MICROEARTHQUAKES — A TOOL TO TRACK INJECTED WATER IN THE GEYSERS RESERVOIR

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ABSTRACT

Based on proprietary and public data from the last 14 years I find good spatial and temporal correlation between injection and microearthquake (MEQ) activity at The Geysers. Comparison with geochemical and steam production data suggests that MEQ clusters associated with injection wells form a rough three-dimensional image of injected liquid in the formation. These images can help to track injected water, estimate reservoir thickness, and provide early warning of possible water breakthrough situations.

The spatial correlation, though not simple, can be seen in maps of seismicity deeper than 4,000 feet subsea (see Figure 1a). Every injector or group of injectors can be associated with a MEQ cluster. Where the clusters extend far from the injectors, the producing wells tend to show the "heavy" isotopic signature of flashed injectate (Figure 1b). Some of the "heavy" steam producers coincident with extended MEQ clusters are found in zones of higher reservoir steam pressure than the nearby injection wells. A simple explanation is that those MEQs occur where injected water flows as a liquid, driven by hydraulic pressure or by gravity.

Temporal correlations between injection and nearby seismicity are generally clear, especially for the relatively deep events (e.g. Figures 2 and 3). Based on visual inspection, lag times between changes in injection rate and seismicity typically range from days to weeks.

Roughly half of the MEQs at The Geysers may be induced by injection and appear to represent shear slip triggered along surfaces already stressed tectonically to near the failure point.

INTRODUCTION

The U.S. Geologic Survey (USGS) has monitored MEQs in The Geysers region since 1975. Epicenters are concentrated along known fault zones and at The Geysers. Although there is little pre-exploitation data, it has long been suspected (Hamilton and Muffler, 1972; Ludwin and Bufe, 1980) that most of The Geysers MEQs are induced by development-related activities. Injection was identified as a likely cause, based primarily on case histories worldwide involving earthquakes associated with fluid disposal and water impoundment. Majer and McEvilly (1979) recognized the possibility of production-induced seismicity and, along with Allis (1982), offered possible mechanisms.

Eberhart-Phillips and Oppenheimer (1984) concluded that production, rather than injection, shows the best correlation with seismicity. They also suggested that injection under zero wellhead pressure, as practiced at The Geysers, would be unlikely to induce the pore pressures required for the Hubbert and Rubey (1959) mechanism of induced seismicity.

Study of proprietary operational and geochemical data does reveal a correlation between injection and seismicity. Furthermore, the effective normal stress in the reservoir could be reduced by the effects of hydraulic head and/or cooling due to the injected water, thereby inducing MEQs by the Hubbert-Rubey mechanism. Since 1986 we have

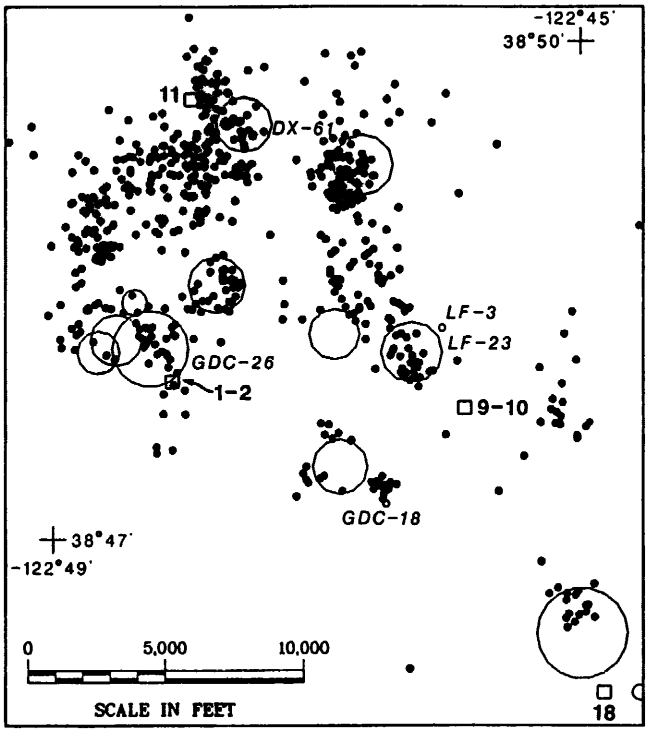

Figure 1a. Epicenters (dots) deeper than 4,000 feet subsea located by Unocal MEQ net, November 1988 - August 1989, with coda magnitudes >0.7. Open circles represent Unocal injection wells centered on mid point-of-steam (circle area is proportional to volume injected November 1988 - August 1989); well names referred to in text are posted in italics. Numbered squares are selected Pacific Gas & Electric power plants.

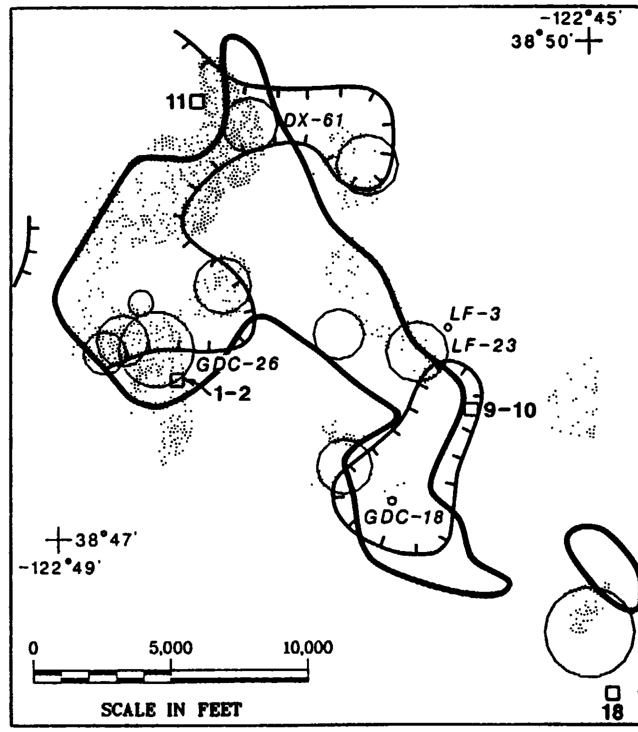

Figure 1b. MEQ clusters (dot pattern) interpreted from Figure 1a. Heavy contours enclose areas where >20 percent of 1988 produced steam comes from flashed injectate (Gambill, 1990). Lighter contours are 200 psi isobars (May 1989 Unocal data), teeth on low side. Injection wells and power plants shown as in Figure1a.

been analyzing the injection-related seismicity to yield interpretations on the flow of injected water and reservoir bathymetry.

Documented examples of seismicity induced by injection in vapor-dominated geothermal fields include Larderello and Travale, Italy (Batini, Console and Luongo, 1985). Examples from liquid-dominated fields include: Latera, Italy (Batini, Console and Luongo, 1985); Wairakei, New Zealand (Sherburn, 1984); and Tongonan (Sarmiento, 1986) and Puhagan, the Philippines (Bromley, Pearson and Rigor, 1986). In these cases the data were insufficient to show much beyond the correlation itself, primarily due to lower levels of induced MEQ activity.

Seismologists working on hydraulic stimulation projects have used MEQs to track water injected into granitic rocks in Fenton Hill, New Mexico (House, 1987), Rosemanowes Quarry, Cornwall, United Kingdom (Pine and Batchelor, 1984) and near Vichy, France (Cornet, 1989). Using tightly focussed arrays incorporating deep downhole sensors, they mapped planes of MEQs along which injected water was interpreted to move, thereby defining targets for production wells.

Not all the seismicity at The Geysers appears to be induced by injection; production and tectonics probably contribute to the MEQ activity (Eberhart-Phillips and Oppenheimer, 1984). The shallower events correlate in a complex manner, if at all, with both production and injection. Conversely, not all injection causes MEQs; several counter-examples suggest that some of the injected water flows aseismically. The purpose of this paper is to explore the nature and applications of injection-induced MEQs at The Geysers.

DATA BASE

The Geysers is extremely active seismically, more so in the northwestern part of the field than in the southeast. Events occur at apparently random intervals rather than in swarms. Few are deeper than 20,000 feet.

The USGS data set (Oppenheimer, 1986) now consists of over 40,000 events recorded from 1976 through 1989, using the 37-station CALNET array. Since 1981 the detection threshold has been about magnitude 0.8 for The Geysers, yielding thousands of events per year, with an estimated epicentral uncertainty of 1,300 feet, and a depth uncertainty of 2,100 feet. The largest events recorded were a magnitude 4.0 in 1982 and a 4.1 (preliminary estimate, D. Oppenheimer, USGS, personal communication) in

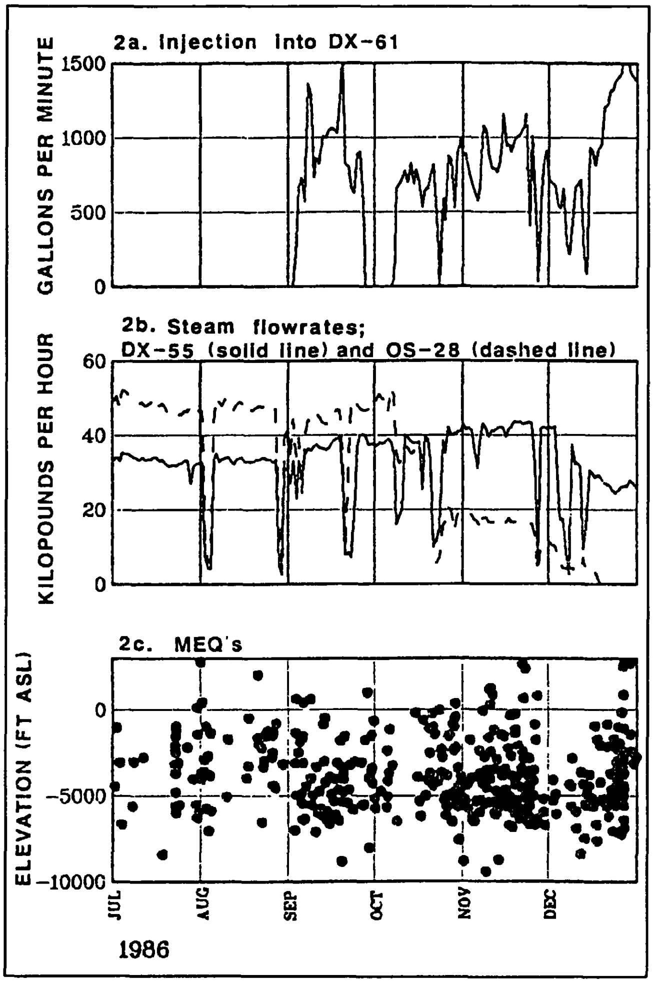

Figure 2. Time history (July 1986 - December1986) of injection into DX-61 (location in Figure 1), steam flowrates at DX-55 andOS-28, and MEQ depths within a 4,000 feet square centered on DX-61. After the onset of injection on 2 September, the two producers experienced temporary flowrate increases and MEQ activity deeper than 3,000 feet subsea more than tripled.

1990. The USGS data have been extremely valuable for long term fieldwide coverage.

The Unocal-NEC-Thermal partnership (U-N-T) supplies steam for 1,103 MWe of the current installed capacity of about 2,000 MWe at The Geysers. U-N-T has monitored portions of the field since 1985 and expanded the array in November 1988 to cover most of the U-N-T leases (Figure 4). With 21 stations at an average spacing of 1 mile (including five 3-component stations), the current array locates about 20,000 events per year, with an estimated coda magnitude threshold of 0.3. All events are picked by computer (P arrivals only) and located; those of special interest are repicked by hand, including S arrivals if any, and relocated. Most of the epicenters in Figure 1a are based on autopicks only, so only those of coda magnitude greater than 0.7 are shown, because their hypocentral solutions

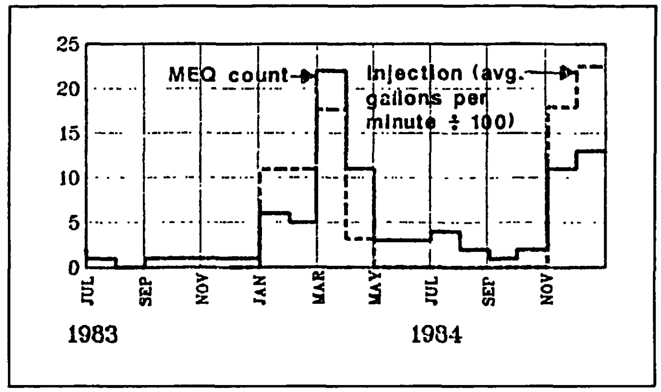

Figure 3. Time history of injection into GDC-18 (location in Figure 1) in average gallons per minute (GPM) andmonthly count of MEQs deeper than 3,000 feet subsea within a 2,000 feet square centered on GDC-18. MEQ count is based on USGS data.

are generally better constrained than those of smaller events.

Based on numerical experiments with picks and station corrections I estimate that hypocentral inaccuracy averages 700 feet horizontally and 1,300 feet vertically; values of 300 and 600 feet respectively apply for high-quality, hand-picked MEQs. For the time period June 1986 - August 1989 absolute accuracy of hypocenters has been enhanced by the use of station corrections estimated by Crosson's (1976) joint inversion method in conjunction with downhole calibration shot data.

Other MEQ surveys at The Geysers (e.g. Majer and McEvilly, 1979; O'Connell, 1986); and various proprietary

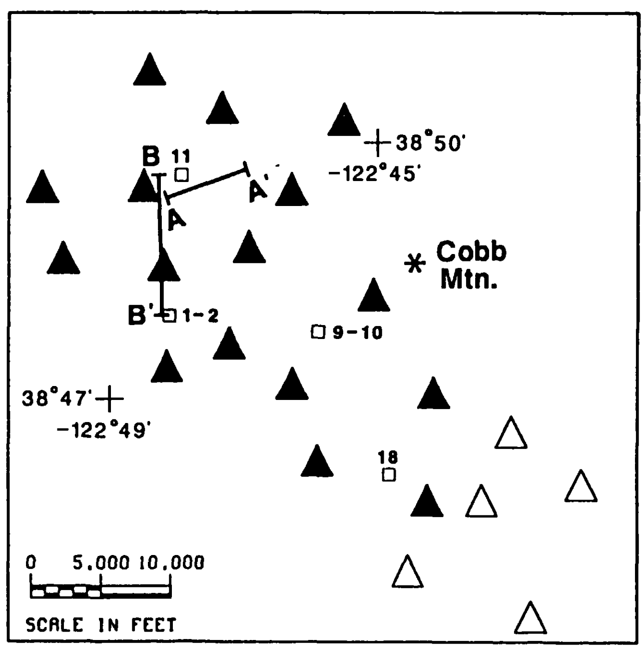

Figure 4. MEQ stations operating before September 1989 (solid triangles; these recorded the events shown in Figure 1a) and those installed since September 1989 (open triangles). Also shown are traces of cross sections A-A' and B-B'. Numbered squares are selected Pacific Gas & Electric power plants.

surveys) were geared towards more specialized research and were thus too limited in area and/or duration to add information of relevance to this study.

U-N-T's isotopic sampling (Gambill, this volume), tracer and flowrate data have been valuable in interpreting the links between injection and seismicity.

SPATIAL CORRELATION WITH INJECTION

Figure 1a shows the epicenters on U-N-T leases deeper than 4,000 feet subsea, based on U-N-T data for the time period November 1988 - August 1989. Maps from other time periods and those based on USGS data show similar patterns. The depth cutoff was determined empirically and is fairly consistent fieldwide; above 4,000 feet subsea the hypocenter distribution is much more diffuse.

Each injector or group of injectors has an associated MEQ cluster indicated on Figure 1b (the epicenters east of power plants 9 and 10 may be associated with non-U-N-T injectors which are not shown). However, some of the clusters extend rather far from their associated injectors. Figure 1b shows contours of injectate production based on isotopic composition of produced steam (Gambill, this volume) and reservoir steam pressure which illustrate two explanations for the extent of some of the clusters:

1. Steam wells near the extensions of clusters far from injectors produce a significant percentage of the isotopically "heavy" steam associated with flashed injectate, suggesting that the injectate flowed at least that far from its source.
2. The heavy injectate has migrated into areas of higher reservoir pressure in two areas - northwest from LF-23, and north from DX-61 - where MEQ clusters coincide. A simple explanation for migration up the reservoir pressure gradient is that the injected water is driven as a liquid by hydraulic pressure or gravity, before flashing and being produced. The coincident seismicity in these areas agrees with the hypothesis that the MEQs are induced where liquid is present.

TEMPORAL CORRELATION

Eberhart-Phillips and Oppenheimer (1984) reported three cases where the onset or cessation of injection at a particular well had little effect on nearby seismicity, therefore suggesting a very weak or nonexistent correlation. However in all of these cases the rate of injection into the area was not significantly changed; the water was diverted to nearby alternate injectors (often a convenient strategy when an injector goes out of service). For example, no major changes in seismicity were recorded around LF-3 (see Figure 1 for locations) after injection was curtailed there in 1979, probably because the water was diverted about 1,500 feet southwest to LF-23.

Figure 2 shows how MEQ activity around DX-61 responded to the September 2 startup of injection there. The response is especially clear deeper than 3,000 feet subsea, where the number of events per month rose from 18 to 61 after injection began. Also evident is a pronounced seismic hiatus lagging the injection hiatus of September 27 to October 6, and a similar seismic lull associated with the decreased injection rate of late November - early December.

Figure 3 shows the seismicity recorded by the USGS before and after the January 1984 onset of injection at GDC-18 in the central part of the field. Here the number of MEQs per month deeper than 3,000 feet subsea increased from a background level of one to a high of 22 by March 1984. Injection ceased during the summer, and the deep seismicity fell to an average of three per month, then returned to about 12 per month as injection resumed in November.

These kinds of responses have been observed in about ten cases where we have MEQ data during the onset of injection in an area not subjected to injection for the previous few months. The timing, rate of occurrence and shapes of the MEQs vary, but recognizable MEQ responses to injection have been observed in all parts of The Geysers field.

THEORY OF INJECTION-INDUCED SEISMICITY

Hubbert and Rubey's (1959) theory shows how changes in pore fluid pressure can trigger rock failure. Failure occurs when shear stress exceeds, by a critical value, the effective normal stress, where the latter is defined as normal stress minus pore pressure. If a rock volume is already near failure, a small increment of pore pressure can reduce the effective normal stress to trigger failure. This mechanism has been cited in numerous cases where seismicity has been induced due to fluid injection or filling of reservoirs behind dams (Simpson, 1976).

Majer and McEvilly (1979), Allis (1981) and Eberhart-Phillips and Oppenheimer (1984) pointed out that at The Geysers water is injected under vacuum, requiring no wellhead pressure, so the Hubbert and Rubey mechanism might not apply. However water levels in operating injection wells generally stabilize hundreds to thousands of feet above their total depth, and the columns of MEQs can extend thousands of feet below the well. At over 400 psi per thousand feet of water column, hydraulic pressures considerably greater than the reservoir steam pressure (200-500 psi) could be transmitted into the reservoir. Furthermore, P. G. Atkinson (Unocal, personal communication) proposed that effective normal stress could be diminished by thermal contraction, as well as by increased pore pressure, as the relatively cool water contacts the hot rock.

For these reasons I believe that the injection under vacuum could reduce effective normal stress and thereby trigger MEQs by the Hubbert and Rubey mechanism. Whether instigated by increased pore pressure or decreased rock temperature, the mechanism requires the presence of water in the liquid phase to induce MEQ's,

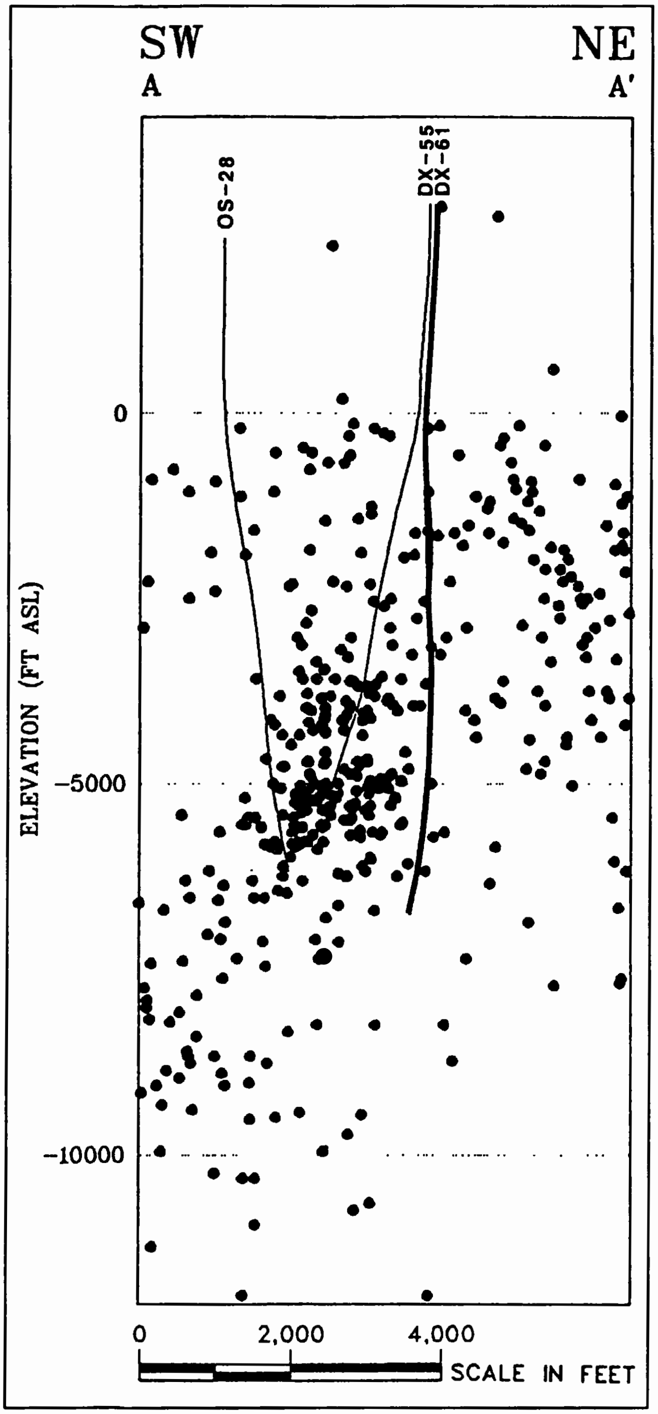

Figure 5. MEQ cross section A-A', DX-61 area, September 1986 - December 1986, immediately after startup of injection into DX-61 (bold well course). Note how the MEQ plumes dip southwest from DX-61 towards producing wells OS-28 and DX-55. Figure 2 shows pertinent temporal correlations. Cross-section width is 3,000 feet; trace is shown on Figure 4.

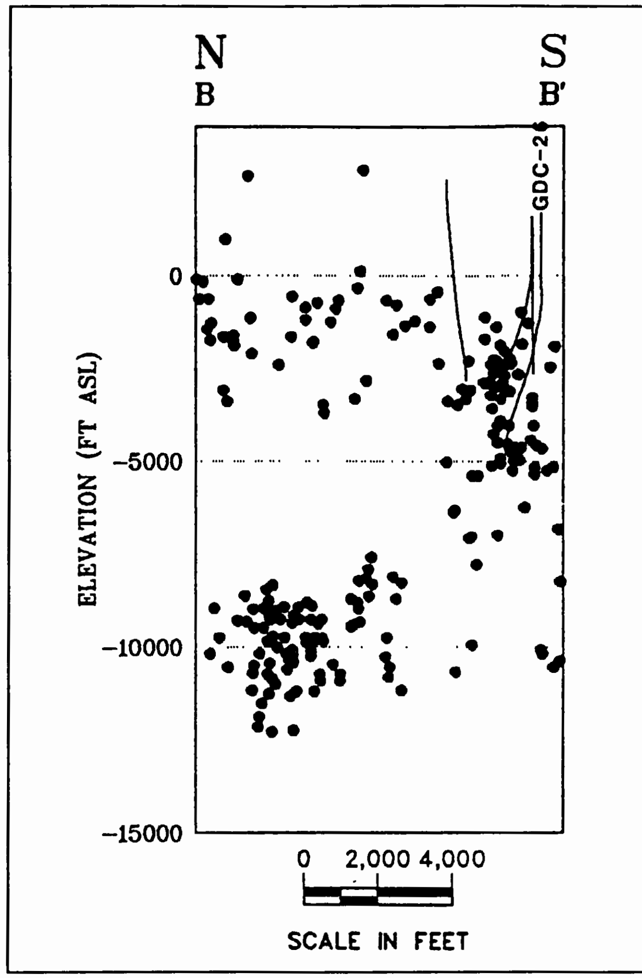

Figure 6 MEQ cross section B-B', GDC-26 area, November 1988 -August 1989, coda magnitudes >0.7. All four injection wells shown were active during this time span. Note how the deep MEQ plumes spread north and south from the injectors. Cross-section width is 3,000 feet; trace is shown on Figure 4.

which is the hypothesis underlying all the interpretations presented in this paper.

APPLICATION AND INTERPRETATION EXAMPLES

Injectate Tracking

The injection-related MEQs can help delineate in a broad sense where injected water travels. Figure 5 shows in cross section the MEQs located during the early stages of injection at DX-61 in late 1986. The events are all hand-picked to maximize hypocentral precision.

The increase in seismicity was concentrated southwest of DX-61 in the vicinity of producing wells OS-28 and DX-55 (the events northwest of DX-61 seen in Figure 1 did not appear until 1987). Figure 2b shows that the flow rates of these producers reversed their normal declines starting about 1 week after injection began (this was a temporary phenomenon sometimes seen in the early stages of injection). OS-28 later suffered precipitous declines probably due to wellbore sloughing, while DX-55 continued to produce. Other producers around DX-61 showed little or no response to the onset of injection. The steam isotope compositions told a similar story; OS-28 and DX-55 saw the largest increases in isotopically heavy steam production in late 1986. These data were interpreted to mean that the water injected into DX-61 quickly found a path southwest towards DX-55 and OS-28, possibly destabilizing the latter. This is a good example of the use of MEQ data to infer flow of injectate and, in a qualitative sense, permeability variations.

Figure 6 shows in cross section another style of MEQ cluster associated with a group of four injection wells including GDC-26. Below the injectors the MEQs form a poorly defined vertical column down to 8,000 feet subsea, then spread north in a dense distribution in the depth range 8,000 to 12,000 feet subsea.

Reservoir Bathymetry Soundings

The pattern in Figure 6 has been stable for at least 6 years, suggesting that the depth limits are controlled by a permeability barrier. The MEQ floor can thus be tentatively interpreted as the local reservoir bottom.

Several scenarios could invalidate this interpretation, including: aseismic (e.g. low pressure) flow below the floor; or flow of injected water into dead-end fractures, rendering them unproductive. A purely thermal barrier would probably migrate downwards over the years, rather than remain stable, due to the constant downpour of relatively cool water.

In the absence of more definitive constraints, stable MEQ floors were used by Williamson (this volume) to help estimate reservoir bathymetry for simulation purposes. Each injection well with a stable MEQ depth floor can act as a depth sounding. In the few areas where downhole evidence for reservoir bottom overlaps with an MEQ floor the depths are consistent.

CONCLUSIONS

The data presented indicate that injection induces MEQs at The Geysers. Excellent temporal correlation is observed, and isotope sampling and steam production data help to understand and support the spatial correlation.

I hypothesize that the MEQs are induced where injected water is present as a liquid, relying on established rock mechanics theory and on corroborating isotopic and production data. This implies that the MEQs form an image of the injected water. The applications include: tracking of injected water to understand and possibly anticipate effects on nearby producers; and rough estimates of reservoir bathymetry.

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