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# ROOSEVELT HOT SPRINGS GEOTHERMAL FIELD, UTAH – RESERVOIR RESPONSE AFTER MORE THAN 25 YEARS OF POWER PRODUCTION

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## ABSTRACT

After more than 25 years of production, Roosevelt Hot Springs geothermal field continues to produce in excess of 400,000 pounds/h (about 200 metric tons/hour) of steam from much the same borefield area as drilled during the late 1970s. Initial tests of two wells drilled in 2008 east of the production borefield indicate that the high-temperature reservoir may be more extensive than previously thought. The plant was originally built as a single-stage flash plant with a 23 MW net installed capacity. In 2007 a binary plant was installed to generate 10 MW of additional power from the separated hot liquid. The reservoir pressures are presently declining at about 0.3 bar/year (5 psi/year), after declining at a much higher rate during the early production years. The total pressure decline is about 40 bars (600 psi). Deep reservoir temperatures appear to be declining at about 0.7 ºC /year (<1.5 ºF/year), and a substantial thermal resource remains after more than 25 years of production. Temperatures of 260 ºC (500 ºF) still exist on the east side of the production borefield. Shallow temperatures have locally increased along the Opal Mound fault zone due to formation of a steam zone over the hot liquid reservoir. Based on the original heat flow, the undisturbed liquid inflow to the field was about 50 kg/s (~400 kp/h), and this will have increased due to the reservoir pressure decline with development. Past reservoir modeling efforts appear to have been too conservative in predicting development potential. PacifiCorp Energy is initiating an investigation of fluid flow paths between the injection and production wells so that future heat extraction from the reservoir can be optimized. Expansion of power generation from the field in the future is anticipated.

## INTRODUCTION

The first production well (3-1) was drilled at the Roosevelt Hot Springs geothermal field in 1975, and subsequent drilling and testing resulted in a 23 $MW_e$ (net), single-stage flash steam plant being commissioned in 1984. The field operators have changed several times (Phillips Petroleum Company, Chevron Resources Company, California Energy Company), with the long-term owner of the Blundell power plant, PacifiCorp Energy, acquiring the field in 2006. The history of development is summarized by Forrest (1994). Moore and Nielson (1994) summarized the considerable geoscientific research supported by the United States Department of Energy and largely carried out at the University of Utah, and reservoir engineering studies have been reported by Faulder (1991, 1994) and Yearsley (1994). A binary power plant was commissioned in 2006 to generate an additional 10 $MW_e$ (net) from the separated water. The production history is summarized in Figure 1. The capacity factor for the steam plant in 2010 was 99% and that of the binary plant was 94%, demonstrating the plants' reliability for base load power generation. The typical deep production temperature today is about 245 - 250ºC (470 - 480ºF), the separation pressure and temperature and are typically in the range of 8 – 10 bar g (110 – 130 psi g; all pressures in this paper are gauge [g]) and 175 – 180ºC (347 – 356ºF), and the discharge temperature from the binary plant is about 104 ºC (220 ºF). Sulfuric acid is used to minimize the risk of silica scaling in the injection system. Carbonate scale inhibitor is also used in the production wells. The difference between the total mass of fluid produced (about 20 billion pounds/year [9 million metric tons/year]) and total injection (about 17 billion pounds/year [7.7 million metric tons/year]) is mostly the mass of water evaporated from the forced-draft cooling towers.

A map of production, injection and deep exploration wells is shown in Figure 2, and this highlights what are considered to be the critical permeability structures – the north-northeast trending Opal Mound fault zone and the Negro Mag cross-fault. Production today is being supplied by wells 54-3, 45-3, 28-3, and 13-10, with most injection water (about 70%) going into well 14-2. Wells 12-35 and 82-33 are used for the remaining injection water. In 2008 wells 58-3 and 71-10 were drilled as part of an investigation of an expansion of the power plant. Both wells confirmed high temperatures at depth (261 ºC [501 ºF] in 71-10) and could be used as either producers or injectors. Most wells are between 800 and 2000 m (2500 – 6000 ft) deep.

In this paper we review the response of the reservoir to over 25 years of production and injection. Despite impressive continuity in the power production and well productivity over this time, subtle changes have been occurring at depth. Particular attention is given to the temperature and pressure changes, and the expansion of the steam cap that formed during the late 1980s and was considered by Yearsley (1994) to cover about 1 $mi^2$.

## THERMAL CHANGES

The original temperature distribution of the Roosevelt Hot Springs geothermal field is shown in Figure 2. This distribution differs slightly from that shown in Faulder (1991) and Yearsley (1994) because it uses the extrapolated temperature of a deep gradient well in the south (OH8; taken from Forest, 1994), and the temperature in well 24-36 in the northeast. It also uses the recently drilled well 71-10, which confirmed that temperatures of over 260 ºC (500 ºF) still exist below 1500 m (4920 ft) depth east of the production wells. The highest temperatures were observed in well 14-2 in 1976 (268 ºC, 515 ºF) at 1858 m (6091 ft). This well is now the main injector.

The temperature changes due to 25 years of production vary with each well, and are sometimes uncertain because of possible non-thermal equilibrium when logging is done soon after production wells are taken off-line. Two wells near the center of the field, which are not producers (3-1 and 58-3), provide a good indication of the changes (Figure 3).

Prior to 1984 most wells immediately east of the Opal Mound fault zone showed a boiling-point-for-depth profile from near-surface. Wells 3-1 and 58-3 now show a pronounced temperature gradient at shallow depth, which has increased with time (see 1988 and 2010 profiles for well 3-1). The simplest interpretation is that this high-gradient zone (between about 200 and 600 m; 700 – 2000 ft depth) indicates a perched groundwater zone overlying a steam zone that has developed due to a pressure decline in the reservoir (discussed in more detail below). The top of the groundwater zone appears to have declined from about 150 to 250 m (490 – 820 ft) depth between 1988 and 2010, and the lower interface of the groundwater/steam zone has risen from about 550 to 450 m (1800 to 1480 ft) depth as the steam zone pressure has declined from 45 to 38 bars (650 – 550 psi) and the temperature has declined from 257 to 244 ºC (495 to 471 ºF). The steam saturation pressure for these temperatures is 44 and 35 bars (640 and 508 psi) respectively (steam tables), so a small partial pressure of gas in the steam is likely present and this could have increased with time (from 1 to 3 bars [15 – 44 psi] based on observed pressure profiles). This is not unexpected for a boiling reservoir with most gas separating from the liquid with first boiling induced by the pressure decline.

The rate of reservoir temperature decline within the deep liquid reservoir is shown in Figure 4 for well 13-10. Over the last decade the rate of change has been about 0.7 ºC/year (1.3 ºF/year). Most of the temperature decline occurred during the 1990s, in contrast to the pressure decline which occurred a decade earlier. This is due to thermal buffering by the host rock delaying the thermal effects of the pressure decline caused by production and injection. Using the average reservoir temperature decline since the late 1990s of 0.7 ºC/year (1.3 ºF/year), and assuming the brine injection temperature is the same as the steam separation temperature, the net heat extracted from the produced water requires an effective reservoir area of about 2 $km^2$ (0.8 $mi^2$) for a reservoir thickness of about 1 km (~ 3000 ft). These numbers seem reasonable, being an area that encloses the four producers and the main injector (well 14-2). This also suggests that with the binary plant recently reducing the injection temperature from about 177 to 100 ºC (350 to 212 ºF) the rate of reservoir temperature decline will approximately double. However, the open-ended nature of the temperature contours to the east of the existing production wells, and also with depth, implies there is a significant thermal resource to support an increased rate of development for future production/injection wells eastward from the existing field. Figure 5 shows another version of the reservoir temperature decline due to development in several well east of the Opal Mound fault zone. Here the temperature seems to have declined by about 7 – 10 ºC (13 – 18 ºF) between 1000 and 1500 m (3300 – 4900 ft) depth.

## PRESSURE CHANGES

Figures 3 and 4 highlight the pressure changes both vertically (wells 3-1, 58-3) and with time (wells 28-3 and 25-15). The total pressure decline due to the initial well testing (up to 1984, 1 – 2 bar [15 – 30 psi]) plus the subsequent effect of production and injection is close to 40 bars (600 psi) (up to 2010). Most of this occurred during the first six years of production, and the long-term rate of decline as seen in production wells 28-3 and 25-15 is now about 0.3 bar/year (5 psi/year).

All the pressure data is compiled in Figure 6 with depths converted to elevation (above sea level, asl). With the exception of well 54-3, the compiled data confirms the liquid reservoir draw down of about 40 bars (600 psi). The top of the liquid zone (i.e. bottom of the steam zone) varies between 1000 m asl (3300 ft above sea level) (wells 3-1 and 58-3) and 1200 m asl (3940 ft) (wells 28-3 and 13-10) depending on the overlying steam zone pressure.

Production well 54-3, which is closest to injection well 14-2, shows a clear pressure effect due to injection. These two wells are 0.8 km (0.5 mi) apart, and well 54-3 shows less than half the total liquid pressure decline (~ 17 bar [250 psi]) of that seen in the other producers and monitor wells. Surprisingly, there has not been a major cooling effect on the feed-zone temperature of well 54-3, which appears to be centered between the bottom of the casing (520 m [1700 ft]) and 850 m (2790 ft) depth where a temperature maximum of 254 ºC (489 ºF) presently occurs (Figure 5). A minor reversal to 248 ºC (478 °F) occurs between 850 and 1160 m (2790 – 3810 ft) depth, and the temperature at the total depth of 1250 m (4100 ft) is 252 ºC (486 °F). The open section of well 14-2 is between 550 m (1800 ft) and its total depth of 1550 m (5085 ft). It is possible most of the injection water is dispersing at about 1000 m (3300 ft) depth and well 54-3 is mostly pulling on shallower hot water that has flowed laterally from an upflow zone to the southeast, such as near well 71-10 where the temperature is still 260 ºC (500 ºF) below 1500 m (4920 ft) depth. Well 71-10 appears to have a similar pressure profile to the wells adjacent to the Opal Mound fault zone indicating it is connected to the productive reservoir. Chemical and tracer surveys that compare the injected and produced water compositions should help resolve the present fluid flow between the injection and production wells.

Prior to development the two wells west of the Opal Mound fault zone (82-33 and 9-1) had pressures below the hot reservoir trend (upper graph, Figure 6). The reservoir is now drawn down below those original pressures in wells 82-33 and 9-1, so there may now be natural recharge flow from west of the fault zone towards the production wells. Recent pressure monitoring in well 9-1 suggests the pressure at depth in this well is now following the main reservoir pressure trend (PacifiCorp Energy data). Because well 82-33 is still used as an injector, the amount of water returning to the reservoir from this well needs to be investigated.

## STEAM ZONE EVOLUTION

The development of a steam zone overlying the main liquid reservoir is a common occurrence in liquid systems that are being exploited. Yearsley (1994) noted that by 1988 static surveys of pressure and temperature showed the steam zone was about 600 m (2000 ft) thick and covered an area of about 2.5 km$^2$ (1 mi$^2$) based on snow melt anomalies. However, he concluded that the steam cap was having no obvious effect on production at that time because the main feed-zones in the wells were much deeper. A 2008 comparison of (1) the observed steam fraction at the separation temperature with (2) the theoretical steam fraction calculated from the inferred feedzone temperature from both static and producing downhole surveys suggests that between about 50 and 100 kp/h of the 450 kp/h (23 - 46 of 200 metric tons/h) total separated steam could be excess steam (PacifiCorp Energy production figures). This 10 – 20% benefit in steam production could now be compensating for the gradual decline in feed-zone temperatures.

The snow melt anomalies noted in 1988 have evolved into expanded areas of warm ground along the Opal Mound fault zone as well as several areas of steaming ground adjacent to the original Roosevelt Hot Spring location. An informal estimate of the surface heat loss suggests at least 10 MW$_{th}$ of steam loss is now occurring. Future power generation options may include a new well that directly taps the steam zone.

## CONCLUSIONS

A substantial geothermal resource remains after 25 years of power generation at Roosevelt Hot Springs geothermal system. Additional power generation has been considered intermittently since the power plant was commissioned (e.g., Yearsley, 1994). The trends discussed here allow for improved modeling of future development options, which should include some direct tapping of the steam zone. Steam zone pressures are 20 - 35 bars (300 – 500 psi), so at least one well should be considered as an additional producer to investigate production potential of the steam zone. Critical reservoir modeling uncertainties are the interdependence of the effective pore volume and recharge rate, as discussed by Yearsley (1994) and Faulder (1994). The larger the pore volume, the higher the inferred recharge for a given pressure change due to a production change. One factor constraining the recharge to the field is the natural flow rate prior to development. The observed natural heat loss of 60 MW$_{th}$ observed by Ward et al. (1978) implies a natural inflow of about 50 kg/s (~ 400 kp/h) assuming a deep recharge enthalpy of 1150 kJ/kg (265 ºC [510 ºF]). The recharge to the reservoir now that there is a sustained pressure decline of about 40 bars (580 psi) will be significantly higher than this, although a portion of this enhanced recharge could be cooler fluid drawn laterally into the reservoir. The implied recharge is significantly higher than that used by Yearsley (1994), which means that his model over-predicted the effects of additional development on the reservoir.

## ACKNOWLEDGMENTS

We thank PacifiCorp Energy for permission to publish this paper. Comments attached to the well logs measured by Kenny and Gary Foster and observations by Steve Austin have helped the interpretation of reservoir changes. Many reviewers including Bob Blackett, Gary Chapman, and Joe Moore provided helpful suggestions. This work builds on the reports and publications of many from scientists and engineers who have worked on Roosevelt Hot Springs field over the years.

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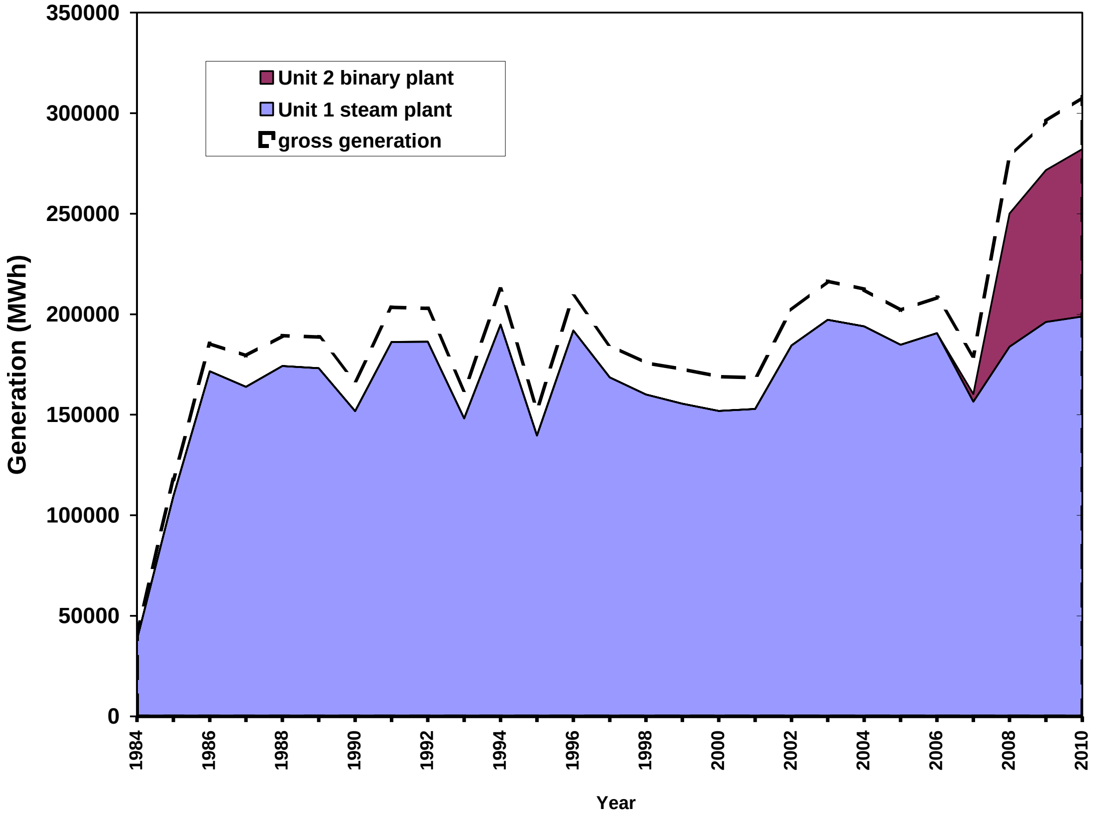


***Figure 1**: Power generation from the Blundell facility since its commissioning in 1984.*

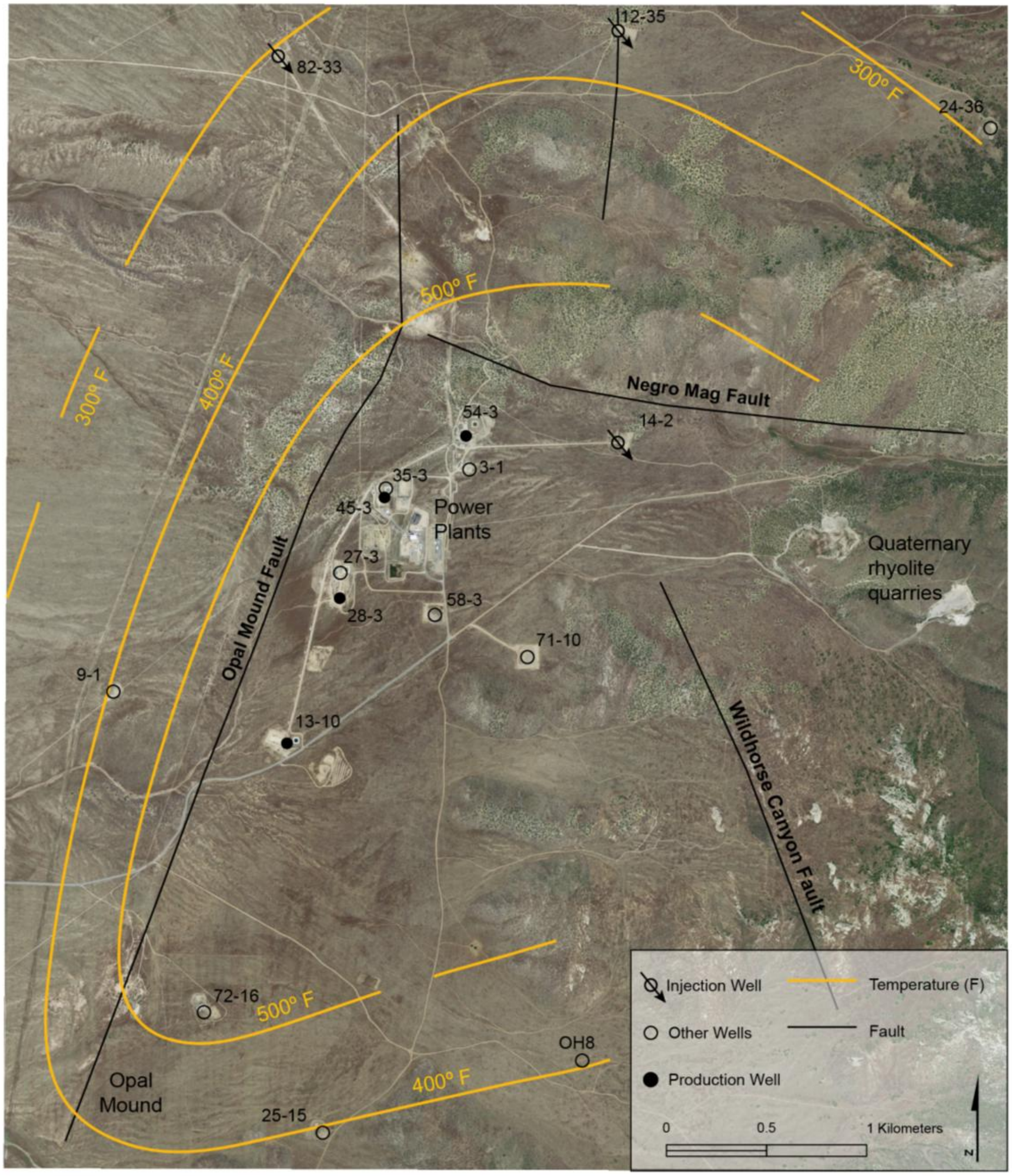
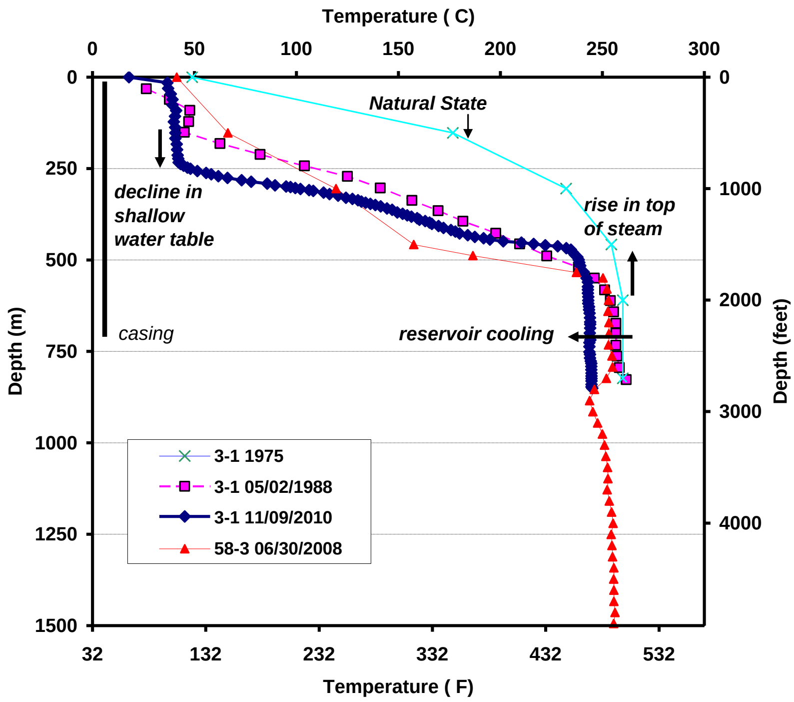


***Figure 2:*** *Map of the Roosevelt Hot Springs geothermal field, with original temperature contours for 1500 – 1800 m (5000 - 6000 ft) depth superimposed on a 2009 orthophoto (500 ºF is 260 ºC).*



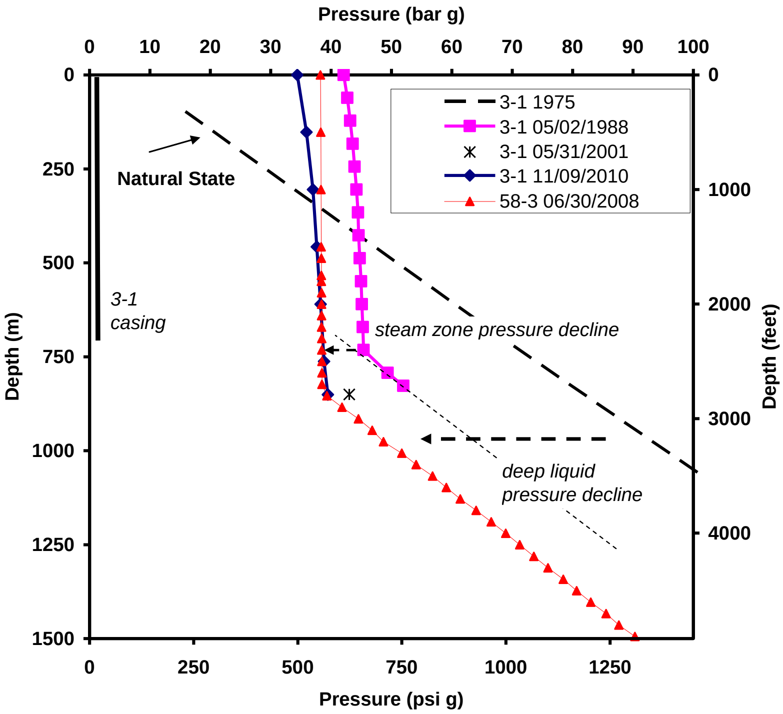


***Figure 3**: Changing temperature (upper graph) and pressure (lower graph) profiles in two nearby, shut-in wells (3-1, 58-3). Taken together, the two graphs indicate an expanding steam zone and a thinning groundwater zone due to the pressure decline in the liquid reservoir. In 1988 the steam zone appears to extend from 600 to 750 m (2000 – 2500 ft) depth. It now extends from about 500 to 850 m (1640 to 2800 ft) depth.*

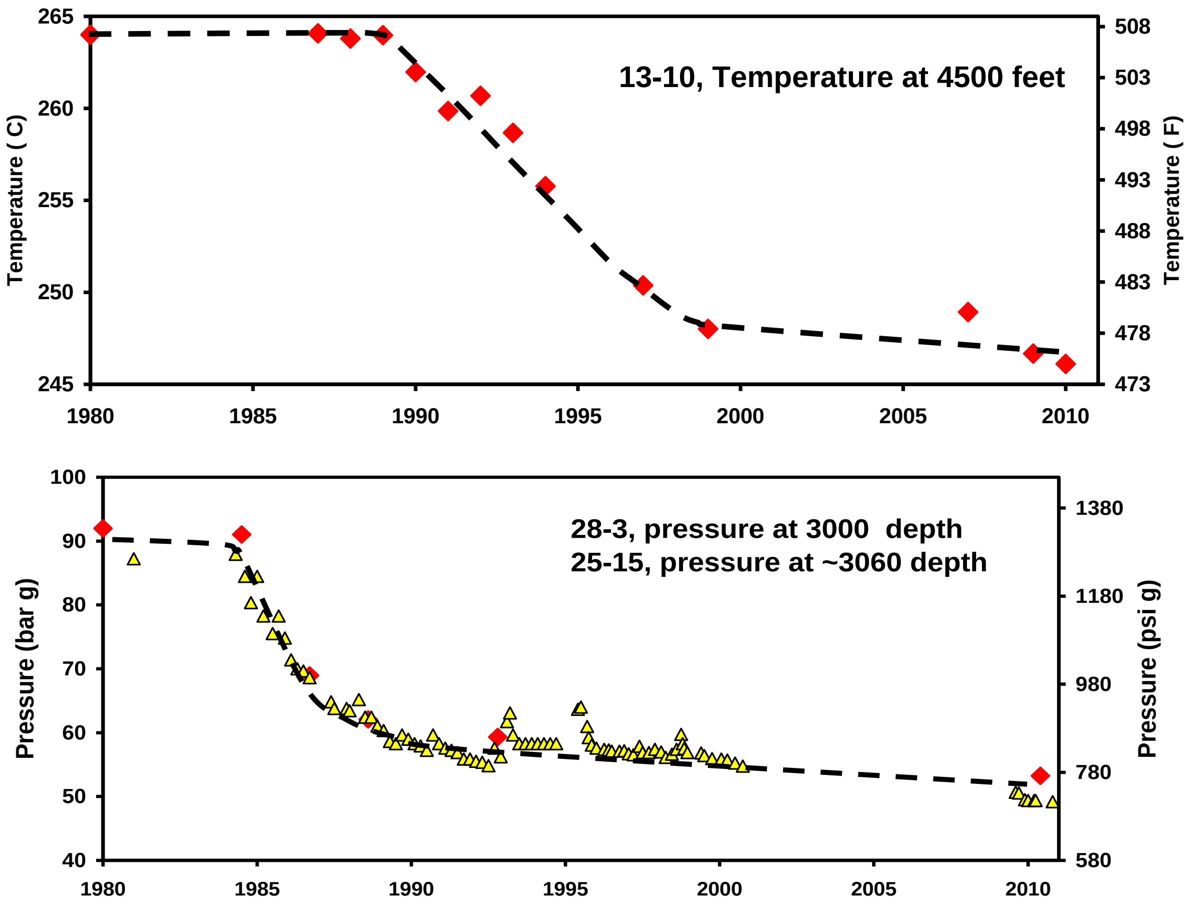


***Figure 4**. Rate of change in temperature (well13-10) and pressure (wells 28-3 and 25-15) within the liquid zone of the reservoir. Note the main temperature decline occurs about a decade after the pressure decline. The pressure in 25-25 has been adjusted from the usual datum of 610 m (2000 ft) depth by adding 30 bars (435 psi).*

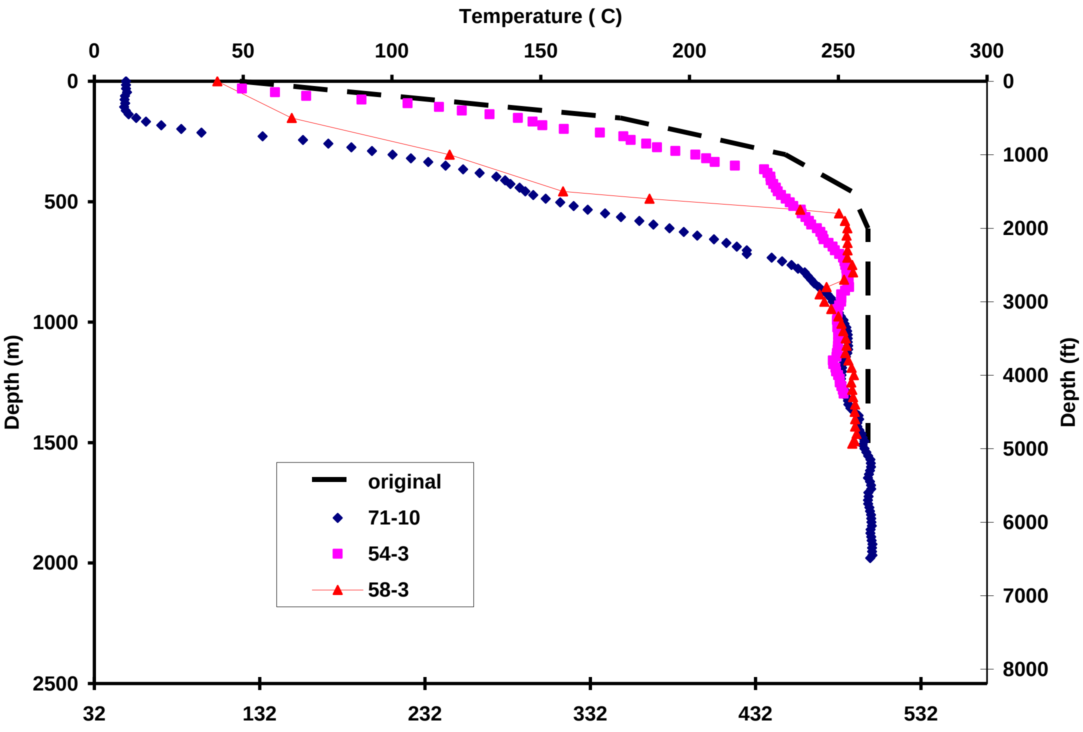


***Figure 5:** Comparison of recent static temperature profiles in wells 71-10, 58-3 and 54-3. The "original" profile is from Faulder (1994). Although the temperatures shallower than about 1000 m (3300 ft) depth are variable, a consistent pattern of cooling is evident between 1000 and 1500 m (3300 – 4900 ft).*

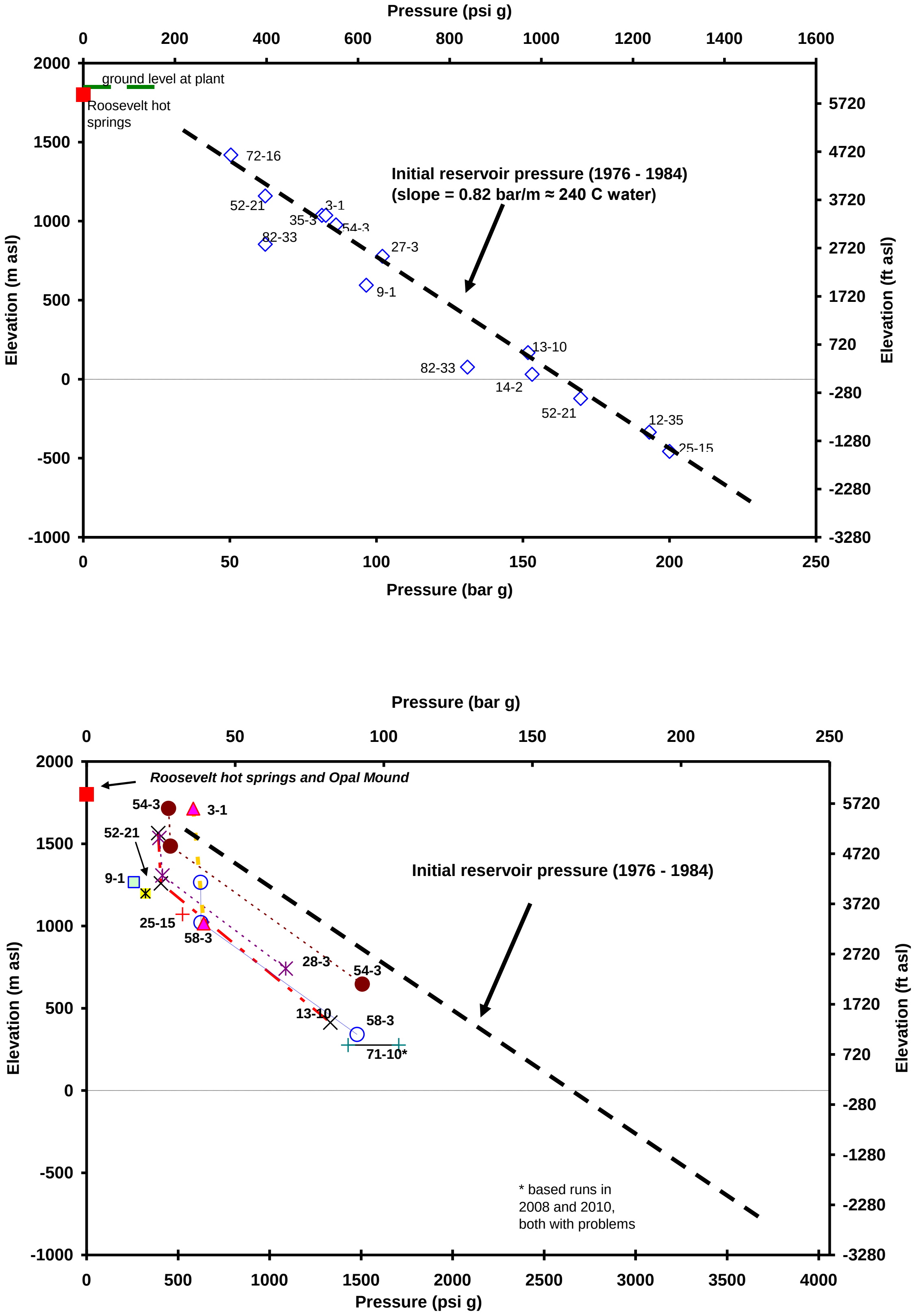


***Figure 6**. Spatial pressure trends in wells at Roosevelt Hot Springs. Upper graph is the original pressure distribution derived from Faulder (1991) and Yearsley (1994). Lower graph shows recent pressures (2006 – 2010) with the initial reservoir trend superimposed ("asl" is above sea level).*