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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 in a risk assessment process that supports effective resource decision making. During these workshops, short lectures introduce the components of geothermal conceptual models and how they are constrained using geochemistry, geology, geophysics, and basic concepts of thermodynamics of water flow in rock. The exercises using real data from geothermal fields are interspersed among the lectures to provide participants an opportunity, within small teams, 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. Plans for additional curriculum development include the development of public domain online short courses and tests 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. 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.

Geothermal geoscience generalists who have spent decades making well targeting and resource capacity predictions based on conceptual models and who also have critically reviewed the success of their predictions are more likely to effectively use conceptual models to make realistic predictions and assessments of confidence. In contrast, specialized researchers, educators and less experienced geoscientists seldom have the broad contextual knowledge required to build conceptual models and so they tend to base their predictions on favored data sets. For example, the reservoir perimeter used in probabilistic capacity assessments is commonly based on a particular MT resistivity map contour and wells are often targeted to cross fault traces with doubtful subsurface relevance, both without reference to conceptual models. Because members of the human species unconsciously look for easily recognized patterns on which to base a decision, even experts in geothermal assessment who have already developed consistent conceptual models will sometimes revert to using an arbitrary contour when choosing a reservoir perimeter. Therefore, although conceptual models and uncertainty analyses have become industry standards, 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 has been developed and its expansion is planned to improve the application of the conceptual model approach to geothermal assessment and to provide geothermal professionals with realistic opportunities to practice making resource decisions on well targeting and resource capacity decisions. These are not lecture courses but hands-on workshops focused on practical exercises that have demonstrated success in providing geothermal professionals, managers and investors with sufficient understanding to review the validity of geothermal conceptual models and their application to 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 the current workshop program meets the needs of most introductory courses, ongoing projects include putting lectures online, adding cases more relevant to Iceland and East Africa, and formalizing the workshop as a GRC-hosted curriculum.

1. THE CONCEPTUAL MODEL APPROACH TO GEOTHERMAL RESOURCE ASSESSMENT

1.1 Conceptual Models versus Anomaly Hunting

Targeting wells using conceptual models 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. 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.

Ideally, all decisions will be conceptually informed even if data is being directly used to make decisions. For example, choosing which spring samples should be submitted for a full geothermal geochemistry analysis is a relatively low cost decision that would be appropriate to make directly from a data measurement. For example, a decision might be made to conduct a full analysis on all springs > 30°C measured temperature. However, this decision would be more effectively based on a data targeting strategy that also considers the local conceptual context, perhaps expanding the criteria for full analysis to all springs with either >30°C temperature or >100 ppm chloride. That is, effective anomaly hunting strategies are still conceptually based. 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.

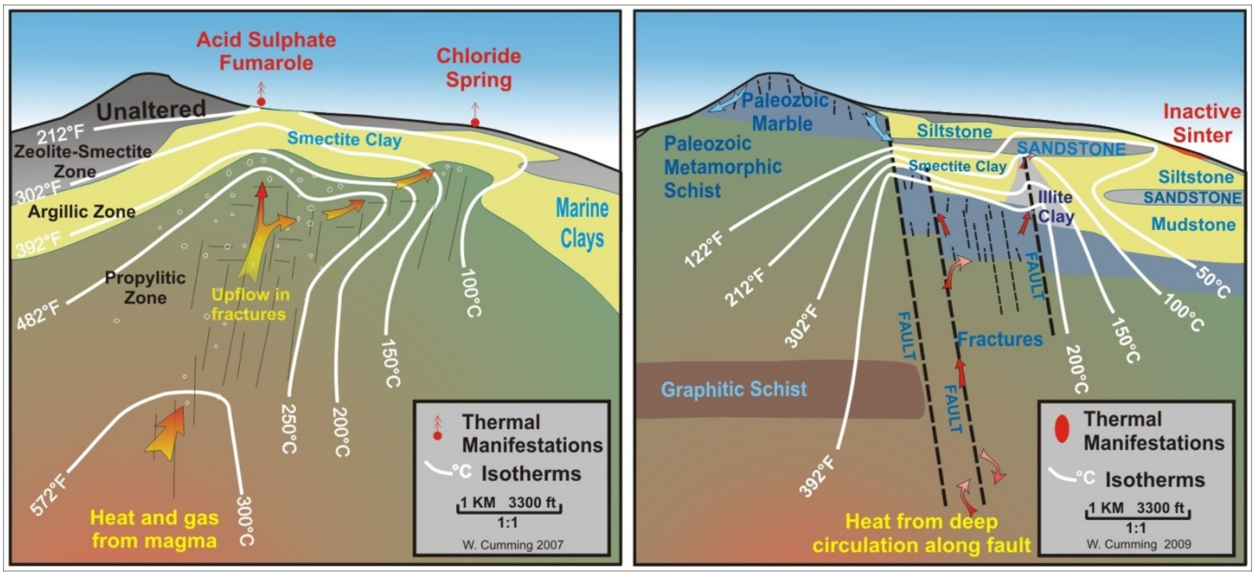

Figure 1: Geothermal resource conceptual models, a magmatically-heated, volcano-hosted reservoir (left) and a deep-circulation-heated, fault-zone-focused, sediment-hosted reservoir (right)

1.2 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 (although the same cognitive biases apply to anomaly hunting).

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 use it requires a significant investment. 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 who has wide experience building many conceptual models in analogous settings. Making effective geothermal assessments requires advice from an expert 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.

- **Probabilistic thinking**: The workshop exercises emphasize developing a range of conceptual models that illustrate the uncertainty in the assessment (Cumming, 2000a). Geothermal resource capacity is assessed using a probabilistic approach, (Cumming, 2016b).
- **Counterfactual data**: The workshop exercises require that teams consider counterfactual data, particularly with respect to reliability and relevance of data.
- **Multiple approaches**: The coaches encourage teams to assess power capacity using simple analogy as well as power density statistics.
- **Backwards thinking**: This is assuming the end and thinking backwards to what it implies. The workshop exercises require that teams consider what would be observed if the reservoir was very large or if the reservoir did not exist, and so on.
- **Reframe questions**: 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 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.

2.3 Resource Risk as a Distraction from Real Risk

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, an issue that geothermal developers encounter when specialists from outside the geothermal industry choose well targets with much greater confidence than the 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).

Some geothermal practitioners have claimed that unforeseeable "black swan" events (Taleb, 2010) make it unreliable to use a conceptual model approach that relies on analogies. However, the likelihood of outlier events is already high in realistic geothermal resource assessments. Moreover, at least some geothermal investors who are said to have experienced "black swan" events have experienced financially disastrous events unrelated to resource risk. This is an issue of cognitive bias but not one that would be part of a resource risk 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 will be 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, one of the authors, Pete Stelling, has used a similar decision-oriented workshop for teaching Western Washington University undergraduates 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 fifty workshops worldwide since 2000, including 2 day Geothermal Resources Council short courses in 2016 and 2017, a 2 day ARGeo-C7 short course in 2018, 3 day courses for GRD Uganda and

TGDC Tanzania in 2018, a 5 day University of Nevada Reno course in 2018, University of Auckland 2 and 3 day courses in 2017 and 2019 and a 2 day USGS workshop in 2019.

4. RESOURCES AVAILABLE TO CONDUCT WORKSHOPS

The most serious drawback of these workshops is that they are labor-intensive. 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. 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 7. 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 four trial runs, the materials and lectures for this deep circulation exercise developed by Nick Hinz have recently matured into an effective 1 day 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.

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.

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.

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.

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.

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

5.1 Developing New Exercise Modules

Developing the exercises is particularly labor intensive and has previously been a volunteer effort. Because the time available to complete the hands-on part of a workshop is typically 4 to 12 hours over one or two days, a typical case history data set must be reduced to a manageable set of less than a dozen handout sheets. 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 2 to 4 day 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.

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.

5.2 Online Preliminary Instruction and Test

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.

5.3 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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