A Model for the Shallow Thermal Regime at Dixie Valley Geothermal Field

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ABSTRACT

Pressure drawdown of the Dixie Valley reservoir supplying Oxbow's power station has caused an increase in steam-heated thermal activity around the Senator fumarole, and subsidence centered near the toe of the fan immediately east of the fumarole. Analysis of shallow well data in the area shows that a 1 km^2 area of the fan is now dominated by steam below about 1000 m asl, or 50 m below the elevation of the adjacent valley floor. Two wells within this shallow, high temperature anomaly have temperature maxima at 1035 m asl, suggestive of an outflow zone at about this elevation. Although this zone is now steam-filled, our model suggests that this was the original liquid outflow of this part of the geothermal field. It has a temperature of at least 165°C. The inferred pressure profile prior to development implies lateral outflow from the Stillwater fault zone into the fan above about 800 m asl. Drawdown of the reservoir liquid has drained the outflow zone and caused two-phase conditions. Where relatively competent material beneath the fan merges with weak playa sediments, the pressure decline has caused subsidence. Heat loss considerations suggest that the original liquid mass flow into the outflow zone was 5 kg/s (factor of two uncertainty).

Introduction

The Dixie Valley geothermal field, like many Basin and Range hydrothermal systems, had relatively few surface thermal manifestations prior to development. A steam vent (Senator fumarole) was present high on an alluvial fan near the Stillwater range front, adjacent to what has become the production wellfield (Figure 1). A patch of weakly steaming ground (~100 m^2) also was present on the range front near the inferred southern extent of the field. The drilling of temperature gradient wells up to 160 m depth during the 1970s and 1980s defined two lobes of anomalously high thermal gradient between 60 and 160 m depth extending into the center of the valley from near the areas of known thermal activity (unpublished Oxbow data). The gradient anomaly is consistent with two outflow plumes of hot water emanating from the foot of the Stillwater Range, although no hot springs or seepage were evident at the surface. The nearest warm surface waters occur a further 13 – 20 km south (Dixie-Comstock Mine and Dixie Meadows) and 10 - 15 km to the northeast of Dixie Valley (Hyder hot springs, Sou hot springs; Figure 1; Garside and Schilling, 1979). The temperature gradient data suggests that these are separate outflows unrelated to the Dixie Valley geothermal system now developed by Oxbow Power Company.

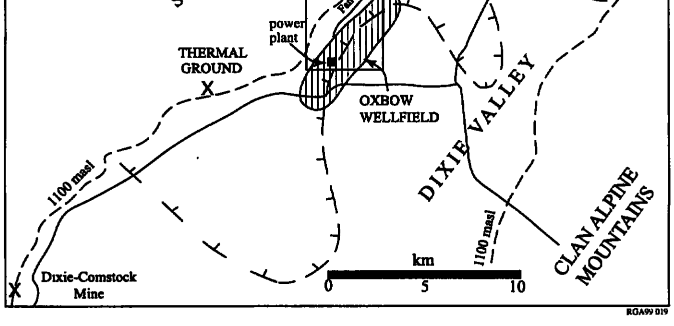

Figure 1. Location map of northern Dixie Valley showing occurrences of hot springs and thermal activity. The bold dashed line with ticks outlines a thermal gradient anomaly of 70°C/km based on the temperature between 60 and 150 m depth in early, widely-spaced exploration wells (unpublished Oxbow data). The shape of this anomaly is suggestive of two hot water outflow zones into the center of the valley. The outflow zone discussed in this paper actually lies between these two zones, and is situated within the box labeled Figs. 2, 5.

During the 10 years of geothermal power generation at Dixie Valley, significant thermal changes have occurred around the Senator fumarole and on the adjacent fan, apparently in response to development of the geothermal field. These changes have been discussed by Johnson and Nash (1998), Bergfeld *et al.* (1998), and in a companion paper (Allis *et al.*, in prep.). A small subsidence bowl has also developed near the toe of the Senator fan causing ponding of runoff water in its center (Figure 2). No obvious changes have occurred to the other thermal features around Dixie Valley, including the area of steaming ground on the southern part of the field.

As part of a mineral exploration initiative, and also in order to better understand the groundwater resource over the geothermal field, a number of shallow wells have been drilled around the Senator fan. Temperature logging of these wells has provided

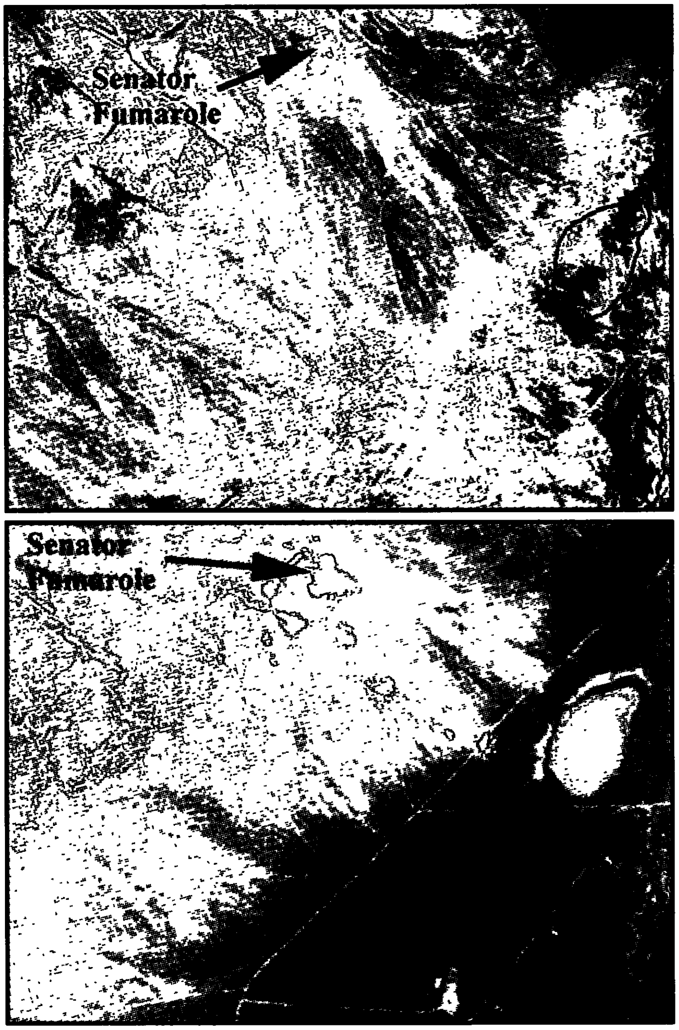

Figure 2. Comparison of a vertical air photograph taken in 7/1990 (upper image) and a processed thermal infrared image taken in 7/1998. The two images are from the same area, centered on the Senator fumarole. Most of the thermal activity away from the fumarole has occurred since 1995. The grey pond in the 1998 image marks the inferred center of the subsidence bowl. Its outline is shown on the 1990 image to assist comparisons. The light colored ground between the pond and the fumarole on the thermal image is hot ground.

insight to the nature of the geothermal outflow zone beneath the fan, and the reasons for the changes that have occurred at the surface. In this paper we compile the data to enable a conceptual model of the outflow zone to be formed that is capable of explaining the changes. We suggest that the surface thermal changes and much of the subsidence are a consequence of pressure drawdown in an outflow zone beneath the fan at 50 – 300 m depth below the elevation of the valley floor.

Evidence from Well 27-32

This well was drilled near the toe of the Senator fan in two stages (well located on Figure 5, page 496). In stage 1 it was drilled to 150 m depth and logged for temperature. The presence of gas in the well presumably initially allowed a temperature maximum of 148°C to be seen at 30 m depth on the downgoing log. If true, this temperature implies about 1 bar of over-pressure relative to hydrostatic conditions at this depth, outside the casing. Beneath the this high temperature zone, slightly cooler steam/gas at 140°C is evident down to a water level at 111 m depth (slotted casing exists below 79 m depth). Leakage of gas and steam around the wellhead gland while logging meant that the shallow temperature maximum was masked during the logging up profile. On testing, the well flowed minor steam and no significant water, suggesting limited permeability above the water level, and a steam feed. This feedzone is assumed to be immediately beneath the solid casing at 80 m depth, with the 140°C temperature implying a feedzone pressure of 2.7 bar g. The correction to absolute pressure requires an additional 0.9 bar for the elevation of Dixie Valley.

The elevation of the shallow temperature maximum at 30 m depth coincides with the elevation of a temperature maximum and inversion in another hot well on the fan (DJ10), suggesting an aquifer at this elevation (i.e. at 1035 m above sea level, or 10 m below the adjacent valley floor. The aquifer here is likely to be steam-filled now, but may have been an outflow of hot reservoir water prior to development. (i.e. of at least 148°C water near the upflow zone).

The well was deepened to 305 m, but before logging, the well was tested with an airlift tube from near the bottom of the well. This discharge was also largely steam with minor water. Even after pumping water into the well for short periods, the discharge rapidly reverted to steam discharge. The temperature profiles under static conditions soon after this testing (9-16-97), and later (11-6-97), plus subsequent profiles after major injection tests (11-11-97) indicate multiple zones of permeability between 100 and 200 m depth. The log under flowing conditions (also 11-6-97) confirms steam feedzones in this depth range, with the deep liquid water level rising passively in the deepest part of the well as steam pressure declines with production. The stability of the pressure in the liquid portion of the bottom of the well suggests pressure control here even although this part of the well is not contributing to the discharge. Given the steam feedzones at shallower depth, and the large drawdown in the main reservoir at depth, the static liquid column in the wellbore could be balanced by another steam feedzone in the country-rock. Based on the injection and flowing logs, this may be at 258 m depth, and therefore at a pressure of 6.5 bar g (assuming thermal equilibrium at this depth).

The pattern of a steam-filled well with a short liquid column in the well which descends as the well is deepened is consistent with a steam zone with increasing pressure and temperature with depth. This suggests the vertical permeability here is not high, but there are zones of near-horizontal permeability with moderate permeability.

The geology based on the well cuttings in 27-32 leaves some doubt over whether the entire sequence is alluvium and silicified landslide material, or an in-place block of basement below 145 m depth (Figure 3). In the interpretation presented below, we suggest the former, but this assumption does not affect the conclusions about the geothermal state of the outflow zone and the nature of the changes with development.

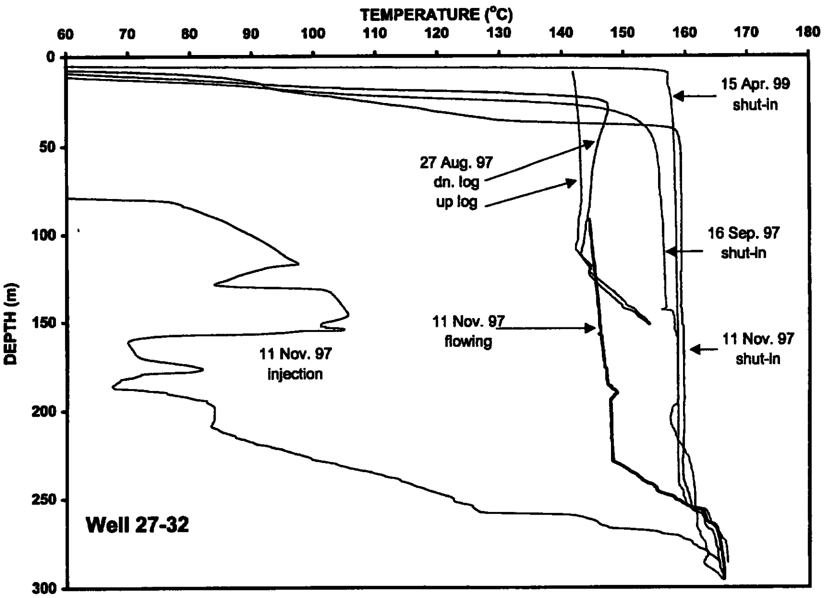

Figure 3. History of temperature measurements in well 27-32. The well was initially drilled to 152 m depth, and was later deepened to 296 m. Measurements were made under static and flowing conditions, and after injection tests. The results indicate steam feedzones with progressively increasing pressure below the solid casing at 79 m depth. Refer to text for further discussion.

Thermal Regime Beneath the Senator Fan

A composite plot of the temperature profiles of wells in the vicinity of the Senator fan is shown in Figure 4, adjusted for the elevation of the wellhead. The wells are located on Figure 5. Most of the profiles were measured during March, 1999. Comparisons with profiles in the DJ wells made during July, 1998 show changes of less than 3°C, over restricted intervals. Although rapid changes over the high temperature part of the fan are clearly not occurring, this does not preclude significant changes on the 10 year time-scale as a result of development. Unfortunately there were no wells in this part of the fan prior to 1997, so changes have to be surmised from the temperature and pressure regimes present today and the observed changes in thermal activity. At the southern edge of the high temperature anomaly, the profiles in 8-76-14 (measured in the 1970s) and 32-6 in 3/1999 are overlapping and are not suggestive of a significant change with time. A lack of change here is not surprising because the gradient of 10 – 15°C/100 m, similar to the conductive gradient overlying much of the reservoir, is indicative of low permeability and therefore a very long thermal response time to changes at 2 – 3 km depth.

Most of the DJ wells, 38-32, 27-32 and 46-38 suggest temperatures of about 150°C at an elevation below 1000 m asl. When temperatures are mapped at an elevation of 1035 m asl, the level of the thermal maximum in DJ10 and 27-32, the contours show a lobe of high temperature extending from vicinity of the Senator fumarole

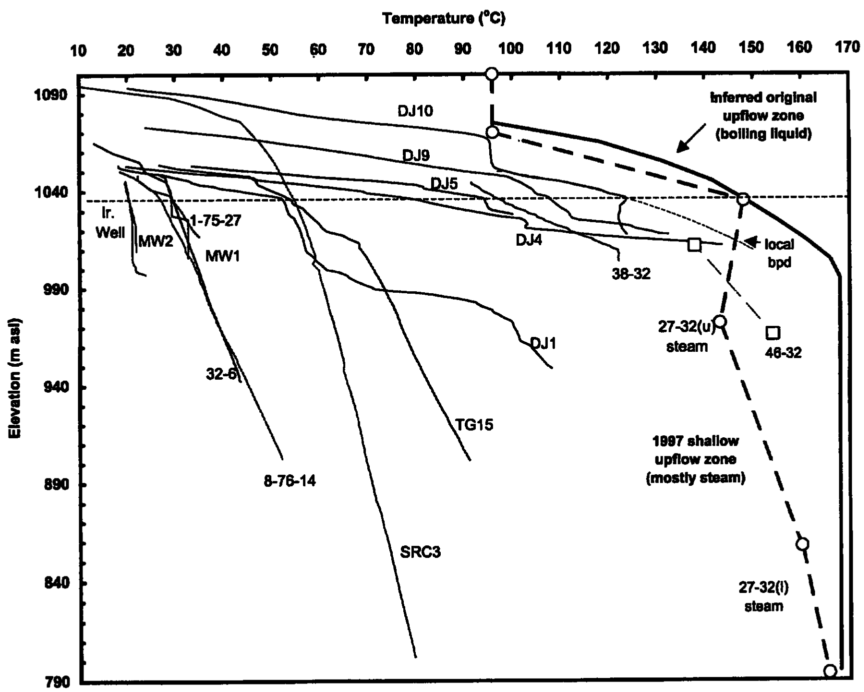

Figure 4. Compilation of temperature profiles from shallow wells around the Senator fan. Most of the data is from surveys carried out between 1997 and 1999. The dashed line at 1035 m asl coincides with temperature maxima in DJ10 and 27-32, and may mark the elevation of significant liquid outflow prior to development.

towards the valley (Figure 5). Three wells are on the boundary of the lobe (TG15, DJ1, SRC3). In the case of DJ1 there appears to be a mixing zone of intermediate temperatures between 1035 and 1000 m asl, and at greater depth the temperature rises rapidly towards that seen beneath the center of the high temperature anomaly.

The expansion of thermal activity on the Senator fan has mostly occurred centrally over the high temperature anomaly on Figure 5. However steaming ground has also spread northeast along the rangefront from the Senator fumarole. The temperature profile in well SRC3 is from the mid 1970s, so it is conceivable this area may now be hotter than indicated by that profile.

The center of subsidence, inferred to be beneath the pond occurs at the outer limit of the thermal anomaly and suggests a possible causative link. This is discussed in detail below as part of the conceptual model.

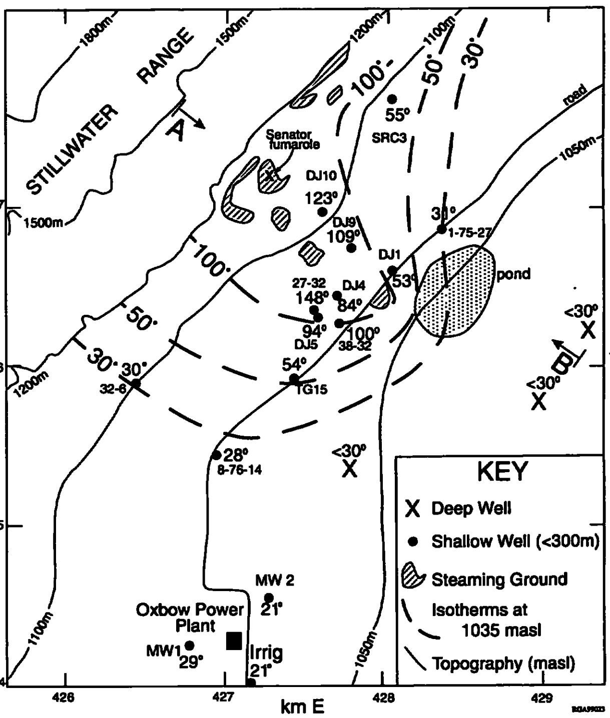

Figure 5. Map of the temperature field at 1035 m asl derived from Figure 4. The map shows a zone of high temperature zone extending towards the valley from the vicinity of Senator fumarole. Contouring has assumed that the temperature exceeds 100°C where steaming ground exists. The data point for northern well SRC3 is from a survey in the mid 1970s, and may not be representative of conditions today. Points A-B mark the location of the cross-section shown in Figure 7.

Pressure Trends

The DJ series wells are sealed pipes filled with water and do not directly yield pressure information. Also, few pressure logs were run in the other hot shallow wells. Pressure trends therefore have to be inferred from the temperature logs when two-phase conditions are recognizable. In DJ10 and 5 for example, isothermal intervals at 95°C indicate local steam outside the pipe at atmospheric pressure (Figure 4). In the case of DJ10, the temperatures immediately beneath this zone follow a boiling point curve down to the local maximum at an elevation of 1035 m asl., indicating a boiling liquid zone between 1050 and 1035 m asl. The slightly cooler conditions at the bottom of the well may indicate cooler water beneath the hot aquifer. The temperature gradient in the lower portion of DJ4 actually exceeds a boiling point gradient, presumably indicating a low permeability zone.

The characteristics of the high temperature aquifer depend on location. The two deepest wells (27-32 and 46-32) have steam feedzones over a range of depths implying pressures between 3 – 6.5 bar g (Figure 6). The exact depth of the feedzones in these wells is often difficult to pick, and uncertainties of up to 20 m are possible. However, despite the uncertainties, there is a trend of gradually increasing steam pressures with increasing depth down to at least 800 m asl.

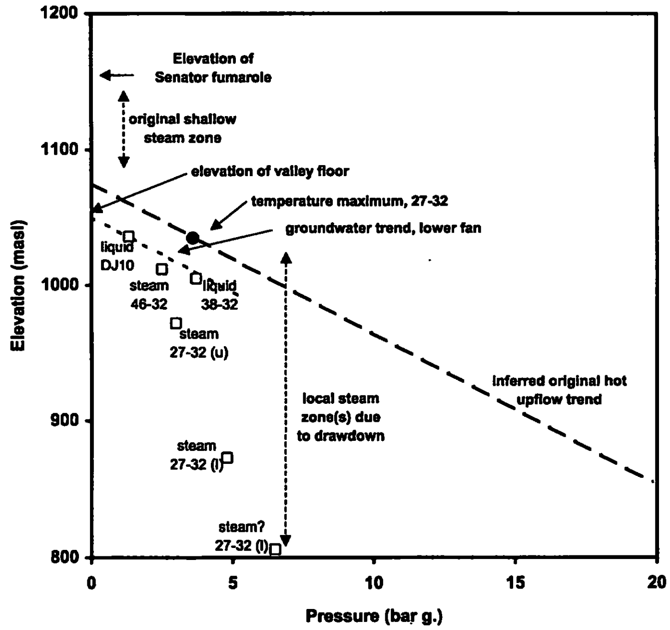

Figure 6. Compilation of pressure trends around the Senator fan derived from interpretations of some of the profiles shown in Figures 3 and 4. The interpretation implies significant pressure drawdown below about 1000 m asl due to drainage within the outflow zone. The outflow zone has changed from being liquid-dominated to being steam-dominated. (u = upper) and (l = lower) refer to the two stage drilling of well 27-32.

The pressure trend before development is poorly constrained. The field was liquid-dominated, and presumably had an upflow zone with boiling at shallow depth and a liquid outflow zone in order to sustain the steam discharge seen in the Senator fumarole. If the temperature maxima in DJ10 and 27-32 at 1035 m asl are taken as the main liquid outflow zone, and the 148°C maximum temperature in 27-32 is assumed to be representative of predevelopment temperatures, then the pressure here has always been at least 3.6 bar g. This allows an original liquid pressure trend to be drawn for the shallow upflow zone. If this model is correct, it shows that the pressure decline due to development has been small (< 2 bar) down to about 1000 m asl, but in the shallow upflow zone between 800 and 1000 m depth, the pressure decline has been of the order of 10 bar (Figure 6). If the inferred outflow zone at 1035 m asl has always been steam-heated waters, then the original pressure profile shown on Figure 6 is too high.

The inferred pressure profile for the upflow zone predicts a pressure of at 220 bg at 2500 m depth, assuming 240°C in the upflow zone from reservoir depths, and a boiling point for depth profile between 670 m asl to the zero pressure surface at 1070 m asl. This deep pressure is similar to that recorded in early exploration wells. Away from the upflow zone where the temperature profile is largely conductive above the reservoir (i.e. region of most production wells), the equivalent head based on 240°C at 2500 m and a conductive profile to the surface would be 250 m lower than that in the upflow zone. This difference would be smaller if there is a significant over-pressure driving water along the upflow zone, or if there is mixing with cooler water. Despite the uncertainties, there is likely to a significant difference in pressure in aquifers at shallow depth depending whether they are in equilibrium with local cold groundwater in Dixie Valley or the hot upflow zone. Both these situations will differ from the static water level seen in production wells where a conductive temperature gradient is present down to reservoir depths.

Conceptual Model

A model capable of explaining most of the changes that have occurred around the Senator thermal area at Dixie Valley field is illustrated in Figure 7. The cross-section extends south-eastwards from the rangefront adjacent to the Senator fumarole, down the fan and out into the valley where the Section 33 production wellfield is located. The features of the model are as follows.

Prior to development, there was an upflow of 240°C water from the deep reservoir on the Stillwater faultzone, close to the location of the Senator fumarole. The pressure trends and permeability regime within the fan were such that the water dispersed laterally into the lower fan rather than appearing as a hot spring. In the shallow upflow zone, the water began to boil at between about 700 masl (240°C upflow) and 1000 m asl (170°C upflow) depending on the extent of cooling along the upflow path. The original hot water head appears to have been at about 1070 m asl. Low pressure steam migrated up to the fumarole at 1150 m asl. The main hot water outflow into the fan is inferred to have been at about 1035 m asl, but lateral outflows at greater depths probably also occurred. Outflow is unlikely to have deeper than 800 m asl, because the nearby local cold/warm water aquifers over the field have a head of 1040 ± 10 m, implying pressures in excess of that in the hot upflow zone at < 800 m asl.

The upflow zone at shallow depth appears to be in a mix of faulted basement, landslide debris, and alluvium, and probably has a complex history of silicification and rupturing with fault movement on the Stillwater faultzone. Beneath the toe of the fan this material probably interfingers with playa sediments, perhaps analogous to that seen in the north wall of the mine trench at Dixie-Comstock (Vikre, 1994). Here layers of finely laminated lake sediments and tuff underlie the alluvial fan material. The mix of silicified alluvium and basement rubble in the Senator fan should be relatively competent compared to the adjacent, poorly compacted lake sediments.

Pressure drawdown of the reservoir due to fluid extraction from the production wellfield has reduced pressure in the upflow zone. This has caused boiling and the formation of a steam zone at shallow depth. The pressure drop has also affected the outflow zone(s) beneath the fan, and where the temperatures are high enough, local steam zones have formed. Steam is now leaking to the surface where previously there was single-phase hot water. This has caused the spread of thermal activity and vegetation to locally die back on the fan.

The pressure decline beneath the fan will also have affected the adjacent lake sediments. Such sediments are renowned for

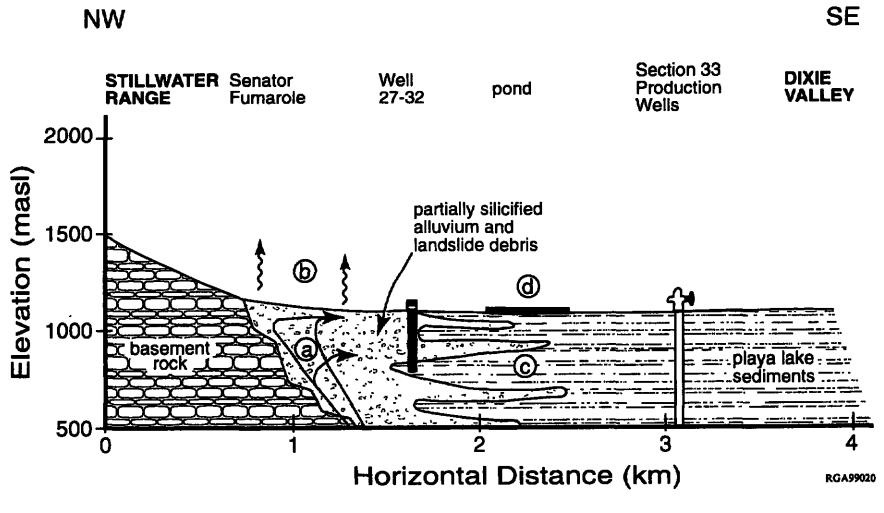

Figure 7. Schematic cross-section through the Senator fan (A-B on Figure 5). The elements of the conceptual model for the outflow zone of the field are highlighted.

their compaction potential (Helm, 1984; Allis, 1999, Allis and Zhan, 1999). The restriction of the center of subsidence to just the toe of the fan is due to the dominance of more competent alluvium and basement material closer to the range. This model does not preclude some more widespread subsidence originating from the pressure drawdown at reservoir depths.

The area of the hot outflow zone is at least 1 km^2, excluding a boundary zone with intermediate temperatures. Considering just the conductive heat losses above the outflow zone, the typical temperature gradient from Figure 4 of 30°C/10m, implies a heat loss of about 5 MW for a thermal conductivity of 1.5 W/m °C. There is an uncertainty factor of two in this estimate given the various assumptions about area, temperature gradient and thermal conductivity. The original, convective heat losses as steam through the fumarole would have been small compared to this figure and can be ignored. If some cooling is also occurring by mixing with cool groundwater flowing through the fan, then this heat loss estimate is a minimum. Since the liquid in the deep reservoir has an enthalpy of ca. 1 MJ/kg, the 5 MW total loss implies a mass flow of hot water in the outflow zone of the order of 5 kg/s (prior to development).

Although the data has not been presented here, a comparison of measurements in shallow gradient wells (<160 m depth) around the southern side of Dixie Valley field in 1994 and 1999 shows no significant changes during this time. This is consistent with the lack of obvious change in thermal activity around the nearby steaming ground area (Figure 1; marked as "thermal ground" and by a cross). A distinct shallow outflow zone also exists here, but this appears to tap a part of the field poorly connected to the present production reservoir beneath the Senator fan.

Conclusions

Although the production zone at Dixie Valley field is at 2–3 km depth, the changes in surface thermal activity and much of the nearby subsidence are attributed to the effects of pressure drawdown on an outflow zone at an elevation above 800 m asl, or typically at depths of less than 300 m. Prior to development, a liquid outflow zone with a temperature of at least 165°C is inferred to have been present beneath the Senator fan. The main aquifer for the outflow may have been at an elevation of 1035 m asl, or about 10 m below the valley floor adjacent to the toe of the fan. Pressure drawdown in the 1 km^2 outflow zone has caused the spread of two-phase conditions, and this is capable of explaining both the increase in steam-heated activity and the local subsidence where the fan merges with the playa. These changes are not unusual in geothermal developments (Allis, 1981, 1983; Wood *et al.*, 1997).

Acknowledgements

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