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UPDATE OF A TRIAL OF CO_2-BASED GEOTHERMAL AT THE ST. JOHNS DOME

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ABSTRACT

In September of 2010, GreenFire Energy received a DOE grant to attempt a real-world trial of CO_2-based geothermal energy (CO_2G) at a site on the St. Johns-Springerville CO_2 Dome near the Arizona-New Mexico border. Though CO_2G was proposed in 1998, and there has been a significant amount of computer modeling, there has never until now been an attempt to test the idea in the field. The chosen site is uniquely suited for testing CO_2G, as it incorporates the St .Johns CO_2 reservoir, from which approximately 450 MM tons of CO_2 is recoverable from relatively shallow deposits. The CO_2-bearing formations overlie a moderate-temperature geothermal area. Thus the plan is to produce CO_2 from the shallow formations, compress as necessary to obtain supercritical CO_2, which will then be injected into the hot basement granite/schist formation containing the geothermal heat. This paper will describe the work to date, including a summary of the pertinent literature and early results from passive seismic monitoring of the site. Plans for further research will also be discussed.

INTRODUCTION

This paper will start with a quick review of why CO_2-based geothermal energy (more particularly, CO_2-based EGS, which GreenFire calls CO_2G) is a reasonable thing to attempt. We will then consider the location of GreenFire Energy's project and its current status, including what we know of the site's geology and geophysics, geothermal energy potential of the area, and the permitting process in which we are engaged.

Conventional geothermal and conventional Enhanced Geothermal Systems (EGS) have always been about water. The Geysers Field, the US' best-known hydrothermal field, for example, uses naturally-heated water for its power generation facilities. Heat gradients in that field range up to over 250°C/km of depth.[18] EGS is sometimes known by its alternative name, "Hot Dry Rocks;" those rocks presumably need only water to turn into conventional geothermal systems.

Perhaps the best-known US EGS study was the DOE/Los Alamos project at Fenton Hill, NM.[16] It was a 20-year effort (1975-1995) that cost roughly $175 million, mostly from the Department of Energy, but with about $32.5 million from Germany and Japan. A reservoir was created by fracturing, and several short- and long-term tests were conducted by injecting water into the newly-created void spaces. Don Brown, one of the Los Alamos researchers, speculated that fluids other than water might be appropriate for EGS and filed for a patent[5] that today protects the idea of using CO_2 rather than water as heat carrier in EGS projects.

WHY CO_2?

There are a number of reasons why CO_2 might be considered for geothermal applications and a couple of reasons why caution might be necessary. First, in geothermal applications, CO_2 will essentially always be in the supercritical state. The phase diagram of CO_2 is shown in Figure 1.

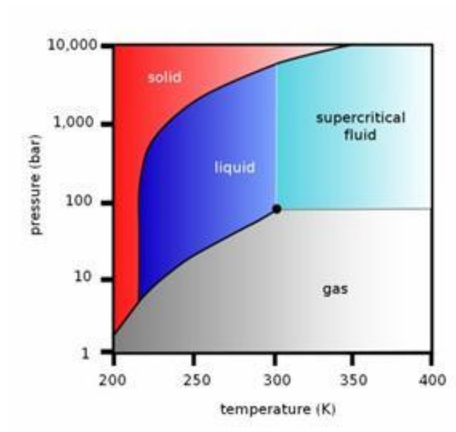

Figure 1: Phase Diagram for CO_2

Note that the critical point is only at 31.1°C (88°F) and 73.77 atm (1070 psi), so the supercritical state is easily achievable. By comparison, water's critical temperature and pressure are 369.1°C and 218.3 atm, conditions much harder to attain. Remember that supercritical fluids have density much like that of liquids, but many other properties like those of gases. Moreover, for CO_2, the solubility properties change immensely, in that supercritical CO_2 tends to behave like an organic solvent, much like pentane or hexane.

Of course, when considering geothermal applications, the heat capacity of the fluid is of primary concern. Figure 2 compares the heat capacities of water and CO_2 at 150°C.

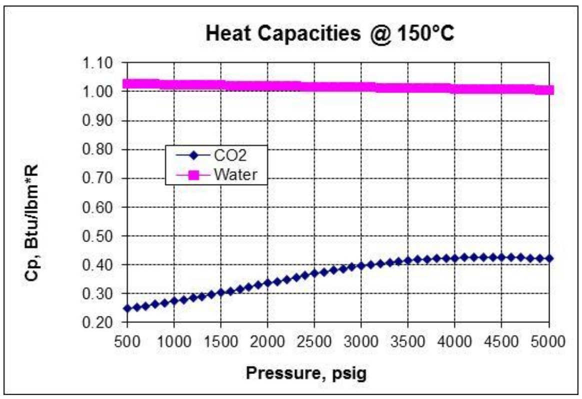

Figure 2: Comparative heat capacities for water and CO_2

Clearly, water has greater heat capacity by factors of 2½ to 5.

Another important property in heat transfer, since heat capacity has units of heat per unit mass, is the density of the fluids. Figure 3 compares the densities of water and CO_2 under the same conditions as the heat capacities shown in Figure 2. Again, water clearly has an advantage.

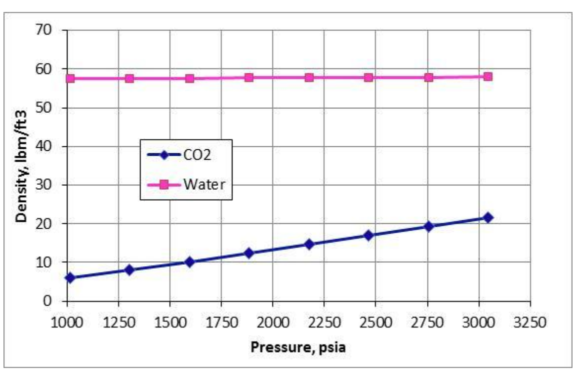

Figure 3: Densities of water and CO_2 at 150°C

Let us now consider the viscosities of water and CO_2, since the viscosity is a critical determinant of fluid flow through pores in heated rock formations. Note in Figure 4 that the viscosity of CO_2 is a factor of 4 to 9 less than the viscosity of water.

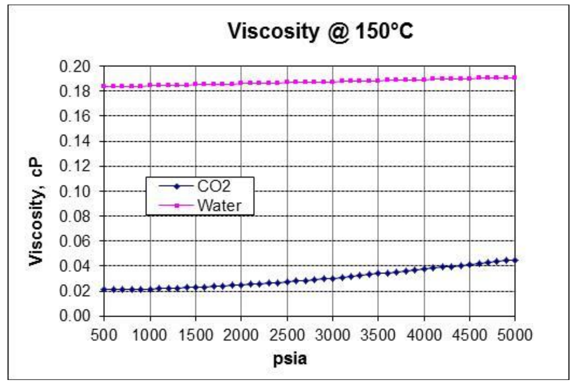

Figure 4: Viscosities of water and CO_2 at 150°F

Moreover, since CO_2 in geothermal applications will be a supercritical fluid – and supercritical fluids do not exhibit surface tension – CO_2 will flow much more easily through formations than water. In fact, some calculations suggest that overall, CO_2 will be 50% more efficient at removing heat from rock than water!

Obviously, because of CO_2's lower density and viscosity, pumping CO_2 will be far less difficult than pumping water, though volumetrically more CO_2 than water will have to be pumped for the same amount of heat removal.

CO_2 has two other significant advantages over water. First, CO_2 is not generally as reactive to rock formations as water. Secondly, the changes in density with temperature and pressure of supercritical CO_2 suggest that the use of pumps for moving CO_2 could be partially or completely eliminated by formation of a thermosiphon.

Figure 5 show the ratios of supercritical CO_2 density at several different temperatures over some pressure ranges typical of geothermal projects.

Note that CO_2 at 2600 psi is nearly four times as dense at 75°C as at 350°C. At 2400 psi, it is twice as dense at 75°C as at 150°C. Exploitation of this difference in density by setting up a siphon, called a thermosiphon, may allow supercritical CO_2 to flow through the entire system without any pumps at all! Though this sounds totally unreasonable, a similar density siphon has been used in refineries for more than sixty years on a routine basis.

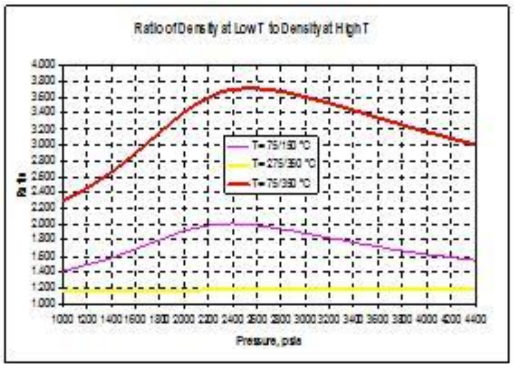

Figure 5: Density ratios of hot CO_2/cool CO_2

GREENFIRE'S PROJECT

GreenFire Energy was awarded a DOE grant in September 2010 aimed at implementation of a CO2-based EGS system at the Springerville-St. Johns Dome in Eastern Arizona.[14] With funding from that grant, we intend to accomplish the following:

1. Perform a feasibility study for the project at the location chosen
2. Construct a small seismic network and obtain background seismic information about the site; the same network will be used to monitor drilling and fracturing later in the project
3. Obtain the necessary permits for drilling, fracturing, and injection of CO_2
4. Drill a single well to about 6500' in depth, well into the granitic basement rock, depending on financing and ease of drilling
5. Perform a 'huff and puff' test by injecting and re-producing CO_2 to determine formation characteristics and verify previous modeling efforts for CO_2-based geothermal
6. Assuming all goes well to this point, install and test a small (1-2 MW) electrical generation system

We have chosen a site about a mile west of the Arizona-New Mexico border, just off US Highway 60, east of Springerville, AZ.

THE ST. JOHNS DOME

The St. Johns Dome covers approximately 1,800 sq. km. in Apache County, Arizona and Catron County, New Mexico. The nearest population centers are Springerville/Eager, Arizona, west of the dome near its southern margin and St. Johns, Arizona, to the northwest of the dome.

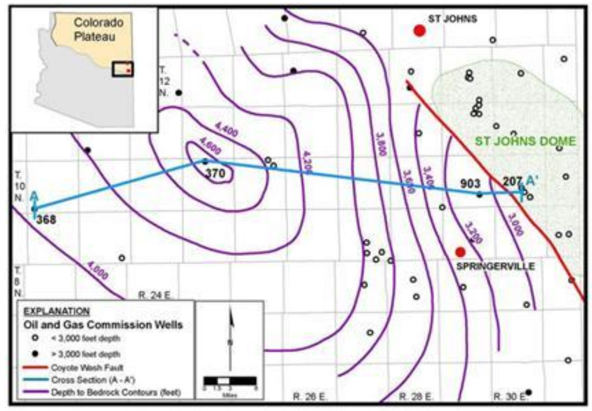

Figure 6: Location of the St. Johns Dome, and bedrock contour map

Geology of the Area

The dome is known both as the "Springerville-St. Johns Anticlinal Dome" and the "St. Johns Dome." In this paper, it will be referred to as "the St. Johns Dome" or, more simply, "the Dome." It consists of a broad anticline with an axis that trends northwest. A second anticline that trends northeast crosses the first and provides the dome structure. The dominant fault in the area is the Coyote Wash Fault. It defines the western margin of the dome. It and the other faults in the area appear to be high angle.

With respect to CO_2 reservoirs, the most important units are basement rock and the Supai Formation.[6, 12] Basement rock underlying the dome consists of weathered and faulted granites of pre-Cambrian age. Within the area of the dome, only a couple of wells have penetrated basement and then for no more than 100 meters. Depth to basement averages about 800 meters locally, but can be as deep as 1,300 meters.

The basement rock is overlain by an unconformity and then by a suite of sedimentary rocks of Permian Age. These rocks were laid down at the southeastern margin of sea; similar rock units are present to the west across the Coyote Wash Fault and to the north. Going from older to younger, they consist of the Supai Formation, the Coconino Sandstone (locally known as the "Glorieta Sandstone") and the Kaibab Limestone (locally known as the "San Andres Limestone"). A granite wash is present at the base of the Supai Formation and overlying the unconformity. A second unconformity defines the upper surface of these units.

A number of intercalated layers of anhydrite and mudstone are present within the Supai Formation. They are relatively impermeable and form cap rocks for the various CO_2 reservoirs. The University of Utah and others conducted a detailed study[2] of the behavior of CO_2 in several large, anticlinal domes of the Colorado Plateau. The St. Johns Dome was among the domes examined. A primary focus of this study was the formation of travertine deposits. Among the Quaternary units at the St. Johns Dome are travertine deposits that are some of the largest in the United States and range in age from 3,500 to 887 years BP. Their presence indicates that CO_2 has leaked from the dome in the past. At present, however, little or no deposition of travertine is occurring.

Figure 7 shows a northwest-southeast cross section of the Springerville-St. Johns area, including the dome. The CO_2 reservoir is confined to the Supai formation in this vicinity.[1]

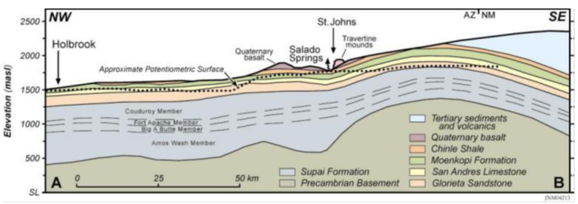

Figure 7: Geologic cross-section of the Springerville-St. Johns area

The generalized stratigraphy of the area is shown in Figure 8.[6] Three aquifers are generally present in the upper stratigraphy, usually at about 250', 800' and 1350' in depth.

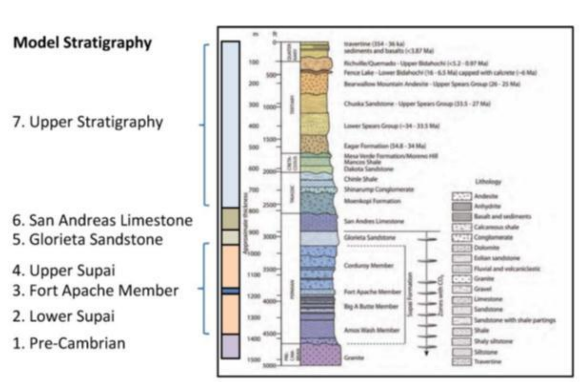

Figure 8: Generalized stratigraphic column for the Springerville area

Rocks from the Mesozoic, Tertiary and Quaternary Eras are also present in the region. They are of lesser interest because they do not contain the principal CO_2 reservoirs. Among the Quaternary units are travertine deposits that are some of the largest in the United States and range in age from 354,000 to 36,000 years BP. Their presence indicates that CO_2 has leaked from the dome in the past.[2] At present, however, there is little or no deposition of travertine occurring.

The dome is extensively faulted, not surprising since it is located at the intersection of two major regional structural areas. Figure 9[6] shows a generalized geologic cross-section through the Springerville area; the dip on the faults is inferred, since detailed information is not yet available.

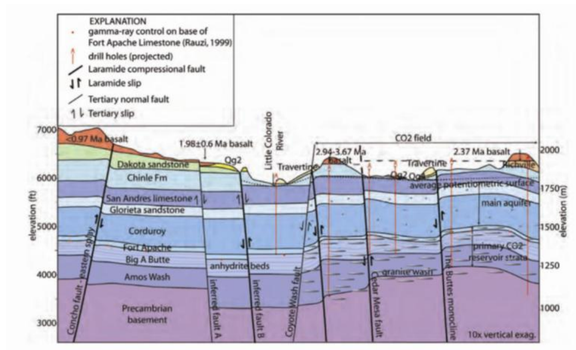

Figure 9: Geologic cross section through the Springerville area, showing faulting, with dip inferred

Geothermal Potential of the Dome

Local hot springs, geothermometry indicators and some relatively high down-hole temperature gradients are all indications of potential geothermal resources underlying the St. Johns Dome. As described below, a number of efforts have been made to determine the geothermal potential of the St. Johns Dome.

Measured temperature gradients are the most direct evidence of the presence of geothermal resources. A total of eight wells at the dome have been logged for temperature. The temperature gradients in these wells range from 22° C/km to 54° C/km. GreenFire Energy calculated these values by subtracting the average annual temperature in Springerville, AZ, (9° C) from measured bottom-hole temperatures and then dividing the result by well depth in kilometers. The results suggest the presence of a moderate geothermal resource underlying at least some portions of the dome. Note that these wells either did not penetrate the basement rock or penetrated it less than 100 meters. Also, the driller measured temperatures and that it is therefore possible that the fluid in the well bores had not come to thermal equilibrium prior to measurement. As a result, the calculated gradients are, at best, only general indicators of the geothermal resources at the dome.

The likelihood that there is a geothermal resource underlying the dome is also supported by temperature mapping in the region including the dome. Figure 10 was part of a map of temperatures at a depth 7.5 km that was prepared by the geothermal group at

Southern Methodist University. The larger map provided contoured temperatures at depth based on several factors. It was originally downloaded from Google Earth. It is the equivalent of Figure 2.7e in a recent MIT report on geothermal energy.[17] The larger map is centered on the Four Corners Area. The inset map shows an expanded vies of the St. Johns Dome area. The black line outlines the lease holdings of Ridgeway Arizona Oil Corp, the primary leaseholder of CO_2 rights at the dome. The background colors represent temperature ranges inferred from the data. These data suggest the presence of a moderate temperature geothermal resource below the dome.

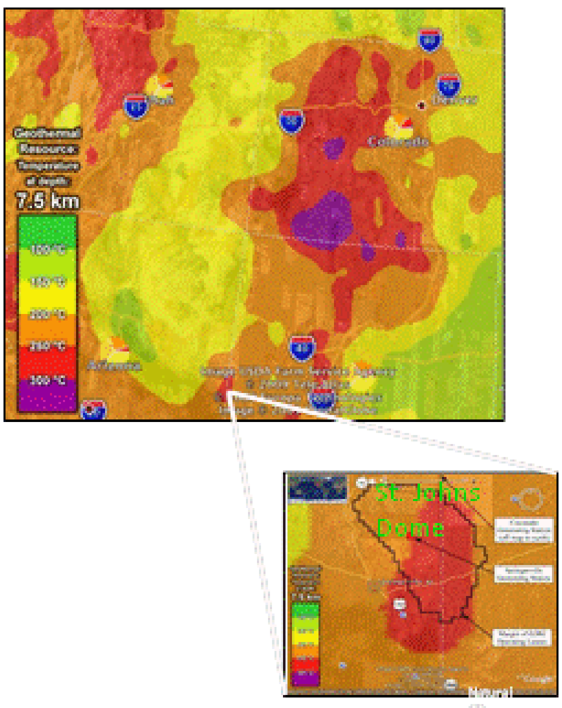

Figure 10: Estimated geothermal heat at the Dome

History of Drilling at the Dome

The St. Johns Dome has been the site of a small amount of exploration for oil and gas, but by far the largest number of wells at the Dome has been for the purpose of exploiting its CO_2 resources. The Arizona Oil and Gas Conservation Commission lists 78 wells drilled on or near the structure, starting in 1939.

Exploration for CO_2 started only in 1994; Ridgeway Arizona Oil Corp (RAZO), a subsidiary of Enhanced Oil Resources, Inc. (EORI), of Houston, has been the primary driller, responsible for 43 of those wells. EORI's announced intent was originally to produce CO_2 at the Dome, then send that CO_2 to the Permian Basin oil field via pipeline for use in tertiary oil recovery. However, EORI was never able to obtain sufficient financing for the pipeline.

EORI has also looked at separating and selling the helium found in the St. Johns Dome CO_2; again, lack of financing has prevented that from happening.

In December, 2011, EORI announced that it is selling its assets at the Dome to Kinder Morgan, one of the US' largest pipeline companies; that sale is scheduled to close January 31, 2012.

Though EORI owns most of the CO_2 production area at the Dome, several other entities also own portions. Of those other owners, Hunt Oil of Houston is the largest. Figure 11 shows the boundaries of the unitization agreement.

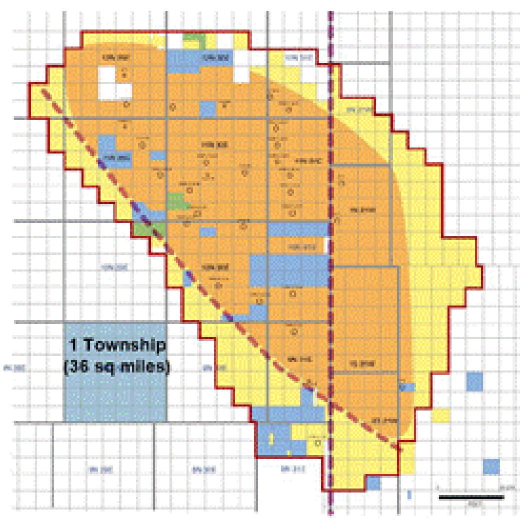

Figure 11: St. Johns Dome Unitization Agreement Map; EORI parcels in gold, Hunt Oil in blue.

GEOTHERMAL PROJECT IN ARIZONA

General

Arizona has a very slim history of geothermal projects; in fact, until last year, the Arizona Land Department had not issued a geothermal exploration permit in more than 25 years! Surveys of the entire state's geothermal potential were published in 1978,[7] 1979,[19] 1980,[8] and 1982.[15] In addition, specialized geothermal surveys of various areas of the state were published between 1979 and 1982,[3] and a complete bibliography of citations from 1900 through 2009 on geothermal energy in Arizona can be downloaded from the Arizona Geological Survey.[4]

In addition to these publications, there have been two other geothermal projects near ours in the last twenty years, the Alpine project, and the Navopache project.

The Alpine Project

In 1993-94, the State of Arizona and U. S. Department of Energy funded a drilling project to determine if near-term hot dry rock (HDR) geothermal potential exists in the eastern portion of the White Mountains region of Arizona.[20] A 4,505 feet deep slim-hole exploratory well, Alpine l/Federal, was drilled within the Apache-Sitgreaves National Forest at Alpine Divide near the Alpine Divide campground about 5 miles north of Alpine, Arizona in Apache County, or roughly 25 miles south of GreenFire's project. The results of this project are recounted in two technical reports, discussing in Part 1[21] the drilling operations, logging program, permitting and site selection for the hole and in Part 2[22], the temperature gradients, heat flow, geothermal potential, and subsurface geology of the site.

Originally, the project was designed to drill into the Precambrian basement rock where it was anticipate that sufficiently hot granitic rock would be found. However, it was discovered that the basement rock was at least 800-2000 feet deeper than the well drilled. Because the exact temperatures in the basement rock were still almost unknown at the end of the project, and because of the additional drilling cost that would be incurred to reach that depth, power production from this site was deemed uneconomical, and the project was terminated.

The Navopache Project

Interestingly, despite the presence of two large coal-fired power plants, Apache County, Arizona receives none of its electric power directly from those plants. Rather, the Navopache Electric Co-op serves the Navajo and Apache Indian reservations (hence its name) and surrounding areas; it has only about 32,000 customers altogether. As described in a 2009 webinar[9] sponsored by the Geothermal Resources Council, Navopache was planning a 50 MW EGS facility in the Nutrioso Valley near the Alpine 1 project. However, according to a webinar in 2011,[10] because they were unable to obtain funding for the project, the location has been changed to an area on the St. Johns Dome, about a mile southwest of the Springerville Power Generation Station. So far, Navopache has obtained the first round of permits (i.e., about the same place in the permitting process as GreenFire), but funding for the Navopache project is extremely uncertain.

SEISMIC ACTIVITY NEAR THE DOME

The area of the project appears on seismic activity maps as nearly inactive. It is, however, important to note that very little study of the area has ever been accomplished, and the area is sparsely populated, so the "nearly inactive" label is best taken with a grain of salt. One survey of short-term microearthquake activity correlated with potential geothermal areas in Arizona was published in 1980.[13]

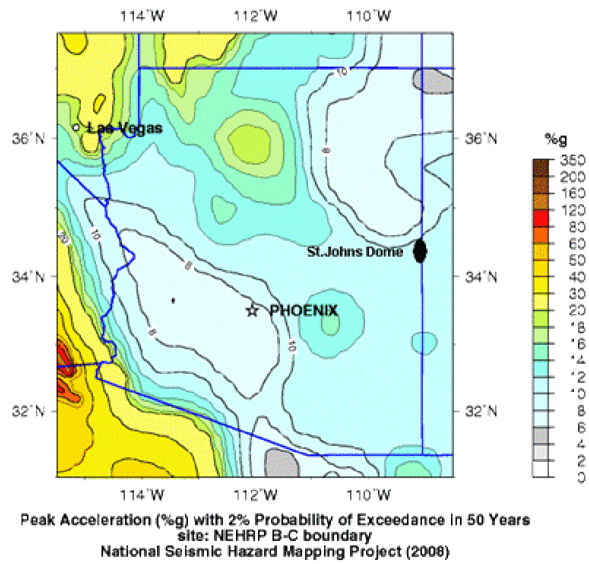

Figure 12: Distribution of seismic activity in Arizona

In order to obtain a good baseline seismic activity before commencing our drilling, a seismic array was designed and installed in August 2011.

The seismic network

Figure 13 shows the design and planned positions for the five sensor stations; the design is a 5-spot, with each of the four peripheral sensors approximately one mile from the central station (SJ1), which is about 10 meters from the planned drilling site. The figure is based on the USGS map of the area; the red lines are section boundaries. By convention, each section is approximately one mile square, with the exception of those on the Arizona/New Mexico border.

Figure 13: Seismic station locations

Each station is comprised of a three-component seismometers with natural frequency 2 Hz, recording on a data logger. The sensors were buried in small pits 1-2 feet deep, floored with small cement pads. The instruments were leveled and orientated north. The sensor pits were then back-filled with dirt.

The rest of the equipment at each site was installed in electrical wiring boxes bolted down to ~150-lb concrete pads to deter theft. A 50-watt solar panel is attached to each box lid, tilted up and faced south to increase its efficiency. Sealed lead-acid batteries provide enough power to run the stations for ~ 20 days, ensuring continuous operation if the solar panels become covered with snow for short periods in the winter. Stomp tests confirmed the proper working of all the stations; a few days of recorded data were examined before leaving the field area.

<u>Initial Results</u>

Of the 112 days of data recorded at the time of the first report, so far only 39 days have been fully processed. It is obvious that the seismographs are responding at least as well as expected to signals of all types. For example, the station closest to Highway 60, SJ1, recorded nearly 112,000 triggers in the first 39 days, most of them due to road traffic. The quietest station, SJ2, recorded only about 1100 triggers in the same time period.

Most of the signals appear to be due to natural noise (e.g., wind, thunder, animals nearby) or of cultural origin (e.g., road traffic, gunshots, aircraft.) There are also signals that were identified as those of regional earthquakes tens to hundreds of kilometers distant. Identification of earthquake signals is facilitated by recognizing that an arriving seismic P-wave should cross the network in no more than two seconds. Scanning for windows containing nearly-coincident signals for at least four of the five stations yielded a shortlist of 1176 windows for closer examination.

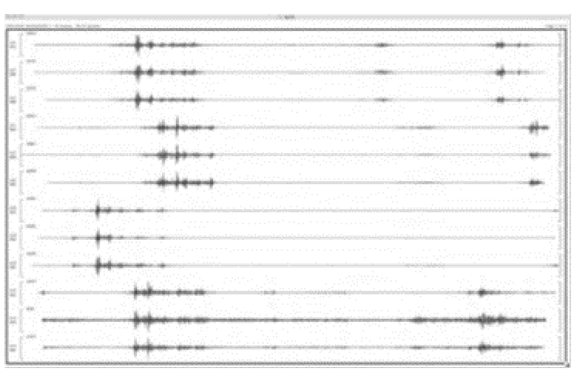

Figure 14: Recording of a non-earthquake event, possibly thunder. The onset times at the different stations vary by more than 2 s, indicating that the event passed across the network more slowly than expected for a true earthquake.

A significant number of triggers are earthquakes. The majority of these are distant, with time delays between the arriving S- and P-waves of the order of 30 s (Figure 15). This translates to distances of the order of 150 km (~ 90 miles). These earthquakes are termed “regionals” (they are in the same geographic region, but they are not local to the network). Since they lie so far outside of the St. John’s Dome network, they cannot be well-located by it, and we thus have not attempted to do so.

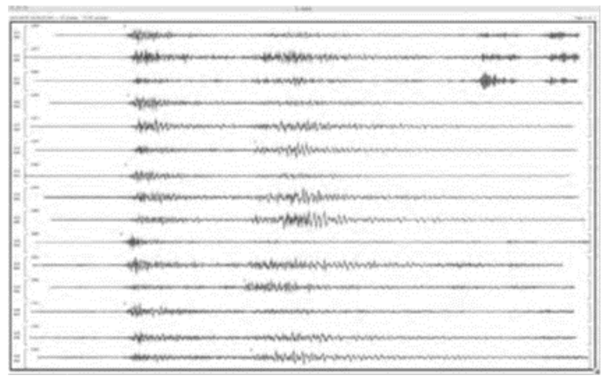

Figure 15: A regional earthquake with an S – P time of ~30 s, indicating an epicentral distance of ~150 km (~90 miles)

A map of regional earthquakes taken from the ANSS[24] catalog for the time-period 1980 through 6 January, 2012 is shown in Figure 16. This gives some idea of the likely locations of the regionals recorded by our network. Most of the activity is north and west of the Colorado River and in the Gulf of California; earthquakes near the St. Johns Dome large enough to be recorded on the national network are rare.

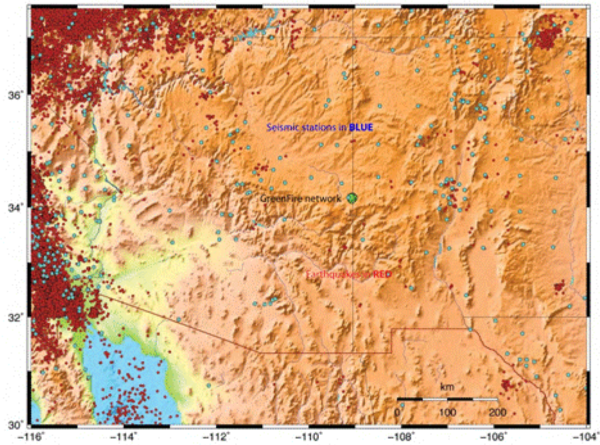

Figure 16: Map of regional earthquakes for the period 1980 through 6 Jan 2012 (red dots.) Seismic stations shown as turquoise dots. Not all of these stations operated for the entire period; not all are still operating. The St. Johns Dome network shown as large green dots.

In the 39 days of initial data, we have found 21 earthquakes with epicentral distances less than 25 km (15 miles.) The locations for these earthquakes are shown in Figure 8.

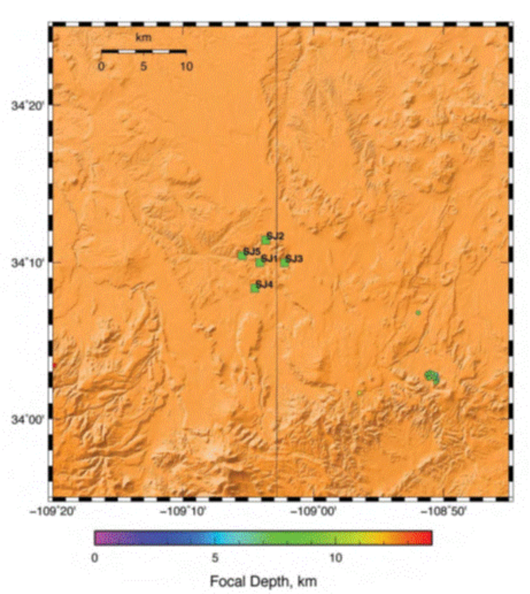

Figure 17: Locations of earthquakes from early data from St. Johns seismic network.

Nineteen of the earthquakes form a tight cluster in both time and space about 22 km (13 miles) southeast of the network over the span of November 1-10, 2011; most have a calculated hypocentral depth of 6-11 km, though the one furthest west is somewhat deeper. The location of the seismic swarm appears to be the Red Hill volcanic field.

It is worth noting that calculation of locations and depths so far outside the seismic network is somewhat unusual, but does indicate the sensitivity of our instrumentation. Nevertheless, the absolute accuracy of the calculated hypocenters is relatively low because, being outside the network, there are geometrical constraints, and because we have only an approximate crustal model.

In the future, we will attempt to add data from other regional seismic stations, if available, which will ease the geometric constraints. We will also modify our crustal model as more information is obtained.

CONCLUSIONS - WHERE THE PROJECT STANDS

Seismic Work

As shown above, the seismic network is in place and operating well. We expect that it will provide data about the near-term environment of the project, plus important seismic data during drilling and fracturing of the formation, and during CO_2 injection.

Well Plan, etc.

We are negotiating with several firms to design the well itself, including the details of logging and coring, plus associated surface equipment. Help from Ridgeway Arizona Oil Corp will enable us to avoid some of the problems associated with earlier drilling at the Dome.

Permitting

Table I describes each major permit that we are required to obtain and the status of our applications. We are negotiating with consultants familiar with the permits and agencies to assist with the permits that have yet to be issued.

Table 1: Permits required and their status

Permit	Purpose	Responsible Agency	Status	Issue Date
Mineral exploration	Access site, drill exploration well	AZ Land Department	Issued, #08-115809	17-Aug-11
Site access	Access sites for well and seismic stations	AZ Land Department	Issued	9-Sep-11
Well drilling	Drill, complete, and (eventually) close in well	AZ Oil and Gas Conservation Commission	In process	March 2011?
Class V Injection	Inject CO2	US Envir. Protection Administration	In process	Late 2012/ early 2013
Aquifer Protection	Assure no contamination of	AZ Dept. of Envir. Quality	In process	Late 2012/ early 2013

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