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Mixing of thermal and non-thermal waters in the Steamboat Hills area, Nevada, USA

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Abstract

Groundwater monitoring began in 1985 at two geothermal facilities in the Steamboat Hills area, Nevada. Wells representing non-thermal, thermal, and mixed waters are evaluated by assessing temporal variations in B and Cl concentrations, water levels, and temperature. The objective is to assess the hydrologic and geochemical connection between the fractured bedrock geothermal reservoir and the alluvial aquifer. Results suggest that fault-controlled groundwater flow between the geothermal system and the alluvial aquifer is the dominant hydrologic process. Temporal trends suggest that the thermal water component in the alluvial aquifer has increased in most areas but decreased in at least one area. © 2002 CNR. Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

Rapid growth in the southern Truckee Meadows (south of Reno, Nevada) during the past decade has placed a large demand on water resources near the Steamboat Hills area (see Fig. 1). The demand has been for non-thermal water to satisfy municipal and domestic needs, and for thermal water to produce electric power at two power facilities. Development of these resources to serve the growing suburban community poses special problems related to the close proximity and interconnected

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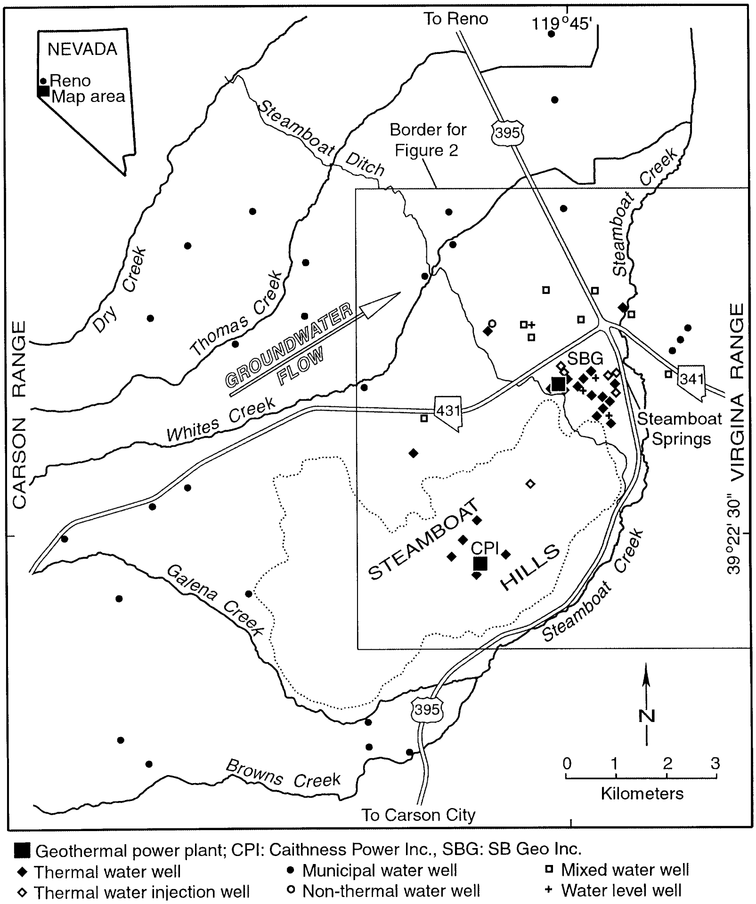

Fig. 1. Location map of the Steamboat Hills area, Nevada.

nature of these two water resources. Many communities in the western United States face similar questions regarding management of water resources for competing uses.

The Washoe County Department of Water Resources, Utility Services Division (Washoe County) began producing the municipal water supply from alluvial aquifers around the Steamboat Hills in 1985. The two geothermal production facilities, currently SB Geo, Inc. (SBG) and Caithness Power, Inc. (CPI), began operating in the Steamboat Hills in January 1987 and February 1988, respectively. Washoe County, SBG, and CPI are interested in long-term production of their resources but recognize that a thorough understanding of the hydrogeology of the collective groundwater system is essential for preservation of the water resources in the area. The key question regarding the hydrogeology of the system is the nature of the hydraulic connection between the fractured bedrock geothermal reservoir and the alluvial aquifer. By evaluating the interconnection between the geothermal reservoir and alluvial aquifer systems, resource management decisions can be made in attempts to minimize adverse impacts to both resources. This study employs geochemical data to evaluate mixing of non-thermal and thermal waters to provide insight into the hydrogeology of the area.

Hot-spring flow at Steamboat Springs, located northeast of the Steamboat Hills, began declining in 1986 and ceased completely in 1987. Below-normal precipitation from 1986 to 1994, as well as reduced irrigation (resulting in reduced recharge to the alluvial aquifer) in fields along the Steamboat Ditch (Fig. 1), caused water-level declines in alluvial aquifer monitor wells. The initiation of non-thermal water and thermal water production was coincident with these events and prompted the US Geological Survey to initiate a study to evaluate factors affecting hot-spring activity in the area (Sorey and Colvard, 1992). The focus of that study was to identify the pertinent causes for the change in hydraulic conditions in the area. Additional studies were conducted following initiation of resource production to evaluate water chemistry relationships in the area and assess potential impacts from geothermal production (Yeamans, 1988; van de Kamp and Goranson, 1990; Goranson, 1991; Environmental Management Associates, 1993). Major and trace element chemistry and stable isotope data were also obtained from thermal and non-thermal waters in Steamboat Hills, Steamboat Springs, regional streams and creeks, and precipitation (Nehring, 1980; Ingraham and Taylor, 1991; Mariner and Janik, 1995). These data suggest that the same thermal source fluid is intercepted at the two geothermal power facilities; however, the existing data did not provide clear evidence that the recharge origin for the geothermal system is similar to the alluvial aquifer.

The development of both thermal and non-thermal water resources has affected wells in the combined discharge area east of Steamboat Hills near Steamboat Creek (Fig. 1, near the junction of US 395 and Nevada 431 and 341). The purpose of this study is to identify causes of water quality degradation or improvement at public and domestic water supply wells in this discharge area, and to document changes in the contribution of thermal waters to this area, along with possible causes. The temporal relationship of production activities and water quality trends for both of these water resources is evaluated to determine the importance of faults to fluid flow.

2. Background

2.1. Location and climatic setting

The Steamboat Hills consist of a northeast-southwest trending topographically prominent bedrock ridge located at the southern boundary of Truckee Meadows in central Washoe County, Nevada. The Truckee Meadows is a north-south trending basin bordered on the west by the Carson Range and on the east by the Virginia Range. The Steamboat Hills lie between US 395 and Nevada 431 (Fig. 1). The city of Reno is located approximately 15 km to the north but recent expansion has filled in most of the area between Reno and the Steamboat Hills.

Precipitation is influenced greatly by oroclinal effects from the Carson Range, which creates a strong rain-shadow effect. Annual precipitation, falling primarily as snow, averages 147 cm at higher elevations in the Carson Range (based on a 19 year average at Marlette Lake), whereas the average annual precipitation in Reno, falling primarily as rain, is only about 18 cm (based on a 54 year average at Reno/Tahoe International Airport; Desert Research Institute, 2000). Steamboat Creek is the principal drainage within the area and is a major tributary to the Truckee River, which originates at Lake Tahoe (located 20 km southwest of Steamboat Hills) and discharges into Pyramid Lake (located 60 km northeast of Steamboat Hills). The majority of runoff comes from snow that precipitates on the east flank of the Carson Range. The predominant tributaries in the area include: Dry Creek, Thomas Creek, Whites Creek, Galena Creek and Browns Creek. The Steamboat Springs geothermal area is located on the northeastern flank of the Steamboat Hills (Fig. 1).

2.2. Geology

The geology of the area has been described by White et al. (1964), Thompson and White (1964), Tabor and Ellen (1975), Bonham and Rogers (1983), and Bonham and Bell (1993). The basement bedrock consists of fractured Cretaceous granodiorite intruded into older metasedimentary and metavolcanic rocks. The basement rocks are overlain by faulted andesite, dacite, and basalt flows, flow breccias, intrusive bodies, and tuff-breccias of the Tertiary Kate Peak Formation. These rocks are disrupted by at least three prominent fault systems that trend north–south (range-front system), northeast–southwest, and northwest–southeast. Quaternary rhyolite domes occur along the northeast–southwest fault trend. Geothermal production is primarily from the fractured granodiorite, predominantly along the northeast-southwest trending fault system.

The generally sandy cobble to boulder gravel-rich sediments of the Mount Rose fan complex are the dominant alluvial deposits located west and north of the Steamboat Hills. These alluvial deposits, as well as the fractured volcanic rocks, are the primary sources of municipal and domestic water supply. Drilling logs indicate that the maximum thickness of these sediments is over 365 m (Washoe County, internal files) and gravity data suggest that the depth to bedrock may be as much as 400 m (Abbott and Louie, 2000).

2.3. Hydrogeology and geochemistry

Cohen and Loeltz (1964) discuss the hydrogeology and geochemistry of Truckee Meadows. The hydrology, activity, and heat flow of Steamboat Springs are discussed by White (1968) and time-variant hydrogeology and geochemistry are presented by Lyles (1985). Cooley et al. (1971) developed numerical models of surface water and groundwater hydrology in the Truckee Meadows. Bateman and Scheibach (1975) and Flynn and Ghusn (1984) have evaluated geothermal activity in the Truckee Meadows area. Goranson (1991) and DeRocher (1996) summarize the geochemistry from geothermal well monitoring in the Steamboat Hills.

Water-level contours show that the general groundwater gradient in the alluvial aquifer is from the range fronts (Carson and Virgina Ranges) toward Steamboat

Creek. In the study area, the groundwater flows generally toward the northeast (Fig. 1). Streamflow measurements show that Steamboat Creek is a gaining stream throughout the southern Truckee Meadows and thus is a discharge region for both thermal and non-thermal waters (Lyles, 1985). Similarities in water chemistry characteristics and decreases in hydraulic head at monitoring wells suggest that the fractured bedrock geothermal reservoir and alluvial aquifer are hydrologically connected within a regional scale flow system (Sorey and Colvard, 1992). Isotope data have been used to delineate possible recharge areas in the Steamboat Hills area. Oxygen and hydrogen isotope data show that hot-spring waters from Steamboat Springs are enriched in ^{18}O due to high-temperature (140–230°C) rock–water interaction; however, deuterium values for the hot-springs water match values for present-day precipitation falling at elevations near 2100 m in the Carson Range (Nehring, 1980).

Production testing at both facilities indicates that flow of thermal water is fracture controlled. van de Kamp and Goranson (1990) postulate two geothermal systems within the Steamboat Hills: a high temperature system (220°C) tapped by CPI wells with a maximum depth of 760 m (elevation of 915 m above mean sea level [amsl]), and a moderate temperature system (170°C) tapped by SBG with depths between 122 and 213 m (elevations between 1220 m and 1430 m amsl). Sorey and Colvard (1992) and Mariner and Janik (1995) postulate a single geothermal reservoir that supplies thermal water to both plants.

Thermal and non-thermal waters are chemically distinct in the Steamboat Hills area. Thermal waters are characterized by: temperatures greater than 20°C; total dissolved solids concentrations up to 2200 mg/l; elevated concentrations of arsenic (As), boron (B), and chloride (Cl); and a uniform Cl/B ratio of about 20 (White, 1968; Bateman and Scheibach, 1975). Cl, which is assumed to act as a conservative tracer in groundwater, is characteristically found at higher concentrations in thermal water relative to non-thermal water. Concentrations of Cl in flashed thermal water range from 800 to 900 mg/l (Goranson, 1991; DeRocher, 1996), whereas concentrations in non-thermal water are generally less than 3 mg/l (Cohen and Loeltz, 1964).

3. Methods

Data compiled by Washoe County (available from the third author, M.C. Widmer, upon written request) from SBG and CPI reports and data from Nehring (1980), Ingraham and Taylor (1991), and Mariner and Janik (1995) were used for this study. Wells selected to represent non-thermal, thermal, and mixed waters (Fig. 2) were evaluated by assessing the temporal variations in B and Cl concentrations, water-levels, temperature, and by calculating the percentage of thermal water in alluvial wells located in the discharge area of the geothermal system. Available well log data (Washoe County internal files) and mapped faults (Tabor and Ellen, 1975; Bonham and Rogers, 1983; Bonham and Bell, 1993) were used to assess groundwater flow paths and the possible hydrologic connections between the fractured bedrock geothermal system and the alluvial aquifer.

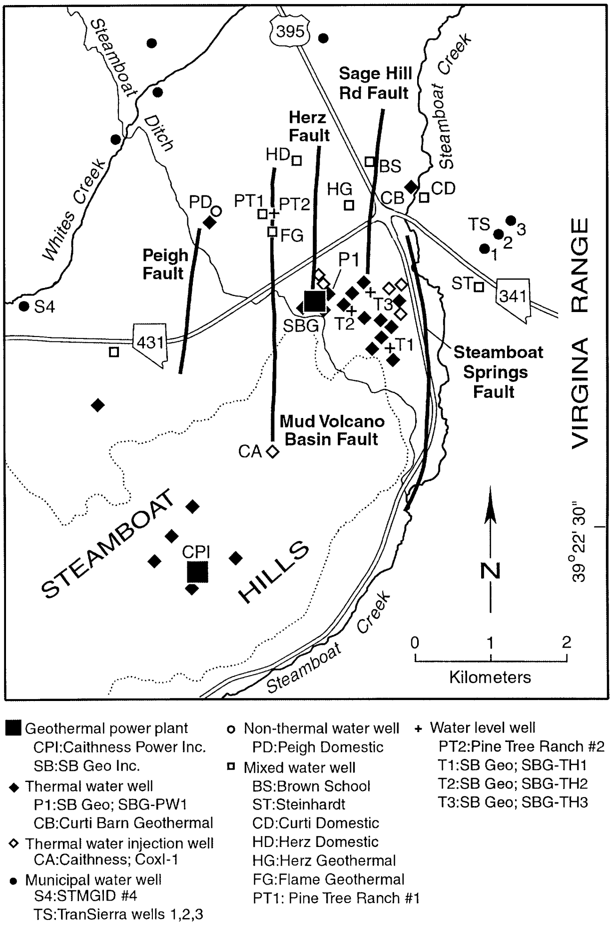

Fig. 2. Study area location map. Thermal, non-thermal, mixed water, and water level wells and hydrologically significant faults referenced in this study are labeled.

4. Results

Completion details for wells evaluated in this study are provided in Table 1. A summary of available water chemistry for the study wells is presented in Table 2. The summary includes minimum and maximum temperature and B and Cl concentrations, date of the maximum value of each, factor of increase from minimum to maximum, and the range of sampling dates.

The B versus Cl data from the current work, Nehring (1980), Ingraham and Taylor (1991), and Mariner and Janik (1995), are plotted on Fig. 3. These data represent cold waters (springs, creeks, snowmelt, non-thermal wells: Nehring, 1980; Ingraham and Taylor, 1991; and Washoe County data reported here), non-thermal domestic and municipal wells, domestic wells with mixed non-thermal and thermal water, and

Table 1
Completion details for selected wells in Steamboat Hills, Nevada

Well name	Date drilled	Well elevation (m)	Total depth (m)	Screen interval (m)	Seal depth (m)	Water depth[a] (m)	Water temperature[a] (°C)
Brown School	NA[c]	1384	116	NA	NA	NA	NA
CoxI-1	1980	1538	1058	538–1058[b]	538	116	182
Curti Barn Geothermal	1982	1379	79	55–74	15	6	102
Curti Domestic	1982	1379	29	24–29	24	5	54
Herz Domestic	1955	1399	34	12–34	NA	9	Cold
Herz Geothermal	NA	1402	47	NA	16	NA	57
Flame	NA	1412	30	NA	NA	11	NA
Peigh Domestic	1959	1442	44	16–26	NA	18	Cold
Peigh Pool Geothermal	1970	1442	70	OB[d]	24	27	115
Pine Tree Ranch No. 1	1971	1415	34	18–32	14	17	43
Pine Tree Ranch No. 2	1959	1414	133	OB	38	16	Hot
SBG-PW1	1985	1438	192	181–192	181	9	165
SBG-TH1	1991	1420	272	169–272[b]	169	15	164
SBG-TH2	1991	1423	262	183–262[b]	183	19	163
SBG-TH3	1991	1414	277	201–277[b]	201	20	163
STMGID No. 4	1981	1570	253	213–253	33	150	Cold
Steinhardt	1979	1402	41	33–41	16	23	Cold
TranSierra 4	1970	1391	57	55–57	15	20	Cold

[a] Following well completion.
[b] Open hole interval.
[c] NA: not available.
[d] OB: open at bottom.

geothermal production wells (Mariner and Janik, 1995 and current work). The majority of data fall along the same linear trend suggesting simple mixing of thermal and non-thermal waters and indicate a common source fluid for the thermal waters produced at both power plants. These data suggest a single geothermal system for Steamboat Hills as postulated by Sorey and Colvard (1992) and Mariner and Janik (1995). Subsequent B versus Cl plots include this local mixing trend line. For the purpose of this study, the data from the CPI wells are assumed to represent the geothermal reservoir water.

Temporal plots of B versus Cl for wells screened in the alluvial aquifer show that the waters are either non-thermal (e.g. Peigh Domestic well, Fig. 4a,), thermal (e.g. Curti Barn Geothermal well, Fig. 4b), or of mixed (e.g. Herz Geothermal well, Fig. 4c) water chemistry. These results show no temporal variation and thus can be used as type members for comparison with other wells. Based on these data, the Herz Geothermal well has mixed type water chemistry that has not varied appreciably over time.

Table 2
Summary of chemistry data from study wells in Steamboat Hills, Nevada

	Brown School	Curti Barn Geothermal	Curti Domestic	Flame	Herz Domestic	Herz Geothermal	Peigh Domestic	Pine Tree Ranch No. 1	Steinhardt
Temperature (°C)									
Minimum	15	35	21	44	3	49	26	33	32
Maximum	42	54	37	59	31	55	42	48	34
Maximum date	Sep-98	Sep-98	Sep-97	Dec-87	Sep-94	Aug-89	Dec-98	Jun-90[b]	Jun-92
Factor increase	2.8	1.5	1.8	1.3	10.3	1.1	1.6	1.5	1.1
Boron (mg/l)									
Minimum	0.1	32	1.6	6.9	0.1	1	0.1	0.1	5.6
Maximum	40.5	41.1	16.7	25.7	4.5	19	0.3	4.9	13
Maximum date	Jun-94	Jun-97	Jun-97	Jun-90[b]	Jun-93	Oct-89	Sep-97[c]	Jul-89	May-87[a]
Factor increase	405.0	1.3	10.4	3.7	45.0	19.0	3.0	49.0	2.3
Chloride (mg/l)									
Minimum	3	660	43	112	1	184	1	2	130
Maximum	743	844	317	485	297	390	15	94	300
Maximum date	Sep-96	Mar-96	Mar-93	Jun-90[b]	Dec-92	Jul-89	Sep-97	Jun-90[b]	May-87[a]
Factor increase	247.7	1.3	7.4	4.3	297.0	2.1	15.0	47.0	2.3
Range of dates									
Beginning	Dec-84	May-87	May-87	Dec-84	Dec-84	Dec-84	Dec-84	Dec-84	May-87
Ending	Dec-98	Sep-98	Dec-98	Jun-90	Dec-94	Jun-93	Dec-98	Jun-90	Jun-92

[a] First data point collected from the well.
[b] Last data point collected from the well.
[c] Data fluctuate; maximum attained on more than one date.

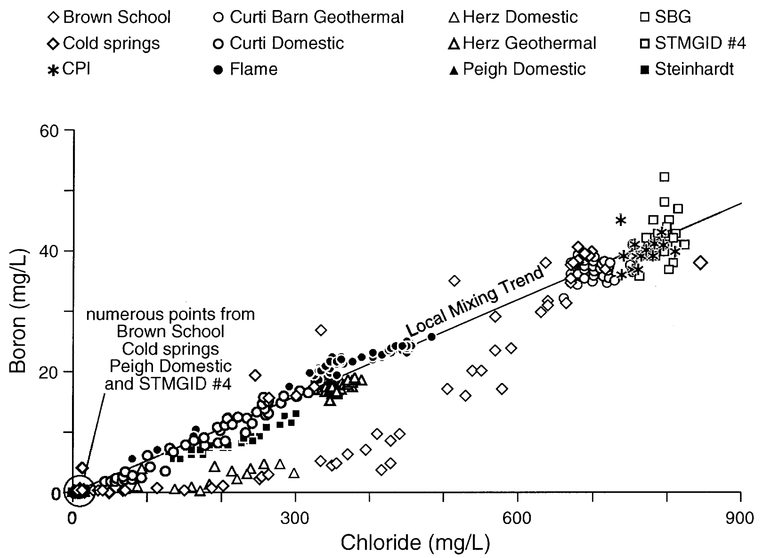

Fig. 3. Boron vs Cl for various water types in the Steamboat Hills area, Nevada. Local mixing trend is from the origin to maximum B/Cl concentration represented by the CPI/SBG geothermal production data. This local mixing trend is included on subsequent B versus Cl plots. Data for Cold Springs, Peigh Domestic, and STMGID No. 4 plot near the origin but are hidden under other symbols.

The temporal variation of B versus Cl for the Curti Domestic well shows a steady trend from non-thermal to mixed type water in 1988, with the maximum occurring in 1993, and with large variability during 1990 and thereafter (Fig. 5a). The Flame well also shows a steady trend from predominantly non-thermal water in 1985 to mixed type water chemistry through the last sampling date in June 1990 (Fig. 5b). The Pine Tree Ranch No. 1 well shows a similar trend (Fig. 5c) to the Flame well (i.e. trend from non-thermal water in 1985 to mixed type water chemistry in June 1990); however, the maximum concentrations in the Pine Tree Ranch No. 1 well are approximately 20% of the maximum concentrations in the Flame well. The Steinhardt well exhibits the opposite B versus Cl variation, trending from mixed water in 1987 toward non-thermal type water chemistry through 1992 (Fig. 5d). The mixing trend at each of these wells follows the local mixing trend for the study area.

Cl vs B concentrations in the Herz Domestic well illustrate three distinct mixing trends (Fig. 6a). The Brown School well shows the same three trends but with greater definition due to higher concentrations and greater variability through time (Fig. 6b). The first trend shows significant increases in Cl with only slight increase in B through 1991 for the Herz Domestic well and through 1989 for the Brown School well. The second trend shows B and Cl variations trending toward the thermal type water signature through 1992 (Herz Domestic well) and through 1996 (Brown School well). The 1996 Cl and B concentrations in the Brown School well are nearly identical to the thermal type water found in CPI wells. The third trend is defined by decreasing B and Cl concentrations through the last sampling date of 1994 (Herz Domestic well) and 1998 (Brown School well). The mixing trends observed for these two wells with respect to B adsorption and the proximity to faults are discussed below.

Water levels from 1985 to 1998 in domestic wells and geothermal reservoir monitoring wells are shown in Fig. 7. The Herz Geothermal well shows relatively consistent water levels whereas other wells show declining water levels through 1995, with distinct water-level increases in all eight wells between 1995 and 1998. Seasonal fluctuations are evident in the Pine Tree Ranch No. 1 and Steinhardt wells. Water levels were measured from the Pine Tree Ranch No. 2 well rather than the Pine Tree

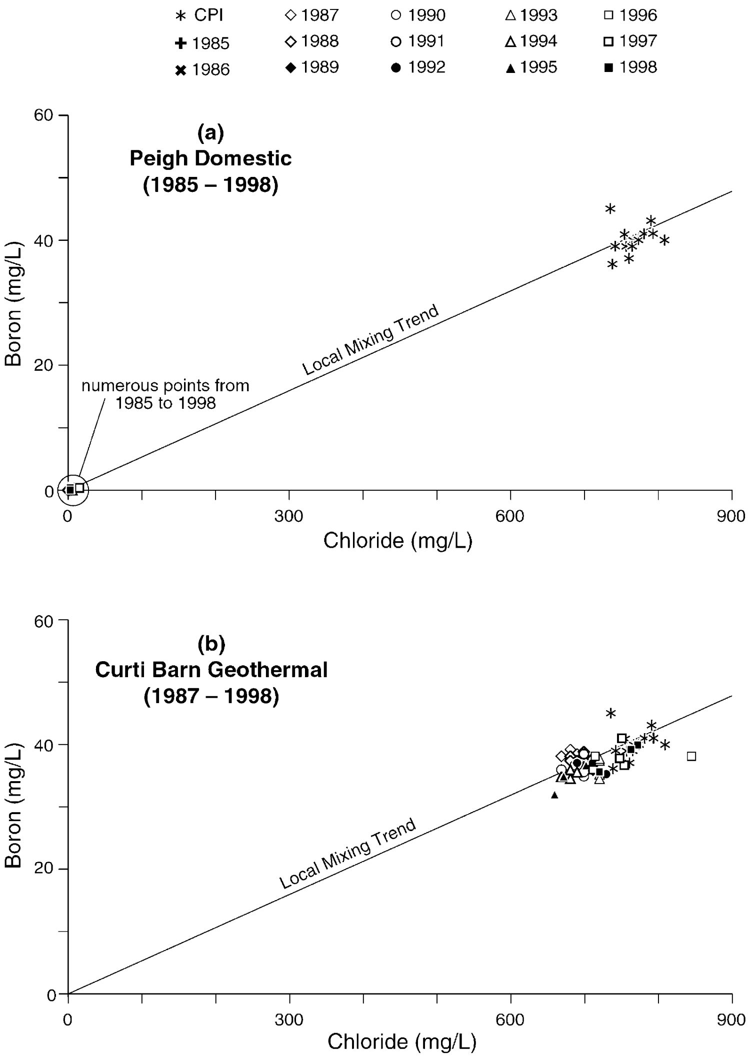

Fig. 4. Boron vs Cl over time for each well with consistent water chemistry. (a) Peigh Domestic well shows non-thermal type water chemistry. (b) Curti Barn Geothermal well shows thermal type water chemistry. (c) Herz Geothermal well shows mixed type water chemistry (*continued on next page*).

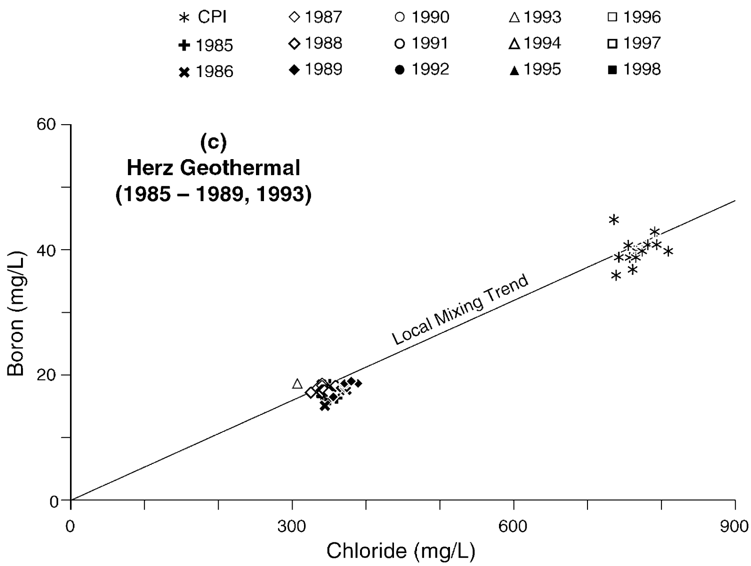

Fig. 4 (*continued*).

Ranch No. 1 well beginning in September 1996. Water levels for these wells were similar following well completion (see Table 1) and appear consistent following September 1996.

Water temperatures over time for alluvial aquifer wells are shown in Fig. 8. The higher temperature wells (Curti Barn Geothermal, Flame, Herz Geothermal) generally range from 40 to 60°C. Consistent temperatures between 49 and 53°C occur in the Herz Geothermal well. Low temperatures (3–30°C) occur in the Brown School, Curti Domestic, and Herz Domestic wells with strong seasonal fluctuations exhibited in the Brown School and Herz Domestic wells. After 1990, temperatures steadily increased in the Brown School well to 42°C in September 1998, and in the Curti Domestic well to 37°C in September 1997. Temperatures in the Pine Tree Ranch No. 1 well also show seasonal variation with a range from 33°C in January 1985 to 48°C in June 1990 (last measurement date). The Peigh Domestic and Steinhardt wells show relatively consistent temperatures of 30–40°C.

5. Discussion

Regional groundwater flow in the alluvial and fractured volcanic rock aquifer is generally toward the northeast. The general flow direction in the geothermal reservoir system is also toward the northeast; however, the flow of thermal fluids is strongly controlled by faults, so that local directions of flow can vary greatly. The degree of non-thermal and thermal water mixing at a particular well is highly dependent on the location of the well with respect to faults. In some areas vertical flow is important and evaluation of relative well depths and subsurface geology is discussed. The discussion is based on the following three groups of wells: (1) wells showing no temporal variability, (2) wells showing local mixing, and (3) wells showing mixing associated with B adsorption. The final section discusses mixing in the discharge area.

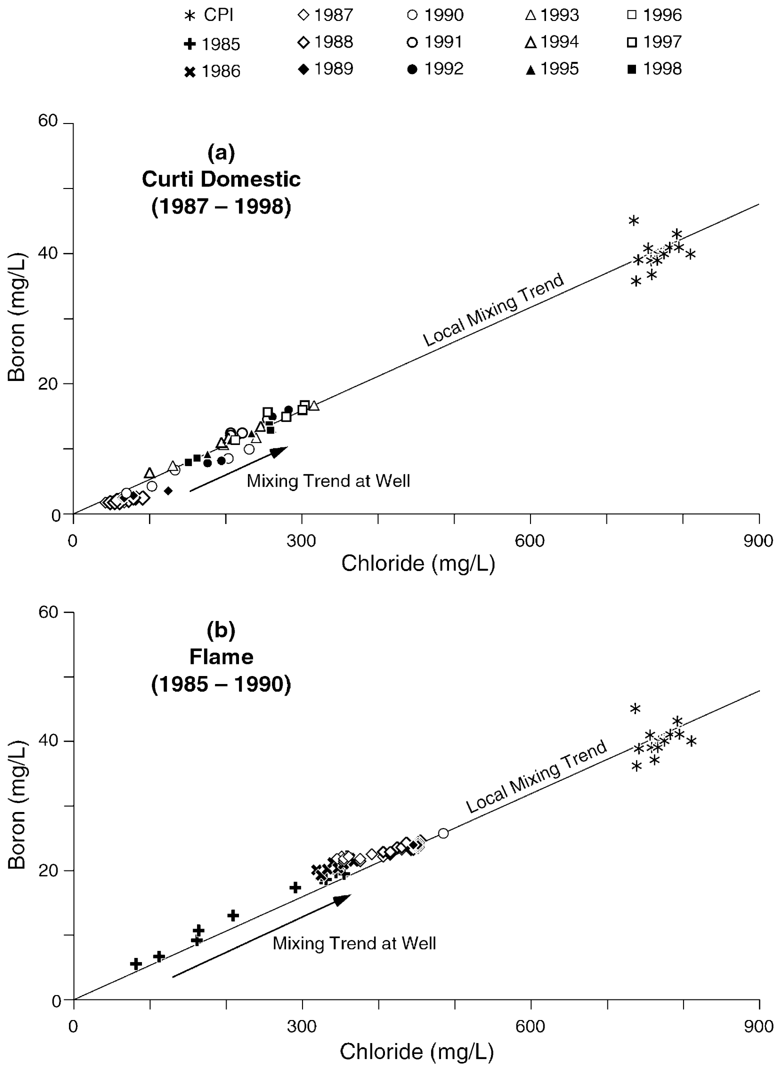

Fig. 5. Boron vs Cl over time for each well shows mixing with time along the local mixing trend. (a) Curti Domestic well shows trend from non-thermal to mixed type water chemistry (increased thermal component). (b) Flame well shows a trend from non-thermal to mixed type water chemistry. (c) Pine Tree Ranch No. 1 well shows increased mixing to a lesser degree than the nearby Flame well. (d) Steinhardt well shows a trend from mixed to non-thermal type water chemistry (decreased thermal component) (*continued on next page*).

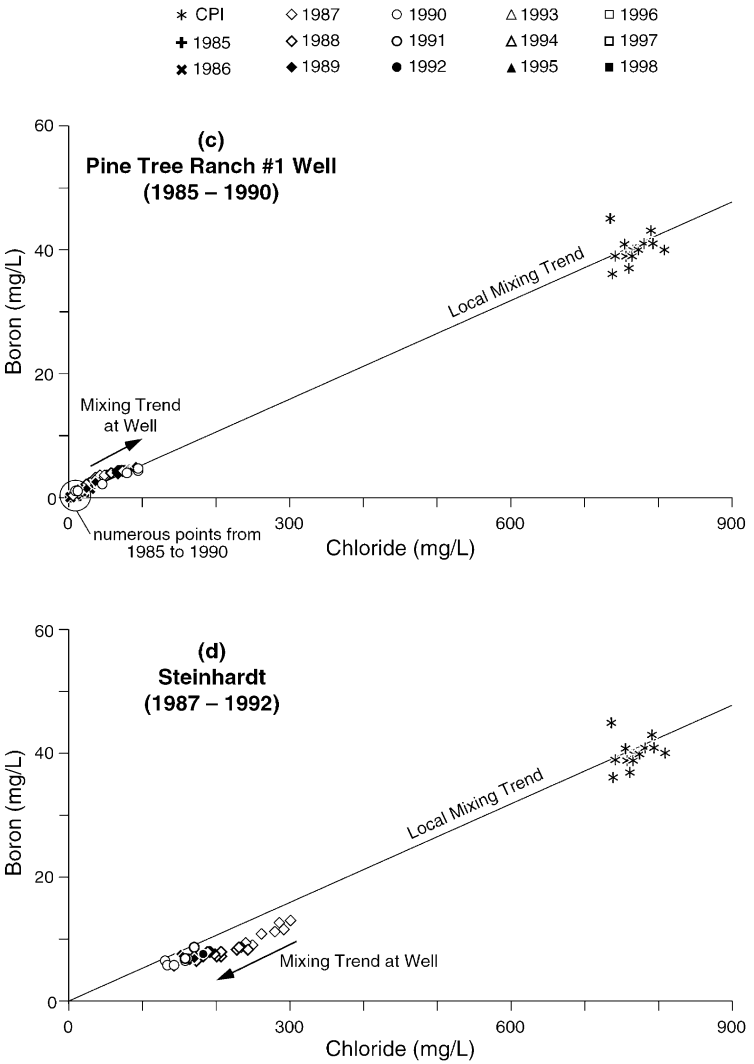

Fig. 5 (*continued*).

5.1. Wells showing no temporal variability

The Peigh Domestic well is located adjacent to a north-trending unnamed fault (Peigh Fault for the purpose of this paper) mapped entirely within the alluvial fan (Bonham and Rogers, 1983). The fluid chemistry for this well indicates that it contains non-thermal water, yet the temperature of this water is warm (26–42°C) relative to other domestic wells. This suggests a nearby thermal source may heat non-thermal water conductively, without any accompanying mixing of thermal water. The Peigh Domestic well is screened from 16 to 26 m below ground surface (bgs) in

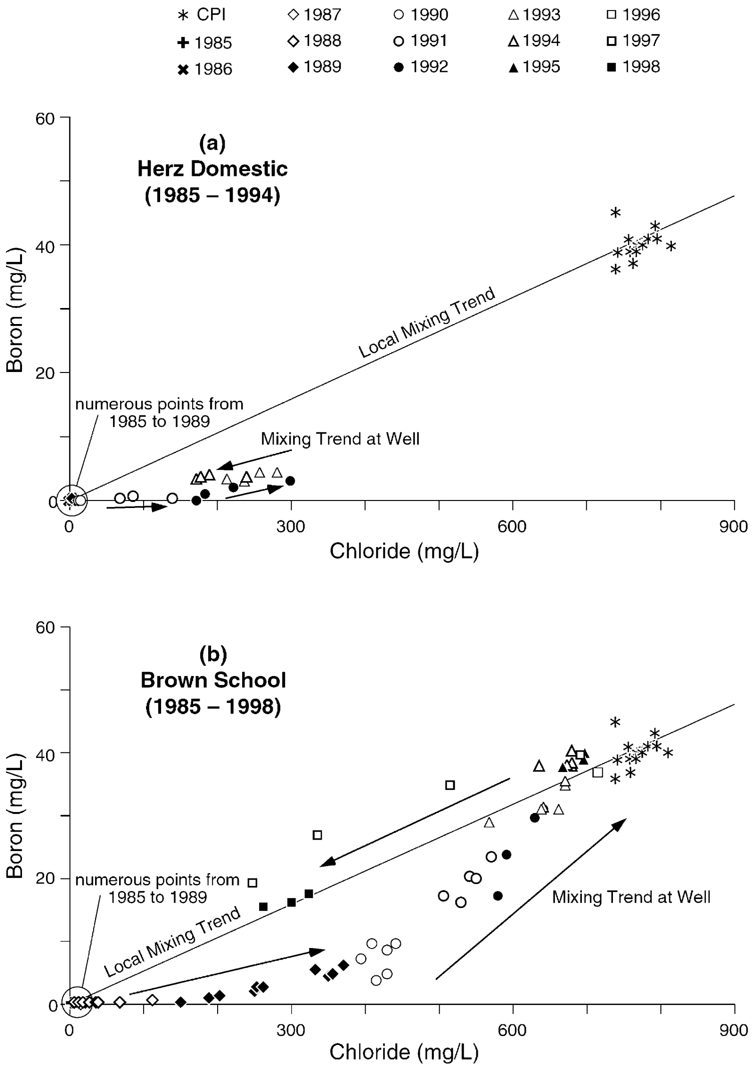

Fig. 6. Boron vs Cl over time for each well where mixing may indicate boron adsorption onto clays in the alluvial aquifer. (a) Herz Domestic well shows increasing chloride concentrations with minimal change in boron concentrations. (b) Brown School well shows multiple mixing trends, suggesting temperature-

alluvial gravel, which is underlain by approximately 8 m of clay and the fractured volcanic bedrock (Fig. 9a). The nearby Peigh Pool Geothermal well, with temperatures between 110 and 115°C, is cased to a depth of 70 m bgs with an open bottom in fractured bedrock. The log for this well indicates that approximately 12 m of clay was encountered between the alluvial gravel and the fractured bedrock (Fig. 9a). The clay layer in this area appears to function as an aquitard limiting vertical fluid

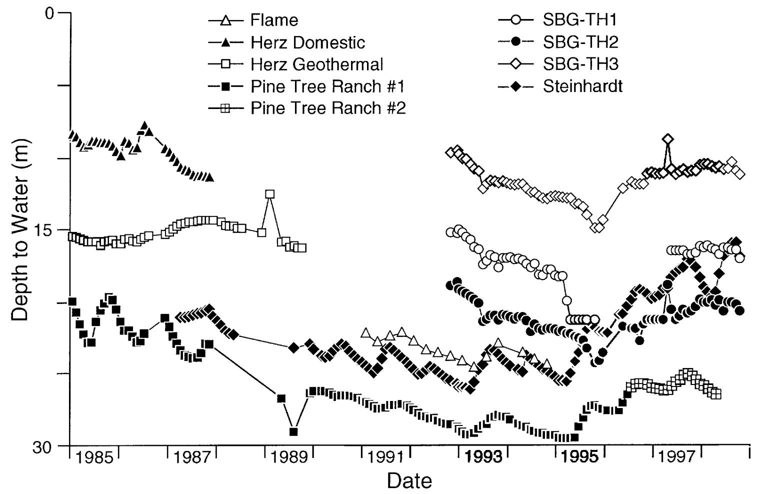

Fig. 7. Water levels over time for alluvial aquifer wells and geothermal reservoir monitoring wells.

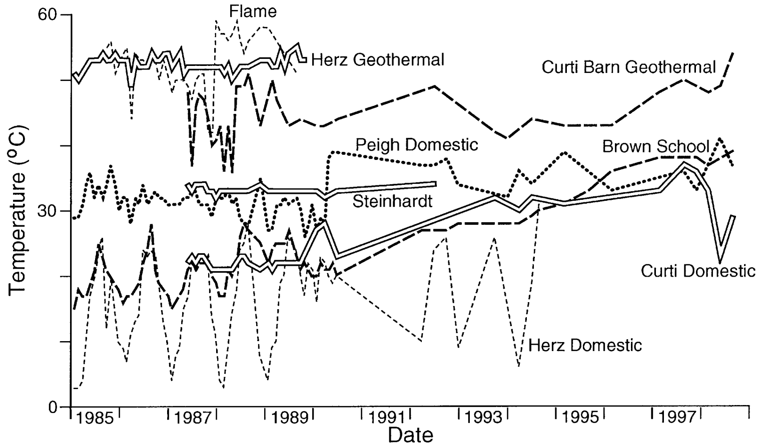

Fig. 8. Temperature over time for alluvial aquifer wells.

mixing in this area but may allow thermal conduction to produce the elevated temperatures observed in the Peigh Domestic well.

The Herz Geothermal well is located between the north-trending Herz Fault and Sage Hill Road Fault (Yeamans, 1988) as shown in Fig. 2. The southern extent of these two faults is coincident with SBG injection wells IW-1 and IW-2. The Herz Geothermal well exhibits remarkably consistent B and Cl data of mixed type water chemistry as well as consistent temperature and water level data over time. These relationships suggest that the proportion of non-thermal to thermal water has not varied at this location.

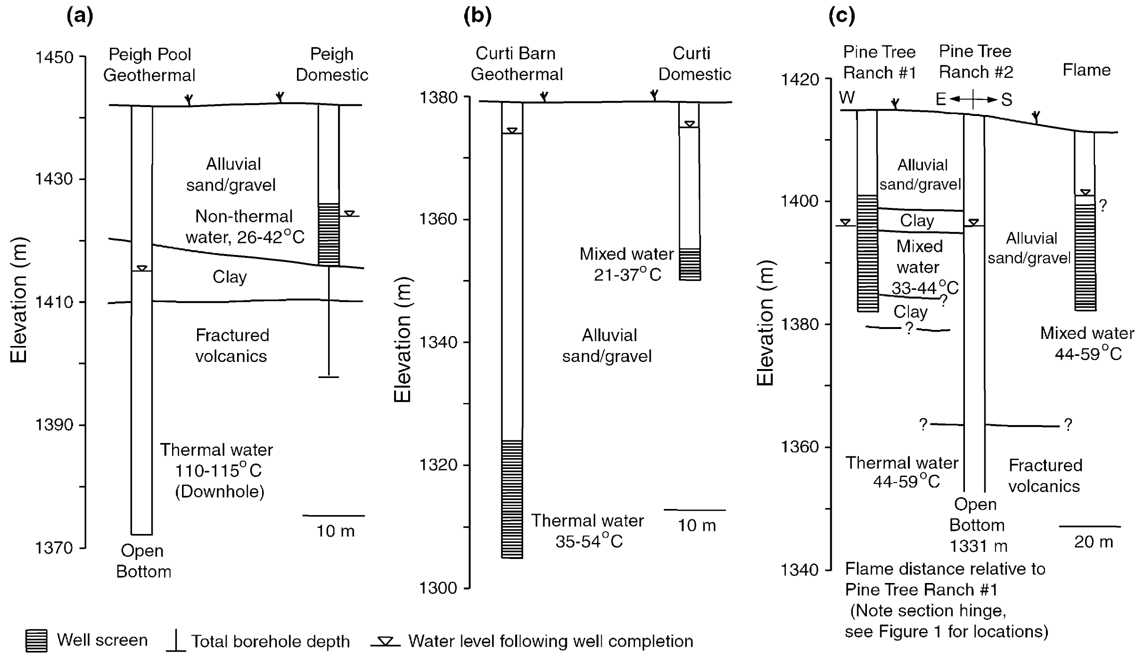

Fig. 9. Cross sections of local geology, well completion details, water chemistry type and water temperatures. Temperature for Peigh Pool Geothermal well was measured downhole; temperatures for other wells measured from samples. (a) Peigh Domestic and Peigh Pool Geothermal wells. (b) Curti Domestic and Curti Barn Geothermal wells. (c) Pine Tree Ranch Nos. 1 and 2 and Flame wells. Note: horizontal distances between wells are from the well centers and well diameter is not to scale.

The Curti Barn Geothermal well is located northeast of the SBG production field within the discharge area of the geothermal system. The Curti Barn Geothermal well, screened within the alluvial aquifer from 55 to 74 m bgs (Fig. 9b), exhibits nearly constant thermal type water chemistry and relatively consistent temperatures, generally above 40°C. These data suggest that the lower portion of the alluvial aquifer is in direct connection with thermal water leaking from the geothermal reservoir. The characteristics of the upper portion of the alluvial aquifer are illustrated through the results of the Curti Domestic well, as discussed in the following section.

5.2. *Wells showing local mixing*

The Curti Domestic well is screened from 24 to 29 m bgs and is located within 30 m of the Curti Barn Geothermal well (Fig 9b). Temperature data are consistent with B and Cl data, indicating an increased component of thermal water beginning in 1990. The B and Cl data indicate that mixing for this well is coincident with the local mixing trend, suggesting a direct hydraulic connection with the geothermal system. The chemistry data suggest that an upward vertical hydraulic gradient within the alluvial aquifer may produce mixing in the Curti Domestic well; however, no water level data are available to confirm this hypothesis. The dynamics of mixing in this geothermal discharge area will be further discussed in a following section.

The Flame well is located along the northern portion of the north-trending Mud Volcano Basin Fault (Fig. 2). The B versus Cl temporal variation along the local mixing trend suggests a direct connection with the geothermal reservoir, with steadily increasing inputs of thermal water to this well from 1985 to 1990. No data are available from the Flame well after 1990. Well completion information is not available for the Flame well; however, Yeamans (1988) reported that the well is thought to be completed with a similar total depth to the nearby Pine Tree Ranch No. 1 well, which has a total depth of 30 m (Fig 9c). Thus, the Flame well is likely completed in the alluvial aquifer. The Flame well illustrates that migration of geothermal water occurs along a permeable fault. The CPI Cox I-1 geothermal injection well, situated near the southern extent of the Mud Volcano Basin Fault, was likely installed to utilize the permeable nature of this fault. The Cox I-1 injection well was completed in May 1981 and began accepting thermal fluid in May 1987.

The Pine Tree Ranch No. 1 well is located approximately 30 m west of the Pine Tree Ranch No. 2 well and approximately 60 m north of the Flame well (Figs. 2 and 9c). The Pine Tree Ranch No. 2 and the Flame wells are both located within the trace of Mud Volcano Basin Fault, so that the Pine Tree Ranch No. 1 well is located approximately 30 m from this fault. The Pine Tree Ranch No. 1 well is screened from 18 to 32 m bgs within the alluvial aquifer while the Pine Tree Ranch No. 2 well has an open bottom at 133 m bgs within the fractured volcanics. Historical sampling has not been conducted for the Pine Tree Ranch No. 2 well but recent sampling indicates thermal water in this well. The B and Cl variation for the Pine Tree Ranch No. 1 well is along the local mixing trend, indicating a direct connection with the geothermal reservoir; however, the B and Cl concentrations are less than those in the

Flame well. This decrease of B and Cl concentrations with distance from a fault suggests that most of the geothermal fluid flows along the permeable fault rather than through the matrix of the geothermal reservoir. Mixing of thermal and non-thermal water is greatest in close proximity to a permeable fault and thermal water characteristics decrease with distance from the fault.

The Steinhardt well is located east of the SBG production field on the opposite side of the north-trending Steamboat Springs fault system. This fault system is spatially coincident with historical hot springs and is likely a zone of upward vertical groundwater flow. The declining B versus Cl temporal trend in the Steinhardt well indicates a decrease in the thermal water component that is consistent with the decline in hot spring activity. Clearly, less thermal water migrates across this fault system after 1987. In addition, cessation of Washoe County production from nearby Trans Sierra 1, 2, and 3 wells in 1985 (Washoe County internal files) could have contributed to the observed decrease in B and Cl concentrations. Reduced production by Washoe County may have resulted in more non-thermal water and initiation of production at the power plants may have resulted in less thermal water available for mixing. Relatively constant temperatures for this well do not provide any corroborative evidence for changes in the amount of thermal and non-thermal water inputs to this area.

5.3. *Wells showing mixing associated with boron adsorption*

The Brown School well is located approximately 50 m west of the north-trending Sage Hill Road Fault, whereas the Herz Domestic well is situated between the north-trending Herz Fault and Mud Volcano Basin Fault approximately 250 m from each fault (Fig. 2). As discussed above, the greater changes in B and Cl concentrations at the Brown School well compared to those at the Herz Domestic well could be a result of its closer proximity to a north-trending fault. The mixing trends observed in these two wells may result from B adsorption on clays in the alluvial aquifer as fluids flow away from the faults into the porous media of the alluvial aquifer. The B and Cl concentrations observed in other wells plot along the local mixing trend line; however, the first mixing trend observed at the Herz Domestic and Brown School wells clearly shows that B is retarded relative to Cl. This trend suggests that clays in the alluvial aquifer may adsorb B.

The second mixing trend observed after 1989 (Brown School well) and after 1991 (Herz Domestic well) may represent desorption of B from clays as a result of increasing temperature, or decreased adsorption of B on clays in the alluvial aquifer. The period of dates over which this second mixing trend occurs is coincident with increasing temperature in the Brown School well. Goldberg et al. (1993) have demonstrated that B adsorption on clays in soil decreases with increasing temperature. However, data for the Herz Domestic well do not conclusively show an increase in temperature for this time period. An alternative interpretation could be decreased adsorption of B on clays in the alluvial aquifer. Vengosh and Keren (1996) found delayed arrival times of B relative to Cl migrating vertically through the unsaturated zone and suggested that cation-exchange reactions might control ion transport in groundwater. These authors conclude that once exchangeable and adsorbed sites are filled, B is no longer adsorbed and behaves conservatively like Cl.

The third mixing trend, illustrated best by the Brown School well, shows the B and Cl variation following the local mixing trend, which suggests that both ions are behaving conservatively. The decrease in concentrations is coincident with alluvial aquifer water level recovery in the study area and suggests that more non-thermal water is available for mixing.

5.4. Discharge area mixing

The close proximity of the Curti Domestic and Curti Barn Geothermal wells, located in the discharge area of the geothermal system, allows for evaluation of mixing relationships. The factor increase (Table 2) for each constituent (except for As) of the Curti Barn Geothermal well is nearly identical with the temperature factor increase, suggesting a clear, uncomplicated mixing relation between thermal and non-thermal water. Because As concentrations are low, slight variability in As concentrations can lead to high variability in the factor increase. The Curti Domestic well shows an identical temperature factor increase to that of the Curti Barn Geothermal well but with greater and variable increases for each constituent, suggesting non-thermal and thermal water mixing in this well. Since Cl acts conservatively in groundwater, the Cl concentration can be used to calculate the percentage of thermal water in the Curti Domestic well over time (Fig. 10). The percent of thermal water for each sample date was calculated assuming a constant non-thermal Cl concentration of 3 mg/l (average concentration in Peigh Domestic well) and the Cl concentration in the Curti Barn Geothermal well (660–844 mg/l). The percentage of thermal water in the Curti Domestic well ranges from 6 to 44%, with a peak value in March 1993. A strong seasonal trend is evident with lower thermal input in the fall and greater percentages of thermal water in the spring. This trend shows an inverse relationship between groundwater recharge of non-thermal water and the percentage of thermal water in the Curti Domestic well. More non-thermal water is available for

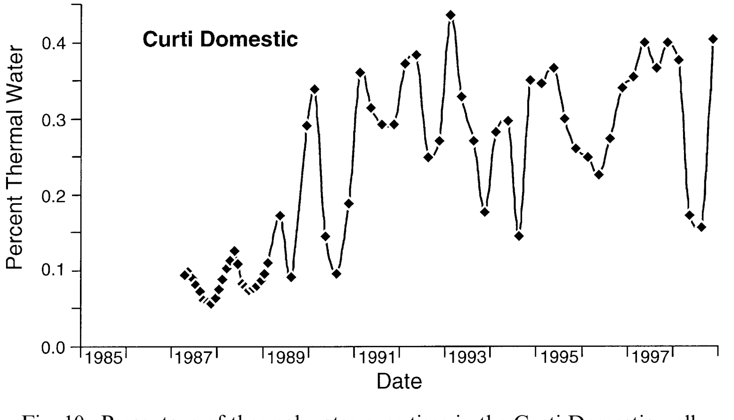

Fig. 10. Percentage of thermal water over time in the Curti Domestic well.

mixing in the fall due to groundwater recharge from irrigation in surrounding agricultural fields over the summer months. A similar relation between Cl and static water levels was attributed to groundwater recharge from irrigation (Yeamans, 1985). The overall trend shows an increase in the thermal water component over time, suggesting that more thermal water is available due to shallow injection of spent fluid at geothermal power facilities.

6. Conclusions

B and Cl data for non-thermal, thermal, and mixed type waters fall along a common trend suggesting simple mixing of thermal and non-thermal waters and a common source of thermal water for both power plants. Three wells (Peigh, Curti Barn Geothermal, Herz Geothermal) show consistent B and Cl values over time. These wells represent type members of non-thermal, thermal, and mixed waters that are used for comparison with other wells. Temporal B versus Cl trends show strong mixing in the geothermal discharge area and along prominent north-trending faults (e.g. Herz Fault and Mud Volcano Basin Fault) that apparently connect the geothermal reservoir to the alluvial aquifer. Temperature and water level data provide supporting evidence for the timing of the mixing. Potential mechanisms for the initiation of changes in the proportions of thermal and non-thermal waters include: (1) increased groundwater extraction from alluvial aquifers for municipal water supply, thus reducing the available non-thermal component (eg. Herz Domestic and Pine Tree Ranch No. 1 wells); (2) water level declines because of decreased recharge due to reduced irrigation and below normal precipitation from 1986–1994, also reducing the available non-thermal component (eg. Herz Domestic and Pine Tree Ranch No. 1 wells); and (3) injection of thermal waters in geothermal reservoir areas that may have greater connectivity to the alluvial aquifers than the extraction areas, increasing the thermal water component (e.g. Curti Domestic and Flame wells). Comparison of the Pine Tree Ranch No. 1 well with the Flame well illustrates that the amount of thermal water decreases with distance from a permeable fault. The Steinhardt well shows reduced thermal water component with time; cessation of municipal production of non-thermal water has likely increased the percentage of non-thermal water in the area. The calculated percent of thermal water in the Curti Domestic well in the geothermal discharge area shows a strong inverse relation with seasonal groundwater recharge (maximum recharge in the fall). The geothermal reservoir and the alluvial aquifer are hydraulically connected in at least some portions of the study area and fault-controlled flow apparently provides the connectivity.

Based on data discussed here, a number of faults that conduct thermal fluids from the geothermal system to the alluvial aquifer have been identified. Wells located near these faults respond to hydrologic changes to a greater degree than wells located between faults. Further delineation of these hydrologically significant faults, and identification of others, will allow for a better understanding of the connectivity of these two resources.

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