

Hydrogeologic Investigation of the Ojo Caliente and Chise Warm Springs of the Winston Graben, Rio Grande Rift, New Mexico

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ABSTRACT

The Winston graben in the western Rio Grande rift of south-central New Mexico features two low-temperature warm springs discharging along the eastern basin margin and within the Sierra Cuchillo horst. Aside from the known location of the warm springs, the hydrogeology controlling the thermal manifestations is poorly characterized. Here we develop a conceptual model for the hydrothermal system in the Winston graben integrating geologic, aqueous geochemical, and temperature gradient datasets. Geologic mapping shows structural trends as well as extensive fracture networks developed around the warm springs that affect groundwater movement; both springs discharge from fractured bedrock buried beneath basin fill. Temperature gradient data and heat flow values reveal significant thermal anomalies around the warm springs. Furthermore, a shallow outflow plume emanating from a buried horst has been identified at Ojo Caliente. Both warm springs have high TDS and Cl/Br ratios that are distinct from non-thermal waters sourced from basin fill, however mixing has been identified in some samples. Stable-isotope data in water from Ojo Caliente warm spring indicate a meteoric source recharging at higher elevation and lower temperature than the spring. The resource temperature is estimated to be 60-65°C with good agreement between low temperature geothermometers and mineral speciation models.

Introduction

Low temperature hydrothermal systems in the southern Rio Grande rift (RGR) are common and have potential for greater exploitation of direct use (Witcher, 1988; Fleischmann, 2006), yet their occurrence is poorly understood. The RGR is the easternmost expression of continental extension in the western US. The province is characterized by high heat flow (75-100mW/m²) (Reiter et al., 1975; Reiter and Chamberlin, 2011) and structural

complexity, much like the Great Basin. The RGR consists of normal-fault-bound basins filled with sediments of the Santa Fe Group (Hawley et al., 1969). The basins are segmented by fault termini at structural margins marked by both antithetic/synthetic accommodation zones and transfer zones (Faulds and Varga, 1998). Early authors attributed the expression of hydrothermal systems in the RGR to intersection of mid-Cenozoic caldera ring-fracture zones with extensional faults (Chapin et al., 1978; Elston, 1981; Elston et al., 1983). Later works studying the hydrogeology of these systems showed that discharge can be described in terms of two end-member models: the constriction and hydrologic window models. The “constriction model” describes forced convective upwelling on the downstream end of a rift basin through accommodation zone structures and basin-fill sediments (Harder et al., 1980; Morgan et al., 1981). The “hydrologic window model” presented by Witcher (1988) involves upflow through fractured bedrock; permeability in the windows is enhanced by tectonic uplift, intrusion, and/or the erosion of confining units to create vertical flow in these zones. A combination of both models in which fractured permeable bedrock and hydrogeologic windows are located in the regional discharge zone of such rift basins seems to best explain many systems in the southern RGR.

The Winston graben hosts two hot springs discharging along fault zones, one, juxtaposing different Cenozoic volcanic units (Ojo Caliente spring complex), another juxtaposing Paleozoic sedimentary and Cenozoic volcanic units (Chise warm spring). Both springs are located within regional discharge zones and show signs of mixing of thermal and non-thermal waters. The Ojo Caliente complex discharges along the Red Paint Canyon fault zone, which separates the northern Winston graben from the Sierra Cuchillo and San Mateo Mountains, while the Chise warm spring discharges along the Montoya Canyon fault within the Sierra Cuchillo (Figure 1). We attempt to describe the hydrologic pathway of warm spring manifestations from the point of recharge using geochemical tracers and temperature gradient data. This study investigates the unique structural pathways necessary for upflow of hydrothermal fluids in similar structural and hydrologic settings in the RGR and the potential temperatures available for exploitation.

Background

The Winston graben (WG) is a N-S trending rift basin within the RGR physiographically defined by borders with the Plains of San Agustin, San Mateo Mountains, Sierra Cuchillo, Black Range, and Chise lineament (Figure 1). The Chise lineament is an accommodation zone/structural high coinciding with an alignment of late Cenozoic volcanic centers that separates the Winston graben from the Animas graben to the south (Harrison, 1992). The San Mateo Mountains, Black Range and Sierra Cuchillo are ranges surrounding the Winston graben and are comprised of Proterozoic metavolcanic and Paleozoic sedimentary rock overlain by a succession of Cenozoic volcanoclastic and volcanic units. The graben is filled with late-Cenozoic-to-Quaternary alluvial basin fill. Gravity data shows that the basin is deepest in the north with an asymmetric geometry bounded by a down-to-the-east master fault along its western margin; the basin is relatively thin and symmetric in the south (Koning, 2012; Gilmer et al., 1986; Cikoski and Harrison, 2012). The Red Paint Canyon fault is a down-to-the-west normal fault separating the northern Winston graben from the San Mateo Mountains. The fault is expressed in basin fill sediments as well as volcanic bedrock in the foothills of the San Mateo Mountains; its N-S trend projects to the western structural margin of the Sierra Cuchillo.

Three deformation events have affected the Winston area including pre-Cenozoic wrench faulting, Cenozoic volcano-tectonic faulting, and ongoing normal faulting associated with Rio Grande rift extension. These structures provide extensive fracture networks that serve as permeable pathways for fluid flow. Laramide-aged wrench faults are steeply dipping, dextral, NNE and WNW structures exposed in the Black Range that cut units up to the mid-Cenozoic. Volcano-tectonic structures that occur in varying orientations were formed during middle Cenozoic caldera formation. Extensional N-S structures that dip 70 to 90 degrees were formed during the opening of the RGR, forming the structural boundaries of the WG. The importance of structural control of thermal discharge is evident as both the Ojo Caliente complex and Chise warm spring discharge along structural zones within bedrock.

Hydrogeologic Framework

The Black Range and San Mateo Mountains are high elevation recharge areas with sufficient head to drive groundwater flow through the basin (Figure 2). Surface drainage patterns also follow this pattern. A groundwater divide in the central Winston graben separates flow into two drainage basins, the Alamosa Creek drainage to the north and the Cuchillo Negro drainage to the south (Figure 2). The Ojo Caliente complex is north of the drainage divide and is recharged from the Black Range and San Mateo Mountains. Chise warm spring is south of the drainage divide and is likely recharged from the Black Range; the Sierra Cuchillo may serve as a local recharge area.

Ojo Caliente

The Ojo Caliente complex is a series of springs that surface near the entrance to the Monticello Box, a canyon incised between the Sierra Cuchillo and San Mateo Mountains (Figure 1). Thermal fluids emerge along the Red Paint Canyon fault zone

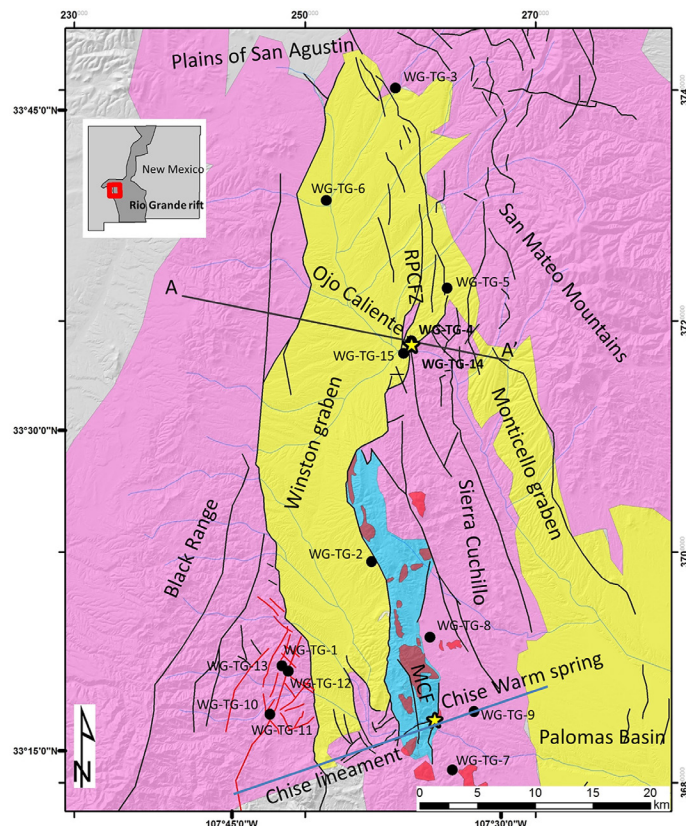


Figure 1. 1:350,000 scale map showing major physiographic and tectonic features of the study area: Plains of San Agustin, San Mateo Mountains, Sierra Cuchillo, Black Range, Monticello graben, Palomas Basin, Winston graben, Alamosa Creek (AC), Cuchillo Negro Creek (CNC), Chise lineament (Harrison, 1992). Red Paint Canyon Fault Zone (RPCFZ) (McLemore, 2010), and Montoya Canyon Fault (MCF) (Jahns et al., 2006). Black lines are normal faults related to rifting (Harrison, 1992), bold red lines are Laramide strike slip faults (Harrison, 1992). Inset map shows regional setting in the Rio Grande rift (RGR). Blue unit is Precambrian-Cretaceous metamorphic and sedimentary rocks, pink unit is Cenozoic volcanic rocks, red units are Cenozoic intrusions, yellow unit is Cenozoic/Quaternary basin fill.

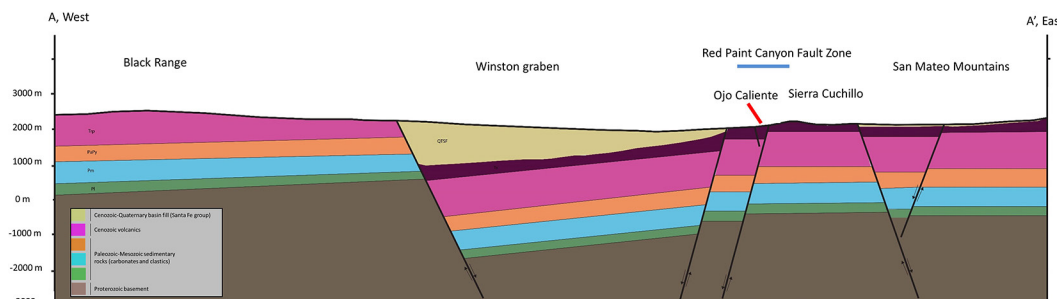


Figure 2. 1:100,000 scale East-west cross sections across the northern Winston graben through Ojo Caliente. Winston graben is asymmetric with a master fault on the western margin of the basin. The eastern boundary of the basin is marked by the Red Paint Canyon Fault zone, along which Ojo Caliente discharges. Groundwater recharging from the San Mateo Mountains may flow west towards the basin, then south towards Ojo Caliente in faults and fractures of the Red Paint Canyon Fault.

Chise

Chise warm spring is located within the Sierra Cuchillo and discharges along the N-S trending Montoya Canyon fault (MCF), which juxtaposes Paleozoic limestone and Cenozoic volcanic rock (Figure 1). Aerial photo mapping and historical photos of the Chise warm springs reveals a series of springs and seeps discharges into the Cuchillo Negro Creek; a sample from one spring was recorded at 30°C.

Methods

This study integrates new aqueous geochemical and hydro-geologic data with temperature-gradient data from the National Geothermal Data System (www.geothermaldata.org). Geochemical and hydrologic data were collected by the authors and New Mexico Bureau of Geology and Mineral Resources Aquifer Mapping program between 2010 and 2012. Temperature gradient and heat flow/thermal conductivity data as well as well discharge temperatures were compiled from unpublished industry data and Reiter et al. (1975).

A geographic representation of possible groundwater sources of the hydrothermal system were sampled through collection of waters in the recharge and interbasin areas (Figure 2). Water samples in the discharge area were collected to evaluate the relative contribution of thermal and non-thermal sources. Wells on the margins of the basin produce from fractured Cenozoic volcanic and Paleozoic sedimentary rocks, although the majority of wells in the study area produce from Santa Fe Group basin fill and Quaternary alluvium. Major and trace ion chemical analyses were measured at the New Mexico Bureau of Geology and Mineral Resources Analytical Chemical Laboratory. Precipitation collectors were placed in the Black Range, San Mateo Mountains, Winston graben, and Sierra Cuchillo to collect samples for oxygen and hydrogen stable isotopic analysis. The oxygen and hydrogen stable-isotope signature of precipitation was quantified in order to establish the meteoric component in groundwater samples within the basin. Stable isotopic analyses were done on the New Mexico Institute of Mining and Technology Department of Earth and Environmental Science's Picarro Cavity Ring Down Spectrometer. The data are tabulated in Sophy (2013).

Results

Water Chemistry

Piper diagrams of major ion geochemistry of samples in the study area tend to group together well when plotted by position in the flow system and somewhat more weakly when plotted by aquifer lithology (Figure 3). Recharge and intrabasin aquifers (Paleozoic, volcanic, Santa Fe Group) produce Ca-HCO₃ fluids, thermal waters in the discharge zone (Ojo Caliente-volcanic, Chise- Paleozoic) produce Na-Cl fluids. Samples from Santa Fe Group aquifers trend from Ca to Na from recharge to intrabasin, suggesting basin location has a stronger influence on chemical composition than does aquifer type.

Thermal and non-thermal samples exhibit strong correlations between Cl and TDS. Additionally, thermal samples at Ojo Caliente and Chise warm spring show positive correlations between chlorine and the trace elements arsenic, boron, fluorine, and

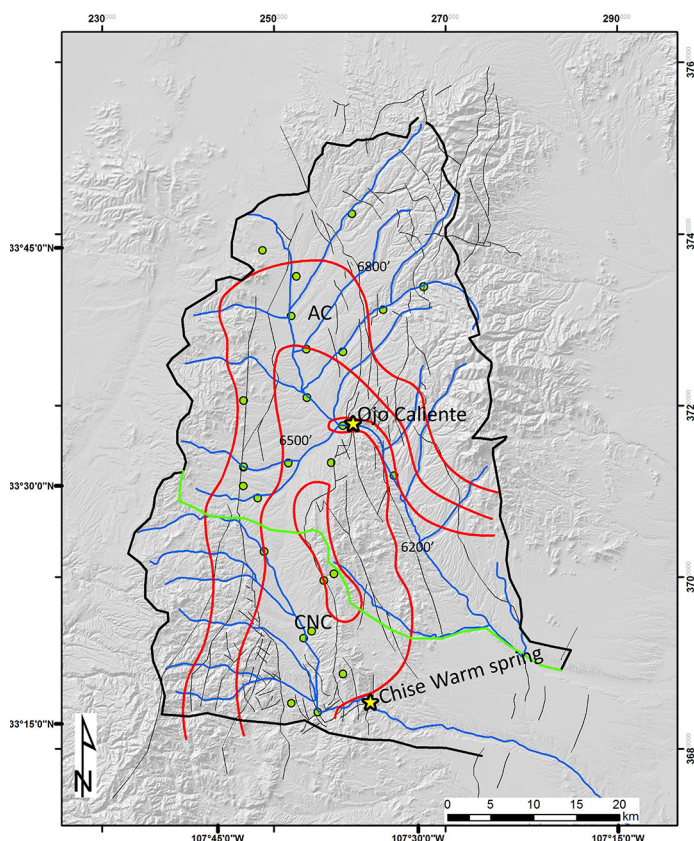


Figure 2. Regional groundwater contours in feet above sea level. Heavy-black lines are watershed boundaries that define the surface-water divides while green line denotes Ojo Caliente and Chise warm spring watersheds. Green dots are water chemistry samples. Thin-black lines are faults. The Ojo Caliente complex and Chise warm spring discharge at the Monticello and Chise boxes, through which the Winston graben is drained by Alamosa Creek (AC) and Cuchillo Negro Creek (CNC).

within Santa Fe Group sediments atop volcanic bedrock. The suite of springs consists of four discharge zones, two of which are thermal (>26°C) and three are non-thermal, (<26°C). The Northern spring complex and Ojo Caliente spring discharge at 24-30°C and the Alamosa Box, Alamosa Creek, and Alum springs discharge at 9-11°C. The Northern and Ojo Caliente springs are located to the north of Alamosa Creek, the headwaters of Alamosa Creek Alamosa Box spring discharge near the banks of Alamosa Creek, and Alum spring discharges south of the creek.

The geology and geometry of the northern Winston graben is such that recharge from the Black Range and San Mateo Mountains may be separated until meeting at Ojo Caliente. The asymmetry of the basin may host north-to-south groundwater flow within a thick section of basin fill, up to 1000 m in the east along an east-dipping master fault along the Black Range (Koning, 2012). Basin fill within the hanging-wall of the master fault thins westward towards the Red Paint Canyon Fault, a series of north-striking normal faults that separated the WG from the San Mateo Mountains. The faults may act as barriers to groundwater moving toward the basin; water may flow east-to-west, encounter the faults and flow north-to-south along the faults to Ojo Caliente.

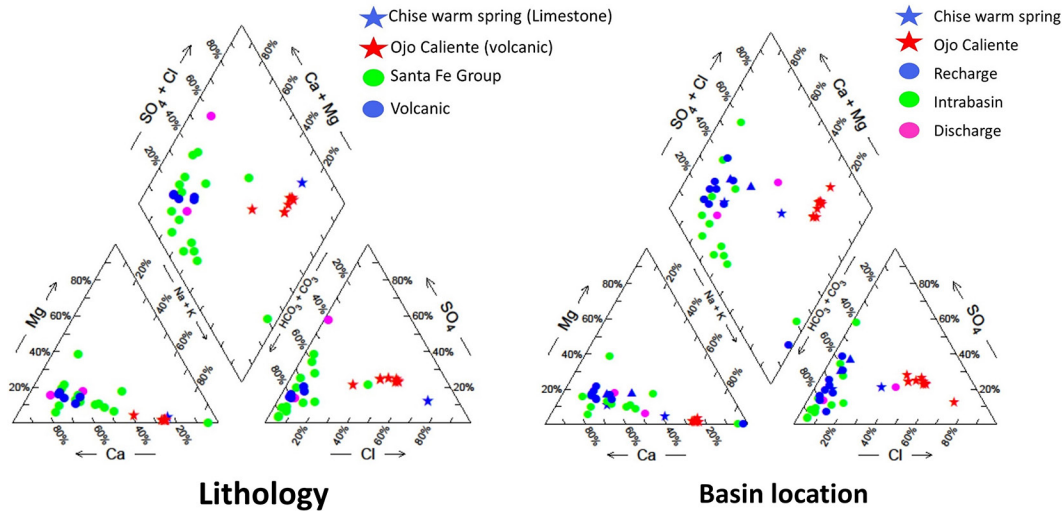


Figure 3. Piper diagram of all waters sampled in the Winston graben and surrounding areas. Samples are plotted by lithology (left) and basin location (right).

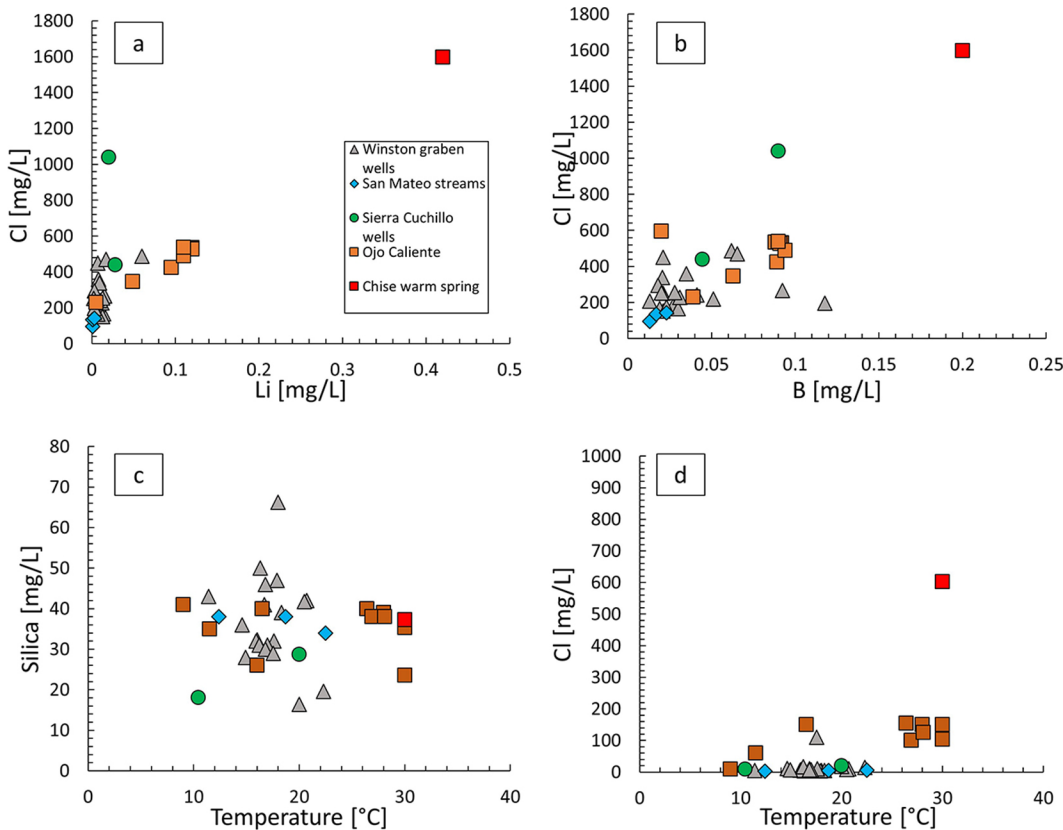


Figure 4. a) Plot of chloride [mg/L] versus TDS [mg/L]. Chloride concentrations are clearly correlated with increasing TDS. Thermal samples from Ojo Caliente and Chise warm spring have high Cl values, suggestive of water-rock interaction along a long traveled flowpath. b) Plot of silica [mg/L] versus sample temperature. Thermal waters cluster at silica ranges of 25-40 mg/L.

lithium, which preferentially liberate at elevated temperatures (Ellis and Mahon, 1964) (Figure 4a,b). Potential sources of fluoride are volcanic rocks and localized fluorite (CaF₂) mineralization in Paleozoic (Frencken, 1992) Thermal samples from Ojo Caliente have elevated arsenic concentrations and have distinctly higher As/Cl ratios, possibly derived from exchange with volcanic and po-

tassium metasomatized Cenozoic units (Chapin and Dunbar, 1994). The distinct cluster of Ojo Caliente waters on Figure 4 suggests higher temperature water-rock interaction with volcanic units at depth.

Silica concentrations range between 16-66 mg/L SiO₂ throughout the broader study area, yet show no linear correlation with temperature (Figure 4c). Thermal samples from Ojo Caliente and Chise warm spring cluster between 25 and 40 mg/L SiO₂. Temperatures of warm spring samples, however, do correlate strongly with chloride compositions (Figure 4d) suggesting high chloride can be used to ‘fingerprint’ thermal fluids in this system. At the low temperature ranges observed, silica concentration can be controlled by temperature as well as amorphous silica dissolution of volcanic rocks (Witcher and Stone, 2005); therefore silica concentration alone cannot be used to identify thermal fluids.

Stable isotope data for all samples in the study area plot near and on the GMWL (Global Meteoric Water Line; Figure 5). Ojo Caliente samples had the lightest oxygen and hydrogen isotope values of all groundwater samples (-10 to -8‰ and -70 to -60‰). Lighter isotopic composition of the thermal waters suggests a different source of recharge than heavier samples, either from precipitation at higher elevation (Gonfiantini et al., 2001) or primarily sourced from mountain-derived winter snowpack, as is common in arid systems (Clark and Fritz, 1997).

Temperature Gradient and Heat Flow

Temperature gradient data for 15 wells that are between 25 and 250 m deep were compiled for the Winston graben and surrounding foothills (Figure 6, locations on Figure 1). The highest temperature gradients occur in the vicinity of the Ojo Caliente complex. Unfortunately, the nearest temperature gradient well to Chise warm spring is 5 km away.

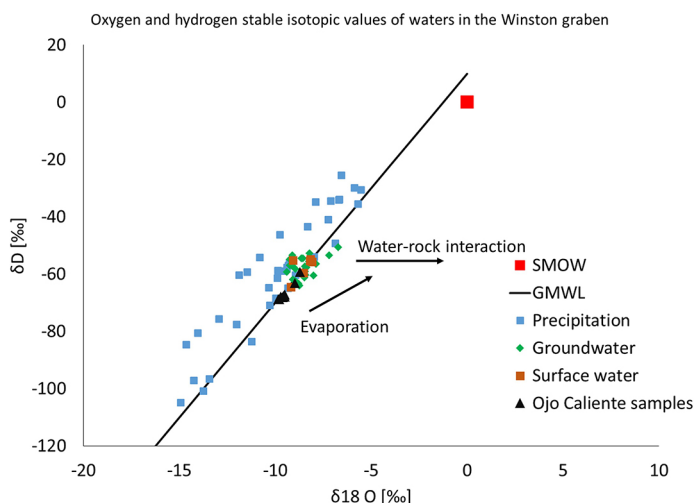


Figure 5. Stable-isotope values of water samples from the Winston graben. Data are reported relative to the SMOW standard and are in per mille units. The GMWL (Global Meteoric Water Line) is a best-fit line to oxygen and hydrogen isotopic compositions of precipitation samples from around the world (Craig, 1961). Water-rock interaction with silicate minerals causes a positive oxygen shift; evaporation of lighter isotopes causes heavy enrichment.

Ojo Caliente

Three wells drilled in the vicinity of the Ojo Caliente complex help constrain the shallow and deep thermal regime. Wells WG-TG-4, 14, and 15 are located near the Red Paint Canyon fault, the major geologic structure at Ojo Caliente. WG-TG-15 is the deepest well in the field, completed to 250 m. The well has a linear profile and the calculated interval geothermal gradients of 79 and 82 °C/km correspond to intervals at 110-190 m and 200-250 m. The temperature profile of WG-TG-14 (230 m TD) shows a linear thermal gradient below 150 m. This is interpreted to reflect background conductive temperatures at these depths. The calculated interval gradient from 100-230 m is 42 °C/km. The linear profiles of these deep wells indicate a conductive temperature regime at depth south of the Ojo Caliente complex.

The shallow thermal regime near Ojo Caliente is recorded in WG-TG-4, which has a maximum depth of 33 m. WG-TG-4 has the highest interval geothermal gradient in the Winston graben with a value of 217°C/km. This well encounters warm water at a shallow depth, but as depth increases the temperature appears to become isothermal at 23°C.

Chise Warm Spring

WG-TG-9 and WG-TG-7 are the wells that are closest to Chise warm spring (Figure 1) and drilled shallowly to 94 and 58 m, respectively. The wells are located within the Sierra Cuchillo horst and are completed near faults in volcanic rocks. WG-TG-9 has a linear temperature profile throughout the well and geothermal gradient of 59°C/km between 20 and 90 m. The temperature profile of WG-TG-7 shows shallow thermal effects in the 20-40 m interval and a linear gradient of 46°C/km in the 40-60 m interval. These wells have high gradients, though they lack any signs of upflow or outflow; thermal conductivities are unknown. Deeper

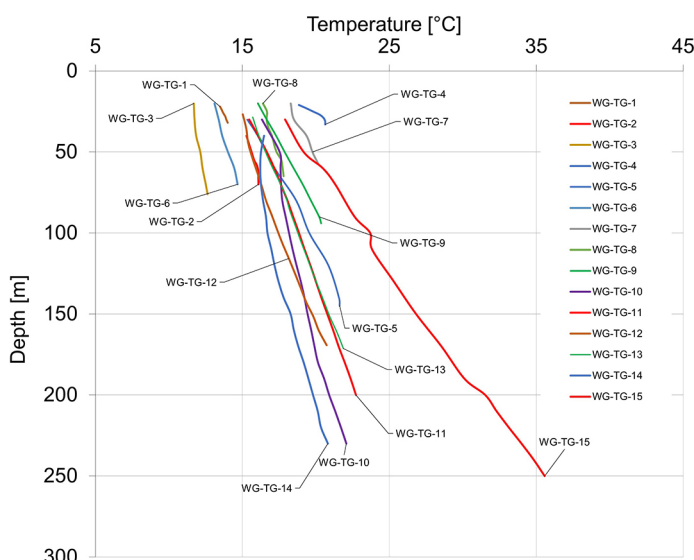


Figure 6. Temperature (°C) versus depth (m) for wells in the Winston graben. Well locations shown on Figure 1.

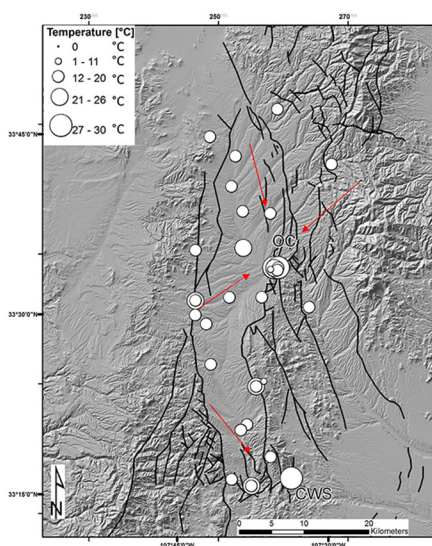
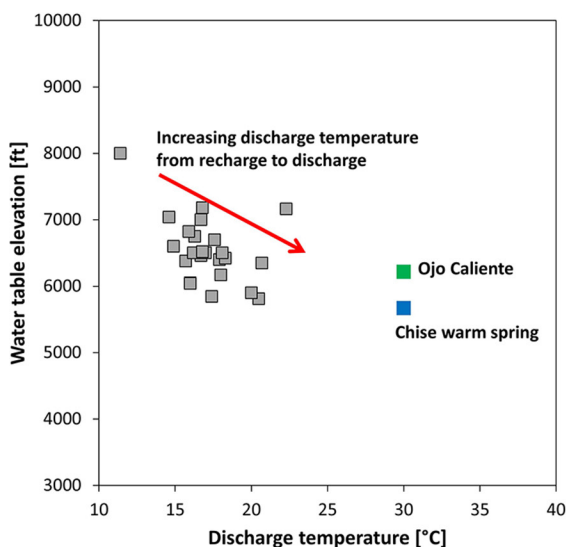


Figure 7. Left: Plot of sample discharge temperature [°C] versus water table elevation [feet above sea level] showing increase in temperature with decrease in elevation. This pattern indicates topography driven flow causes heating of samples at depth and discharge at low elevation. Ojo Caliente and Chise warm springs are low elevation samples with the highest discharge temperatures. Right: Spring and well discharge map showing highest temperatures occur in discharge areas of the Winston graben at Ojo Caliente (OC) and Chise warm spring (CWS); arrows indicate groundwater flow direction. Larger dots represent higher temperatures.

wells below the volcanic suite are necessary to assess the actual thermal regime east of the Chise warm spring.

Five wells located west of the Winston graben in the Black Range all have similar geothermal gradients ranging 39-46°C/km (WG-TG-1, WG-TG-12, WG-TG-13, WG-TG-10, and WG-TG-11). This range is likely the background geothermal gradient of the Winston graben and serves to highlight the thermal anomalies at Ojo Caliente.

Well Discharge Temperature

A spatially robust set of groundwater and spring discharge temperatures identify heat as a tracer in the hydrothermal system. In map view, no clear increase in temperature is apparent between recharge to discharge aside from the highest discharge temperatures at Ojo Caliente and Chise warm spring (Figure 7). The relation between topography-driven flow and groundwater temperature is investigated on a cross-plot of water-table elevation versus discharge temperature (Figure 7). The plot shows discharge temperature increasing with lower water-table elevations. This pattern indicates topography driven flow causes heating of samples at depth and discharge at low elevation. Ojo Caliente and Chise warm springs are low elevation samples with the highest discharge temperatures. In a hypothetical topography-driven forced-convective hydrothermal system, if all wells were thermally equilibrated and completed in the same formation, lower elevation samples would have the highest gradients due to upflow of thermal fluid.

DISCUSSION

Ojo Caliente

Geochemistry

Chloride compositions of thermal waters have been demonstrated to fingerprint a geothermal source. Looking at the chloride and bromide ratios, two conservative anionic species, may be useful in determining the origin and movement of groundwater as well as tracking water-rock interaction (Davis et al., 1998). Thermal springs at Ojo Caliente have high Cl/Br ratios (1500-2590) with Cl concentrations between 100 and 155 mg/L; Chise warm spring has a distinctly lower Cl/Br ratio (773) than Ojo Caliente (Figure 8). At Ojo Caliente, non-thermal samples have varying Cl/Br ratios, suggesting different fluid sources; Alamosa Box Head spring is a low Cl fluid (60 mg/L) that has a high Cl/Br ratio (600) while Alamosa Creek Headwaters is low Cl (10 mg/L) with a low Cl/Br ratio (111); The elevated Cl/Br values cluster separately from non-thermal samples. The elevated Cl/Br ratios may occur as a result of thermal processes as ratios in excess of 700 have been observed in many geothermal systems (Davis et al., 1998).

Geochemically, springs at the Ojo Caliente complex show evidence of primary brine, fresh water, and mixtures of the two. Primary brine samples are high-Cl, high-F, high-Li, and high Cl/Br. Cl/Br mixing trends between primary brine from Ojo Caliente and Northern spring with Alamosa Creek headwaters suggest that brine is being diluted with fresh water; Alamosa Box head spring plots on this trend and may be a diluted thermal sample (Figure 8).

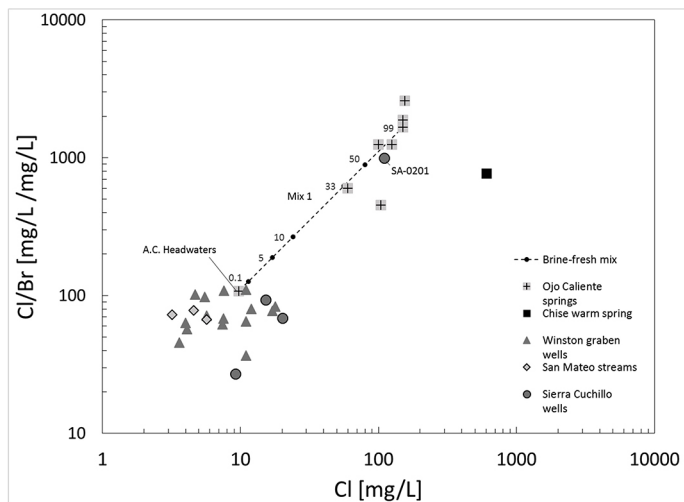


Figure 8. Cl/Br ratios versus Cl with mixing trends between warm springs and San Mateo Mountain stream water. Mix 1 is between Alamosa Creek (A.C.) Headwaters (Cl/Br: 111; Cl: 10 mg/L) and Ojo Caliente brine (Cl/Br: 1650; Cl: 150 mg/L).

The convergence of groundwater flowpaths at Ojo Caliente may cause mixing of thermal and non-thermal fluids. A mixing relationship between Ojo Caliente (Cl/Br: 1650; Cl: 150 mg/L) and Alamosa Creek Headwaters (Cl/Br: 111; Cl: 10 mg/L) (Figure 8) shows samples at Ojo Caliente may be slightly mixed with non-thermal waters, represented by Alamosa Creek (A.C.) Headwaters. Alamosa Box head spring has a signature similar to thermal samples at Ojo Caliente and is likely a diluted sample. Based on mixing hypotheses models, primary, unmixed-geothermal brine samples have high Cl/Br ratios, high Cl, and silica ranges between 20-40 mg/L.

Thermal and Hydrogeologic Constraints

Temperature gradient well WG-TG-4 is within the Spring Canyon horst, along the same fault as Ojo Caliente. The temperature log of WG-TG-4 is 20°C at 20-40 m depths and displays either an upflow or outflow pattern that suggests Ojo Caliente is likely in an outflow zone of the hydrothermal discharge from the Spring Canyon horst. The Northern spring, with chemistry and temperature that is almost identical to that of Ojo Caliente, is also likely in the outflow zone. The conductive temperature logs of WG-TG-14 and 2 restrict outflow to the north of Alamosa Creek; a conductive regime to the south is likely present; Alum spring is a non-thermal spring located in this zone.

Hydrologically, the Ojo Caliente complex is located just west of Monticello Box, where Alamosa Creek flows west-to-east from the Winston graben through the Sierra Cuchillo. Alamosa Creek flows perennially at Monticello Box and is likely fed by regional groundwater discharge (Myers et al., 1994). The box is at the intersection of two potential groundwater flow systems, one in basin fill sediments and the other within bedrock sourced mostly from the San Mateo Mountains and restricted from entering the Winston graben by a series of N-S striking faults. The constriction occurs as Santa Fe Group sediments depositionally thin towards the box. The contrast of basin fill sediments on bedrock of the Sierra Cuchillo likely makes this a location for basin flow constriction.

Chise Warm Spring

Geologically, Chise warm spring is located in the southern Sierra Cuchillo along the north-striking Montoya Canyon fault zone that separates Paleozoic (footwall) and Cenozoic rocks (hanging wall). The southern Sierra Cuchillo is characterized by N-S, NNW-SSE-striking faults and fractures, but locally the horst is cut by NE-SW striking normal faults that create the Chise box graben; the southern footwall of the graben exposes the lower Paleozoic and brings the Proterozoic section close to the surface. The hanging wall of the Montoya Canyon fault is composed of low-permeability volcanoclastic rocks intruded along a steep contact by a fractured dike or plug of uncertain age, forming a possible hydrologic-window into deeper Paleozoic and/or Proterozoic units. The fractured intrusion and fault zone near the Chise warm spring may allow heated waters to upwell and discharge along Cuchillo Negro Creek. An alternative hypothesis is that the intrusion is low-permeability and acts as a dam, forcing upflow along the Montoya Canyon fault. Regardless, the footwall of the Montoya Canyon fault plays an important role as it brings lower-Paleozoic and Proterozoic rocks hosting thermal waters close to the surface.

Resource Temperature Estimates

Table 1 summarizes geothermometry calculations for all primary brine samples in the study area. The chalcedony (silica) and K-Mg geothermometers are most applicable in low temperature (<150°C) systems because of their rapid, low-temperature

Table 1. Geothermometer estimates for selected samples. Temperature in Celsius. N/A designates samples without SiO₂ values.

Sample Name	Sample ID	Cl [mg/L]	Discharge Temp [°C]	Chalcedony cond ¹	Quartz cond ¹	Quartz adiabatic ¹	Na-K-Ca ²	Na-K-Ca Mg corr ²	Na/K ³	K/Mg ⁴
Ojo Caliente Complex										
Ojo Caliente west seep (#2)	SA-1011	155	26	61	92	94	60	60	156	70
Ojo Caliente spring #4	SA-1013	150	27	N/A	N/A	N/A	58	58	151	69
Ojo Caliente spring #3	SA-1012	150	17	61	92	94	57	57	154	69
Ojo Caliente main pool (#1)	SA-1010	150	28	60	91	93	63	63	165	72
Ojo Caliente	NGD-1	150	30	38	70	75	66	66	168	74
Ojo Caliente	NGD-2	104	30	55	87	89	67	67	169	75
Northern spring complex #3	SA-1009	100	24	N/A	N/A	N/A	61	61	166	72
Northern spring complex #2	SA-1008	125	28	59	90	92	64	64	168	74
Northern spring complex #1	SA-1007	100	27	59	90	92	61	61	167	71
Chise Warm Spring										
Chise warm spring	NGD-3	603	30	58	89	91	150	70	189	86
Non-Thermal Water										
Coil 74 Ranch New well	SA-0201	110	18	47	79	82	37	37	169	49

¹Fournier and Potter, 1982

²Fournier, 1981

³Fournier, 1979

⁴Giggenbach, 1988

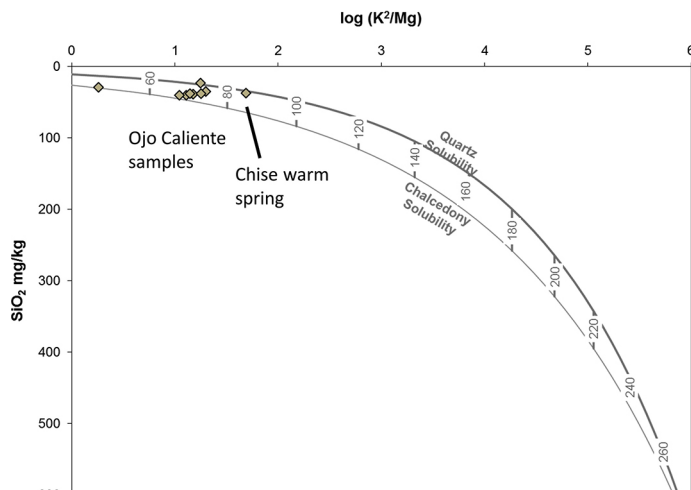


Figure 9. Cross-plot of log (K² (mg/kg)/Mg (mg/kg)) versus SiO₂ (mg/kg) with quartz and chalcedony solubility curves overlain (Giggenbach and Goell, 1989).

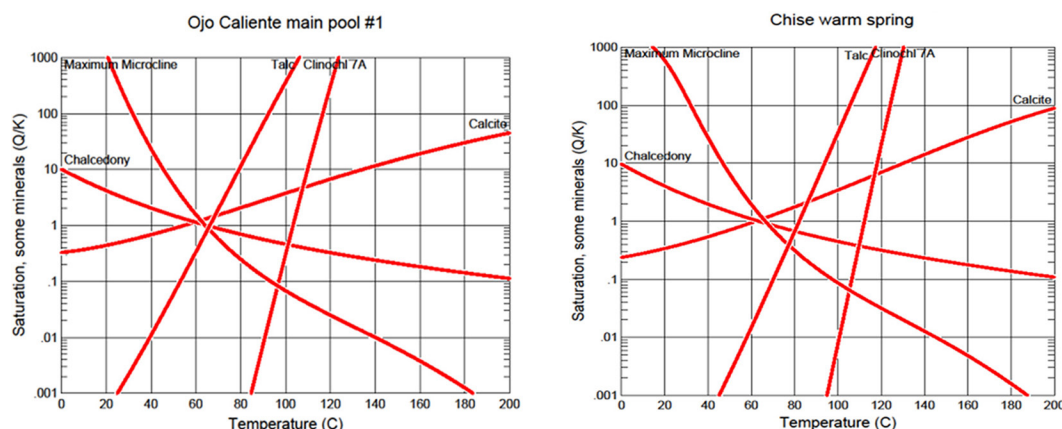


Figure 10. Mineral speciation models run on primary brine samples from Ojo Caliente and Chise warm spring. Equilibration temperatures are between 60-70°C.

equilibration with clay minerals. Thermal and non-thermal samples from Ojo Caliente and Chise warm spring have chalcedony-predicted temperatures around 60°C. K-Mg temperature estimates for thermal samples at Ojo Caliente and Chise warm spring are 69-75° and 86°C respectively. Plots of silica (SiO₂ [mg/kg]) versus log (K²/Mg) concentrations highlight samples that show good agreement between the geothermometer calculations (Figure 9) (Giggenbach and Goell, 1989). Mineral speciation model temperature estimates using Geochemists’s workbench predicted equilibration temperatures of 65-75°C and 65°C for Ojo Caliente and Chise, respectively (Figure 10).

Conclusions

The Black Range and San Mateo Mountains are the recharge areas for the hydrothermal system in the Winston graben. The adjacent highlands are comprised of frac-

tured volcanic and volcanoclastic rocks and recharge likely occurs through permeable pathways. Groundwater elevation data show a groundwater divide between Ojo Caliente and the Chise warm spring; this indicates that the Chise warm spring is fed by recharge in the Black Range and the Ojo Caliente complex is recharged from the Black Range and San Mateo Mountains. Stable-isotope data from Ojo Caliente indicate that thermal spring and non-thermal waters are meteoric in origin and have values consistent with high elevation, low temperature (snowmelt) recharge.

Thermal springs are pH neutral, Na-Cl waters with high TDS/Cl, and silica values between 25 and 40 mg/L. All thermal samples have high Cl/Br ratios (>500); values that are consistent with other geothermal systems (Ellis and Mahon, 1977). Sample SA-0201 is located on the eastern margin of the Sierra Cuchillo, near the Monticello graben. This sample has a chemical signature nearly identical to samples at Ojo Caliente and may be a conductively cooled sample that discharged from a reservoir similar to that of Ojo Caliente. The geographic distance between Ojo Caliente and SA-0201 limits a similar upflow origin.

The Chise warm spring discharges along the Montoya Canyon fault where upflow may occur through highly fractured bedrock; an intrusion may provide a hydrologic window to deeper reservoirs.

Ojo Caliente contains thermal and non-thermal discharge zones as a result of the meeting of two flow-paths in the northern Winston graben. Thermal waters emerge from a fractured bedrock horst along the Red Paint Canyon fault zone, non-thermal waters discharge at the constriction caused by a thinning of basin fill.

Reservoir temperatures between 60 and 80°C were calculated with geothermometers; mineral speciation models converge near 60°

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