsequent activities (see Chapter 2). The geographic scope of the preliminary survey may be regional or national, perhaps a country, a territory, or an island. At the highest level, the survey seeks to identify geological settings that might host economically viable geothermal systems. In practice, the survey essentially involves a "desk-top" review of geological, hydrological and/or hot spring/thermal data, drilling data, anecdotal information from local populations, and remote sensing data from satellites, if available.If the area has a history of petroleum, mineral, and/or water resource exploration, then records of these activities may provide very useful background and subsurface information.

Example

Most countries have existing databases 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 all relevant data prior to designing and planning a new exploration program. Remote sensing using data gathered from satellites and aircraft (see Section 4.2.4), in particular, is playing an increasingly significant role in preliminary surveying for geothermal resources.

Information on land access processes and potential issues should also be gathered during the Preliminary Survey Phase. Different countries have different requirements and priorities for the environment, land use, indigenous rights, and other land access issues. In other words, what are the national, regional, and/or local regulations that govern 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 important. Could a geothermal development live harmoniously with other existing or possible land uses? Identifying and addressing potential conflicts is critical at an early stage of a geothermal project, prior to committing to an exploration program.

Surveying and addressing public awareness issues is essential in the earliest phases of a project. The explorer must understand local perceptions regarding geothermal development. In some countries, indigenous populations consider geothermal features to have religious significance. For example, planned developments in Hawaii, Greece, Peru, and Bali received hostile responses to development proposals on religious grounds. Identifying any such concerns is an essential component of early geothermal investigations. Local communities should be made aware of the impacts, positive and negative, of any geothermal development. Public meetings and surveys should be undertaken to determine preexisting public attitudes towards development and to provide information in response. Having good communications with local communities is essential from the outset of any program.

Example

In Japan, the majority of identified high temperature geothermal systems are located within or adjacent to national parks, where access for exploration has, until recently, been forbidden (Meltzer, 2012).

In Indonesia, over 50 percent of known high temperature geothermal systems are located within or adjacent to protected forests or national parks (Abimanyu and Warsito, 2010).

In New Zealand, almost half of the identified geothermal systems are in protected areas where development is limited or forbidden (Luketina, 2000).

In Turkey, few hard rules or regulations currently exist regarding geothermal exploitation. The Turkish government has, however, established a Protected Area Special Committee, which decides on a case-by-case basis the appropriateness of drilling 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 affect or be affected by a geothermal development. As with any major infrastructure development, geothermal power plants have their own unique social and environmental impacts and risks that require awareness and management. Developing relationships and communication channels 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. Understanding the impacts geothermal developments locally have on groundwater availability and quality is critical.

Necessary infrastructure such as roads, water, power supplies, and availability of equipment and contractors 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 both the exploration and test drilling phases might be delayed.

The explorer also needs to understand the processes for obtaining and retaining legal rights to the geothermal resource and other essential project requirements (e.g., surface water and land tenure) throughout the life of the geothermal project. Regulatory frameworks (and potential risk they will change in the future), which are relevant to obtaining access along with land rights for early stages of work and subsequent development, power supply agreements, and so on, should all be understood. Geothermal resources may be either publicly or privately owned. Payments may be required to secure leases or to obtain options to extract the resource if the detailed exploration is successful. Some countries legislate geothermal rights under mining laws; others consider them water rights, while many countries still have no legal framework for geothermal development. The geothermal permit process may be fast or very slow. Fully understanding these issues is critical from the outset.

All the factors mentioned here can significantly impact the time and cost required to move through the subsequent phases of project development. The preliminary survey aims to show whether the area of interest (country, region, or island) has a geological setting or features that may indicate the presence of an economically exploitable geothermal system. Once this is established, the developer must then determine the feasibility of obtaining concessions over the most promising areas and, if they become productive, how would geothermal power fit with the existing energy infrastructure?

Although the Preliminary Survey Phase is primarily desk-based, one or more short field visits might greatly assist in confirming the geothermal play type(s), the regional geology, the surface thermal features, and in identifying key environmental and social issues.

Basic background information collected during the preliminary survey phase covers

- the power market and possible power purchase agreements (PPA) or feed-in tariff;
- other/additional demands and possibilities for geothermal energy use such as district or greenhouse heating;
- infrastructure issues (roads, water, communication, transmission);
- resource ownership issues (in some countries geothermal permits are under mining laws; elsewhere it may be considered a water right 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;
- collection and interpretation of available remote sensing or aerial survey data;
- information from available literature on any known geothermal systems, including geological, hydrological, and/or hot spring/thermal data and historic exploration data; and
- information from previous explorations or wells that may have been drilled in the area of interest.

All these factors need to be considered in order to identify possible barriers to development or potential roadblocks that might derail or slowdown a development program. Based on the outcomes of the preliminary survey, the explorer or developer may decide to proceed to the Exploration Phase. Obtaining finance and/or partners to share the risks and expenses of this phase may also be necessary. There may be several potential sites to investigate, which could effectively spread the risk but require higher overall expenditures.

Engaging experienced geothermal consultants during the Preliminary Survey Phase is one of the keys to identifying and thoroughly assessing relevant background information, identifying possible non-geological issues, and designing an effective forward exploration program.

The time required for the preliminary survey depends on a range of factors. The time may be as short as several months. However, if there are many potential sites to investigate and if environmental approvals and the permit process are complex and finance is difficult to secure, the survey may take a year or longer.

3.3. Phase 2: Exploration

The purpose of the Exploration Phase is to cost-effectively collect new geoscientific data to minimize uncertainty related to estimates of key reservoir parameters (temperature, depth, extent, permeability, etc.) prior to the Test Drilling Phase. Exploration may start at a regional level and progressively focus on smaller target areas as data reveal the most attractive locations. Exploration typically begins with gathering new samples and data from existing surface manifestations (and perhaps wells if they are available). Exploration then proceeds to surface and sub-surface surveying using geological, geochemical, and geophysical methods. Environmental studies during the Exploration Phase establish key background (or baseline) information. Some countries require detailed environmental impact statements as an early outcome of any exploration program.

For most projects, the decision to mobilize and contract equipment for the Test Drilling Phase is a significant financial commitment. For this reason, uncertainties about the characteristics of the drilling target and conditions should be reduced as much as cost-effectively practical during the Exploration Phase. In order to make an exploration program cost effective while reducing uncertainty, this typically begins with relatively low cost regional reconnaissance methods and then proceeds to more complex and expensive surveys over smaller identified areas of interest. Table 3.1gives some examples of surveying techniques often used in the Exploration Phase. Chapter 4 provides a more comprehensive list.

Table 3.1. Examples of geoscientific and other techniques applied in the Exploration Phase.

Note: See Chapters 4, 5, 6 and 7 for more comprehensive information.

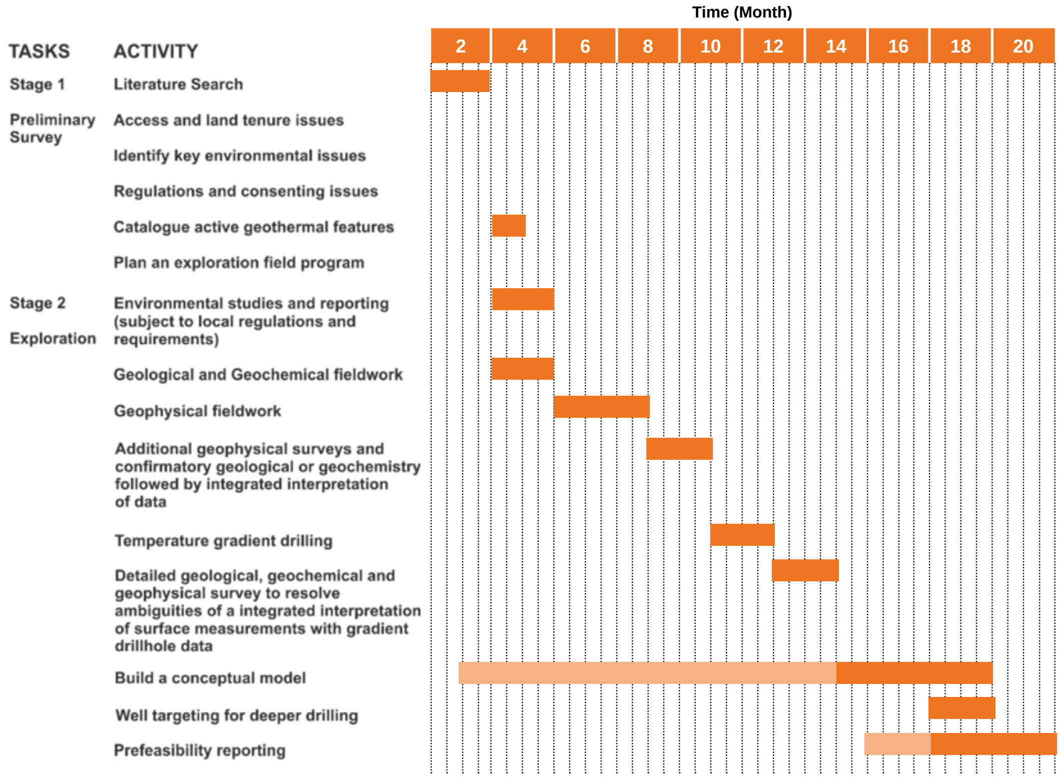
GEOLOGICAL AND SURFACE STUDIES	GEOCHEMICAL SURVEYS	GEOPHYSICAL SURVEYS
• Mapping surface geology (Puente and De La Peña, 1979) • Locating and mapping active geothermal surface features • Structural geological interpretation • Earthquake locations and focal mechanisms	• Collect samples from all thermal features for analysis • Geothermometry (water and gases) (Ellis, 1979; Giggenbach and Goguel, 1989) • pH + electrical conductivity • Flow rate and temperature of fluids discharging from active thermal features • Soil sampling and gas flux (Harvey et al., 2011)	• Remote sensing • Heat flow survey of fluid discharge sites (Fisher, 1964) • Gravity and magnetics (Pálmason, 1975) • Electrical resistivity • Magnetotellurics (Anderson et al., 2000) • Passive seismic monitoring • 2D and 3D seismic reflection • Temperature gradient and conductive heat flow

Of all these techniques, drilling for temperature gradient (or conductive heat flow) measurements is usually one of the most expensive activities. Such drilling may be well justified, however, if surface geological, geochemical and geophysical surveys have been completed and substantial uncertainty remains about the nature of the target reservoir. Temperature gradient drilling might then provide a cost-effective approach to risk mitigation by obtaining additional subsurface information about the temperature and extent of the potential reservoir (Coolbaugh et al., 2007).

By the end of the Exploration Phase, sufficient data should have been collected and analyzed to prepare a pre-feasibility study and select sites and targets for the Test Drilling Phase, in which the first deep wells are drilled directly into the predicted reservoir.

Figure 3.1shows an example of a time line for the preliminary survey and exploration phases of a project. However, timelines can vary significantly between projects: if any obstacles to a smooth execution of the program are encountered; if the geological setting is complex; or if the interpretation of geoscience results remains ambiguous after the initial planned exploration program (requiring additional exploration). The timeline can stretch beyond two years.

Figure 3.1. Example of a timeline for a well-planned and effective preliminary survey and exploration work program in a relatively straight forward geothermal project



3.3.1. Conceptual Model

A conceptual model (discussed further in Section 4.4) is a schematic representation of the current best understanding of a geothermal system, consistent with all known data and information. The first iteration of a conceptual model for any new project might be little more than a generic representation of the type of geothermal play under investigation. While the initial conceptual model is expected to be crude or incomplete, it is important to have an initial model that can be refined and improved as the exploration, test drilling and field development phases proceed and more data become available. During the Exploration Phase, the conceptual model of the geothermal system is continually updated as new data are gathered. The model needs to contain sufficient geological, hydrological, and tectonic information to allow a first pass estimate of reservoir depth, temperature, and extent. This is used during the Test Drilling Phase to target production scale wells toward lithological units and/or geological structures with the highest probability of delivering commercial flow rates of geothermal fluids.

3.3.2. Non-Technical Data Compilation

At the completion of the exploration program, the developer will be at a decision point, whether or not to proceed with the project. This is the time to update or confirm current information (Cassel et al., 1981) relating to these factors:

- Power market and possible PPAs
- Purchase agreements for district or greenhouse heating
- Infrastructure issues (roads, water, communication, transmission)
- Resource ownership issues
- Environmental and social issues
- Institutional and regulatory frameworks
- Issues relating to political and financial stability

3.3.3. Pre-feasibility Study

The final product of the Exploration Phase is a “pre-feasibility study” – an assessment of all the technical and non-technical data within the framework of a risk-weighted financial model of the project prior to committing to the Test Drilling Phase. This is a very significant milestone since proceeding to test drilling involves major financial commitments to the project. This is at a time when uncertainty about the reservoir characteristics is still high and the expenditure curve is steep. The pre-feasibility study should recommend either for or against continuing the project after considering all relevant factors.

3.4. Phase 3: Test Drilling

The first wells are drilled into the target reservoir during this phase, with well design, location, and depth based on the outcomes of the preliminary survey and exploration phases. These wells are sometimes termed exploratory or appraisal wells since they are often the first opportunity to obtain direct information about the reservoir and resource characteristics. The term delineation wells may also be used when subsequent wells are drilled to assist in defining the margins of a productive geothermal field. Drilling the first wells into the predicted reservoir zone represents the period of highest financial risk in any project (Figure 1.1), because geological uncertainty remains high.

Test drilling should provide the potential developer with a good understanding of the remaining uncertainties around reservoir temperature and size, depth, permeability, productivity, and sustainability; these uncertainties should have been reduced to a level that justifies the significant cost of the drilling. A preliminary estimate of the magnitude of the resource (expressed in terms of potentially recoverable thermal energy or thermal power) should be possible at this time, fully acknowledging the uncertainty of the estimate. Revised conceptual and initial numerical models can be developed.

Typically at least two, but more often three, wells are drilled at this time to test the existence of a geothermal reservoir capable of sustaining commercial rates of fluid production and injection. In some circumstances, more than three test wells may be required, depending on the success of the first wells, the size of the project to be developed, and the predicted extent of the reservoir. Drilling, logging, and subsequent well testing is a complex and expensive undertaking (Grant and Bixley, 2011). The design of the wells and the well testing program, and the interpretation of the resulting data by specialist geothermal engineers and scientists significantly improve the understanding of the reservoir. This enables

- refinement of the conceptual model and estimate of the recoverable heat resource;
- determination of the average well productivity (critical for defining the scope of future drilling);
- provision of geochemical data that can constrain estimates of resource temperature; highlight any potential for scaling of corrosion; delineate different aquifers; help develop mixing models of the geothermal fluids with near surface waters or magmatic components; and add to subsurface understanding in other ways; and
- selection of the optimal well sites, targets, well paths and designs for subsequent production and injection wells.

Upon completing the Test Drilling Phase, the project moves into the Project Review and Feasibility Phase.

3.4.1. Updating the Conceptual Model

The conceptual model of the geothermal system should be progressively updated as more data become available during the Test Drilling Phase (Cumming, 2009). In particular, the results from the first well might modify the explorer's geological understanding of the system and help better target the second and subsequent wells.

3.4.2. Numerical Modeling

A conceptual model consistent with all available data can form the framework of a numerical model for forecasting the performance of the geothermal reservoir during future production. 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 reservoir, and to predict possible degradation of the reservoir temperature and/or pressure and resultant power output.

3.5. Phase 4: Project Review and Feasibility

Once test drilling has confirmed the existence of a viable geothermal resource, the geological uncertainty and financial risk of the project are substantially reduced and a robust "feasibility report" can be prepared. A minimum of one successful production well must usually be drilled before preparing a feasibility report for a geothermal investment. A successful production well is fundamental to understanding the possible behavior of the geothermal reservoir during production and to developing a realistic numerical model. The private sector assigns significant importance to successful geothermal production wells to justify investments.

Information on reservoir performance collected during the Test Drilling Phase permits the developer to build a numerical reservoir model, estimate the likely output per production well, size and cost the planned development, and hence build a reasonably robust financial model. Such a model, incorporating a risk analysis, is critical for the developer to obtain finance to move the project ahead to the Field Development Phase and to negotiate acceptable terms for a PPA.

Preliminary sites for production and reinjection wells are chosen at this time. Good well targeting is critical to drilling successful wells. A sound appreciation of the geological setting and the specific formations and/or structures likely to have adequate permeability is critical to designing the wells, specifying their targets, and planning the drilling program. This process requires input from the geoscience team, led by geologists and drilling engineers, which draws on information gained during previous phases of project development.

A feasibility report is compiled to provide both the developer and potential financiers with confidence in the commercial viability of the project. The feasibility report typically is in two parts: the technical report and the financial report. The compiled feasibility report contains the following elements:

- Recommended location and design of drilling pads and other civil works (roads, preparation of power plant site, etc.)
- Specification of drilling targets for all production and reinjection wells
- Well design
- Forecasts of reservoir performance from the numerical reservoir model
- The power plant design
- A transmission access plan
- Construction budget, costs and timeline for all of the above
- Clarification of market issues
- Demand analysis (regional and national)
- Take-off and transmission issues
- The terms of the PPA
- Project budget and revenue projections

Based on the feasibility report, funding is sought and a decision is made to develop or not to develop the project. All sections of a feasibility report need to be updated as the project progresses and as more data about the market situation and reservoir characteristics become available.

3.6. Phase 5: Field Development

The project now proceeds to the Field Development Phase with the drilling of a sufficient number of production and reinjection wells to support the proposed power production. In parallel with the drilling, work starts on the gathering system to convey the geothermal fluid from the wells to the power plant.

Once a large project proceeds to field development, two or more drilling rigs operating simultaneously is optimal in order to shorten the development time and bring revenue from generation as soon as possible. Predicting with great confidence the precise productivity of wells prior to drilling is rarely possible, as this remains subject to natural geological variance between locations. The success rate for geothermal wells to achieve their minimum anticipated productivity or injectivity varies around the world, but a recent analysis of global geothermal well success commissioned by the International Finance Corporation (IFC, 2013) suggests that success rates typically improve from 50 percent during test drilling to 70-80 percent during field development. Achieving or exceeding these success rates depends strongly on the quality of prior exploration and the validity of the conceptual model. In areas where many similar geothermal systems have already been developed, the success rate is generally higher than the global average.

For a well of 2 km depth, a drilling time of 40 to 50 days (24-hour operation) is not unusual for a production scale well. The developer therefore has to determine the number of production wells that will be required and the time needed to complete such drilling (including an allowance for some unsuccessful wells, which often exceed 20 percent of wells drilled). In addition, re-injection wells are required to return the geothermal fluid to the reservoir to minimize pressure decline. The ratio of production to reinjection wells ranges from as high as 4:1 for resources with a high steam fraction to as low as 1:1 for liquid resources. The actual number of reinjection wells required depends on the enthalpy of the production fluid, well productivity, the fluid-to-steam ratio, and the power plant technology. The location and depths of reinjection wells is a decision based on the conceptual and numerical models, which are continuously updated as new data become available.

Some excess production capacity should be included in the field development plan and allowed for in the financial model. A realistic temperature and pressure decline rate for production wells should also be allowed for in the initial numerical and financial models, and updated as real data become available.

The Field Development Phase requires closely managing a range of suppliers (rigs, casing, drill rods, drilling chemicals, drilling mud, etc.). Well testing, and perhaps tracer testing, should follow each well completion to build knowledge of both production limits and subsurface conditions. This enables both continuous updating of the conceptual model and testing of any previous predictions. The numerical model should also be updated.

Once a certain percentage of the total required fluid production rate is confirmed, the project’s financial risks are significantly reduced, and debt financing might become available on commercial terms. Such financing is usually not available until after the majority (or all) of the resource is confirmed through drilling, a PPA is signed, and the conceptual design of the power plant is available; the PPA, especially, provides security for long-term debt.

Any delays during field development can seriously impact the timelines for completing the project. Timing may be critical for meeting deadlines in PPAs and for generating revenue for investment returns.

3.7. 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 designed and constructed under a single engineering, procurement, and construction (EPC) contract awarded following a tender process.

3.8. Phase 7: Commissioning

The Commissioning Phase should be planned and costed as a separate exercise prior to operation. This includes the testing of all power plant components and associated equipment to ensure their operability meets the respective design conditions. This also includes fine-tuning the power plant’s efficiency, pressures from the wells, and other parameters, which can take several months to complete and could require resolving technical and contractual issues with the supplier of the plant (Gehringer and Loksha, 2012).

3.9. Phase 8: Operation

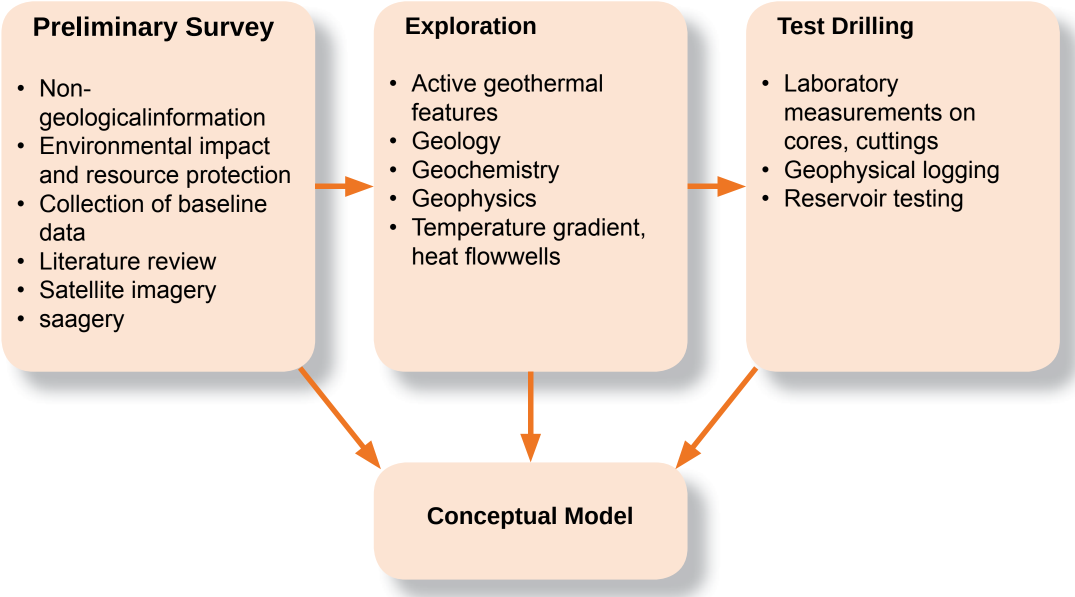
The power plant begins operations once the power plant construction and commissioning phases are complete. Since the fuel supply for the life of the plant has effectively been fully provided during the Field Development Phase, the main focus is to optimize the production and injection scheme to enable the most efficient and sustainable 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 over the lifetime of the plant to make up for any decline in productivity or adjustment of the reinjection strategy as the reservoir responds to exploitation.

4. DATA COLLECTION AND EXPLORATION METHODS

4.1. Introduction

This chapter provides in-depth information about a range of data collection and exploration methods and contains details of how exploration data are typically acquired in geothermal projects. The chapter also provides examples of “good outcomes” for each method, although subjective and variable from one geothermal project to the next depending on the geological setting and type of reservoir. Each geothermal project is different, and the exact exploration methods most appropriate for a given project depend on specific conditions. However, as outlined in Chapter 3, geothermal projects generally go through the same eight-phase development process, with the first three phases summarized in Figure 4.1below.

Figure 4.1. Data inputs to the conceptual model.



The goal of this Guide is to help minimize uncertainty regarding reservoir characteristics before commencing the Test Drilling Phase of a project. To that end, this chapter is divided into two broad sections that focus on the first two phases of a geothermal project: preliminary survey and exploration. The chapter is also written from the viewpoint of assisting the project explorer, but is equally relevant to potential financiers to assess whether a potential developer has applied best practices to the project.

4.2. Phase 1: Preliminary Survey

4.2.1. Non-Geoscientific Information

This topic is discussed in detail in Chapter 3.

All non-geological information should be compiled and presented in such a manner as to illustrate, if required, that the explorer is competent and understands local requirements and perceptions towards geothermal development. Documents and maps detailing easements or other rights of use should be collated, as well as documents and maps detailing any land-use restrictions in the area. A fundamental task is to unify all data to a common coordinate system (e.g., UTM with zone or latitude and longitude). Projection and datum information should be clearly indicated (e.g., World Geodetic System 84, European Datum 1950, etc.). 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) suffice where tabular compilation is inappropriate.

The development company should also collate a dossier of relevant information about the company. Information may be requested about ownership, management, financial structures, personnel experience with similar projects, or other commercial issues relevant to the project.

Though maybe not required for several years, the explorer should also think about selecting a drilling company at the earliest phases of a project. When selecting a geothermal driller, considering the driller’s equipment and experience with similar projects would be wise.

4.2.2. Environmental Impact and Resource Protection

4.2.2.1. Local Requirements

A thorough understanding of the local regulations for environmental protection is an essential early step for any geothermal development addressed in Chapter 3. Although geothermal development is frequently viewed as an environmentally friendly option for power generation, the fact that any development impacts the environment and land use must be appreciated. In some locations, geothermal systems might be protected from development 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 culture, environment, history, or tourism. Geothermal systems in close proximity to urban areas may also be protected.

Even when geothermal development is permitted, an environmental and social impact statement (ESIS) may be a prerequisite to embarking on a survey or exploration program. The environmental impact of each exploration method itself should be considered. Some exploration methods may be restricted in nature reserves or water protection zones. In urban areas, the permitted gross vehicle weight for roads may pose an issue for some exploration methods, while other methods may be prohibited near listed historic monuments.

Example

In Germany, off-road driving in nature reserves is often prohibited, but access by foot is allowed. Bird sanctuaries are often off limits during breeding seasons. The total weight of vehicles (e.g., seismic vibrators) must be considered since heavy vehicle traffic is restricted on certain public roads and bridges.

In Turkey, potential developers aiming to build a geothermal power plant with capacity over 5 MWe must prepare an environmental impact statement. There is no need to prepare the statement for a project aiming to build a plant of less than 5 MWe capacity, but the explorer must apply for a certificate confirming exemption from this requirement.

4.2.2.2 Baseline Environmental Data

Baseline environmental data define the starting conditions of any development and should be collected as early as possible. In many countries, license terms impose strict conditions relating to any potential environmental impact of a geothermal project. For example, a license may be granted only on the condition that the geothermal project has minimal or no impact on other existing land uses. This might cover such impacts as land subsidence, air quality, surface geothermal features, groundwater quality, visual amenity, and seismic activity. Collection of robust baseline data is critical to ensuring and demonstrating compliance with such conditions, but collecting this data 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 the explorer identify environmental parameters that might be sensitive and address these early in the project. Baseline data can be presented, if requested, by using maps, charts, graphs, tables, databases, or other appropriate formats.

4.2.3. Literature Review

An early step in evaluating a geothermal play is to find and assess any existing data and previous research pertaining to the play area. In many cases, previous studies offer valuable insights into the geological setting through hydrology, geochemistry, geophysics, or other surveys. This step is critical to avoid duplication of effort and to enable the explorer to apply exploration funds prudently.

A thorough literature review by experienced geothermal specialists can save the explorer significant time and expense by avoiding duplication of effort during the Exploration Phase of the project. Such a review may, for example, uncover valuable baseline environmental data. Historical data might also provide a useful comparison to newly collected data, enabling the explorer to assess the quality and consistency of new data against previously collected information.

The literature review should focus on uncovering articles, reports, maps, databases and figures concerning the geothermal play, geothermal system, and/or cultural and environmental information about the project area. Table 4.1lists the types of data typically gathered during this stage of the Preliminary Survey, but this should not be considered an exhaustive list.

Table 4.1. Published data and information typically sought during the literature review

MAPS	DATA FROM LITERATURE	PURCHASABLE DATA
• Topographic map(s) showing geothermal license area(s) • Map(s) showing areas licensed to others around subject license area(s) • Map(s) of easements or other rights of use • Map(s) of land use restrictions • Geological maps • Geophysical maps • Other maps • Regional heat flow	• Active geothermal features • Geological data and reports • Tectonic history • Geochemical data and reports • Geophysical data and reports • Surface temperature data • Subsurface temperature data from existing wells • Seismicity records	• Maps • Aerial photos • Satellite imagery • Digital elevation model • Geological data • Geochemical data • Well logging data • Geophysical data • Satellite imagery, • Aerial photogrammetry • LIDAR

The literature review should include a thorough online search, but should also include visits to local government agencies, universities, and other institutions where public documents (and human recall) relevant to the project area might be held. Data provided on a commercial basis by third-party suppliers should be checked for quality and usefulness before purchase. These are possible sources of data:

- Academic publications and theses from local and foreign universities or research programs
- Data, results and/or reports from previous leaseholders including mining tenements, or previous exploration campaigns for minerals or oil and gas
- Reports and documents from agencies of the national, provincial, and municipal governments
- Data and information found through internet searches
- Data purchasable from third-party suppliers
- Commercially produced maps

Example

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

A good outcome after reviewing the literature and published data is a high level of confidence knowing all relevant existing data and maps are identified, collated, and assessed for inclusion in what might be a very preliminary conceptual model of the resource. At this stage, the best practice is to build a geographic information system (GIS) database to hold and present all relevant geospatial information about the geothermal play and license area.

4.2.4. Satellite Imagery, Aerial Photogrammetry, and LIDAR

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 (Haselwimmer & Prakash, 2013); thermal data acquired by Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors onboard Landsat-5 and Landsat-7 satellites (Qin et al., 2011); digital elevation models from airborne LIDAR instruments; and data from the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER), launched in 1999 as part of NASA's Earth Observing System. Data from all of these sensors are increasingly being applied around the world to identify surface geothermal features.

Data from these sensors should be purchased and assessed during the preliminary survey phase, if the explorer knows or expects that the license area contains relevant surface features with a strong thermal or mineralogical signature. Remote sensing data can be added to the GIS database for integration with data compiled from surface surveys to produce detailed maps for each project area. The maps can be interpreted to identify the locations and extent of possible current or historic surface geothermal features. The technique may be especially useful in difficult terrain where ground access is difficult. Note, however, that confirmation of thermal or mineralogical anomalies always requires on-ground verification and assessment.

4.2.5. Conclusion of Preliminary Survey

At the conclusion of the Preliminary Survey Phase, the explorer should have a thorough understanding of the legal, social, environmental, and geological parameters within which the project has to operate. The explorer will have legal and social license to proceed to the Exploration Phase of the project, with confidence that development of a power plant will be allowed should a viable geothermal resource be discovered. All previous data relevant to the geothermal play will have been collated and assessed, revealing where key data gaps and critical geological uncertainties remain. Efficiently and effectively minimizing geological uncertainties by filling these data gaps is the goal of the Exploration Phase of the project.

4.3. Phase 2: Exploration Methods

4.3.1. Overview

The purpose of the Exploration Phase is to cost-effectively collect new geoscientific data to minimize uncertainty related to estimates of reservoir temperature, depth, productivity, and sustainability prior to the Test Drilling Phase.

Beginning the Exploration Phase with broad, regional-scale methods is common in order to constrain the "big picture" conceptual model of the geothermal system, before focusing in more detail on areas showing the most promise for economic extraction of geothermal resources. Regional-scale exploration methods include geological mapping, outcrop sample collection and analysis, geochemical sample collection and analysis, airborne geophysical surveys, and broad-spaced surface geophysical surveys. Even where similar data already exist, resampling or resurveying partially or fully may be cost effective to verify the quality of the earlier data or to allow proper "stitching" of old and new data sets.

At the end of the regional exploration stage, the data are evaluated to assess the likelihood of an economically viable geothermal system existing. To proceed to the next stage of exploration, there should be at least prima facie evidence of a geothermal system with heat source, heat migration pathway, and reservoir, and some indication of the likely geographic extent, all of which can be presented as a conceptual model consistent with all data.

If the regional data are encouraging, the exploration program moves to more localized exploration methods, geographically focused on the most promising areas. Each method employed should aim in some way to improve the confidence in the estimates of reservoir temperature, depth, productivity, and sustainability. The same type of data collected during regional exploration may be collected again during localized exploration. The difference between the two stages might be the spacing between data stations, level of detail of the data analysis, or both. Regional exploration is generally carried out at a broad-scale and station spacing, while localized exploration focuses on finer details and employs closer station spacing.

Table 4.2lists a broad range of geoscientific datasets and methods that might be employed during a geothermal exploration program, separated broadly into geological, geochemical, geophysical, and other methods. Any single exploration program will very likely employ all of the listed methods. An appropriate set of methods for a specific project should be chosen based on a cost-benefit analysis of the different options, where the benefit can be quantified to the degree the method will reduce the uncertainty in the explorer's understanding of critical reservoir parameters. The following sections describe each method in more detail.

Table 4.2. Geoscientific datasets and methods that may be relevant to geothermal exploration

ACTIVE GEOTHERMAL FEATURES

- Location (latitude/longitude or UTM)
- Temperature (°C)
- Electrical conductivity (µS/cm)
- pH
- Flow rate (l/s or kg/sec)
- Presence of gas bubbles and their compositions
- Presence of odors (sulfur derivatives or other odors)
- Presence of precipitates in the fluids
- Detailed local map(s) of area(s) with thermal features clearly labeled

GEOLOGICAL DATA

- Geological map(s) of license area(s)
- Geological cross sections of license area(s)
- Summary descriptions of stratigraphy and lithology with stratigraphic columns
- Summary descriptions of regional and local structure with accompanying maps
- Identification and characterization of potential heat source(s)
- Identification and characterization of potential reservoir unit(s)
- Presence of mineralization associated with hydrothermal systems

GEOCHEMICAL DATA

- Location, name, and characteristics of sampling points
- Temperature (°C), pH, EC (µS/cm) , and flow rate (approximate) at time of sampling
- Sample filtration and preservation method(s) used
- Chemical analyses of collected samples
- Name of laboratory providing analysis
- Calcite inhibition treatment information (if sample is from producing well)
- Names, descriptions, and locations of scale or mineral deposits
- Geothermometry estimates
- Interpretations and/or plots of geochemical data
- Reference data of neighboring wells and projects (if available)

GEOPHYSICAL DATA

- Remote sensing
- Gravity surveys
- Geomagnetic surveys
- Magnetotelluric (MT) surveys, CSEM
- Electrical resistivity, DC
- Self-potential method (SP)
- Seismic surveys (2D and 3D)
- Heat flow/temperature gradient surveys
- Other surveys

SUBSURFACE TEMPERATURE DATA	CONCEPTUAL MODEL
• Raw temperature from logs • Flowing temperature from hot springs or wells • Maps of temperature contours at various depths • Cross sections showing temperature distribution	• Incorporates all data and gathered information

4.3.2. Geology

A thorough understanding of the project area's geology and how it fits into the surrounding regional geological and tectonic setting are crucial to understanding a given geothermal system. A geological understanding assists in assessing fluid flow (especially through identifying faults and permeable rock units) and temperature anomalies (through mineral alterations). At an early stage of the literature review, a decision should be made as to which is the most likely geothermal play type to exist in the area (see Chapter 2). The following sections discuss the method of assessing the geology and the focus areas of analysis of gathered data.

4.3.2.1. Mapping and Identification of Play Type

Once data have been gathered from available literature, geological studies (including field work) can be carried out at both a regional and local level. Initial geological studies focus on understanding the overall geology of the project area and identifying the most promising areas for more detailed exploration. Efforts focus later on the most promising areas, generally 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.

An assessment should be made of 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. Data from existing wells may also be useful to constrain subsurface data and structures.

In many cases, explorers find that the existing geologic mapping is of good quality, but there is a need for additional mapping focusing 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 4.2.

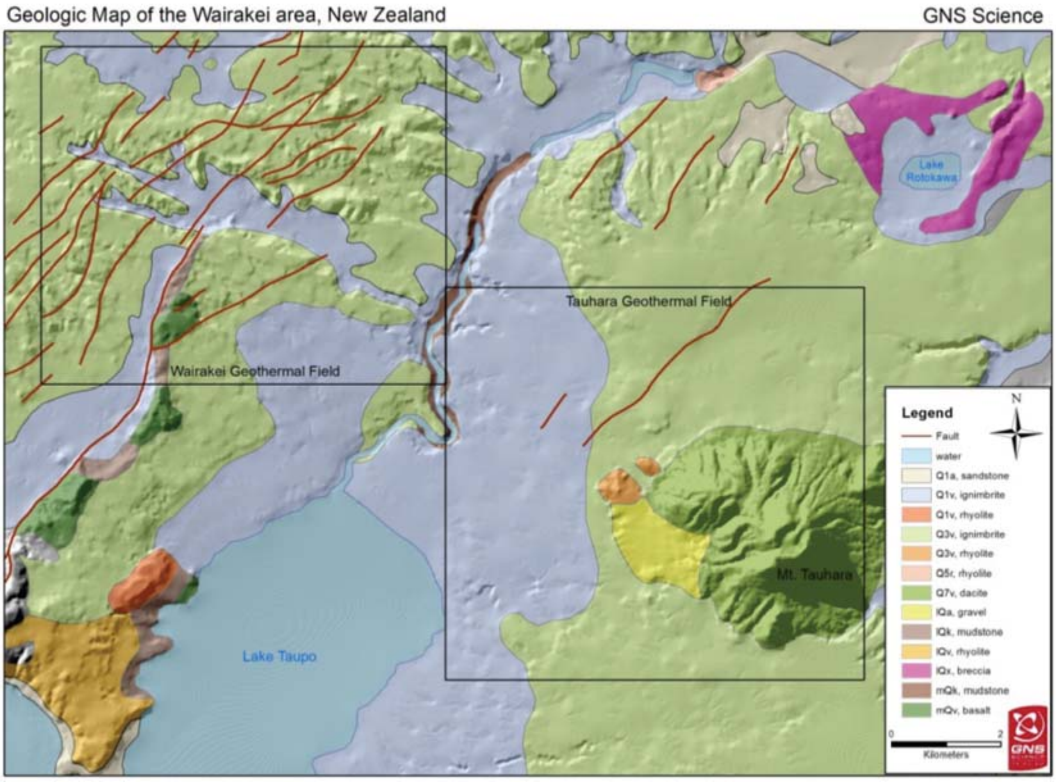


Figure 4.2. Example of a geological map of a geothermal prospect.

Source: GNS Science, New Zealand.

4.3.2.2. Heat Source

The possible heat source for the geothermal system should be identified or inferred. The heat source may be associated with active magmatism 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 shallow geothermal system (Elders et al., 1984). The most interesting igneous rocks are of Pliocene or younger age (less than five million years old); they are most likely to be associated with magma chambers that still retain significant heat. For example, there is some significant young volcanism in the central and eastern parts of Turkey. Despite this, the major focus of geothermal development in Turkey is currently in Western Anatolia, where regional heat flow is known to be high. In conductive plays the heat source may not be known in detail.

4.3.2.3. Hydrothermal Alteration

Geothermal manifestations are direct indicators of hot water flowing in the subsurface and therefore warrant special attention when preparing maps. Areas that lack active geothermal manifestations, but show evidence of their earlier presence, are also of special 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 (Browne, 1989)

Certain types of mineralization are often associated with hydrothermal systems, including deposits of sulfur (S), mercury (Hg), gold (Au), silver (Ag), and antimony (Sb). The presence of such deposits can indicate the potential existence of a geothermal system, because circulating geothermal fluids concentrate these minerals into economically attractive deposits. Any such occurrence should therefore be mapped. However, there are limitations to the use of mineral deposits as indicators of active geothermal systems. While concentrations of these minerals are sometimes associated with active geothermal systems, most such deposits on the surface are associated with long extinct geothermal systems that, while providing potentially attractive mining targets, are no longer associated with economic accumulations of heat (Lawless, 1988; Browne, 1989).

In addition to concentrating certain economic minerals, geothermal fluids break down the rocks though which they are passing, changing their mineral content. The most common result of this water-rock interaction is the formation of clays (Browne, 1978). 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 into the history of thermal activity.

4.3.2.4. Mineral Geothermometers

Certain minerals that typically form from neutral pH waters in geothermal systems have well defined and restricted temperature stability ranges (Browne, 1993). They include clay minerals, zeolites, and calc-silicates, and are widely used as mineral geothermometers. Much useful data may be gathered from surface samples and supplemented by data from core drilling where appropriate.

Clays are hydrated aluminosilicate minerals, whose structures are sensitive to changes in both temperature and the geochemical environment. They are extremely fine in particle size and therefore their compositions can change rapidly to remain in chemical equilibrium with their immediate environment. In the study of hydrothermal alteration, they are widely used as sensitive mineral geothermometers and as indicators of changes in chemical environment.

For example, specific clay minerals that are stable under acid conditions (kaolinite, dickite, pyrophyllite, and diaspore) can be associated with acid alteration above upflow zones, along faults or within the reservoir. The neutral pH clays, which include smectites (sometimes called montmorillonites), chlorite, and illite, show a progressive transformation with temperature. Indeed, Harvey and Browne (1991) studied the transition from smectite through a mixed illite-smectite layer more extensively at Wairakei than elsewhere (Harvey and Browne, 2000). They found the following:

- Smectites are stable to about 70°C, above which they begin a transformation through a series of mixed-layer clay structures towards illite or chlorite. In some geothermal systems smectite may survive at higher temperatures, perhaps due to the inability for water-rock interaction to reach equilibrium in low permeability settings that can result from swelling clays.
- Interlayered illite-smectites or chlorite-smectites are stable in the range 70°C–210°C.
- The crystallinity of clays increases with increasing T.
- Discrete illite is stable above ~210°C.
- In some geothermal systems in more basic (basaltic) settings, changes in chlorite composition have been found to be temperature dependent.

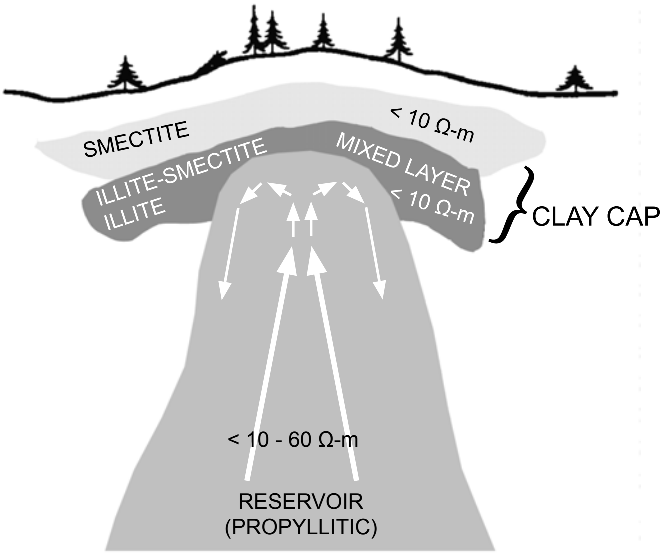
With respect to zeolites and calc-silicates, the following was found:

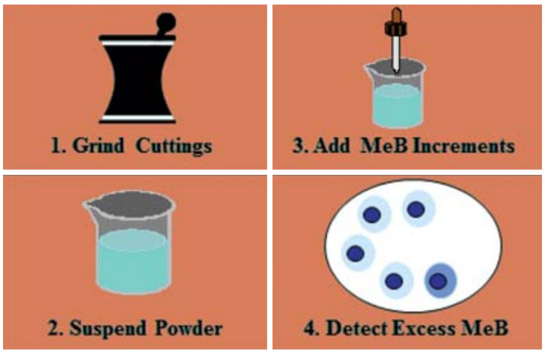
- Mordenite is stable up to 120°C.
- Laumontite is stable from 120°C to 210°C.
- Wairakite is stable from 210°C to > 300°C.
- Epidote is stable above 250°C.
- Ca-garnet is stable above ~290°C.
- Prehnite is stable above ~220°C.
- Actinolite is stable above ~290°C.

Figure 4.3is a schematic illustration of a typical clay alteration zone above a high temperature geothermal system. There is a clear advantage in geothermal exploration to be able to distinguish between the smectite layer and the mixed smectite-illite layer. Because of their very fine particle size, not until the development of X-ray diffraction analysis in the 1930s did the structure of clay minerals become well understood. Today most analytical laboratories involved in geothermal exploration have X-ray diffraction equipment. However, because X-ray diffraction laboratories are usually remote from exploration sites, there is typically a delay in interpretation due to the time taken to transport the samples from the field to the laboratory. In the 1990s, Harvey et al. (2000) developed a rig geologist tool that partly overcomes this problem by enabling the presence of smectite clays to be identified, using a specific chemical dye (methylene blue). Figure 4.4summarizes the methodology in which Gunderson et al. (2000) successfully used the methylene blue technique in Indonesia to ground-truth resistivity data (Figure 4.5and Figure 4.6).

Figure 4.3. Typical clay alteration zone above an active high temperature geothermal system.

Source: After Johnston et al., 1992.

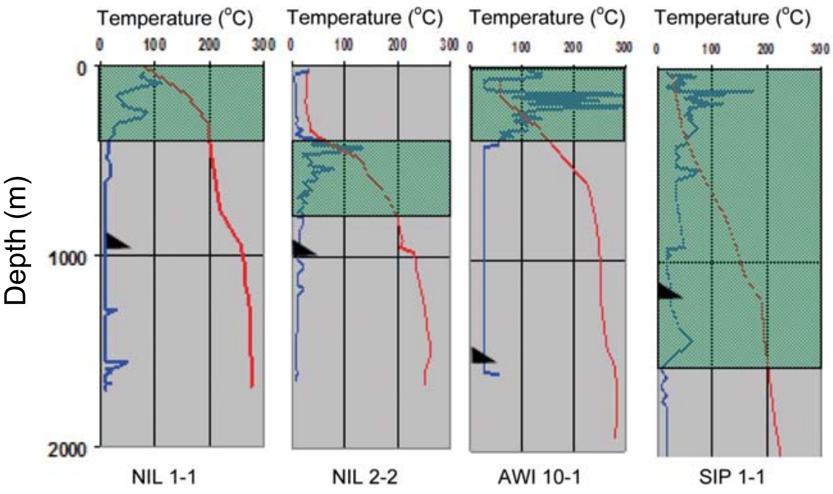




MeB Analysis of Cuttings

Figure 4.4. Methodology for analyzing the presence of swelling smectite clays in drill cuttings.

Source: Harvey et al., 2000.

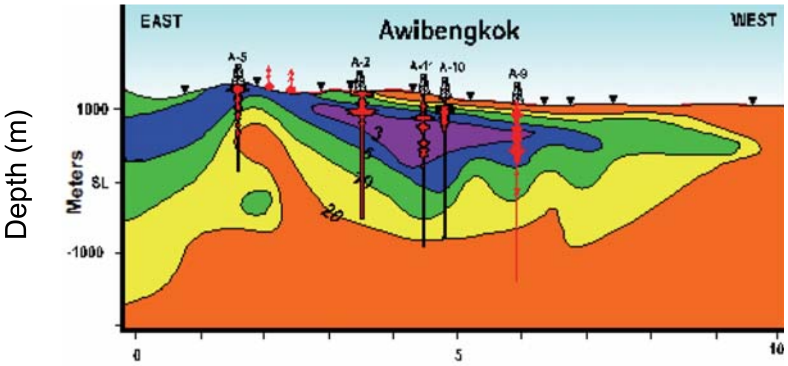


Smectite (MeB) & Temperature (C) versus Depth (m)

Figure 4.5. Depth versus temperature (red lines) in four Indonesian wells.

Note: The green-blue shaded zones had high smectite content (as indicated by the blue lines) based on the methylene blue test.

Source: After Gunderson et al., 2000.



Awibengkok Geothermal Section

Figure 4.6. High smectite clay zones (marked in red on vertical drill lines) correlating with resistivity survey data (Awibengkok, Indonesia).

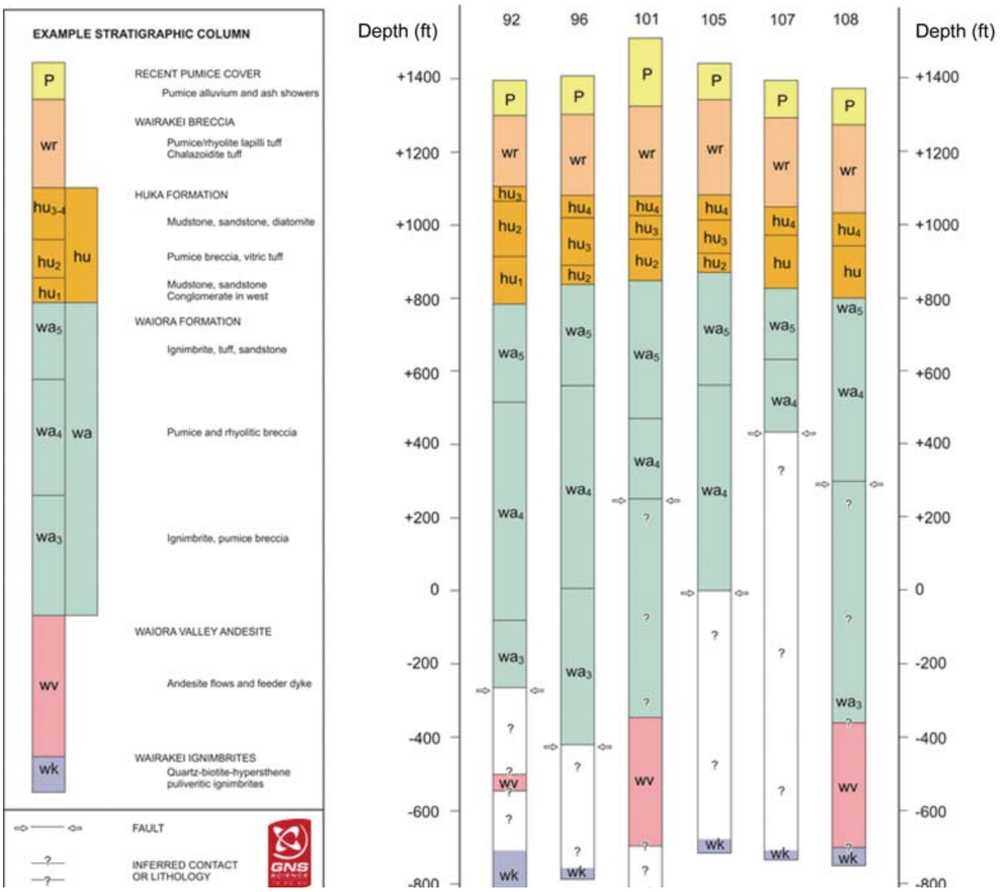
Source: After Gunderson et al., 2000.

4.3.2.5. Lithology and Stratigraphy

Understanding the stratigraphic sequence in the area allows a better understanding of the distribution of various lithologies (Rosenberg et al., 2009). 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 (Sepulveda et al., 2012). An example of constructed stratigraphic columns based on drill hole data from the Wairakei Geothermal Field in New Zealand is illustrated in Figure 4.7.

Figure 4.7. Example of a stratigraphic column and comparison between wells.

Source: GNS Science, New Zealand.



Permeability is almost always a limiting factor in geothermal projects. Therefore, identifying units that are likely to have good permeability is of primary importance when targeting wells. Certain lithologies have greater potential to be reservoir rocks. Such lithologies may have high primary permeability and/or secondary permeability. Rocks with high primary permeability include sandstone, limestone, quartzite, marble, gneiss, lava flows, breccia, and pyroclastic flows. The presence of brittle rock units that can sustain fractures when deformed may provide fracture-controlled (secondary) permeability, which may provide major flow paths for thermal fluids.

Potential capping rocks (aquitards and aquicludes) are important to identify (Facca and Tonani, 1967). These are units with low permeability such as clays, silt, shale, schist, and other rock types. The distribution of low permeability and high permeability rocks may therefore define fluid flow pathways, resulting in a geothermal reservoir of a particular size or shape. In addition, argillic (of or pertaining to clay or clay minerals) alteration and/or silicification of existing lithologies associated with an active geothermal system may create a low permeability cap above a geothermal reservoir or low permeability zones at the margins of the system.

4.3.2.6. 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 (Blewitt et al., 2003).

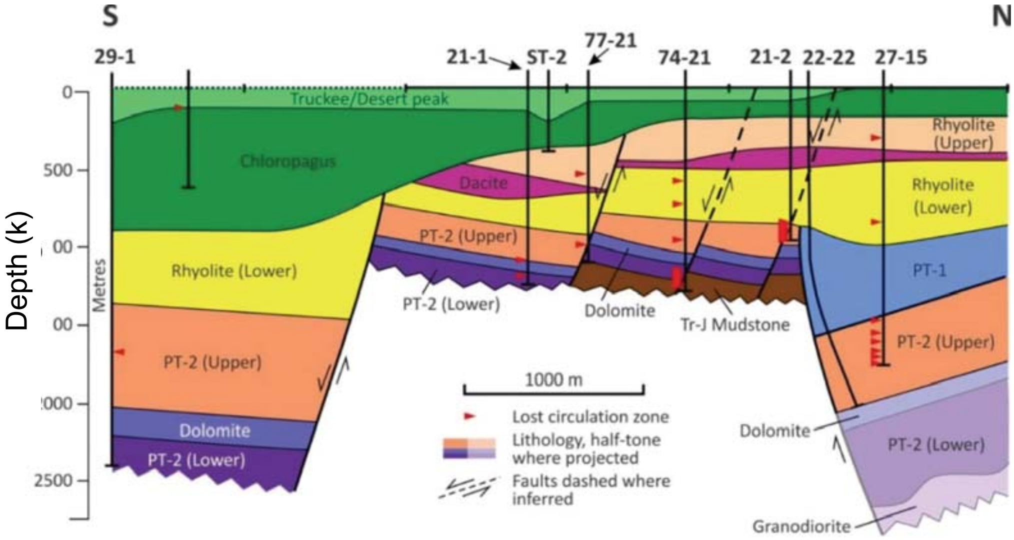
Local geologic structure is of paramount importance in any geothermal project. Geothermal systems are often associated with structural highs and in many cases dipping units may transmit geothermal fluids from depth across significant distances (i.e., the source or reservoir may be laterally offset from 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. It is equally important to understand the locations, orientations, and sense of slip along both regional structures (e.g., graben-bounding faults), and local structures (e.g., cross-cutting faults).

4.3.2.7. Two-Dimensional (2D) Geologic Cross-Sections

As more and more subsurface data becomes available from the ongoing exploration activities, it should be possible to develop two-dimensional (2D) cross sections to illustrate the basic stratigraphic and structural framework of the geothermal play (Figure 4.8).

Figure 4.8. Example of 2D geologic cross section through the Desert Peak geothermal system.

Source: Lutz et al., 2009.

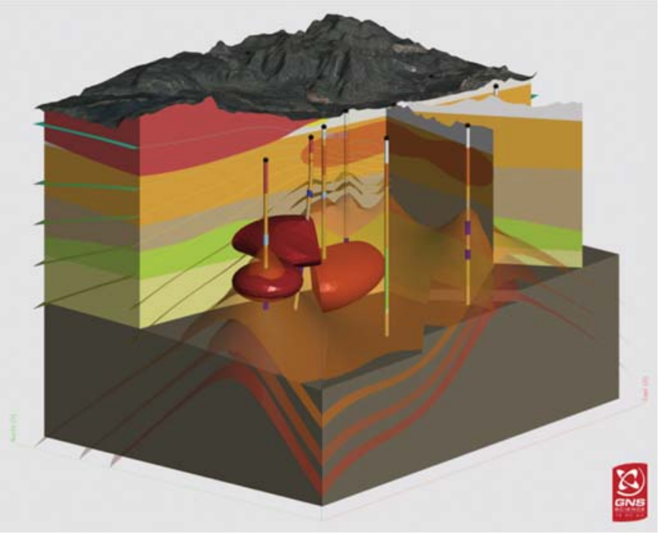


4.3.2.8. Three-Dimensional (3D) Geologic Models

When further drill hole information is available, all structural and stratigraphic information can be integrated into a 3D model (Figure 4.9). The 3D models have proved to be extremely useful for well targeting and structural and stratigraphic visualization (Milicich et al., 2010). Such sophisticated models can only be developed after several wells have been drilled, but the figure illustrates the direction in which conceptual models can develop.

Figure 4.9. Example of a 3D geologic cross section through a geothermal system.

Source: GNS Science, New Zealand.



4.3.2.9. Geological Hazards

The geologist also should prepare a geological hazards map, identifying potential geological hazards in and around the project area. These could include volcanic activity, landslides, areas prone to flooding, slope stability, or other site-specific factors.

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 needing 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.

4.3.3. Geochemistry

4.3.3.1. Overview

Geochemistry presents an extremely useful set of tools for the exploration of high enthalpy geothermal resources. Even at the early stages of exploration, sampling of fluids and gases, followed by analyses and calculation and interpretation of chemical geothermometry, is very useful to develop an understanding of the temperatures and extent of the possible geothermal reservoir. This gives an early indication of whether a sufficiently well-developed resource might exist that is hot enough to be utilized for geothermal electricity generation.

Geochemical studies later in the Exploration Phase 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 carbon dioxide (CO2) soil gas surveys, a recent advancement in geochemical evaluations at the regional exploration stage, are becoming increasingly popular to supplement geothermometry techniques, because variations in CO2 concentrations at the surface may delineate permeable faults or the extent of an active geothermal system.

4.3.3.2. Active Geothermal Features

Active geothermal features include any or all of the following:

- Hot/warm springs and seeps (hot = >50°C and 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
- Geysers
- Mud pots
- Steaming ground

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 area. 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 should be plotted on a map (Figure 4.10).

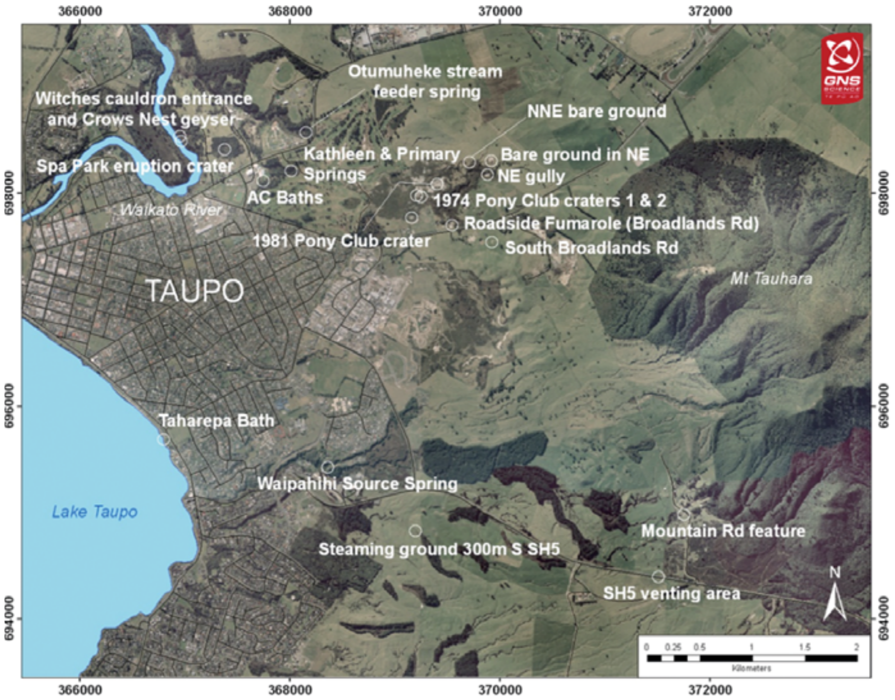


Figure 4.10. Example map of active geothermal features.

Source: GNS Science, New Zealand.

Before entering a thermally active area, it is critical to assess safety issues in the project area. Hydrothermally altered ground is frequently unstable; the margins of hot springs may have overhangs that collapse; and gas discharges associated with the features can prove fatal to animals, birds, and humans. All precautions should be taken as follows:

- Presence of suitably qualified support personnel
- Accident evacuation plan
- Gas masks and sensors
- Insulated field equipment, boots, and gloves
- Designated sample equipment including extended poles for sampling pools

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

- Location in UTM with zone or latitude and longitude: In each case, projection and datum information should be clearly indicated (e.g., WGS 84, ED 1950, etc.) along with elevation.
- Temperature in degrees Celsius (°C)
- Electrical conductivity (EC): Also known as specific conductivity (SC), measured in μS/cm units
- pH
- Flow rate in liters per second (l/s) or kilograms per second (kg/s): Estimates are sufficient; the measurement does not need to be exact, only accurate to within an order of magnitude; highest flow rate, highest temperature springs are more likely to give the best geochemical estimates of reservoir temperatures since high flow rates and high temperatures suggest rapid ascent to the surface from the reservoir.
- Presence of gas bubbles
- Presence of 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: Quartz sinters around active springs indicate high temperature reservoirs; lower temperature geothermal fluids or near surface mixing with cool groundwater, more often result in amorphous silica or chalcedony.
- Samples of the spring discharges collected and preserved using standard techniques (Giggenbach and Goguel, 1989): Samples should be analyzed by experienced geochemical laboratories prior to interpretation and graphical presentation (See Section 4.4).

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

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

- Intended purpose (objectives) of the well
- Well spud date (drilling start date)
- Completion date (date hole is completed)
- Total depth (bottom hole depth, both depth drilled and true vertical depth)
- Drilling history (daily drilling reports and/or summaries of drilling conditions)
- Drilling results (temperature and flow rate upon hole completion)
- Bottom hole temperature (BHT)
- 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 (may be multiple casing strings, if so, should record information for each one)
  - Liner diameter as well as depth of the hanger and depth of the bottom of the liner (may be multiple liners, if so, should record information for each one)
  - Nature of any open interval (open hole, gravel pack, etc.)
- Geological logs (mud logs, core logs)
- Geophysical logs (temperature pressure spinner logs, resistivity logs)
- Well test results
- Any other relevant tables

This information can be very helpful in determining which lithological units and/or structures are associated with the production of hot water. 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. 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.

4.3.3.3. Fluid and Gas Sampling Procedures

Once geothermal manifestations have been identified, located, and characterized, geochemical samples should be taken of representative fluids, steam, and/or gases (Giggenbach and Goguel, 1989). The sampled fluids should be properly preserved and analyzed for silica, cations, anions, and isotopes in water and sulfate. When numerous geothermal manifestations exist in an area, those with the highest discharge 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 (D’Amore and Panichi, 1985).

If no thermal manifestations are located in the area, then 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. For example, EC can vary due to the host rock type. Therefore, an appropriate method is needed to determine what constitutes "elevated" EC levels. One such method is to analyze numerous non-thermal water sources in the area to establish an average "baseline" EC for the area. Any spring water with the EC just one standard deviation or more above the average would be considered to have an elevated EC level. Note that close proximity to the coast can complicate measurement and interpretation of EC data.

A laboratory with experience in analyzing geothermal fluids should carry out all analyses. A typical suite of elements and species should include 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.

Checking the quality of all analyses is important. A cation-anion balance (CBE) is typically used where

$$\text{CBE (\%)} = [(\Sigma z \times m_c - \Sigma z \times m_a) / (\Sigma z \times m_c + \Sigma z \times m_a)] * 100$$

And where

- m_c is the molality (moles per kilogram) of cation;
- m_a is the molality (moles per kilogram) of anion; and
- z is the ionic charge (Coulomb).

For good quality analyses, the CBE should be less than 5 percent.

The completed analyses should be compiled into a spreadsheet or entered into a database prior to interpretation using chemical geothermometers, mixing models and possible speciation calculations, which are described below.

4.3.3.4. Assumptions and Applications of Chemical Geothermometers

Chemical geothermometers were first proposed in the 1960s, arising from water-rock interaction studies. Various approaches have been tried, including empirical experimental results (Hemley, 1967), theoretical thermodynamic calculations (Helgeson, 1969), and field studies associated with the early exploration of New Zealand's geothermal fields (Browne and Ellis, 1970). A basic assumption for all fluid and gas geothermometer calculations is that equilibrium conditions exist within the geothermal reservoir (Giggenbach, 1980. 1981). Other assumptions are as follows:

- Water pH is controlled by salinity and aluminosilicate equilibriums involving hydrogen and alkali metal ions.
- Calcium and bicarbonate ion concentrations are related to pH.
- Carbon dioxide content is controlled by solubility product and ionization constant relationships.
- Magnesium concentrations are controlled at low levels by silicate equilibriums (chlorites and smectites).
- Cation concentrations in solution are controlled by temperature-dependent reactions between clays, feldspars, and other minerals.

Silica Geothermometers

Fournier (1992) reported on numerous experimental studies of silica solubility, which formed the basis of several silica geothermometer equations. These are listed below, where T is the calculated equilibrium reservoir temperature (in degrees Celcius), and S is the silica concentration in parts per million (ppm):

Quartz (no steam loss)	$T = 1{,}309/(5.19-\log_{10}S) - 273.15$
Quartz (Maximum steam loss @100^{o}C)	$T= 1{,}522/(5.75-\log_{10}S) - 273.15$
Chalcedony	$T= 1{,}032/(4.69-\log_{10}S) - 273.15$
α-Cristobalite	$T= 1{,}000/(4.78-\log_{10}S) - 273.15$
Opal-CT	$T= 781/ (4.51-\log_{10}S) - 273.15$
Amorphous silica	$T= 731/(4.52-\log_{10}S) - 273.15$

Cation geothermometers

The literature contains a large number of cation geothermometers published by many different researchers. D'Amore (1992) and Giggenbach (1992) reviewed many that were available at the time. All have been determined from empirical relationships between reservoir temperatures and chemical analyses of liquids and gases over a range of geothermal systems. The number of published equations for cation geothermometry is too large to list them all here. However, as an example, the equation for calculating the sodium potassium geothermometer (using cation concentrations in parts per million) of Fournier and Potter (1979) is:

$$T = 1{,}217 / [1.699+\log_{10}(Na/K)] - 273.19$$

Another commonly used cation geothermometer is the Na-K.Ca geothermometer of Fournier and Truesdell (1973) which is widely used and has frequently provided excellent agreement with measured reservoir temperatures.

Isotope geothermometers

Gerardo-Abaya et al. (2000) reviewed a number of published multicomponent isotope geothermometers. These generally require more elaborate testing equipment and procedures, and are not discussed any further here.

4.3.3.5. Selection of Appropriate Geothermometers

The response rates of fluid and gas geothermometers to changes in temperature varies greatly. Geothermometers also respond differently to interactions between various rock types and different reservoir conditions (Giggenbach, 1992). Silica geothermometers respond relatively quickly but can be invalidated due to mixing and dilution with near surface non-geothermal waters (groundwater). Cation geothermometers respond more slowly and, since they are based on ratios, they are less affected by dilution. The cation geothermometers often provide more reliable estimates of deep reservoir temperatures. As a generalization, hot springs having the highest flow rates and the highest temperatures tend to give the most useful and reliable data from chemical geothermometry. However, all discharging springs with flow rates of great that 1 liter/sec should be sampled and analyzed.

It is recommended that the geochemist calculate a broad range of geothermometers as a set (Powell and Cumming, 2010). Silica, cation, and isotope geothermometers should be calculated and compiled in a table in which the various results can be compared against each other. Based on assessing the chemical geothermometers against geological and mineralogical well information and other geoscientific data, the geochemist then selects what he/she considers to be the most appropriate geothermometer temperatures.

4.3.3.6. Use of Triangular Diagrams and Chemical Ratios to Develop Mixing Models

Chemical parameters (including isotopes) can be plotted against each other in a variety of ways to assess the characteristics of the geothermal fluids. Figure 4.11 through to Figure 4.17illustrate a range of plots on which geochemical data can be displayed to develop mixing models, identify end members such as groundwater and reservoir fluid compositions, and thereby build an understanding of the evolution of fluid compositions in a geothermal system. Such plots can answer questions like whether mixing, boiling and/or dilution is taking place within a system. Publications by Harper and Arevelo (1982) on the Baslay-Dauin prospect in the Philippines and by Lovelock et al. (1982) on the Tongonan Geothermal Field also in the Philippines provide useful case studies that include some integration of geochemical data with geological and geophysical data.

Figure 4.11. Example plot of fluid stable isotope data from a number of hot springs and shallow wells in New Zealand.

Source: GNS Science, New Zealand.

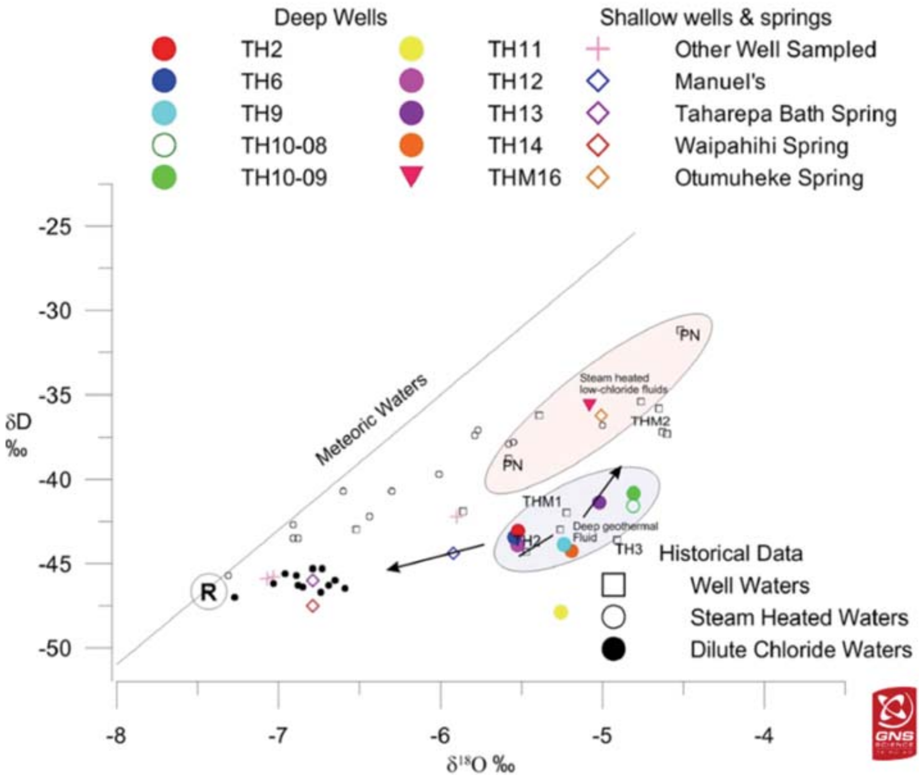


Figure 4.12. Examples of various plots of fluid geochemistry from the Rotorua Thermal Areas in the North Island of New Zealand.

Source: GNS Science, New Zealand.

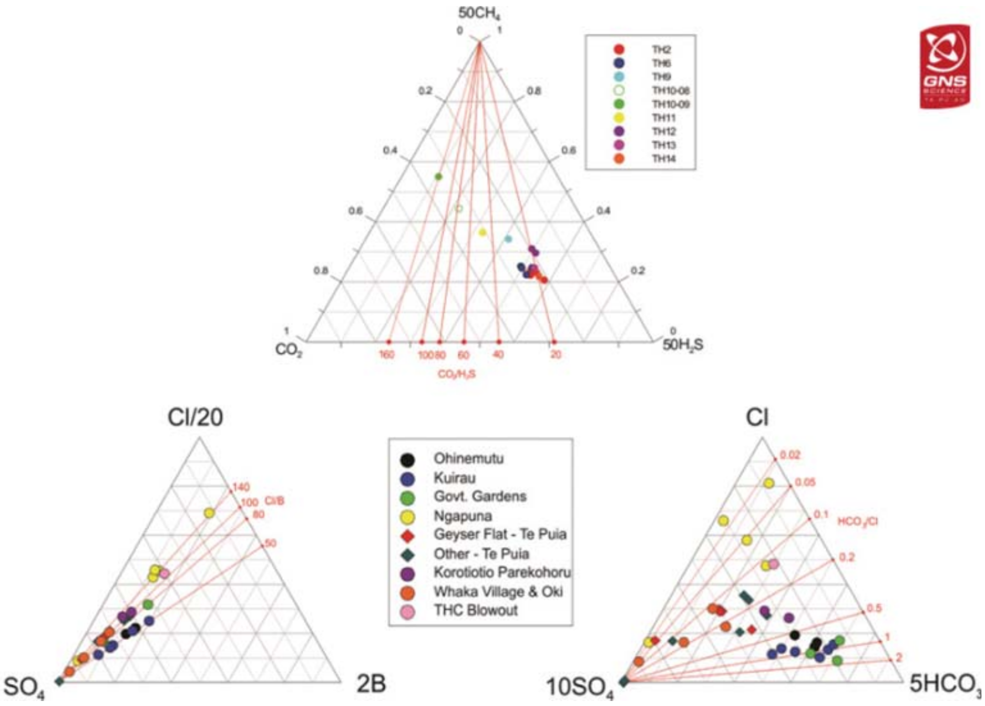


Figure 4.13. Example of a "piper diagram".

Source: GNS Science, New Zealand.

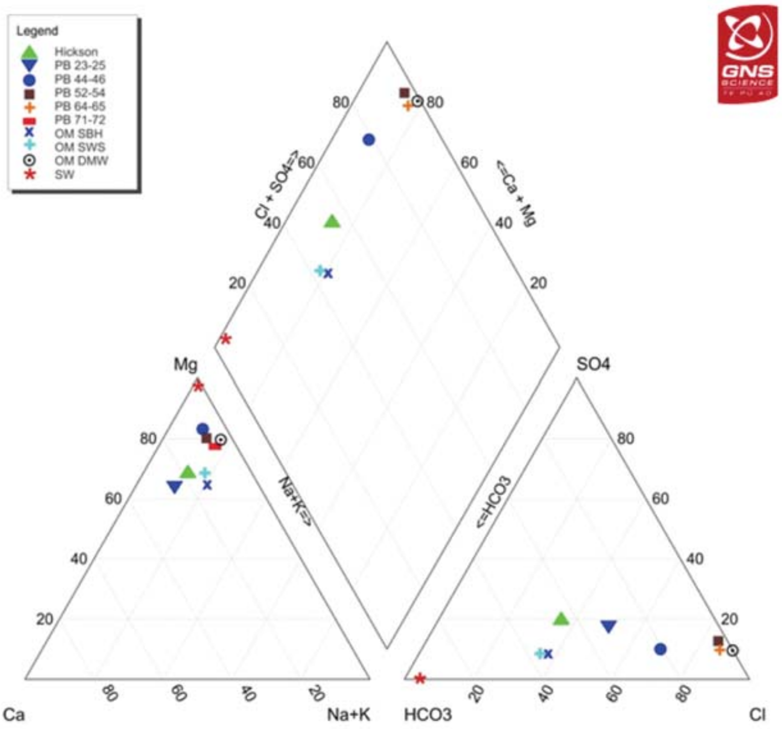


Figure 4.14. Example of the Na-K-Mg ternary geothermometer plot (Giggenbach, 1992) for a range of geothermal fluids (colored boxes and shapes) illustrating temperature dependence of these key cations.

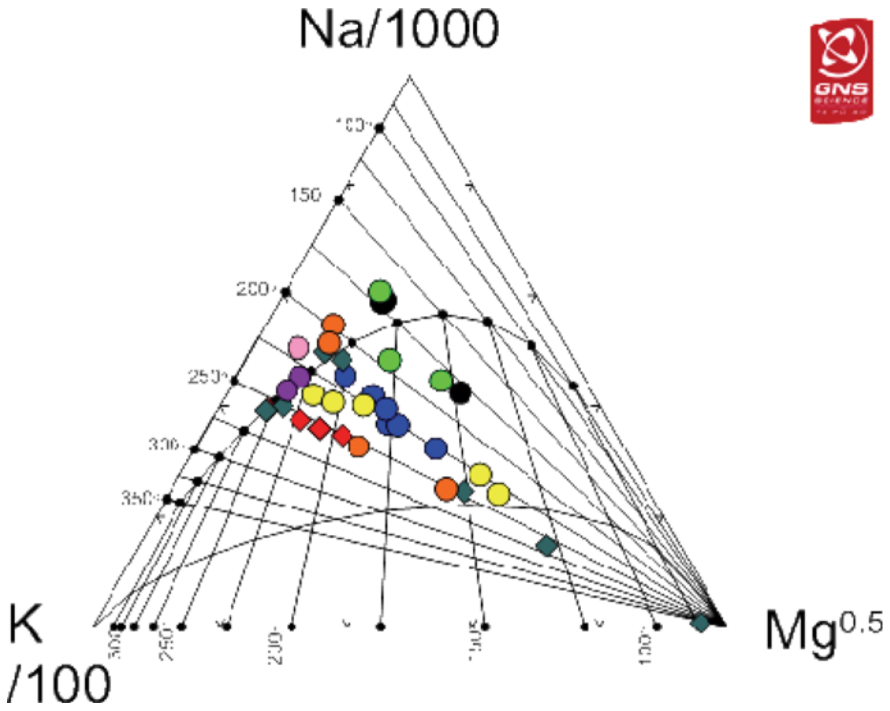


Figure 4.15. Example of an enthalpy (H) vs. Cl plot with various well numbers from the Ohaaki geothermal field shown in the key.

Source: GNS Science, New Zealand.

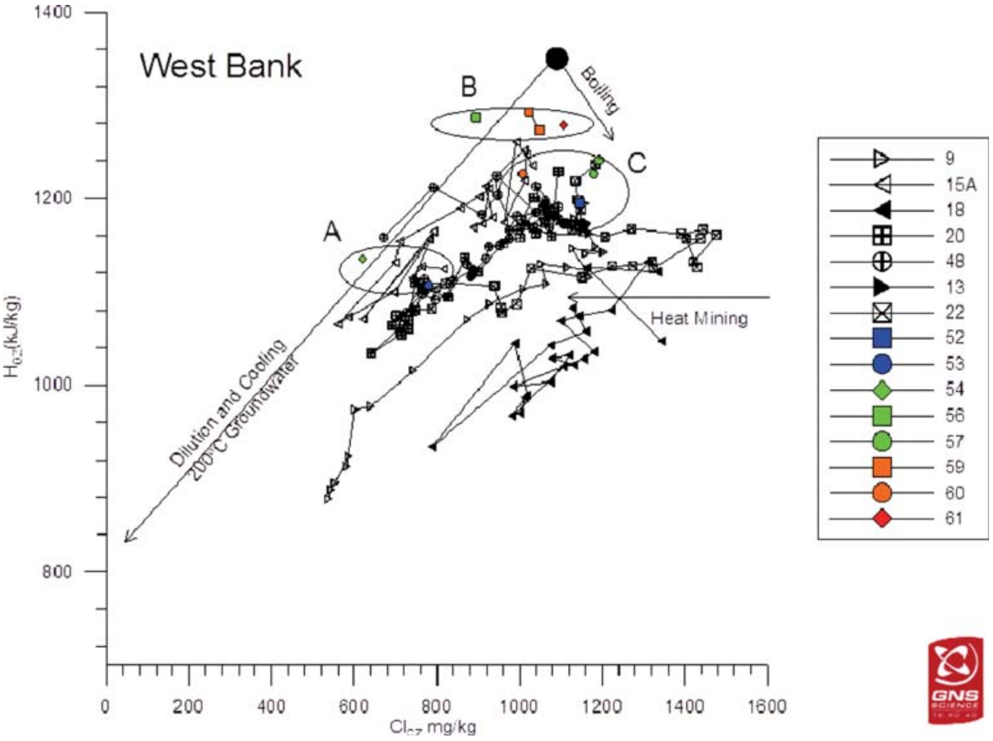


Figure 4.16. Graph showing argon, CO_2 and N2 in the gases of various thermal features.

Source: GNS Science, New Zealand.

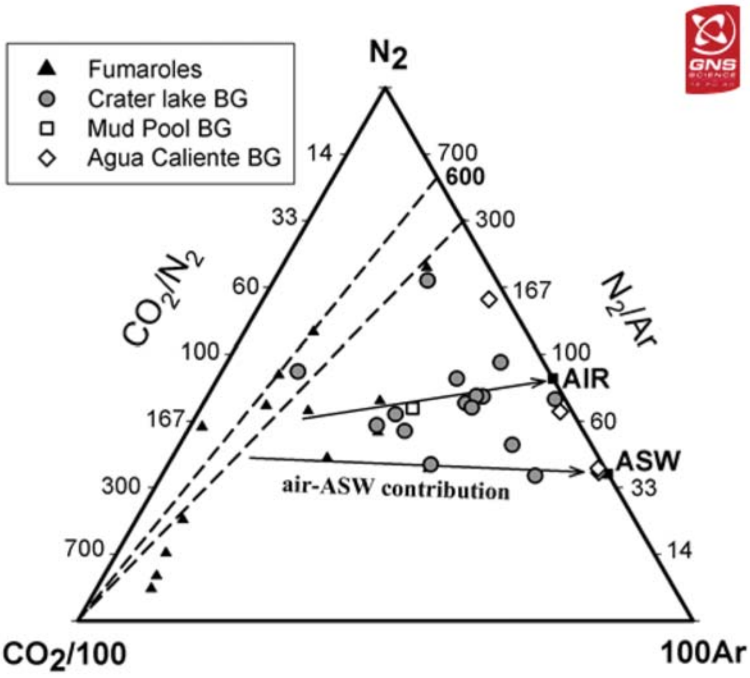
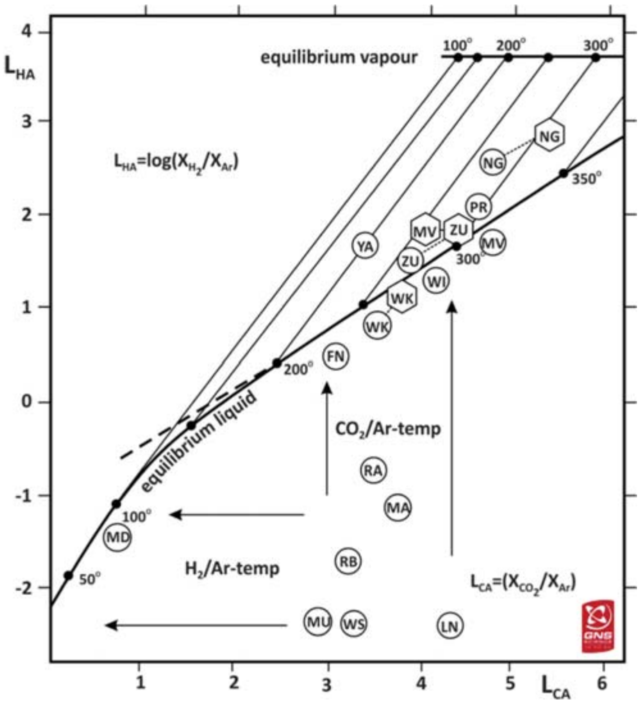


Figure 4.17. Example of a “Giggenbach gas ratio grid” relating equilibrium temperatures with ratios of carbon dioxide, argon, and hydrogen.

Source: GNS Science, New Zealand.



4.3.3.7. Geochemical Modeling Software

Although more extensively used during Phases 3 and 4 of a geothermal project, very sophisticated geochemical modeling software is available, which is worth noting. Such software can model the down hole concentrations of chemical components and speciation in geothermal fluids. For example, Arnorsson et al. (1982), building on the earlier work of Truesdell and Singers (1971), developed the WATCH geochemical software. With inputs of well chemistry data, WATCH and other programs can simulate a range of reservoir processes including scaling, cooling, boiling, and mixing of reservoir fluids.

4.3.3.8. Carbon Dioxide Flux and Soil Sampling

Another commonly used geochemical exploration technique is to survey for CO_2 soil flux and/or mercury (Hg) in soil. Geothermal systems contain non-condensable gases, the principal component of which is CO_2, and often have elevated mercury levels. Therefore, soil sampling surveys (Figure 4.18) are designed to locate anomalously high concentrations of CO_2 and/or mercury that could indicate a potential geothermal system at depth.

Figure 4.18. Soil CO_2 flux measurement.

Note: The CO_2 flux analyzer is worn as a backpack, and an accumulation chamber is placed over the soil. Source: Harvey et al., 2011.

Increased CO_2 flux occurs near many active geothermal manifestations, and CO_2 flux can suggest a geothermal system at depth. Surveys on CO_2 soil flux surveys are performed with a portable meter that measures the active flux of CO_2 through the soil. While CO_2 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 (Harvey et al., 2011), these surveys rarely provide significant geologic or geochemical insight. However, they can often confirm the results of other methods (notably geologic mapping) and 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 sources of mercury aside from active geothermal systems, which tends 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 mercury survey data.

Radon detection methods and studies of radon isotopes may also be useful in identifying active faults or surface activity (Kreuger, 1979).

4.3.3.9. Summary of Geochemical Data

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 the following:

- Estimated reservoir temperature at depth
- Genesis (origin) of the geothermal fluids
- Locations of different aquifers or reservoirs in two or three dimensions
- Mixing between aquifers
- Sources of recharge to the geothermal system
- Pathways of discharge from the geothermal system
- Potential for corrosion and/or scaling by the geothermal fluids

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

- Map of sample locations showing the local or assigned names of the geothermal features from which the samples were taken
- Table summarizing the fluid geochemistry of the sampled geothermal features keyed to the map and including field parameters (location, temperature, EC, pH, flow rate, gas bubbles, odors, precipitates)
- Table summarizing the gas geochemistry of the sampled geothermal features keyed to the map and including
    - 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, $^3He/^4He$, $^{40}Ar/^{36}Ar$, noble gas concentrations and ratios, and stable isotopes in steam condensate – all very valuable in assessing the system's geochemistry; should include standard deviation of each sample and/or other evidence of quality control on analyses undertaken
    - Total flux and makeup of non-condensable gases for any well in production
- Table showing geothermometry calculation results; should include these 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 (18O).

- 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 oxygen-18 (δD vs. $\delta^{18}O$)
  - A ternary plot of the major anions (SO_4-HCO_3-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 sodium potassium calcium geothermometer versus temperature of potassium over magnesium geothermometer: Temp Na/K/Ca (°C) vs. Temp K/Mg(°C)
  - Discharge temperature versus chloride concentration: Temp (°C) vs. Cl(mg/L)
  - A ternary plot of nitrogen, carbon dioxide, and argon (N_2, CO_2/100, 100*Ar)
  - Giggenbach gas ratio grids (H_2/Ar vs. CO_2/Ar, H_2/Ar vs. T, CH_4/ CO_2 vs. CO/ CO_2, CO/ CO_2 vs. H_2/Ar)
- Contour maps showing sample points and their values appropriate to depict soil survey data, as well as tables including 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 reservoir, a fluid-mixing model, and the identification of uncertainties and data gaps that need to be addressed in the subsequent stages of exploration.

4.3.4. Geophysics

The term geophysics refers to the measurement of a range of physical parameters that vary in response to variations in the physical properties of the earth. Geophysical surveys (Figure 4.19) are indispensable tools in geothermal exploration (Wright et al., 1985). They allow us to infer relevant rock and fluid properties and the existence and geometry of reservoirs and permeability pathways, with reasonable confidence prior to drilling. Deciding which geophysical techniques are the most appropriate and cost-effective in any specific exploration program requires input from experienced geothermal scientists. As for the overall exploration strategy, the selection of adequate geophysical methods will mainly depend on the type of geothermal play under investigation (Chapter 2).

Figure 4.19. Electrical resistivity survey.

Source: WesternGeco, United Kingdom.

There are many types of geophysical surveys from which to choose. Each responds to a specific property of the earth or to similar properties at different time and space scales. They include gravity and magnetic surveys and electrical and electromagnetic resistivity surveys, particularly magnetotelluric (MT) or controlled source electromagnetic (CSEM), but there are also several others, along with active and passive seismic techniques. Table 4.3lists these and others. Note that heat flow surveys (also referred to as temperature gradient drilling) are also included as a geophysical exploration method, distinguishing the relatively shallow temperature gradient drilling activity from the later Test Drilling Phase that targets the predicted reservoir zones.

Table 4.3. Geophysical techniques relevant to geothermal exploration.

- Gravity surveys
- Magnetic surveys
- MT surveys
- CSEM surveys
- Electrical resistivity (DC)
- Self-potential methods (SP)
- Seismic surveys
- Passive seismic surveys
- Temperature mapping
- Geophysical logging
- Heat flow/temperature gradient surveys
- Temperature contour maps and cross sections

Quality results from a geophysical survey depend on many factors:

- Quality and suitability of the equipment
- Appropriate survey parameters
- Proper operation of the equipment in field
- Quality control (QC) of collected data
- Appropriate data processing and interpretation
- Understanding of noise sources

For this reason, an experienced geophysicist should be involved in all stages of a geophysical survey. Important tasks for the geophysicist are as follows:

- Evaluation of preexisting data
- Reprocessing of purchased data
- Defining objectives of the measurements
- Choosing appropriate method(s)
- Overseeing the tendering process for a contractor
- Verifying proposals
- Survey planningQC
- Fieldwork QC
- Data QC
- Data processing and interpretation QC

4.3.4.1. Gravimetric Surveys

Gravimetric (or gravity) surveys are relatively simple to implement and map small variations in the force of gravitational attraction of the earth. These small variations are due primarily to bulk density variations of the rock sequence beneath the survey site. The careful design and implementation of a gravity survey can make the difference between a highly successful interpretation tool and a waste of resources.

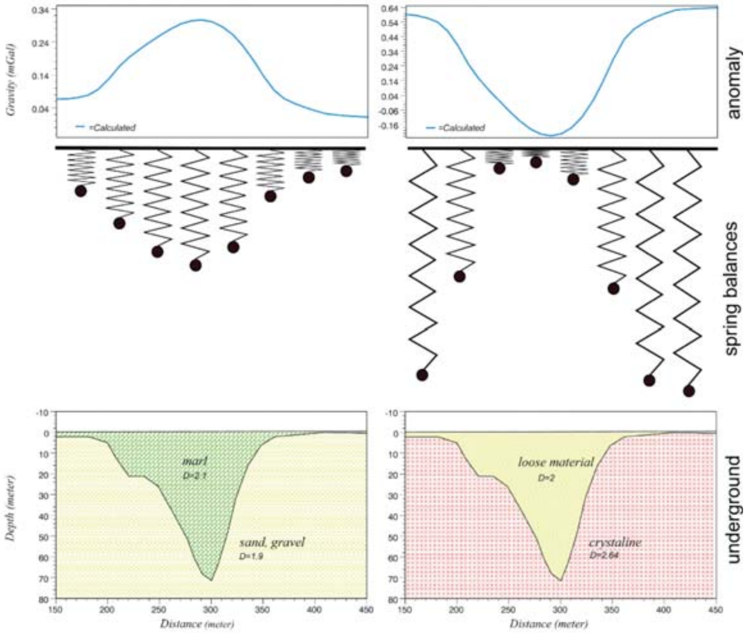
A gravity survey involves measuring the earth's gravitational field at specific locations on the earth's surface (or along a flight path during airborne gravity surveys) to detect the locations of subsurface rock density variations. Most of the instruments (Figure 4.20) for gravitational field surveys (e.g. LaCoste and Romberg, Scintrex, Worden) are spring based, with the local strength of the gravitational field deduced by measuring the amount by which a constant mass stretches a spring (Figure 4.21). High precision superconducting gravimeters are an available alternative for field use (Sugihara and Nawa, 2012).

Figure 4.20. Example of a field survey gravimeter.

Photo: David Monniaux (license: CC)

Figure 4.21. Principle of gravimetry.

Note: Left: Compact fill causes a positive gravity anomaly and a greater amount of stretching of the internal spring. Right: Loose fill results in a negative gravity anomaly and less stretching of the spring.
Source: Data courtesy of H. Lindner.



Gravitational attraction is sensitive to the precise distance from the center of the earth's mass, so the location and precise elevation (centimeter accuracy) are two of the most important factors to record during a gravity survey. This is normally achieved using a differential GPS (DGPS). Table 4.4lists other factors to record.

Table 4.4. Information recorded or generated at different stages of a gravity survey.

FIELDWORK	DATA PROCESSING	INTERPRETATION
• Field report	• Processing report	• Report
• Instruments used	• Information about instrument and local tidal drift and removal	• Geological information
• Map(s) showing all survey stations	• Detailed information about applied corrections and software used	• Detailed information about assumptions and software used
• Coordinates (xyz) of all survey stations along with gravity value	• Bouguer maps and profiles	• Detailed information about modeling process
• Raw data (ASCII) on file	• Processed data on file	• Assessment of how well the data fit the model
		• Interpreted Bouguer maps and profiles
		• 2D/3D images of interpreted structures

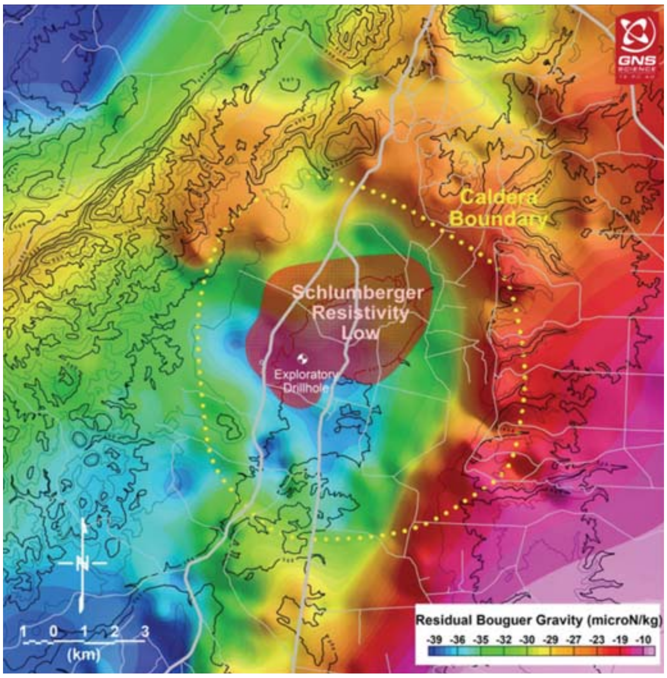
Survey parameters such as the number of stations and station spacing should be decided according to the size, depth, and relative density of the bodies and structures being sought. For quality control, measurements at one or more survey stations should be repeated several times to confirm results. After the fieldwork is completed, several corrections must be applied to the gravity data during processing to produce a final result called a Bougueranomaly map or simply a Bouguermap. The usual sequence of corrections is as follows:

- International gravity formula corrects for the variation of gravity with latitude.
- Free air correction corrects for the elevation at which a measurement is made;it adjusts readings of gravity to what would have been measured at sea level if the intervening elevation were composed entirely of air.
- The Bouguer correction accounts for the attraction of the terrain; Bouguer reduction is called simple or incomplete, if the terrain is approximated by an infinite flat plate (called a Bouguer plate).
- Terrain reduction (complete Bouguer correction) accounts for the effects of terrain more precisely.
- Bouguer anomaly map/Bouguer map is the result of gridding or contouring all data points after the above corrections are applied.

Figure 4.22 shows an example of a Bouguer map plotted over a topographic map of a caldera in New Zealand, characterized by a low gravity anomaly in the center of the map. The interpretation of a Bouguer map on its own is limited by the inherent ambiguity of gravitational fields. A small density anomaly at a shallow depth can produce the same gravitational effect as a large density anomaly at greater depth. Either depth or composition must be constrained by independent data (e.g., depth estimates from reflection seismic data, or composition from geological history models or rock property measurements) before reliable inferences can be drawn about the other. Note, also, that the spatial resolution of geological interpretations from gravity and magnetics (see below) is insufficient to map permeable structures like smaller faults or structurally weak zones.

Figure 4.22. Example of gridded gravity data.

Source: GNS Science, New Zealand.



A gravity survey should only be considered as part of a new exploration program if underground structures are expected to result in detectable lateral and vertical density contrasts. To properly assess this possibility requires some preexisting knowledge of the subsurface, including the expected lithologies, the depths at which they are expected to lie, and the geometrical relationships between them. A general rule of thumb is that a body must be almost as big as it is deep in order to be detectable with a gravity survey. The distances between stations must also be small enough to resolve any surface anomaly produced by the subsurface body.

A good outcome of a gravity survey is a reliable Bouguer map, revealing variations in the gravitational field strength that can be related to the geological structures relevant to geothermal exploration, including geometry and depth of significant rock units or faults. Variations of gravity surveys such as “airborne gravity gradiometry” or “microgravity surveys” provide similar data at different spatial scales.

4.3.4.2. Geomagnetic Surveys

Geomagnetic (or magnetic) surveys are also relatively inexpensive and simple to implement. Spatial variations in the magnetic properties (such as remnant magnetization, magnetic susceptibility, and magnetic permeability) of near surface rocks cause local variations in the strength and/or direction of the earth's magnetic field. Geomagnetic surveys map these variations and highlight anomalies. The main magnetic components of rocks are the minerals magnetite (Fe3O4) and maghemite (Fe2O3). Most of the variation in the measured magnetic field can be attributed to different concentrations of these minerals in the near surface. For example, the impact of basaltic rocks on the earth's magnetic field is significantly higher than that of granitic rocks.

In many liquid-dominated geothermal fields, hydrothermal processes alter magnetic rocks to mostly nonmagnetic minerals. Such processes cause volcanic rocks to become partly or completely demagnetized, and a significant magnetization contrast then exists between the reservoir rocks and the unaltered volcanic rocks beyond the reservoir (Soengkono and Hochstein, 1995). Another application of magnetic surveys to geothermal exploration involves identifying the depth of the curie point or curie temperature (Bhattacharyya and Leu, 1975). At the curie point, materials change from ferromagnetic to paramagnetic. Estimating the depth to this point provides an estimate of average thermal gradient (Salem et al., 2000).

Application of the magnetic method involves measuring the total field strength (and possibly inclination and declination) of the earth's magnetic field at specific locations or along a line on the earth's surface (Figure 4.23). As for gravity surveys, robust design of a magnetic survey can prevent a waste of resources and yield optimum interpretable data. Surveys can be performed on foot or using piloted aircraft or unmanned aircraft systems (UAS) along a flight path. The aim is to determine the location of subsurface magnetic susceptibility and magnetization variations.

Figure 4.23.
From left to right: base station magnetometer, walking mode data collection, sensor height 3 m; UAS.

Source: HarbourDom GmbH, Germany.

The magnetic field strength at the earth's surface generally drifts over the period of a typical magnetic survey, due to atmospheric effects (or spherics). A static base station is used to correct for this drift by collecting field strength measurements at regular intervals at the same location in order to quantify the drift over time. Raw data from the survey are then corrected relative to the base station record. Airborne magnetic data must additionally be corrected for heading and level (Green, 1983). In general, the distance between individual data points must be small enough to resolve the target.

The magnetic susceptibility of key lithologies is an important input parameter to reliably model the results of a magnetic survey, and therefore should be measured. Field Kappa meters can be used to make susceptibility measurements onsite. Alternatively, rock samples can be collected to measure susceptibility and determine the magnitude and direction of remnant magnetism in the laboratory.

The measured value of magnetometers is the total field intensity or tesla (T) in units of nanotesla (nT). Before interpretation of geomagnetic data, all contributions to the total field not originating from geological sources have to be subtracted from the measured values where

ΔT = Magnetic Anomaly = $T - T_V - T_A - T_R - T_0$
and where

- T = measured value;
- T_V = diurnal variation;
- T_A = altitude correction;
- T_R = terrain correction; and
- T_0 = normal field.

The results can then be gridded or contoured and plotted as a magnetic anomaly map (Figure 4.24). Table 4.5lists parameters that should be recorded during a magnetic survey.

Figure 4.24. Magnetic anomaly map.

Note: The map is generated from data collected using a land magnetometer in walking mode, highlighting a large positive magnetic anomaly (purple) in the western part of the survey area. Source: HarbourDom GmbH, Germany.

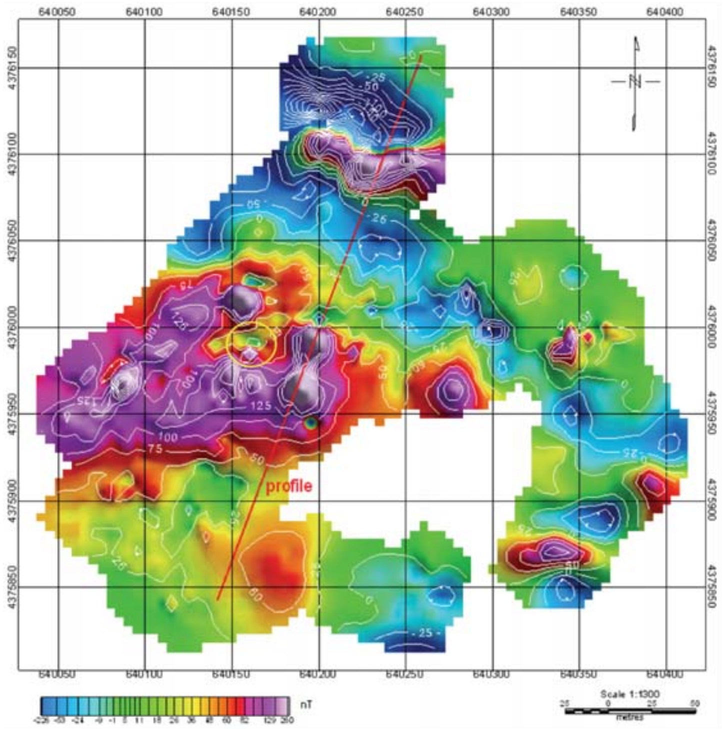


Table 4.5. Information recorded or generated at different stages of a magnetic survey.

DATA ACQUISITION	DATA PROCESSING	INTERPRETATION
• Field report • Instruments used • Map(s) showing all data points and base station(s) • Time series from base station(s) • Coordinates (xyz) of all data points • Time and date • Measured magnetic field strength • Raw data (ASCII) on file • Altitude for each sample point (for airborne data)	• Processing report • Leveled data (for airborne surveys) • Detailed information about applied corrections and software used • Magnetic anomaly maps and profiles • Processed data on file (ASCII or GEOSOFT-database format) • Gridded data on file	• Report • Geological information • Detailed information about assumptions and software used • Detailed information about the modeling process • Assessment of how well the data fit the model • Interpreted anomaly maps and profiles • 2D/3D images of interpreted structures

A geomagnetic survey will only provide useful information for geothermal exploration if there is an expected detectable contrast in magnetic susceptibility and/or magnetization in the underground layers or structures. To distinguish between anomalous and undisturbed magnetic areas, the size of the survey area has to exceed the size of the expected anomaly.

A good outcome of a geomagnetic survey is a reliable magnetic anomaly map, revealing variations in magnetic properties that can be related to the geological structures relevant to geothermal exploration, including geometry and depth of intrusions, dikes, etc. Geomagnetic surveys are most appropriate for constraining the “big picture” of the underground.

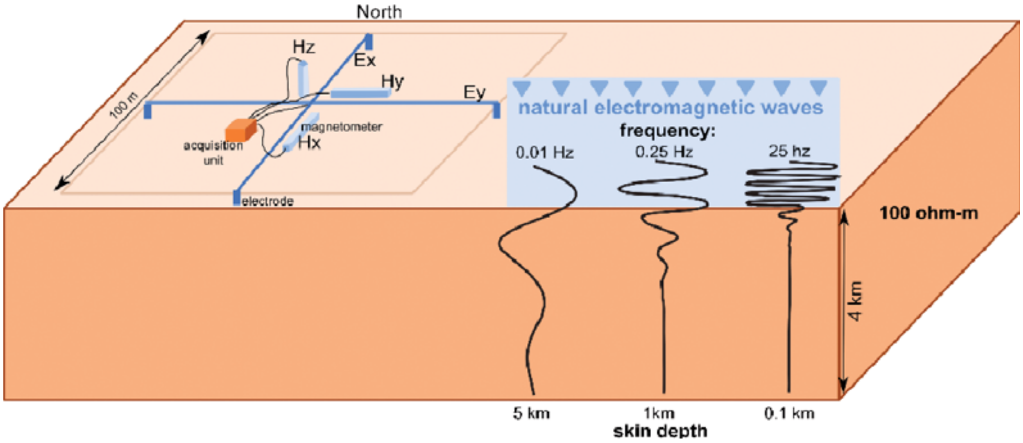
4.3.4.3. Magnetotelluric Surveys

The magnetotelluric (MT) method responds to the earth's electrical resistivity structure (Simpson and Bahr, 2005). The method involves taking a time series recording of natural, low frequency, orthogonal electric and magnetic fields at the earth's surface, then interpreting the data in the frequency domain. Natural fluctuations in the earth's magnetic field are generated by lightning, ionospheric resonances or variations in the solar wind. These fluctuations induce electric currents (or telluric currents) beneath the surface of the earth. The ratio of the electric field to the magnetic field in the induced electromagnetic (EM) wave is a function of the frequency of the signal and the bulk electrical resistivity of the ground. Lower frequency magnetic fluctuations induce currents through a greater thickness of ground (Figure 4.25). Recording data over a wide frequency spectrum effectively gives information about a great thickness of ground. Lower frequency records (i.e., information about greater depths) require longer collection times.

The MT method is one of the very few geophysical techniques that can provide information about rock units deeper than about 1,000 meters. This makes it useful for geothermal exploration, where target depths are typically in the range of 1,000-3,000 meters for convection-dominated geothermal plays and even deeper for conduction-dominated plays. The MT method is particularly useful for convection-dominated plays because it can potentially image low resistivity and low permeability smectite clay units that often cap high enthalpy geothermal reservoirs (Melosh et al., 2010). For this reason, the MT method is often used to reduce uncertainties about reservoir depth, geometry, and areal extent.

Figure 4.25. MT station layout and skin depths for natural electromagnetic waves depending on frequency.

Note: Low frequencies respond to deep structures, high frequencies respond to shallow structures. Source: HarbourDom GmbH, Germany.



During an MT survey the horizontal electric and magnetic fields at the earth's surface are measured using electrodes and magnetometers buried in the ground (Figure 4.26, left-hand side). The non-polarizing electrodes often contain solutions of copper sulfate or cadmium chlorate. Metal electrodes can be used, but electric field data quality can be low since they generate electrical noise as they corrode. The magnetometers are induction coils for frequencies above 0.01 Hz and fluxgate magnetometers for lower frequencies. Figure 4.26 shows examples of coil preparation, storage, and data acquisition in the field.

Figure 4.26. Left: preparing coils (blue tubes) for an MT station. Middle: MT coils. Right: acquisition unit at an MT station.

Source: HarbourDom GmbH, Germany.

Recorded MT data are processed and represented as a complex impedance tensor relating the electric and magnetic field values and expressed as the apparent resistivity and impedance phase (Vozoff, 1986). Interpretation involves estimating the shallow resistivity structure using the higher frequency information, then deriving progressively deeper resistivity structure from the longer wavelength bulk resistivity information and the shallow resistivity estimates. By its nature, MT interpretations become less precise at greater depths.

MT surveys can be performed at a regional scale. In these cases, the station spacing may be less than one per square kilometer. It is usually more cost effective to identify a prospective area with other methods and then conduct an MT survey with relatively high station spatial density in that area, with perhaps as many as 10 to 15 stations per square kilometer.

Carrying out a time domain electromagnetic (TDEM) survey (see below) covering the same MT station locations (Wameyo, 2005) is a good practice in order to apply a “static shift correction” to the MT data for more robust interpretations (Irfan et al., 2010). The TDEM survey effectively provides high frequency electromagnetic information that the MT survey is unable to record. This allows greater resolution of the resistivity structure at shallow depths (typically a few hundred meters), hence improving the structure’s interpretation at greater depth from the MT data.

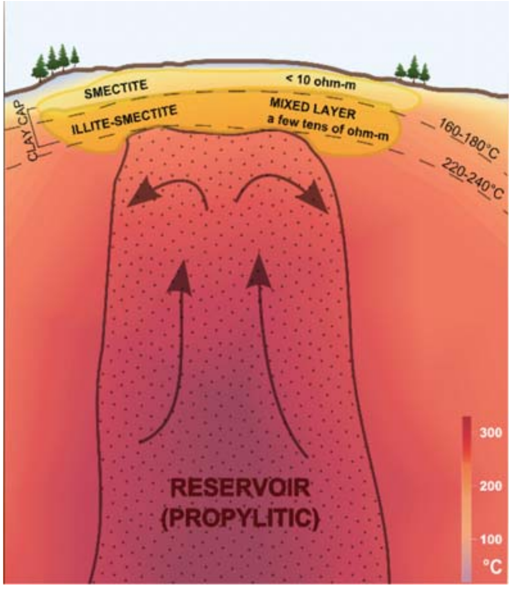
Unaltered volcanic rock generally has high electrical resistivity. Hydrothermal fluids tend to reduce the resistivity of volcanic rocks in three ways:

- By altering the rocks to clay
- By increasing the salinity of the fluids in the rocks
- By increasing the temperature of the rocks

Hydrothermal alteration has a dominant effect on resistivity in high enthalpy reservoirs. In volcanic areas, acid-sulfate water can interact with the surrounding volcanic rocks to produce different alteration products depending on the temperature and hence on the distance from the heat source. With basalt as the surrounding rock, low-resistivity smectite becomes the dominant alteration product in the temperature range from 100°C to 180°C. At higher temperatures mixed layer clays are produced (Figure 4.27).

Figure 4.27. Diagram of a generalized geothermal system.

*Note: Geothermal system (modified after Johnston et al., 1992). The smectite cap or "claycap" typically displays resistivity of around 2 Ohm*m, and the mixed layer around 10 Ohm*m.*
Source: HarbourDom GmbH, Germany.



Magnetotelluric data are normally interpreted through an "inversion" process, whereby a semi-automated algorithm determines the simplest and most likely "apparent resistivity" structure consistent with the collected data. Inversions can also be carried out in 1D, 2D or 3D, referring both to the spatial distribution of recording stations and the dimensions of the model simultaneously solved. A 1D inversion produces a vertical "sounding" from a single station; a 2D inversion, a profile from a line of stations; and a 3D inversion, a self-consistent block model from an array of stations (Siripunvaraporn et al., 2005). Higher dimension inversions require significantly greater computing power and time to complete.

Inversions might be carried out by the MT contractor or by an independent third party. Inversion algorithms typically need to be constrained in some way, usually through limiting the allowable number of discrete layers and/or the depths between layers. For this reason, inversion results are subjective because they depend on input from the data processer. The results from 1D, 2D and 3D inversions can differ significantly from each other for the same set of data, because the models depend on the dimensionality and complexity associated with the magnetotelluric responses. The resolution and accuracy of inversion models in terms of both depth and apparent resistivity decrease with depth.

The results of magnetotelluric inversion are normally presented as apparent resistivity on 1D soundings, 2D profiles (Figure 4.28) or maps (Figure 4.29), or 3D block figures (Figure 4.30).

Figure 4.28. Cross section showing apparent resistivity from MT data.

Source: HarbourDom GmbH, Germany.

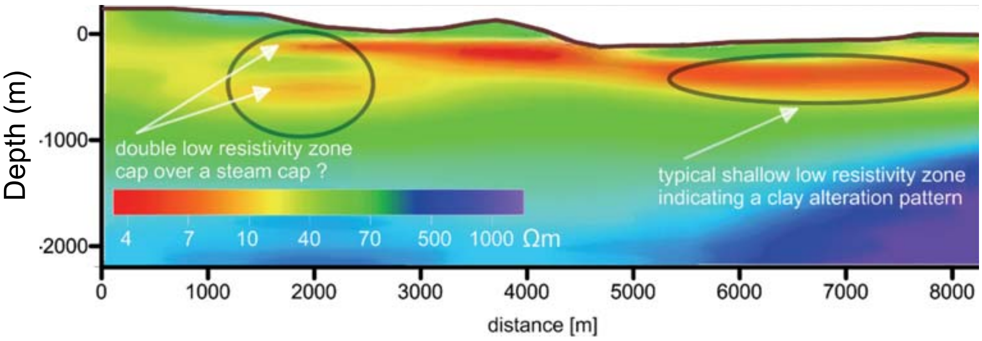


Figure 4.29.
MT resistivity map with station locations shown.

Source: GNS Science, New Zealand.

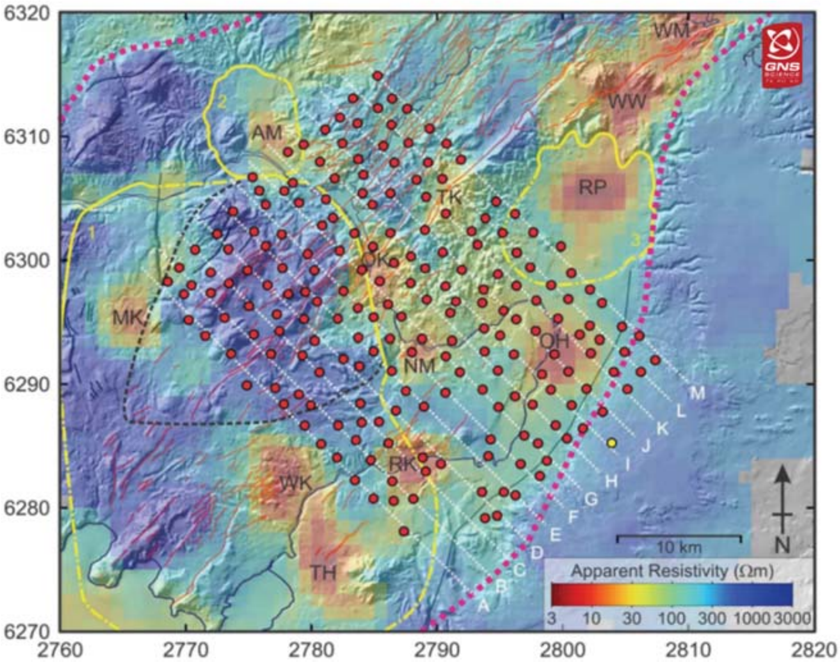
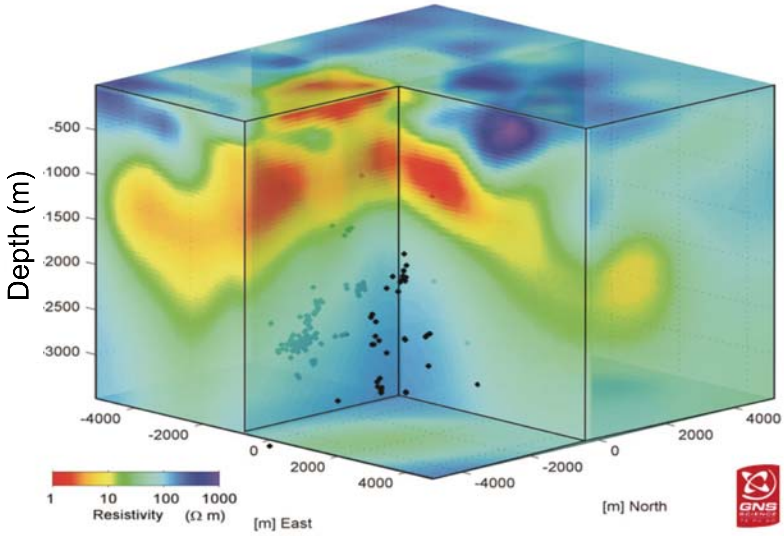


Figure 4.30.
3D MT resistivity block model.

Source: GNS Science, New Zealand.



A phenomenon called magnetotelluric polarization is of particular and growing interest for geothermal exploration as it has the potential (when interpreted jointly with other data sets) to reveal the dominant orientation of fractures (e.g., Onacha et al., 2010). Joints or fractures lying in a preferred orientation and filled with conductive brine tend to conduct electricity more efficiently (i.e., lower resistivity) parallel to their strike, compared to perpendicular. If the electrical and magnetic fields are each recorded along perpendicular axes, then deriving a resistivity tensor is possible in describing how the electrical resistivity varies with direction. A preferred direction of higher apparent resistivity within a particular depth interval might be interpreted as being perpendicular to a dominant fracture orientation. The evidence becomes more compelling when combined with other directionally sensitive techniques such as "seismic shear-wave splitting" (see below). Table 4.6lists parameters that should be recorded during an MT survey

Table 4.6. Information recorded or generated at different stages of an MT survey.

DATA ACQUISITION	DATA PROCESSING	INTERPRETATION
• Field report • Noise sources • Instruments used • Map(s) showing all data points and remote reference station(s) • Coordinates (xyz) of all data points, time and date, and values • Data on file (EDI format)	• Processing report • Detailed information about applied corrections and software used • Inversion results • Apparent resistivity maps and profiles • Processed data on gridded data on file	• Report • Geological information • Detailed information about assumptions and software used • Detailed information about the modeling and interpretation process • Assessment of how well the data fit the model • Interpreted anomaly maps and/or profiles • 2D/3D images of interpreted structures

A good outcome from an MT survey is a 3D apparent resistivity block model derived from stacked 1D or 2D inversions (incorporating static shift corrections from a TDEM survey), or a full 3D inversion. The inversion model should suggest regions of contrasting electrical resistivity consistent with the conceptual model of the geothermal system.

4.3.4.4. Controlled Source Electromagnetic Surveys

Controlled source electromagnetics (CSEM) is the general term for electromagnetic sounding methods that use an active transmitter and antenna to generate their own electromagnetic source fields with known properties. For frequency domain methods (FDEM), the transmitter generates a sinusoidal electromagnetic wave at a fixed frequency that is selected for the desired depth of exploration (lower frequencies for greater depths; higher frequencies for shallower depths). Some CSEM methods operate in the time domain (TDEM methods) by recording the decay over time of a secondary electromagnetic field induced by a finite electromagnetic pulse. The main advantage of CSEM methods over the MT method, which utilizes natural electromagnetic sources, is that CSEM data acquisition is faster. However, the depth of imaging for CSEM is generally shallower than that for MT.

A huge variety of CSEM methods have been developed, distinguished mainly by the frequency (or frequencies) at which they transmit and detect electromagnetic waves and in the geometry of their source and receiver antennae (Figure 4.31). The primary electromagnetic fields are generated by electrical current waveforms passed through a loop (Árnason, 1989) or grounded dipole (Figure 4.32). Those primary fields generate eddy currents in the ground, which induce secondary electromagnetic fields that can be measured at the surface using a receiver coil or receiver electrodes. The properties of the induced field depend on the electrical resistivity distribution of the subsurface rocks.

Figure 4.31. Examples: CSEM source signals (left), sources (middle), sources/ receivers (right).

Source: HarbourDom GmbH, Germany.

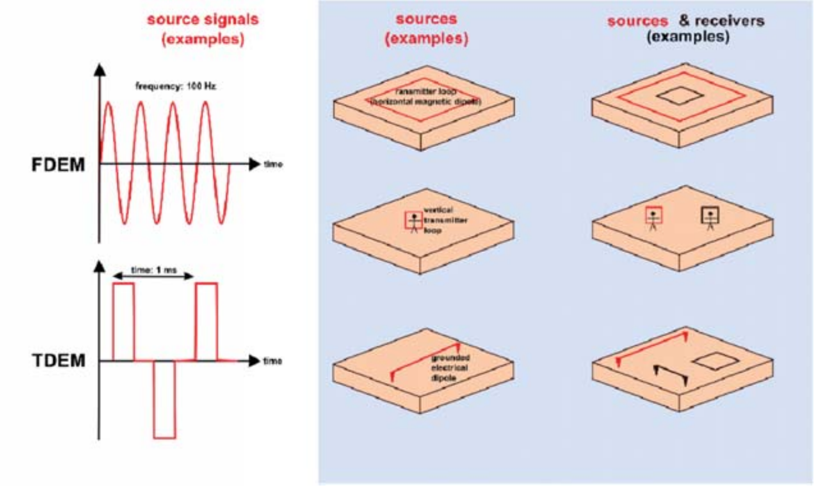
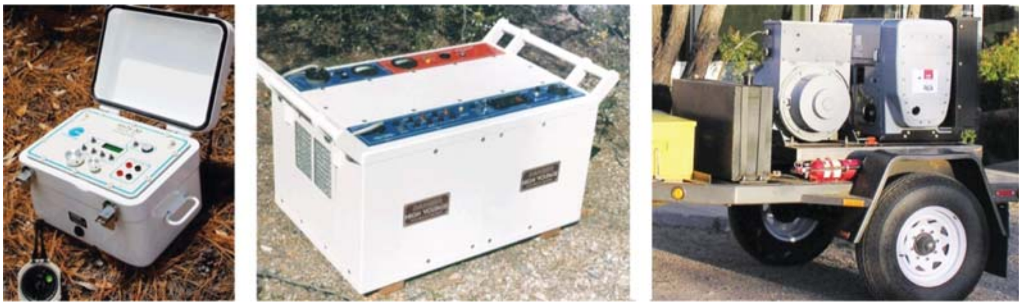


Figure 4.32. CSEM transmitters and generator.

Note: Left: battery-powered transmitter;Middle: generator-powered transmitter;Right: 32kva, 400 Hz diesel-powered motor generator. Source: Zonge Engineering.

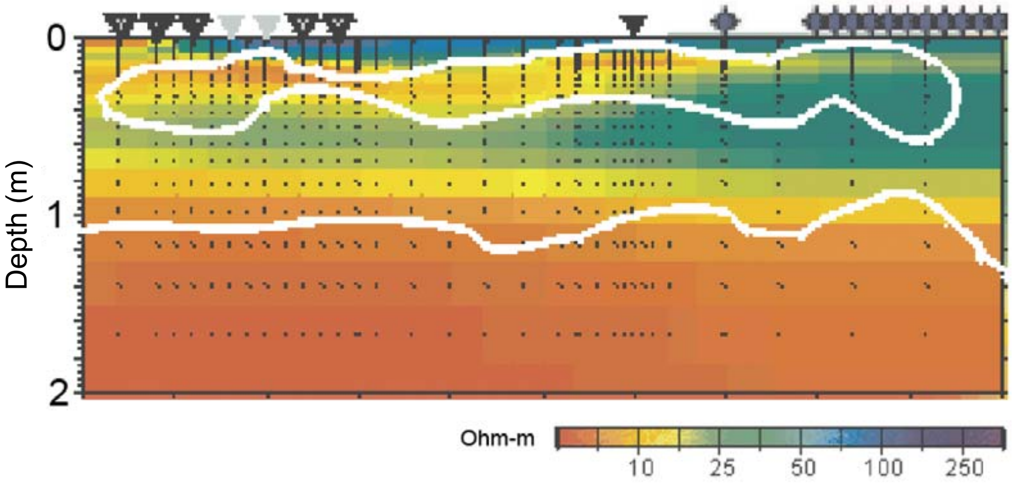


Data from FDEM surveys are normally processed to reveal the amplitude and phase of the induced field (relative to the primary field) after compensating for the primary field. Data are further processed to derive apparent resistivity with depth. In most TDEM instruments, the current is transmitted as a periodic square wave. The induced electromagnetic field is recorded at the receiver stations during the transmitter off time, in absence of the primary field. After processing, the data are represented as apparent resistivity – depth curves, profiles (Figure 4.33) or maps. Modeling and inversion can be carried out in 1D, 2D or 3D.

Figure 4.33. Result of a 2D LOTEM inversion.

Note: The white outline shows low resistivity zones from 2D MT inversion.

Source: Scholl et al., 2003.



The penetration depth of an induced electromagnetic wave depends on the signal strength (current or voltage), the distance between transmitter and receiver (meters to kilometers), and the frequency of the transmitted wave (lower frequencies penetrate deeper). The transmitter-receiver distance is approximately equivalent to the maximum depth of exploration, which good survey design should reflect. The best practice is to record multiple receiver measurements relative to the same transmitter station to enhance signal-to-noise ratio at all depths.

Working in areas with steep changes in topography creates challenges in laying out antennae wires, as well as in processing and interpreting the collected data.

The parameters that should be recorded during a CSEM survey are similar to those collected during an MT survey, and are listed in Table 4.7.

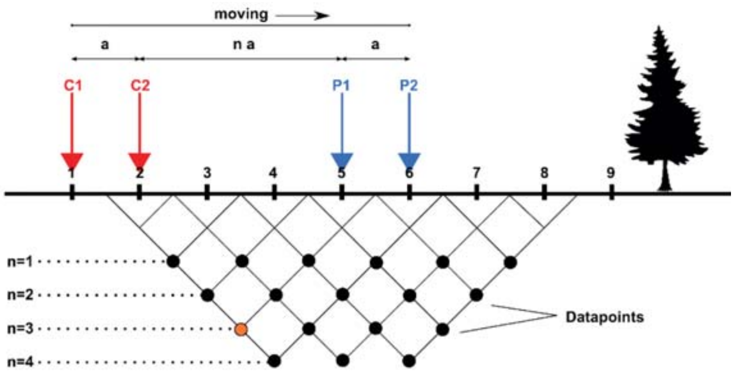
Table 4.7. Information recorded or generated at different stages of a CSEM survey.

DATA ACQUISITION	DATA PROCESSING	INTERPRETATION
• Field report • Instruments used • Map(s) showing all data points, transmitter and receiver locations • Coordinates (xyz) of all data points, transmitter and receiver locations, time and date, and values or time series • Information about system responses, if acquired • Data on file (ASCII)	• Processing report • Detailed information about noise reduction, applied filters, stacking, and used software • Apparent conductivity, phase, and resistivity maps and profiles • Processed data and gridded data on file	• Report • Geological information • Detailed information about assumptions and software used • Detailed information about the modeling process • Assessment of how well the data fit the model • Interpreted anomaly maps and profiles • 2D/3D images of interpreted structures

4.3.4.5. Electrical Resistivity (Direct Current)

Direct current (DC) soundings also image the vertical apparent resistivity distribution of the subsurface. The resistivity of soils and rocks is governed primarily by the amount of pore water and its resistivity. DC soundings are based on the principle that the electrical field produced in the ground around a current-carrying electrode is a function of the distribution of electrical resistivity of the surrounding soils and rocks. The usual practice is to generate an electric current in the ground between two electrodes (current electrodes) and to measure the resulting difference in electrical potential (voltage) between two other electrodes (potential sondes) not connected to an active current. Surveys can be designed to generate 1D soundings or 2D profiles. Many different electrode configurations have been applied, including the dipole-dipole array, Schlumberger array, Wenner array, pole-pole array, and others. In an example of a four-electrode DC dipole-dipole array (Figure 4.34), there are two electrodes (C1 and C2) and two potential sondes (P1 and P2). A series of electrode (current and potential) station locations (Numbers 1-9) is separated by a fixed distance (a). The separation between dipoles is always a multiple (n) of the fixed distance (a).

Figure 4.34. Configuration of a four-electrode DC dipole-dipole array used for 2D resistivity measurements.



The exact array parameters need to be accurately known before a reliable inversion (Figure 4.36) can be performed.

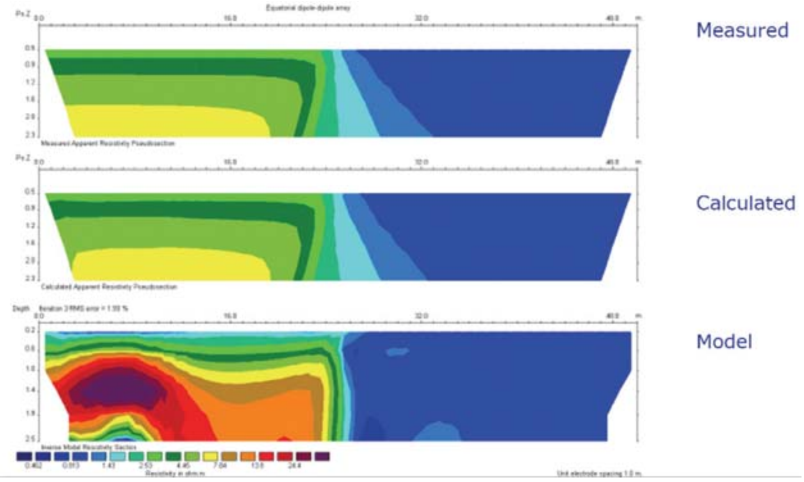


Figure 4.35. Example of results of DC measurements and 2D inversion modeling for a pole-pole array.

The parameters to be recorded and reported for a DC survey are mostly the same as for a CSEM or MT survey.

4.3.4.6. Self-Potential Methods

There are two standard designs for a self-potential (SP) survey. In one design, electrodes are separated by a constant distance (Figure 4.36, bottom), commonly 5 or 10 meters, and both electrodes move to a new location for each measurement. Alternatively, voltages can be measured across the survey area relative to a fixed base, in which case one electrode remains in a constant location while the second electrode is moved around (Figure 4.37, top). Figure 4.37shows an example of SP mapping.

The SP survey is a relatively low-cost method (Ross et al., 1995), but the results can be difficult to interpret. The SP survey is often used for reconnaissance surveys, mapping major boundaries or tracing faults. In Japan, the method has also been used to monitor geothermal reservoirs, especially for liquid-dominated geothermal systems (Yasukawa et al., 2005).

Figure 4.36. Two variations on SP survey techniques.

Source: HarbourDom GmbH, Germany.

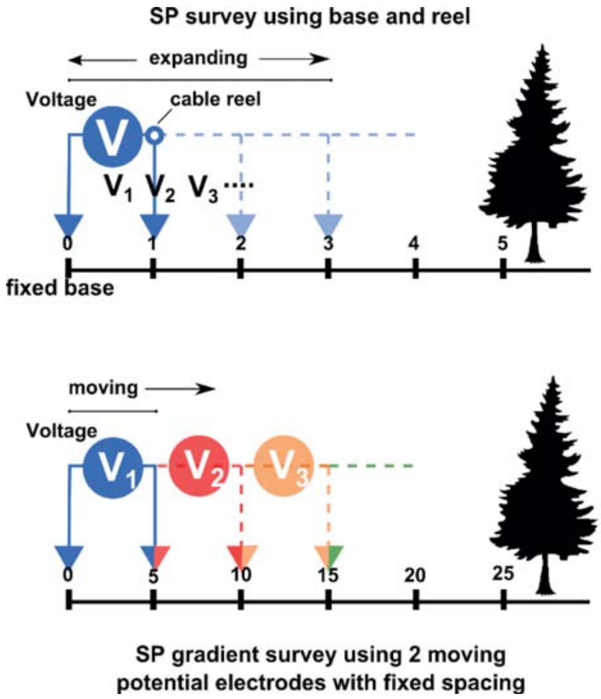


Figure 4.37. Example of SP mapping results

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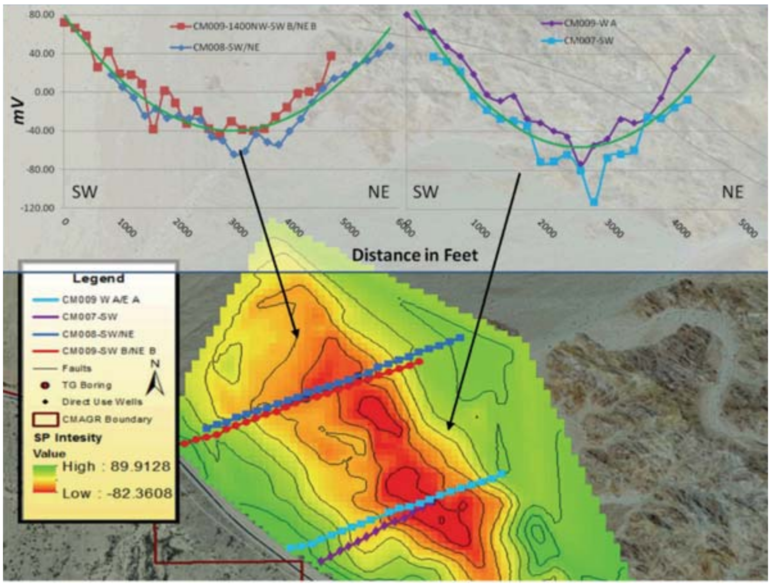
Note: The charts in the upper half of the figure compare the results of two surveys carried out over the same anomaly at different times. Both datasets are consistent with each other and demonstrate the dipolar nature of the anomaly. Sources: Alm et al., 2012; HarbourDom GmbH, Germany.



4.3.4.7. Seismic Surveys

Seismic surveys are sensitive to differences in the “acoustic impedance” (the product of density and seismic velocity of rocks). Seismic waves propagate and interact with subsurface structures, with part of the seismic signal typically reflecting and the remainder of the signal refracting at each rock contact. The surveys can yield important information on the location and orientation of subsurface structures, such as faults and rock discontinuities, which may help to explain fluid flow.

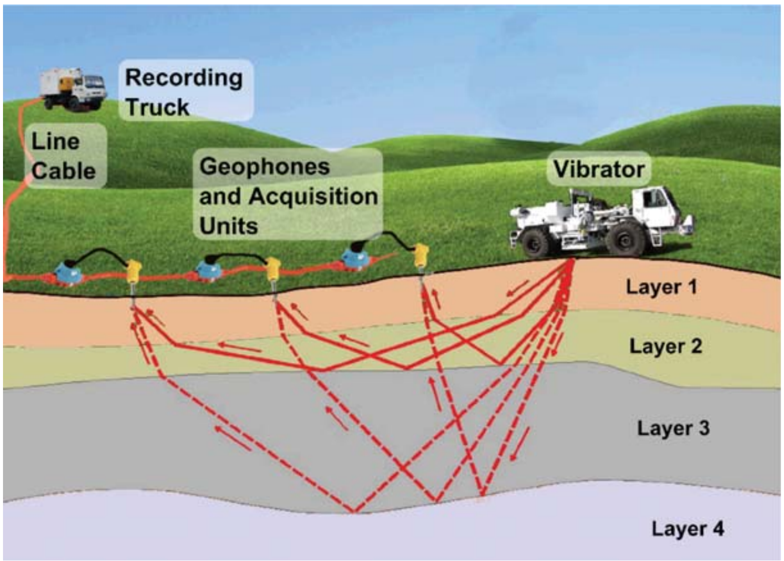
Seismic surveys can be divided into two subcategories based on the source of the seismic signal. Reflection surveys rely on using induced or man-made vibrations or single sources (e.g., explosive source) at the surface. Passive surveys, however, rely on natural tremors or earthquakes, volcanic eruptions, or other tectonic activity as sources.

Seismic Reflection Surveys

A seismic reflection survey is an “active” technique that images boundaries between rock layers of different acoustic impedance and requires a controlled source of seismic energy, such as seismic vibrators (commonly known as vibroseis), dynamite explosives, or air guns for marine surveys. The general principle of seismic reflection is to send elastic waves from the source into the underground, where each layer reflects a part of the wave’s energy and allows the rest to refract through. The reflected wave field is recorded at the surface by a number of seismic receivers (geophones) that sense the motion of the ground in which they are placed (Figure 4.38). Surveys can be designed to image the underground along a profile (2D survey) or within a volume (3D survey).

Figure 4.38
Main components of a reflection seismic survey.

Source: HarbourDom GmbH, Germany.



Reflection seismology is one of the more expensive geophysical methods and requires considerable permitting efforts, extensive field logistics, and complex data processing. Surveys to collect 3D data can require crews of hundreds of workers depending on the survey size.

A seismic survey begins by obtaining all necessary permitsmonths in advance of field activities. The permits might include compensation for expected damages to land, roads, pipes, buildings, or other infrastructure caused by the heavy machinery of the survey equipment. The next step before measurements begin is mobilizing the equipment and the seismic crew and setting up the field camp, offices, and workshops. During a topographic survey, the coordinates of all seismic stations are recorded. The acquisition of seismic data is the next step, which also includes real-time quality control and possibly re-measuring the stations. Processing of data is completed offsite in specialized processing centers during or after acquisition. Demobilization includes the removal of all equipment, rehabilitation of the survey area, and the departure of the seismic crew. Post-survey data processing can take months, as can the subsequent interpretation of the processed data.

The design of a seismic reflection survey must consider such things as the distance between the shot point and geophones, line distance, source/receiver parameters, survey size, coverage, receiver patch, sampling rate, recording time and bin-size. All these parameters should be evaluated before the survey, or even before tendering for the contractor. The choice of survey parameters depends greatly on the depth and characteristics of the geological target. Most of the parameters can be 'fine-tuned' once a survey starts. Some typical layout parameters for 2D and 3D seismic reflection surveys are shown in Figure 4.39 and Figure 4.40.

Figure 4.39.
2-D seismic lines.

Source: After Chaouch and Mari, 2006.

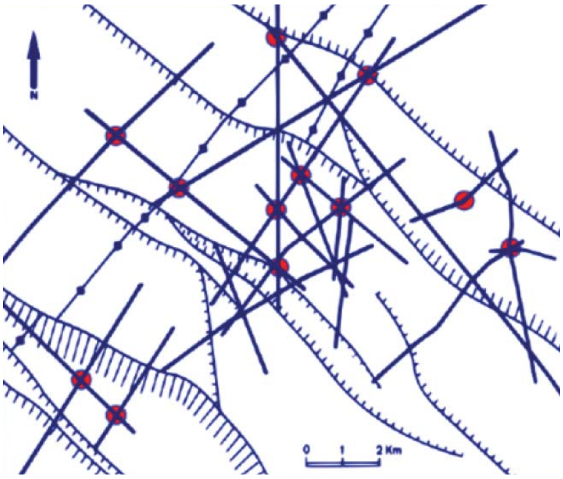
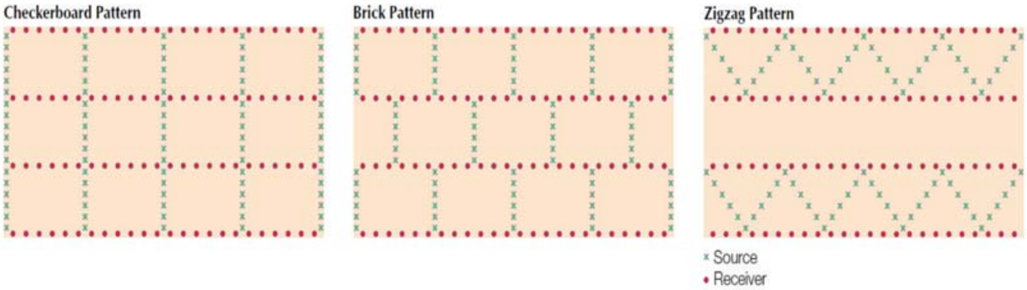


Figure 4.40.
Common 3D seismic survey designs.

Source: After Ashton et al., 1994.



Seismic data require more detailed processing (Figure 4.41) and interpretation than most other geophysical methods. An important element of seismic processing is the development of a seismic velocity model based on known or inferred geological conditions. The velocity model allows the processed data to be converted from their "two-way-travel-time" vertical scale to a more physically meaningful and useful "true depth" scale. How well a velocity model is constrained depends primarily on the presence or absence of deep wells to which the seismic data may be tied in the survey area.

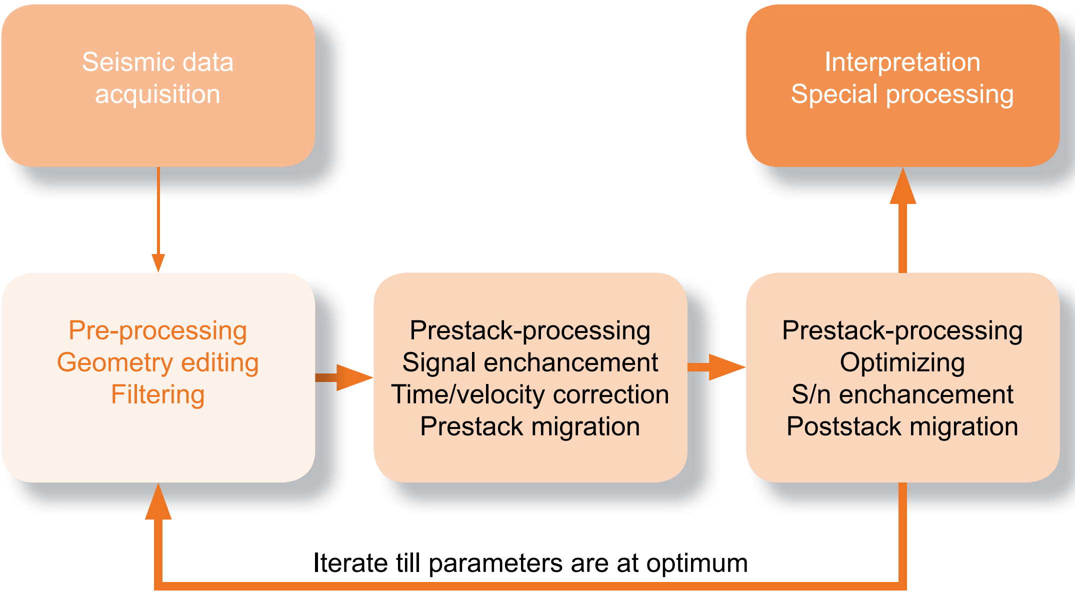


Figure 4.41. Typical seismic data processing flowchart.

Source: HarbourDom GmbH, Germany.

A complementary seismic field technique is called vertical seismic profiling (VSP), referring to measurements made using geophones inside a well and a seismic source (vibrator, explosives) at the surface. One advantage of VSP measurements is that depths and times are known, so the seismic velocity of the rocks is much better constrained than for surface seismics.

In general, the accuracy of true depth interpreted from a seismic image depends on the presence of deep wells for reliable velocity information.

Processed seismic data are most commonly presented as cross sections or slices (horizontal and vertical) from a seismic cube, with two-way-travel-time converted to true depth using the seismic velocity model and seismic migration techniques. Interpreted sections typically show the most important seismic reflectors (i.e., boundaries between rock units with the greatest contrast in sonic impedance) and faults as solid colored lines on top of the actual processed data (Figure 4.42 and Figure 4.43).

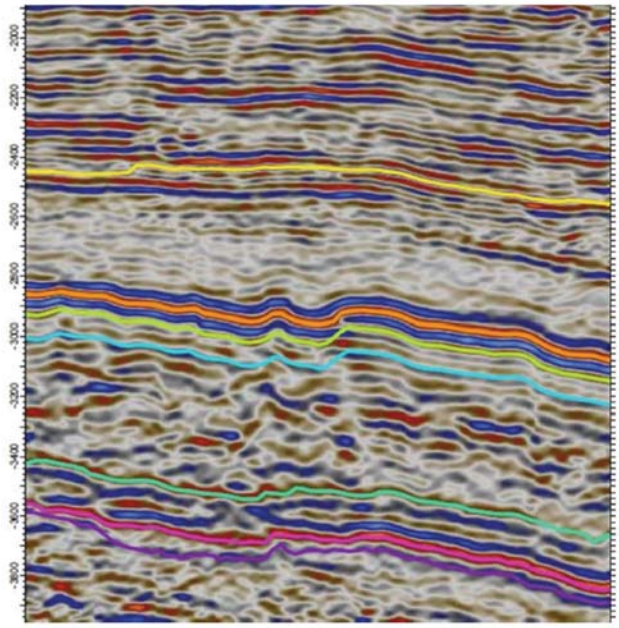


Figure 4.42. Interpreted seismic reflection cross section with important reflectors highlighted.

Source: Erdwärme BayernGmbH & Co. KG.

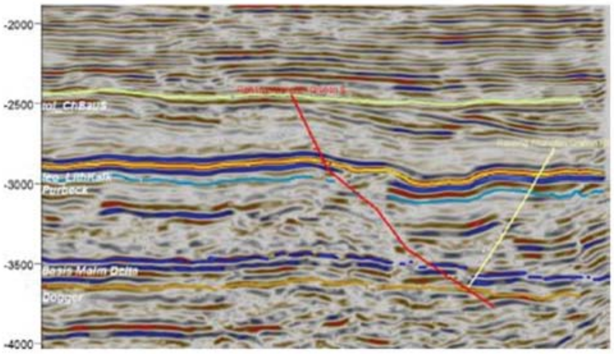


Figure 4.43. Interpreted seismic reflection cross section with interpreted faults highlighted.

Source: Erdwärme BayernGmbH & Co. KG.

Seismic reflectors (often called horizons), faults, and other geological featuresare handpicked or semi-automatically picked by a geologist during the data interpretation stage. Geophysicists (data processing) and geologists (interpretation) should work hand in hand at this stage of a project. Seismic cross sections should be presented both with and without interpreted features highlighted, enabling the reviewer to assess the quality of the reflections and the interpretation provided. Table 4.8lists parameters that should be recorded during a seismic reflection survey.

Table 4.8. Information at different stages of a seismic reflection survey.

DATA ACQUISITION	DATA PROCESSING	INTERPRETATION
• Field report • Instrumentation used • Report of equipment acceptance test • Report of parameter tests • Map(s) showing all data points, transmitter and receiver locations • Coordinates (xyz) of all data points, transmitter and receiver locations • Surveyor's log • Vibrator statistics • Brute stacks for QC • Data on file (SEG2 and geometry files)	• Processing report • Detailed information about noise reduction, applied filters, velocity model, stacking, migration and software used • Seismic cubes and cross sections • Processed data on file (SEG-Y)	• Report • Geological information • Detailed information about assumptions and used software • Detailed information about interpretation and modeling process (e.g., attributes used) • Interpreted cross sections and cubes • 2D/3D images of interpreted structures • Data on file

The applicability of 2D and 3D seismic reflection as an exploration tool for geothermal energy depends on the local geology, local cost of deployment, and relative cost of drilling. Seismic reflection is most appropriate in sedimentary basins where experienced crews are readily available and the cost of drilling is very high (e.g., target depth is great). Under such conditions, seismic reflection can deliver high-resolution images of the subsurface stratigraphy and faults prior to deep drilling. Seismic reflection is generally inappropriate in geological regions where seismic energy tends to be highly attenuated (e.g., on thick basalt or thick coal layers), where logistics are too challenging (e.g., on steep, forested terrain), or where the cost of a seismic survey is comparable with the cost of drilling (e.g., where the target reservoir is expected to be relatively shallow).

A good outcome of a seismic reflection survey is a clear and detailed image of the main geological structures, faults, and stratigraphy beneath the survey region. Seismic reflection surveys provide a "detailed picture" of the underground to a depth of several kilometers.

Passive Seismic Surveys

Passive seismic surveys use natural seismic signals from earthquakes either within the geothermal field or from outside. In passive seismics, recorders (seismometers) are placed on the surface of the earth or in shallow boreholes and signals are continuously recorded. The measured seismic components are commonly processed using tomographic techniques in which source positions and velocity distribution are jointly inverted. The result is a 3D picture of the velocity distribution in the subsurface.

Compared to reflection seismic data, which consists of numerous records collected spatially very close together over a relatively short time, passive seismic surveys must be run for significantly longer time to be able to acquire the same amount of data. However, it has some advantages over reflection seismology.

The method is comparatively inexpensive, even though it requires instrument deployment over long enough periods to record a sufficient number of events for useful analysis. The recording period can be determined from the rate of natural seismic events times the number of stations. Preferably more than 10,000 observations should be recorded, for example, from 1,000 events recorded by more than 10 stations. With modern computer analysis codes, a data set of this size can be analyzed and interpreted in about a month.

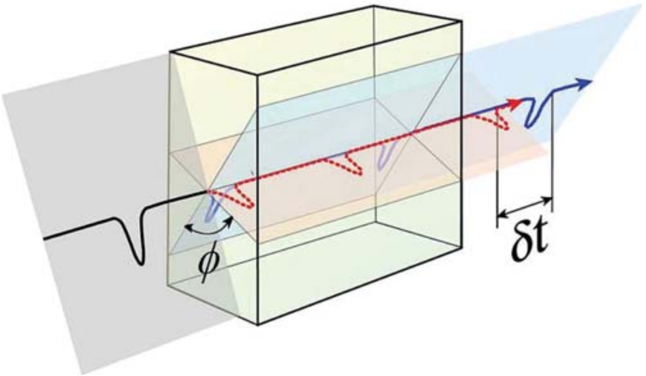
The seismometer stations record movements on all three axes. This means information about the different seismic wave velocities. The size and depth of possible shallow geothermal fluid pathways can be mapped by analyzing seismic data for reflected arrivals and converted waves, gaps, wave attenuation, and variations in wave velocity ratios. In particular, mapping the hypocenters of seismic events in seismically active areas has proved useful for identifying active faults (Simiyu, 2009).

Seismic Shear Wave Splitting

When seismic waves travel through a layered or fractured rock volume, the shear component of the waves can split (or polarize) into two components traveling with different velocities (Figure 4.44). Full waveform passive seismic data can record these two distinct sets of shear waves. In the context of exploring for geothermal reservoirs, “shear wave splitting” may provide additional value from passive seismic surveys. The degree to which the effect can be observed and the observed arrival time offset, the angular difference between the waves, together with models of the seismic ray paths, might be interpreted to discriminate between zones more and less likely to have high fracture density in a particular orientation, giving indications of potential routes of fluid flow within a geothermal reservoir. High-quality, full waveform seismic data are required.

Figure 4.44.
Shear wave splitting or polarization.

Note: The two shear wavelets are polarized at different angles (Ø) and travel at different speeds. There is thus a difference of δt seconds in their arrival time at any given location. Source: Ed Garnero.



4.3.4.8. Ground Temperature Mapping

Ground temperatures at shallow depths can be used to measure the conductive heat flow. Higher levels of conductive heat flow may indicate a shallow sub-surface anomaly.

Temperatures within the top 30 meters of the earth's surface are typically affected by daily and seasonal atmospheric temperature cycles. The magnitude of the effect is directly proportional to the magnitude of the temperature cycle and decays exponentially with depth. At a depth of 1 meter, temperature variations induced by the 24-hour solar irradiation cycle are typically more than 99 perfect damped out (Beardsmore and Cull, 2001; pp. 78-79). Variations induced by the season cycle persist to greater depth, but the drift in temperature is slow relative to the typical time taken for a ground temperature survey. Mapping the relative temperature of the ground at a depth of 2 meters can therefore delineate relatively hot areas related to subsurface geothermal features (Coolbaugh et al., 2007) and reduce the number of temperature gradient wells required to delineate thermally anomalous zones. Ground temperature can be measured with portable systems (Figure 4.45) that deploy a temperature sensor at a 2-meter depth using handheld hammer drills.

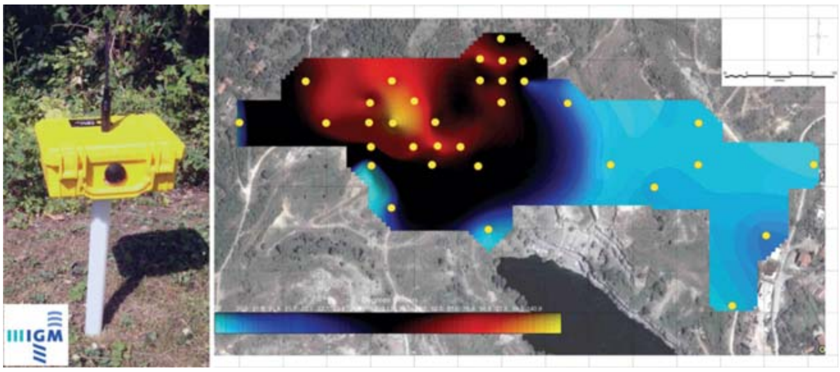


Figure 4.45.
Left: Equipment deployed for monitoring ground temperature at 2-meter depth Right: Relative ground temperature gridded and displayed over an air photo of a survey area.

Sources: IGM Überlingen, Germany (left); HarbourDom, Germany (right)Source: Ed Garnero.

When used in this manner, ground temperature is a proxy measurement for conductive heat flow. High rates of conductive heat loss, resulting in high thermal gradient, can be expected above shallow thermal anomalies, but subsurface anomalies can only be detected if the magnitude of the effect is significant with respect to other influences on shallow ground temperature. These include the following:

- Variations in the albedo of the ground, resulting in different amounts of absorption of solar radiation
- Variations in the thermal diffusivity of the ground resulting in different depths of penetration of the daily and season temperature cycles
- Variations in slope resulting in different angles of incidence of solar radiation
- Short-term temperature disturbances from weather events

Sladek et al. (2012) found that the above factors contribute to ground temperature variations on the order of 1°C at a 2-meter depth across a typical survey area, so the contribution from a buried thermal anomaly must be significantly greater than 1°C in order to be clearly detected. Anomalies of that magnitude can only be sustained by heat sources shallower than about 100 meters. Ground temperature mapping might, for example, provide a useful and cheap method for delineating the subsurface extent of an outflow zone.

4.3.4.9. Heat Flow (or Thermal Gradient) Drilling

Often not appreciated, the temperature distribution within the earth represents a “potential field” in the same way as do gravitational and magnetic fields. Delineating variations in the shallow temperature field can reveal information about the deeper thermal structure in the same way that gravity and magnetic surveys reveal information about the deeper rocks. A key difference between temperature surveys and gravity/magnetic surveys, however, is that boreholes are required to measure the temperature field.

Heat flow (or temperature gradient) drilling provides the most direct insight into the temperature distribution within a geothermal system. Heat flow wells are typically less than 500 meters deep and have a relatively slim diameter (up to 6 inches or 15 cm) compared to production wells. The primary objective of such drilling is to obtain temperature gradient and rock property information to improve the confidence around temperature and depth predictions. Secondary objectives might be to ground-truth geophysical survey data or to obtain additional geochemical data.

Heat flow drilling is not always preferable or possible. Whether it makes sense in a given project depends on the expected characteristics of the reservoir, the availability of an appropriate drill rig and experienced drillers, and the rock composition in the subsurface. Very fractured or unconsolidated shallow rocks can be difficult to drill and complete successfully, though this information will also be useful in planning the Test Drilling Phase.

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. Being able to mobilize small, locally available drill rigs may enable valuable subsurface data to be obtained at relatively low cost during the Exploration Phase. If such rigs are not available locally, then high mobilization costs and time may significantly compromise the value of such activities.

Such wells are typically completed in two or three weeks. In some cases, heat flow wells are 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. In all cases, the collection of core from the drilled interval can provide valuable information (see below) to constrain the conceptual model, but could add significant cost to the drilling program.

Heat flow wells drilled with a rotary rig are typically completed with inner tubing that is capped on the bottom, and the annular space between the tubing and the wellbore walls is backfilled with gravel or cuttings. Heat flow wells drilled with a coring rig might leave the coring rods in the hole to form an effective casing. Both types of completion aim to keep the hole open for logging while reducing the potential for fluid flow into or out of the well. Restricting the movement of fluid between the well bore and surrounding rock is critical to ensuring that the temperature measured inside the well reflects the actual formation temperatures of the penetrated rock, rather than being an artifact of internal flow. To the extent that internal flow within or behind the casing might occur, this needs to be considered when the borehole temperature data are interpreted.

Because the drilling process itself disturbs the natural temperature, a series of “heat-up” temperature logs (perhaps 3 or 4 over the course of several weeks) is typically collected to establish the final stabilized temperature. The time-series data can reveal zones of fluid flow into or out of the borehole, but the stabilized data are used for the main analyses.

Occasionally, a heat flow well might encounter a shallow geothermal reservoir. 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 the reservoir. All subsurface data gathered from the drilling helps refine the conceptual model of the geothermal system.

The time-series of temperature logs represent the main data set collected from a heat flow well. Temperature logs should be collected

- using a specialist temperature logging tool (many commercial tools on the market);
- during descent from top to bottom of the well (so measured borehole temperatures are relatively undisturbed by the passage of the tool itself);
- at a relatively slow speed (so the tool remains close to thermal equilibrium with the well at all times); and
- at a depth and temperature resolution and accuracy appropriate to delineate conductive gradients at the specific location.

Best practice includes collecting core samples of the intersected rocks for thermal conductivity measurements. Such data allow the temperature logs to be translated into conductive heat flow logs to

- quantify the rate of conductive heat loss over the survey area, which, in conjunction with estimates of advective heat loss from surface features, serves as a measure of the magnitude of the underlying heat source;
- delineate conductive zones from zones of convection in the well; and
- allow extrapolation of temperature at greater depth based on thermodynamic principles of heat transfer (so long as the bottom of the well is in a conductive zone).

At a minimum, all temperature logs should be presented graphically with a legend listing the dates each log was collected. Data are most usefully presented on a separate chart for each well (Figure 4.46), but can be combined on a single chart to illustrate the regional variations in temperature profiles (Figure 4.47). In all cases, the data should demonstrate that final, stabilized temperatures have been reached.

Figure 4.46. Example of four shallow temperature logs collected at different times after drilling presented on the same set of axes to reveal heating trends.

Note: Other useful information is also presented on the graph including the "boiling point with depth" curve.Source: Ed Garnero.

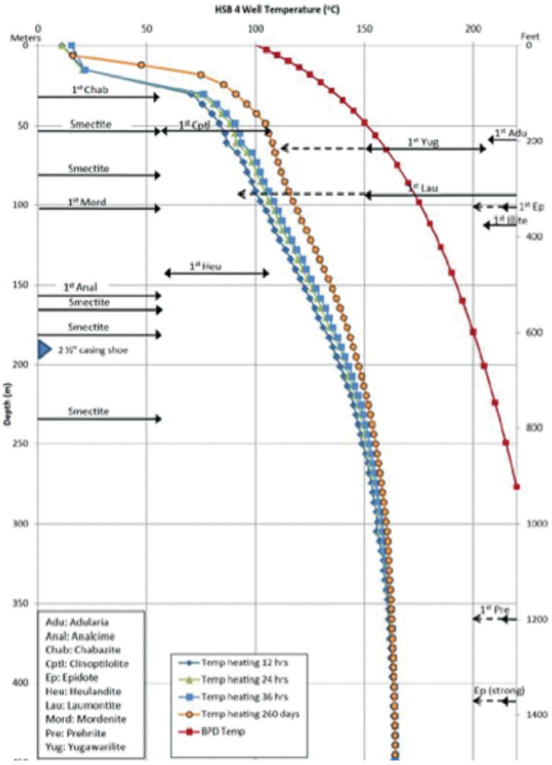


Figure 4.47. Example of many shallow temperature logs presented on the same set of axes to highlight anomalous wells.

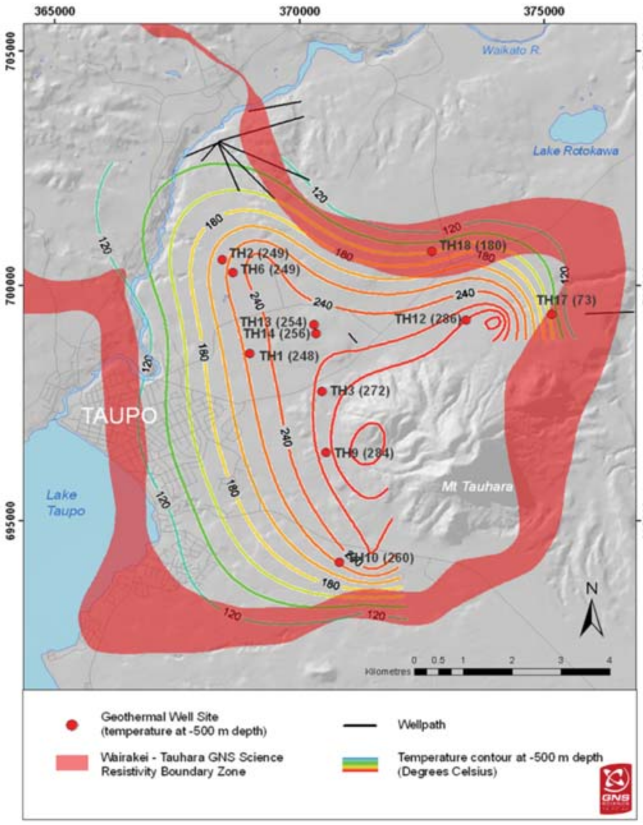
Source: Lazaro et al., 2011.

If temperature alone is 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, although gradients typically change across lithological boundaries, limiting its use in some play types. If thermal conductivity measurements are also made, then an interpretation of the heat flow profile should also be presented. In a purely conductive setting, conductive heat flow should be relatively constant with depth and provide a firm basis for temperature prediction beyond the maximum well depth.

Temperature data from specific depths or elevations can be gridded and presented as “temperature contour maps” to illustrate the distribution of isotherms (Figure 4.48). Alternatively, isotherms can be presented on cross sections that include the shallow geology. Another alternative, of particular use for conductive geothermal plays, is to present gridded maps of surface conductive heat flow.

Figure 4.48. Example of a temperature contour map.

Source: GNS Science, New Zealand.



Each heat flow survey should be designed and interpreted by a person who understands the fundamentals of heat transfer and is experienced in interpreting the nuances of borehole temperature profiles. That person, or another member of the geoscience team, should also have a deep insight into the tectonic setting and geology of the area and how they might impact the thermal structure. The acquired and interpreted data should be summarized in a document setting out the survey parameters, analytical methods, results, and interpretations.

Heat flow drilling is commonly one of the last activities of the Exploration Phase, focusing financial resources to improve the confidence in estimates of reservoir depth and temperature in areas deemed to be the most promising based on earlier exploration and analysis. In this sense, heat flow drilling is an excellent complement to geochemical geothermometry, which estimates the temperature within the reservoir, but is unable to constrain its depth.

Good outcomes from combined temperature and heat flow surveys include, but are not limited to, an indication of the temperature distribution both horizontally and vertically, detection of the limits of convective zones, indications of fluid migration pathways, and quantification of conductive heat loss from the survey area.

4.3.5. Laboratory Measurements on Shallow Cores, Cutting, and Outcrop Samples

The interpretation of all geological, geochemical, and geophysical data is greatly improved if actual samples of the relevant rock units can be obtained for laboratory analyses. Information about the fundamental rock physical properties (density, magnetic susceptibility, thermal conductivity, sonic velocity, electrical resistivity) enhances the confidence of interpretations and inversions of geophysical data. Mineralogical studies aid predictions of water-rock interactions and the interpretation of geochemical data. Observations of anisotropic rock fabric and measurements of rock strength assist with predicting how a rock might respond to hydraulic stimulation. Assaying rock or fluid samples for precious mineral content might reveal commercial value to the wells beyond the geothermal energy while tests for radioactivity can highlight potential hazards or radiogenic heat sources (potentially radioactive samples require special handling).

Heat flow drilling provides the opportunity to collect fresh core samples of the shallow section of the stratigraphy in a region. It is often possible to find existing core samples of deeper sections of the stratigraphy from previously drilled bores (perhaps some distance away from the actual area of interest but still representing relevant formations), or it might be possible to find outcrops of relevant formations in the region from which to collect samples for laboratory analyses (Figure 4.49).

In general, rock analyses are a relatively inexpensive way to add significant value to a drilling program or geophysical survey. The range of possible laboratory analyses on rock samples is wide. The specific analyses appropriate for any given rock unit and exploration program strongly depends on the set of exploration tools being applied, but could include any of the following:

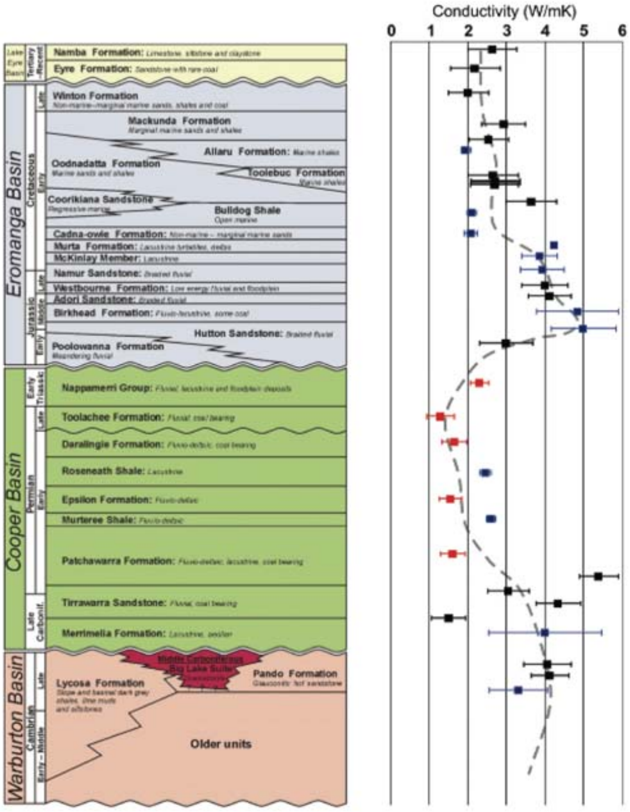


Figure 4.49. Profile of measured thermal conductivity of samples of the stratigraphic units of the Cooper-Eromanga sequence in Central Australia, drawn from a number of different wells across a wide region.

Source: Beardsmore, 2004.

- Density
- Magnetic susceptibility
- Remnant magnetism
- Electrical resistivity (including with different pore fluids)
- Seismic wave velocities (including anisotropy)
- Thermal conductivity (including anisotropy)
- Radiogenic heat generation (potassium, uranium, and thorium concentrations)
- Mineralogy
- Structural fabric
- Oxygen isotope composition (for bedrock and mineral separates)
- Rock strength
- Geochemical assays
- Porosity/permeability (including simulated overburden and temperature)
- Fluid inclusion studies

No one laboratory will be able to carry out all of the above tests. Some tests are routine while others are highly specialized and provided by only a handful of laboratories around the world. In all cases, a reputable, experienced laboratory should be chosen.

It is rarely possible to obtain fresh samples of all the relevant stratigraphic units during the Exploration Phase. This is to be expected and is unavoidable. However, reasonable efforts should be made to obtain fresh samples of as many units as possible. The properties of weathered samples will typically be significantly altered from their fresh state. For this reason, using laboratory measurements on weathered samples to constrain geophysical or geochemical models is not recommended; the results could be significantly misleading.

A good outcome from a rock sampling and measurement program would be to obtain real measurements of physical properties relevant to the geochemical and geophysical techniques employed during the Exploration Phase of both the unaltered rocks and altered rocks. These measurements should constrain and maximize the confidence of the derived geochemical and geophysical models and improve the confidence in the conceptual model.

4.3.6. Stress Field Estimates

The prevailing stress field influences the distribution and preferred orientation of permeability pathways in natural geothermal systems and controls the growth of engineered reservoirs during hydraulic shearing. Following Anderson’s faulting theory (Anderson, 1951), a stress field is defined by three orthogonal principal compressive stress axes, S1>S2>S3. One of these axes is vertical, SV, and the other two axes are horizontal; SH (maximum horizontal compressive stress) and Sh (minimum horizontal compressive stress). The relative magnitudes of SV, SH and Sh determine whether a rock is in a normal faulting, strike slip faulting, or reverse faulting stress regime, or a hybrid transitional state. The orientations of SH and Sh determine the most likely orientation of maximum fracture permeability. An estimate of the magnitude and orientation of the principal stress components can, therefore, help predict zones of maximum fracture permeability, and should be investigated in the early stages of a project. Stress estimates can be refined as more detailed information becomes available.

Stress in units of pressure or megapascals (MPa) cannot be measured directly but can only be derived through a range of techniques of perturbing the rock mass, measuring displacements or strain, or measuring hydraulic parameters. Ljunggren et al. (2003) and Ask (2004) provided good overviews of the different methods for determining stress, their limitations, and applications. Table 4.9provides a summary of their findings. Among the variety of stress determination methods, not all may be applicable for any given geothermal project, and different methods may be applicable at different stages of the project.

Table 4.9. Methods for rock stress determination and their applicability for geothermal projects.

Source: Modified from Ljunggren et al., 2003.

METHOD	2D/3D	ADVANTAGES	LIMITATIONS	SUITABILITY
Overcoring	2D/3D	Most developed technique	Scattering due to small tested rock volume; requires drill rig	Reservoirs <1,00 m depth
Doorstopper	2D	Works in joined and highly stressed rock	Only 2D; requires drill rig	Shallow and deep reservoirs
Focal mechanisms	3D	For great depth	Only stress regime and stress orientations; information only from great depth	Regional stress regime estimate; at early project stage; in seismically active areas
Analysis of geological data	2D/3D	Low cost field work; applicable also in 3D seismic	Very rough estimation; only together with additional information	At early project stage before drilling; during geological reconnaissance
Borehole breakouts	2D	Relatively quick; Occurs in most deep boreholes	Only orientation; theory needs to be further developed for magnitudes	Shallow and deep reservoirs
Leak-off tests (LOT)	2D	Popular method in hydrocarbon exploration; quick	Requires open borehole; only S_h.; disturbed by water chemistry and injection test	Shallow to deep reservoirs; stress profiles can be obtained
Hydraulic test on preexisting fractures (HTPF)	2D/3D	Can be applied when high stress exists, when LOT or over-coring fails	Time consuming; requires open borehole with fractures of variable orientation	When other methods fail, in low permeability rock
Core disking	2D	Quick estimate on core material	Requires several meters of drill core material; only qualitative	When coring material is available
Geophysical measurements	2D/3D	Usable for great depth on drill cores	Complicated measurement on microscale; methods need further developing	Estimation of stress state at great depth and only when core material is available

Stress does not behave linearly, either laterally or vertically. Therefore, an estimated stress field should not be linearly extrapolated to depth. Stress field measurements are affected by stress disturbing factors such as geological environment (e.g., nearby faults, geo-mechanical anisotropy in rock mass through variations in lithofacies, diagenesis), borehole location and orientation, and the technical circumstances of the measurement method itself.

Figure 4.50presents five activities that can sometimes be carried out to estimate the key stress parameters during the Exploration Phase. The aim is to derive the orientations of the principal stress axes (S1>S2>S3) and to determine whether the stress regime is in a normal faulting, strike-slip faulting, reverse faulting, or hybrid transitional state.

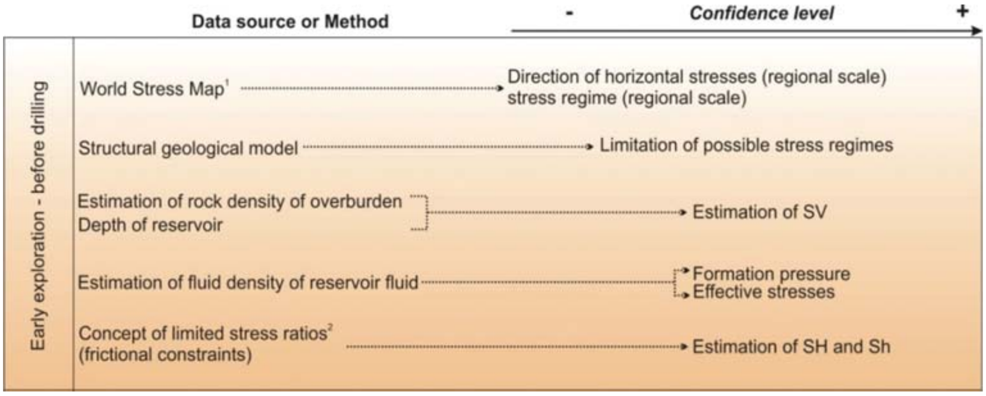


Figure 4.50. Recommended steps for estimating stress field parameters during the Exploration Phase.

Note: SV=vertical stress; SH=maximum horizontal stress; Sh=minimum horizontal stress.

Source: Modified from Moeck, 2012.

Regional scale stress orientations might be found on the World Stress Map (Heidbach et al., 2008; http://dc-app3-14.gfz-potsdam.de). The World Stress Map provides the trend of the maximum horizontal stress, SH, for many regions (Figure 4.51). However, the map does not show the stress regime for any given location. The question is whether SH is the maximum principal stress, S1, or the intermediate principal stress, S2. If the region is seismically active, then information about the local stress regime might be derived from focal mechanism solutions for local earthquakes. Fault slip and fault throw data from field or seismic surveys can also suggest the current stress regime in areas of active faulting, although fossil faults or reactivated faults may reflect paleostress regimes rather than the current stress field.

If rock density is known, then the vertical stress, SV, can be calculated from the density of overburden, the thickness of overburden, and the gravitational constant. The magnitude and direction of horizontal stress axes are harder to determine.
If previously drilled and logged boreholes are present in the area, then drilling induced borehole breakouts and tensile fractures might provide indicators of the Sh and SH directions (Figure 4.52). Borehole breakouts can form when the drilling mud pressure is below hydrostatic formation pressure in underbalanced drilling, while tensile fractures are initiated when the mud pressure exceeds the fracture gradient.

Figure 4.51. Example of World Stress Map data and possible interpretation of principal stress axis.

Note: Borehole breakouts (BBO) and tensile fractures (TF) indicate the direction of SH and Sh, but not their magnitude with respect to SV.

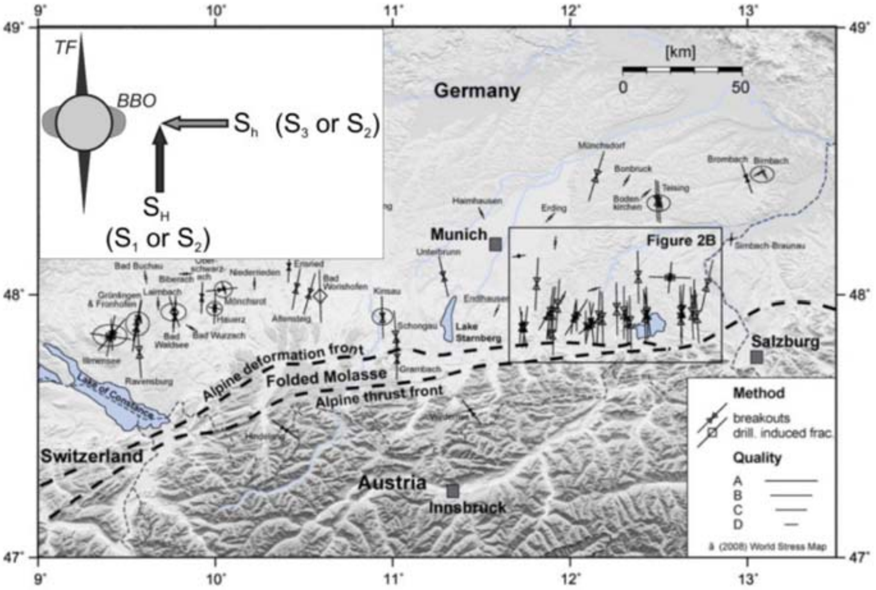


Figure 4.52 (a) Determination and illustration of borehole breakouts from ovalities in caliper logs. (b) Vertical tensile fractures along the borehole wall. (c) Result of stress direction analysis from borehole breakouts and tensile fractures. (d) Fault plane solutions from earthquakes and stress. The maximum principal stress is in the center of the white quadrants, the minimum principal stress is in the center of the colored quadrants by convention.

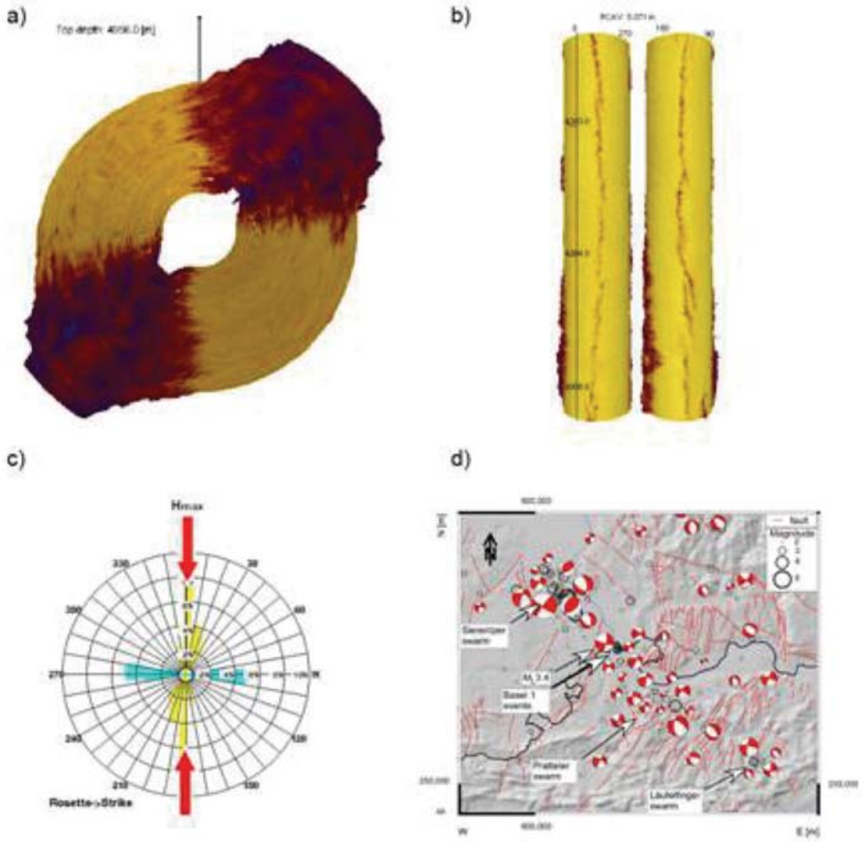
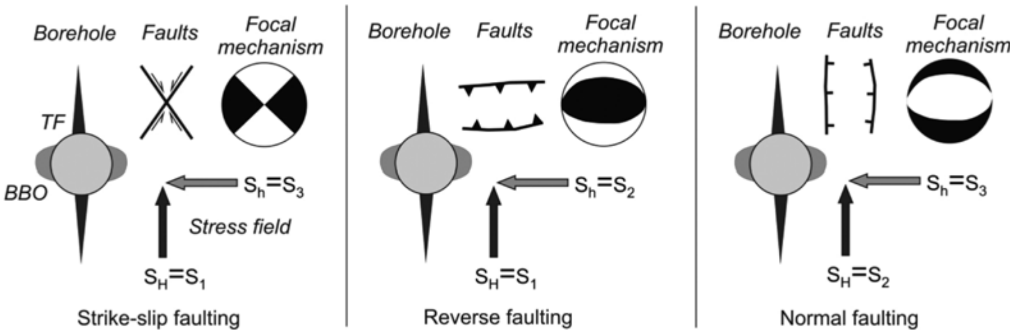


Figure 4.53. Relationship between direction of borehole breakouts, tensile fractures, strike of faults, focal mechanism and horizontal stresses to resolve the stress regime.

Source: After Reinecker et al., 2010.



The magnitudes of horizontal stresses can also be estimated using the concept of limiting stress ratios (Jaeger et al., 2007). This concept is based on the assumption that stresses in the earth's crust are limited by the frictional strength of rock. The stress limits for normal faulting, strike slip faulting, and reverse faulting stress regimes can be calculated for a certain depth (i.e., estimated reservoir depth) using "best guess" values for pore pressure and frictional strength of rock where

$$\frac{S_{1eff}}{S_{3eff}} = \frac{S_1 - P}{S_3 - P} = \left(\sqrt{\mu^2 + 1} + \mu\right)^2$$

and where μ is the friction coefficient, S1eff and S3eff are the maximum and minimum effective stresses, respectively, and P is pore fluid pressure (Moeck et al., 2009). The friction coefficient is a material parameter, ranging between 0.36 and 1.0, and can be derived from the angle of internal friction. Most reservoir rocks have a friction coefficient between 0.6- 0.85, depending of the strength of rock and reservoir depth. The application of this method to geothermal projects is relatively new (Moeck et al., 2009).

Fractures parallel to the prevailing maximum compressive stress direction are most likely to exhibit the highest natural permeability, while those critically aligned (i.e., angle of ~25°-45°) with the prevailing maximum compressive stress direction will typically be the first to slip during hydraulic stimulation. The degree of slip and the effect of slippage on the average aperture and permeability of a fracture can be investigated using geomechanical modeling.

4.4. Conceptual Model

As indicated in Figure 4.1, the preliminary survey, exploration, and test drilling phases of a project are all about defining, refining, and testing a "conceptual model" of the geothermal system under investigation; a conceptual model is the schematic representation. A good conceptual model should encapsulate the geological framework, heat source, heat and fluid migration pathways, reservoir characteristics, and surface geothermal features, and should be consistent with all available data and information. The conceptual model is continually refined as each new set of data is collected and assessed, with each refinement adding a new level of detail or confidence to the overall model.

An initial conceptual model should be developed at the earliest stages of the geothermal project. At this time, the model will necessarily be quite crude, perhaps illustrating little more than a generic representation of the expected geothermal play type, as shown in Figure 2.2 to Figure 2.9in Chapter 2. The model should then be regularly updated as new data become available to ensure the model respects and remains consistent with all known information. In this way, the most current conceptual model should incorporate all available exploration data. By the end of the Exploration Phase, the conceptual model should be of sufficient detail to allow an estimate of reservoir depth, temperature, and geometry with sufficient confidence to justify and site wells for the Test Drilling Phase.

The conceptual model can be illustrated with maps, 2D cross sections, or 3D block models. These might be simple free-form drawings at the early stages of a project, but will develop into robust geological models as more information is incorporated. Cross sections should be created at the same scale as the maps that underpin them, preferably with a 1:1 ratio between horizontal and vertical scales. All diagrams should include a representation of the assumed heat source, an estimate of the subsurface temperature distribution (isotherms), some indication of fluid flow directions, and a representation of the expected geothermal reservoir, even if these are only approximate.

A good conceptual model provides clear evidence that the explorer 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 demonstrates a justifiable understanding of the geology, temperature, and fluid pathways within the geothermal system. By utilizing the conceptual model, the explorer can select sites for the Test Drilling Phase that maximize the chances for a successful well based on all current data.

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. Figure 4.54provides a flow chart of typical data that may be used to build and develop the model. The model needs to be of sufficient detail to allow a first pass estimate of resource temperature and size and, in the Test Drilling Phase, 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 fluidat commercially viable temperatures.

Figure 4.54.
Flow chart showing project stages with typical data acquired and integrated into the conceptual model .

Source: GeothermEx Inc., California.

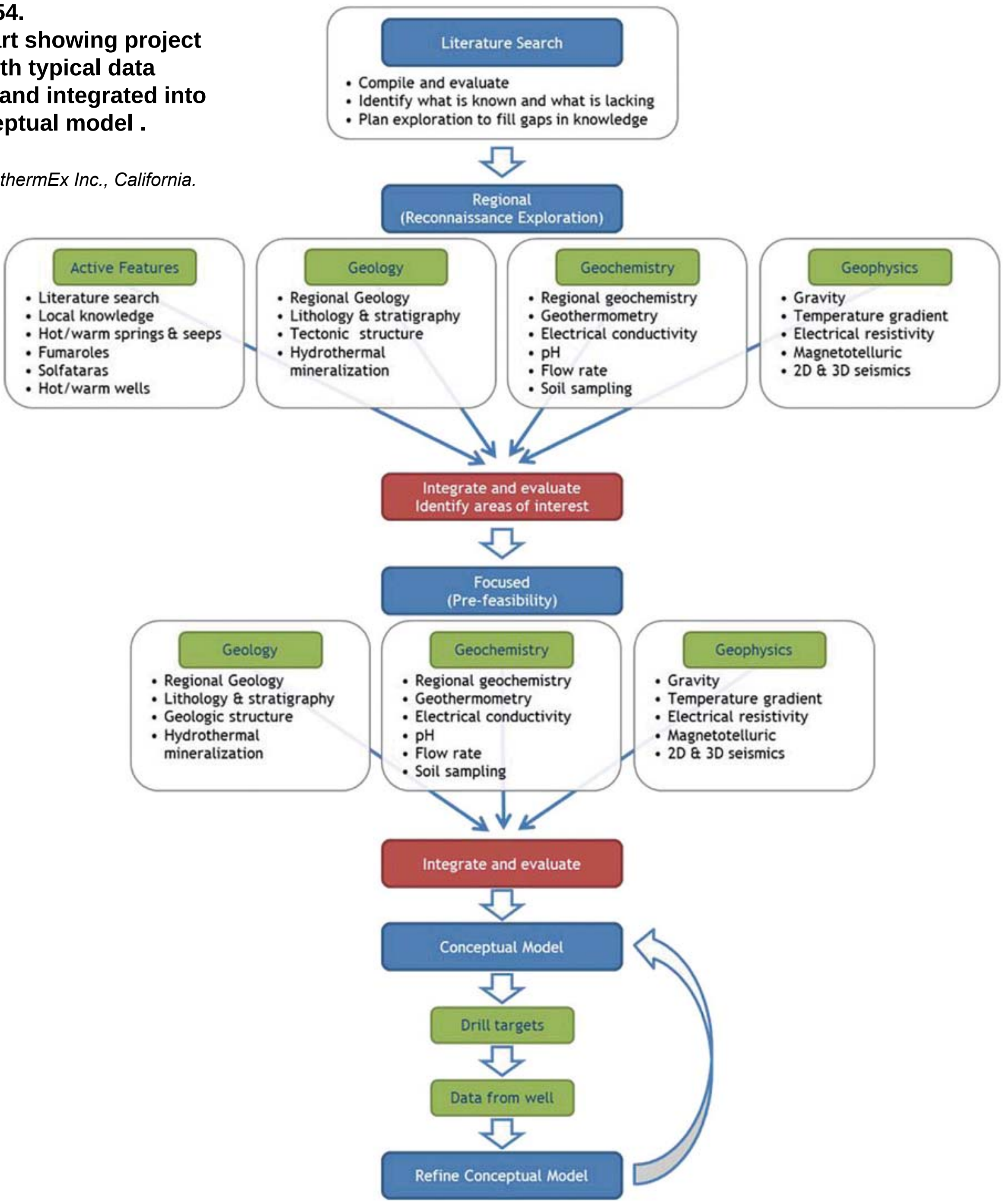


Figure 4.55 shows a surface map representation of a conceptual model, Figure 4.56 is a cross section through a conceptual model, and Figure 4.57 presents a 3D visualization.

Figure 4.55. Example of a surface map based on a conceptual model.

Source: GeothermEx Inc., California; redrawn by GNS Science, New Zealand.

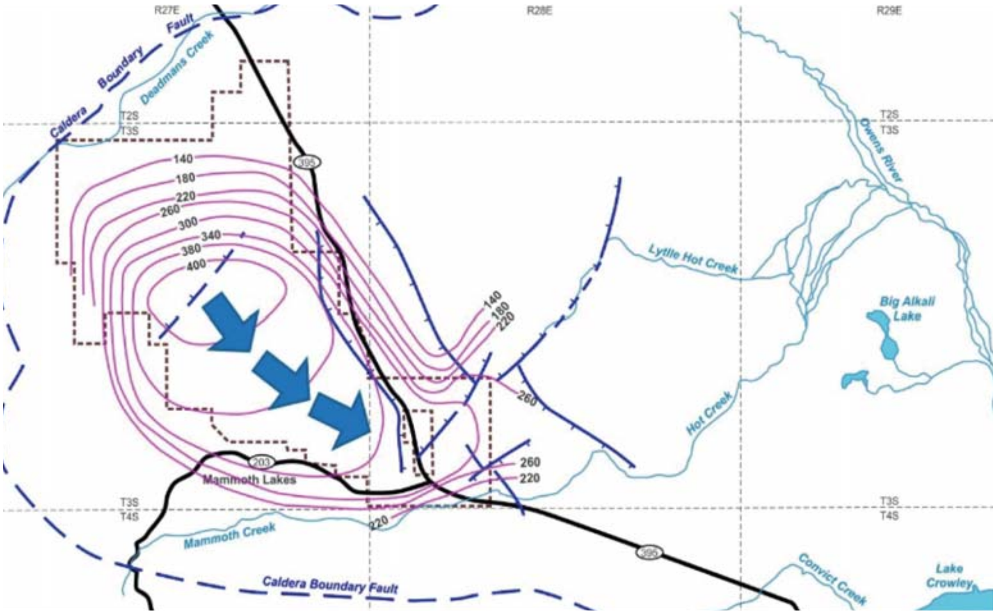


Figure 4.56. Example of a cross section through a conceptual model of a geothermal system.

Source: GNS Science, New Zealand.

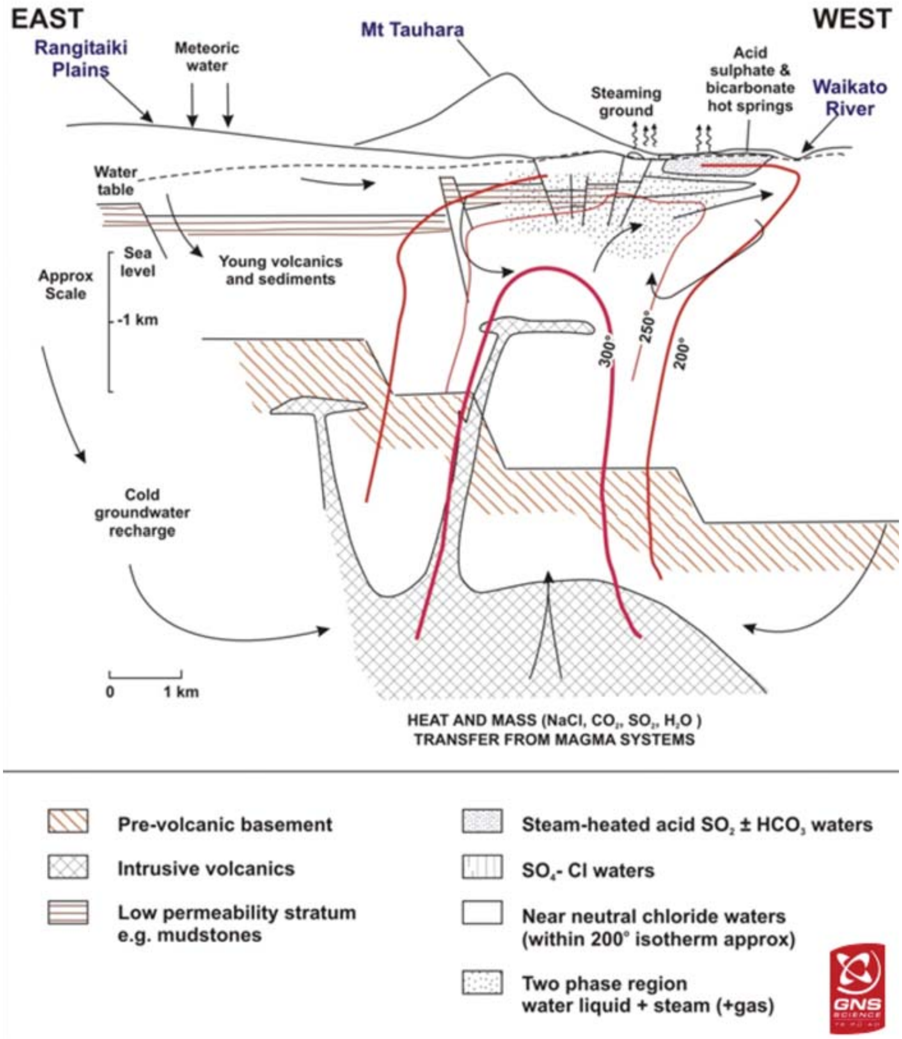
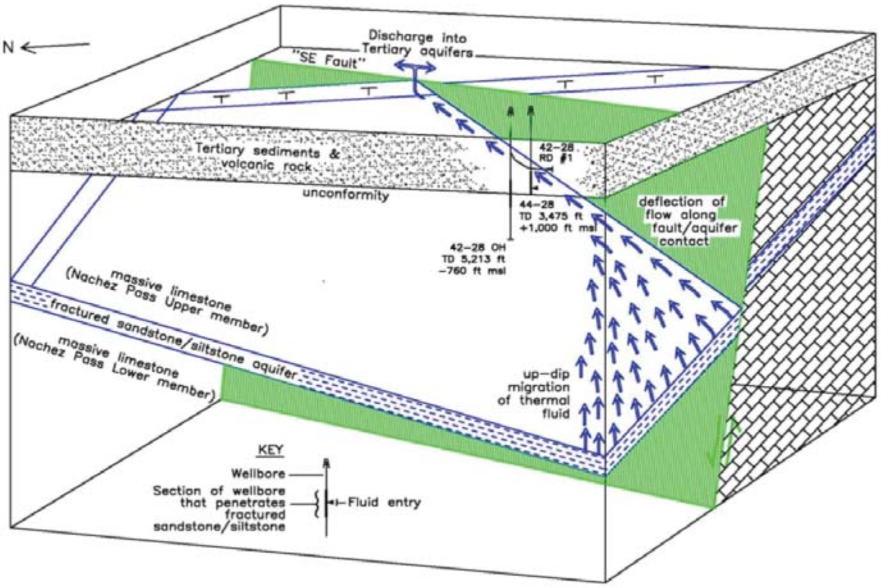


Figure 4.57. Example of a 3D conceptual block-model.

Source: GeothermEx Inc., California.



A geo-referenced database isthe most efficient way to integrate all geospatial data. This facilitates developing maps at uniform scales (changing the scale as needed) and overlaying different data to investigate interrelationships. 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.

4.5. Numerical Model

Once its suitability has been constructed, the conceptual model can form the basis of a numerical model (Newson et al., 2012). 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. The numerical model 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 historical matching, and then forecasts under a number of selected scenarios predicting the future behavior of the reservoir under various levels of production.

However, the requirements for numerical modeling include data from deep drilling and well testing. An in-depth discussion of numerical modeling is therefore considered to be beyond the scope of this exploration guide.

4.6. Justification to Proceed to Test Drilling (Phase 3)

The aim of all preceding steps is to prepare a pre-feasibility study to evaluate the potential for economically viability geothermal power production, to mitigate financial risk associated with development, and to build a business case for funding support from private, public, or institutional bodies to proceed with the project (if deemed viable). 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 and risk of deep drilling.

5. STRATEGIES FOR GEOTHERMAL EXPLORATION AT MAGMATIC (CV1) PLAYS

5.1. Introduction

Chapter 5 presents the geological, geochemical, and geophysical strategies proven to be most useful for exploring CV1 plays. However, because all geothermal systems are unique, the exact selection and order (sequence in which these techniques are applied) will almost certainly vary from prospect to prospect. Experienced geothermal scientists or engineers will select what they consider the most appropriate sequence of techniques to efficiently reduce the uncertainty regarding reservoir characteristics for the geothermal play in which the potential system has developed.

5.2. Conceptual Models

The starting point for developing an exploration strategy for geothermal systems in CV1 plays is to review the conceptual models most widely used:

- Volcano/pluton-hosted water-dominated systems
- Volcano/pluton-hosted vapor-dominated systems
- Graben-hosted water-dominated systems.

5.2.1. Water-dominated Volcano/Pluton-Hosted Systems

Figure 5.1(modified after Henley and Ellis, 1983) shows the “classic” water-dominated geothermal system developed beneath elevated volcanic edifices. Such systems are commonly encountered in island arc settings. The heat source can be either magmatic or plutonic. Theyhave thermal features that occur at different elevations. Boiling of geothermal fluids immediately above the heat source causes the dominant gases (CO_2 and H_2S) to partition into the steam phase. Condensation of the steam and gases in the water table results in acid conditions and subsequent acidic water-rock alteration. Deeper fluids progressively boil and degas as they move towards the outflow, experiencing ongoing water-rock interaction at progressively lower temperatures until discharging at the surface, typically at boiling temperature. The outflowing fluids may mix with groundwater, becoming diluted and cooled.

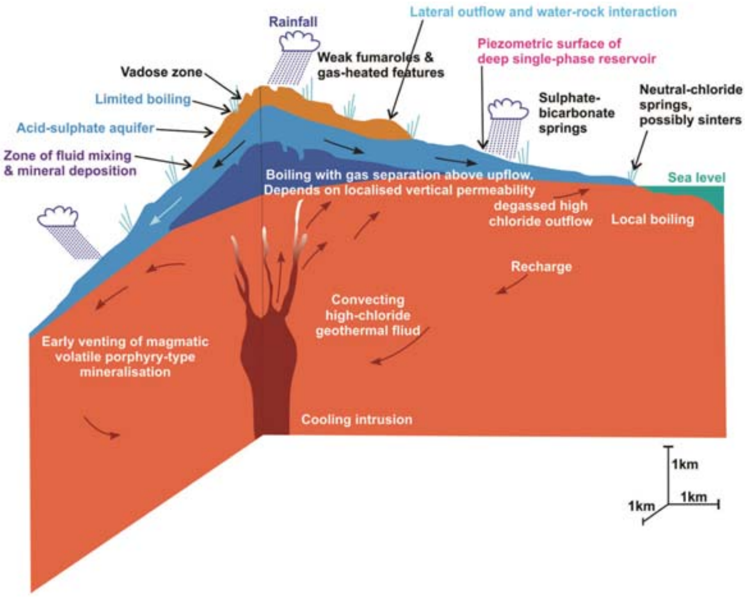


Figure 5.1. Conceptual model of a water-dominated volcano-hosted geothermal system in an elevated volcanic setting.

Source: Modified after Henley and Ellis, 1983.

Directly above the heat source, near the surface at high elevations, up-flowing acid fluids alter the rocks to acid clay minerals (kaolinite and perhaps dickite) plus alunite and carbonates. Fumaroles and perhaps gas-generated features might be evident on the surface. If the heat source is active magmatism, then magmatic features (sometimes discharging hydrogen chloride and hydrogen fluoride) may also be present. The chemistry of the surface features changes progressively downslope towards the outflow of cooled neutral pH hot springs that outcrop at lower elevations. At the outflow, the clay cap may be evident at the surface, composed of smectite clay minerals. Silicification may also be present above the up-flow and at the outflow. In some systems, where high CO_2 concentrations occur in the reservoir fluids, the loss of CO_2 on boiling results in precipitation of carbonate, which can form spectacular surface travertine deposits. There may be a distance of several or many kilometers between the up-flow and outflow features.

The silicification, carbonates, and clays associated with both the acid and neutral alteration are very useful surface indicators of a possible geothermal system since they may be entirely unsuitable for plant growth, so they are evident as open (bare) altered ground. Aerial reconnaissance using satellite imagery, aerial photographs, or visual aerial reconnaissance may identify areas of bare (altered) ground and thermal features. Discharging surface features (springs and fumaroles) are obvious evidence of an active geothermal system. Geochemical surveys, with subsequent geothermometer calculations and assessment, are key parts of the early exploration strategies for CV1 plays. Chapter 4 describes the full range of possible geochemical techniques.

The relationships between the geology and thermal features can also provide information on the geological controls on fluid pathways. For example, is the distribution of thermal features controlled by certain rock types? Are thermal features aligned along structural trends? Is there evidence of an elevation control on the different chemistries of the thermal features? These questions should be addressed during the Preliminary Survey Phase if possible.

Geophysical tools appropriate for CV1 play types tend to focus on mapping the electrical resistivity of the ground in order to identity the extent and other characteristics of the relatively conductive (i.e., low resistivity) clay cap. Which resistivity tool is most appropriate will depend on a range of factors including land access, expected reservoir depth, and survey cost. Certain techniques may be rapidly employed for low cost while others are more complex, requiring special permits, ground clearing, transfer of expensive and delicate equipment, or access for aerial-based equipment.

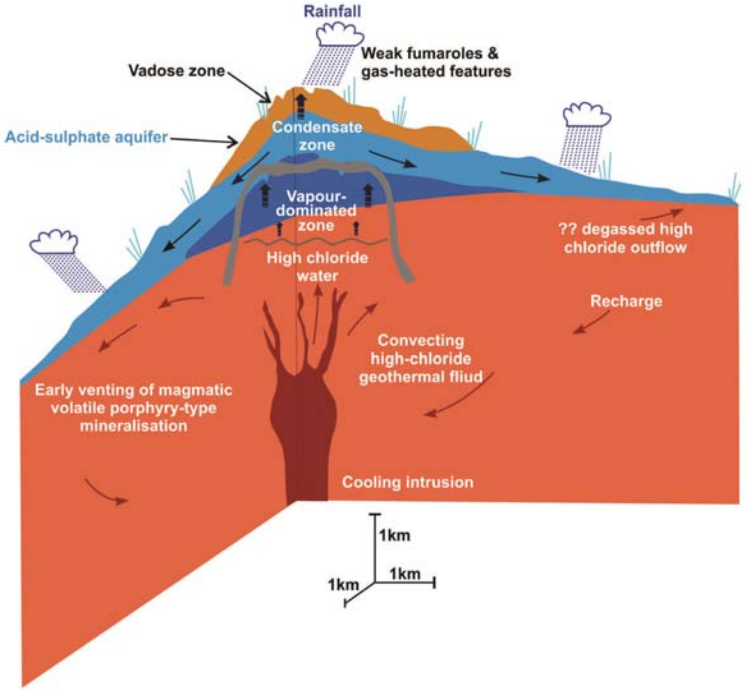
Details on the numerous available geophysical techniques are provided in Chapter 4. The success of any geophysical technique depends on the existence of a detectable contrast in the physical properties of the rocks and fluids within and outside a geothermal system.

5.2.2. Vapor-Dominated Volcano/Pluton-Hosted Systems

Some CV1 type geothermal systems evolve as dry steam or vapor-dominated reservoirs. The term vapor-dominated was introduced by White et al. (1971) and emphasized by Truesdell and White (1973), with specific reference to The Geysers geothermal field in California. Other examples include Kamojang and Darajat in Indonesia. Figure 5.2is modified from Figure 5.1and incorporates the modifications of Ingelbritsen and Sorey (1988) to provide a conceptual model of such vapor-dominated systems. Vapor-dominated zones can be attractive exploration targets from a commercial perspective since you may exploit dry steam rather than the water plus steam output of water-dominated systems of Figure 5.1

Figure 5.2. Conceptual model of a vapor-dominated geothermal system in a volcanic setting.

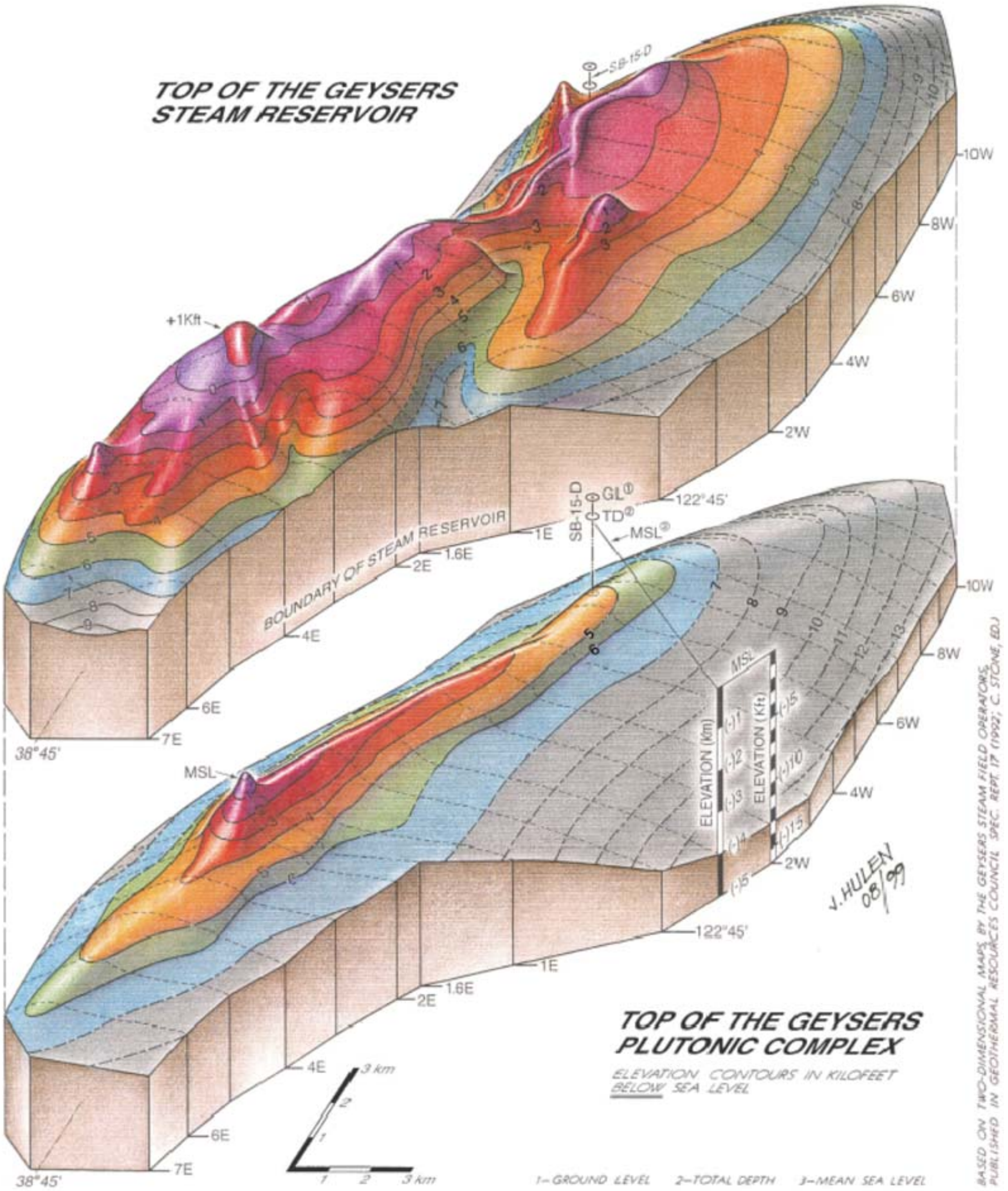
Source: Modified after Henley and Ellis, 1983 and Ingebritsen and Sorey (1988).



The Geysers geothermal resource in California is currently the world's largest exploited vapor-dominated geothermal resource, extending over an area of more than 100 square kilometers (Hulen and Norton, 2000). The top of the steam zone was defined in 1989 (Hulen, pers. comm) by contouring the elevations of the first (topmost) "commercial" steam entries based on data from an estimated 1,100 wells (Mark Walters, pers. comm). Figure 5.3shows this surface along with the top of the felsite plutonic complex at The Geysers.

Figure 5.3. The Geysers Plutonic Complex in California.

Sources: Data and 2-D top-of-steam and top-of-felsite maps by Unocal, Calpine, and NCPA (Geothermal Resources Council, The Geysers Monograph, 1989); 3-D conversion and artwork by Jeffrey B. Hulen, ca. 1999.



Volcano-hosted vapor-dominated geothermal systems may have few (if any) surface features in close proximity above the heat source. There may be weak fumaroles or clay alteration; fluid and gas geothermometry on these features may provide early justification to proceed with geophysical surveys and test drilling. However, since any outflow springs may be many kilometers away from the heat source and main vapor accumulation, these surface springs may have re-equilibrated to suggest low resource temperatures. Exploration for these systems therefore relies less on the geochemistry of the surface features and more on geophysical surveys plus drilling.

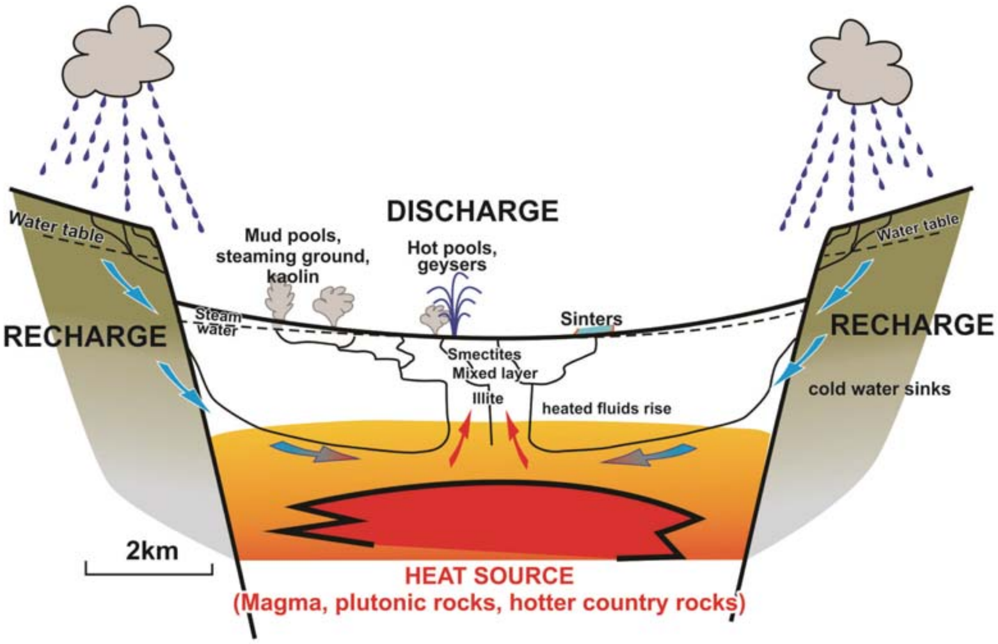
5.2.3. Graben-Hosted Systems in CV1 Plays

In graben settings, convection-dominated geothermal systems may develop with thermal features distributed quite differently to the volcanic models. Figure 5.4shows a conceptual model of a magmatically heated graben-hosted system, based on extensive studies of geothermal systems within New Zealand's Taupo Volcanic Zone. Similar hydrological settings may occur in parts of the East African Rift Valley.

In graben-hosted CV1 systems, the thermal features associated with up-flow and outflow zones may have mineralogies and chemistries identical to volcano-hosted CV1 systems, but in close proximity to each other with few or no elevation differences. The exploration strategy for such systems focuses on electrical resistivity methods to map the extent of the hydrothermal alteration.

Figure 5.4. Conceptual model of a magmatically heated geothermal system in a graben setting.

Source: GNS Science. New Zealand



5.3. Exploration Methods for Geothermal Systems in CV1 Plays

Several authors have compiled inventories of specific techniques they consider most applicable to exploration for geothermal resources within CV1 play types. They include Richter et al. (2010) discussing exploration techniques successful in Iceland; Manzella et al. (2010) presenting experiences from Italy; and Hochstein and Hunt (1970) and Bibby et al. (1995) reporting on geophysical techniques especially successful in the exploration of the Taupo Volcanic Zone in New Zealand. With respect to the United States, Thorsteinnsson and Greene (2011) recommended the development of a possible exploration technologies roadmap, which has since been reported by Phillips et al. (2013). The following sections synthesize the methodologies that might be applied to exploration in any CV1 play.

5.3.1. Satellite Imagery, Aerial Photogrammetry, and LIDAR

More and more potentially useful data are being obtained from satellite and airborne sensors, which is more fully described in Chapter 4. Since the majority of exploited CV-1 systems throughout the world have surface thermal features or altered ground at the surface, such features are readily identified and perhaps quantified by these techniques.

The technique is used during the Preliminary Survey Phase (or reconnaissance) at the survey design stage. Interpreted data can be added into a GIS database for integration with data compiled from surface surveys to produce detailed maps for each project area identifying the locations and extent of current or historic surface geothermal features. The technique has proven to be especially useful in difficult terrain in tropical regions where ground access is difficult. Note, however, that confirmation of thermal or mineralogical anomalies always requires on-ground verification and assessment.

5.3.2. Geology and Mineralogy

Regardless of information gained from the literature review (Section 4.2.3); it is essential for an experienced geothermal geologist to visit any specific project area to verify previously collected data and to develop an understanding of the geological setting. This typically includes regional geological surveys followed by more focused fieldwork to develop an understanding of hydrology, stress regimes, geological history, lithologies, and the distribution of alteration minerals. Asummary ofpotentially useful geological and mineralogical techniques is presented in Table 5.1.

Table 5.1. Potentially useful geological and mineralogical techniques.

TECHNIQUE	COMMENT AND FREQUENCY OF USE
Mapping; aerial photographs	Essential
Ground mapping and recognition of appropriate play type	Essential; recognition of geologic play types assists in developing exploration strategy
Distribution of alteration minerals and precipitates	Essential; alteration minerals may reflect relict or current hydrothermal alteration; silica polymorphs (quartz, chalcedony or amorphous silica) may give indications of resource temperature
Age dating	Essential; age of volcanic or plutonic bodies may assist greatly to improve confidence in possible presence of high temperature heat source
Structural mapping and interpretation	Essential
Stratigraphic studies	Essential
Petrography	Essential
Scanning electron microscope and electron microprobe	Sometimes used for clarification of specific problems in interpretation
X-ray diffraction	Widely used to identify finer particle size minerals for use in geothermometers (clay minerals and zeolites)
Fluid inclusions	Useful to recognize and distinguish between various episodes in the evolution of a geothermal system, boiling, and high gas concentrations
Methylene blue	Useful during drilling to quantify clay mineral content; (address formation stability); assist in the interpretation of mixed-layer clay mineral geothermometers and ground-truth resistivity data

A geological report at the completion of the survey may include the following:

- Thorough understanding of the hydrology and geology of the project area and how it fits into the surrounding regional geological and tectonic setting
- Geothermal play type to which the possible system belongs
- Identification of potential geological hazards
- Assessment of the accuracy and suitability of existing maps and cross sections by comparing them to field observations
- Understanding role of structural geology in controlling any potential geothermal system: Is structure-controlled permeability likely to play a significant role in fluid flow for the geothermal system?
- Identification of lithological units that may control or impact both the regional hydrogeology and the fluid flow in the geothermal system

- Age dating and composition of the volcanic units present within and around the prospect
- Identification of lithologies that might negatively impact geothermal development
- Identification of lithologies that might result in ambiguities of interpretation of geophysical data
- A review of the quality of previous mapping and/or cross sections: Are they sufficient or what new or additional geologic mapping should be undertaken?
- Construction of multiple cross sections through the project area to visualize the three dimensional subsurface structure
- Mapping the distribution of alteration minerals and developing an understanding of the their temperature and pH significance
- Drill hole data and borehole cuttings or cores (If available, the methylene blue technique (Harvey et al., 2000) to identify smectite might be useful to ground-truth resistivity data.)

5.3.3. Geochemistry

Following a review of previously collected data, a site visit to the project area by an experienced geochemist is an essential step in the early exploration stage. This visit involves identifying, sampling, and analyzing fluids and gases from surface thermal features. Collecting a sample of non-thermal surface water at a range of elevations and locations may provide useful background analyses for mixing models. Analysis and interpretation of the geochemical data is carried out as detailed in Chapter 4. The areal distribution of features may indicate the extent (size) of the geothermal system, while flow rates can provide estimates of the throughput of a system. Table 5.2summarizes the range of geochemical techniques typically useful in exploring for CV1 geothermal plays.

Table 5.2. Summary of potentially useful geochemical techniques for CV1 plays.

TECHNIQUE	COMMENT AND FREQUENCY OF USE
Sampling all active thermal features and background non-thermal waters	Essential
Sample any existing wells	Essential even if they are shallow or groundwater
Analysis of fluids and gases	Essential use of experienced laboratories with analysis of chemical species and isotopes
Interpretation of geochemical data	Essential; geothermometry of fluids and gases; development of mixing models and preliminary assessment of resource temperatures
Integration of geochemistry with mineralogy	Essential; integrate geochemical data with primary and alteration mineralogical information
Soil gas surveys	CO_2 flux may indicate resource size; mapping CO_2 flux may provide estimates of areal extent of a system; high CO_2 flux zones may identify active faults (potential fluid path ways)
Sample and analysis of temperature gradient wells	Sample natural discharges or use down hole sampling tools to gain subsurface information

5.3.4. Geophysics

Since geophysics plays an especially important role in CV1 systems, a geophysicist frequently accompanies the geologist and the geochemist on the initial field reconnaissance. This gives the geophysicist the opportunity to assess the field conditions since different geophysical methods require specific ground conditions to be successfully utilized. The geophysicist has a large repertoire of techniques from which to draw (see Chapter 4). Table 5.3 provides a general summary of the usefulness of different geophysical techniques in CV1 plays. However it should again be emphasized that the selection of exactly which techniques are used in CV1 plays relies on input from a suitably experienced geophysicist.

Table 5.3. Potentially useful geophysical techniques in CV1 systems.

TECHNIQUE	COMMENT AND FREQUENCY OF USE
Remote sensing and LIDAR	Becoming increasingly widely used in the early reconnaissance stage of exploration
Heat flow	Extensively used at the early stages of exploration
Electrical resistivity	Extensively used at early stage to investigate the relatively shallow distribution of alteration (Cumming, 2009)
Magnetics	Frequently used to identify demagnetized rocks due to alteration
Gravity	Frequently used to assist in stratigraphic interpretation/ structural interpretation and possibly identify plutons
TEM	Used in conjunction with MT to define the shallow (<500m depth) resistivity structures during exploration of systems in CV plays
Magnetotellurics	Extensively used to investigate the deeper distribution and alteration patterns in CV1 Plays (Cumming, 2009)
Self-potential methods	Not extensively used
Passive seismic	Setting up seismic array around active systems may define active faults which are flow paths for geothermal fluids
Active seismic	Not currently extensively used for exploration of systems in CV1 Plays in volcanic terrain but may be useful in sedimentary basins
Stress field estimates	Useful to define structural control on systems
CSAMT	Not widely used to date but has proved to be useful in some prospects

5.3.4.1. Surface Heat Flow

Heat flow measurement is a relatively inexpensive technique that can permit estimates to be made of the extent and throughput of a system. The technique was extensively used in early exploration and prioritization of CV1 plays in New Zealand. Measurements in temperature gradient wells may be extremely useful or essential to gain an understanding of the shallow thermal gradients for carrying out preliminary assessments of a region.

5.3.4.2. Temperature Gradient Drilling

Temperature gradient (TG) drilling is commonly used in the exploration for CV1 systems. Since it may involve a significantly increased level of expenditure beyond surface exploration, drilling is most commonly applied towards the end of the Exploration Phase. At this time, a reasonably detailed conceptual model has been developed and the drilling can focus on clarifying ambiguous data or screening a number of areas to identify the most promising area for more detailed exploration. TG drilling may therefore enable

- direct measurements to be made of subsurface temperature;
- information to be gathered on subsurface lithologies;
- ground-truthing of various geophysical interpretations;
- sampling of subsurface fluids which may be critical for developing mixing models; and
- testing the validity of the conceptual model.

5.3.4.3. Seismics

In many countries passive seismic data are collected as a component of seismic monitoring networks. Such data may be very useful in regional surveys of CV1 prospects by identifying deep structures that may outline the general location of geothermal systems or indicate some structural control on the fluid flow (for example, the possible alignment of thermal features along faults). In the more advanced stage of investigation of geothermal prospects, setting up seismic arrays around an explored prospect may be appropriate since induced seismicity may be the result of exploitation of the system.

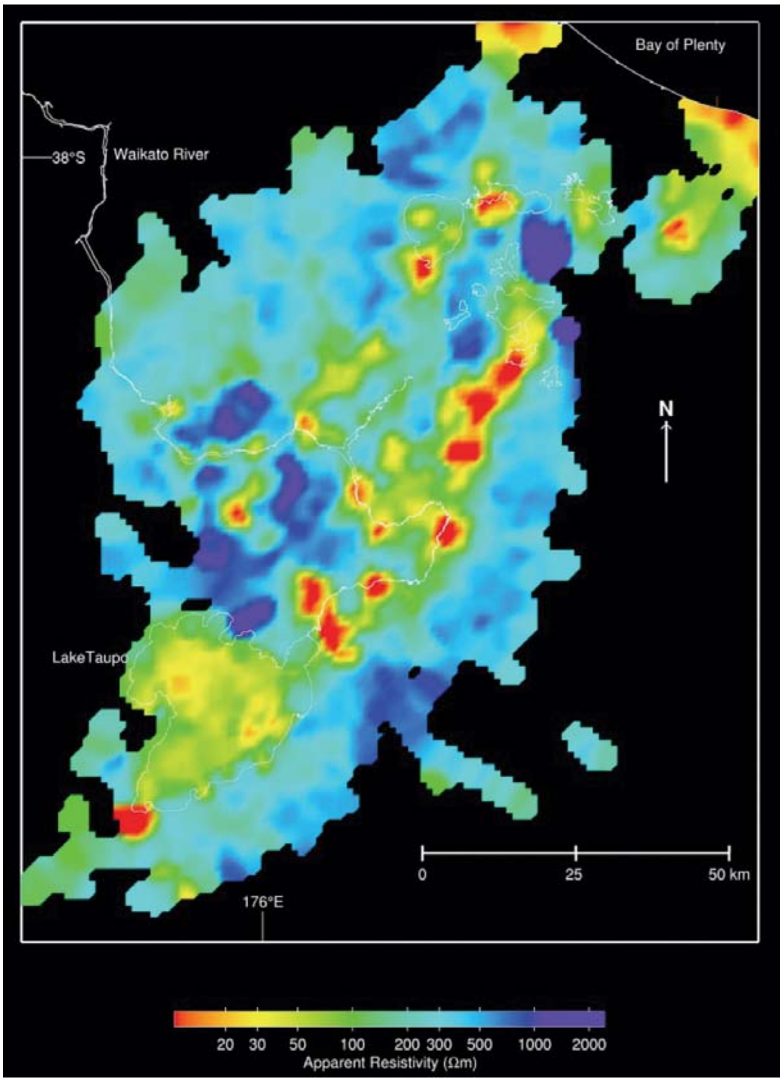
Active seismic surveys have been carried out on many CV1 geothermal prospects, but in volcanic terrain, the absence of suitable density contrasts of volcanic units may limit its effectiveness. However, in the sedimentary sequences at Cerro Prieto (Mexico) seismic reflection studies provided support for gravity and magnetic interpretations (Fonseca and Razo, 1979).

5.3.4.4. Resistivity (Excluding Magnetotellurics)

Resistivity methods are used to map the areal extent of clay haloes and the presence of conductive fluids above and marginal to convective systems (Bibby et al., 1995). Such techniques, including Schlumberger resistivity, audio magnetotelluric (AMT), and controlled source audiomagnetotellurics (CSAMT), are especially appropriate for reservoirs shallower than 500 meter depth (Cumming, 2009). In early exploration of the graben-setting Taupo Volcanic Zone in New Zealand, the Schlumberger resistivity technique was extremely successful in mapping the clay cap and presence of conductive fluids above numerous active hydrothermal systems. Figure 5.5 provides a regional view of the shallow resistivity in the Taupo Volcanic Zone, with red areas representing conductive zones. In that setting, the resistivity haloes create “bull’s-eyes” for siting test wells.

Figure 5.5. Regional shallow resistivity map of the Taupo Volcanic Zone, New Zealand, where numerous CV1 type geothermal systems have developed in volcanic or graben settings.

Source: Bibby, 1988.



5.3.4.5. Magnetotellurics

Magnetotellurics is the standard tool for investigating the resistivity structure deeper than 500 meters, and is widely relied on to infer key characteristics of CV1 geothermal reservoirs (Ussher et al., 2000; Anderson et al., 2000; Cumming, 2009). Interpretation of MT data should be integrated with information obtained from surface geological mapping, shallow temperature drilling, and perhaps clay mineral studies (e.g., methylene blue method of Harvey et al., 2000; Gunderson et al., 2000). Figure 5.6 presents an MT resistivity block model of a developed geothermal system in the Taupo Volcanic Zone, New Zealand. MT surveys may also help constrain the regional tectonic setting. An example is shown in Figure 5.7 in which the subduction of the Pacific Plate beneath the Australasian Plate is imaged by MT data and earthquake hypocenters.

Figure 5.6. Example of 3D MT block model.

Note: The black dots record well defined earthquake hypocenters. Source: GNS Science, New Zealand.

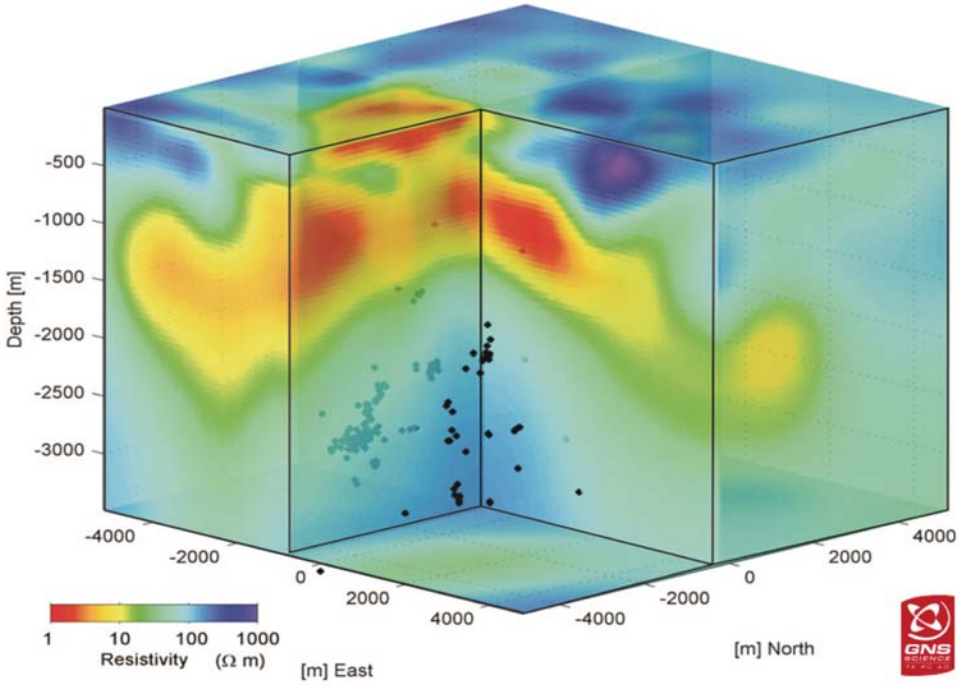
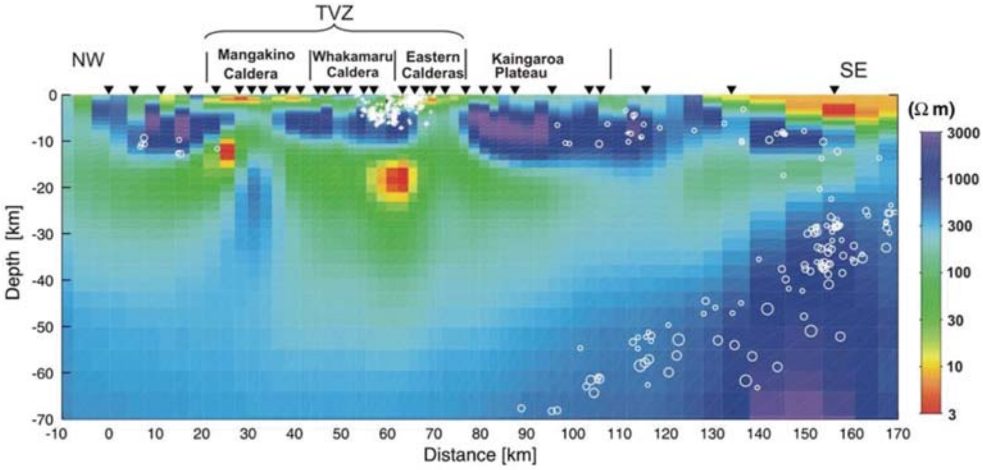


Figure 5.7. Example of regional MT survey across center of North Island in New Zealand.

Note: White circles show earthquake hypocenters. Source: Heise et al., 2007.



5.3.4.6. Gravity

Gravity surveys may add additional useful information on the distribution of subsurface structures to improve the understanding of the structural and lithological controls on CV1 type geothermal systems in the subsurface. Microgravity surveys are increasingly being employed to investigate density variations due to lithology, alteration (silicification), and volcano or basin geometry.

5.3.4.7. Magnetics

At a regional scale, different rock types may be distinguishable by different magnetic properties, allowing broad structural features to be identifies in magnetic data. Aerial or ground-based magnetic surveys may also be worthwhile for CV1 type plays since the host volcanic rocks frequently have small amounts of ferromagnetic minerals such as magnetite or titanomagnetite. The hydrothermal alteration process may alter these to non-magnetic minerals such as hematite, pyrite, leucoxene, or sphene (Browne, 1978), causing the reservoir intervals to become partially or totally demagnetized.

Magnetic surveys in the form of both ground surveys and low-altitude airborne surveys have been successfully used to map geothermal systems in volcanic terrains in both New Zealand (Hochstein and Hunt, 1970; Soengkono and Hochstein, 1995) and Iceland (Bjornsson and Hersir, 1981). In some areas, good correlations have been observed between magnetic anomalies and zones of low resistivity (Soengkono and Hochstein, 1995, 1996).

5.4. Development and Updating the Conceptual Model

Combining all the information from the geological, geochemical, and geophysical surveys enables the explorer of CV-1 prospects to develop an integrated conceptual model. It is never too early to develop a conceptual model (see Section 4.4), but as more and more data become available from the various exploration techniques, the judicious integration of data from geological, geochemical, and geophysical surveys enables the conceptual model to become more and more detailed. There is greater use of computer-based modelling techniques in the refinement of conceptual models (Milicich et al., 2010).

When updating the conceptual model, the geoscience team should always strive to identify potential ambiguities in the interpretation of new data. Resolution of ambiguities can be time consuming and complex. Uncertainties introduced by ambiguities can reduce the level of confidence in any conceptual model and yet sooner or later, a decision has to be made to test the conceptual model by drilling.

5.5. Prioritization of Target Areas

In many CV1 plays the initial exploration may cover large areas in which there may be numerous thermal manifestations. An example is the Taupo Volcanic Zone, New Zealand, where possibly 20 active geothermal systems have been identified (Figure 5.5). Prioritization of target areas following preliminary exploration of any region may be a worthwhile exercise since exploration funds may be limited. Priority should be given to the most promising targets that may enable exploration to proceed at the lowest financial risk. This strategy should enable successful developments to be achieved in the shortest possible time. Selection of priority targets may be based on a number of technical variables discussed previously, but prioritization may also be based on non-geoscientific considerations such as location access, environmental, cultural, or political issues.

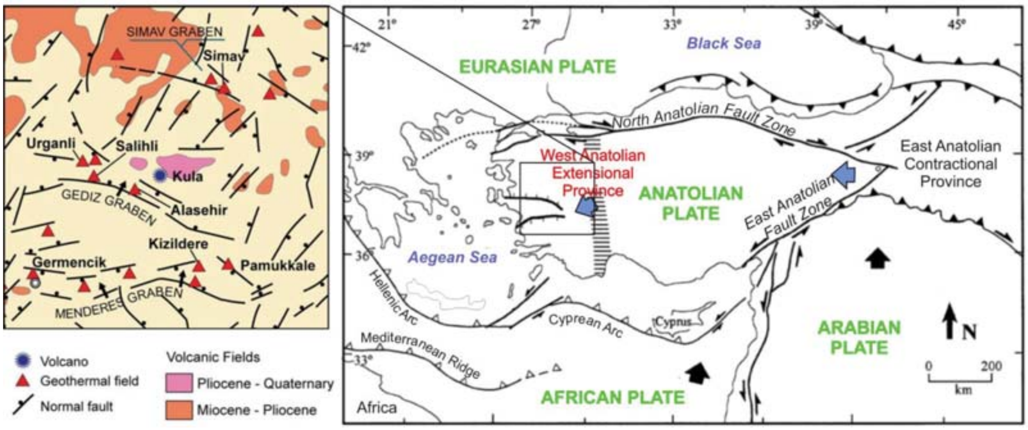
6. STRATEGIES FOR EXPLORATION IN CONVECTION-DOMINATED EXTENSIONAL DOMAIN (CV2) PLAYS

6.1. Introduction

A lack of magmatic activity does not imply a lack of geothermal systems. In regions of active extension, deep-rooted faults in thinned crust can transport heat and thermal water while thinned crust causes elevated heat flow in general. While extension is clearly associated with divergent margins, it is also encountered in other geological settings. The two regions with the largest extensional rates worldwide are the Basin and Range Province (USA) and the Western Anatolian Extensional Province, Turkey (Figure 6.1). Both regions have proven potential for geothermal energy developments. On a local scale, extension can also occur on convergent or transform margins, especially along segmented strike-slip faults.

Figure 6.1. Structural setting of known geothermal systems (fields) in Western Turkey.

Source: Compiled from Faulds et al., 2010 and Bozkurt, 2001.



Active extension is always associated with active faulting along normal to strike-slip faults. Experience has shown that understanding fault controls on the geothermal systems should be the focus of exploration in these extensional domains (e.g., Caskey, 2000; Genter, 2010). Faults typically provide the pathways for geothermal fluids within the crust and are therefore the primary control for the efficient transfer of heat from deep to shallow crustal levels in amagmatic regions. Despite the significance of faults in controlling geothermal activity in such regions, however, relatively little is known about the most favorable structural settings for geothermal systems (Faulds et al., 2010). Present thinking suggests that dilational to shear-dilational faults are prime structures to channel fluids, whereas compressional faults act mainly as barriers to flow (Sheridan and Hickman, 2004; Anderson and Fairley, 2008).

The aim of exploration in extensional domains is to identify specific structural geological settings that can cause local extension, dilation, highly interconnected fracture density, or highly permeable subsurface layers that can act as reservoirs for fluids convecting from deeper levels.

6.2. Structural Setting of Extensional Domains

In extensional-domain geothermal plays, certain structures within a complex fault pattern are more conducive for fluid flow. Understanding the controls on such flow zones would help to identify favorable drilling sites, but global understanding of the most favorable structural settings for geothermal systems is still developing. In the Basin and Range Province, for example, efforts have been made to catalog more than 400 known geothermal systems according to their structural setting (Faulds et al., 2012). This work has found that most of the geothermal systems are located in step-over regions of segmented normal or transtensional faults; a decent number are located at fault tips and fault intersections; while only a small number are situated in the accommodation zones of major range-front faults and pull-apart basins. One valuable finding is that zones of maximum displacement on faults do not seem to host significant geothermal systems.

Structural settings favorable for convection-dominated extensional-domain geothermal plays can be identified through conventional geologic mapping and appear to be

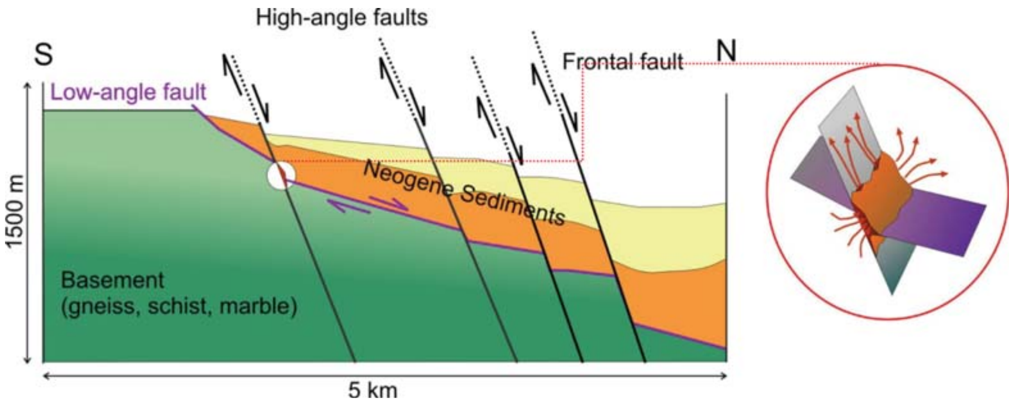
- step-over regions and relay ramps;
- intersections of normal faults or with strike-slip faults;
- fault terminations, horse tail structures; and
- accommodation zones.

Dilational fault segments may represent favorable targets at depths shallower than 2 km, while critically stressed shear fractures seem to control fluid flow deeper than 2 km, according to studies of the Dixie Valley geothermal system in Nevada (Barton et al., 1995). The reason for this may be an increase in normal stresses acting on faults deeper than 2 km while normal stresses at shallower levels are small enough to allow dilation of faults (Ferrill and Morris, 2003).

The intersections of faults dipping at different angles detectable through conventional surface geologic mapping or seismic interpretation represent a specific exploration target. Such fault intersections may serve as prime fractured reservoirs since intersecting fault zones are often associated with high fracture density, hence high permeability. This has been observed in the West Anatolian Extensional Province (e.g., E-W trending Gediz

Figure 6.2. Conceptual model of dilational fault intersections generated by contemporary low- and high-angle faults.

Note: Such interactions of low- and high-angle faults characterize favorable geothermal reservoir settings in the Menderes Graben, Western Turkey. Source: J. Faulds, V. Bouchot, and K. Oguz, pers. comms.



Graben or Menderes Graben), where intersections of high and low angle normal faults generate dilational jogs (Figure 6.2). At this type of fault intersection, thermal water can migrate laterally and vertically, causing hot springs at some locations as evidence of increased permeability. However, these systems can also be concealed or "blind" with no surface manifestations to suggest their presence.

The term blind or hidden geothermal system is used in literature for those convection-dominated play types that have no surface expressions such as hot springs, steaming ground, or mud pots. While blind systems can occur in convection-dominated play types, all conduction-dominated play types are blind.

Example of a blind geothermal field

Desert Peak, Nevada: fracture-hosted geothermal reservoir at 1.2-1.3 km depth and at 218°C. Two installed ORC binary plants with a combined capacity of 33 MWe. Desert Peak is located at a left step-over in a NNE-striking, west-dipping normal fault system (Faulds et al., 2010). The Desert Peak geothermal system was discovered using heat flow drilling in the 1970s.

Another set of targets in these settings are high permeability stratigraphic layers (detectable through geologic mapping combined with geophysical methods such as magnetotelluric) that can store significant amounts of hot fluid transported up intersecting faults and subsequently leaking into the permeable layers. These systems might be “closed” with the fluid continuously cycling through faults and permeable layers in convective loops; or “open” with recharge occurring on bordering ranges. Temperature logs through such systems would show temperature inversion, with elevated temperature in the horizon where the fault leaks hot fluids in, subsiding to the regional geothermal gradient below the leakage formation. Stress field analysis (see Section 4.3.6) helps to identify dilational or critically stressed fault segments that might channel hot fluids from deeper levels.

There are, therefore, two sub-types of convection-dominated extensional domain geothermal play types:

- Fault zone reservoirs like the detachment faults in the grabens of the West Anatolian Extensional Province
- Tilted, high permeability stratigraphic reservoirs at the rim of grabens

6.3. Exploration Methods

As for all other play types, exploration for extensional domain geothermal plays aims to build a conceptual model consistent with all available information. In this play type, faults exert the dominant control on the geothermal system, commonly in interplay with other geological controls such as permeable/impermeable stratigraphic layers. Although the ultimate aim of each exploration campaign is to predict isotherms and reservoir quality (porosity and permeability), starting exploration at a larger scale is important to figure out the overall regional structural geological setting.

An overview structural geological framework model can be derived from gravity surveys. Gravity maps can be interpreted to identify basin geometry, basement depth, and the nature of the basin fill. In general, basins or grabens are expressed by a negative gravity anomaly, although the type of basin fill can increase or decrease this anomaly. Gravity maps are most reliable, if integrated with surface geological mapping and rock property measurements.

Fault and fracture analyses are a major focus of geological mapping for extensional domain plays. Bouguer gravity maps can enhance the depth interpretation of major faults by constraining their geometry (Cashman et al., 2009). Shallow temperature drilling, geochemistry, and geothermometry are standard methods as for other convective geothermal play types. However, geochemistry and geothermometry cannot be conducted on blind geothermal systems prior to drilling.

A conceptual model for blind geothermal systems must include a mechanism that prevents fluid and gas leakage to the surface. Possible mechanisms are impermeable layers as clay caps or a drop of the water table. Inactive sinter or travertine deposits may indicate former discharge zones and should be included in conceptual models.

A combination of resistivity, hydrothermal alteration, lithology, structural geology, and hydrogeology data can be relied on for a robust conceptual model. Magnetotelluric surveys are the prime exploration method for blind extensional-domain geothermal systems insofar as they help to identify the permeability structure or partial melts (Cumming, 2009). In faulted regions, different lithologies are juxtaposed directly against each other, and fault surfaces can contain significant amounts of clay (fault gouge), graphite, or sulfides. Therefore, not all low-resistivity anomalies represent increased permeability (volumes of brine) or partial melts in these settings. MT and other resistivity data must be interpreted within the context of the background geology to build the most likely conceptual model.

Reflection seismic techniques can be employed when a significant sedimentary fill of different lithologies allows the identification of seismic reflectors and faults. Very young extensional domains often host a relatively homogenous sediment package. In these cases, reflection seismic techniques might only distinguish the basement top (and therefore total sediment thickness) rather than internal sedimentological boundaries. Whether reflection seismic techniques represent a cost-effective option to minimize uncertainty in the conceptual model must be decided on a case-by-case basis.

AMT and CSAMT can help to map low-resistivity anomalies at shallow depths. These anomalies can indicate brine accumulations, but can also relate to other causes of resistivity lows (clay in particular). Magnetic surveys can help to map near-surface hydrothermal alteration, as described in Chapter 4. But, again, a magnetic anomaly cannot always be attributed to a single cause since positive magnetic anomalies can be caused by iron sulfides and iron-rich volcanic rock. Self-potential methods can be employed for water table mapping or hydrology mapping, especially in areas of low relief. High self-potential anomalies can indicate an aquifer, water bearing domains, or strong lateral groundwater flow since water has a high electrical conductivity compared to rock or low porosity beds. Self-potential methods are most effective when they are combined with resistivity methods.

A conceptual model approach to exploration is particularly effective for blind extensional-domain geothermal plays because the model makes full use of limited data sets and helps to characterize the shape of isotherms and ultimately well targeting. A conceptual model also helps to identify gaps in information and the degree of uncertainty so that a cost-effective heat flow well, for example, can be drilled in specific zones to constrain predicted temperatures. Such a shallow well would directly test and revise the conceptual model.

Recommended exploration methods are as follows:

- Surface structural geological mapping, fault and fracture analysis, stress field determination, and geothermal manifestations
- Gravity
- Shallow heat flow drilling
- Geochemistry and geothermometry (if surface manifestations are present)
- MT for predicted reservoirs >500 meters depth
- Optional exploration methods on a case-by-case basis
- Other resistivity methods for predicted reservoirs <500 meters depth
- Reflection seismic techniques in graben settings with sedimentary fill
- Magnetic surveys (airborne)
- Self-potential methods (natural surface voltages)

7. EXPLORATION FOR CONDUCTION-DOMINATED PLAYS

7.1. Introduction

As with all geothermal plays, exploration for conduction-dominated geothermal play types is about reducing the uncertainty in estimates of reservoir temperature, transmissivity (permeability-thickness), and geometry prior to the Test Drilling Phase. All conduction-dominated geothermal play types share the common characteristic that the distribution of temperature is mostly controlled by thermal equilibration through conduction. Temperature gradients (vertical and lateral) are a function of the conductive heat flow and the thermal conductivity of the rocks, and any disturbance due to the natural physical movement of fluid is minor. Viable reservoirs might take the form of open faults and fractures, permeable lithofacies, and fractured crystalline rocks that might be developed as reservoirs using EGS techniques or a combination of these. Appropriate exploration methods focus on constraining the stratigraphy, geometry, structural geology, tectonic stress field, heat flow, thermal properties, and porosity/permeability characteristics of the broad geological setting in three dimensions.

Conduction-dominated geothermal play types (CD1–CD3) tend to be associated with sedimentary basins in intracratonic settings. They are always, by definition blind geothermal systems with no surface thermal manifestations. Geothermal reservoirs associated with conduction-dominated plays include naturally permeable (either primary or secondary permeability) sedimentary formations deep within extensional or foreland basins; and thermally insulated, fractured (normally crystalline) basement rocks amenable to permeability enhancement through hydraulic, chemical, or thermal stimulation. Exploration techniques appropriate for conduction-dominated geothermal plays can be divided into techniques that reveal the three-dimensional geometry (structural exploration) and lithological composition of the sedimentary basin and basement; techniques that constrain the distribution of temperature; and techniques that reduce uncertainties in the estimates of the hydrogeological properties of potential reservoir units. The aim is to build an increasingly detailed conceptual model of the basin and underlying basement, constraining their regional extent and variability, stratigraphy, depth, composition, structural elements, temperature, porosity/permeability distribution, stress field, surface features, and land access issues.

7.2. Techniques that Reveal Basin Geometry and Composition

Structural exploration of the basin and underlying basement is the first goal for conduction-dominated plays. Basin geometry and composition exploration techniques are as follows:

- Existing geological information
- Gravity and magnetics
- 2D/3D reflection seismic techniques
- Structural geology

7.2.1. Existing Geological Information

Conduction-dominated geothermal plays are usually associated with sedimentary basins. As is often the case, any given sedimentary basin will have been explored or exploited at some point in the past for other commodities such as groundwater, hydrocarbons, or coal. As a result of these previous investigations, regional geological information about the general basin structure might already be available. All available material such as peer-reviewed or conference publications, student theses, surface geological maps, borehole reports (including any reports of subsurface temperature), interpreted seismic lines, rock petro-physics, and so on should be evaluated and, if necessary, reinterpreted.

7.2.2. Gravity and Magnetics

Previously existing or newly collected aerial or terrestrial gravity or magnetic survey data may provide insights into the basin geometry and the depth of the basement. Alternatively, the petrological composition of the deeper sediments and basement might be inferred from modelled density or magnetic susceptibility valuesbased on such data. Note, however, that gravity and magnetics models are inherently ambiguous (see Section 4.3.4.1).

7.2.3. 2D/3D Reflection Seismic Technologies

Modern reflection seismic technologies represent the most accurate and precise technique to explore the structural detail of deeper strata. Interpretations of fault locations and orientations are typically more accurate for 3D surveys than for 2D surveys. The drilling risk reduction that comes from a detailed structural interpretation (usually possible from 3D seismic techniques) must, however, be weighed against the significant cost of collecting 3D seismic data. The value of 3D seismic data typically increases in proportion to the depth and cost of the anticipated exploration wells. Where deep drilling (perhaps to 6,000 meters) is anticipated, drilling costs will be significant and 3D seismic techniques might be justified. For example, collecting 3D seismic data before drilling for geothermal energy in the Molasse Basin in Germany is a common practice. As 2D seismic data are less expensive to collect, this might be justified in a greater number of locations.

Spatial resolution from 2D/3D seismic interpretations might be in the ±10 meter range for drilling target depths and for the location of faults. Seismic data, however, are largely insensitive to temperature and provide, at best, very limited information on porosity and permeability. Seismic images might indicate the position of faults but do not indicate whether those faults are open (permeable), closed, or recently active.

In addition, some lithologies (for example, thick accumulations of coal or basalt) have a high anelastic attenuation factor. These lithologies effectively absorb seismic energy and conceal reflections from underlying structures. The value of reflection seismic techniques is severely reduced in basins containing such lithologies at shallow levels.

7.2.4. Structural Geology

While conduction-dominated geothermal plays assume there is negligible natural subsurface fluid movement, permeable units or structures are required for the efficient extraction and reinjection of water during energy production. Faults can act as barriers or conduits for subsurface fluid movement, depending on their kinematic evolution (history of movement: magnitude and sense), their position within the current stress field, and the type of rock surrounding them. The dimensions and transmissivity of the fault core and damage zone depend on the rock type surrounding the fault. For example, sandstone may develop deformation bands that act as fluid barriers in fault damage zones (Fossen and Rotevatn, 2012); whereas, under the same conditions, carbonate rocks or granites may develop a fracture network that acts as a fluid conduit (Agosta et al., 2010). The kinematic evolution of a fault also influences the dimensions and transmissivity of the fault core and damage zone. Faults reactivated multiple times or faults offsetting clay-rich formations may be filled with clay ("fault gouge"), becoming barriers to subsurface fluid movement. In contrast, carbonate rocks may dissolve and "karstify" in the fault core, turning the fault into a conduit for fluids.

Structural analysis of faults and their possible impact on transmissivity typically requires a full interpretation of seismic survey data from the surface to at least the base of the target reservoir. Seismic interpretation should cover the full stratigraphic sequence, not focus on the target reservoir alone. The aim is to interpret the fault development and reactivation history.

7.3. Techniques Constraining the Distribution of Temperature

An assumption of thermal conduction as the dominant heat transfer mechanism allows subsurface temperature to be predicted through applying conductive heat flow modeling. Such models, however, require estimates or measurements of thermal conductivity and heat generation for the full stratigraphic sequence from the surface to at least the depth of the target reservoir. They also require estimates or measurements of surface heat flow and/or a number of subsurface temperature measurements to constrain the models.

Thermal gradient is typically not constant with depth or location and varies according to the thermal conductivity of the strata and the magnitude of heat flow from below (e.g., Beardsmore and Cull, 2001). In some specific geological scenarios, the temperature field can be significantly distorted through thermal conduction effects alone. For example, salt diapirs can act as high conductivity heat "chimneys," leading to higher temperatures at shallow depths and lower temperatures at deeper levels compared to the surrounding temperature field. In contrast, low conductivity coal seams act as thermal blankets, depressing shallow temperatures and leading to higher temperatures at depth beneath the coal.

It is important at all times to keep in mind that an assumption of thermal conduction as the dominant heat transfer mechanism down to inferred reservoir depth will not always prove true in reality. Any component of convective heat transfer above the level of the inferred reservoir depth will invariably reduce the true temperature of the reservoir relative to predictions based on conductive models. An anomalously high and/or localized shallow conductive heat flow anomaly, like that observed in the shallow sediment at Soultz-sous-Forêts in France prior to deeper drilling into the granite basement (Baria et al., 1992), could indicate an elevated risk of the presence of a relatively shallow convection cell.

Specific temperature exploration techniques for conduction-dominated plays are as follows:

- Existing subsurface temperature data
- Heat flow drilling
- Rock property measurements
- Numerical conductive heat flow modeling

7.3.1. Existing Subsurface Temperature Data

A search of peer-reviewed papers, conference publications, and student theses might reveal previous temperature modelling exercises, additional data sources, or evidence of non-conductive heat transfer mechanisms in the area of interest. These should be identified and critically assessed prior to commencing any new data collation or collection exercise. Previously measured subsurface temperature data represent the most direct indicators of natural rock temperature in conduction-dominated geothermal plays, so any such data should be collated and critically assessed. Such data could come from wireline logging reports, petroleum production tests, underground mines, pumped or artesian water bores, or other sources. It is important to correlate each temperature datum to a particular depth and location.

Unless specifically collected for geothermal purposes, most subsurface temperature data are affected to some extent by the wellbore environment and do not exactly represent the undisturbed ground temperature. Such impacts can be due to the recent circulation of drilling fluid, cooling within the borehole during production, curing of casing cement, gas expansion into the well, or other effects. Most of these effects result in temperature measurements lower than the natural rock temperature. Older temperature data that relied on manual readings from thermometers are also prone to random transcription errors. It is important to recognize and allow for all of these potential errors and uncertainties in subsequent extrapolations or interpolations of temperature at other depths and locations.

7.3.2. Heat Flow Drilling

Heat flow drilling, as described in Section 4.3.4.9, is arguably of greater value for conduction-dominated geothermal plays than convection-dominated plays. This is because the laws of thermodynamics (specifically conservation of energy) and the assumption of conductive heat flow dictate that the heat flow measured at the surface can be extrapolated to arbitrary depth to predict temperature. Ideally, this is carried out in three dimensions to account for possible lateral heat flow in complex structural settings.

For overall suitability, the number of wells and locations for heat flow drilling should be decided based on the degree of uncertainty over the temperature at inferred reservoir depth; cost of heat flow drilling; cost of drilling to inferred reservoir depth; accessibility to appropriate sites; and surface conditions. With respect to surface conditions, significant surface topography can locally affect surface heat flow, so heat flow wells should be located at least one kilometer from positive or negative topographic features of 250 meters or more relative elevation.

At least two companies in Australia have previously carried out exploration programs of heat flow drilling at approximately 15-20 km spacing to constrain 3D heat flow models and predictions of temperature at depth across relatively large exploration areas (Holgate et al., 2009; Matthews and Godsmark, 2009).

7.3.3. Rock Property Measurements

Conductive heat flow models require estimates or measurements of thermal conductivity and, ideally, heat generation for the full stratigraphic sequence from the surface to at least the depth of the target reservoir. Representative samples of the relevant lithologies might be collected from surface outcrops (if relatively unweathered), preexisting core, or analogues from other locations.

Good practice is to measure several specimens of each lithology or formation in order to derive an average value and variance. Experienced laboratories should be used for all measurements. The temperature at which thermal conductivity is measured in the laboratory should be recorded because conductivity is temperature-dependent and corrections are required if laboratory conditions vary from in situ conditions, as is usually the case.

Where no samples can be collected, global average conductivity values can be assumed for specific lithologies, although the uncertainty in such values is inherently higher than for local measurements.

7.3.4. Numerical Conductive Heat Flow Modeling

The differential equations governing the conductive flow of heat are well understood and relatively simple to solve using finite difference numerical methods. Different levels of sophistication are possible with such approaches, from simple one-dimensional models with static thermal conductivity values (which can be solved with simple spreadsheets) to much more complex three-dimensional models incorporating temperature dependence of thermal conductivity. Given the limited market and specialist nature of the requirements for conduction-dominated geothermal play exploration, identifying and procuring appropriate software to carry out the modeling can be difficult. A number of geothermal exploration consulting groups and individuals have conductive heat flow modeling capabilities, and explorers are encouraged to enlist the assistance of such groups for this task.

7.4. Techniques Reducing Uncertainties in Estimates of Hydrogeological Properties of Reservoir Units

Transmissivity (integrated permeability over a given thickness) is arguably the hydrogeological property that best characterizes the potential of a given volume of rock to act as a geothermal reservoir. In the case of conduction-dominated geothermal plays, target reservoirs are either relatively thick, naturally permeable (primary or secondary) sedimentary formations; hydraulically “open” fracture and fault networks; or naturally fractured rocks amenable to enhancement through stimulation.

The natural porosity and permeability of sedimentary formations tend to diminish with depth of burial due to compaction. Heating and diagenesis can either amplify or suppress the compaction effect. The degree to which natural permeability is retained is largely a function of depth, temperature, and lithology. Some predictions can be made based on sedimentation and burial history models, with a consideration of possible diagenesis.

Active or critically stressed faults are considered prime targets for deep geothermal reservoirs (Barton et al., 1995). Secondary fracture networks often accompany such faults, and these remain relatively permeable because any mineralization within the fractures is continuously broken up though active slip. Active dilational faults and extensional fractures are often conduits for fluid flow at depths less than two kilometers, while critically stressed faults provide potential flow paths at greater depths (Ferrill and Morris, 2005; Moeck et al., 2009). Mapping the locations and orientations of faults and fracture zones was covered in Section 7.2.4. Whether faults are critically stressed or dilated depends on their orientation within the present-day stress field (Morris et al., 1995; Moeck et al., 2009). Stress field analysis and rock mechanical modeling are therefore important exploration techniques for conduction-dominated geothermal plays.

Exploration techniques specifically addressing transmissivity include the following:

- Seismic sequence stratigraphy for porosity/permeability prediction
- Diagenesis investigation
- Seismic signal attributes for porosity estimates
- MT polarization for identifying fractured rock
- Seismic shear wave splitting for identifying fractured rock
- Stress field analysis and geo-mechanical modeling

7.4.1. Seismic Sequence Stratigraphy for Porosity/ Permeability Prediction

Reflection seismic sections image the sequence and geometry with which sediment layers fill basins. The methods of seismic sequence stratigraphy group formations into units bounded by unconformities, based on their geometric relationships, and explain these units in terms of changes in relative sea level. Clastic units with high initial porosity and permeability tend to be associated with periods of low sea level, while initially porous calcareous units tend to be associated with periods of high sea level (Ali et al., 2010). In this way, making qualitative predictions of reservoir quality based on geometric relationships observed in the seismic profiles might be possible.

Moreover, identifying specific high-energy clastic sediment facies, such as braided river systems or basal conglomerates, on seismic profiles might also be possible. Such facies might host poorly sorted sediment with higher than average porosity.

7.4.2. Diagenesis Investigation

According to Ali et al. (2010), “diagenesis is a continually active process by which sedimentary mineral assemblages react to regain equilibrium with an environment whose pressure, temperature, and chemistry are changing. These reactions can enhance, modify, or destroy porosity and permeability.” The processes and controls on the diagenesis of any given package of sediment are complex functions of the initial sediment composition, pressure and temperature history, and interaction between the sediment and chemically varying pore fluids through time. The field of diagenesis investigation is advancing rapidly, driven by its importance in petroleum exploration for reservoir quality. Clearly, this field is also highly relevant when exploring for permeable geothermal reservoirs in the deeper parts of sedimentary basins.

General rules for predicting zones of diagenetically enhanced or retained permeability are still rare, but some general indicators have become apparent. For example, some coatings (e.g., chlorite, micro quartz) on quartz grains act as inhibitors to quartz cementation and can result in the retention of primary permeability (Taylor et al., 2010).

7.4.3. Seismic Attributes for Porosity Estimates

The attributes of reflected seismic signals (e.g., wavelet phases and amplitudes) relate to physical properties of the imaged rocks such as sonic velocity, density, porosity, Poisson's ratio, and others. Under certain conditions, "machine learning" or "neural network" methods might allow a computer algorithm to "learn" the relationship between the physical properties and the seismic attributes and thus develop an operator or function to predict the properties from the seismic data. This is only possible where wire-line log responses (showing the relative variability in the relevant properties with depth) and high quality 3D reflected seismic signal attributes can be correlated against a number of physical measurements of the relevant properties (e.g., from core samples). These data sets are only likely to be available for conductive geothermal plays. The accuracy of the resulting predictions away from the calibration points depends on the accuracy of all the input data; degree of "learned" correlation between the seismic data and modeled parameters; distance from the control points; and degree to which the assumed correlation actually exists in nature.

If high quality 3D seismic data are available, the method might be attempted using commercial products such as Schlumberger's Petrel software package. Pavlova and Reid (2010) presented a case study of this method to predict the porosity of the Pretty Hill Formation in the Otway Basin, Australia, using 3D reflection seismic data, interpreted wire line sonic porosity, and core-measured porosity.

7.4.4. Magnetotelluric Polarization for Identifying Fractured Rock

As described in Section 4.3.4.3, magnetotelluric data might be interrogated for evidence of preferred subsurface fracture orientation. If the electric and magnetic fields are each measured along more than one orthogonal axis (or component) during an MT survey, then several different electric-magnetic (E:H) component field strength ratios can be calculated as a starting point for processing and interpreting. Common practice with modern instruments is to collect two orthogonal horizontal components of the electrical field and three components of the magnetic field. This provides for up to six different E:H ratios. If different E:H ratios produce different results for the subsurface resistivity distribution, this might indicate electrical anisotropy in the subsurface. In some instances, the magnitude and orientation of the anisotropy ellipse might be estimated. While various explanations might explain the anisotropy, in some instances, this could be due to a preferred fracture orientation, with the magnitude related to the fracture density. Where secondary porosity and permeability is being targeted, such MT polarization might be investigated for its potential to discriminate between areas more and less likely to have high fracture density.

7.4.5. Seismic Shear Wave Splitting for Identifying Fractured Rock

Seismic shear wave splitting is a useful technique to determine the fracture orientation in conduction-dominated play types and can be used to model potential fluid flow paths in a geothermal system.

7.4.6. Stress Field Analysis and Geo-mechanical Modeling

The development of geothermal reservoirs within basement type conduction-dominated plays will almost always require hydraulic stimulation of preexisting fracture networks to enhance the overall transmissivity of the rock mass. The success of the stimulation program in enhancing the natural permeability of the rock depends on a complex interplay between the tectonic stress field, orientation and density of preexisting fractures, characteristics of those fractures (length, aperture, stiffness, roughness, etc.), characteristics of the surrounding rock (coefficient of thermal expansion, hardness, etc.), and stimulation parameters (injection pressures, water volumes, water chemistry, water temperature, etc.).

Section 4.3.6presents a detailed description of the methods and significance of stress field analyses. Many of the parameters controlling the response of critically stressed fractures to stimulation are poorly constrained prior to drilling (or even after drilling), but numerical simulation software (e.g., Universal Distinct Element Code or UDEC produced by Itasca Consulting Group Inc.) can be used to investigate the range of possible outcomes and the sensitivity of outcomes to specific rock and fracture characteristics. Such packages can also be used to predict locations that are more likely to have existing open fracture networks, based on the present stress field, rock, and fracture properties. This work can help in the design of rock property measurements or well-testing programs.

7.5. Exploration Outcomes

At the conclusion of the Exploration Phase for a conduction-dominated geothermal play, the explorer should have a clear idea of the nature and location of the target geothermal reservoir. The explorer should be able to present a geological model of the basin (or at least the relevant region within the basin) and, if appropriate, the underlying basement. The model should encompass information about the stratigraphy, depth, composition, structural elements, temperature, porosity/permeability distribution, stress field, and surface features of the location. Importantly, the explorer should be able to communicate the uncertainties in predictions of the key reservoir parameters: location, depth, thickness, lateral extent, temperature, and transmissivity.

The combination of exploration methods applied to a specific conduction-dominated geothermal play will be guided by the value of each option with respect to reducing the overall financial risk of the Test Drilling Phase. In some places, undertaking relatively expensive programs of 3D reflection seismic or heat flow drilling will make financial sense, because target reservoirs are deep (expensive to drill) and reservoir temperature and/or optimal location and depth are poorly constrained. In other places, progressing directly to the Test Drilling Phase to answer questions about depth and temperature might be the course of action that represents the lowest financial risk.

8. REQUIREMENTS FOR THE PRE-FEASIBILITY STUDY

8.1. Introduction

This chapter provides the geothermal explorer with guidelines on what information and data should typically be assembled during the preliminary survey and exploration phases and on how this information should be presented to potential financiers. Collectively, this information forms the basis of the pre-feasibility study to justify proceeding to the Test Drilling Phase of the project. This chapter repeats some of the non-geoscientific material presented earlier in the Guide, to accentuate its importance to the economic viability of a geothermal project. These guidelines should be considered as suggestions rather than rigid prescriptions.

8.2. Preliminary Information

Background information should be compiled and presented in such a manner as to illustrate the explorer understands local requirements and perceptions about 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.

Relevant data should include information on these topics:

- Power market and possible PPAs
- Infrastructure issues (roads, water, communication, transmission)
- Resource ownership issues
- Environmental and social issues
- Institutional and regulatory frameworks
- 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 addressed. A suggested table of contents is provided in Appendix A1.

8.3. Environmental Impact and Resource Protection

A thorough understanding of the local regulations on environmental protection is an essential early step for any geothermal development. Although geothermal development is frequently acknowledged as an attractive option for power generation, the fact that a development of any kind has impacts on environment and land use must be appreciated. An environmental and social impact statement (ESIS) is a standalone document and is almost always a prerequisite to embarking on a survey or exploration program. Any such ESIS should be presented in full to a potential financier.

8.4. Collection of Baseline Data

Baseline environmental and social data, which essentially define the starting conditions of any development, should be collected as early as possible. In many countries, resource permits impose strict conditions relating to any potential impact of a geothermal project. For example, permits 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. It is important that the potential developer identify environmental parameters that might be sensitive issues 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, building consensus, or pursuing financing. Some baseline data collection may also require significant time (e.g., collection of background seismic data).

8.5. Literature Review

A thorough literature review by experienced geothermal specialists can save the explorer significant time, effort, and expense in the Exploration Phase of the project. Such a review may uncover both essential baseline environmental information and relevant technical data. Historical data of previous geothermal exploration can also provide a useful contrast to new explorer-generated data, enabling an assessment to be made of the quality and consistency of new data against previously collected information.

All relevant 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 focus on addressing the gaps or augmenting information where needed.

Examples of data sources to be sought and collated include the following:

- Academic publications from both local and foreign universities and research programs
- Data, results and/or reports from previous leaseholders 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
- Maps pertaining to geology, infrastructure, and lease boundaries

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

Key findings should be summarized in one or more standalone documents covering such things as the geologic setting, tectonic history, development history, and so on. This document(s) should include a comprehensive bibliography of all source material identified and reviewed and should note whether any identified material could not be reviewed (e.g., due to confidentiality, obscure source, or other reasons.)

8.6. Active Geothermal Features

Active geothermal features are proof of an existing geothermal system on some scale, although not proof of a system capable of supporting economic power generation.

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 with geological and tectonic information for each project area. Characteristic of the geothermal features should be compiled into tables that correspond directly to what is shown on the map. Ideally, all of these data would be geo-referenced to include estimates of the rate of geothermal fluid movement through the system and an idea of the extent, chemistry, and general geometry of the geothermal system.

8.7. Geology

Identification of the likely geothermal play type under investigation is an essential first step. The geological history of the area should be summarized in a separate document, specifically covering the age of any local volcanism. Geological data for the project area should be presented in the form of geological maps, structural maps, stratigraphic columns, and cross sections. A three-dimensional geological model could be presented using specialized modeling and visualization software. The data should include lithology, stratigraphy, hydrothermal mineralization, geological structure, tectonics, and sense of movement on faults. This information should indicate which units or structures could provide fluid pathways or host a geothermal reservoir. The geological analysis should also identify any uncertainties and data gaps that remain unresolved after the Exploration Phase.

8.8. Geochemistry

Fluid and gas geochemical data should be presented on maps, tables, drawings, and plots for the project area. Accompanying reports should explain the inferences and conclusions drawn from the data; an indication of temperature distribution within the geothermal system; a maximum and minimum temperature range for the resource; possible indications of future scaling or corrosion issues; and a fluid-mixing model. As with geologic studies, the geochemical interpretation should also identify uncertainties and data gaps that remain unresolved after the Exploration Phase.

8.9. Geophysics

All collected and interpreted geophysical data should be presented as maps, cross sections, or 3D models as appropriate. The data and interpretations for each survey 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, as well as any uncertainties and data gaps remaining after the Exploration Phase.

8.10. Drilling Data

For heat flow wells, drill hole locations and all temperature versus depth data should be presented graphically, with a legend listing the dates that each profile (temperature log) was made. Presentation of the results of heat flow drilling might include maps of temperature at specific depths or elevations by contouring temperatures or heat flow values; and/or cross sections that include the shallow geology and may show how temperature varies with depth due to conductive heat flow or advection of heat with convecting fluids.

8.11. 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 and be of sufficient detail to allow a first-pass estimate of resource temperature and size. The conceptual model is the primary guide during the Test Drilling Phase for targeting deep, full-diameter wells toward particular lithological units and/or structures judged most likely to deliver commercial rates of geothermal fluid and for future numerical modelling (Newson et al.,2012). The conceptual model forms the basis for cost and revenue estimates for the pre-feasibility financial model.

A geo-referenced database isthe most efficient way to integrate all of the geospatial data. This facilitates developing maps at uniform scales (changing the scale as needed) and overlaying different data to investigate interrelationships. 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.

The conceptual model can also be presented as cross sections or maps. 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 estimates 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. Any non-geological rationale of this kind must be clearly discussed when presenting well sites and drilling targets. Deviated directional drilling may be an option, but its cost implications should be factored in. Allowance of significant funds for detailed well testing and reservoir engineering (Grant and Bixley, 2011) should also be included in forward planning and costing.

Regardless of the mode of displaying the conceptual model, the magnitude and nature of uncertainties about key model parameters (depths, temperatures, fault locations and orientations, lithologies, porosity/permeability, and so on) that remain after the Exploration Phase should be clearly disclosed to potential financiers.

8.12. The Pre-feasibility Study and Financial Justification to Proceed

The data assembled from the technical and non-technical studies and surveys are brought together and incorporated into a pre-feasibility report that includes a financial model (including an estimated power capacity of the planned power plant) to predict returns on investment and to justify the next phase: the significantly higher level of funding required for the Test Drilling Phase (Phase 3) and well testing. The specific purposes of the pre-feasibility report are

- to demonstrate a reasonable probability that the geothermal system will support economic power production;
- to mitigate financial risk associated with the Test Drilling Phase of development; and
- to build a business case for funding support from private, public, or institutional bodies to proceed with the project.

Due to the uncertainties in the project before the drilling is complete, the pre-feasibility should include an assessment of risks.

APPENDIX

APPENDIX A1:

Example Table of Contents for Pre-feasibility Report

The following table of contents is an example for a very detailed pre-feasibility report. Not all geothermal projects will have this much data available; therefore, many reports will not be this extensive. However, this is an example with all data types collected and analyzed.

- TABLE OF CONTENTS
- SUMMARY
- 1. INTRODUCTION
  - 1.1 Terms of Reference
  - 1.2 Purpose
  - 1.3 Sources
  - 1.4 Scope
- 2. RELIANCE ON EXPERTS/DISCLAIMER
- 3. PROPERTY
  - 3.1 Description and Location
  - 3.2 Nature and Extent of Title
  - 3.3 Location of Known Resources
  - 3.4 Environmental Issues and Permit Requirements
- 4. ACCESSIBILITY, CLIMATE, LOCAL RESOURCES, AND PHYSIOGRAPHY
  - 4.1 Accessibility
  - 4.2 Climate
  - 4.3 Infrastructure and Physiography
- 5. DEVELOPMENT HISTORY
- 6. GEOLOGICAL SETTING
  - 6.1 Regional and Local Geology
  - 6.2 Location of Thermal Features
  - 6.3 Bore Holes
  - 6.3.1 Shallow
  - 6.3.2 Deep
  - 6.3.3 Temperature Gradients
  - 6.4 Geophysical Surveys
  - 6.4.1 Gravity
  - 6.4.2 Resistivity
  - 6.5 Fluids Chemistry and Chemical Geothermometry
  - 6.5.1 Stable Isotopes
  - 6.5.2 Dissolved Solids and Gases
  - 6.5.3 Geothermometers
- 7. RESERVOIR TYPE (CONCEPTUAL MODEL)
- 8. EXPLORATION
- 9. DRILLING AND SAMPLING

10. ADJACENT PROPERTIES
11. HEAT RESOURCE ESTIMATE
    11.1 Methodology
    11.2 Parameter Estimation
    11.3 Results
12. OTHER RELEVANT DATA AND INFORMATION
    12.1 Geothermal Energy in Location
    12.2 Energy Market
13. INTERPRETATION AND CONCLUSIONS
14. RECOMMENDATIONS
15. REFERENCES
TABLES
FIGURES

APPENDIX A2: Glossary of Terms

A	
Accommodation zone	The area between two sub-parallel, non-collinear, overlapping faults, transferring displacement or strain from one fault to another fault. Very often oblique shear is involved.
Active fault	A fault pre-dispositioned to further movement due to its orientation in the present-day stress field and strength of rock.
Advection	The physical transport of a substance (including heat) utilizing the bulk motion of a convecting fluid (see *convection* below). Note*:* When applied to subsurface heat transfer, the term *convection* is often used as a synonym for *advection*. The rate of heat transfer by advection is proportional to the rate of fluid flow, the phase of the fluid (liquid or vapor), and the specific heat capacity of the fluid.
Aeolian	Made by wind, also *Eolian*.
Amagmatic	Absence of magmatic activity.
Andesite	A dark-colored, fine-grained extrusive rock with no quartz and about 75% plagioclase feldspars of which one is andesine and widely characteristic of mountain-making processes on convergent margins.
Aquifer	A large permeable body of underground rock capable of yielding quantities of water to springs or wells. Note: Underground aquifers of hot water and steam form geothermal reservoirs.
B	
Back-arc basin	Formed by the process of back-arc spreading, which begins when one tectonic plate subducts under (underthrusts) another. Note: Subduction creates a trench between the two plates and melts the mantle in the overlying plate, which causes magma to rise toward the surface. Rising magma increases the pressure at the top of the overlying plate that creates rifts in the crust above and causes the volcanoes on the island arc to erupt. Back-arc basins are sites of significant hydrothermal activity.
Basalt	A fine-grained extrusive mafic rock dominated by dark-colored minerals consisting of plagioclase feldspars (>50%) and ferromagnesian silicates. Note: Basalts and andesites represent about 98% of all extrusive rocks.
Baseload plants	Electricity-generating units that are operated to meet the minimum load on the supply system.

Basement	The deepest geological formation for potential geothermal development. Note: Although different geological formations can be defined as *basement* depending on the goal of exploration, the term in exploration geology refers to any rock below sedimentary rocks or sedimentary basins that are of metamorphic or igneous origin.
Basement fault	A fault that cuts the basement, which originated before deposition of cover sediments and which may be reactivated.
Basement rock	A term sometimes used to define metamorphic or igneous rocks underlying a sedimentary sequence.
Binary-cycle plant	A geothermal electricity generating plant employing a closed-loop heat exchange system in which the heat of the geothermal fluid (the primary fluid) is transferred to a lower-boiling-point fluid (secondary or working fluid), which is thereby vaporized and used to drive a turbine/generator set.
Biofacies	A rock unit differing in biologic aspect from laterally equivalent biotic groups, identified by fossils in carbonate rock.
Boiling point	Temperature at which a single substance, such as water, changes from a liquid to a gas (steam) at a given pressure. Note: Some liquids boil at a lower temperature than water, a principle utilized in binary power plants. Boiling point is also affected by pressure. The greater the pressure, the higher the boiling point. This principle is put to work in geothermal (flash) power plants when geothermal water is brought up wells. Some of the hot water boils to steam when the pressure is released as it rises to the surface or passes through surface equipment. This phenomenon also occurs naturally, resulting in such features as geysers.
Breccia	A rock made up of very angular coarse fragments and may be sedimentary in origin or formed by grinding or crushing along faults.
Brine	A geothermal liquid containing appreciable amounts of sodium chloride or other salts.
C	
Caldera	A bowl-shaped landform, created either by a huge volcanic explosion (which destroys the top of a volcano) or by the collapse of a volcano's top.
Cap rocks	Rocks of low permeability that overlie a geothermal reservoir.
Carbon dioxide (CO_2)	A gas produced by the combustion of fossil fuels and other substances. Note: CO_2 also occurs naturally in large amounts in molten magma, which is involved in the explosive eruption of volcanoes.

Carbonates	Rock types such as limestone and dolomite that consist chiefly of carbonate (CO_3^{2-}) minerals (> 50% by weight of carbonate minerals); biochemistry sediments formed in marine environment.
Cascading heat	A process that uses a stream of geothermal hot water or steam to perform successive tasks requiring lower and lower temperatures.
Chalcedony	General name applied to fibrous cryptocrystalline silica with waxy luster; deposited from aqueous solutions and frequently found lining or filling cavities in rocks. See also *opal*.
Chloride	A compound of chlorine with another element or radical; a salt or ester of hydrochloric acid.
Chloride spring	Chloride springs produce hot or boiling, heavily mineralized alkaline water that is high in chloride and silica. Note: All geysers and springs that produce sinter terraces are chloride springs. Chloride springs are vulnerable to damage from the extraction of the geothermal fluid for other uses, which diverts the chloride water away from the springs.
Chlorite	Family of sheet silicates of iron, magnesium, and aluminum, characteristic of low-grade metamorphism; often of green color.
Condensate	Liquid water formed by condensation of steam
Condense	Change from a gas to liquid. Note: In conventional condensing geothermal power plants, steam is vented from turbines into a condenser where cooled water is sprayed on the steam to condense it. The condensate can be recycled using a cooling tower to extract more heat. An equivalent system exists for binary power plants, but with the organic liquid being recycled in a closed loop.
Condenser	Equipment that condenses turbine exhaust steam into condensate.
Conduction	The direct redistribution of heat within a material or between materials in contact with each other. Note: Conduction occurs in any material (solid, liquid, or gas) or across any boundary exposed to a thermal gradient. The rate of heat transfer by conduction is proportional to the thermal gradient and the thermal conductivity of the material.
Convection	The physical motion of liquid or vapor through the subsurface due to pressure gradients. Note: Gravitational head, thermal buoyancy, salinity contrasts, or other factors can drive convection. Under certain circumstances, convection can result in the advective redistribution of heat (see *advection* above).

Convergent plate margin	Boundary between two tectonic plates moving toward each other. Note: Compare *divergent plate margin*.
Cooling tower	A structure in which heat is removed from hot condensate through heat exchange with air.
Crystalline rock	A consolidated rock formed by a mesh of individual mineral crystals that formed *in situ*; generally implies metamorphic or igneous rocks.
D	
Dacite	A fine-grained extrusive rock with the same general composition as andesite, but having a less calcic plagioclase and more quartz. Synonym: *quartz andesite*
Deposition	The process of natural accumulation of mineral grains through the actions of water, wind, or volcanic activity.
Diagenesis	The set of processes that cause physical and chemical changes in sediment after being deposited and buried under another layer of sediment.
Diffusion	The natural dispersion of a substance through a medium due to a potential gradient. Note: Diffusion processes do not require bulk motion and should not be confused with *convection* or *advection*. Fluids, heat, gases, chemicals, and other substances can all diffuse through a medium. For example, heat naturally diffuses by conduction from regions of higher to lower temperature (i.e., down a temperature gradient).
Direct use	The use of geothermal energy other than converting it to electricity, such as for space heating and cooling, food preparation, industrial processes, or bathing.
Divergent plate margin	Boundary between two tectonic plates moving apart. Note: New oceanic-type lithosphere is created at the opening.
Drilling	Boring into the earth to access geothermal resources, usually with oil and gas drilling equipment that has been modified to meet geothermal requirements.
Dry steam	Superheated steam without a water phase.
Dry-steam reservoir	Geothermal reservoir where subsurface pressures are controlled by steam rather than by water.
E	
Earth's crust	Outermost shell of the earth. Note: Continental crust averages 35 km thick, density 2.6 t/m^3; oceanic crust, about 5 km thick, density 3 t/m^3.
Earthquake	A movement within the earth's *crust* or *mantle*, caused by the sudden rupture or repositioning of underground rocks as they release *stress*.

Efficiency	The ratio of useful energy output of a machine or other energy-converting plant to the energy input. Note: Technology with higher energy efficiency will require less energy to do the same amount of work.
Emission	The release or discharge of a substance into the environment; generally refers to the release of gases or particulates into the air.
Enhanced geothermal systems	Portions of the earth's crust where the product of flow rate and fluid temperature is naturally too low for economic geothermal energy extraction, but where the flow rate can be enhanced by technological solutions such as hydraulic fracturing or using injected carbon dioxide (CO_2) as thermal transport fluid; alternatively, where the flow rate of an existing producing geothermal reservoir can be increased by enhancing the natural permeability. Also known as "engineered geothermal systems".
Evaporites	A class of sedimentary minerals and sedimentary rocks that form by precipitation from evaporating aqueous fluid. Note: Common evaporite minerals are halite, gypsum and anhydrite, which can form as seawater evaporates, and the rocks limestone and dolostone. Certain evaporite minerals, particularly halite, can form excellent cap rocks because they have minimal porosity and tend to deform plastically (as opposed to brittle fracturing that facilitates leakage).
Exploration	Prospecting for geothermal resources that have the potential to be developed under economic conditions. Note: This work can include surface mapping, remote sensing, exploratory drilling, geophysical testing, geochemical testing, and other prospecting activities.
Exploration Geology	The applied branch of geology to discover resources of value; involves a number of techniques as geological mapping, geochemistry, hydrogeology, 3D geological modeling based surface or subsurface data and general geosystem analysis; provides background information for geophysical exploration and covers reconnaissance stage of exploration.
Exploration Geophysics	The applied branch of geophysics which uses surface methods to measure the physical properties of the subsurface earth, along with the anomalies in these properties, in order to detect or infer the presence and position of geothermal reservoirs and other geological structures.
Extensional fault	A fault in which crustal tension is a factor, such as a normal fault.
Extensional fracture	A minor rock fracture developed at right angles to the direction of maximum tension; also known as *subsidiary fracture.*
Extrusive	Igneous rocks that crystallize at the earth's surface.

F	
Facies	Assemblage of mineral, rock, or fossil features reflecting the physical environment in which rock was formed.
Fault	Surface of rock rupture along which has been differential movement.
Fault termination	Lateral end of a fault. Note: A number of splays or branches may indicate the end of a fault, e.g., the termination of a strike-slip fault is referred to as a *horse tail structure*.
Felsic	Derived from the adjectives (*fe*) for feldspar, (*l*) for lenad or feldspathoid, and (*s*) for silica, and applied to light-colored rocks containing an abundance of one or all of these constituents; also applied to the minerals themselves, the chief felsic minerals being quartz, feldspar, feldspathoid and muscovite.
Flash plant	Pressure vessels designed to effectively separate vaporized steam from the liquid phase.
Flash steam	Steam produced when pressure on a geothermal liquid is reduced, a process known as *flashing.*
Foot wall	The body of rock lying below an inclined fault.
Foreland basin	A stable area marginal to an orogenic belt, toward which the rocks of the belt were thrust or over-folded. Note: Generally the *foreland* is a continental part of the crust and is the edge of the craton or platform area.
Formation	A volume of rock generally of consistent age, fabric, mineralogy, and depositional environment.
Fracture	A crack, joint or fault in a rock resulting from the mechanical failure of the rock due to stress.
Fumarole	A hole or vent from which superheated gas and steam discharges under pressure.
G	
Geomechanics	The discipline that integrates rock mechanics, geophysics, petrophysics, and geology to quantify the mechanical response of the earth to any changes in state of stress, pore pressure, and formation temperature.
Geothermal	Of or relating to the earth's interior natural heat.
Geothermal energy	The earth's interior heat available for extraction and exploitation.
Geothermal gradient	The rate of temperature increase in the earth as a function of depth.

Geothermal heat pumps	Devices that take advantage of the relatively constant temperature of the earth’s subsurface, using it as a source and sink of heat for both heating and cooling. Note: When cooling, heat is extracted from a space at the surface and dissipated into the earth; when heating, heat is extracted from the earth and pumped into the space.
Geothermal play	A geological setting with *prima facie* evidence of a heat source, heat migration pathway, heat/fluid storage capacity, and the potential for economic recovery of the heat.
Geothermal power plant	A facility that uses geothermal heat to drive turbine-generators to produce electricity. Note: Different types of plant are most efficient at different resource temperatures; for example dry steam, flash and binary.
Geothermal reservoir	An underground repository of hot fluid that can be extracted to the surface to recover geothermal energy. Note: Generally, a geothermal reservoir is a large volume of porous and/or fractured rock, which can be natural or engineered.
Geothermal resource	A subsurface accumulation of heat for which there are reasonable prospects for eventual economic extraction.
Geothermal system	A combination of heat source, heat transfer mechanism, heat trap, fluid source, fluid pathways, fluid trap, and geothermal reservoir that together provide the conditions for the accumulation of a geothermal resource. Note: A geothermal system can be natural or engineered.
Geothermometer	A mineral assemblage or fluid chemical composition that yields information about the temperature at which it formed or equilibrated.
Geothermometry	Study of the temperatures at which geological and geochemical processes occur or occurred.
Geyser	A natural hot spring that sends up a fountain of water and steam into the air. Note: Some geysers *spout* at regular intervals while some are unpredictable.
Graben	An elongated, downthrown crustal block bounded by two steeply dipping normal faults; produced in an area of crustal extension.
H	
Hanging wall	The body of rock lying above an inclined fault.
Heat exchanger	A device for transferring thermal energy from one fluid to another.
Heat flow	Movement of heat from within the earth to the surface, where it is dissipated into the atmosphere or surface water.

Heat source	A distinct geological feature identifiable as the primary origin of thermal energy in a geothermal system. Note: A heat source can be a liquid magma chamber, a cooling pluton, elevated mantle material, a concentration of radioactive material, or a combination of factors.
Heat transfer mechanism	The means by which thermal energy is transported from a heat source to a geothermal reservoir. Note: Possible heat transfer mechanisms include conduction; or advection with water/steam along narrow faults, through fracture systems, through permeable sedimentary formations, or a combination of pathways. The heat transfer mechanism is the dominant control on the 'recharge' of a geothermal resource.
Hot dry rock (HDR)	Subsurface, normally crystalline, geological formations of abnormally high heat content that contain little or no water.
Hot Spot	A deep source of volcanic material that remains relatively stationary as tectonic plates move above it.
Hot springs	A natural spring that ejects water warmer than body temperature and therefore feels warm or hot; may collect in pools or flow into streams and lakes; a geothermal phenomenon.
Hydrothermal	Hydro, prefix for *water* plus *thermal* meaning *heat* or literally *hot water.* Note: Steam and hot water reservoirs are hydrothermal reservoirs. Hot dry rock resources and magma resources are not considered to be hydrothermal resources.
I	
Igneous rock	A rock formed by the crystallization of magma or lava.
Illite	A group of gray, green, or yellowish-brown mica-like clay minerals found in argillaceous sediments. Note: The mineral smectite progressively polymorphs to illite at increasing temperature.
Impermeable	Not allowing liquids to pass through easily. Certain rock types and clay soil are impermeable.
Indirect use	Involves converting geothermal energy into electricity or using the heat in binary power plants. Note: Heat pumps represent another indirect use of geothermal heat. Geothermal heat pumps are used to further increase the temperature of pumped water or warm liquids.
Induced seismicity	Seismic activity beyond the normal level of natural seismic activity, resulting from human activity. Note: Induced seismicity is generally below a magnitude at which humans can naturally detect it.
Infiltration	The movement of surface water into porous soil or rock.
Injection	The process of returning spent geothermal fluids to the subsurface; also referred to as *reinjection.*

Injection well	A well through which geothermal water is returned to an underground reservoir after use. Note: Geothermal production and injection wells are constructed of pipes layered inside one another and cemented into the earth and to each other. This protects any shallow drinking water aquifers from mixing with deeper geothermal water.
Intracontinental	Term for *Plate tectonic*, refers to within or on a continental plate.
Intracratonic basin	An accumulation of sediment over a large area within a stable continental crustal mass. Note: Generally round or oval shaped, with a long history of relatively slow subsidence. Classic examples include the Williston, Michigan and Illinois basins in North America; Paraná, Parnaíba, Solimões and Amazonas basins in Brazil; Murzuk and Al Kufra basins in Libya; Karoo and Congo basins in Africa; Surat Basin in Australia, and others.
Intrusion	An igneous rock body that formed from magma that forced its way into, through, or between subsurface rock units.
Island arc	A group of islands lying along a curve or arc. Note: Most island arcs lie near the continental masses, although they are not a part of the continents proper because they rise from the deep ocean floor. See *back-arc basin*.
K	
Kappa meter	An instrument for measuring magnetic susceptibility of rock samples.
Karstification	A process of dissolution of limestone, gypsum and other rocks by water, characterized by sinkholes, caves, and underground drainage.
Kilowatt (kW)	A unit of power in the metric system; one thousand joules per second; usually accompanied by subscript *t* when referring to thermal power or subscript *e* when referring to electrical power (i.e. kW_t or kW_e).
Kilowatt hour (kWh)	A unit of energy, equivalent to that generated by a one-kilowatt source in one hour.
L	
Lava	Molten magma that has reached the earth's surface.
Lithofacies	A mappable subdivision of a designated stratigraphic unit, distinguished from adjacent subdivisions on the basis of physical and organic characteristics.
Logging	The measurement versus depth or time, or both, of one or more physical quantities in or around a well. Note: The term comes from the word *log* as in a record or note.

M	
Mafic	Igneous rock pertaining to or composed dominantly of the ferromagnesian rock-forming silicates.
Magma	Molten rock within the earth, from which igneous rocks are formed by cooling.
Magmatism	The formation of igneous rock from magma.
Mantle	A major subdivision of the interior of the earth, lying beneath the crust and above the outer core of liquid iron and nickel.
Megawatt (MW)	A unit of power in the metric system; one million joules per second, or one thousand kilowatts, or one million watts; usually accompanied by subscript *t* when referring to thermal power or subscript *e* when referring to electrical power (i.e., MW_t or MW_e).
Mélange	A heterogeneous medley or mixture of rock materials; specifically, a mappable body of deformed rocks consisting of a pervasively sheared, fine-grained, commonly pelitic matrix, thoroughly mixed with angular and poorly sorted inclusions of native and exotic tectonic fragments, blocks, or slabs, of diverse origins and geologic ages.
Meta-greywacke	A greywacke that shows evidence of metamorphism. Note: A greywacke is a dark, coarse-grained sandstone characterized by rock fragments in a fine-grained clay matrix.
Metamorphic core complex	Result of major continental extension, when the middle and lower continental crust is exposed from beneath the fracturing, extending upper crust. Note: Movement zones capable of producing such effects evolve in space as well as with time.
Metamorphism	Mineralogical and structural changes of solid rock in response to environmental conditions (specifically temperature and pressure) at depth in the earth's crust.
Mineralized fluids	Water and steam containing minerals such as silica, lithium, and boron; also called *geothermal water* or *geothermal fluids.*
Mineralogy	The scientific study of the minerals from which rocks are composed.
Mud pool	A thermal surface feature formed when steam and gas vapor bubbles up through mud formed by the thermal and chemical erosion of rock. Note: Mud pools typically develop where there is not enough liquid water ejected to support a geyser or hot spring.
N	
Normal fault	A fault in which the *hanging wall* is displaced downwards in relation to the *foot wall*. Note: The term originated in English coal mining, where *normal faults* were the most common.
Normal stress	Stress acting perpendicular to a surface or plane.

O	
Opal	Amorphous silica, with varying amounts of water; a mineral gel; occurs in cracks and cavities of igneous rocks, flint-like nodules in limestone, in mineral veins, in deposits of hot springs, in siliceous skeletons of various marine organisms (such as diatoms and sponges), in serpentinized rocks, in weathering products, and in most chalcedony and flint.
Orogen	A belt of deformed rocks in many places accompanied by metamorphic and plutonic rocks (e.g., the Appalachian orogen or Alpine orogen).
Orogenic belt	A linear or arcuate region of folded and uplifted rocks.
Organic Rankine cycle (ORC)	Power plant technology that makes use of an organic fluid with a boiling point lower than water. Note: The organic fluid enables recovery of heat and conversion to electrical power from geothermal fluid at a lower temperature than required for *flash* plants.
P	
Parental melts	A primary magma composition from which an observed range of magma chemistries has been derived through a process of igneous differentiation; see also *primary melts.*
Permeability	The capacity of a substance (such as rock) to transmit a fluid. Note: The degree of permeability depends on the number, size, and shape of the pores and/or fractures in the rock and their interconnections. It is measured by the time it takes a fluid of standard viscosity to move a given distance under the influence of a known pressure gradient. The unit of permeability is the *Darcy*.
Petajoule (PJ)	A unit of energy in the metric system; one petajoule is 10^{15} joules.
Petrothermal	Petro, prefix for *rock* plus *thermal* meaning *heat*; literally *hot rock.* Note: Hot dry rock and magma resources are considered petrothermal resources, devoid of natural hot water or steam.
Plume	A rising column of hot, low viscosity material within the earth's mantle; also called *mantle plume*.
Pluton	A large, coherent body of medium- to coarse-grained igneous rock that forms in the subsurface by crystallization of magma.
Porosity	The ratio of the aggregate volume of pore spaces in rock or soil to its total volume, usually stated as a percentage.
Porous	Containing many small intergranular spaces (pores) able to be filled by water, air, or other medium.

Primary melts	The liquid formed when a rock melts, before it undergoes any differentiation. Note: The primary melt represents the starting composition of magma. It is rare to find primary melts in nature.
R	
Radiogenic	Produced by radioactivity or decay of unstable radioactive elements.
Recharge	The process by which the heat and/or water within a geothermal reservoir is replenished, both in the natural geothermal system and during production. Note: Recharge of water and heat might be by different mechanisms. Recharge of heat has to be by natural means, whereas recharge of water might be by artificial reinjection.
Recovery factor	The amount of valuable commodity (usually energy) ultimately extracted from a geothermal reservoir, expressed as a percentage of the original amount; a measure of extraction efficiency.
Relay ramp	An area of reoriented bedding between two normal faults that overstep in map view and that have the same dip direction.
Reservoir	See *geothermal reservoir.*
Resource	A subsurface concentration of an economically valuable commodity (e.g., mineral, liquid, or gaseous hydrocarbon, heat) in such form and amount that economic extraction is currently or potentially feasible. Note: See *Geothermal resource*.
Rift	A relatively narrow trough or belt of subsidence bounded on either side by normal faults. Note: Rifts commonly contain or consist of grabens or half-grabens. A *rift valley* is a valley with steep parallel walls, formed by subsidence of a part of the earth's crust.
S	
Salinity	A measure of the quantity or concentration of dissolved salts in water.
Salt diapir	A dome structure with a central salt plug, generally more than one kilometer in diameter, which has risen through the enclosing sediments from a salt bed 5 km to more than 10 km beneath the top of the plug. Note: Many salt plugs have a cap rock of less soluble evaporite minerals (especially anhydrite). The enclosing sediments are commonly turned up and complexly faulted adjacent to the salt plug.
Sediment	Loose, unconsolidated deposit of weathering debris, chemical precipitates or biological debris that accumulates on earth's surface.

Sedimentary basin	Large areas of subsidence in which sediment can accumulate to considerable thickness and be preserved for long geological time periods.
Sedimentary rock	A rock formed from the accumulation and consolidation of sediment, usually in layered deposits.
Seismic attributes	A quantity that can be extracted or derived from reflection seismic data and analyzed in order to enhance information that might be more subtle in a traditional seismic image, leading to a better geological or geophysical interpretation.
Seismic sequence stratigraphy	A geological method applied in reflection seismic interpretation to impose the dimension of time on the relationships of rock units in space (area and depth); based on recognition of unconformity-bound sequences using geometry and termination patterns of seismic reflectors. Note: A critical assumption is that seismic reflectors follow time surfaces rather than facies boundaries.
Serpentinite	Magnesium silicate common among metamorphic minerals.
Silica	Naturally occurring silicon dioxide; occurs in five crystalline variations and can form quartz, chalcedony, amorphous and hydrated forms of opal, and combined in silicates.
Siliciclastic	Pertaining to clastic, non-carbonate sedimentary rocks that are almost exclusively silicon bearing, either as forms of quartz or as silicates.
Smectite	A family of clay minerals and their chemical varieties characterized by swelling properties and high cation-exchange capacities.
Sinter	A mineral crust or deposit formed at the surface from the minerals (mainly silica) ejected in geothermal water, especially from geysers.
Steam	The vapor form of water that develops through boiling. Note: Steam pressure can be put to work turning a turbine connected to an electricity generator.
Step-over region	The area between two sub-parallel, non-collinear faults. Note: For normal faults, an along-strike step-over region is neither contractional nor extensional, and is marked by a transfer zone.
Stress field	Intensity and direction of forces acting on a body as to force per unit area. Note: The stress field can usually be represented by three components. The largest principal stress is usually designated σ_1 and the least stress σ_3, with σ_2 being intermediate between the two.

Strike-slip fault	Fault with predominately lateral displacement; either left- or right-lateral. Note: The sense of slip is defined as slip direction of one fault block observed from the opposite fault block.
Subduction	A geologic process by which one crustal plate is forced below the edge of another. Note: See also *back-arc basin*.
Subsidence	A sinking of an area of the earth's surface due to subsurface fluid withdrawal and pressure decline.
T	
Transform fault	A strike-slip fault occurring at the boundary between two tectonic plates.
Transtension	A system of stresses that tends to cause oblique-extension, i.e., combined extension and strike-slip.
Travertine	A form of limestone deposited by springs, especially hot springs.
Turbine	A machine for generating rotary mechanical power from the energy of a stream of fluid (such as water, steam or other hot vapor). Note: Turbines convert the kinetic energy of fluids to mechanical energy through the principles of impulse and reaction.
V	
Vapor-dominated	Pertaining to a dominant fluid in the gas or *vapor* phase; referred to as *dry steam* if only*vapor* is present. Note: If any liquid phase is present then it is referred to as *wet steam*.
Volcanic field	An area of the earth's crust that is prone to localized volcanic activity and a set of geological processes that result in the expulsion of lava, pyroclastic material, and gases at the earth's surface.
W	
Water phases	Phases: *melting*, change from ice to liquid; *freezing*, the reverse process; *evaporation*: change from liquid to gas, either water vapor or steam; *condensation*, change from water vapor to liquid. Note: Evaporation and condensation are important phenomena in geothermal systems and in geothermal technology.
Wet steam	See *vapor-dominated*.
Z	
Zeolite	Any of a group of hydrated aluminosilicate minerals with alkali metals, commonly occurring as secondary minerals in cavities in basic volcanic rocks.

APPENDIX A3: References

Chapter 1

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