Dixie Valley Geothermal Workshop

JUNE 12-13, 2002

Executive Summary

Meeting Agenda with Links to Presentations

Notes from Working Group Breakout Sessions

Executive Summary

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Introduction

A workshop was hosted by the University of Nevada, Reno, Great Basin Center for Geothermal Energy in Reno, Nevada June 12 through 14, 2002 to highlight and discuss DOE Sponsored Research at the Dixie Valley Geothermal Area. Researchers funded by the Department of Energy to conduct research on the Dixie Valley geothermal system met and presented preliminary and final results of their work. Twenty-three speakers made technical presentations, and breakout discussion sessions were held on the following topics:

- Geotectonics/Geologic Setting
- Reservoir Geology, Structure and Analysis
- Exploration Technology Applications
- Geochemical Studies

The workshop successfully brought together researchers from a variety of fields in the geosciences, resulting in lively cross-discipline debate. Consensus was reached on some topics, whereas differences of opinion remain on others.

Research Benefits

DOE-funded research at the Dixie Valley Geothermal Field is benefiting the country in four ways. The DOE research has

- Increased the amount of clean renewable energy produced from the field.
- Improved field management practices that can be applied to production at other fields.
- Developed a conceptual model or template to be used to explore for new geothermal fields in extensional, non-magmatic regions such as the Basin and Range province.
- Added basic scientific knowledge about the extensional tectonics in the Basin and Range province, as is documented in scientific publications.

Dixie Valley is an ideal site to study because the operator recognizes that additional knowledge is necessary for the efficient operation of the field, and is willing to openly share information in order to obtain that additional knowledge. The following summarizes the progress in each of the three benefit areas. The first benefit area was a quantifiable success; the significance of results in the remaining areas can be subjectively assessed.

1. **Increased renewable energy production from this field.** Before the DOE research at Dixie Valley began, the output of the field was declining; pressure within the field was

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declining at a rate of about 50 psi per year. Concurrent with the DOE investment, the rate of decline has been reversed and reservoir pressure is increasing at about 50 psi per year.

There are several mechanisms by which the DOE research contributed to the reduction of the decline.

- Collecting specific knowledge. Before this project started, the drilling target was assumed to be a single range-bounding fault. It is now known that the production occurs in multiple and perhaps more steeply-dipping zones that require a different drilling target. Several other areas of specific knowledge are discussed later in this summary.

- Increasing the intellectual pool thinking about how the field works and should be operated.

- Encouraging the operator to invest in scientific studies. The operator raised their confidence in the research conclusions enough so that, for example, they used the research to site injection wells and to manage substantially increased injection, without adversely affecting the production temperature.

2. **Improved field management practices**. Several ideas about the operation of geothermal fields have developed as a result of the DOE funded work at Dixie Valley. Examples include

- the use of multiple tracer sets to study compartmentalization of a field
- the use of in-situ stress indicators to understand why certain fracture systems are productive
- the need for dedicated injection wells.

Although we cannot point to specific uses of this information at other fields, the body of knowledge is there to be used when and where it is applicable.

3. **Developed an exploration model for locating new systems in the Basin and Range.** The research has identified a number of characteristics of the Dixie Valley System. Examples include

- It exists in an area without fault movement that my have existed for tens of thousands of years, but with recent activity to both sides.
- It contains fluid that is old and may have come during a flooding episode (Pleistocene lake formation) in the valley
- It occurs on a fault that has one of the largest vertical displacements in the Basin and Range
- It occurs in an area where the range-bounding fault system is complex both in plan and in cross sectional view
- It occurs in an area where the local in-situ stress field is favorable for opening the range-bounding fault system
- It occurs in an area of recurring, cyclic fumarolic activity

These attributes lead to a number of elements of a geothermal exploration strategy using seismicity and seismic prospecting, strain information, remote sensing and other methods to look for similar features.

However, there are two issues that limit the usefulness of Dixie Valley as a prototype exploration target. First, the attributes of Dixie Valley need to be interpreted within a more regional setting to see if the attributes of Dixie Valley also occur in nearby valleys that are not thermally active. Second, since the research focused on a site with an existing geothermal plant, we have limited knowledge of what exploration signatures might have existed before production started. Consequently, we do not yet have cost-effective methods to extrapolate the interpretations based on relatively expensive data at Dixie Valley to a screening process of other candidate sites in the region. Additional work that deals with these issues might make Dixie Valley a more effective prototype for Basin and Range exploration.

Breakout Sessions

The reports of the four working groups are presented here. These reports summarize the workshop's results and address the central question: Is Dixie Valley a good analog for other Basin and Range geothermal systems? The results will be used as a guide to future investigations of hydrothermal systems in the Great Basin.

During the breakout sessions, all participants agreed that the Dixie Valley system can be used as an analog because it is a typical fault-controlled, deep-circulation Basin and Range geothermal system not associated with magmatic activity. This system, as are most others in the Basin and Range, is associated with active, extensional tectonism, although the field itself appears to be located in a seismic gap. The importance of this seismic gap with respect to the existence and location of the Dixie Valley field and as a potential exploration tool for other systems is debatable. An additional issue of contention identified by the researchers is the true configuration of the range-bounding fault (system) through which the geothermal fluids flow. At present, there is no consensus on fault structure, the detailed geometry and dip of the productive faults (zones), the number of faults involved, the depth to the brittle/ductile transition zone, or the context of why the field is where it is. Another area of varying opinion concerned the necessity for a Pleistocene lake to recharge the system, although there was little dispute that the system was recharged by waters >10,000 years old.

Without doubt, useful information has been obtained for the system, but these data require synthesis and evaluation across disciplines in a controlled, organized manner. In order to come to a better understanding of the nature of the Dixie Valley geothermal system and to test the various models of the system, the participants recommended that a chief scientist be appointed to oversee the synthesis. The synthesis could involve database and GIS development and the collective, cross-discipline evaluation and interpretation of the data to test the various models of the system. As a first step, considerable geochemical data have been collected, but not thoroughly interpreted. An important goal of the synthesis should be an estimate of how many similar systems may exist in the Basin and Range and how they can be found.

Because many of the studies discussed at the workshop were conducted after the field was put into production, we cannot answer the question of which techniques would be most useful in the exploration of other Basin and Range geothermal systems. With current data, we cannot determine how open, productive fractures evolved, although a better understanding is being gained by evaluating the evolution of tectonics and strain over time. Micro-seismic activity data has not been collected in the field and whether these data could help refine the model of the system or be used as part of an exploration program remains unknown. Researchers should apply the same techniques used at Dixie Valley at a site that has not yet been put into production (e.g., Rye Patch) in order to determine how a system "looks" prior to exploitation. However, research has identified a number of characteristics of Dixie Valley that may be useful in exploration of additional Basin and Range systems. These characteristics include: the occurrence of a seismic gap, large vertical displacements along complex range-bounding faults, favorable orientation of local in-situ stress field and fractures, and the presence of recurrent, cyclic fumarolic activity, among others. Dixie Valley needs to be evaluated in a regional context to determine if these features are uniquely associated with productive geothermal systems or if similar characteristics can be identified in nonthermal basins.

All of the DOE-funded research at the Dixie Valley Geothermal Field benefited the public interest in four ways:

- Increased the amount of clean, renewable energy produced from the field.
- Improved field management practices that can be applied to production at other fields.
- Developed a conceptual model, or template, to be used to explore for new geothermal fields in extensional, non-magmatic regions such as the Basin and Range province.
- Added basic scientific knowledge about the extensional tectonics in the Basin and Range province.

Agenda

Great Basin Center for Geothermal Energy

presents

The Department of Energy's

workshop

"Dixie Valley Geothermal Research"

June 12 & 13, 2002

at

Desert Research Institute

Wednesday, June 12

7:15am- 8:00am	**Registration/Continental Breakfast**
8:00am- 8:15am	**Introduction** *James Taranik, Great Basin Center for Geothermal Energy; and* *Bob Creed, Department of Energy*
	Geotectonics/Geologic Setting (Moderator: Joel Renner, INEEL)
8:15am- 8:40am	**General Setting and History of Dixie Valley Geothermal Field** *Stu Johnson, Caithness*
8:40am- 9:05am	**Basin and Range Character of Dixie Valley** *David Blackwell, SMU*
9:05am- 9:30am	**Neotectonics** *John Caskey, San Francisco University; and Steve Wesnousky, University of Nevada, Reno*
9:30am- 9:55am	**Structural Geology of Stillwater Range in Vicinity of Dixie Valley Geothermal Field** *Gabe Plank, Techsoft America*
9:55am- 10:15am	***BREAK***
10:15am- 10:40am	**Overview of Dixie Valley Geothermal System** *David Blackwell, SMU*
10:40am- 11:05am	**Detailed Aeromagnetic Studies** *Tien Grauch, USGS*
11:05am- 11:30am	**Geologic Studies in Dixie Valley** *Richard Smith, INEEL*
11:30am- 12:30pm	***LUNCH (provided)***

Exploration Technology Applications (Moderator: Bob Creed, DOE)

12:30pm-1:15pm **Repeat High-Precision Gravity and GPS at Dixie Valley Geothermal Field**
Dave Chapman, University of Utah; and Paul Gettings, University of Utah

1:15pm-1:40pm **Remote Sensing Studies**
Greg Nash, University of Utah, EGI

1:40pm-2:00pm **Deformation at Dixie Valley from InSAR Measurements**
Bill Foxall, Lawrence Livermore National Laboratory

2:00pm-2:20pm ***BREAK***

Geochemical Studies (Moderator: Lisa Shevenell, UNR)

2:20pm-2:45pm **Dixie Valley Region Geochemistry**
Fraser Goff, Los Alamos

2:45pm- 3:10pm **Origin, Age, and Geochemical Evolution of Dixie Valley Geothermal Fluid**
Cathy Janik, USGS

3:10pm-3:35pm **Geochemistry of Noble and Other Gases at Dixie Valley**
Mack Kennedy, LBNL

3:35pm-3:55pm **Structure and Mineralization in the Northern Portion of Dixie Valley**
Jeff Hulen, University of Utah, EGI

3:55pm-4:20pm **Alteration History and Evolution of Fluids in the Dixie Valley Geothermal System**
Sue Lutz, University of Utah, EGI

4:20pm-4:45pm **Scale Formation and Fluid Chemistry at Dixie Valley**
Carol Bruton, Lawrence Livermore National Laboratory

Thursday, June 13

7:15am-8:00am **Registration/Continental Breakfast**

Reservoir Geology, Structure and Analysis (Moderator: Ray Fortuna, DOE)

8:00am-8:10am **Borehole Electrical Measurements at Dixie Valley**
Paul Kasameyer, Lawrence Livermore National Laboratory

8:10am-8:35am **Recent Tracer Testing at Dixie Valley**
Pete Rose, University of Utah, EGI

8:35am-9:00am **Thermal Modeling**
Colin Williams, USGS

9:00am- 9:20am	***BREAK***
9:20am- 9:45am	**Stress and Fracture Permeability at Dixie Valley** *Steve Hickman, USGS*
9:45am- 10:10am	**Applications of Natural Fracture and In-Situ Stress Analysis to Production in the Geothermal and Oil and Gas Industries** *Colleen Barton, Amy Day-Lewis and Judith Sheridan, GeoMechanics*
10:10am- 10:35am	**Structural Interpretation of the Dixie Valley Geothermal Field Derived from Re-Interpretation of Active Source Seismic** *Bill Honjas, Optim LLC; and Satish Pullammanappallil, Optim LLC* *[Presentation canceled by speaker]*
10:35am- 11:00am	**Perspectives on How Dixie Valley Relates to New Prospects in the Basin and Range** *Dick Benoit, Consultant*
11:00am- 12:00pm	**General Discussion**
12:00pm- 1:00pm	***LUNCH (provided)***
1:00pm- 3:00pm	**Break-out Discussion Groups**
3:00pm- 3:15pm	***BREAK***
3:15pm-	**Wrap-up, Summary**

AUTHORS: Dave Blackwell, Dick Smith

NOTE TAKER: Richard Smith

GROUP: Summary of Discussion Group on ***Geotectonics/Geologic Setting***, Workshop on Dixie Valley Geothermal Research, June 12-14, 2002

GROUP MEMBERSHIP: Dick Benoit, David Blackwell, John Caskey, Stuart Johnson, Richard Smith, Paul Spielman, Philip Wannamaker, and Steve Wesnousky

1. *What do we know about Dixie Valley?*

There is an extensive region of high temperature (>200°C) in the shallow crust. The system is related to deep circulation, not a magmatic system, although the He isotopes indicate a small mantle component. The environment is extensional and this is the factor that allows the deep circulation that is required to obtain the high temperatures observed. The area is tectonically active. The area (regionally) has had three large historic earthquakes (1916, 1954, 1954). However, based on present data, the immediate system lies at least partially in a gap of Holocene activity. The flow paths for the fluid are apparently along permeable zones that are parallel to the maximum extension direction and that are critically stressed for failure.

There was a lengthy discussion instigated by Steve Wesnousky about the necessity for deep convection in a fault system to get the high temperatures observed near the surface. It seems that we concluded that no information exists about how far west the thermal anomaly goes, and that it could lie under the whole range and manifest itself in the thermal features in Carson Sink on the other side of the range. If the system is that big, questions remain whether it has to be connective, or if it be a large conductive anomaly.

2. *How can we explain the origin and nature of the geothermal system in place?*

Addressed in response to question 1.

3. *Which exploration and characterization techniques or models have seemed to work best and which ones have apparently not been so effective?*

The system is complicated and no one exploration technique gives a full picture. The original drilling was probably located based on land position first (accepting the general existence of fumaroles in the area) because no federal leases had been issued at that time. General tectonic and seismic data were used second to site drilling. Once the first Sun wells were successful, the focus never shifted much except to go northward toward the Senator fumaroles. The north end was ultimately limited by deep drilling. The south end was not tested past the Lamb Ranch wells until the DIXIE VALLEY POWER PARTNERSPP drilling in 1993/1994. Thus there is a need to develop an exploration procedure that would work, based not on the actual process, but on an optimal process. As described, the exploration and development at Dixie Valley has not been optimal for reasons that have nothing to do with knowledge, or lack thereof, of the details of the target.

4. *What don't we know? Identify inconsistencies and differences of opinion among experts in our knowledge of Dixie Valley and its geothermal system.*

The main unknown is the detailed geometry and dip of the productive faults (zones). Secondly, the uncertainty between the single versus multiple fault system model is significant. It is also unknown what the system looked like before exploitation. Other questions that remain include:
What is the western boundary of the heat anomaly?
Are Pleistocene lakes necessary for recharging the system with water?
What is the importance and significance of seismic gap, and can seismic gaps be used as an exploration tool?
What is the microearthquake (MEQ) activity in the reservoir?

5. *Do we need more research/What should be done?*

There is a need to synthesize the existing data in a controlled, organized manner. All break-out groups unanimously agreed that integration of data was a high priority. The depth to the brittle/ductile transition (MT, Seismic, and Curie point techniques might be used) should also be determined to verify the depth of circulation. A local seismic net could be used to determine the deep geometry of the faulting, determine the type of faulting based on focal mechanisms, and look for microearthquakes related to field production.

The geothermal system needs to be set in the regional geophysical and geological context. There was a strong feeling that there was information about how to evaluate and understand the geothermal system to be obtained from a more complete set of data and analysis of regional geology and geophysics. The limits of such data collection were not established, however.

The detailed fault and fracture structure in the bench area (between the range/valley contact and the piedmont fault) needs to be known for several important reasons. This detailed picture could be obtained by a combination of dense network of electrical station measurements (CSAMT) across the bench, squeezing as much information as possible out of the aeromagnetic data, drilling near the range front to define the fault geometry and temperature distribution, and new high frequency shallow focused (down to about 1.0 sec two way travel time) seismic reflection surveys. The feeling from the group was that all that could be obtained from the old seismic data has been obtained. The focus needs to be on high fold coverage in the depth range of 0-5,000 ft to pick the up-dip points of the piedmont faults and the strike and offset of subsidiary breaks in the bench area. Additionally, all l old industry exploration data (if any) should be collected and evaluated. Also, the local strain rate needs to be determined (INSAR data) both in a vertical and a horizontal direction.

6. *Would doing more research make a real difference in our understanding of DixieValley and of geothermal systems in the Great Basin in general?*

The group felt that there were still significant lessons to be learned at Dixie Valley and, as noted below, these lessons will impact geothermal development in the rest of the Basin and Range.

7. *Does a lack of knowledge prevent us from drawing meaningful conclusions about the geothermal system or have we learned enough?*

We certainly know more about the system than we did 10 years ago and this information is very significant to the understanding of the Dixie Valley geothermal system in particular and to Basin and Range systems in general. The reservoir information that is available is especially crucial to the understanding that extensional systems can have a large reservoir capacity. However, the information that we now have is still being developed and there are still major difficulties in understanding how to find and evaluate these systems.

8 & 9. *Is Dixie Valley a model/prototype for other systems in the Basin and Range*? *Can the understanding/knowledge gained at Dixie Valley be applied to other Basin and Range geothermal systems?*

There was unanimous agreement that Dixie Valley is a model for Basin and Range extensional geothermal systems. It was felt that the long term, large-scale displacements on a fault are not necessary for the development or existence of a geothermal system (examples & counter examples). The presence of old water (Pleistocene) appears to be a common thread. A general study of the similarities and differences would be useful. Recently extended crust is probably necessary, or at least a very good feature. One puzzling factor is that other analogous areas have not been explored by industry for some reason. The Wasatch and Sierra Fronts ought to be explored. Saline Valley is Dixie's big brother, yet there is no information there.

There is a need to develop a template for exploration based on Dixie Valley, not the history, but based on what is known at this time.

In all the breakout sessions, everybody said that the first step in application of Dixie Valley knowledge/understanding to other areas is to integrate (synthesize) the knowledge gained at Dixie Valley. This is more than a matter of getting everyone's work published in a single volume. The synthesis should consist of:

Step 1. Acquiring all the spatially referenced data in a common format so that the spatial relationships between the different disciplines can be recognized. Such data would include:

- Well locations, lithologic logs, geophysical logs
- Geologic mapping
- Geophysical surveys (gravity, aeromagetics, seismic reflection, GPS, seismicity, etc.)
- Geochemisty and isotopic composition of rocks, soils, water, gas, and vegetation
- Remote sensing data
- Age determinations

Other special studies (sinter studies, tracer tests, thermal modeling, in-situ stress, etc.)
Prior to assembling any data sets, a decision has to be made about the format for assembly of the spatial data. All the researchers should provide their information in a simple x,y,z format, but the 3D analysis and comparisons need to be made on a robust 3D spatial analysis system. GIS

(ArcInfo, ArcView) can do much of it, but is not as robust as some other software at modeling subsurface information. There are a whole gamut of systems that could be used, ranging from very cheap and simple to use systems such as RockWare, to expensive and hard to use state-of-the-art systems such as Landmark (which would probably require a dedicated operator to work in conjunction with the scientists to get the data properly input and adequately analyzed (compared). Such a centralized, dedicated GIS operator should be considered to avoid duplication of efforts among research teams.

Step 2. Summarizing the various conceptual models for the system or parts of the system, specifying the steps to test each model. Each model should be tested against the integrated spatial data from step 1.

Step 3. Developing a tabular comparison of Dixie Valley to all the other known geothermal systems in the Basin and Range. This will help to discover important common threads and necessary conditions for development of Basin and Range geothermal systems.

Step 4. Developing a set of maps or overlays to place the Dixie Valley-specific data within the context of regional information (structural and tectonic models, geophysics, geochemistry, age, lithologic distributions, etc).

AUTHOR: Jeff Hulen

NOTE TAKER: Sue Lutz

GROUP: Summary of Discussion Group on ***Reservoir Geology, Structure, and Analysis***, Workshop on Dixie Valley Geothermal Research, June 12-14, 2002

GROUP MEMBERSHIP: Clay Cooper, Gilles DeBroucker, Steve Hickman, Jeff Hulen, Susan Lutz, Susan Petty, John Pritchett, Peter Rose, Colin Williams, and, intermittently, Allan Jelacic, Jay Nathwani, Bob Creed, and Ray Fortuna

1. *What do we know about Dixie Valley?*

Numerous talented researchers have studied the Dixie Valley geothermal system over the past quarter century – intensively for the past 15 years – and a wealth of new information and insight has been gained during that time not only about this particular resource but about generally analogous systems elsewhere in the Basin and Range. As a result of this work, there is a near-universal agreement that the Dixie Valley geothermal system:

- Derives its heat by deep circulation of waters in fractures and fracture networks in a region of thinned crust and anomalously high heat flow; and does not have an immediate magmatic heat source (i.e., a large, cooling pluton).

- Is characterized, like other systems (and oil reservoirs) in the Basin and Range, by thermal waters that likely accumulated in Pleistocene time in a much colder and wetter climate than at present, the same climate that fostered formation of large intermontane lakes like Lahontan, Bonneville, and Dixie.

- Is not undergoing significant recharge under present-day arid climatic conditions. This does not preclude modern mountain recharge from being a factor, for example, in supporting hydrologic head for portions of the system.

- Is hosted in the immediate producing area by moderately to steeply dipping faults and associated fractures of the Dixie Valley (or Stillwater) fault system, which has undergone several kilometers of normal displacement since Middle Miocene time.

- Where sufficiently mapped and measured, produces principally from large, open, extensional fractures that are ideally oriented for frictional failure in the currently prevailing stress regime.

- Is hydrologically compartmentalized.

- Is capped by a combination of Late Cenozoic lacustrine mudstones and hydrothermally altered lithologies of various ages and compositions.

- Is a nearly "blind" system, with very little hydrothermal alteration or obviously active surface thermal phenomena considering the resource's relatively large size.

These are arguably the major known aspects of the system; there have been numerous other, no less interesting, discoveries that are not listed in the interest of brevity.

2. *How can we explain the origin and nature of the geothermal system in place?*

We interpreted this question to mean, "why is there a Dixie Valley geothermal system-type system at this site, and not in a superficially similar Basin and Range setting elsewhere?" There is still much debate about this issue, and answering the question will go a long way toward reducing risks for future exploration here in the Basin and Range. Virtually all range-valley margins in the Basin and Range are characterized by normal fault zones, a product of the regional extension that has shaped the region's topography. Yet, to date, it is the only deep-circulation system this size and temperature that has been found in the province. The group agreed that the occurrence of the system in a very active seismic belt with significant historic activity is unlikely to be a coincidence. The system occurs in a segment of this seismic belt without historic offsets in alluvium along the range front, and this could mean that, for reasons yet unknown, stresses otherwise focused (apparently) at the immediate range front during an earthquake are distributed throughout the volume of the geothermal system, pervasively and pentratively restoring fracture permeability inevitably occluded with time by the precipitation of secondary minerals.

3. Wh*ich exploration and characterization techniques or models have seemed to work best and which ones have apparently not been so effective?*

Initial interest in this part of Dixie Valley as a geothermal exploration target was spurred by the region's warm springs, few fumaroles, and scant range-front hydrothermal alteration. These phenomena prompted a shallow drilling and temperature-logging program that delineated several promising thermal-gradient anomalies, one of which was shown to be the near-surface expression of the Dixie Valley geothermal system. Some other techniques were applied subsequently, and their effectiveness as gauged by the group, are listed below:

- Early standard gravity, magnetic, seismic, and resistivity surveys helped to define (but not unambiguously) the concealed resource.

- Detailed geologic mapping of the immediate Stillwater range-front (escarpment) apparently was not done until many years after the discovery, but the technique would have provided valuable early clues to the subsurface configuration of the Dixie Valley geothermal system.

- Regional hydro-geochemical studies tabled for programmatic reasons and still awaiting publication proved beyond doubt that the Dixie Valley geothermal system was not being significantly recharged in "real time."

- Tracer studies have been extremely valuable for mapping fluid-flow paths and travel times in the geothermal reservoir. These parameters, in turn, are essential to Caithness Operating Corporation for designing optimum injection strategies.

- Gas geothermometry would have identified the famous Senator fumarole as indicative of a >200^{o}C potential geothermal resource at depth, although the technique was, we understand, not sufficiently refined for this purpose at time the Dixie Valley geothermal system was discovered. The method apparently would not have identified the other, more feeble fumaroles above the Dixie Valley geothermal system as emanating from a high-temperature system, so it still seems that a geothermal target could not be ruled out in this and similar geologic settings simply on the basis of unfavorable fumarole-gas geothermometry.

- ^{14}C dating of siliceous sinters has proven useful for constraining the recent hydrothermal history of the Dixie Valley geothermal system in a regional seismic context. The results have even suggested that a vigorously spouting geyser may have formed briefly above the Dixie Valley geothermal system during the 1954 Dixie Valley-Fairview Peak earthquakes.

- Thermal-infrared (TIR) imaging clearly indicates the subsurface presence of the Dixie Valley geothermal system, and in addition, points to other promising targets in Dixie Valley. TIR, in combination with other remote-sensing methods, may prove to be one of the most effective and inexpensive techniques for "grass-roots" geothermal exploration of large portions of the Great Basin.

- Hydrochemical geothermometry, so effective in many other locales, apparently did not indicate a high-temperature geothermal resource at the Dixie Valley field. We suspect that this is not a poor reflection on the technique, but that it represents an isolated or unusual case.

4. *What don't we know? Identify inconsistencies and differences of opinion among experts in our knowledge of Dixie Valley and its geothermal system.*

- The principal issue of contention about the Dixie Valley geothermal system discussed at the Workshop was the nature of the fault/fracture system along which the bulk of the system is localized. For example, is the production zone confined essentially to a single, moderately-dipping fault, or is it spread among several, subparallel, steeply-dipping faults and intervening fractures? The answer to this question is critical not only for production purposes, but also for designing the most accurate exploration models for similar undiscovered systems in the region. As Dave Blackwell noted in his presentation, the multiple-fault model would imply larger potential reservoir volumes and greater system sustainabilities.

- We don't know why the Dixie Valley geothermal system has such a high maximum temperature (285^{o}C) relative to other "deep-circulation" systems at equivalent depths. Is it because the region has undergone a greater degree of extension and seismic activity than elsewhere in the Basin and Range? Is it because the brittle-ductile transition is positioned at a higher elevation in the crust at this site? Are cooling igneous intrusions actually involved (even though helium-isotope data collected to date would seem to rule out this possibility)?

- We know that the Dixie Valley geothermal system production fluids are meteoric and that they accumulated beneath the floor of Dixie Valley probably >10,000 years ago when the climate was cooler and wetter. We know that the accumulation of these waters here likely occurred beneath Pleistocene Lake Dixie. We do not know for certain that the accumulation actually required the presence of such a lake, or if similar volumes of groundwater could have accumulated in other Basin and Range valleys that did not become lacustrine.

- The reasons for the reservoir's distinct compartmentalization remain to be determined. Are they structural in nature, or do they involve the precipitation of secondary minerals in fractures that would otherwise be fluid channels? Do the wells of the Dixie Valley Power Partners tract adjoining the geothermal field to the southwest penetrate a completely separate system? Why are some of these wells so highly overpressured (up to 700 psig at the wellhead)? Does this overpressuring imply the possibility of natural hydraulic fracturing (and permeability enhancement) at depth?

- We suggest that the origin, evolution, and configuration of the Dixie Valley geothermal system in a regional context have not been sufficiently addressed by this research program. For example, we do not know how and to what extent older regional fault patterns that developed under different than modern stress regimes have influenced the formation and longevity of the geothermal system. Also, is there a distinctive pattern of structures here that could be used to help narrow the search for similar systems in this part of the Basin and Range? Mining companies as a critical initial component of their exploration programs routinely utilize regional geological evaluations. Epigenetic ore deposits, which are simply fossil high-temperature geothermal systems, tend to be localized systematically with respect to regional structural patterns. There is no reason that active geothermal systems in this area should behave otherwise.

5. *Do we need to do more research? What should be done?*

In our estimation, there is very good potential in Dixie Valley itself and throughout the Basin and Range for discovery of numerous additional "deep-circulation" geothermal systems. The potential in Dixie Valley alone, with its already-installed power line, warrants gaining a still-clearer understanding of the Dixie Valley geothermal system, the only system here presently under development. A few good ways to help achieve this goal are suggested below.

- Evaluate the geologic setting of the Dixie Valley geothermal system, central Dixie Valley, and the adjacent Stillwater Range in a regional context. This study could probably be completed in a year from existing publications and other data sources supplemented by field checks as necessary. A good place to start would be the voluminous mining literature for the region. There is also a great deal of published information and archived data from the DOE-sponsored Industry-Coupled Drilling Program that could be usefully incorporated. Many of the geothermal prospects evaluated (and the fields found) as a result of that program are adjacent to producing gold mines, yet synthesis of the geothermal and precious-metal data has yet to be done. There are also a few petroleum wells in the region that could supply information about the deeper parts of basins like the Carson Sink west of the Stillwater Range.

- Strictly subject to Caithness Corporation review, and the company's reasonable proprietary and financial concerns, acquire information from modern reservoir-engineering methods (pressure-transient testing, etc.) on the behavior of the Dixie Valley geothermal system under production and through time. There seems little doubt that if this information were made judiciously available to the DOE research community, the researchers and the operator alike would ultimately gain a much clearer understanding of how the resource really functions.

- Update an early reservoir model prepared for the Dixie Valley geothermal field with input from the multiple DOE studies of the resource completed and in progress. An example of the need for such an update is provided by the 20% overall reservoir porosity assumed for the early model; this figure is now known to be too high by at least an order of magnitude. The model also assumes a single fault as the producing zone, and as has been noted, the production may actually come from multiple such structures. Caithness reservoir engineers may already be working on this task, but access to a new Caithness model by DOE researchers would, as always, be contingent on the need for corporate confidentiality.

- Drill a scientific corehole, on the model of the 1994 Geysers Coring Project, to determine, among many other things, the configuration of the Stillwater Range-front fault zone, the main producing conduit or conduit system in the Dixie Valley geothermal system. The Senator thermal area seems to us like an especially good place for this project. The corehole arguably wouldn't have to penetrate the producing zone at great depth, just the structures that provide those conduits, but at higher elevations. Drilling expense would thereby be greatly minimized. A slant hole angled back toward the range from the middle of the so-called Senator "dead zone" would provide a great test of the single-fault vs. the multiple-fault hypotheses, and additionally would penetrate several hundred meters of silicified and mineralized alluvium; a massive young hydrothermal vein up to meters thick; the principal percolation pathway for injection in the northern Dixie Valley geothermal system; and a probable major buried gravity-slide block.

- Carry out more extensive age-dating and thermal-history modeling of the Dixie Valley geothermal system. ^{14}C dating of sinter deposits above the system suggests to some that the field could be very young, a few thousand years. Other large systems that have been more extensively dated are generally much older than this, typically several hundred thousand years, so it would be useful to learn if the Dixie Valley geothermal system is the largest and hottest known deep-circulation system in the Basin and Range simply because of its (apparent) youth. The problem in Dixie Valley for age-dating heretofore has been the lack of suitable secondary minerals. However, recently-drilled injection well DV 38-

32 in the Senator area penetrated numerous hydrothermal veins and silicified alluvium bearing abundant hydrothermal adularia. This mineral lends itself extremely well not only to age-dating, but also detailed thermal-history modeling. We should know quite soon if the field has been characteristically long-lived, or is a relatively recent feature.

- Complete a detailed, 3-D geological and conceptual model for the Dixie Valley geothermal system. The model would encompass stratigraphy and lithology; the fracture network (the “plumbing system”; hydrothermal alteration mineralogy and zoning; vein mineralogy, zoning, and paragenesis; the nature of the caprock; temperatures; temperature gradients; fluid compositions; and fluid inflow, outflow, and upflow zones.

- Complete, interpret, and model a high-resolution magnetotelluric transect through the Dixie Valley geothermal system. This work would help constrain the structural setting, fluid distributions, and the depth to the brittle-ductile transition in central Dixie Valley and the adjacent Stillwater Range.

- Critically evaluate similarities and differences between Dixie Valley and the much more thoroughly drilled but otherwise broadly analogous Railroad Valley in eastern Nevada. The latter basin has produced about 45 million barrels of oil from structural and stratigraphic traps in the basement immediately beneath its thick alluvial and lacustrine-sedimentary fill. The valley has therefore been extensively investigated by seismic and other geophysical techniques, geologic mapping in the adjacent ranges, and, most importantly, by hundreds of wells as deep as 4,000 m or more. One of the Railroad Valley oil fields even coincides with (and was generated by) an active, moderate-temperature geothermal system. We believe there is a great deal of insight to be gained by intensively comparing and contrasting Railroad Valley with its less-explored analogue in the west-central Basin and Range.

- Continue to hold workshops on the Dixie Valley geothermal system at appropriate intervals. These gatherings provide a wonderful forum for discussion and lively debate; for bringing newer members of the scientific team up to date on past and ongoing work; and for consensually developing new strategies to enhance geothermal exploration and development in the region.

6. *Would doing more research make a real difference in our understanding of Dixie Valley and of geothermal systems in the Great Basin in general?*

From our responses to the preceding questions, it will come as no surprise that we unanimously answer this one in the affirmative.

7. *Does a lack of knowledge prevent us from drawing meaningful conclusions about the geothermal system or have we learned enough?*

As we have indicated, we believe there is still a great deal of useful information to be gained from further investigation of the Dixie Valley geothermal system and its regional setting. This conclusion in no way detracts from the immense scientific and practical return from the many fine DOE-sponsored research projects already completed or still underway in Dixie Valley. That body of work provides an unmatchable groundwork for the studies that we all agree should follow.

8. *Is Dixie Valley a model/prototype for other systems in the Basin and Range*?

There is no doubt in our minds that all deep-circulation geothermal systems are "variations on a theme," just as, for example, all Carlin-type precious-metal deposits conform to a general model. However, like the ore bodies, each deep-circulation geothermal system will differ in many ways from others of its kind. We suggest that the differences do not detract from the value of a general model in exploring for or developing both types of resource.

9. *Can the understanding/knowledge gained at Dixie Valley be applied to other Basin and Range geothermal systems? If so, identify the steps and strategies that should be followed to find and develop other Basin and Range fields based on the Dixie Valley experience.*

Our group's positive answer to the first part of this question will not be unanticipated. However, we also believe that the geothermal companies actually assuming risk and spending good money to explore for and develop deep-circulation systems in the Basin and Range are far more qualified to devise integrated strategies for these activities than the researchers assembled for this workshop. We believe that all of the research techniques developed and applied at Dixie Valley have provided valuable new insight into the way that the system works and what controls its location. In answers to the foregoing questions, we have listed several of these methods and applications that we agree have been or will be particularly effective in this regard. We can advise, but the companies themselves are in the best position to select and deploy these techniques in the most effective and economical combinations and sequences.

10. *Would further study of the Dixie Valley geothermal system provide meaningful information of use in developing Enhanced Geothermal Systems (EGS) in the region?*

This question was not on the list of nine provided by the Workshop organizers, but we took the liberty of adding and discussing it because EGS will clearly play a big role in future geothermal development in the Basin and Range and elsewhere. As Colin Williams insightfully noted during the discussion, most of the things we need to know for optimal development of a conventional geothermal system are equally applicable to EGS.

We appreciate the opportunity to have participated in this Workshop, and thank the Great Basin Center for Geothermal Energy, the Department of Energy, and Caithness Operating Corporation for making the event possible. Our thanks to Sue Lutz for managing to contribute effectively to the discussion while meticulously recording the notes on which this summary is based.

AUTHOR: Paul Kasameyer

NOTE TAKER: Mike Shook

GROUP: Summary of Discussion Group on ***Exploration Technology Applications,*** Workshop on Dixie Valley Geothermal Research, June 12-14, 2002.

GROUP MEMBERSHIP: Ben Barker, Brian Bernard, Dylan Canoles, Paul Gettings, Paul Kasameyer, Greg Nash, Gary Oppliger, Mike Shook, John Stodt, and Jim Taranik.

Summary

This group did not work through all of the questions individually; rather, we answered most of them in somewhat roundabout ways. The consensus of the group was stated as:

"We want to look at cost-effective tools to extrapolate relevant information from Dixie Valley studies for Basin and Range exploration; i.e., develop a template to derive (extract) information, and subsequently apply the information."

The following are questions and discussions that were held.

1. *What are the data holes? This includes 'what do we know, and what don't we know' in our discussions.*

- Issues such as 'where is the ductile zone?' We could use that sort of information to look for blind systems (e.g., if it's shallow here, where else is it shallow?)
- How long is Dixie Valley "steady state" (what does steady state mean)? What is the period of episodic changes?
- We know it is structurally controlled; what tectonic activity keeps it open and over what characteristic time period? Various solutions were proposed, including more dense (and accurate) GPS surveys, ground magnetics, INSAR, etc. Arguments arose over relevant time periods (e.g., INSAR would require multiple years of measurements before being applicable).
- We don't know what the structural control is. We don't know effective strain rates, methods for maintaining open fractures, etc. We could conceivably use a study hole (to measure strain?), INSAR, etc.

2. *What more is needed?*

- Several members of the group noted that, while there is an abundance of researchers involved in Dixie Valley, not a single attempt was made at integrating the data/interpretations collected into a reservoir model of any sort. This was somewhat disconcerting, since the reservoir is ultimately the resource, and its behavior is that which we seek to predict
- A universal recommendation was that a regional study was warranted in order to put Dixie Valley in its regional context. Various arguments arose. Some suggested studying three valleys in either direction (to the NW and SE, where no current

development exists); others suggested comparing Dixie Valley to, a nearby (~ 50 mile) field.

- The second recommendation that was adopted was conditional. If DOE were to continue funding research, the first activity should be to integrate all study results into a single Dixie Valley model. This serves two purposes: first, it identifies what has been done to researchers in other fields of study (for their use and interpretation), and it also better identifies what specific new pieces of information are required.
- Should DOE elect to not continue funding work at Dixie Valley (or Basin and Range), then the final task should be to collect and catalog the data, interpretations, etc. that have been done. Little or no attempt should be made to integrate, etc. The effort should be relatively low effort; create a library of the datasets, put them on CDs, and make available to interested users.

3. *Should DOE continue to support research at Dixie Valley?*

The researches are enthusiastic about their research at Dixie Valley, and, as is expected, most believe that further research at Dixie Valley is important.

AUTHOR: B. Mack Kennedy

NOTE TAKER: Carol Bruton

GROUP: Summary of Discussion Group on ***Geochemical Studies***, Workshop on Dixie Valley Geothermal Research, June 12-14, 2002

GROUP MEMBERSHIP: Carol Bruton, Fraser Goff, Cathy Janik, Mack Kennedy, Dave Norman, Joel Renner, Lisa Shevenell

1. *What is known about Dixie Valley?*

- There is no evidence for an active magmatic system. Excess ^{3}He may represent active flux of mantle volatiles into and through the range front fault system combined with deep recharge of the system.

- The ^{14}C ages of valley waters are consistently older than ~10,000 years, whereas mountain waters are younger than ~10,000 years.

- Most spring waters of the Stillwater Range are older than those of the Clan Alpine Range.

- The hydrogen and oxygen isotope values of the mountain waters are higher than those of the valley groundwaters, hot spring waters, and geothermal reservoir fluids, suggesting that the valley waters were recharged during a colder Pleistocene climate. This is consistent with a model ^{14}C age of <20,000 years for the reservoir water.

- ^{36}Cl concentrations and ^{36}Cl/Cl ratios indicate that valley waters and reservoir fluids evolved from water with exceptionally low meteoric chloride concentrations. In contrast to the valley waters, mountain waters contain excess ^{36}Cl from meteoric chloride accumulation in soils due to near-surface evaporation of rain water. These relations indicate that recharge to the geothermal reservoir occurred through a water-saturated zone, presumably a lake bottom during the Pleistocene as inferred from the ^{14}C age model.

- Waters of the Dixie Valley system are fundamentally of two types, and both have been altered to varying degrees and compositions by subsequent water-rock interaction and temperature of interaction. Sr and C isotope compositions are consistent with widespread interaction with lithologies containing marine carbonates.

- Helium isotopic compositions and He/Ar ratios indicate that every Dixie Valley thermal feature sampled from well 45-14 in the south to Sou spring in the north (except perhaps well 66-21) has a component indistinguishable from the Dixie Valley geothermal fields reservoir fluid.

- Travertine and sinter deposits associated with the present day range front fault vary in age from recent (1954?) to at least 12,000 years. Other deposits have ages up to ~140,000 years.

- Production-induced pressure declines allowed cooler waters from the reservoir margins to be drawn into the system, as supported by the existence of low-maturity oils and magnesium-rich scales deposited on hangdown strings and at wellheads.

2. *How can we explain the origin and nature of the geothermal system in place?*

- Current ^{36}Cl and $^{36}Cl/Cl$ data suggest that vertical recharge occurred downward through saturated rock to deep enough depths to attain 250-285^{o}C. The Pleistocene age Dixie Valley Lake is the inferred recharge source. The reservoir fluid could not originate from ^{36}Cl-rich mountain waters, and no recharge from the mountains into the reservoir should be expected today. However, further work needs to be done to further explore issues related to the hypothesis.

3. *What exploration and characterization techniques or models have seemed to work best and which ones have apparently not been so effective?*

- Stable isotopes ($\delta^{18}O$, δD, $\delta^{13}C$), noble gas isotopes and abundances, and ^{14}C and ^{36}Cl proved to be viable and important geochemical tools for reservoir characterization and for determining fluid origins.

- Chemistry and isotopic compositions of fumarole gases indicate source temperature (e.g. gases from the Senator fumarole suggested a 200–240^{o}C source).

- The SO_4-H_2O oxygen isotope geothermometer applied to compositions of the early production waters is expected to indicate the most accurate original reservoir temperatures due to the "long memory" (i.e. slow re-equilibration kinetics) of this isotope system.

- Presence of sinter deposits suggests source temperatures of at least 180^{o}C, according to conventional wisdom.

4. *What don't we know? Identify holes or inconsistencies and differences of opinion among experts in our knowledge of Dixie Valley and its geothermal system.*

- Regional water chemistries suggest many different water-rock equilibration paths. Yet He and Ar data imply only two fluid types. Does this imply that the water chemistry and noble gases are decoupled and if so, why, how, and what are the implications for fluid source and history?

- There is not enough Basin and Range He isotope data to evaluate if the Dixie Valley He isotopic values of 0.75 Ra, which imply that ~10-15% of the He is mantle derived, are anomalous in a regional context.

- A detailed hydrologic model of deep fluid flow. What are the circulation paths from shallow recharge to depth and back. What controls where the deep fluids rise? What determines and maintains deep permeability?

- There seems to be a connection between the deeper and shallow systems. How and where is the mixing occurring? What effect does mixing have on water chemistry and isotopic compositions.

- There is no consensus on the fault structure.

- We do not know the history of the system, how old it is, or the timing of heating of the system.

5. *Do we need more research? What should be done?*

- Place further constraints on the age and thermal history of the system.

- Conduct a regional study of another Basin and Range geothermal system to determine to what extent the chemical and isotopic signatures and patterns are similar to that observed at Dixie Valley, and which signatures can be used in exploration programs.

- Synthesize and integrate the considerable data that have been collected thus far that have not yet been thoroughly interpreted, creating a database and web site.

- Map geochemistry into the geologic and structural models to further our understanding of compartmentalization, etc., particularly the barrier between section 33 and 7 wells where the nature of the barrier is unknown.

6. *Would doing more research make a real difference in our understanding of Dixie Valley and of geothermal systems in the Great Basin in general?*

- There are some existing gaps in the geochemical data base, such as chemical and isotopic composition of fluids from well 35-14.

- The existing vast chemical and isotopic data base acquired as part of the regional hydrologic study needs to be synthesized before this question can be adequately addressed.

- Additional studies of the geothermal reservoir would be focused on geochemical monitoring of the effects of injection and other operator practices, but these should not be a DOE activity.

7. *Does a lack of knowledge prevent us from drawing meaningful conclusions about the geothermal system or have we learned enough?*

- Presently, the geochemists, geophysicists, structural geologists, etc. tend to operate and communicate within their separate groups. There needs to be more communication/coordination among the individual specialties.

8. *Is Dixie Valley a model/prototype for other systems in the Basin and Range?*

- Not at the edges of the Basin and Range, where systems have a larger and perhaps active magmatic contribution.

- Have no reason to believe that other central Basin and Range systems would be different from the Dixie Valley geothermal system. Economically viable systems in the central Great Basin may occur primarily in areas where Pleistocene lakes provided localized vertical recharge.

- What we have learned studying Dixie Valley has been extremely useful in studying the Lightening Dock system in the southern Basin and Range; there are numerous similarities between the systems.

9. *Can the understanding/knowledge gained at Dixie Valley be applied to other B & R geothermal systems? If so, identify the steps and strategies that should be followed to find and develop other B & R fields based on the Dixie Valley experience.*

- Yes. – see above.

- Steps/strategies to find/develop other Basin and Range systems:

  - Collect available water well data.
  - Sample surface waters and gases, as available, for chemistry, isotopes and noble gases.
  - Collect evidence from structural features, paleo-surface deposits, etc.
  - Do not restrict sampling and investigations to the range fronts and thermal features.