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Geothermal Resource Decision Workshops: Hands-On Training for Geothermal Resource Professionals Using a Conceptual Model Approach

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ABSTRACT

Best practice publications in the geothermal industry emphasize integrating geoscience data to build geothermal resource conceptual models as the basis for well targeting and resource capacity assessment at all stages of exploration and development. Hands-on workshops have been developed based on actual field case histories for both magmatic volcano-hosted systems and deep-circulation fault-controlled systems, so that participants can get experience with the similarities and differences in approach and decision making for these different types of systems. These workshops are directed at geoscientists, researchers, engineers and managers who wish to better appreciate how geothermal conceptual models are constructed and how they are used to support an effective resource decision risk assessment process. During these workshops, short lectures introduce the components of geothermal conceptual models and how they are constrained using the basic physics of hot water buoyantly flowing through rock in a manner that can be predicted by combining evidence from geochemistry, geology and geophysics. The exercises using real data from geothermal fields are interspersed among the lectures to provide participants an opportunity, within small teams and with the assistance of expert coaches, to design conceptually effective exploration surveys, interpret real geoscience data in an integrated geothermal context, build resource conceptual models, complete well target and resource capacity risk assessments, interpret drilling results to critically review and update conceptual models, propose follow-up drilling programs, and recommend constructing a power plant or terminating the investment. Based on experience with over 50 of these workshops conducted over 20 years for geothermal developers, conferences and universities, in 2020 the program was successfully adapted to an online remote format that provides the flexibility of infinite virtual whiteboards for group exercises more efficiently supported by lectures and coaching from worldwide experts. Plans for additional curriculum development include freely available online lectures that would replace the presentations during the workshops so that the hands-on exercises can be more effectively completed in a typical two day format of an industry workshop or in an online seminar format extended over several months. In addition, exercises are being developed based on a wider variety of geothermal settings so that participants can choose workshops that are more closely analogous to the types of resource decisions that they are encountering in their exploration, development or research work.

1. INTRODUCTION

For over a decade, geothermal industry professional organizations and publications on geothermal assessment have recommended the development of geothermal resource conceptual models and an explicit analysis of uncertainty as best practices when justifying investment decisions for geothermal exploration and development (e.g. IGA Service GmbH, 2014). However, as Grant (2015) emphasized, it is very difficult to specify a procedure to predict the size of geothermal resources or the probability of success for a well target in a manner that guarantees realistic results, even if (perhaps, especially if) the input parameters and results of the procedure are expressed as statistical probabilities.

Decision research predicts that geothermal geoscience generalists who have spent decades making well targeting and resource capacity predictions based on conceptual models and testing these predictions against outcomes are more likely to build a range of conceptual models representative of uncertainty that informs more reliable predictions and decisions. However, less experienced geoscientists, specialized researchers and educators seldom have the opportunity to develop the broad practical knowledge required to build geothermal conceptual models consistent with the relevant range of geoscience and engineering information. Moreover, before they retire, few senior geothermal professionals have been able to validate their decisions on more than one or two prospects since establishing outcomes with high confidence typically takes one or two decades from initial prospect identification through to confirmation by extended generation. Although reading a wide range of case histories is an essential qualification for a geothermal resource assessment expert, this cannot replace actual experience making and testing resource predictions. Lacking sufficiently broad geothermal experience, specialists tend to focus on data for which they have greatest interest and/or easier access. They necessarily use these data directly to guide decisions, typically with a cursory comparison with the results of others rather than a thorough conceptual integration. For example, when assessing resource capacity, a particular magnetotelluric (MT) resistivity map contour is often assumed to correspond to the geothermal reservoir perimeter without a conceptual justification (Cumming, 2016b). Wells are commonly targeted across lineaments that have no ground confirmation or conceptual association with stress models and formation properties that would more reliably predict permeable fracturing in the subsurface (Faulds and Hinz, 2015). Therefore, although conceptual models and uncertainty analyses are industry standards for geothermal resource assessment, the average assessment nominally based on them still probably skews to being unrealistically optimistic, for reasons independent of the pitfalls in volumetric approaches to capacity assessment identified by Grant (2015). The Geothermal Resource Decision Workshop curriculum is designed to remedy the lack of experience in making and testing geothermal resource predictions and decisions without waiting for geothermal practitioners to accumulate decades of experience.

The workshop curriculum includes introductory lectures but primarily consists of hands-on practical exercises mentored by expert geothermal professionals. Aside from training technical professionals in the practical construction and application of geothermal resource conceptual models, this approach has succeeded in providing managers and investors an understanding of how to assess the validity of these models and an appreciation for the uncertainty that they imply for high value decisions. A review of the rationale, alternatives and pitfalls of the conceptual model approach to geothermal assessment introduces the need for the workshops as a training method. The design of the geothermal workshops has been informed by recent research on prediction and decision-making. Although all of the existing modules of the workshop program have been very well reviewed by participants, ongoing projects include putting introductory lectures online, implementing more modules in an entirely remote online workshop format, adding new cases relevant to broader range of geothermal settings and system types, and further formalizing the workshops as industry training opportunities and university curriculum elements.

2. THE CONCEPTUAL MODEL APPROACH TO GEOTHERMAL RESOURCE ASSESSMENT

2.1 Conceptual Models versus Anomaly Hunting

Targeting wells using conceptual models (Figure 1) is preferred to targeting wells on a particular feature of a data set (that is, “anomaly hunting”) because conceptual models like those in Figure 1 integrate all of the available data in a manner that implicitly weights each data type by its relevance to the model in a manner consistent with the thermodynamic and petrophysical constraints on the flow of hot water in rock (Cumming, 2009; 2016a). However, building a conceptual model is much more difficult than choosing an anomalous contour. Therefore, for a geoscientist who is inexperienced in building consistent conceptual models and so chooses to target a data anomaly that experience has proven to be relevant to the decision, anomaly hunting may have better prediction performance. That is, effective anomaly hunting strategies are still conceptually based. In practice, for most low value decisions, the ease of anomaly hunting makes it the preferred approach whereas, for high value decisions that justify a greater investment in training, development and validation, the conceptual model method is the preferred approach. Because most geoscience professionals have much more experience making low cost than high cost decisions, they tend to get much more experience with data targeting and anomaly hunting, which leads many practitioners to prefer these approaches in high value cases, an unsatisfactory situation that the Geothermal Resource Decision Workshops should improve.

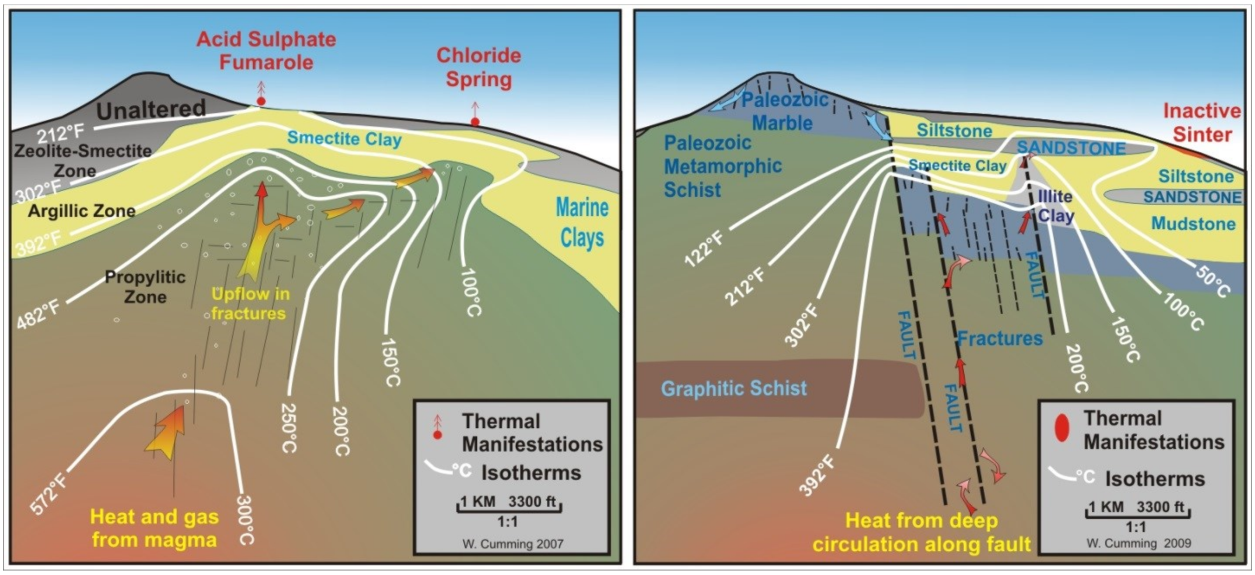

Figure 1: Geothermal resource conceptual models, a magmatically-heated, volcano-hosted reservoir (left) and a deep-circulation-heated, fault-zone-focused, sediment-hosted reservoir (right)

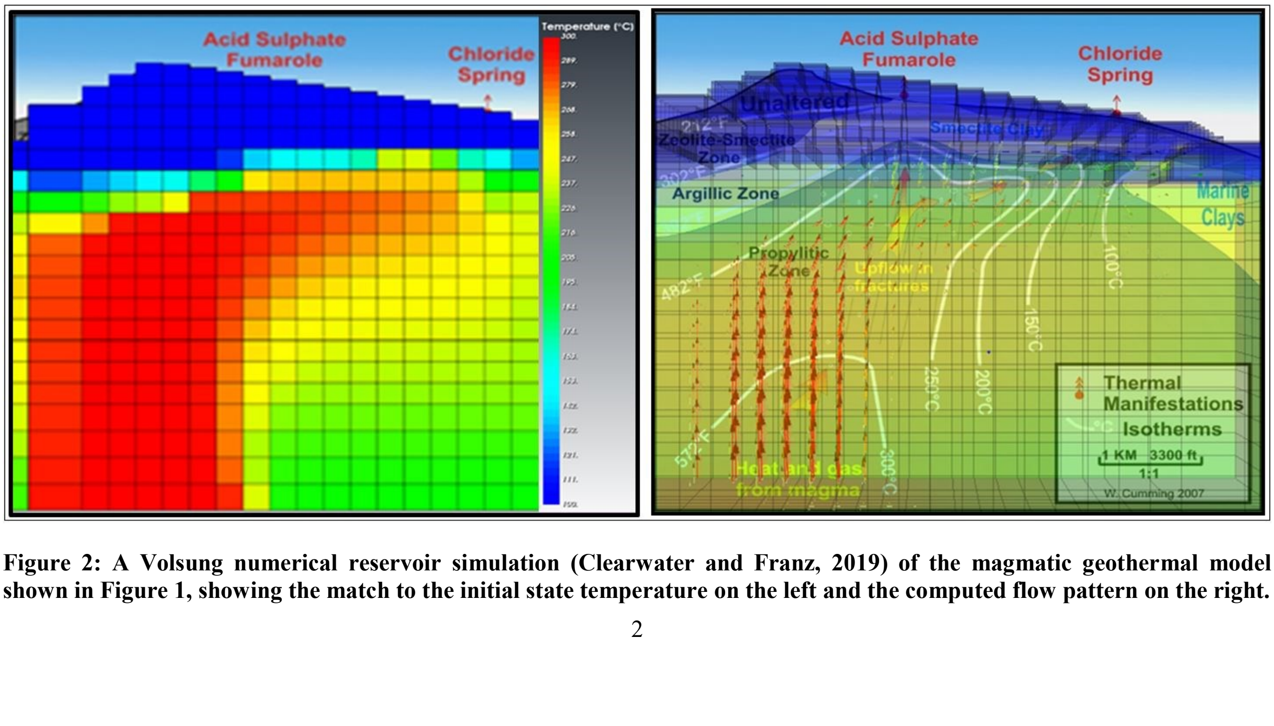

Figure 2: A Volsung numerical reservoir simulation (Clearwater and Franz, 2019) of the magmatic geothermal model shown in Figure 1, showing the match to the initial state temperature on the left and the computed flow pattern on the right.

2.2 Conceptual Models and Reservoir Simulations

Figure 1 shows the geothermal resource conceptual models that are the end result of the conceptual model construction process detailed in Cumming (2016a) for the volcano-hosted magmatically-heated case and in Cumming (2009) for the sediment-hosted deep-circulation case. These publications are used as a step-by-step guideline in the workshop exercises, supported by coaches and, to a lesser extent, by the lectures that are customized to the length of the workshop and the specific geothermal resource case history that is the subject of the workshop. The crucial role of isotherms, highlighted in Figure 1, in describing geothermal conceptual models are a focus of the workshop, further illustrated by the numerical reservoir simulation generated using the Volsung simulator (Clearwater and Franz, 2019) based on the volcano-hosted magmatically-heated case in Figure 2. The overall permeability pattern of the numerical reservoir model has been constrained so that the temperature pattern shown as color shading in Figure 2 matches the temperature contours in Figure 1. The computed flow arrows on the right of Figure 2 fit the general pattern of the arrows in Figure 1 but their differing magnitudes also illustrate the shortcomings of an overreliance on flow arrows rather than isotherms when building conceptual models.

Building an understanding of the close relationship between the temperature pattern and overall permeability (and, therefore, overall field performance and, to some extent, well productivity) is an important goal of the workshops. Initial workshop exercises are designed to build intuition for the resource implications of fault permeability, cap geometry and outflow geometry by comparing numerically simulated responses for simple geometries against responses predicted by participants. The Volsung simulator has also been used to extrapolate well test results throughout a reservoir, giving participants more freedom to target wells where none was actually drilled and receive a synthetic result for that location, greatly improving the freedom of the participants to learn.

2.2 Pitfalls in the Conceptual Model Approach to Geothermal Assessment

Merely building geothermal conceptual models and considering their uncertainty is not a panacea. A reviewer with a checklist cannot assume that the use of a plausible range of conceptual models to support a risk assessment is necessarily an indication that a reliable assessment has been completed. For example, cognitive biases routinely distort conceptual model assessments and require formal mitigation, like using a peer reviewer to check for any motivated reasoning that can make assessments too optimistic. The same cognitive biases apply to anomaly hunting and, because it is less constrained by other data sets, exaggeration tends to be easier, as is commonly demonstrated by MT assessments of very large reservoir perimeters based on a resistivity pattern without support by a plausible conceptual model.

Because conceptual models are complex abstractions inferred from data, they are more uncertain than their supporting data, which makes advocating the use of conceptual models in decision-making seem counterintuitive to many experts in particular disciplines. Proponents of the conceptual model approach argue that the increased uncertainty is more than offset by the much greater relevance of conceptual models to resource prediction. However, this is true only to the extent that the conceptual models are consistent with the most relevant data and with thermodynamic constraints – that is, an inconsistent conceptual model may be less effective than anomaly hunting. Some participants in conceptual model workshops have recognized that they prefer to focus on data rather than models and some have adjusted their career goals as a result, specializing in improving data analysis rather than in developing conceptual models from it.

The main pitfall in the application of a conceptual model approach is that the combination of training and experience required to apply it effectively requires a significant investment in long term training of geoscientists as well as short term development of conceptual models. Geoscientists unfamiliar with the process cannot just review the publications in the workshop reading list, attend one of these workshops and then mechanically apply it as a method. A team that is building a conceptual model could study the geothermal literature for examples of conceptual models of geothermal fields that appear to be roughly analogous in their geoscience properties to the resource being assessed. However, in practice, this usually requires the advice of a geothermal generalist who has accumulated experience conducting assessments in similar settings. The two day versions of the Geothermal Resource Decision Workshops supply this expertise through the coaches. The workshop coaches also lead the teams through the process of building conceptual models, they provide peer reviews to mitigate cognitive biases, and so on. That is, in a two day workshop, participants will learn what the conceptual model assessment process is but they will still need expert coaching to build conceptual models using their own data. Some geoscientists who have participated in several of the workshop modules have become more confident making assessments on their own, but most effective conceptual models are built by teams with at least one member or coach who has wide experience building many conceptual models in analogous settings. That is, making effective geothermal assessments requires advice from one or more experts familiar with many geothermal reservoirs – there is no way around this basic requirement for expert competence.

2. IMPLICATIONS OF DECISION RESEARCH FOR GEOTHERMAL GEOSCIENCE TRAINING

Research on how experts make predictions and decisions in conditions of uncertainty that are comparable to the geothermal subsurface indicates that two of the most important prerequisites for sustained success are: 1) realistic experience making decisions informed by predictions based on relevant information; and 2) analyzing the reliability of predicted outcomes as soon as the actual outcomes of a decision are known and updating the prediction and decision process accordingly (Tetlock and Gardner, 2015; Klein, 2009). Therefore, after geothermal practitioners have developed a realistic conceptual understanding of what they are predicting, they need opportunities to practice making and testing predictions and decisions that balance opportunity and risk. However, a typical geothermal career provides few opportunities to practice making high stakes decisions like targeting wells or committing to a power plant capacity. The Geothermal Resource Decision Workshops are designed to synthesize opportunities to develop skills building conceptual models, making high-value decisions and testing performance without risking a real investment loss.

2.1 Strategies from Prediction Research Adapted to Workshop Exercises

Based on habits of successful forecasters, Tetlock and Gardner (2015) emphasize continuous improvement involving practicing, testing and updating a prediction approach but they also describe other practices of effective forecasters, some of which have been integrated into the Geothermal Resource Decision Workshops. The prediction strategies included in workshop exercises depend on the duration of the workshop but all of the exercises illustrate at least a few strategies for testing and improving predictions. These include the probabilistic thinking emphasized by the need to produce a range of conceptual model representative of 10%, 50% and 90% confidence levels as illustrated in Cumming (2016a and 2016b). In the workshops, geothermal resource capacity is assessed using a probabilistic approach (Cumming, 2016b) supported by the statistics of at least 103 geothermal field worldwide supplied by Wilmarth et al. (2021). The coaches role includes reminding the assessment teams to check counterfactual data for consistency with their conclusions, without steering teams to the conclusion known by the coach (teams learn a lot from making mistakes in these low stakes workshops, instead of in real resource situations). Coaches also encourage teams to practice methods like backwards thinking, that is, assuming some conclusion and thinking backwards to what it implies and whether that is consistent with available data, which is also a useful method of assess whether a planned MT survey or drilling plan is likely to be effective.

One subtle but particularly useful prediction strategy is to reframe resource questions that most influence the decision so that answers are more reliably constrained by evidence. For example, a common question that arises in geothermal exploration is, “What resistivity contour in the MT cross-section corresponds to the top of the geothermal reservoir?” This question sometimes has a locally valid answer but it is often seriously misleading when an answer is applied too generally. More effective questions might be, “When considered in the context of the other geoscience data, what part of the low resistivity zone is consistent with a clay cap overlying a high temperature geothermal reservoir, what part is more likely to indicate a clay cap over low temperature outflow, and what part is more likely to be clay unrelated to an active geothermal reservoir?”

2.2 Mitigating Cognitive Biases

Silver (2012) and Klein (2009) argue that in order to consistently make good decisions, people must practice making risky decisions so that the necessary skills become intellectual muscle memory (i.e. intuition). These skills include mitigating the cognitive biases that are characteristic of humans making risky decisions (Kahneman, 2011). Although many experts assume that they are immune to such biases, even when extrapolating from their area of expertise to interdisciplinary decision-making, ample evidence contradicts this assumption (Thaler, 2015). Techniques to mitigate these biases generally follow strategies that appeal to common sense but they still take practice and discipline, something that the workshops and coaches attempt to provide.

A “pre-mortem” analysis (Klein, 2009) can be an effective way to highlight overconfidence or to check for Group Think. Teams in workshops are encouraged by coaches to complete such an analysis if they reach a rapid and perhaps premature consensus. A “pre-mortem” analysis involves assuming failure, outlining the most likely reasons for the failure, and assessing how likely they are. Finally this is checked for consistency with the predictions and recommended decisions. It usually takes several reminders from coaches and some guidance and practice before teams will conduct a pre-mortem analysis.

Workshop presenters and exercise coaches also fill the role of peer reviewer, the geothermal industry’s imperfect standard for mitigating motivated reasoning, arguably the most troublesome cognitive bias in the geothermal industry. Geoscientists are motivated to be optimistic about the relevance of their own discipline to geothermal decisions. A geothermal team may be motivated to be optimistic about a prospect if it is their employer’s only geothermal asset. Researchers are motivated to be optimistic about interpretation choices likely to interest editors of prestigious publications. The workshops are intended to give teams practice soliciting independent peer advice to test for motivated reasoning, with the instructors and coaches functioning as the independent experts who they can consult.

A common pattern that coaches must adjust to is the tendency of specialists from outside the geothermal industry to choose well targets with much greater confidence than the more experienced geothermal industry generalists. Generalists are typically less optimistic about targeting success, often because they have a better appreciation of baseline probabilities and the likelihood that any particular data set will change probability of success (Tetlock and Gardner, 2015).

A common cognitive bias that is only indirectly addressed by the economics part of the exercises is that geothermal companies often invest too much in assessing resource risk and too little assessing other risks. Some managers have explained that project risks like access cost or power prices are not being considered because they are too uncertain. Kahneman (2011) explains why investors might prefer a decision-process that is objectively less successful but feels better, commonly because it simplifies the decision process by focusing on risks that are more quantifiable, like resource risk. In studies of the competence of experts, Shanteau (1992) argues that assessments often focus on sources of expertise rather than sources of risk. These issues are being addressed, in part, by the resource classification specifications in UNECE-IGA (2016) together with case history examples in UNECE(2017), part of an ongoing project directed at geothermal assessment.

3. GENERIC SYLLABUS FOR A GEOTHERMAL RESOURCE DECISION WORKSHOP

3.1 Objective

This workshop provides hands-on experience using real data to construct geothermal conceptual models, practice using them to predict probabilistic outcomes, make resource decisions, and test predictions against real experience. Best practice publications in the geothermal industry emphasize integrating geoscience data to build geothermal resource conceptual models as the basis for well targeting and resource capacity assessment at all stages of geothermal exploration and development.

3.2 Program

To simulate the experience of professionals advising a geothermal developer in making high-value resource decisions, participants will form teams to complete exercises using real data to make predictions and recommend decisions. Brief opening lectures will introduce the components of geothermal conceptual models for two types of systems: 1) magmatically-heated, volcano-hosted geothermal reservoirs; and 2) deep-circulation heated, fault- and sediment-hosted reservoirs. Further lectures will be interspersed among the exercises as needed to introduce geothermal geochemistry, geology, geophysics, basic concepts of thermodynamics of water flow in rock, well temperature log interpretation, and decision risk

3.2 Exercises

The hands-on exercises provide participants opportunities to:

- design a conceptually effective and financially efficient exploration survey;
- interpret and integrate real geoscience data using a conceptual model approach;
- build an initial range of resource conceptual models;
- complete probabilistic well target and resource capacity risk assessments;
- interpret drilling results, update conceptual models and reassess targets and capacity;
- based on well results, recommend constructing a power plant at the minimum economic capacity or terminating the investment

3.3 Who should attend and why?

Because this workshop is directed at geothermal students, researchers, professionals and managers with widely varying backgrounds, expert coaches are provided to bridge technical gaps to assure success without undermining the opportunity to build hands-on experience with geothermal prediction and decision making. Research on how experts make predictions and decisions in conditions of uncertainty comparable to the geothermal subsurface indicates that the two most important prerequisites for sustained success is, 1) realistic experience making predictions and decisions, and 2) quickly analyzing prediction success based on outcomes. In a typical geothermal career, it may take decades to accumulate sufficient experience. This type of workshop is directed at accelerating this process by simulating realistic experience in making geothermal resource decisions and responding to consequences. The exercises are also designed to give participants experience in identifying gaps in their expertise and in effectively acquiring advice from suitable experts and mentors.

3.4 Expectations

At the completion of this workshop, participants should expect to understand the basic components and construction of geothermal resource conceptual models, the role of the most commonly used geoscience data in constraining geothermal conceptual models, the rationale for the use of conceptual models in well targeting and capacity assessment, and simple strategies used to address decision uncertainty. More generally, participants should better appreciate the strengths and weakness of basing decisions directly on data (anomaly hunting) versus basing decisions on an integration of data in a conceptual model.

Participants are provided supporting publications in PDF format and an Excel worksheet to compute resource capacity distributions, and so laptops will be needed. To prepare for the course, participants should, at a minimum, review Cumming (2016a), a tutorial developed to support these workshops.

3.5 Background

The concept of hands-on education that is promoted in the Geothermal Resource Decision Workshops is not new, except perhaps in its focus on geothermal resource assessment. To train employees, many businesses use either supervised actual job experience or, where on-the-job training is impractical, they use supervised simulated job experience. Simulation training for pilots, for military systems, and for emergency responders is ubiquitous. For example, a similar decision-oriented workshop has been used to teach the principles of volcano eruption monitoring and evacuation. The prospect of ordering an evacuation (albeit in a simulation) motivates students to learn about the processes of eruption and to focus on the most relevant data sets.

This workshop is based on a curriculum developed in over sixty workshops worldwide since 2000. In 2018, the first seven exercises became sufficiently developed to cover both high temperature magmatic and low temperature deep circulation cases in one workshop and, since then, eight proprietary one week events have been held for developers that opened with workshop lectures and exercises customized to the developer's prospects and then focused on conceptual analyses of those prospects. Recent public workshops and course include two day Geothermal Resources Council (GRC) short courses in 2016 and 2017, a two day ARGeo-C7 short course in 2018, a five day University of Nevada Reno course in 2018, University of Auckland two and three day courses in 2017 and 2019, a two day USGS workshop in 2019 and, most recently, a well-reviewed three day online virtual workshop held as part of the 2020 GRC virtual annual meeting.

4. RESOURCES AVAILABLE TO CONDUCT WORKSHOPS

The workshops require support from presenters and coaches who are highly skilled both as professionals and as mentors. To facilitate planning by potential hosts of these workshops, an inventory of presentations, supporting materials, exercises and presenters/coaches has been prepared.

4.1 Existing Workshop Modules Based on Real Case Histories

Participants benefit most from exposure to several independent exercises based on different resource decision case histories. Universities can efficiently offer a one week program that includes as many as four exercise case histories supported by a common set of lectures. Sponsors should be discouraged from squeezing several exercises into a two day format and, for online virtual workshops, the GRC three day format was as short as could be feasible and an extended seminar format would cost no more and would be more effective. Ideally the exercises would be provided as a connected series that illustrate a variety of conceptual model variation, data uncertainty and failure risk. The existing exercises have been named Modules 1 through 10. These modules benefit from being based on widely drilled, extensively developed geothermal fields for which resource capacity and well targeting uncertainty is constrained by extensive data. However, when these modules have been presented at organizations and companies that are in the process of developing conceptual models for projects under active exploration or development,

Module 1 *Volcano-hosted Geothermal Exercise from Exploration To Power Plant Decision Exercise*: Although very mature and widely tested in dozens of 1.5 to 5 day workshops, this exercise developed by William Cumming has been updated numerous times, including in the last year with respect to the geochemistry and well data based on recommendations from Irene Wallis and Elisabeth Easley. Further updates are planned, particularly to improve map clarity.

Module 2 *Deep Circulation Structure and TGH Exercise*: After its introduction at a 2017 GRC workshop and subsequent refinement , the materials and lectures for this deep circulation exercise developed by Nick Hinz have matured into an effective 1 to 3 day workshop program that includes structural mapping and development of realistic structure and related conceptual models in cross-section. Updates are planned to improve the efficiency of building the conceptual cross-sections based on TGH temperature data. Some data sets, such as the geophysics, are optional and can be omitted if time is short.

Module 3 *Volcano-hosted Alteration and Well Test Failure Case Exercise*: Developed by William Cumming and Richard Gunderson for a 2017 GRC short course, this exercise needs to be slimmed from its current 32 handouts. Although this specific case history was chosen in order to fit into a one day workshop format, the need for lectures and coaching on alteration and casing points, geochemistry and reservoir gas, and well test pressure response makes this at least a two day workshop.

Module 4 *Deep Circulation Prospect Ranking Exercise*: Developed by Nick Hinz, this ranking of up to 10 prospects has been tested in four workshops and has proven to be more effective as a follow-up to Module 2 than as a standalone exercise.

Module 5 *Volcano-hosted Attractive Failure Exercise*: Developed by William Cumming as a very attractive failure case to illustrate a prospect with compelling evidence in its favor but also some indications of potentially decisive risks. It has been presented with Module 1 at the longer workshops of 3 to 5 days. The take-away should not be that such prospects should necessarily be rejected but, if their size warrants the risk, an exploration strategy should be designed to invest the minimum drilling budget that would resolve the most worrisome issues. A roughly analogous success-case exercise is planned to illustrate this point.

Module 6 *Deep Circulation Sedimentary-hosted Outflow-Upflow Well Exercise*: Developed by William Cumming, this exercise illustrates appraisal drilling to target an upflow based on a large amount of well data that does not detect the upflow but that can be supplemented with resistivity imaging. It has been presented on three occasions and is being updated.

Module 7 *Mafic Rift Volcano-hosted Resource Assessment and Well Targeting Exercise*: In development by Sam Scott and William Cumming, this exercise is expected to be available by May 2020. It will be roughly analogous to geothermal prospects in Iceland or in the western branch of the East African Rift.

Module 8 *Elementary Model Exercises*: This exercise developed by Irene Wallis illustrates the resource implications of a permeable crack in a thermal gradient with or without a cap, or with an outflow exit and so on.

Module 9 *Deep Circulation Basin and Range* provides participants experience exploring for deep-circulation moderate temperature systems similar to those found in the US Basin and Range, Turkey, the west branch of the East African Rift and Sumatra

Module 10 *Financial lecture and exercise:* This module developed by Amanda Lonsdale in conjunction with the team that developed Model 9 can be adapted to other Modules. This financial module illustrates how geoscience resource assessments interact with costs related to access, drilling and generation technology to constrain decision criteria like minimum resource size in the overall context of the economics of market constraints and power price.

4.2 Presenters and Coaches

Participants need a basic introduction to hydrology, geophysics, geology, geochemistry and reservoir engineering to understand the data and its implications for the conceptual model. The lectures have been developed and refined over the years to provide this foundation efficiently. They have been distilled to a minimalist set of technical information that a wide range of participants can comprehend and use the notes as a reference to complete the exercises. Because most of the learning takes place in the exercises, the lecturers avoid adding material to the lectures without solid justification. There is a plan to convert the lectures into a web-hosted format that could be completed before the two day workshops, leaving more time for the exercises.

The most serious drawback of these workshops is that they have become more labor intensive as the coaching of the exercises has been given greater emphasis. This has required that a coach join each team of 4 to 6 participants. Because most of the learning is done in the exercises, not the lectures, the coach must adapt to the participants' needs, rather than the usual case where the student must adapt to the lecturer. Participants who have already completed one or more module need much less coaching. However, an experienced coach greatly enhances the experience of first-time participants. Fortunately, over 30 well-regarded experts with extensive experience in the process outlined in Cumming (2016a) have already volunteered ongoing support.

The organization of participants in teams more closely matches the real experience of developing a resource assessment as part of a geoscience team and it usually facilitates the process and reduces the load on the coaches. On the other hand, it can sometimes create challenging interpersonal dynamics, for instance, if one participant in a team is in competition to have their opinions prevail.

Because most participants will lack the technical knowledge and case history experience needed to assess the likelihood of their conceptual models, they must learn to exploit the experience of experts and mentors to provide that information. Before coaching a workshop, ideally presenters and coaches would participate in one or more workshops and, before leading a workshop, they would support one as a coach.

Coaching these workshops does require teaching skills that require practice. For example, coaches might encourage participants to ask, "Does this pattern of gases suggest upflow more likely here or there?" Rather than a direct answer, the coach could explain what aspects of the data fit different interpretations and why. Participants often ask what temperature corresponds to a particular resistivity, which can be simplified to an explanation that a gradient to higher resistivity usually corresponds to the base of the low resistivity clay cap, with a reference to the provided literature. Or participants might ask, "Does an upflow ever occur below a temperature reversal?" A coach might answer, "Rarely, yes, but depth matters, the deeper the reversal, the less likely that an upflow exists beneath it." That is, coaches usually answer in terms of confidence based on both general case history experience and professional expertise. The section on decision research highlights several roles that the instructors and coaches play in facilitating the exercises, such as acting as a Peer Reviewer.

Coaches should also provide unsolicited advice, ideally as questions. Most participants will need coaching on contouring isotherms. Questions might be, “Do you mean that the resource is impermeable, which is the implication of this evenly spaced isotherm pattern?” Or “Do you mean to imply that cold water is deeply penetrating into your reservoir, which is implied by this steep lateral gradient at 1500 m depth.” And so on. The most common pitfall in resource targeting is to target data rather than the model and “data” that proves to be misleading commonly includes lineaments assumed to be faults or low resistivity values. Coaches should be alert to opportunities to ask teams, “Are you targeting data or your conceptual model?”

The workshop has been delivered as part of credit university courses at University of Nevada Reno and The University of Auckland. The nature of the workshop is incompatible with a simple test or quiz format of student evaluation. Some students have been graded on their group contribution and some specific assessment products and a test at the end of the workshop.

4.3 Pre-Workshop Reading for Participants

Participants should be aware that this is a hands on course during which most of their time will be directed at completing the exercises in a team using real data to make collective decisions. The course is intended to simulate the experience of professionals who are in a team at a geothermal resource consultancy that is providing resource advice to a geothermal developer. The pre-read publication, exercise materials, lectures and coaching support have been designed so that a third year undergraduate geoscience or engineering student is usually adequately prepared to understand the material and effectively participate in the course. Participants should also be prepared to practice efficiently and effectively soliciting the advice of team members, mentors and consultants, an important skill for professionals conducting resource assessments. The presenters and coaches act as expert mentors and consultants to teams.

All of the pre-read publications previously used in these workshops are available through the IGA geothermal conference data base. Several publications have been prepared specifically to support the workshop exercises, including Cumming (2009) directed at developing conceptual models to support exploration of “hidden” deep circulation systems hosted in sediments, Cumming (2016a) on volcano-hosted geothermal reservoir conceptual models and how exploration process used in the workshops develops them (2016b), and Cumming (2016b) on the resource capacity assessment spreadsheet that has been used in the workshops and its pitfalls. Additional tutorial publications are being prepared to address those topics on which workshop participants have required the most coaching, including tutorials focused on assessing the conceptual reliability and relevance of exploration and development geochemistry and structural geology.

Depending on the background of participants, pre-read publications may be recommended to introduce concepts covered in the workshop presentations at a level suitable to most participants, typically including IGA Service GmbH (2014) on best practices in geothermal exploration, Faulds and Hinz (2015) on structural geology, Hinz et al. (2016) on prospective settings for geothermal fields, Hochstein and Sudarman (2015) on general geoscience characteristics of vapor core volcanoes, Grant (2015) on resource capacity assessment pitfalls, Klein (2007) on geochemistry applications and Ussher et al. (2000) on the relationship between resistivity and geothermal systems. Wallis et al. (2018 and 2019) illustrate basic geometries and constraints on geothermal resource conceptual models.

Other publications are recommended as background references. DiPippo (2016) covers many geothermal disciplines at an introductory level. Siler at al. (2018) and Stelling et al. (2016) are directed at all geoscientists. Although Boden (2016), Nicolson (1993) and Grant and Bixley (2011) are likely to be of greatest interest to geologists, geochemists and reservoir engineers, respectively, introductory discussions opening the chapters of these books have general relevance.

The presentations are short, focusing on what each type of data means in terms of the resource conceptual model exercise and what types of questions participants should ask their expert coaches. Presentations should include a brief illustration of the practical application of the technology relevant to the exercise. Examples of such demonstrations would be to show how neutral chloride springs can be used for cation geothermometry and water table determination and how that type of spring can be differentiated from bicarbonate and acid sulfate springs. Participants should be warned that naive or promotional assessments commonly omit consistency checks, for example, emphasizing high geothermometry obtained from bicarbonate springs that support no reliable temperature estimates. However, in the exercises, participants can assume that the geology, geochemistry and geophysics data provided has been appropriately assessed by experts and will not be misleading, except typically for one or two hopefully obvious exceptions that participants will identify by asking coaches about what data is likely to be reliable and why?

5. CHALLENGES

The most serious drawback of these workshops is that they are labor intensive to develop and execute. Moreover, only senior geothermal professionals with broad experience in developing and applying conceptual models in exploring and developing geothermal fields experts in assembling and vetting real data and constructing conceptual models.

5.1 Developing New Exercise Modules

Developing these Geothermal Resource Decision Workshops takes a month or sometimes many months of time from several professionals who are expert in assembling geothermal conceptual models from real data and who have the software resources and expertise to verify data and outcomes from the case history, realistically synthesize data to fill any gaps, and prepare a compact and clear set of exercise handouts. This typically requires several weeks to several months of effort by several people a month or more. they are labor-intensive. Thus far, this has been a volunteer effort. Because the time available to complete the hands-on part of a workshop is typically 4 to 12 hours, possibly distributed over only two days, a typical case history data set must be reduced to a manageable set of less than twenty handout sheets containing the data used in the exercises. Although funding has supported some recent customization of one exercise, it represents only a small fraction of the effort invested in developing the exercises. Further progress on building additional exercises will likely require support from developers supplying at least data and possibly also funding to avoid unsustainable amounts of volunteer work.

Case history data sets from several magmatically-heated and deep-circulation fields might be made available to support workshops. Some of these data sets have already been made into exercises for in-house proprietary use and a release for general use will require significant negotiation with the developer. As this program gains general acceptance, it may be possible to obtain releases for exercises already developed based on case histories of several reservoirs hosted in andesite arc settings and rhyolite rift settings.

Some developers that have enthusiastically supported this training program have provided information supplementing published data to support an exercise and then have been obliged by securities laws to announce restrictions on disclosures. For the 2020 GRC one such case, the prospect has been disguised by rotating the prospect, changing geological details and adjusting the temperatures and production results to fit a numerical simulation model exactly (and the actual wells only approximately). This

As the potential value of this program is better understood by industry leaders, universities and research groups, it may be possible to obtain releases for exercises already developed based on case histories of several reservoirs hosted in andesite arc settings and rhyolite rift settings. These had been previously released in a trade of exercises between developers.

Developing online introductory lectures with an online test that encourages participants to review the lectures and/or reading list would make it feasible to focus more time in the workshop on the exercises.

The geothermal field case histories used for the exercises must have been sufficiently explored, drilled, produced and modeled so that realistic data sets can be provided to workshop participants at each stage of the exercise to build resource conceptual models, target wells and assess capacity and also to provide participants feedback about their performance based on actual outcomes. This implies that the exercises do not include types of geothermal systems that have not yet been commercially developed such as >380°C supercritical magmatic systems or enhanced geothermal systems (EGS) in low permeability hot rocks (DiPippo, 2016).

5.2 Recruiting and Training Workshop Coaches

The workshops require support from coaches who are highly skilled both as professionals and as mentors. Although the workshops are likely to continue to depend on the generosity of industry professionals and educators (or their employers), it should not presume upon this generosity. Suitable decision workshop coaches would have many qualities common to the superpredictors of Tetlock and Gardner (2015). In the geothermal context, they would be willing to investigate a broad range of relevant information, they would not give preference to specific areas of expertise, and they would not bias their coaching in order to promote their (or their firm’s) private interests.

6. CONCLUSIONS

The rationale for using geothermal resource decision workshops to train geothermal professionals is based on relatively robust observations from behavioral economic research that are consistent with the common sense proposition that those who make geothermal resource decisions will perform better if they get relevant practice making decisions with immediate performance feedback.

To explain why some geothermal experts more consistently target successful wells than other experts, the results of Klein (2009) are relevant, since he investigates how experts who do consistently make objectively successful decisions achieve that success. Improvement in making decisions requires practice making decisions and immediate review of decision performance. However, because accumulating sufficient decision experience in a typical geothermal career may take decades and reviews of outcomes are seldom immediate (and thorough reviews of the decision process are rare), the Geothermal Resource Decision Workshops are directed at accelerating this process by simulating realistic experience in making geothermal resource decisions and responding to consequences. The exercises are also designed to give participants experience in identifying gaps in their expertise and effectively acquiring advice from suitable experts and mentors.

Although reading about case histories or previous decisions provides important information to support a decision, it cannot provide the type of experience provided by the workshops, actually building conceptual models to support realistic predictions, using these predictions to make decisions, and then reacting to the consequences of those decisions.

Most geothermal professionals, researchers and students who have participated in the Geothermal Resource Decision Workshops have endorsed the approach to providing decision experience and motivating study and research.

A meeting held at the 2018 Geothermal Resource Council Annual Meeting confirmed institutional and professional support for developing a Geothermal Resource Decision Workshop curriculum directed at hands-on learning using real data to build geothermal conceptual models used to inform decisions in realistic scenarios. Three main resources were identified to promote a program based on this concept: 1) exercise materials held by an entity that would appropriately distribute them and retain their confidentiality, most likely the Geothermal Resource Council; 2) lecture materials and, ideally, online courses, that would cover the background material required for the exercises in the workshops; and 3) training of expert presenters and coaches and support from academic and industry experts.

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