Interpretation of hydrothermal conditions, production-injection induced effects, and evidence for enhanced geothermal system-type heat exchange in response to >30 years of production at Roosevelt Hot Springs, Utah, USA

Stuart F. Simmons1,2, Rick G. Allis3, Stefan M. Kirby1, Joseph N. Moore1, and Tobias P. Fischer4

1EGI, University of Utah, 423 Wakara Way, Suite 300, Salt Lake City, Utah 84108, USA
2Department of Chemical Engineering, University of Utah, 50 S. Central Campus Drive, Salt Lake City, Utah 84112, USA
3Utah Geological Survey, P.O. Box 146100, Salt Lake City, Utah 84114-6100, USA
4Department of Earth and Planetary Sciences, MSCD3-2040, University of New Mexico, Albuquerque, New Mexico 87131-0001, USA

ABSTRACT

The Roosevelt Hot Springs hydrothermal system is located at the base of the Mineral Mountains in southwestern Utah on the eastern side of the Basin and Range. Hydrothermal activity is related to relatively recent bimodal magmatism, and the system is hosted in coarsely crystalline rock made of Oligocene–Miocene granitoids and Precambrian gneiss. The hydrothermal plume covers ~5 km², with a maximum temperature of 268 °C at ~750 m depth, and a vertically extensive fault-fracture mesh east of the Opal Mound fault controls the upflow of hydrothermal fluids. Power generation (currently 38 MW gross) began in 1984, and up through 2016, four wells were used for fluid production, and three wells were used for edge-field injection. Chemical analyses of produced fluids show that modern reservoir fluid compositions are similar to but more concentrated than those at the start of production, having near-neutral pH, total dissolved solids of 7000–10,000 mg/kg, and ionic ratios of Cl/Na~50–100, Cl/IO~50–100, and Na/K~4–5. Chemical geothermometers indicate equilibration temperatures that mainly range between 240° and 300 °C. Early production induced a steep drop in pressure (~3.0–3.5 MPa), which was accompanied by a 250–300 m lowering of piezometric levels in wells. Steam-loss and injection breakthrough, which is reflected by gradual increases in chloride of up to 35% and stable isotope ratios of up to ~2‰ δD. Simple mixing model calculations suggest that there has been a significant amount, ~10–20 MW, of sustained multi-decadal heat mining and enhanced geothermal system (EGS)–type heat transfer by the injectate as it returns to the production zone. Overall, the two factors that have sustained long-term power production (currently 38 MW gross) are the increased upflow of deep chloride water and, to a lesser extent, the mining of heat at <1 km depth.

INTRODUCTION

Roosevelt Hot Springs is a high-temperature hydrothermal system located in southwestern Utah along the west flank of the Mineral Mountains, ~20 km northeast of Milford (Fig. 1). Like most such systems, it is of intrinsic scientific interest because of its intimate relationship with magmatism and faulting, and because it is a long-producing geothermal resource (e.g., Nielson et al., 1986; Allis and Laren, 2012). Roosevelt Hot Springs is distinguished in being one of the hottest hydrothermal systems in the Basin and Range and also one of the few systems globally to be entirely hosted in faulted and fractured crystalline rock (Benoit and Butler, 1983; Nielson et al., 1986; Faulder, 1991, 1994; Allis et al., 2018; Bartley, 2019), providing a rare modern example of near-total structural control on the movement of hydrothermal fluids in the crust. With the development of the nearby Utah FORGE, or Frontier Observatory for Research in Geothermal Energy enhanced geothermal system (EGS) laboratory (Allis and Moore, 2019), investigations of Roosevelt Hot Springs take on another level of interest because of its analogue to engineered fluid flow, water-rock interaction, and heat transfer in stimulated volumes of hot impermeable crystalline rock.

Comprehensive geoscientific investigations of Roosevelt Hot Springs began during an accelerated phase of geothermal exploration across the western United States in the 1970s, and exploration drilling success proved a maximum reservoir temperature of 268 °C at ~750 m depth (Ward et al., 1978; Capuano and Cole, 1982; Faulder, 1994; Moore and Nielsen, 1994). Geothermal fluid production and electricity generation commenced in 1984, with the commissioning of a single-stage Blundell flash plant (26 MW gross), and supplementary generation came on line in 2007 with the commissioning of a bottom cycle binary plant (12 MW gross); the production field and power plants are operated by PacifiCorp. Many of the early reports cover geology, heat flow, petrology-mineralogy, and preproduction fluid chemistry (Ward et al., 1978; Parry et al., 1980; Wilson and Chapman, 1980; Bowman and Rohrs, 1981; Capuano and Cole, 1982; Nielson et al., 1986). Subsequent studies concentrated on topics of
Figure 1. Location maps of the Roosevelt Hot Springs: (A) regional setting showing the locations of Roosevelt Hot Springs and nearby producing geothermal fields at Cove Fort and Thermo, Utah FORGE, and hot springs (Crater, Meadow-Hatton, Monroe, Joseph, and Thermo); (B) physiography of area surrounding the production field (dashed outline) and the locations of cold springs (Bailey and Kirk) in the western Mineral Mountains; (C) locations of production, exploration, and injection wells in relation to faults and surface thermal activity.
reservoir characterization and fluid-flow modeling, and changes in pressure and temperature induced by geothermal production (Faulder, 1991; Becker and Blackwell, 1993; Faulder, 1994; Yearsley, 1994; Allis and Larsen, 2012).

In this paper, we examine the compositional evolution of hydrothermal fluids and the corresponding changes in pressure and temperature in the Roosevelt Hot Springs geothermal reservoir over the period from 1984 to 2016. This study builds on new water and gas data obtained from production wells in 2015 and 2016. These data, when combined with earlier data, provide snapshots of reservoir response to fluid production and injection. These results are used to trace fluid flow and steam-loss, interpret subsurface equilibration temperatures, and quantify heat and mass transfer through application of well-known and well-calibrated methods in hydrogeochemistry (e.g., Henley et al., 1984; Fournier, 1991; Giggenbach, 1991a, 1991b, 1997; Arnórsson, 2000). This investigation comprises an overview of the native state conditions of the drilled part of the system, an integration of time series data that document production-induced changes in the geothermal resource, and quantification of continuous injection breakthrough that reveals evidence of EGS-type heat transfer.

**GEOLOGIC SETTING**

The Roosevelt Hot Springs hydrothermal system is located within a geologically complex region (Fig. 1) that lies inside the southeast margin of the Basin and Range province near the western edge of the Colorado Plateau (e.g., Wannamaker et al., 2001; Dickinson, 2006). Hydrothermal activity is widespread across the region, and Roosevelt Hot Springs is one of three producing geothermal fields, including Cove Fort–Sulphurdale, and Thermo, which are associated with young extensional faults, centers of Quaternary basalt-rhyolite magmatism, and high regional heat flow (e.g., Mabey and Budding, 1987; Blackett, 2007; Simmons et al., 2015; Allis et al., 2019).

The Roosevelt Hot Springs hydrothermal system is localized along and just east of the Opal Mound fault, which runs north-south subparallel to the base of the western Mineral Mountains. The production field, hot springs, and steaming ground occur within an elongate area ~5 km² that is situated on the upper reaches of gently sloping alluvial fan deposits fed by drainages incised into uplifted granitic rock (Fig. 1). The rugged topography that characterizes the Mineral Mountains ranges between 1800 and 2500 m above sea level (i.e., 6000–8000 ft elevation), and perennial cold springs are scattered through western foothills (Fig. 1). The combination of arid conditions, western sloping topography, alluvial basin fill, fractured basement rocks, and steeply dipping faults are the main influences on groundwater flow in and around Roosevelt Hot Springs (Kirby et al., 2019).

Modern surface thermal activity is largely restricted to a zone of steaming ground near the intersection of the Opal Mound and Mag Lee faults (Fig. 1), but in the recent past, before 1980, near-neutral pH chloride water, resembling produced geothermal water, discharged from surface springs and seeps (e.g., Mundorff, 1970; Capuano and Cole, 1982; Allis et al., 2019). Two small areas of thermal ground and steam vents occur near well 28-3, and these are relatively recent manifestations that developed since the start of geothermal production in 1984. Ancient hot spring activity is marked by deposits of silicified and hematized alluvium, which occur all along the Opal Mound fault (Nielson et al., 1986; Knudsen et al., 2019), but the most significant of these deposits is the silica sinter sheet at Opal Mound (Fig. 1), which was active 1600–1900 years ago (Lynne et al., 2005). The evidence of paleo–hot water discharge at the surface along the Opal Mound fault indicates that this structure sporadically acts as a conduit for hydrothermal flow to the surface.

The rocks that host the hydrothermal system form a relatively simple stratigraphy of crystalline basement overlain by thin deposits of Quaternary alluvium (Fig. 2). The basement is dominated by coarsely grained, equigranular and porphyritic plutonic rocks of Oligocene–Miocene age that range from diorite to granite in composition and that are composed of plagioclase, hornblende, biotite, clinoptyroxene, quartz, K-feldspar, magnetite-ilmenite, and accessory titanite, rutile, apatite, and zircon (Nielson et al., 1986; Coleman and Walker, 1992; Jones et al., 2019). The oldest intrusion has a U-Pb zircon date of 25 ± 4 Ma (Aleinikoff et al., 1987), whereas the younger intrusions are dated at ca. 18 Ma, followed by emplacement of bimodal basalt and rhyolite dikes dated at 11–8 Ma (Nielson et al., 1986; Coleman and Walker, 1992; Kirby, 2019). These
plutons were intruded into Precambrian gneiss (1720 Ma), which is tightly
folded and composed of biotite, plagioclase, quartz, hornblende, K-feldspar,
and sillimanite (Nielson et al., 1986; Aleinikoff et al., 1987). The gneiss is a rem
nant of Proterozoic basement, and it forms isolated rafts engulfed by Tertiary
granitoids. There is no evidence of any Paleozoic–Mesozoic strata in the vicinity
of Roosevelt Hot Springs despite being a major component of the regional
stratigraphy; the closest exposures of such strata occur in the southern and
northern parts of the Mineral Mountains (Nielson et al., 1986; Kirby, 2019).

The Mineral Mountains host several discrete Pleistocene volcanic centers
(1–15 km²) that comprise basaltic cones and rhyolite flow dome complexes,
which erupted 0.9–0.5 Ma (Lipman et al., 1978; Hintze et al., 2003; Kirby, 2019).
Of these, the prominent Bailey Ridge flow, which is made of obsidian and
pyroclastic deposits, lies 2–5 km east of Roosevelt Hot Springs. Within the
area of hydrothermal activity, the uppermost stratigraphic unit is Quaternary
alluvium (<200 m thick) made of inter-bedded sand, silt, gravel and clay, shed
off the Mountain Hills (Nielson et al., 1986; Knudsen et al., 2019).

Two well-defined faults form subvertical structures that coincide with the
periphery of hydrothermal activity (Nielson et al., 1986; Knudsen et al., 2019).
The Opal Mound fault extends north-south for ~7 km, forming the western
boundary of the hydrothermal system (Fig. 1). It has an inferred steep eastward
dip with <15 m of down-dip vertical offset; however, the total displacement is
difficult to measure due to the absence of kinematic markers. The Mag Lee fault
is an east-west–striking structure that can be traced on the surface over a dis
tance of ~1 km where it is represented by a step offset (<15 m) in an old alluvial
fan deposit east of well 14-2 (Knudsen et al., 2019), and it is believed to extend
westward to where it intersects the Opal Mound fault (Nielson et al., 1986).

In addition to these major fault structures, multi-directional fracture patterns
are well developed in outcrops of granite in the Mineral Mountains (Bartley,
2019). The predominant strike orientations are north-south, northeast-southwest,
and east-west, with dips that range from subvertical to subhorizontal. Fractures
range in length from 20 to 200 m, and they are spaced as close as 5–15 m apart,
probably reflecting the main source of permeability in Roosevelt Hot Springs
hydrothermal system. Most of this fracturing seems to have been generated
during a relatively brief period in the late Miocene when the plutonic complex
was tilted 40°–70° to the east (i.e., east side down, west side up) as it was uplifted
and exhumed from mid-crustal depths (Nielson et al., 1986; Bartley, 2019).

The mineralogical products of hydrothermal activity occur along and east
of the Opal Mound fault. Quartz, alunite, kaolinite, and hematite result from
the steam-heated acid alteration in the vicinity of steam vents and steaming
vent and the thermal ground north of the Mag Lee fault are nearly the same
elevation of ~1700 m asl. For reference, the elevations of the Opal Mound
hot spring and the thermal ground north of the Mag Lee fault are nearly the same
at ~1800 m asl. From these trends, it is clear that the trace of the Opal Mound

In the late 1970s to early 1980s, numerous deep and shallow gradient and
test wells were drilled (Allis et al., 2019). These wells provide a three-dimen-
sional understanding of the thermal structure and the level of the piezometric
surface prior to the development and production of the Roosevelt Hot Springs
geothermal resource. Regionally and to the west of the Opal Mound fault lies
a large area of anomalously high conductive heat flow that covers 100 km²
(Allis et al., 2019). This area, however, is distinct from the much higher convex-
tive heat flow associated with the upflow plume of the hydrothermal system
described and discussed herein. Using data from over 40 thermal gradient
wells, Wilson and Chapman (1980) delineated the thermal signature of the
hot-water upflow east of the Opal Mound fault and the shallow outflow to the
northwest extending from the intersection of the Opal Mound and Mag Lee
faults. They calculated a total heat output of 70 MW, equivalent to a natural
hot-water (265 °C) upflow of ~60 kg/s (Allis et al., 2019).

Preproduction temperature gradients for deep vertical wells are shown
in Figure 2, and these are used to construct profiles of the thermal structure
shown in Figure 3. These wells are only cased in the upper part, down to
~400–550 m depth, with the lower part being represented by a long vertical
interval of open uncased hole. The hottest temperature of 268 °C was mea-
sured in well 14-2 at a depth of ~750 m, below which the temperature profile
is effectively isothermal, reflecting advective hot-water flow; a loss circulation
zone occurs at ~50 m depth (Butz and Plooster, 1979; Glenn and Hulen,
1979). Nearby wells 54-3, 45-3, and 28-3, have similar but slightly cooler pro-
files. In all four wells, the temperature profiles were close to hydrostatic boiling
temperature gradient in the depth interval between 200 and 500 m below the
surface. Down to 500 m depth, the temperature profile in well 13-10 matches
the other wells, but below this depth, the well 13-10 gradient is cooler, just
reaching 250 °C at the bottom of the hole. Outside the production field, 72-16
is the only well to have a boiling point for depth profile, but this well was
only drilled to 380 m depth. In well 12-35, the shallow temperature gradient
increases linearly, reaching 180 °C at 460 m depth, then bending sharply to form
a near-vertical gradient with a maximum temperature of 204 °C. Wells 25-15
and 52-21 have similar temperature gradients except for a thermal excursion
at ~1500 m depth in 52-21, which probably reflects fracture-controlled entry
of hot water (Fig. 3). The linear temperature gradient in 9-1 is the lowest and
reflects conductive heat transfer occurring over a broad area extending west
of the Opal Mound fault (Allis et al., 2019).

Preproduction pressure profiles are shown in Figure 4. Wells east of the
Opal Mound fault plot on a linear trend, representing a hydrostatic pressure
gradient across the hydrothermal system with a piezometric level of ~2000 m
above sea level (asl). Data from 9-1 and 82-33, which lie west of the Opal Mound
fault, fall on a separate hydrostatic pressure gradient having a piezometric level
of ~1700 m asl. For reference, the elevations of the Opal Mound hot spring
vent and the thermal ground north of the Mag Lee fault are nearly the same
at ~1800 m asl. From these trends, it is clear that the trace of the Opal Mound

- TEMPERATURE AND PRESSURE PROFILES
fault closely coincides with a sharp pressure gradient in which water levels are prevented from equalizing across both sides of the fault.

**GEOTHERMAL FLUID PRODUCTION AND INJECTION**

Geothermal fluid has been continuously produced from four wells that were initially fed by hot-water inflows, with permeability being controlled by a zone of interconnected fractures in crystalline host rocks directly east of the Opal Mound fault (e.g., Nielsen et al., 1986; Faulder, 1991). As previously mentioned, the productive intervals in all four production wells are uncased and open hole as is the injection interval in well 14-2, and the rock volume relating to the productive part of the reservoir is hachured in Figure 3. For at least the first ten years, the total two-phase fluid production supplied ~50 kg/s steam and 240 kg/s water that was separated near the wellhead by cyclone separators at ~0.9–1.1 MPa (Yearsley, 1994; Allis and Larsen, 2012). In 2015 and 2016 when the production fluids described below were sampled, the total two-phase fluid production had dropped to 40 kg/s steam and 210 kg/s water at pressures of 0.8–0.9 MPa. This type of self-flowing two-phase production is characteristic of liquid-dominated geothermal reservoirs in which hot water entering the well partially flashes to steam upon ascent and depressurization (e.g., Grant and Bixley, 2011; Watson, 2014).

After separating steam from the produced two-phase fluid for power generation, the residual water is injected into the subsurface, primarily to provide pressure support to the reservoir and to manage the disposal of non-potable waters. From 1984 to 1991, water was injected into just two wells—14-2 and 82-33. A third well, 12-35, was added in 1991, and all three injectors were in continuous use through 2016. Despite the fact that initial testing proved
14-2 to be hot and productive, it has always been used as an injector, taking roughly between 40% and 70% of the total injectate between 1984 and 2008. Injection records are unavailable for the next six years, but in 2014 and 2015, only 25%–40% of the total injectate went into 14-2.

Geothermal fluid production induced changes to the pressure and temperature, as reported for other production fields (e.g., Grant and Bixley, 2011). At Roosevelt Hot Springs, the pressure-drop occurred early and precipitously over the first four years of production, declining by as much as 3.0–3.5 MPa in wells 25-15 and 28-3 and as far south as 52-21 (Fig. 4; Yearsley, 1994; Allis and Larsen, 2012). In this same period, the amount of 14-2 injection at the end of 1986 was increased from 115 kg/s to 190 kg/s. At the same time, the piezometric level dropped by 250–300 m, forming a shallow steam zone (Yearsley, 1994) and the modern-day steaming ground near the intersection of Opal Mound and Mag Lee faults; the latter effect killed a number of juniper trees, the trunks of which are still standing. From the mid-1990s onward, the pressure and temperature continued to decline but much more gradually. By 2010, most of the wells displayed a total drop in water level pressure of nearly 4.0 MPa from preproduction conditions, the only exception being well 54-3, which had dropped only 1.7 MPa presumably as a result of pressure support from injection into nearby well 14-2 (Fig. 4; Allis and Larsen, 2012).

The decline in pressure across the production field was accompanied by decrease in subsurface temperatures of ~10–20 °C. For example, downhole measurements in 54-3 show the maximum temperature cooled from the initial condition of 265° to 246 °C by 2012 (Allis and Larsen, 2012). Two deep wells drilled in 2008 (58-3 and 71-10) had measured temperatures above 260 °C, and this simply shows that temperature decline and cooling occurred at different rates and at the production depths in wells (Allis and Larsen, 2012).

The reservoir hot liquid volume has been calculated to be between 0.5 and 1.3 km$^3$ based on reservoir modeling and flow testing (Faulder, 1994; Yearsley, 1994). The reservoir porosity is difficult to constrain due to heterogeneities in the fractured granitoid, but assuming it is 5% (Faulder, 1991), fluid could be produced from a total rock volume of 10–25 km$^3$. For comparison, the total volume of the deep liquid produced from 1984 to 2016 is ~0.3 km$^3$, based on an annual average fluid production of ~8–9 million tonnes (i.e., 250–290 kg/s). The reservoir is, however, open and dynamic, and as is shown below, it has been continuously recharged by deep upflow and the breakthrough of injectate.

**HYDROTHERMAL FLUID COMPOSITIONS**

Fluid samples were obtained from all four production wells in 2015 and 2016. Steam and geothermal water were taken from the two-phase pipeline on wells 28-3 and 45-3, using a mini-separator attached to a horizontal port (Fig. 5). Wells 54-3 and 13-10 lack suitable sampling ports, and water samples were instead obtained from permanently installed stainless steel capillary tubing that supplies a separate stream of conductively cooled (from ~180° to 100 °C) liquid from just downstream of the separator vessel at each well (Fig. 5).
Samples of thermal water were filtered and acidified in the field and stored in high-density polyethylene bottles, whereas untreated samples were stored in glass bottles for stable isotopes, alkalinity, and pH. Water samples were also collected in copper tubes for noble gas analysis. Steam samples were collected separately in evacuated glass bottles partially filled with sodium hydroxide.

Alkalinity and pH were determined at the Utah Department of Health lab, and oxygen and hydrogen isotopes were analyzed using cavity ring-down spectroscopy at the Stable Isotope Ratio Facility for Environmental Research (SIRFER) lab, University of Utah. Treated water samples were analyzed at the Winchell School of Earth Sciences, University of Minnesota; anions were analyzed by ion chromatography, and cations and weak acids were analyzed by inductively coupled plasma–optical emission spectroscopy (ICP-OES) and inductively coupled plasma mass spectrometry (ICP MS). Gas samples were analyzed at the Department of Earth and Planetary Sciences, University of New Mexico, using a gas chromatograph and titration methods. Helium isotopes were analyzed via mass spectrometry in the noble gas laboratory, Department of Geology and Geophysics, University of Utah. The resulting data, along with legacy information, are presented in Tables 1 and 2, and Figures 6–9. Calculated values of equilibration temperatures are presented in Table 3, and the characteristics of geothermal fluids at reservoir conditions are presented in Table 4.

In general, the 2015 and 2016 hot-water compositions are similar to those at the start of geothermal production, having near-neutral pH and total dissolved solids of 7000–10,000 mg/kg, with ionic ratios of Cl/HCO$_3$ ~50–100, Cl/ SO$_4$ ~50–100, Na/K ~4–5 (Fig. 6; Table 1). The main gases comprise H$_2$O, CO$_2$, and H$_2$S, with mole ratios of H$_2$O/CO$_2$ ~400–450 and CO$_2$/H$_2$S ~10–15 (Table 3). The relative proportions of N$_2$, Ar, and He, and R/Ra helium isotope values of 2.1–2.2, which indicate a mantle component, reflect a deep mafic magmatic source region (Fig. 7; Table 3) as summarized in earlier reports (Welhan et al., 1988; Monastero et al., 2005). The isotope analyses of hydrothermal calcites in deep drill cuttings from well 14–2 (Bowman and Rohrs, 1981) indicate equilibrium $\delta^{13}$C$_{calc}$ values in the range of $-4.5\%$ to $-6.0\%$ and suggest the possibility of a mantle source of carbon (Rohrs, 1980).

Based on the widespread occurrences of quartz, plagioclase, K-feldspar, chlorite, illite, and calcite in subsurface rocks (e.g., Capuano and Cole, 1982), equilibration temperatures were calculated using thermodynamic aqueous and gaseous geothermometers (Table 3; Fournier and Potter, 1982; Giggenbach, 1988, 1991a; 1997; Fournier, 1991). Quartz-silica values for production fluids from 1991 to 2015 range from 245°C to 265°C, which are similar to but slightly hotter than measured enthalpy values. Chloride-silica values for production fluids are slightly cooler than quartz-silica values, and they give a better empirical fit to measured enthalpy values (Fig. 8; Table 3), which was also observed over a long production period at Wairakei (Glover and Mroczek, 2009). Na-K values are hotter and range from 270°C to 310°C, which conceivably reflects thermal conditions at a deeper level in the upflow zone. K-Mg values are the hottest, ranging from 300°C to 390°C, but their credibility may be compromised by increase in potassium concentration associated with mixing of injected water (see below). The H$_2$Ar and CO$_2$/Ar temperature values range from 174 to 199°C and 258–287°C, respectively.

The reservoir compositions of stable isotopes were calculated using heat and mass balance expressions and equilibrium fractionation factors between steam and liquid (Truesdell et al., 1977; Giggenbach and Stewart, 1982; Giggenbach, 1991b). In Figure 9, these results are compared to the preproduction reservoir value for well 14–2 and the compositions of modern meteoric waters represented by cold springs in the Mineral Mountains. Overall, the trends indicate that local meteoric water is the primary source of recharge for the hydrothermal system.
| Date      | Sampling pressure (mPa) | Steam fraction (y) | Lab pH | Li  | Na  | K   | Ca  | Mg  | SiO2 | Al  | Fe  | Cl  | SO2 | HCO3 | Sources                          |
|-----------|-------------------------|---------------------|--------|-----|-----|-----|-----|-----|------|-----|-----|-----|-----|-----|-------|
| 1950      | 356                     | 0.1                 | 0      | -   | -   | -   | -   | -   | -    | -   | -   | -   | -   | -    | -      |
| 1977      | 1160                    | 1.3                 | 0.18   | -   | 25  | 2070 | 384 | 11  | 0.28 | -   | -   | 23  | -    | -    | -      |
| 1977      | 1160                    | 2.5                 | 0.11   | -   | 25  | 2320 | 461 | 8   | -    | -   | -   | 562 | 30   | 6.8  | 3860 | 72  |
| 1978      | 850                     | 7                   | 0      | -   | -   | -   | -   | -   | -    | -   | -   | -   | -    | -    | -      |
| 1978      | 967                     | 0.1                 | 0      | 10  | 1780 | 440 | 69  | 1.00| -    | -   | -   | 190 | 28   | -    | 2860 | 120 |
| 1981      | 1098                    | 0.8                 | 0.185  | 24  | 2980 | 479 | 17  | -   | -    | -   | 635 | 38  | -    | 8.1  | 4760 | 71  |
| 1981      | 1065                    | 0.9                 | 0.164  | 23  | 2551 | 422 | 11  | -   | -    | -   | 639 | 33  | -    | 8.0  | 4200 | 44  |
| 1981      | 1058                    | 0.9                 | 1.61   | 22  | 2400 | 399 | 18  | -   | -    | -   | 611 | 32  | -    | 6.8  | 3900 | 60  |
| 5/4/1992  | 1076                    | 0.9                 | 0.167  | 25  | 2480 | 554 | 26  | -   | -    | -   | 605 | 37  | -    | 1.3  | 4350 | 66  |
| 5/4/1992  | 1067                    | 0.9                 | 0.162  | 25  | 2338 | 535 | 15  | -   | -    | -   | 619 | 37  | 1.7  | 4180 | 49  |
| 5/4/1992  | 1071                    | 0.9                 | 0.164  | 25  | 2230 | 530 | 20  | -   | -    | -   | 599 | 35  | 1.6  | 3880 | 53  |
| 7/20/2015 | 1305                    | 0.9                 | 0.277  | 27.9| 2894 | 544 | 30  | 0.14| 1.70 | 0.30| 7.5 | 5114| 77   | 68   | -107.3|
| 7/21/2015 | 1043                    | 1.2                 | 0.120  | 7.11| 26.2| 2690 | 535 | 24  | 0.04| 1.18 | 0.60| 41   | 0.18 | 7    | 4728 | 66 |
| 7/20/2015 | 995                     | 1.3                 | 0.092  | 8.27| 23.7| 2297 | 477 | 16  | 0.06| 0.90 | 0.36| 3.08 | 7.2  | 4032 | 54  |
| 7/20/2015 | 1080                    | 0.9                 | 0.169  | 8.04| 25.0| 2164 | 466 | 17  | 0.04| 0.78 | 0.85| 3.27 | 7.7  | 3783 | 50  |
| 9/27/2016 | 1212                    | 1.0                 | 0.225  | 7.33| 32.0| 2869 | 628 | 36  | 0.03| 3.45 | 0.38| 0.17 | 5.4  | 5379 | 56  |
| 9/27/2016 | 1042                    | 1.3                 | 0.119  | 7.93| 30.0| 2651 | 597 | 27  | 0.03| 3.20 | 0.56| 0.11 | 5.5  | 4856 | 54  |
| 9/27/2016 | 996                     | 1.3                 | 0.090  | 8.34| 28.0| 2312 | 534 | 17  | 0.12| 0.98 | 0.54| 0.08 | 5.2  | 4213 | 45  |
| 9/27/2016 | 1015                    | 0.9                 | 0.131  | 7.92| 26.0| 2030 | 481 | 20  | 0.01| 0.77 | 0.58| 0.19 | 5.3  | 3834 | 40  |
| 11/30/2016| 955                     | 1.3                 | 0.070  | 8.17| 27  | 2302 | 534 | 16  | 0.02| 4.03 | 0.57| 0.07 | 6.1  | 4278 | 43  |
| 11/30/2016| 1048                    | 1.2                 | 0.134  | 7.82| 28  | 2710 | 612 | 27  | 0.02| 2.53 | 0.60| 0.12 | 5.7  | 4935 | 53  |

Cold Springs

Bailey: 8/1/1976
Bowman and Rohrs, 1981

Bailey: 10/5/1977
Bowman and Rohrs, 1981

Bailey: 11/6/1977
Bowman and Rohrs, 1981

Kirk: 8/1/1976
Bowman and Rohrs, 1981

Kirk: 11/7/1977
Bowman and Rohrs, 1981

Note: SMOW—standard mean ocean water. Dashes indicate no data.
### TABLE 2. GAS ANALYSES OF PRODUCED FLUIDS

| Date | H₂O (mmol/kg) | CO₂ (mmol/kg) | H₂S (mmol/kg) | Ar (mmol/kg) | N₂ (mmol/kg) | H₂ (mmol/kg) | He (mmol/kg) | CH₄ (mmol/kg) | Helium isotopes R/Rₐ air corrected |
|------|---------------|---------------|---------------|--------------|--------------|--------------|--------------|--------------|----------------------------------|
| 28-3 | 7/20/2015     | -             | -             | -            | -            | -            | -            | -            | 2.10                             |
| 45-3 | 7/21/2015     | -             | -             | -            | -            | -            | -            | -            | 2.19                             |
| 28-3 | 11/30/2016    | 997.59        | 2.187         | 0.211        | 0.00029      | 0.01130      | 0.000633     | 0.000044     | nd                               |
| 45-3 | 11/30/2016    | 997.34        | 2.437         | 0.156        | 0.00126      | 0.06570      | 0.001229     | 0.00006      | nd                               |

Note: nd—not detected. Ra—³He/⁴He ratio of air = 1.39E-06. R—³He/⁴He ratio of sample. Dashes indicate no data.

System. Furthermore, the isotopically light δD value of 14-2 possibly traces back to the late Pleistocene, as inferred for the meteoric recharge of other hydrothermal systems in the Basin and Range province (Flynn and Buchanan, 1990, 1993). The data show that thermal water compositions are heavier by 2‰–4‰ in δ¹⁸O compared to local meteoric water, which is commonly observed and attributed to isotope exchange resulting from high-temperature water-rock interaction (e.g., Craig, 1963; Blattner, 1985). That the 2015 and 2016 data are also heavier in both δ¹⁸O and δD compared to the 1978 composition from 14-2 implies time dependent modification associated with in-mixing of isotopically enriched injectate. For comparison, the curve labeled “steam-loss” (Fig. 9) shows how the composition of residual water, starting from a parent composition at 14-2, becomes isotopically heavier through adiabatic steam-loss and cooling as geothermal water ascends to the surface (Giggenbach and Stewart, 1982). Clearly, steam-loss alone fails to account for the isotopic compositions of reservoir waters in 2015–2016, and this point is discussed below.

#### STEAM-LOSS AND MIXING EFFECTS ON PRODUCED FLUID COMPOSITIONS

Between the reservoir and the surface, the dominant controls on the compositions of produced fluids and hot spring waters in hydrothermal systems are...
generally related to steam-loss and mixing (e.g., Giggenbach, 1971; Fournier, 1979; Henley and Ellis, 1983; Henley et al., 1984). To quantify these effects, the enthalpies and reservoir compositions of produced fluids (Table 4) are plotted as graphs in time series (Fig. 10), chloride versus enthalpy (Fig. 11), and δ¹⁸O versus chloride and δD versus chloride (Fig. 12).

The well enthalpy values are based on two different types of measurements. Prior to the commissioning of the Blundell power plant, well enthalpies are determined from downhole temperature measurements and assume the reservoir fluid is single-phase liquid-only. Once power generation commenced, enthalpies in producing wells are determined from measurements of mass flows of steam and hot water at known pressures in surface pipework.

The reservoir compositions are calculated (Table 4) by correcting for steam-loss (Henley et al., 1984), assuming the reservoir fluid enters the well at a deep level as a single liquid-phase and using the following heat and mass balance equations:

\[ H_{TD} = H_{\text{liquid, sample}}(1 - y) + H_{\text{steam, sample}}(y) \]  \hspace{1cm} (1)

\[ C_{TD} = C_{\text{liquid, sample}}(1 - y) + C_{\text{steam, sample}}(y), \]  \hspace{1cm} (2)

where \( H_{TD} \) = total discharge (TD) enthalpy measured at the wellhead; \( H_{\text{liquid, sample}} \) = vapor saturated enthalpy of water at the pressure of sampling; \( H_{\text{steam, sample}} \) = vapor saturated enthalpy of steam at the pressure of sampling; \( y \) = mass fraction of steam in the two-phase fluid at the pressure of sampling; \( C_{TD} \) = calculated total discharge (TD) concentration in the reservoir; \( C_{\text{liquid, sample}} \) = analyzed concentration of aqueous species (e.g., Cl, SiO\(_2\)) in the sample; and \( C_{\text{steam, sample}} \) = analyzed concentration of gaseous species (e.g., CO\(_2\)) in the sample. All enthalpy values are obtained from the International Association for the Properties of Water and Steam (IAPWS) Industrial Formulation (IF97) properties for steam and water (http://xsteam.sourceforge.net).

To check the validity of this approach, the enthalpies determined from the chalcedony-silica temperature (\( H_{\text{chalcedony}} \) kJ/kg) are also calculated (Table 4). The results are reasonably close, and most differ by less than 10%, satisfying the assumption of a single-phase liquid phase feed in wells 13-10, 28-3, and 45-3 (Truesdell and Singers, 1974). The two notable exceptions are the...
### TABLE 3. EQUILIBRATION TEMPERATURES (°C) CALCULATED FROM AQUEOUS AND GASEOUS GEOTHERMOMETERS

| Site            | Date       | T (°C) enthalpy | T (°C) quartz | T (°C) chalcedony | T (°C) Na-K | T (°C) K-Mg | T (°C) CO₂/Ar | T (°C) H₂/Ar |
|-----------------|------------|----------------|---------------|-------------------|-------------|-------------|---------------|--------------|
| Hot Springs/Seeps |           |                |               |                   |             |             |               |              |
| 85°C            | 1950       | 258            | 234           | 308               | 208         | -           | -             | -             |
| 55°C            | 1957       | 213            | 292           | -                 | -           | -           | -             | -             |
| 17°C            | 1973       | 123            | 272           | 165               | -           | -           | -             | -             |
| 28°C            | 1975       | 141            | 270           | 148               | -           | -           | -             | -             |
| Wells           |            |                |               |                   |             |             |               |              |
| 14-2            | 1977       | 265            | 300           | 273               | 288         | 301         | -             | -             |
| 14-2            | 1978       | 265            | -             | -                 | 287         | 260         | -             | -             |
| 54-3            | 1979       | 265            | 258           | 240               | 294         | -           | -             | -             |
| 72-16           | 1977       | 242            | 254           | 236               | 295         | 261         | -             | -             |
| 52-21           | 1978       | 200            | 197           | 177               | 259         | 191         | -             | -             |
| 9-1             | 1978       | 225            | 177           | 155               | 317         | 233         | -             | -             |
| 54-3            | 8/1/1991   | 248            | 262           | 243               | 306         | -           | -             | -             |
| 28-3            | 8/1/1991   | 246            | 265           | 246               | 276         | -           | -             | -             |
| 13-10           | 8/1/1991   | 244            | 261           | 242               | 277         | -           | -             | -             |
| 45-3            | 5/4/1992   | 253            | 259           | 240               | 273         | -           | -             | -             |
| 28-3            | 5/4/1992   | 246            | 262           | 243               | 308         | -           | -             | -             |
| 13-10           | 5/4/1992   | 247            | 258           | 240               | 313         | -           | -             | -             |
| 54-3            | 7/20/2015  | 293            | 249           | 231               | 288         | 302         | -             | -             |
| 45-3            | 7/21/2015  | 241            | 264           | 245               | 294         | 344         | -             | -             |
| 28-3            | 7/20/2015  | 231            | 264           | 245               | 298         | 321         | -             | -             |
| 13-10           | 7/20/2015  | 249            | 255           | 237               | 301         | 333         | -             | -             |
| 54-3            | 9/27/2016  | 275            | 249           | 231               | 304         | 365         | -             | -             |
| 45-3            | 9/27/2016  | 241            | 255           | 237               | 307         | 359         | -             | -             |
| 28-3            | 9/27/2016  | 231            | 259           | 240               | 309         | 305         | -             | -             |
| 13-10           | 9/27/2016  | 235            | 250           | 233               | 312         | 396         | -             | -             |
| 45-3            | 11/30/2016 | 242            | 264           | 245               | 307         | 389         | 258           | 174           |
| 28-3            | 11/30/2016 | 223            | 265           | 246               | 310         | 367         | 287           | 199           |

Note: Dashes indicate no data.

2015 and 2016 results for 54-3 in which calculated C\(_{\text{SiO}_2-\text{TD}}\) values are 389 and 417 mg/kg, and the T\(_{\text{chalcedony}}\) values are 215 °C and 222 °C, respectively; these correspond to H\(_{\text{chalcedony}}\) values of 921 and 953 kJ/kg, which are much lower than the H\(_{\text{TD}}\) values in Table 1. The preliminary total discharge concentrations for 54-3, however, are artifacts of anomalously high steam fractions that reflect the development of two-phase fluid (liquid plus steam) feed zones and that require correction to obtain more realistic results.

The development of a two-phase fluid feed in 54-3 is also represented by the increase in enthalpy from 1098 to 1305 kJ/kg from 1992 to 2015 (Fig. 11; Table 1). For comparison, the maximum measured downhole temperatures in 54-3 were 253 °C in 2007, 251 °C in 2010, and 246 °C in 2012, which are equivalent to hot-water enthalpies of 1100, 1091, and 1066 kJ/kg, respectively, and consistent with measurements in nearby wells 45-3 and 28-3 (Fig. 10). From extrapolation of the 2007–2012 trend, the hot water entering 54-3 is estimated to have cooled to ~242 °C by 2015 and to 240 °C by 2016. Taking these values as representative, the proportions of excess steam contributing to the two-phase fluid entering the well can be calculated from the heat balance expression:

\[
H_{\text{TD}} = H_{\text{liquid, reservoir}}(x) + H_{\text{excess steam, reservoir}}(y')
\]

\[1 = x + y',\]
where $H_{\text{vapor, reservoir}} = \text{saturated enthalpy of water at the reservoir temperature}$; $H_{\text{excess steam, reservoir}} = 2800 \text{ kJ/kg}$; $x = \text{mass fraction of liquid in the two-phase reservoir}$; $\gamma = \text{mass fraction of excess steam in the two-phase reservoir}$. The enthalpy values for the reservoir waters are $1047 \text{ kJ/kg}$ in 2015 and $1038 \text{ kJ/kg}$ in 2016. Accordingly, the mass fractions of excess steam are 0.15 in 2015 and 0.14 in 2016. The results also constrain the mass fractions of steam flashed from produced reservoir liquid ($\gamma = 0.15$ in 2015 and $\gamma = 0.14$ in 2016), from which reservoir concentrations are calculated to be $4350 - 4600 \text{ mg/kg Cl}$ and $460 \text{ mg/kg SiO}_2$ (Table 4), giving $T_{\text{flash reservoir}}$ values $231 \text{ °C}$ (Table 3) and $H_{\text{flash reservoir}}$ values of $995 \text{ kJ/kg}$ (Table 4), which are within 5% of the extrapolated hot-water enthalpies.

The enthalpy-chloride plot in Figure 11 shows the evolution in the thermal and chemical characteristics of the produced geothermal fluid. In the preproduction state, the reservoir water was single phase having a chloride concentration of $3000 - 3500 \text{ mg/kg}$ and an enthalpy of $1050 - 1160 \text{ kJ/kg}$. By their proximity to one another, wells 14-2 and 54-3 represent the hottest and least diluted liquids in the reservoir, corresponding to the central upflow zone of the system, whereas 72-16 lies on the periphery of the upflow zone (Fig. 3). By 1992, the reservoir fluid composition is modified, mostly by in-mixing of injectate from 14-2, which has a low enthalpy and a high chloride concentration compared to the original deep upflow water. This effect is observed in the change in 54-3 to higher chloride and lower enthalpy. Data for 13-10, 28-3, and 45-3 first appear in this time period. An internal report indicates that the injectate at this same time is a mixture of separated water from these three production wells, and ~15% steam condensate (pure water), which dilutes the chloride concentration (PacifiCorp memo to Utah Department of Water Quality, written commun., 1999). By 2008, the chloride concentration of the injectate had risen to ~4800 mg/kg, based on an analysis of a sample obtained from the inlet of newly commissioned binary plant (PacifiCorp, written commun., 2008).

By 2015–2016, the reservoir compositions show continued increase in chloride accompanied by minor decrease in enthalpy (Fig. 11). Again, these effects reflect the in-mixing of injectate from 14-2. The least modified reservoir water is represented by 13-10, with the first measurable increase in

### TABLE 4. RESERVOIR CHARACTERISTICS DERIVED FROM WELL MEASUREMENTS AND DISCHARGES

| Well | Date       | Temperature (°C) | $H_{\text{vapor, reservoir}}$ (kJ/kg) | $T_{\text{sat reservoir}}$ (°C) | $H_{\text{sat reservoir}}$ (kJ/kg) | Cl TD | SiO$_2$ TD (mg/kg) | CO$_2$ TD (mg/kg) | $\delta^{18}$O SMOW | $\delta^{2}$H SMOW |
|------|------------|------------------|--------------------------------------|-------------------------------|-------------------------------|-------|-------------------|-------------------|------------------|------------------|
| 14-2 | 8/1/1991   | 231              | 1100                                  | 243                           | 1052                          | 3879  | 518               | 942               | $-108.6$         | $-11.6$          |
| 54-3 | 9/27/2015  | 249              | 1047                                  | 231                           | 995                           | 4350  | 460               | -                 | $-114.20$        | $-12.90$         |
| 13-10| 9/27/2015  | 241              | 1043                                  | 245                           | 1062                          | 4161  | 528               | -                 | $-111.70$        | $-12.00$         |
| 13-10| 9/27/2015  | 241              | 1042                                  | 245                           | 1062                          | 4161  | 528               | -                 | $-111.70$        | $-12.00$         |
| 13-10| 9/27/2015  | 241              | 1042                                  | 245                           | 1062                          | 4161  | 528               | -                 | $-111.70$        | $-12.00$         |
| 13-10| 9/27/2015  | 241              | 1042                                  | 245                           | 1062                          | 4161  | 528               | -                 | $-111.70$        | $-12.00$         |
| 13-10| 9/27/2015  | 241              | 1042                                  | 245                           | 1062                          | 4161  | 528               | -                 | $-111.70$        | $-12.00$         |
| 13-10| 9/27/2015  | 241              | 1042                                  | 245                           | 1062                          | 4161  | 528               | -                 | $-111.70$        | $-12.00$         |
| 13-10| 9/27/2015  | 241              | 1042                                  | 245                           | 1062                          | 4161  | 528               | -                 | $-111.70$        | $-12.00$         |
| 13-10| 9/27/2015  | 241              | 1042                                  | 245                           | 1062                          | 4161  | 528               | -                 | $-111.70$        | $-12.00$         |

*Enthalpy and temperature obtained from temperature profiles as these wells did not produce fluid.

**Corrected for excess steam in the produced fluid, using $y$ values of 0.15 in 2015 and 0.14 in 2016.

Note: SMOWQ—standard mean ocean water; TD—total discharge. Dashes indicate no data.
chloride and decrease in enthalpy being detected between 2015 and 2016; the maximum measured temperature in this well dropped from 264 to 248 °C between 1989 and 1999 (Allis and Larsen, 2012). Going northward, wells 28-3, 45-3 and 54-3 show progressively increasing concentrations of chloride coinciding with decreasing distance from 14-2. Not surprisingly, well 54-3 being the closest well to 14-2, shows the greatest amount of injectate in-mixing over time (Figs. 10–12). Well 54-3 also shows ~25 °C of cooling through to 2016, and enough pressure draw down to become two-phase at the well feed zone, which occurs somewhere in the open hole interval between 520 m and 850 m depth. Although well 13-10 is farthest from 14-2 and shows the least amount of injectate in-mixing, the reservoir enthalpy-temperature cooled by nearly 15 °C from 2015 to 2016 (Fig. 10; Table 3).

As previously described, the effects of reservoir boiling and mixing are also reflected in the stable isotope trends. Similar to the chloride and silica values, the oxygen and hydrogen isotope data are corrected to single phase waters at reservoir conditions according to the following mass balance expression:

\[
\delta_{\text{reservoir}} = \delta_{\text{liquid, sample}} - F(y),
\]

where \(\delta\) is the hydrogen or oxygen isotopic composition of the water (\(\delta_{\text{reservoir}} = \text{reservoir water}\); \(\delta_{\text{liquid, sample}} = \text{water sample obtained from surface pipeline port}\), and \(F\) is the temperature-dependent fractionation factor for steam and water at the pressure of sampling (Giggenbach, 1991b). The reservoir compositions for 54-3 are corrected for the presence of excess steam in the reservoir by using the revised values of \(y\) (0.15 for 2015 and 0.14 for 2016) as above. In Figure 9, the 2015 and 2016 data sets form subparallel arrays that resemble the adiabatic steam-loss trend calculated for the preproduction 14-2 reservoir water composition. Just as in the enthalpy-chloride plot (Fig. 11), the shift to heavier isotope compositions is due to the in-mixing of injectate, followed by steam-loss and cooling as water rises in the production well to the surface. Comparison of chloride versus \(\delta^{18}O\) and \(\delta^D\) compositions in Figure 12 reflect the same steam-loss-mixing trends interpreted in Figure 9, and the evolution in the compositions of three independent natural conservative tracers (Cl, \(\delta^{18}O\), and \(\delta^D\)) give consistent results. Notably, there is no evidence that cold meteoric water has diluted or shifted the reservoir compositions of produced waters.

Over the production period, the concentrations of CO\(_2\) in deep thermal waters have deceased in response to steam-loss (Table 4). Initially, the CO\(_2\)
reservoir composition was ~8000 mg/kg (180 mmol/kg; Butz, 1980; Capuano and Cole, 1982). By the early 1990s, the values had fallen to between 800 and 2400 mg/kg CO$_2$ (18–55 mmol/kg), and by 2016, the CO$_2$ concentration ranged from 374 to 798 mg/kg (8.5–18 mmol/kg). Despite the significant decrease in CO$_2$ concentration, calcite anti-scalant was continuously used to prevent mineral deposition in the wells up through 2016.

### MIXING MODEL CALCULATIONS

In order to quantify how much injectate mixed with reservoir water to cause the increase in the produced chloride concentration, simple two- and three-component mixing models were evaluated. The aim of these models is to replicate the effects of continuous steam-loss and mixing between a single producer well and a single injector well as represented by wells 45-3 (or 54-3), and well 14-2, respectively. A schematic representation is shown in Figure 13, wherein the mixing zone, which is the focus of the model, lies between the injection and producing wells. Within each modeled mixing run, the mass fractions of the end-member components are fixed over a series of steps in which successive packets of in-mixed injectate increase the chloride concentration and decrease the enthalpy of the water entering the well. In addition to determining the degree of mixing required to match the chloride evolution of the produced water, the results provide insights regarding the sources of heat that sustains the produced fluid enthalpy. In sum, we tested five models: (A) two-component mixing between reservoir water and injectate; (B) two-component mixing between reservoir water and injectate, plus added heat; (C) three-component mixing between reservoir water, and a one-to-one mixture of injectate and preproduction geothermal water; (D) three-component mixing between reservoir water, and a one-to-one mixture of injectate and preproduction geothermal water plus added heat; and (E) three-component mixing between reservoir water, and a two-to-one mixture of injectate and preproduction geothermal water plus added heat.

**Model A**

This model is based on an arithmetic series of chloride and heat balance calculations using the following expressions:

$$\text{Cl}_{\text{reservoir}} = a \text{Cl}_{\text{reservoir (n–1)}} + b \text{Cl}_{\text{injectate}}$$

$$\text{H}_{\text{reservoir}} = a \text{H}_{\text{reservoir (n–1)}} + b \text{H}_{\text{injectate}}$$

$$\text{Cl}_{\text{injectate}} = \frac{\text{Cl}_{\text{reservoir (n–1)}}}{1–y_{(n–1)}}$$

$$y_{(n–1)} = \frac{\text{H}_{\text{reservoir (n–1)}} – \text{H}_{\text{injectate}}}{\text{H}_{\text{evaporation}}}$$

where $\text{Cl}_{\text{reservoir}}$ = calculated reservoir chloride concentration of the mixed water entering the well; $\text{Cl}_{\text{reservoir (n–1)}}$ = calculated chloride concentration in reservoir liquid entering the well in the preceding step; $\text{Cl}_{\text{injectate}}$ = calculated chloride concentration based on steam-loss from the produced fluid represented by $\text{Cl}_{\text{reservoir (n–1)}}$; $y_{(n–1)}$ = mass fraction of steam removed from produced fluid at the surface; $\text{H}_{\text{reservoir}}$ = calculated reservoir enthalpy of the mixed water; $\text{H}_{\text{reservoir (n–1)}}$ = calculated reservoir enthalpy in the preceding interval; $\text{H}_{\text{injectate}}$ = 700 kJ/kg, based on vapor-saturation and steam separation at 0.7 MPa; $\text{H}_{\text{evaporation}}$ = 2065 kJ/kg, based on vapor-saturation and steam separation at 0.7 MPa; $a$ = mass fraction of reservoir water; $b$ = mass fraction of injectate; and $n$ = arbitrary time step.

At $n = 0$, the values of $\text{Cl}_{\text{reservoir}}$ and $\text{H}_{\text{reservoir}}$ are 3200 mg/kg and 1160 kJ/kg, respectively, based on the preproduction data (Table 5). The time step, $n$, is
Figure 12. Stable isotope versus chloride compositions for produced geothermal waters: (A) $\delta^{18}$O and chloride compositions of reservoir preproduction water in 1984 (based on the composition of 14-2), and reservoir waters in 2015 and 2016; (B) $\delta D$ and chloride compositions of reservoir preproduction water based on the composition of 14-2, and reservoir waters in 2015 and 2016. The blue filled circle represents the approximate composition of injectate in 2016. The orange mixing line represents the interpreted evolution of the reservoir water in the vicinity of wells 54-3 and 45-3 due to the continuous inmixing of injectate from 1984 to 2016. The curved dashed, dotted, and solid arrows represent the steam-loss trends for waters from the same wells (Giggenbach and Stewart, 1982) for preproduction, 1990–2010, and 2016 conditions, respectively. The compositions of meteoric water and steam overlap (0 ppm Cl, −15.8‰ to −13.8‰ $\delta^{18}$O, −120‰ to −114‰ $\delta D$), but there is no evidence that these waters have modified the reservoir water compositions.

Figure 13. Production-injection flow model showing the main processes (italicized labels) that have caused increase in the concentrations of chloride and enrichments in the oxygen and hydrogen isotope ratios of produced waters from wells 54-3, 45-3, and 28-3. Steam for power generation is separated from the two-phase fluid downstream of the well head. An unquantified but minor fraction of steam is condensed and mixed into the produced separated water prior to injection.
### TABLE 5. MODEL RESULTS OF MIXING AND STEAM-LOSS EFFECTS ON THE RESERVOIR LIQUID RELATED TO INJECTION BREAKTHROUGH

| Step | 0  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|------|----|----|----|----|----|----|----|----|----|----|----|
| **Model A** |    |    |    |    |    |    |    |    |    |    |    |
| 0.95 Reservoir Water + 0.05 Injectate |    |    |    |    |    |    |    |    |    |    |    |
| Reservoir Cl (mg/kg) | 3200 | 3246 | 3289 | 3331 | 3370 | 3407 | 3443 | 3477 | 3509 | 3539 | 3568 |
| Reservoir H (kJ/kg) | 1160 | 1197 | 1130 | 1094 | 1075 | 1056 | 1038 | 1021 | 1005 | 990 | 975 |
| Produced steam fraction | 0.22 | 0.21 | 0.20 | 0.19 | 0.18 | 0.17 | 0.16 | 0.16 | 0.15 | 0.14 | 0.13 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| 0.9 Reservoir Water + 0.1 Injectate |    |    |    |    |    |    |    |    |    |    |    |
| Reservoir Cl (mg/kg) | 3200 | 3292 | 3374 | 3449 | 3515 | 3576 | 3630 | 3678 | 3722 | 3762 | 3797 |
| Reservoir H (kJ/kg) | 1160 | 1114 | 1073 | 1035 | 1002 | 972 | 944 | 920 | 898 | 878 | 860 |
| Produced steam fraction | 0.22 | 0.20 | 0.18 | 0.16 | 0.15 | 0.13 | 0.12 | 0.11 | 0.10 | 0.09 | 0.08 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| 0.85 Reservoir Water + 0.15 Injectate |    |    |    |    |    |    |    |    |    |    |    |
| Reservoir Cl (mg/kg) | 3200 | 3338 | 3455 | 3554 | 3638 | 3710 | 3771 | 3823 | 3867 | 3905 | 3937 |
| Reservoir H (kJ/kg) | 1160 | 1091 | 1032 | 982 | 940 | 904 | 873 | 847 | 825 | 807 | 791 |
| Produced steam fraction | 0.22 | 0.19 | 0.16 | 0.14 | 0.12 | 0.10 | 0.08 | 0.07 | 0.06 | 0.05 | 0.04 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| 0.8 Reservoir Water + 0.2 Injectate |    |    |    |    |    |    |    |    |    |    |    |
| Reservoir Cl (mg/kg) | 3200 | 3383 | 3550 | 3648 | 3741 | 3817 | 3877 | 3925 | 3963 | 3994 | 4019 |
| Reservoir H (kJ/kg) | 1160 | 1068 | 994 | 936 | 888 | 851 | 821 | 796 | 777 | 762 | 749 |
| Produced steam fraction | 0.22 | 0.18 | 0.14 | 0.11 | 0.09 | 0.07 | 0.06 | 0.05 | 0.04 | 0.03 | 0.02 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| 0.75 Deep Water + 0.25 Injectate |    |    |    |    |    |    |    |    |    |    |    |
| Reservoir Cl (mg/kg) | 3200 | 3429 | 3601 | 3730 | 3827 | 3899 | 3954 | 3995 | 4025 | 4048 | 4065 |
| Reservoir H (kJ/kg) | 1160 | 1045 | 959 | 894 | 846 | 809 | 782 | 761 | 746 | 735 | 726 |
| Produced steam fraction | 0.22 | 0.17 | 0.13 | 0.09 | 0.07 | 0.05 | 0.04 | 0.03 | 0.02 | 0.02 | 0.01 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| 0.7 Reservoir Water + 0.3 Injectate |    |    |    |    |    |    |    |    |    |    |    |
| Reservoir Cl (mg/kg) | 3200 | 3475 | 3668 | 3803 | 3897 | 3963 | 4009 | 4042 | 4064 | 4080 | 4091 |
| Reservoir H (kJ/kg) | 1160 | 1022 | 925 | 858 | 810 | 777 | 754 | 738 | 727 | 719 | 713 |
| Produced steam fraction | 0.22 | 0.16 | 0.11 | 0.08 | 0.05 | 0.04 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| 0.66 Reservoir Water + 0.35 Injectate |    |    |    |    |    |    |    |    |    |    |    |
| Reservoir Cl (mg/kg) | 3200 | 3521 | 3730 | 3865 | 3953 | 4011 | 4048 | 4072 | 4088 | 4098 | 4105 |
| Reservoir H (kJ/kg) | 1160 | 999 | 894 | 826 | 782 | 753 | 735 | 723 | 715 | 710 | 706 |
| Produced steam fraction | 0.22 | 0.14 | 0.09 | 0.06 | 0.04 | 0.03 | 0.02 | 0.01 | 0.01 | <0.01 | <0.01 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |

(continued)
| Step | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------|---|---|---|---|---|---|---|---|---|---|----|
| **Model A (continued)** | | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3567 | 3787 | 3919 | 3998 | 4046 | 4074 | 4091 | 4102 | 4108 | 4112 |
| Reservoir H (kJ/kg) | 1160 | 976 | 866 | 799 | 760 | 736 | 721 | 713 | 708 | 705 | 703 |
| Produced steam fraction | 0.22 | 0.13 | 0.08 | 0.05 | 0.03 | 0.02 | 0.01 | 0.01 | <0.01 | <0.01 | <0.01 |
| Produced liquid fraction | 0.78 | 0.87 | 0.92 | 0.95 | 0.97 | 0.98 | 0.99 | 0.99 | >0.99 | >0.99 | >0.99 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| Reservoir Cl (mg/kg) | 3200 | 3246 | 3300 | 3363 | 3436 | 3519 | 3612 | 3718 | 3836 | 3969 | 4117 |
| Reservoir H (kJ/kg) | 1160 | 1217 | 1271 | 1323 | 1371 | 1418 | 1462 | 1504 | 1544 | 1582 | 1617 |
| Produced steam fraction | 0.22 | 0.25 | 0.28 | 0.30 | 0.33 | 0.35 | 0.37 | 0.39 | 0.41 | 0.43 | 0.44 |
| Produced liquid fraction | 0.78 | 0.75 | 0.72 | 0.70 | 0.67 | 0.65 | 0.63 | 0.61 | 0.59 | 0.57 | 0.56 |
| Injectate Cl (mg/kg) | 4117 | 4330 | 4562 | 4815 | 5091 | 5394 | 5726 | 6088 | 6487 | 6925 | 7408 |
| Reservoir Cl (mg/kg) | 3200 | 3338 | 3485 | 3644 | 3813 | 3994 | 4185 | 4389 | 4605 | 4833 | 5075 |
| Reservoir H (kJ/kg) | 1160 | 1194 | 1225 | 1252 | 1277 | 1299 | 1319 | 1337 | 1354 | 1368 | 1381 |
| Produced steam fraction | 0.22 | 0.24 | 0.25 | 0.27 | 0.28 | 0.29 | 0.30 | 0.31 | 0.32 | 0.32 | 0.33 |
| Produced liquid fraction | 0.78 | 0.76 | 0.75 | 0.73 | 0.72 | 0.71 | 0.70 | 0.69 | 0.68 | 0.68 | 0.67 |
| Injectate Cl (mg/kg) | 4117 | 4327 | 4552 | 4792 | 5050 | 5325 | 5620 | 5935 | 6271 | 6631 | 7014 |
| Reservoir Cl (mg/kg) | 3200 | 3383 | 3571 | 3763 | 3962 | 4167 | 4379 | 4600 | 4830 | 5069 | 5319 |
| Reservoir H (kJ/kg) | 1160 | 1148 | 1138 | 1131 | 1125 | 1120 | 1116 | 1113 | 1110 | 1108 | 1106 |
| Produced steam fraction | 0.22 | 0.22 | 0.21 | 0.21 | 0.21 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| Produced liquid fraction | 0.78 | 0.78 | 0.79 | 0.79 | 0.79 | 0.76 | 0.76 | 0.76 | 0.75 | 0.75 | 0.75 |
| Injectate Cl (mg/kg) | 4117 | 4321 | 4533 | 4755 | 4987 | 5230 | 5483 | 5749 | 6027 | 6318 | 6622 |
| Reservoir Cl (mg/kg) | 3200 | 3429 | 3651 | 3870 | 4087 | 4306 | 4528 | 4755 | 4989 | 5229 | 5479 |
| Reservoir H (kJ/kg) | 1160 | 1125 | 1099 | 1079 | 1064 | 1053 | 1045 | 1039 | 1034 | 1031 | 1028 |
| Produced steam fraction | 0.22 | 0.21 | 0.19 | 0.18 | 0.18 | 0.17 | 0.17 | 0.16 | 0.16 | 0.16 | 0.16 |
| Produced liquid fraction | 0.78 | 0.79 | 0.81 | 0.82 | 0.82 | 0.83 | 0.83 | 0.83 | 0.84 | 0.84 | 0.84 |
| Injectate Cl (mg/kg) | 4117 | 4318 | 4525 | 4740 | 4963 | 5195 | 5437 | 5688 | 5951 | 6226 | 6513 |
| Reservoir Cl (mg/kg) | 3200 | 3475 | 3727 | 3964 | 4193 | 4418 | 4642 | 4869 | 5101 | 5339 | 5584 |
| Reservoir H (kJ/kg) | 1160 | 1102 | 1061 | 1033 | 1013 | 999 | 989 | 983 | 978 | 974 | 972 |
| Produced steam fraction | 0.22 | 0.19 | 0.18 | 0.16 | 0.15 | 0.14 | 0.14 | 0.14 | 0.13 | 0.13 | 0.13 |
| Produced liquid fraction | 0.78 | 0.81 | 0.82 | 0.84 | 0.85 | 0.86 | 0.86 | 0.86 | 0.87 | 0.87 | 0.87 |
| Injectate Cl (mg/kg) | 4117 | 4315 | 4518 | 4727 | 4942 | 5166 | 5399 | 5641 | 5894 | 6157 | 6432 |

(continued)
### TABLE 5. MODEL RESULTS OF MIXING AND STEAM-LOSS EFFECTS ON THE RESERVOIR LIQUID RELATED TO INJECTION BREAKTHROUGH (continued)

| Step | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------|---|---|---|---|---|---|---|---|---|---|----|
| **Model B (continued)** | | | | | | | | | | | |
| Produced steam fraction | 0.65 Reservoir Water + 0.35 Injectate | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3521 | 3798 | 4048 | 4281 | 4506 | 4729 | 4953 | 5181 | 5414 | 5656 |
| Reservoir H (kJ/kg) | 1160 | 1079 | 1026 | 992 | 970 | 955 | 946 | 940 | 936 | 933 | 932 |
| Injectate Cl (mg/kg) | 4117 | 4312 | 4511 | 4714 | 4925 | 5142 | 5368 | 5604 | 5849 | 6104 | 6371 |
| Injectate Cl (mg/kg) | | | | | | | | | | | |
| **Model C** | | | | | | | | | | | |
| Produced steam fraction | 0.6 Reservoir Water + 0.4 Injectate | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3567 | 3864 | 4120 | 4354 | 4576 | 4794 | 5014 | 5238 | 5468 | 5706 |
| Reservoir H (kJ/kg) | 1160 | 1056 | 956 | 934 | 920 | 907 | 904 | 903 | 902 | | |
| Injectate Cl (mg/kg) | 4117 | 4310 | 4505 | 4704 | 4909 | 5122 | 5343 | 5573 | 5813 | 6063 | 6323 |
| Injectate Cl (mg/kg) | | | | | | | | | | | |
| **Model C** | | | | | | | | | | | |
| Produced steam fraction | 0.95 Reservoir Water + 0.025 Injectate + 0.025 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3223 | 3245 | 3265 | 3285 | 3304 | 3321 | 3338 | 3354 | 3370 | 3384 |
| Reservoir H (kJ/kg) | 1160 | 1149 | 1138 | 1127 | 1117 | 1108 | 1099 | 1091 | 1083 | 1075 | 1068 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| Injectate Cl (mg/kg) | | | | | | | | | | | |
| **Model C** | | | | | | | | | | | |
| Produced steam fraction | 0.9 Reservoir Water + 0.05 Injectate + 0.05 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3246 | 3287 | 3324 | 3358 | 3388 | 3415 | 3439 | 3461 | 3481 | 3499 |
| Reservoir H (kJ/kg) | 1160 | 1137 | 1116 | 1098 | 1081 | 1066 | 1052 | 1040 | 1029 | 1019 | 1010 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| Injectate Cl (mg/kg) | | | | | | | | | | | |
| **Model C** | | | | | | | | | | | |
| Produced steam fraction | 0.85 Reservoir Water + 0.075 Injectate + 0.075 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3269 | 3327 | 3377 | 3419 | 3455 | 3486 | 3512 | 3534 | 3552 | 3568 |
| Reservoir H (kJ/kg) | 1160 | 1126 | 1096 | 1071 | 1050 | 1032 | 1017 | 1004 | 993 | 983 | 975 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| Injectate Cl (mg/kg) | | | | | | | | | | | |
| **Model C** | | | | | | | | | | | |
| Produced steam fraction | 0.8 Reservoir Water + 0.1 Injectate + 0.1 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3292 | 3365 | 3424 | 3471 | 3508 | 3538 | 3562 | 3582 | 3597 | 3609 |
| Reservoir H (kJ/kg) | 1160 | 1114 | 1077 | 1048 | 1024 | 1005 | 990 | 978 | 969 | 961 | 955 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| Injectate Cl (mg/kg) | | | | | | | | | | | |
| **Model C** | | | | | | | | | | | |
| Produced steam fraction | 0.75 Reservoir Water + 0.125 Injectate + 0.125 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3315 | 3401 | 3465 | 3513 | 3550 | 3577 | 3597 | 3613 | 3624 | 3633 |
| Reservoir H (kJ/kg) | 1160 | 1103 | 1059 | 1027 | 1003 | 985 | 971 | 961 | 953 | 947 | 943 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| Injectate Cl (mg/kg) | | | | | | | | | | | |
TABLE 5. MODEL RESULTS OF MIXING AND STEAM-LOSS EFFECTS ON THE RESERVOIR LIQUID RELATED TO INJECTION BREAKTHROUGH (continued)

| Step | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------|---|---|---|---|---|---|---|---|---|---|----|
| Model C (continued) | | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3338 | 3434 | 3501 | 3548 | 3581 | 3605 | 3621 | 3632 | 3640 | 3648 |
| Reservoir H (kJ/kg) | 1160 | 1068 | 1013 | 980 | 960 | 957 | 947 | 941 | 936 | 934 | 932 |
| Produced steam fraction | 0.22 | 0.18 | 0.16 | 0.14 | 0.13 | 0.12 | 0.12 | 0.11 | 0.11 | 0.11 | 0.11 |
| Produced liquid fraction | 0.78 | 0.82 | 0.84 | 0.86 | 0.87 | 0.88 | 0.88 | 0.89 | 0.89 | 0.89 | 0.89 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| Reservoir Cl (mg/kg) | 3200 | 3338 | 3434 | 3501 | 3548 | 3581 | 3605 | 3621 | 3632 | 3640 | 3648 |
| Reservoir H (kJ/kg) | 1160 | 1068 | 1013 | 980 | 960 | 957 | 947 | 941 | 936 | 934 | 932 |
| Produced steam fraction | 0.22 | 0.18 | 0.16 | 0.14 | 0.13 | 0.12 | 0.12 | 0.11 | 0.11 | 0.11 | 0.11 |
| Produced liquid fraction | 0.78 | 0.82 | 0.84 | 0.86 | 0.87 | 0.88 | 0.88 | 0.89 | 0.89 | 0.89 | 0.89 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| Reservoir Cl (mg/kg) | 3200 | 3338 | 3434 | 3501 | 3548 | 3581 | 3605 | 3621 | 3632 | 3640 | 3648 |
| Reservoir H (kJ/kg) | 1160 | 1068 | 1013 | 980 | 960 | 957 | 947 | 941 | 936 | 934 | 932 |
| Produced steam fraction | 0.22 | 0.18 | 0.16 | 0.14 | 0.13 | 0.12 | 0.12 | 0.11 | 0.11 | 0.11 | 0.11 |
| Produced liquid fraction | 0.78 | 0.82 | 0.84 | 0.86 | 0.87 | 0.88 | 0.88 | 0.89 | 0.89 | 0.89 | 0.89 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |
| Model D | | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3338 | 3434 | 3501 | 3548 | 3581 | 3605 | 3621 | 3632 | 3640 | 3648 |
| Reservoir H (kJ/kg) | 1160 | 1068 | 1013 | 980 | 960 | 957 | 947 | 941 | 936 | 934 | 932 |
| Produced steam fraction | 0.22 | 0.18 | 0.16 | 0.14 | 0.13 | 0.12 | 0.12 | 0.11 | 0.11 | 0.11 | 0.11 |
| Produced liquid fraction | 0.78 | 0.82 | 0.84 | 0.86 | 0.87 | 0.88 | 0.88 | 0.89 | 0.89 | 0.89 | 0.89 |
| Injectate Cl (mg/kg) | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 | 4117 |

(continued)
| Step | 0   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.9  | 0.6 Reservoir Water + 0.2 Injectate + 0.2 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3298 | 3355 | 3419 | 3487 | 3561 | 3640 | 3723 | 3811 | 3903 |
| Reservoir H (kJ/kg) | 1160 | 1268 | 1314 | 1356 | 1393 | 1427 | 1457 | 1485 | 1509 | 1531 |
| Produced steam fraction | 0.22 | 0.25 | 0.28 | 0.30 | 0.32 | 0.34 | 0.36 | 0.37 | 0.39 | 0.40 |
| Produced liquid fraction | 0.78 | 0.72 | 0.70 | 0.68 | 0.66 | 0.65 | 0.63 | 0.62 | 0.61 | 0.60 |
| Injectate Cl (mg/kg) | 4117 | 4330 | 4550 | 4777 | 5011 | 5251 | 5497 | 5748 | 6005 | 6267 | 6534 |
| 0.85 Reservoir Water + 0.075 Injectate + 0.075 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3269 | 3343 | 3422 | 3505 | 3591 | 3680 | 3770 | 3862 | 3955 | 4048 |
| Reservoir H (kJ/kg) | 1160 | 1206 | 1244 | 1277 | 1305 | 1329 | 1349 | 1366 | 1381 | 1393 | 1404 |
| Produced steam fraction | 0.22 | 0.24 | 0.26 | 0.28 | 0.29 | 0.30 | 0.31 | 0.32 | 0.33 | 0.34 | 0.34 |
| Produced liquid fraction | 0.78 | 0.76 | 0.74 | 0.72 | 0.71 | 0.70 | 0.69 | 0.68 | 0.67 | 0.66 | 0.66 |
| Injectate Cl (mg/kg) | 4117 | 4328 | 4539 | 4749 | 4957 | 5163 | 5366 | 5565 | 5761 | 5953 | 6140 |
| 0.8 Reservoir Water + 0.1 Injectate + 0.1 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3292 | 3386 | 3482 | 3578 | 3673 | 3767 | 3860 | 3960 | 4037 | 4122 |
| Reservoir H (kJ/kg) | 1160 | 1194 | 1229 | 1243 | 1260 | 1274 | 1285 | 1294 | 1301 | 1307 | 1312 |
| Produced steam fraction | 0.22 | 0.24 | 0.25 | 0.26 | 0.27 | 0.28 | 0.28 | 0.29 | 0.29 | 0.29 | 0.30 |
| Produced liquid fraction | 0.78 | 0.76 | 0.75 | 0.74 | 0.73 | 0.72 | 0.72 | 0.71 | 0.71 | 0.71 | 0.30 |
| Injectate Cl (mg/kg) | 4117 | 4327 | 4529 | 4724 | 4910 | 5088 | 5258 | 5420 | 5573 | 5719 | 5857 |
| 0.75 Reservoir Water + 0.125 Injectate + 0.125 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3315 | 3427 | 3535 | 3639 | 3738 | 3831 | 3919 | 4002 | 4079 | 4151 |
| Reservoir H (kJ/kg) | 1160 | 1183 | 1199 | 1212 | 1222 | 1229 | 1234 | 1238 | 1241 | 1243 | 1245 |
| Produced steam fraction | 0.22 | 0.23 | 0.24 | 0.25 | 0.25 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |
| Produced liquid fraction | 0.78 | 0.77 | 0.76 | 0.75 | 0.75 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 |
| Injectate Cl (mg/kg) | 4117 | 4325 | 4520 | 4700 | 4868 | 5024 | 5167 | 5300 | 5423 | 5536 | 5640 |
| 0.7 Reservoir Water + 0.15 Injectate + 0.15 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3338 | 3465 | 3582 | 3688 | 3787 | 3876 | 3957 | 4030 | 4095 | 4155 |
| Reservoir H (kJ/kg) | 1160 | 1171 | 1187 | 1188 | 1188 | 1191 | 1192 | 1195 | 1195 | 1195 | 1196 |
| Produced steam fraction | 0.22 | 0.23 | 0.23 | 0.23 | 0.23 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 |
| Produced liquid fraction | 0.78 | 0.77 | 0.77 | 0.77 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 |
| Injectate Cl (mg/kg) | 4117 | 4324 | 4510 | 4679 | 4830 | 4967 | 5089 | 5200 | 5298 | 5387 | 5467 |
| 0.65 Reservoir Water + 0.175 Injectate + 0.175 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3360 | 3501 | 3623 | 3730 | 3906 | 3906 | 3978 | 4040 | 4095 | 4143 |
| Reservoir H (kJ/kg) | 1160 | 1160 | 1159 | 1159 | 1159 | 1159 | 1159 | 1159 | 1159 | 1159 | 1159 |
| Produced steam fraction | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 |
| Produced liquid fraction | 0.78 | 0.78 | 0.78 | 0.78 | 0.78 | 0.78 | 0.78 | 0.78 | 0.78 | 0.78 | 0.78 |
| Injectate Cl (mg/kg) | 4117 | 4322 | 4502 | 4659 | 4796 | 4916 | 5021 | 5113 | 5194 | 5264 | 5326 |
| 0.6 Reservoir Water + 0.2 Injectate + 0.2 Deep Water | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3383 | 3534 | 3659 | 3764 | 3851 | 3925 | 3987 | 4040 | 4085 | 4123 |
| Reservoir H (kJ/kg) | 1160 | 1148 | 1141 | 1136 | 1134 | 1132 | 1131 | 1131 | 1131 | 1131 | 1130 |
| Produced steam fraction | 0.22 | 0.22 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 |
| Produced liquid fraction | 0.78 | 0.78 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 |
| Injectate Cl (mg/kg) | 4117 | 4321 | 4493 | 4640 | 4765 | 4871 | 4961 | 5038 | 5104 | 5160 | 5208 |

TABLE 5. MODEL RESULTS OF MIXING AND STEAM-LOSS EFFECTS ON THE RESERVOIR LIQUID RELATED TO INJECTION BREAKTHROUGH (continued)
### TABLE 5. MODEL RESULTS OF MIXING AND STEAM-LOSS EFFECTS ON THE RESERVOIR LIQUID RELATED TO INJECTION BREAKTHROUGH (continued)

| Step | 0  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|------|----|----|----|----|----|----|----|----|----|----|----|
| | Model D (continued) | | | | | | | | | | |
| 0.5 Reservoir Water + 0.25 Injectate + 0.25 Deep Water | Injectate Cl (mg/kg) | 0.95 Reservoir Water + 0.033 Injectate + 0.017 Deep Water | Injectate Cl (mg/kg) | 0.95 Reservoir Water + 0.067 Injectate + 0.033 Deep Water | Injectate Cl (mg/kg) | 0.85 Reservoir Water + 0.10 Injectate + 0.05 Deep Water | Injectate Cl (mg/kg) | 0.8 Reservoir Water + 0.133 Injectate + 0.067 Deep Water | Injectate Cl (mg/kg) |
| Reservoir Cl (mg/kg) | 3200 | 3429 | 3594 | 3717 | 3810 | 3882 | 3939 | 3984 | 4021 | 4050 | 4073 |
| Reservoir H (kJ/kg) | 1160 | 1125 | 1108 | 1099 | 1094 | 1092 | 1091 | 1091 | 1090 | 1090 | 1090 |
| Produced steam fraction | 0.22 | 0.21 | 0.20 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| Produced liquid fraction | 0.78 | 0.79 | 0.80 | 0.81 | 0.81 | 0.81 | 0.81 | 0.81 | 0.81 | 0.81 | 0.81 |
| Injectate Cl (mg/kg) | 4117 | 4318 | 4478 | 4606 | 4709 | 4792 | 4859 | 4914 | 4958 | 4993 | 5022 |
| Reservoir Cl (mg/kg) | 0.4 Reservoir Water + 0.3 Injectate + 0.3 Deep Water | Reservoir Cl (mg/kg) | 0.3 Reservoir Water + 0.35 Injectate + 0.35 Deep Water | Reservoir Cl (mg/kg) | 0.3 Reservoir Water + 0.35 Injectate + 0.35 Deep Water | Reservoir Cl (mg/kg) | 0.3 Reservoir Water + 0.35 Injectate + 0.35 Deep Water | Reservoir Cl (mg/kg) |
| Reservoir Cl (mg/kg) | 3200 | 3475 | 3645 | 3757 | 3835 | 3893 | 3935 | 3967 | 3991 | 4009 | 4023 |
| Reservoir H (kJ/kg) | 1160 | 1102 | 1079 | 1070 | 1066 | 1064 | 1064 | 1063 | 1063 | 1063 | 1063 |
| Produced steam fraction | 0.22 | 0.19 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 |
| Produced liquid fraction | 0.78 | 0.81 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 |
| Injectate Cl (mg/kg) | 4117 | 4315 | 4463 | 4576 | 4661 | 4726 | 4776 | 4814 | 4843 | 4866 | 4883 |
| Reservoir Cl (mg/kg) | 0.3 Reservoir Water + 0.35 Injectate + 0.35 Deep Water | Reservoir Cl (mg/kg) | 0.8 Reservoir Water + 0.133 Injectate + 0.067 Deep Water | Reservoir Cl (mg/kg) | 0.8 Reservoir Water + 0.133 Injectate + 0.067 Deep Water | Reservoir Cl (mg/kg) | 0.8 Reservoir Water + 0.133 Injectate + 0.067 Deep Water | Reservoir Cl (mg/kg) |
| Reservoir Cl (mg/kg) | 3200 | 3521 | 3686 | 3783 | 3847 | 3891 | 3922 | 3944 | 3960 | 3971 | 3979 |
| Reservoir H (kJ/kg) | 1160 | 1079 | 1055 | 1047 | 1045 | 1045 | 1044 | 1044 | 1044 | 1044 | 1044 |
| Produced steam fraction | 0.22 | 0.18 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 |
| Injectate Cl (mg/kg) | 4117 | 4312 | 4450 | 4548 | 4619 | 4670 | 4707 | 4733 | 4752 | 4766 | 4776 |
| Injectate Cl (mg/kg) | 4117 | 4331 | 4561 | 4810 | 5076 | 5368 | 5681 | 6020 | 6386 | 6787 | 7220 |
| Injectate Cl (mg/kg) | 4117 | 4332 | 4551 | 4782 | 5024 | 5276 | 5539 | 5812 | 6095 | 6388 | 6693 |
| Injectate Cl (mg/kg) | 4117 | 4327 | 4540 | 4757 | 4977 | 5200 | 5425 | 5752 | 5801 | 6031 | 6262 |
| Injectate Cl (mg/kg) | 4117 | 4325 | 4531 | 4735 | 4936 | 5135 | 5332 | 5525 | 5715 | 5903 | 6087 |

(continued)
TABLE 5. MODEL RESULTS OF MIXING AND STEAM-LOSS EFFECTS ON THE RESERVOIR LIQUID RELATED TO INJECTION BREAKTHROUGH (continued)

| Step | 0  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|------|----|----|----|----|----|----|----|----|----|----|----|
| Model E (continued) | | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3353 | 3502 | 3648 | 3789 | 3925 | 4058 | 4187 | 4312 | 4432 | 4549 |
| Reservoir H (kJ/kg) | 1160 | 1163 | 1166 | 1167 | 1169 | 1170 | 1170 | 1170 | 1171 | 1172 | 1172 |
| Produced steam fraction | 0.22 | 0.22 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Produced liquid fraction | 0.78 | 0.78 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 |
| Injectate Cl (mg/kg) | 4117 | 4323 | 4522 | 4715 | 4901 | 5081 | 5256 | 5424 | 5587 | 5745 | 5897 |
| 0.7 Reservoir Water + 0.2 Injectate + 0.1 Deep Water | | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3383 | 3553 | 3709 | 3856 | 3993 | 4121 | 4243 | 4357 | 4466 | 4568 |
| Reservoir H (kJ/kg) | 1160 | 1148 | 1140 | 1134 | 1130 | 1127 | 1125 | 1123 | 1122 | 1122 | 1121 |
| Produced steam fraction | 0.22 | 0.22 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.20 | 0.20 | 0.20 | 0.20 |
| Produced liquid fraction | 0.78 | 0.78 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.79 | 0.80 |
| Injectate Cl (mg/kg) | 4117 | 4321 | 4513 | 4696 | 4869 | 5033 | 5189 | 5337 | 5477 | 5611 | 5738 |
| 0.65 Reservoir Water + 0.233 Injectate + 0.117 Deep Water | | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3414 | 3600 | 3764 | 3911 | 4044 | 4166 | 4277 | 4381 | 4476 | 4565 |
| Reservoir H (kJ/kg) | 1160 | 1133 | 1115 | 1104 | 1096 | 1091 | 1088 | 1086 | 1085 | 1084 | 1083 |
| Produced steam fraction | 0.22 | 0.21 | 0.20 | 0.20 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| Produced liquid fraction | 0.78 | 0.79 | 0.80 | 0.80 | 0.81 | 0.81 | 0.81 | 0.81 | 0.81 | 0.81 | 0.81 |
| Injectate Cl (mg/kg) | 4117 | 4319 | 4505 | 4678 | 4840 | 4990 | 5130 | 5261 | 5384 | 5499 | 5606 |
| 0.6 Reservoir Water + 0.267 Injectate + 0.133 Deep Water | | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3445 | 3645 | 3814 | 3959 | 4086 | 4200 | 4302 | 4394 | 4479 | 4556 |
| Reservoir H (kJ/kg) | 1160 | 1117 | 1091 | 1076 | 1067 | 1061 | 1058 | 1056 | 1055 | 1054 | 1054 |
| Produced steam fraction | 0.22 | 0.20 | 0.19 | 0.18 | 0.18 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 |
| Produced liquid fraction | 0.78 | 0.80 | 0.81 | 0.82 | 0.82 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 |
| Injectate Cl (mg/kg) | 4117 | 4317 | 4498 | 4663 | 4814 | 4953 | 5080 | 5198 | 5306 | 5406 | 5498 |
| 0.5 Reservoir Water + 0.33 Injectate + 0.17 Deep Water | | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3503 | 3719 | 3883 | 4014 | 4124 | 4217 | 4298 | 4369 | 4432 | 4487 |
| Reservoir H (kJ/kg) | 1160 | 1088 | 1052 | 1034 | 1025 | 1021 | 1019 | 1018 | 1017 | 1017 | 1017 |
| Produced steam fraction | 0.22 | 0.19 | 0.17 | 0.16 | 0.16 | 0.16 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| Produced liquid fraction | 0.78 | 0.81 | 0.83 | 0.84 | 0.84 | 0.84 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 |
| Injectate Cl (mg/kg) | 4117 | 4314 | 4484 | 4663 | 4765 | 4883 | 4987 | 5079 | 5161 | 5235 | 5300 |
| 0.4 Reservoir Water + 0.4 Injectate + 0.2 Deep Water | | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3567 | 3791 | 3945 | 4062 | 4156 | 4235 | 4302 | 4359 | 4408 | 4451 |
| Reservoir H (kJ/kg) | 1160 | 1056 | 1014 | 998 | 991 | 988 | 987 | 987 | 987 | 987 | 987 |
| Produced steam fraction | 0.22 | 0.17 | 0.15 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 |
| Produced liquid fraction | 0.78 | 0.83 | 0.85 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 |
| Injectate Cl (mg/kg) | 4117 | 4310 | 4471 | 4610 | 4728 | 4831 | 4919 | 4996 | 5062 | 5119 | 5169 |
| 0.3 Reservoir Water + 0.47 Injectate + 0.23 Deep Water | | | | | | | | | | | |
| Reservoir Cl (mg/kg) | 3200 | 3631 | 3849 | 3987 | 4089 | 4170 | 4236 | 4292 | 4338 | 4377 | 4410 |
| Reservoir H (kJ/kg) | 1160 | 1024 | 983 | 971 | 967 | 966 | 966 | 965 | 965 | 965 | 965 |
| Produced steam fraction | 0.22 | 0.16 | 0.14 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| Produced liquid fraction | 0.78 | 0.84 | 0.86 | 0.87 | 0.87 | 0.87 | 0.87 | 0.87 | 0.87 | 0.87 | 0.87 |
| Injectate Cl (mg/kg) | 4117 | 4306 | 4460 | 4589 | 4686 | 4786 | 4862 | 4925 | 4978 | 5023 | 5060 |
dimensionless, and reflects a snapshot of protracted and continuous mixing between the evolving reservoir water and the evolving injectate. The injectate enthalpy is fixed at 700 kJ/kg, which is based on measurements in the early 1990s, and this value remains constant in the computation (i.e., the decrease in enthalpy associated with the commissioning of the binary plant in 2008 is ignored). For simplicity, the enthalpy of the water separated from the produced two-phase fluid is also designated 700 kJ/kg, corresponding to a vapor-saturated pressure of 0.7 MPa, which is a little lower than separation pressures of individual wells reported in Table 1; this assumption is required to constrain the enthalpy difference between the produced two-phase fluid and the separated water so that the steam fraction and the chloride concentration of the injectate can both be calculated for each time step. A number of run calculations were made, in which the mass fractions of reservoir water (a) and injectate (b) are held constant throughout each run.

For example, based on a mixture of 75% reservoir water and 25% injectate (i.e., a = 0.75 and b = 0.25) at n = 1, the chloride concentration of the reservoir water (Cl\text{reservoir}) is 3429 mg/kg, with Cl\text{reservoir} (n - 1) = 3200 mg/kg and Cl\text{inj} (n - 1) = 4117 mg/kg; the corresponding reservoir enthalpy (H\text{reservoir}) is 1045 kJ/kg. At n = 2, Cl\text{reservoir} = 3601 mg/kg, Cl\text{reservoir} (n - 1) = 3429 mg/kg, and Cl\text{inj} (n - 1) = 4117 mg/kg; the corresponding reservoir enthalpy (H\text{reservoir}) is 959 kJ/kg. The full range of results is presented in Table 5. Note that the resulting calculated injectate chloride concentration remains unchanged in each successive time step. This is because no new heat is added to the mixed fluid; therefore, the chloride concentrations and the enthalpies of the calculated reservoir water change in precisely the right proportion to reduce the steam fractions of produced fluid to keep the injectate chloride concentration constant. The model mixing results form as a straight line on the enthalpy-chloride plot (Fig. 14), and the line clearly deviates from the observed produced fluid enthalpy-chloride trends shown in Figures 10 and 11. Furthermore, the results imply that with injection breakthrough, the reservoir water has gained heat over time. One source of heat could be derived from the input of rising deep chloride water, and another source is via exchange of heat as cool injectate interacts with hot crystalline rock in a process that is known as heat sweep. These possibilities are evaluated below.

Model B

In Model B, the set of run calculations was the same as Model A—but with addition of a fixed quantity of supplementary heat (H\text{supplementary}) to each reservoir mixture. The revised heat balance equation is:

\[ H_{\text{reservoir}} = aH_{\text{reservoir}} (n - 1) + bH_{\text{inj}} + H_{\text{supplementary}}. \] (10)

For example, the results of substituting 80 kJ/kg for H\text{supplementary} at each time step are shown in Figure 15 and Table 5. In all the runs, the chloride concentration increases over time, but only for mass fractions of injectate of 0.2 and greater do the enthalpy trends decrease over time. The model run that best matches the trends for wells 45-3 and 54-3 is achieved in six steps by an injectate mass fraction of 0.25 (Figs. 15 and 16); this run equates to 320 kJ/kg of heat sweep, assuming the injectate introduces all the new heat. Higher and lower values of H\text{supplementary} were tested, but few of the resulting chloride-enthalpy trends matched the histories of 45-3 or 54-3, and of these, they were all within ~20% of the original 80 kJ/kg value. In other words, by simultaneously evaluating both chloride and enthalpy, a relatively narrow range of apparently valid model results was obtained, centering on the 80 kJ/kg of supplementary heat. From comparison of the modeled and measured time series evolution in chloride and enthalpy (Fig. 16), the interval of the time step (n) is 5.3 years.

Models C, D, and E

Models C, D, and E comprise three-component mixing calculations that build on the two-component models. Accordingly, a fraction of preproduction...
chloride water is added to the reservoir fluid to produce a mixture of injectate, deep upflow, and existing reservoir water, using the following expressions:

\[
\text{Cl}_{\text{reservoir}} = a\text{Cl}_{\text{reservoir}} + b\text{Cl}_{\text{injectate}} + c\text{Cl}_{\text{deep}} \\
\text{H}_{\text{reservoir}} = a\text{H}_{\text{reservoir}} + b\text{H}_{\text{injectate}} + c\text{H}_{\text{deep}} + H_{\text{supplementary}}
\]

where \(\text{Cl}_{\text{deep}} = 3200 \text{ mg/kg}\), the preproduction chloride concentration of the deep upflow water; \(\text{H}_{\text{deep}} = 1160 \text{ kJ/kg}\), the preproduction enthalpy of the deep upflow water; \(a = \text{mass fraction of reservoir water}\); \(b = \text{mass fraction of injectate}\); \(c = \text{mass fraction of deep upflow water}\).

Just as in Model B, the added heat is essential to matching the enthalpy-chloride trends in Figures 11 and 14. To illustrate this, Model C has no added heat (i.e., \(H_{\text{supplementary}} = 0\)). Although Model C results are not graphed, the values in Table 5 show that addition of deep upflow water fails to come close to matching the measured trends in produced fluid chloride and enthalpy through time (Figs. 10 and 11).

In Model D, the proportions of injectate to deep upflow are held constant at 1:1, and \(H_{\text{supplementary}} = 80 \text{ kJ/kg}\). The calculated results are presented in Table 5.

In Model E, however, closer fits to the chloride and enthalphy trends were attained in which the proportions of injectate to deep upflow are held constant at 2:1, and \(H_{\text{supplementary}} = 80 \text{ kJ/kg}\). For this range of model calculations, the best match is obtained in ten steps for a fluid comprising 0.6 reservoir water, 0.267 injectate, and 0.133 deep upflow (Figs. 14–16; Table 5). Assuming again that all the supplementary heat of 80 kJ/kg total is introduced by the injectate indicates 300 kJ/kg (i.e., 80/0.267) of heat sweep between the injector and producer. From comparison of the modeled and measured time series evolution in chloride and enthalphy (Fig. 16), the interval of the time step \(n\) is 3.2 years.

Implications

Simplistic mixing models have been calculated in which the proportions of end-member fluids are held constant, but in which the steam fraction of produced fluid continuously decreases due to modest cooling of the reservoir water. Mass flows and heat sweep are assumed to be unchanging, even though they are likely variable and nonlinear as fluid migrates through fractured rock media (e.g., Bödvarsson and Tsang, 1982; Faoro et al., 2015; Gan and Elsworth, 2016). In the three-component mixing model, the deep upflow composition is assumed to have the same chloride concentration and enthalpy as the preproduction reservoir fluid, and there are no modern data to better constrain these values. Furthermore, the real chloride concentration of the 14-2 injectate through time is not known, but it must exceed the 54-3 and 45-3 reservoir water concentration to account for the enthalphy-chloride trends (Fig. 11). Lastly, the injectate enthalpy is held constant at 700 kJ/kg, but in 2008, this lowered to ~400 kJ/kg with the commissioning of the binary plant.

Keeping in mind all the caveats above, the modeling results in Figures 14–16 show that the proportion of injectate produced by wells 54-3 and 45-3 is ~25%. In comparison, for the other two production wells, 28-3 and 13-10, the produced proportions of injectate are deduced to be much lower (Fig. 11). The modeling also suggests that a significant amount of thermal energy has been transferred by the injectate and then produced from 54-3 and 45-3 reservoir water concentration to account for both the chloride and enthalpy trends of these wells. This amount can be estimated given production well data. In 2015–2016, the combined fluid production rate from the two wells was 140–145 kg/s. Taking the injectate contribution to be 35 kg/s and the added heat to be 300 kJ/kg, plus using a cutoff value of 700 kJ/kg, the produced thermal power is ~10 MW\(_{th}\); but using a lower cutoff value of 400 kJ/kg, the produced thermal power doubles to 20 MW\(_{th}\). Over 32 years, this increase in power equates to at least \(10^{10}\) kJ of heat sweep compared with a minimum value of \(10^9\) kJ of total produced heat (assumes the average enthalpy of all produced water is 1086 kJ/kg; 250 °C, and the cutoff enthalpy is 700 kJ/kg). Overall, the model values provide a first-order estimate of the proportion of injectate and the amount of heat sweep contributing to the composition and enthalphy of the produced fluids.
in 54-3 and 45-3, which are the two wells that are most greatly affected by injection breakthrough.

# EVOLUTION OF THE HYDROTHERMAL SYSTEM

The Roosevelt Hot Springs hydrothermal system represents the shallow part of convective plume of hot water hosted by crystalline rocks made of Tertiary granitoids and Precambrian gneiss. The area of activity covers ~5 km², and the maximum temperature of 268 °C was reached at ~750 m depth under the prevailing hot, near-boiling hydrostatic gradient. There is no major steeply dipping range-front fault with large normal offset, but a vertically extensive fault-fracture mesh east of the Opal Mound fault is inferred to provide the overall control on the upflow of hydrothermal fluids (Nielson et al., 1986; Faulder, 1991; Bartley, 2019). The evidence of Pleistocene rhyolite volcanism (Nielson et al., 1986), helium and carbon isotopes (Bowman and Rohrs, 1981; Kennedy and van Soest, 2007), and the N₂-Ar-He ratios (Fig. 7; Table 2) indicate the existence of a bimodal felsic-mafic magmatic heat source, which is consistent with geophysical evidence of a melt body at mid-crustal depths (Robinson and Iyer, 1981; Becker and Blackwell, 1993; Wannamaker et al., 2020). Based on natural seismicity (Zandt et al., 1982; Pankow et al., 2019; Mesimeri et al., 2021), the deep upflow may originate from ~2 km east of the production field. Two-dimensional numerical modeling suggests that hydrothermal circulation extends to 7–10 km depth, which defines the probable base of the convection cell (Becker and Blackwell, 1993). The minimum period of hydrothermal activity extends at least back ~2000 years based on ¹⁴C dating of the Opal Mound silica sinter (Lynne et al., 2005), and perhaps >10,000 years, if the meteoric recharge dates back to the late Pleistocene (Flynn and Buchanan, 1990, 1993). A much longer period of hydrothermal circulation, exceeding 100,000 years, is implied by the numerical modeling (Becker and Blackwell, 1993).

The neutral pH chloride water that makes up the thermal plume originated from deep circulation of local meteoric water, the acquisition of heat and magmatic volatiles at the base of the convection cell, and subsequent protracted high-temperature water-rock interaction (e.g., Giggenbach, 1997). Based on the absence of readily soluble minerals in the crystalline host rocks, Cl, CO₂, and H₂S likely derived from magmatic sources. By contrast, water-rock interaction and temperature-dependent fluid-mineral equilibria involving feldspars, micas, clays, calcite, quartz, and chalcedony control the ratios and concentrations of Ca, Li, K, Na, Mg, B, and SiO₂, as well as maintain reduced oxidation states and near-neutral pH values (Capuano and Cole, 1982; Giggenbach, 1988, 1997; Fournier, 1991). The very similar and widespread distribution of rock-forming minerals means that the differences between calculated Na-K and chalcedony-silica temperatures (Table 4) primarily reflect depth of equilibration and speed of reaction. Therefore, the chalcedony-silica temperatures best represent reservoir conditions, whereas the Na-K temperatures potentially reflect deeper and hotter conditions of fluid-mineral equilibration in the hydrothermal plume.

In order to sustain hydrothermal fluid flow over the lifespan of the system, the permeability structure comprising the network of interconnected fractures and faults must be resilient to modification. At shallow levels, for example, continuous permeability degradation occurs in response to sharp chemical gradients, mineral deposition, and fracture sealing; this degradation may account for the demise of hot spring discharge at Opal Mound ~2000 years ago. The permeability structure is likely to be maintained by episodic fracturing and seismicity (Pankow et al., 2019; Mesimeri et al., 2021). Even without...
mineral deposition, faults can act as fluid-flow barriers (e.g., Caine et al., 1996) as illustrated by the role that the Opal Mound fault plays in delineating the western boundary of the hydrothermal system. The large difference in the preproduction Cl composition between wells 14-2 and 54-3 (Fig. 11) suggests some degree of fracture-controlled partitioning of the upflow regimes as well, but any sort of flow barrier that might have once existed within the reservoir appears no longer active given the evidence of injection breakthrough.

At less than 1 km depth, the upflow zone of rising hot water intersects the hydrostatic boiling point for depth, and from this level to the surface, steam-loss and mixing become the dominant controls on the fluid composition, from preproduction up to the present, and this explains the spatial and temporal changes induced by production. The reservoir chloride concentration has increased markedly over time due to continuous in-mixing of injectate, which is chloride enriched due to steam-loss during fluid production. The same effects are reflected in the oxygen and hydrogen isotope compositions. The systematic variations in chloride concentration and stable isotope ratios across the production zones (Figs. 10–12) is consistent with differences in distance associated with dispersion and mixing as injectate flows west and south from well 14-2. In-mixing of injectate also accounts for modest reservoir cooling over time of 10–25 °C.

The evolution of the hydrothermal system in response to geothermal production is shown in Figure 17. Temporally, the largest and earliest effect was the decline in pressure across the field extending from wells 54-3 to 25-15 (Allis and Larsen, 2012). As a result, the piezometric level lowered by as much as 250–300 m to an elevation that is nearly equal across both sides of the Opal Mound fault, and pores and cracks formerly filled with hot water were replaced by water vapor and condensed steam as the vadose zone expanded (Fig. 17). A similar magnitude decrement in pressure occurred early in the production histories at Tiwi (Gambill and Beraquit, 1993) and at Wairakei (Bixley et al., 2009), where, in the second example, pressure support from injection was lacking, only to be implemented later on. At Roosevelt Hot Springs, the largest pressure declines were measured in wells 25-15 and 28-3, which are >1 km from the closest injection well 14-2. Based on a production rate of 290 kg/s (≈8 million tonnes/y) and 5% fracture-related porosity (Faulder, 1991), the total fluid mass produced in the first three years of ~36 million metric tonnes is roughly the same as the mass of water occupying a rock volume 2000 × 1000 × 300 m² (i.e., the shallow rock volume through which the piezometric level dropped). The early, sharp lowering of the piezometric level thus implies that the rate of production exceeded the rate of injection and/or that pressure support from 14-2 was impeded or had not yet propagated in this phase of geothermal production. Conceivably, the early pressure drop increased the hydraulic gradient and stimulated the flow of injectate from 14-2 westward into the production zone, where it mixed with upflowing deep chloride water.

By the early 1990s, the physical and chemical effects of injection were evident in 54-3 (Figs. 10–12); these effects continued to spread southward through 2016 as reflected by coupled increase in chloride and decrease in enthalpy and systematic enrichments to the stable isotope compositions of the reservoir waters. By contrast, the rate in the drop of CO₂ concentration in reservoir waters (Table 5) may have mirrored the sharp pressure decline in the early production period. In 2008, evidence of 10%–20% excess steam in the production fluid was detected from well-head enthalpy measurements (Allis and Larsen, 2012). The 2015 and 2016 data for well 54-3 clearly support this (Fig. 11), showing localized development of a two-phase feed zone supplying a mixture of steam and water (Fig. 17); the fact that evidence of two-phase conditions has not spread to 45-3 suggests that enhanced boiling fluid flow has been confined to a relatively narrow subvertical conduit hosted by fractures. The 2015–2016 well 54-3 data also show an enthalpy decline over the two-year period, suggesting that this structurally localized two-phase zone might be contracting, presumably in response to cooling induced by interaction with injectate.
Not evaluated in this study are the effects of subsurface mineral deposition associated with fluid injection, primarily because fluid analyses are unavailable. Instead, the chloride concentration and the isotopic composition of the injectate in well 14-2 are inferred based on the analyses of produced waters. Nonetheless, silica holds interest, because it becomes concentrated in produced waters by steam-loss and cooling, and thus the injectate is silica supersaturated with respect to many of the solid silica polymorphs. Once the flashed liquid is reinjected, aqueous silica concentrations are subject to modification due to reheating and relatively rapid re-equilibration (e.g., Rimstidt and Barnes, 1980; Fournier, 1991). Accordingly, there has been a close match between measured and calculated equilibrium temperatures using the chalcedony geothermometer throughout the 32-year period of production (Fig. 8; Table 4). Although difficult to prove, some modest degree of silica deposition may have accompanied re-equilibration. It is also possible that any impact in the form of reduction in permeability is counteracted by cooling and thermo-mechanical stress that keep fractures open (e.g., Ghassemi and Tao, 2016). At no point, however, is there any evidence of silica breakthrough, a condition that marks the onset of fluid mineral disequilibria between aqueous silica and quartz or chalcedony and that follows chloride breakthrough but precedes thermal breakthrough in response to rapid reservoir cooling (Malate and O’Sullivan, 1991).

The evidence of injectate in produced fluid at Roosevelt Hot Springs is generally consistent with experience in other producing fields (e.g., Malate and O’Sullivan, 1991; Sugiaman et al., 2004; Acuña et al., 2008; Kaya et al. 2011; Rivera-Diaz et al., 2016), except that deleterious cooling has been avoided. The simple mixing models used herein to assess the long-term chemical and thermal consequence of injection breakthrough show that there has been a significant amount of sustained multi-decadal heat mining, possibly equivalent to ~10–20 MW, in respect to the power produced by wells 54-3 and 45-3, combined. Such level of power production has been a longstanding goal of EGS-type technologies. In nearly all the recent field experiments, however, injectivity, tracer return, and/or pressure support rather than rock to fluid heat transfer is all that has been attained or proven (e.g., Rose et al., 2006, 2012; Sanjuan et al., 2010; Ledésert and Hébert, 2012; Mills and Humphrey, 2013; Ayling et al., 2016; Benato and Taron, 2016; Bradford et al., 2016; Cladouhos et al., 2016), and this is in contrast to modest successes at the Fenton Hill hot-dry rock site where relatively short period outputs of 3–10 MW were achieved (Kalkar et al., 2016). One constraint is that fracture-controlled networks are prone to confined fluid flows and short circuiting (e.g., National Research Council, 1996; Tester et al., 2006), and this minimizes effective rock to fluid heat exchange and sustained geothermal energy production (e.g., Grant, 2016). At Roosevelt Hot Springs, detailed information about how fractures control fluid flow, including fracture geometry and density, is lacking except what can be inferred from surface outcrops. Tracer testing could shed some light, particularly with respect to flow velocity, dispersion, and fracture volume for heat transfer (Shook, 1998; Rose et al., 2004; Owens et al. 2018). The main point is that optimal conditions for EGS-type heat exchange appear to have formed naturally in a granitic reservoir where fluid movement is restricted to well-connected fractures, making Roosevelt Hot Springs relevant for future investigations of this type of heat transfer.

The legacy of geothermal energy developments globally shows long histories of production of high-temperature resources at Larderello, Italy (>100 years), Wairakei, New Zealand (>60 years), and The Geysers, USA (>60 years) that continue through today (e.g., Simmons, 2021). At Roosevelt Hot Springs, production-related pressure drawdown has induced a several-fold increase in the supply of deep, hot chloride water, and this has been significant for the sustainability of the resource. The total fluid production is known to have declined from 290 to 250 kg/s from 1984 to 2016. At least 35 kg/s of this total flow are made of injectate based on the mixing model calculations involving wells 54-3 and 45-3. Assuming some modest addition of ~15 kg/s injectate to account for changes in production chemistry in wells 28-3 and 13-10 by 2016 (Figs. 11 and 12) requires a minimum deep upflow of at least 200 kg/s. This value is more than three times greater than the preproduction upflow of deep chloride water of ~60 kg/s (Allis et al., 2019). Thus, in 2016, ~20% of the total power production came from shallow-level heat sweep by injectate from 14-2, and ~80% came from the deep chloride water. Critically, these two sources of energy, which were both stimulated by fluid production, account for the long-term geothermal power output at Roosevelt Hot Springs. Such quantitative assessments are generally difficult to derive, and in this case, they have been possible from the combined evaluation of chemical and physical data sets collected over a long production period.

CONCLUSIONS

Roosevelt Hot Springs shares similarities with high-temperature terrestrial magma-related hydrothermal systems that are exploited for geothermal energy around the world, particularly with respect to the compositions of hydrothermal fluids and the physical regime controlling the temperature, pressure, and fluid flow (e.g., Henley and Ellis, 1983; Giggenbach, 1997; Grant and Bixel, 2011). The geological setting and permeability structure are somewhat unique, in that the fracture-controlled permeability developed in crystalline granite has facilitated fluid flow and heat transfer over the vertical extent of the hydrothermal plume and at reservoir depths between injection and production wells. The most continuous structure, the Opal Mound fault, however, forms a flow and pressure barrier that marks the western boundary of the convection cell. The system has evolved in response to fluid production that includes significant pressure drop and injection breakthrough, but neither of these impacted the power supply, and there is no evidence of cool groundwater inflow. Geothermal power production has been sustained by an increase in the supply of deeply derived chloride water along with the mining of heat stored in rock between injection and production wells. Given the similar geological setting and proximity to the Utah FORGE EGS site, the latter attribute implies the possibility of significant EGS-type heat production from a hot-dry crystalline rock.
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