SEISMIC MONITORING OF THE

JULIA DAVIS PARK WELL

BOISE GEOTHERMAL SYSTEM

BOISE, IDAHO

Report Prepared for
The City of Boise

J. E. Zollweg
October 2001
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Abstract
A sensitive seismograph station was established near Boise to monitor possible changes in
seismicity that might result from injection of water into the Boise Geothermal System at
the Julia Davis Park Well. The seismograph station recorded swarms of extremely small,
shallow earthquakes that may be related to the geothermal system and/or production
activities. These earthquakes probably originate in competent rock formations above the
local basement rock. The thicknesses of these formations are such that the maximum
earthquake attributable to brittle failure within a single formation is about magnitude 1.5
to 2. A small number of tectonic earthquakes originating within about 25 mi of Boise was
also recorded. Some or all of these may be occurring along the Boise Front Fault System,
to which the Boise Geothermal System is closely related. The region in which the
earthquake swarms must occur is spatially well-separated from any of the recorded
tectonic earthquakes.

Hypothetical models were developed to decide whether the swarms are due to tectonic or
geothermal causes. A geothermal cause is preferred. It is not possible to completely rule
out the possibility that injection well activities might trigger more significant earthquakes
on the Boise Front Fault System. The occurrence of earthquake activity within the Boise
Geothermal System provides a potentially worthwhile tool for characterizing the reservoir
system and managing its utilization.
Introduction

The Boise Geothermal System was one of the first geothermal reservoirs in the United States to be exploited. Over the course of more than a century of use, an increase in hot water extraction caused a drop in artesian levels. This prompted the City of Boise, with assistance from the U. S. Department of Energy, to drill an injection well at Julia Davis Park with the purpose of stabilizing and restoring the geothermal reservoir system.

The Boise Geothermal System occurs just east of downtown Boise. Its existence and maintenance are genetically linked to faults and fractures of the Boise Front Fault System (Wood and Burnham, 1987). Geothermal waters originating in the Idaho Batholith are believed to rise along the Boise Front Fault System to a point where they intersect a permeable rhyolite aquifer. Percolation through the rhyolite is probably controlled by fractures, and the horizontal extent of the permeable zones may be influenced by other faults in the system (Wood and Burnham, 1987; Liberty, 1996). The choice of the location of the injection well was in part influenced by the locations of faults in the subsurface (Liberty, 1996).

The Boise Front Fault System, while not currently classified as an active fault, is a potentially active fault based upon its orientation within the regional stress field and its position as a boundary fault of the Western Snake River Plain. On the opposite side of the Western Snake River Plain, active faults have been found near and along the boundary, suggesting that both sides of the Plain may be bounded by active faults and raising suspicion regarding the Boise Front Fault System's status. Some historical earthquakes have been felt in Boise that may have occurred near the city. Seismic stations operated near Boise in the past have observed a low level of microearthquake activity that may be occurring along the Boise Front Fault System or on other fault structures. No detailed study of the locations of these events is possible with existing data and so their exact relationship to geology or the geothermal system is unknown. However, they provide evidence that there may be seismically active structures near the city.

Earthquakes are known to occur in relationship to many geothermal systems, and
earthquakes have also been triggered by deep well injection. Nicholson and Wesson (1990) summarized known cases of earthquake triggering by well injection. While in unfractured rock well bottom pressures must be significant (greater than those planned for the Julia Davis Park Well) in order to directly trigger earthquakes, the situation is less clear in a fault zone which is already fractured to a significant degree. Moreover, if a fault zone is already at the critical stress threshold where loading is in equilibrium with the fault strength, earthquakes can be triggered by small incremental stresses such as those that might result from fluid injection. In addition, changes in fluid circulation in a fault zone can result in changes in the strength of that zone.

The present state of stress on the Boise Front Fault System is unknown and so its susceptibility to induced seismic activity is difficult to project a priori. Since it runs directly beneath the most densely settled part of the state of Idaho, with the geothermal system itself being located less than a mile from downtown Boise, the potential for impact and loss in the unlikely event of the triggering of significant earthquakes must be considered. Therefore, as part of the Julia Davis Park Injection Well project, a seismograph station was established at a good site in the Foothills to characterize seismicity near Boise and monitor any possible changes associated with injection operations.

**Seismograph Station Establishment and Characteristics**

No seismograph station capable of recording small earthquakes related to the BGS existed at the time that the City of Boise decided to move forward with the Julia Davis Park injection well concept. In the mid 1970s, BSU had operated a small seismograph network of 3 stations in the Foothills, but had discontinued it by about 1979. In 1982, the BSU stations were redeployed at distances of 15 – 36 mi from the well area. Because seismic wave amplitudes diminish rapidly as distance from the source increases, even the nearest of these stations to the BGS was not capable of reliably monitoring the system at magnitude levels smaller than about 0 to -0.5. In addition, by the early 1990s, the aged and obsolete equipment in these stations had made them unreliable for studies requiring continuous recording. It was therefore decided that monitoring of possible seismicity
related to injection activities would best be done at a hard rock site close to the BGS. Boise itself sits above several hundred meters of alluvial materials, which are characterized by high levels of seismic background noise due to cultural activities. While basalts and sandstones outcrop in places at the first rise of the Foothills, these usually overlie unconsolidated sediments and are believed to be relatively noisy. Hard granites of the Idaho Batholith outcrop in the Foothills relatively close to the BGS, and are known to have extremely low background noise levels. Some rough calculations suggested that the improvement in detection threshold permitted by a low noise site on granite would more than offset the disadvantage of having to locate the station as much as 5 mi from the BGS.

Granite outcrops were known to exist beginning about 1.5 mi northeast of the VA Hospital wells. These proved unsuitable for establishment of a station, either because they were located in areas where radio telemetry would be difficult, where station equipment could not be concealed to discourage vandalism, on state land (which charges exorbitant land usage fees), or on federal land, where managers prohibited consideration for a site on the basis of the unexploded ordnance believed to be in the area. A good site was finally found on private land near Curlew Creek, about 1.9 mi from the VA Hospital wells. This site was assigned station code CLWI in the BSU monitoring system. Figure 1 shows the location of the seismograph station with respect to the Julia Davis Park Well and the other production and injection wells of the BGS.

A 3-component, 4.5 Hz seismometer was installed directly on hard bedrock, and was covered to a depth of about 2 ft by soil and rocks. A 3-component system was considered necessary since only one station was being installed, and a 3-component system can allow some direction-finding capabilities under optimal circumstances. In addition, S waves are usually better-registered on horizontal component seismometers. If the time intervals between the arrival of the P waves and the S waves can be determined, a measure of the distance to the source of an event can be obtained.

A buried 100 ft cable connects the seismometer to an amplifier and signal conditioning system, which broadcasts the data to BSU on a single low power FM radio transmitter.
Figure 1. Location map of Julia Davis Park Injection Well, geothermal production well field, and seismograph station on Curlew Creek established to monitor potential seismicity associated with changes in the geothermal reservoir due to injection activity.
The entire system is powered by a 20 W solar panel which charges a 12 V 100 AH battery. The battery capacity is sufficient to operate the station overnight and for periods of cloudy weather exceeding a month. The radio signal is received at BSU and the continuous analog signals emanating from the station are demodulated and fed into computer systems with analog-digital converter front ends. The vertical channel was also used as input to a continuous analog drum recorder, which provides a standard 12 x 36 inch paper seismogram covering about 2 days' time. The station's signals were connected to the computer on 25 November 1998. The analog drum recorder required extensive reconditioning and was first placed in operation on 6 January 1999. Drum recording ceased on 21 March 2000 when a change in the electronics at the station made the received signal incompatible with the recorder electronics. CLWI continued to be recorded on the computer until the station was vandalized in March 2001.

The CLWI station's vertical seismometer proved to be exceptionally sensitive, having a gain level within a factor of two of the best stations in the BSU network. Noise from traffic and cultural activities in the city is clearly discernible during working hours, but is at extremely low levels and is far less of a problem than had been feared. In fact, it is doubtful that any city in the US of comparable size has so sensitive a seismograph station situated on the ground surface so close to the center of the city. In that respect, the decision to place the new station on granite bedrock rather than on less consolidated deposits closer to the geothermal system appears vindicated. On the other hand, although a sheltered site was chosen for the seismometer, it still proved to be prone to bursts of wind noise lasting up to a few hours during inclement weather. It is believed that the noise is caused by down-canyon wind gusts striking rock outcrops within about 5 – 50 ft of the seismometer. There does not appear to be a practical solution to this problem since other potential sites in the area to which we have access are at least as exposed to wind, or have other problems that make them undesirable as monitoring sites. To completely alleviate the problem, it would probably be necessary to emplace the sensor in a cased borehole at least 100 ft deep, or conduct a detailed comparative study of surface sites using numerous simultaneously-recording sensors. Both of these potential solutions involve significant effort and expense. In view of the observations that wind noise was
concentrated in the October-April interval, occurred only about 5% of the time even then, and that the rest of the time the background noise was extremely low, it is felt that the station site was adequate for the purposes of this study.

The horizontal seismometers' data were disappointing. Both components proved to have moderate levels of "ringing" (poorly damped harmonic noise) induced by high frequency events. Examples of events that would induce the ringing behavior included P waves of high frequency earthquakes occurring within 150 mi, footsteps or hoofsteps, and some wind gusts. The observed ringing appeared mechanical in nature rather than due to site conditions, although a site condition cannot be ruled out. Its effect was to distort the recordings of any event for which it was observed, so that timing of S waves and use of the directional capabilities of the station was affected.

While we normally would have attempted to replace or repair the seismometer, such an action would have taken the station off line for a few weeks during a critical period prior to the first demand being placed on the well, which took place in February 1999. A temporary replacement was not available in-house and units which we could have borrowed had different gain and response characteristics, which would have made direct comparison of recordings very difficult. Observations of small earthquakes were not seriously contaminated by the ringing problem, and from these it was soon noticed that both P and S waves were affected by regional geology to the point where the horizontal components proved of much less value than had been hoped. Both P and S waves tended to be very emergent on the horizontals. The polarity of the first onset of the P wave on the horizontals is crucial to determining the direction of the event, and this could not be determined with confidence on both horizontals for any event. The time of the S wave is important for estimating distance to the source. In practice, events interpreted to be related to the geothermal system had unrecognizable S waves for most events, and the vertical component recorded those that were recognizable as well as the horizontals did. Consequently, replacing or repairing the seismometer during a critical recording period, with its attendant data outage and/or difficulties in interpreting recordings made before and after, was deemed to be of less value than simply continuing operation.
The poor recordings of P waves on the horizontal and S waves on all components are noteworthy. Geologic complexity along the paths the seismic waves travel to the station is likely to account for significant distortion of the waves. Since the station lies on what is essentially a sliver of rock between closely-spaced faults of the Boise Front Fault System, complexity is to be expected as the trade-off for having a sensitive station close to the BGS. However, as will be described in later sections on observations and interpretation of recordings, the nature of the event sources themselves probably exerts a major influence on the recordings of earthquakes that appear to be occurring within the geothermal system. In short, the complexity that diminishes the usefulness of the horizontal components provides valuable unforeseen clues to where and how the events are occurring.

**Seismograph Data Recording**

Data were recorded in two fundamentally different modes. The first mode was digital format on computers, while the second was analog format on a conventional paper seismogram. Each mode has advantages and disadvantages. For this study, the simple conventional paper record proved the most important information source.

The paper seismogram is a continuous record that usually covers 2 days' data. Its advantage is that it allows a relatively rapid overview of seismicity on that record, which is much more difficult and time-consuming to achieve when examining digital data on a computer screen. Its disadvantage is that the long duration of the record requires that data be seriously compressed, normally to 1 sec/mm. The details of the recording of high frequency waves, which often are 5 – 20 Hz for small local earthquakes, are effectively lost. This disadvantage can actually at times be an advantage, as happened in this study, since the spatial compression of the time axis can make phases that appear emergent on digital records seem more clear and impulsive on the paper seismogram.

Digital data were recorded in two streams, triggered and continuous. In the triggered stream, analog data from all stations in the BSU network are input to an analog-digital
converter (ADC) running in a PC. The ADC digitizes all channels at 100 samples per second with 12 bit resolution. The digitized samples are then analyzed by a program which attempts to determine in real time whether a seismic event is occurring by a series of tests of the instantaneous signals' amplitudes relative to the amplitudes over a longer period of time. Only certain reliable stations are included in these tests, and are referred to as voting stations. If enough voting stations pass the tests within a given amount of time, an event is declared and the digital samples are written to disk, along with a pre-event buffer, until the event is declared over. A post-event buffer is then written, and the search for events is resumed.

The triggered system will record events other than earthquakes and explosions. It also triggers on telemetry glitches, sonic booms, and thunder. Since the BSU network is widespread and seismometers also record footsteps, hoofsteps, traffic, and wind noise, chance associations of these and the other possible causes of triggers at the minimum number of stations during the event time window also result in triggers. Many triggers are usually recorded during the passage of storms. Several BSU stations are not allowed to vote, because allowing them to do so results in unmanageable numbers of noise triggers. All triggers must be reviewed to see if they contain events of interest. Those that do not are deleted from the disk. Triggered earthquakes occurring within about 100 miles of a BSU network station are located, unless they occur in Montana (which has its own dense monitoring network).

The chances of an event being located depend on its magnitude, proximity to voting stations, the operational status of those stations, their sensitivity, the weather and other noise conditions, and the sharpness of the event onset. The list of voting stations may be altered due to storms, temporary local noise sources, and station operational status. Therefore assigning detection levels to the network is complex. In general, prior to the installation of the CLWI station it is believed that magnitude 2¼ events in the Boise area would not be triggered except by chance. During the period of operation of CLWI, magnitude 2¼ events in the Boise area should have triggered the computer except under unusual circumstances. Smaller events may or may not trigger, depending on their
location relative to the next closest voting station on the BSU network at Whitehawk Mountain (station code WHKI, near Lowman), or on the chance occurrence of noise at another voting station of the network. This property will be of importance in analysis of the local tectonic earthquakes recorded on the CLWI visible recorder, none of which triggered. Figure 2 shows the location of the Whitehawk Mountain station with respect to CLWI and the wells of the BGS.

Digital data from CLWI were also recorded in a continuous stream. This mode streams the data from an ADC to disk as a backup in the situation that an event does not trigger the computer system. This mode of recording requires large amounts of disk space and results in huge numbers of digital data files. Visual screening of all these files, similar to what is done with the triggered data, was beyond the effort levels funded in this project. However, if an event was seen on the CLWI paper seismogram that did not trigger the system and looked interesting, it was possible to retrieve CLWI digital data from the continuous data stream for examination. Because of disk space limitations, the continuous data were periodically purged except for individual files that had been retrieved. Since data from the CLWI station only were contained in these files, it was not possible to locate the non-triggered events unless they had both sharp onsets on all 3 components and a clearly recorded S wave. As it turned out, none of the data files retrieved from the continuous system contained events that met these criteria.

Data Analysis
Routine examination of triggered events showed that only two chance triggers occurred on events within 25 miles of CLWI between 25 November 1998 and 01 March 2001. Both were small and recorded at CLWI only. The digital records showed low-amplitude, emergent P arrivals on all components, and the S waves were not clear. Consequently, no locations could be obtained for these triggered events. The frequencies were lower than normal for small tectonic earthquakes and the recordings of the events did not have any similarities in detail. Neither bore any resemblance to tectonic earthquakes. For reasons that will be argued later, these events are hypothesized to be very shallow microearthquakes associated with the Boise Geothermal System.
Figure 2. Map showing the Whitehawk seismograph station, which did not trigger on even the larger tectonic earthquakes occurring within 25 mi of Curlew Creek. The larger ones probably occurred along or southwest of a line between points 5 mi south of Emmett and 20 mi north of Mountain Home, and may be related to the Boise Front Fault System.
Since it was clear from early in the project that the triggered system was likely to be of little practical use, and because the continuous digital system data were impractical to use for initial identification of events, the visible recorder seismograms became the most valuable source of data for interpretation. All records were carefully examined for possible earthquakes having S-P intervals of 5 seconds or less, corresponding to distances less than 25 mi from CLWI. Because unusual-appearing events could reasonably be expected due to the geologic structure and shallow nature of the BGS, the records were searched for all types of signals and those that could not be otherwise explained were noted.

_Tectonic Earthquakes_

Tectonic earthquakes have a fairly characteristic appearance and are easily recognized and differentiated from other types of events. See Figure 3 for an example of a tectonic earthquake recorded at CLWI. The recordings of tectonic earthquakes usually have a fairly high frequency content (5-20 Hz) and well-developed P and S phases, without any other prominent phases being seen in most cases for events at short distances. Following the S wave, there is an exponential decay of the signal amplitude down to background noise. This gives tectonic earthquakes a distinctive appearance that most other classes of events do not share. Although the term "tectonic" is used for events having such an appearance, it has been found that both induced seismicity and geothermal system events can share these characteristics, provided they occur at normal stress levels in competent rock at depths greater than about 1 mi. In the case of events recorded at CLWI, all tectonic-appearing earthquakes at distances greater than about 6 mi from the station must truly be natural tectonic earthquakes, since no major geothermal activity other than the BGS is known and there is no deep hard-rock mining or other likely source of induced seismicity. It should be noted that while some artificial reservoirs have induced seismicity, both Lucky Peak and Arrow Rock reservoirs are shallower than the usually threshold depth for triggering of events, and that a BSU station in close proximity to the reservoirs never recorded possible reservoir-induced seismicity during the time period from 1982 through 1992 when it was recorded nearly continuously on visible seismograms.
Figure 3. Portion of Curlew Creek seismogram showing a magnitude 1.8 tectonic earthquake, located about 12 miles from the station, on 2/10/99. This was the largest earthquake within 25 miles of the station observed during the monitoring period. The seismogram is enlarged by 50% over actual size. Regular square pulses are 1-second long marks indicating minutes’ beginnings. The seismogram reads from left to right and top to bottom like the lines on a book’s page. Each line on the original seismogram represents about 15 minutes’ data.

Figure 4. Portion of Curlew Creek seismogram for 3/20/99, showing events interpreted as microearthquakes related to the geothermal system. The largest events have magnitudes estimated to be about −2. The seismogram also shows a period of wind noise. Events believed to be microearthquakes are more discrete, have sudden onsets, and show somewhat less variability in signal character than wind noise bursts.
Several small tectonic earthquakes occurring within 25 miles of CLWI were recorded. Table 1 lists these events, which ranged in magnitude from -1.6 to 1.8. Magnitudes were estimated from the duration of the signal on the seismogram, using the formula employed in routine BSU event processing. 0.3 unit was subtracted from the result for each event to correct for overestimations which typically occur on sensitive stations for nearby events. Figure 3 shows the largest identified tectonic earthquake. It has an S-P interval of about 2.5 seconds and is estimated to have occurred about 12 mi from CLWI.

S-P time intervals were converted to distance ranges by assuming that the tectonic events occurred at the typical western Idaho depth of 4 miles, and that P waves from these events travel at about 20,000 ft/second while S waves travel at about 11,500 ft/second. These velocities are characteristic of competent upper crustal continental rocks. It is reasonable to assume that in the Boise area earthquakes at such depths are occurring in granite or basalt basement rock. Seismic reflection surveys reported by Liberty (1996) suggest lower velocities in the sediments and basalts above the basement; however minimum time raypaths for earthquakes in the basement will tend to remain mostly in the basement except for a steep ascent through the low velocity materials in the immediate area of the recording station. This consideration justifies the use of the faster velocities in range estimation. Significant range errors are unlikely unless the earthquakes are occurring at radically different focal depths than assumed. Varying the seismic wave velocities within reasonable limits makes a range difference of the order of about 10%.

Only one tectonic microearthquake was noted as having occurred within 6 mi of CLWI and therefore potentially being related to the BGS. It was an extremely small event, magnitude -1.6, and no significance is attached to the occurrence of a single isolated event of such small magnitude in the course of over a year. Few places in the western United States exist that where such an event, or an even larger one, would not be recorded in a similar span of time.

The other identified tectonic earthquakes occurred at distances of 9 to 23 mi from CLWI.
Despite four of them having magnitudes greater than 1, none triggered the online system. Since continuous digital seismograms from CLWI did not have sharp P wave onsets on the horizontal components, directions could not be estimated. Some evidence of the source areas of these earthquakes can be developed by considering the reasons they may not have triggered, however.

As stated earlier, the closest voting station of the BSU network to CLWI is WHKI, near Lowman. This station is very sensitive and is only rarely taken out of the voting station list, for brief periods during storms. None of the tectonic earthquakes occurred during such a period. Earthquakes having magnitude 1.5 or greater between WHKI and CLWI should cause votes on both stations, resulting in a trigger. Since neither of the two events having such magnitudes (10 February 1999, magnitude 1.8; 30 July 1999, magnitude 1.7) triggered, it is likely they occurred to the southwest of a line running roughly from 5 mi south of Emmett to 20 miles north of Mountain Home (see Figure 2). Sources to the southwest of this line maximize the distance to WHKI, thereby decreasing the probability of a trigger.

The remaining tectonic earthquakes have magnitudes of 1.1 or less. Earthquakes of magnitude near 1 occurring near the midpoint of a line between CLWI and WHKI might trigger the computer, but the chances decrease as the epicenter moves more than a few miles from that point. Table 1 shows that 11 of the 15 identified tectonic earthquakes have S-P intervals in the 2 – 3.5 second range (which includes the magnitude 1.8 event mentioned above), and a few events have 4.5 second S-P's (including the magnitude 1.7 event mentioned above). Since the recordings of the events in each of these two S-P ranges bear general similarities to the other events in the same group, it is reasonable to assume that most events in each group probably occurred in the same general area. The Boise Front Fault System (BFFS) is the only known potentially seismogenic structure in this region, so it is a possibility that many or most of the observed tectonic earthquakes are related to it in some manner. If these events are not related to the BFFS, they must be occurring on other, presently unknown fault structures in the Western Snake River Plain or near its margin.

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### TABLE 1. TECTONIC EARTHQUAKES OBSERVED

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### TABLE 2. POSSIBLE SHALLOW, NON-TECTONIC EARTHQUAKE

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The largest tectonic earthquake observed within 25 mi of CLWI, the magnitude 1.8 event on 10 February 1999 (Universal Time, 9 February Mountain Standard Time), deserves some comment since it occurred shortly after injection began at the Julia Davis Park Well (Kent Johnson, personal communication). There is considerable evidence to suggest that this timing is coincidental rather than a cause-and-effect relationship. First, the earthquake must have occurred several miles from the BGS and the Julia Davis Park Well, since it was about 12 mi from CLWI and the Julia Davis Park Well is only about 3 mi away. Even allowing a distance estimation error of up to a couple of miles does not bring the event close enough that it is likely to be related. Second, the earthquake's recording looks like that of an earthquake at normal depth below the surface, which is 4 - 7 mi in western Idaho. The main volume of the BGS is less than a mile below the surface, and since the Julia Davis Park Well does not extend into basement rock it is unlikely that injection from it would trigger so large an event at such great depth without triggering others at shallower depths in the basement. Third, similar tectonic events did not occur at times when other changes were made in the injection pressures at the Julia Davis Park Well. It is therefore concluded that the 10 February 1999 event is unrelated to the Boise Geothermal System. Similarly, it is regarded as highly unlikely that any of the identified tectonic events bear any connection with the Boise Geothermal System, even though they may be occurring on the Boise Front Fault System.

**Possible Shallow, Non-Tectonic Earthquake**

An event on 26 July 1999, magnitude 0.5, had a relatively low frequency content and lacks the exponential decay characteristic of tectonic earthquakes. It was an isolated event and no similar events of such size were noted on the visible records. The possibility that the event was a blast cannot be ruled out. It occurred near noon on a Monday. It would take a few hundred pounds of ammonium nitrate detonated in rock at the surface to produce an event of such size. The only places so close to the station that such blasting seems needed would be along Rocky Canyon Road or at the Table Rock quarry, but it is virtually impossible to track down and confirm so small an event. It is also possible that it is a shallow non-tectonic earthquake. It is assumed that its depth is quite shallow since if it
occurred in basement rock it would be likely that it would have had a tectonic earthquake signature.

The event's S-P was only 1 sec at CLWI. Since it is unlikely that it occurred in basement rock, it is appropriate to use lower P and S wave velocities to estimate its range than those used for the tectonic earthquakes. It was assumed that the event occurred at a depth of about 3000 ft and that the average velocities along the minimum-time raypath to the station were about 13,000 ft/sec for P waves and about 8,000 ft/second for S waves. This results in a distance estimate of about 4 mi from CLWI. Because of the complexity of the geologic structure in the upper mile beneath the BGS, it is probable that the raypath is itself complex, with the first-arriving waves at CLWI getting a speed boost by travelling part of the way as head waves along the top of the basement. The velocities used to estimate the ranges are best interpreted as averages along the raypath and may be in error by up to about 30%, given reasonable constraints on the velocities.

_Swarms of Very Small, Probably Non-Tectonic Earthquakes_

Perhaps the most interesting class of events recorded at CLWI was swarms of extremely small (magnitude -1 to -3) events. Approximately 14 such swarms were noted, the first being on 7 February 1999 (see Table 3). The appearance of these events on the seismograms (see Figure 4) is so unusual that at first they were not thought to be seismic events, but rather some type of noise near the station.

The events in question usually have somewhat sudden onsets on the visible seismograms, although event files examined from the continuous digital data stream show that the onsets are too emergent to pick a direction. Only about 20% show possible S phases. The events shown in Figure 4 are atypical in that respect, since most show apparent S phases; the seismogram shown in Figure 5 is a different part of the same swarm and shows a more typical set of events. The apparent S-P intervals range from ¼ to 1 second when visible, with most being ½ to 1 second. There is wide variability in these intervals for events occurring within the same swarm, and often with events occurring within a few minutes of each other. The events generally lack the exponential decay of tectonic events and events
<table>
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<th>DATE/TIME OF ONSET OF EVENT</th>
<th>DURATION (Hours)</th>
<th>APPROXIMATE NUMBER OF EVENTS</th>
<th>POSSIBLE S-P</th>
<th>DISTANCE (mi)</th>
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* Approximate magnitude of largest event
Figure 5. Portion of seismogram for 3/19 – 3/20/99, showing some of the events in the longest duration swarm observed. Events in all swarms tended to occur in bursts and had generally dissimilar signatures. Most events did not have discernable S phases. A few of the events in the bottom left portion of this figure appear to have discernable phases suggesting S-P intervals of about $\frac{1}{2}$ second, which would correspond to a distance of about 2 miles from the station. The production field is about 2 miles from the station.
occurring within basement rock. Events in a swarm usually do not bear a strong similarity to each other for more than a few minutes' time. Instead, they are notable for the sheer variety of their signatures on CLWI.

More than 800 events were counted in these swarms. It is usually difficult to assign an onset or ending time to a swarm as they seem to begin with events that are almost unrecognizably small. Therefore, onset time and duration are given to the nearest hour in Table 3. Nearly half the swarms began between midnight and 6 AM local time, while none began between 1PM and 5 PM. Of the 12 swarms identified in 1999, 11 occurred in the first half of the year and there was a 5 month gap between the last of these and the next identified swarm. While the data sample is small, these occurrence patterns suggest some non-random processes may be controlling the swarm onsets. The number of events in each swarm is difficult to count precisely because some probable events have extremely small amplitude on the seismograms. The approximate numbers range from a minimum of 20 to a maximum of about 210. Smaller swarms probably occurred, but are difficult to identify as such. Over half of the swarms lasted 7 hours or less. The longest-duration swarm, about 46 hours, began on 19 March 1999 and was more than twice the duration of the next longest.

Possible noise sources were investigated as causes of these events. Such sources include electronic interference in the telemetry, mechanical objects disturbing the seismometer, footsteps and hoofsteps, gunfire, and gusty wind. All were ruled out as probable causes. The reasons for considering these sources, and ruling them out, are described below.

Many of the events lack any apparent S-P and die out almost immediately despite their high amplitude. These characteristics are occasionally seen when a station's telemetered signal is experiencing very short radio interference spikes. One swarm, on 23 February 2000, actually precedes a several-hour period of such interference spikes by a few hours. Generally it is possible to distinguish between swarm events and interference spikes since interference spikes tend to all have about the same large amplitude, are even "spikier" and tend to return directly to background noise without even a hint of an exponential signal
decay. The swarm events, although the exponential decay is almost unnoticeable, can usually be seen to have a short period of coda decay.

Mechanical objects impacting the seismometer could potentially include drops of water and small rocks. Examination of the rock face over the seismometer and the manner in which the seismometer was buried suggest that dripping water is not a possibility. It would be possible for small rocks to exfoliate and drop down the short rock face, but they would land on a rockpile and would be unlikely to make strong, sharp records with such variable signatures as observed. There is also no evidence that enough rocks dropped over the rock face to cause the more than 800 events observed in the swarms.

Footsteps and hoofsteps usually occur much closer together in time than do the swarm events, are usually quite numerous for a fairly short length of time, and do not exhibit exponential decays. Figure 6 shows swarm events together with footsteps made by the author a few hours later, including stomps made only about 5 ft from the seismometer. The differences in record character are great and footsteps and hoofsteps are extremely unlikely to be the cause of the observed swarm events.

Gunfire or reports from gunfire were considered as well. The seismograph station is located about 1 mile from the Boise Police Firing Range, which is used very frequently. Swarm events were observed much less frequently than officers use the range. More importantly, about half of the swarms appear to begin between midnight and 7 AM, when the firing range would not be in use. In particular, the 14 March 1999 swarm began about 3 AM on a Saturday morning. Over half the swarms lasted more than 5 hours (four lasted more than ten hours and one lasted 46 hours), which is also at odds with the way people normally use guns for recreational purposes. For these reasons, gunfire was ruled out as a potential cause.

The events bear some resemblance to gusty wind noise, as is evident from the episode of wind noise about ¾ of the way down Figure 4. However, most swarm sequences occurred in periods of low background noise. The swarm events are also more discrete
Figure 6. Portion of seismogram for interpreted swarm of 3/14/99. This swarm occurred at night and in the morning of a Saturday, during calm weather. The strong spikes near the center of the record are the author’s footsteps and movements as he walked near the seismometer to determine whether any noise sources might have caused signals like the swarm events recorded just a few hours earlier. No likely possibilities were found.
and show less variability in signatures than do the wind gusts. Although in some cases it is still difficult to make identification with complete certainty, it is concluded that gusty wind noise has not been mistaken for events to any significant extent.

Shortly after noticing the occurrence of a swarm in the early hours of Saturday, 14 March 1999, the author drove to the CLWI station to see if any unusual noise sources were present. Although gusty winds had occurred associated with the passage of a front between about 11 PM and 3 AM during the night, the morning was clear and calm, and no wind was noticeable at the station. No one was present at the police firing range, nor was anyone shooting closer to the station. No animals were in the area, nor were any persons present within at least ½ mile. It was concluded that there were no unusual noise sources at the station that could explain the events recorded that day, and that they probably represented some kind of actual seismic disturbance.

Having ruled out all potential noise-based explanations for the observed swarm events, we are forced to conclude that they represent some brittle failure process occurring in the earth. Their signatures bear little resemblance to those of tectonic earthquakes and the variability in signal character during a swarm is extremely unusual for tectonic earthquakes of such small magnitude. The largest event observed in the swarms had a magnitude of about -1 (see Figure 7). A magnitude -1 tectonic earthquake has a source length of 3 to 35 feet. All events in a tectonic earthquake swarm with so small a maximum magnitude event are therefore likely to be occurring within a few yards of a common point. Viewed on seismometers 1 or more miles away with a frequency response like CLWI's, all such events should appear identical to each other except for size. It is concluded that the observed swarm events are occurring under different conditions than those normal for tectonic earthquakes. The apparent S-P's (¼ to 1 second), the wide variety of event signatures in a single swarm, and the overall lower-than-normal frequency content of these events indicate they are occurring at shallow depth in less competent rock than is typical of tectonic events. Assuming the events are occurring at a depth of about 3000 ft in rocks with a P wave velocity of about 13,000 ft/sec and an S wave velocity of about 8,000 ft per second, the swarm events with apparent S-P intervals seem to be occurring at distances of
Portion of 6/13/99 swarm showing largest event

Figure 7. Portion of seismogram for 6/13 – 6/14/99, showing largest event believed to be related to the geothermal system during the monitoring period. This event had a magnitude of about –1 and was part of a series of 5 swarms between 6/15/99 and 6/24/99.
about 1 to 4 miles from the CLWI station. These range estimates are subject to about a 30% uncertainty, owing chiefly to the lack of knowledge of the velocities along the paths the rays follow to CLWI.

Formally, it is not possible to locate these events since none were recorded by any station other than CLWI and since none of the continuous digital recordings for CLWI that were examined showed an unambiguous direction to the source. However, swarms on the Foothills side of CLWI would be occurring in competent rocks of the Idaho Batholith and would be expected to have more tectonic-like signatures and small source areas, leading to less complexity and little variation in the recorded seismograms for events in each swarm. Therefore, it is likely that these swarms are occurring southwest of the edge of the Foothills. The Boise Geothermal System's principal production well field begins about 2 mi southwest of CLWI, and the Julia Davis Park Well is 3 mi from CLWI. Thus, the distance range of events from CLWI (1 to 4 mi) is consistent with these events originating within the Boise Geothermal System.

The swarm observed on 14 March 1999 is particularly interesting. Many alternative noise sources can be ruled out because of its time of day and the onsite investigation within several hours of the swarm's end, as earlier described. In addition, the swarm's onset occurred just a few hours after injection at the Julia Davis Park Well had to be shut down due to a mechanical problem (Kent Johnson, personal communication). A sudden decrease in injection pressure causes a negative pressure wave in the system, which presumably was at equilibrium. This pressure wave interacting with faults in the aquifer rhyolite is hypothesized as the caused of the swarm.

The observations above can be used to formulate some models for how these swarms are occurring. The following section discusses the likelihood that these swarms are caused either by primarily tectonic processes involving the release of regional stress along the Boise Front Fault System, or by primarily by geothermal processes within the Boise Geothermal System. It should be noted that a "combination of causes" model is also possible, but it is not discussed further since the seismicity observations to date are only
capable of favoring one or the other of the tectonic or geothermal models over the other.

**Hypothetical Models for Shallow Swarm Occurrence beneath Boise**

For earthquakes to occur and be observed, brittle failure must take place in rocks competent enough to resist creep (aseismic) failure modes. Commonly, earthquakes are found to only occur in what we tend to think of as solid rock. Sediments and gravels tend to deform and flow plastically because they have practically no shear strength. The rare events that have been reported as occurring in such formations typically are recorded with very low frequencies of wave motion and have long durations, both of which observations are at odds with what is observed for the swarm events recorded at CLWI. Therefore, source rocks for the observed swarm events are sought in rock formations beneath Boise. Based on their recorded characteristics, it is reasonable to assume that the observed swarm events are occurring at shallow depths above the basement rock. It is not possible to entirely rule out sources in badly fractured or altered basement rock, however.

Geologic cross-sections derived from deep well cuttings (Wood and Burnham, 1987; Montgomery Watson, 1998) and seismic reflection lines (Liberty, 1996) indicate that two or three relatively competent and extensive rock units exist between the surface and the basement rocks. At the Julia Davis Park Well, the upper 1600 ft consists of formations that are considered too incompetent to be capable of brittle failure. The shallowest relatively competent formation is a 300 ft sequence of basalt and altered basalt, below which is over 150 ft of sands and clays. The sands and clays overlay the competent rhyolite layer associated with the BGS aquifer. This rhyolite is about 400 ft thick. Beneath it is about 100 ft of sandstone. Since both the sandstone and the rhyolite can be considered competent units, they together form a potential source zone for brittle failure events that is about 500 ft thick.

Beneath the sandstone is about 300 ft of interbedded gravel and sand, which is considered incompetent. Below this is another competent rhyolite unit about 150 ft thick. Beneath this second rhyolite is more sand and gravel. The depth to basement at the Julia Davis Park Well is unknown but is probably not much greater than the bottoming depth, about
3200 ft. Basement rock here probably consists of basalt, although close to the Foothills it may be granite correlative to that exposed in the Foothills.

Model 1: Tectonic Origin of Observed Earthquake Swarms
The first hypothetical model is that the observed earthquake swarms represent tectonically-induced brittle failure in competent formations that occurs due to stresses being applied to those formations by creep in less-competent formations below them. In this model, tectonic stresses are being accommodated by slip along northwest-trending normal faults of the Boise Front Fault System. Although proof of geologically recent faulting on the BFFS has not been found, it is favorably oriented for slip under the current tectonic stress regime, which is generally northeast-southwest extension in western Idaho. The tectonic earthquakes observed in this study suggest that a low level of microearthquake activity may occur along the BFFS.

In this model, a creep event along faults at the top of the basement, which is displaced slightly in a creep event itself. Creep occurs aseismically in the sediments, but the displacement propagates up-dip on the fault unimpeded, perhaps for a period of days, until the displacement reaches a faulted but competent rock layer. Here, because the rock layer resists the creep failure, propagation of the displacement is held up until stresses build up in the rock layer that are large enough to overcome the frictional resistance of the fault in the rock. Earthquakes then begin and signal the propagation of the displacement through the competent formation, where creep resumes in the incompetent formations above it. The process is repeated when the displacement reaches the next competent layer, until all competent formations have been faulted or the slip event dies out.

The thickness of the aquifer rhyolite, together with sandstone immediately below it, is sufficient to allow earthquakes up to the magnitude 1.5 to 2 range if a rupture event (earthquake) is confined to this competent unit alone. The other competent units probably have similar seismogenic capacity. However, the thinness of these formations and their likely fractured nature may prevent stresses along the faults from building to large levels over large fault areas before the failure threshold is reached. In that case, displacement
events would be likely to be expressed by swarms of microearthquakes, as has been observed.

The signatures of these events on a seismograph station might be expected to be quite complex, as is observed at CLWI. The earthquake source rock formations are not continuous with the granite upon which CLWI is situated, and furthermore are underlain and overlain by lower velocity materials. Ray paths need to traverse high and low velocity regions, with generation of phases reflected off the tops and bottoms of different high velocity regions. The earliest arriving waves at the station would probably be low amplitude refractions along the top of a particular high velocity layer which contacts the granite, followed by a "packet" of waves of successively higher amplitude which include reflections. The waves traversing the lower-velocity formations would be attenuated, leading to lower overall recorded frequencies. These expected characteristics well match the actual recordings at CLWI. Even if the earthquake swarms are not ultimately due to a tectonic cause (see the following section on Model 2), it is probable that the swarm events are occurring mainly in the competent rhyolites and associated formations above the basement.

It is not known how long a creep displacement event would take to traverse the formations above the basement rock. Conceivably, it might take only a short period of time. In that case, it would be possible for swarms to be taking place in more than one of the competent units simultaneously or nearly simultaneously. Therefore, it would be possible for the signatures of the observed swarm events to vary considerably in appearance and S-P interval at a nearby seismograph station, as is observed.

The lack of seismic monitoring of the Boise Geothermal Field throughout most of its history precludes knowing for certain whether these swarms occurred before its development. Even if they did occur, it is likely that it would be difficult to distinguish whether they had a primarily tectonic cause. However, the observation of the small number of recorded tectonic earthquakes during this project tends to cast some doubt upon the tectonic origin of the swarm earthquakes, particularly since most of the recorded
tectonic earthquakes must have originated at some distance from the area within 1 to 4 miles of CLWI where the swarms appear to have originated. Tectonically-related creep displacements on faults tend to occur on fairly active faults where the slip rate is high enough that irregularities on the fault plane have been "ground off" by repeated displacement events. The BFFS, if active, probably experiences major earthquakes at long intervals of several tens of thousands to hundreds of thousands of years. It is not considered likely that tectonically-originating creep is occurring on the BFFS.

Even if creep was occurring on the BFFS and was confined to the area of the Boise Geothermal System, it is difficult to reconcile its occurrence with the small number of microearthquakes observed in the basement rocks near the BGS. It would seem that at some point in the competent basement rocks fault friction (and resistance to creep) would increase, and at that point tectonic microearthquakes would be observed as the rocks reacted to the same stress field that induced the creep events.

Model 2. Geothermal Origin of Observed Earthquake Swarms
A second proposed model is that the observed swarms are occurring as the result of stresses induced by geothermally-induced processes. In this model, the observed swarm earthquakes would take place in the same competent formations as in the tectonic model, and would have the same complex observed signatures at the CLWI station. The earthquakes would not necessarily be confined to the faults of the Boise Front Fault System in this model, since geothermal earthquakes may occur along other fractures in the geothermal system as well. Injection and withdrawal pressures from wells, as well as simple circulation of geothermal fluids, can lead to local pressures building beyond the rupture limit along small fractures, thus inducing microearthquakes. In this model, most swarm events would probably be occurring in the aquifer rhyolite and its associated sandstone, since this region is probably subject to the most variety in pressures due to natural and development-induced processes in the BGS. The model does not preclude events occurring in the other competent formations, however, since the full extent of natural circulation in the BGS is not known and since injection and withdrawal pressures may affect these to the point where brittle failure may occur.
The geothermal model may lead to the expectation of even more variety in the signatures of recorded microearthquakes than the tectonic model. In the tectonic model, creep events are confined to a limited number of faults, while in the geothermal model the entire volume of the rhyolite aquifer might be expected to be producing events. While it is the impression of the author that the variety in event signatures is greater than might be expected from the tectonic model, this is difficult to support with available data since tectonically-related creep events might themselves be partitioned over a number of parallel faults, giving rise to a great deal of variety in the signatures.

The primary reasons to support the geothermal model over the tectonic model are (1) any compelling reason to accept that there is any significant amount of displacement on the BFFS occurring as creep; (2) the otherwise very low tectonic microearthquake activity that might be related to the BFFS; (3) the spatial proximity of the observed swarms to the Boise Geothermal System, and (4) the suggestion that the limited number of swarms observed in this study may be occurring non-randomly in time, implying that there may be an external cause to the temporal pattern such as may result from variations in demand on the system or reservoir development activities. Even though the swarms cannot be formally located, there can be little question that they are shallow. Moreover, the rock formations known to exist in the BGS provide a source environment that can explain the observed complexity in the seismograms, while swarm sources in the Foothills at equivalent distances from CLWI should generate simpler-appearing seismograms because of their occurrence in and raypaths through granite. A final consideration, although it is considered rather weak as evidence, is that since many geothermal systems are known to produce microearthquakes, the most probable source of microearthquakes observed near a geothermal system is that system. It is concluded that the model of geothermal origin of the observed microearthquake swarms should be preferred over the model of tectonic occurrence.

Because of the late date at which the project was begun, there was insufficient observation time prior to the beginning of injection at the Julia Davis Park Well to say whether swarms
or isolated events occurred prior to that time. The swarm of 7 February 1999 was the first observed on the paper seismograms, which had begun recording in early January. It is believed that this swarm took place just prior to the beginning of injection, and if this is true shows that swarms had occurred before use of the Julia Davis Park Well had begun. The large number of swarm events with S-P intervals near ½ second (suggesting occurrence near the production well field) is evidence that implies swarms may already have been taking place as the result of production activities. Because these activities were never monitored with seismographs and because of the short period of this study before injection began at the Julia Davis Park Well, it is impossible to know what effect the development of that well had on seismicity related to the Boise Geothermal System. However, it is the opinion of the author that geothermally-originating microearthquakes in the BGS have probably occurred in the past due to both natural causes and development activities.

**Implications for Earthquake Hazards**

This study has shown that there may be a low rate of tectonic earthquake activity along the Boise Front Fault System, and that small microearthquakes which may be related to the Boise Geothermal System occur in an area near Boise. If the microearthquakes are related to the geothermal system, their potential source formation is probably one or two relatively thin rhyolite units. Assuming that association is correct, it is believed that the largest earthquakes that are likely to occur in the Boise Geothermal System as the result of production activities will have maximum magnitudes of 1.5 to 2. Since shallow earthquakes of magnitude 2 and greater can be perceptible to people very close to the source, there is some possibility that production activities in the BGS could give rise to earthquakes that are felt locally. The observation that most shallow microearthquakes recorded during this study period had magnitudes less than 0 would suggest that it would be rare that earthquakes as large as magnitude 2 would occur. The thickness of the competent rock formations appears to provide an upper limit to the size of the earthquakes expected to originate in the geothermal system.

It is usually observed that even shallow earthquakes of magnitude 3.5 or less do not cause
any damage. For tectonic earthquakes beneath cities, the damage threshold is usually
magnitude 4 or higher. It is concluded that earthquakes originating in the Boise
Geothermal System are unlikely to cause damage to surface structures or their contents.

The possibility of tectonic earthquakes in the Boise area causing local damage exists, since
microearthquakes that must have originated close to the city and had magnitudes up to
almost 2 were observed during this study. From the short time sample and limited number
of events, it is difficult to make an estimate of how frequently damaging tectonic events
might occur on the basis of the recorded earthquakes.

The possibility that both tectonic and geothermal earthquakes are occurring on the Boise
Front Fault System gives reason to suspect that interactions between the two might occur.
The limited extent of the BGS suggests that if such interactions occur they may be small,
but the occurrence of some of the swarms over apparently relatively wide areas (based on
the range of S-P intervals at CLWT) in just a few hours indicates either that stress
transmission is very efficient, or that the upper system is already close to the failure
threshold. In either case it would appear a reasonable supposition that BGS injection and
production activities have the potential to induce events on the Boise Front Fault System
if the portion of the fault system in the basement rocks (where a tectonic earthquake
would originate) is itself close to the failure threshold. No information is known that
allows any assessment of the state of stress on the Boise Front Fault System is known.
Arguments regarding its activity status are based on indirect evidence that cannot be used
to determine how close in time the system is to the next significant earthquake. As a
result, any major changes to the BGS reservoir stimulation activities should be planned
with the possibility of induced seismicity on the BFFS in mind.

The observation of microearthquake swarms that may be related to the BGS has a positive
side. The locations and temporal patterns of earthquakes in geothermal systems can give
clues to the circulation patterns, energy, and state of stress in the system. In some
geothermal systems, the seismicity is used as an active reservoir management tool. The
City of Boise and other agencies involved in utilization of the energy resource represented
by the Boise Geothermal System should consider this option in the event that significant changes are observed in or planned for the system.

**Conclusions**

Both swarms of shallow microearthquakes and small tectonic earthquakes have been observed to occur within a few miles of Boise. At least some of the tectonic earthquakes may be related to the Boise Front Fault System or other fault structures in the Western Snake River Plain. The characteristics of the microearthquakes suggest that they are probably related to the Boise Geothermal System and may be affected by reservoir development activities. Swarm earthquakes have extremely small magnitudes, usually between -1 and -3, and are believed to result from brittle failure occurring within competent rock formations above the basement rock. The competent formations include rhyolites, a sandstone and some basalts, all at depths between roughly 1500 and 3000 feet. One of the rhyolites is the main aquifer formation for the Boise Geothermal System. The thicknesses of these formations and their interbedding with formations that are not sufficiently competent to experience brittle failure suggest that the maximum magnitude earthquake likely to occur at very shallow depth within or near the geothermal system is roughly 1.5 to 2.

If the observed microearthquakes are related to the Boise Geothermal System, as believed, they may provide information useful in managing the reservoir.

**Acknowledgments**

Kent Johnson and Chuck Mickelson of the City of Boise both provided information that was useful in the compilation of this report. Claude Spinosa of Boise State University provided inspiration at a critical moment.

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