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THE MOUNT PRINCETON GEOTHERMAL AREA, CHAFFEE COUNTY, COLORADO

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Abstract

The Mount Princeton geothermal area is on the west side of the upper Arkansas Valley near Buena Vista, Colorado, along the northern extension of the Rio Grande rift. The area underwent a complex period of Tertiary igneous activity which terminated with the intrusion of the Raspberry Gulch Rhyolite about 22 m.y. age. Faulting, associated with the Rio Grande rift, began in the Miocene and continued to within the last 30,000 years. Surficial thermal manifestations are characterized by zeolitic alteration, which covers approximately 64 km^2 (34.7 sq. mi.), and many thermal springs and wells which have a maximum temperature of 85°C. Chemical analysis of the thermal waters indicate minimum subsurface temperatures of approximately 125°C. Deep circulation of meteoric water, in a zone of anomalous heat flow associated with the Rio Grande rift, may be the heat source for the thermal features of the area.

Location

The Mount Princeton geothermal area is on the west side of the upper Arkansas Valley between the towns of Buena Vista and Salida in Chaffee County, Colorado (fig. 1). The area is along the western flank of the northern extension of the Rio Grande rift zone and includes a portion of Collegiate Peaks area of the Sawatch Range. The area of thermal manifestations is along the eastern flank of the range and is roughly defined by Cottonwood Creek on the north and Brown's Creek on the south. The thermal manifestations are most pronounced along Chalk Creek where the jagged, zeolitized, white Chalk Cliffs rise approximately 500 meters (1,600 ft.) above the Mount Princeton Hot Springs.

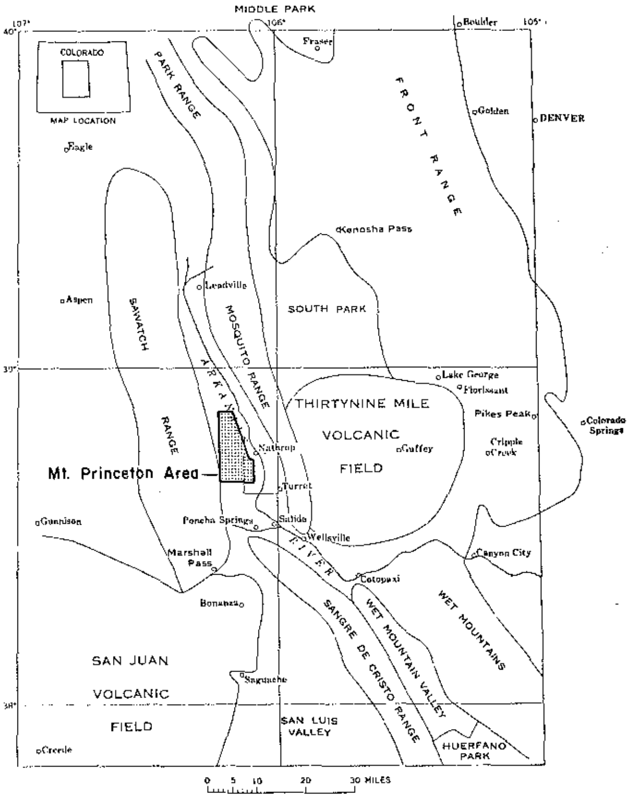

Figure 1. Index map of central Colorado, showing the location of the Mount Princeton area (after Van Alstine and Cox, 1969).

Geology

The oldest rock units in the Mount Princeton area are Precambrian metamorphic and igneous rocks (fig. 2). Paleozoic and

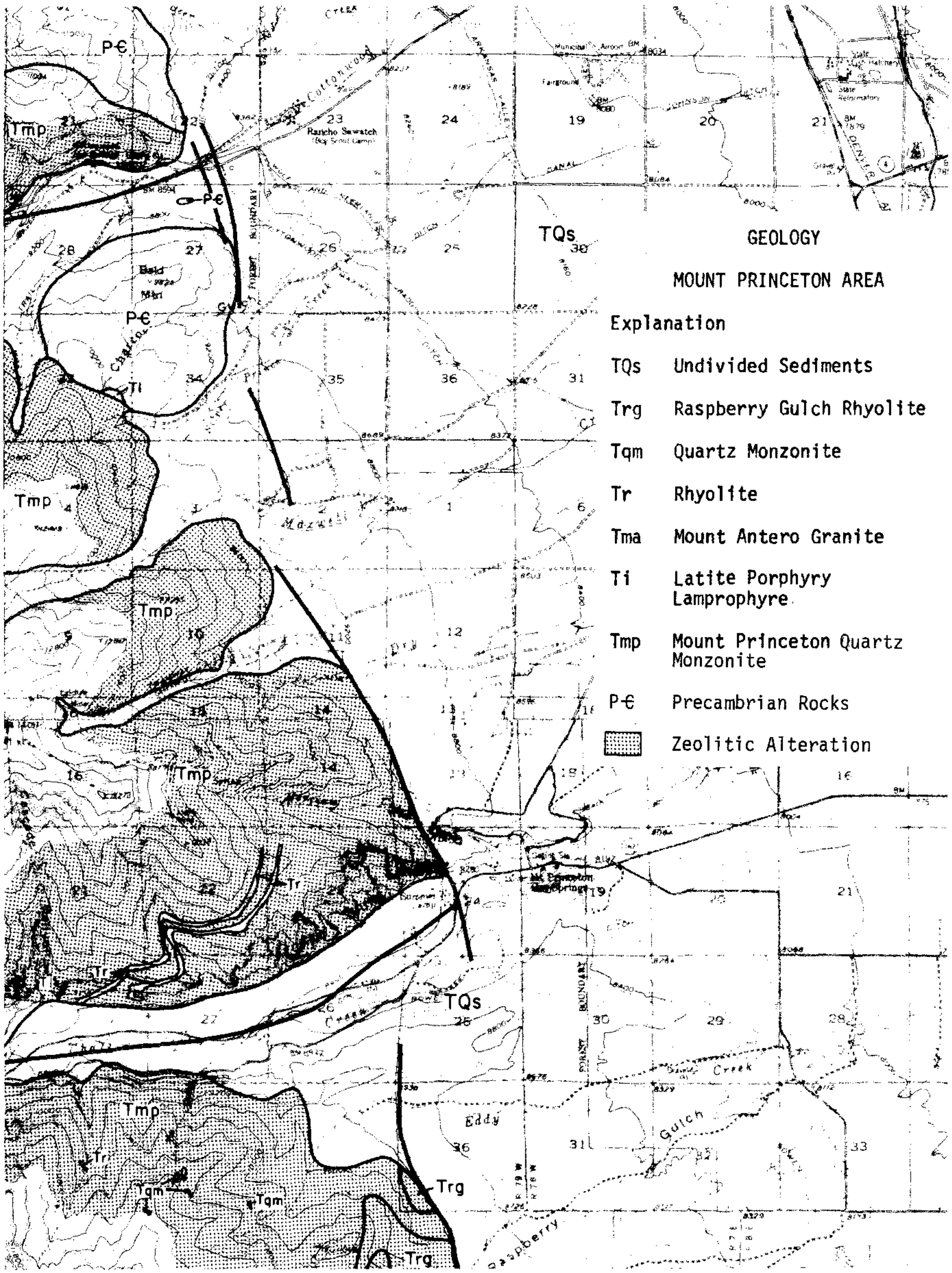

Figure 2. Geologic Map of the Mount Princeton area.

Mesozoic rocks are not present in the area although a thick section of sediments was deposited over the area during this time interval. Apparently, these rocks were removed by the erosional event which followed uplift and the formation of the Sawatch anticlinal structure during the Laramide orogeny.

Tertiary intrusion in the general area may have commenced as early as the Eocene. However, the earliest intrusion in the Mount Princeton area began with the emplacement of the Mount Princeton Quartz Monzonite, dated at 36 ± 2 m.y. This intrusion of batholithic proportion is the most prevalent rock in the area. It was followed by lamprophyre and latite porphyry dikes, and the Mount Antero granite stock, dated at 30.8 ± 1.1 m.y.. Afterwards, rhyolite dikes, dated at 25.4 ± 1 m.y. and small quartz monzonite bodies, dated at 24 ± 1 m.y., were intruded into the Mount Princeton batholith. These were followed by the emplacement, north of the Mount Antero granite near the headwaters of Raspberry Gulch, of the Raspberry Gulch rhyolite (22 ± 1 m.y.), the youngest igneous rock in the area.

Volcanic rocks of Oligocene age are common in the Mosquito Range to the east of the Mount Princeton area, and two possible rhyolitic vents, dated at 28-29 m.y., form conspicuous domes across from the mouth of Cottonwood Creek.

Regional uplift and the development of the Rio Grande rift began in the early Miocene. Rifting continued throughout the Miocene and Pliocene, with deposition of basin-fill sediments, and throughout the Pleistocene with the development of pediment gravels and glacial debris. Faulting along the rift is believed to have continued to at least within the last 30,000 years.

Structure

The Rio Grande rift in the Mount Princeton area is characterized by a series of "en echelon" normal faults on the west side of the valley and parallel normal faults on the east side which give the valley a graben structure. Faults on the east side of the valley drop the basin in a series of steps; whereas, the fault system on the west side of the valley consists of a relatively narrow fault zone characterized by a single large displacement. Parallel north-trending faults on the east side appear to have about 300 m. (1,000 ft.) of displacement each (Van Alstine 1969 and Knepper 1974). Zhody and others (1971) believe, on the basis of resistivity measurements, that there are 1,400 m. (4,600 ft.) of valley fill deposits in the graben immediately south of Buena Vista. Considering the topographic relief present in the Sawatch Range, the total displacement on the west side fault system may be as much as 3,000 m. (10,000 ft.).

The gravity data do not show a sharp gradient of the west side of the graben, possibly due to the Mount Princeton intrusive center.

Two major cross faults are projected along Cottonwood and Chalk Creeks. Evidence for the faults, which are covered, are hot spring and alteration pattern location, the linear nature of the two valleys, and the nonalignment of the mountain front at Chalk Creek.

Alteration

Hot spring systems at the base of Mount Princeton have produced an extensive zone of alteration. The hydrothermal system, which is active at present, is probably producing a similar alteration assemblage at depth. Alteration is characterized by the calcium zeolite, leonhardite (Sharp 1970), which may grade into laumontite below surface. In addition to leonhardite; chlorite, illite, epidote, calcite and fluorite are present as alteration minerals.

Zeolitic alteration covers more than 64 km^2 (25 sq. mi.) and has a vertical exposure of 1,000 meters (3,283 ft.). Alteration is strongest at Chalk Cliffs, above Mount Princeton Hot Springs, but a weaker alteration center is concentrated around Cottonwood Hot Springs. The cliffs get their white color from leonhardite and clays which fill fractures to such a degree that they impart a bright white hue to the normally grey host rock.

The zeolitic alteration is strongest in the Mount Princeton Quartz Monzonite but it is also present in Precambrian gneiss, Mount Antero Granite, aplite, rhyolite, and Raspberry Gulch Rhyolite.

Unweathered Mount Princeton Quartz Monzonite shows weak chloritization of biotite and sericitization of feldspars (Limbach 1975). This weak, widespread alteration is probably related to the crystallization of the Mount Princeton intrusive. Zeolitic alteration, related to more recent hydrothermal activity, converts biotite to chlorite; hornblende to calcite and epidote; orthoclase to sericite; and plagioclase to albite. Leonhardite is confined to fracture openings and does not replace other minerals. The calcium for the zeolite comes from the breakdown of hornblende and plagioclase. Chemical analysis of the strongly altered Mount Princeton Quartz Monzonite shows little change from the unaltered quartz monzonite, except for slight additions in iron and water.

The zeolite alteration assemblage forms at high activities of H_2O relative to CO_2. These conditions prevail where hot water has a pH of 8 to 9 (White and Sigvaldson 1963), which fits the hot springs in the Mount Princeton area. Sharp (1970) has suggested that the zeolitic alteration assemblage present at Chalk Cliffs formed within a range of temperatures of 145-220° C and depths of 150-2,000 m. (4,925-6,566.6 ft.) below the surface, based on comparison with active geothermal areas in New Zealand and Iceland.

Thermal Springs

The thermal springs in the Mount Princeton area have been described by George and others, 1920; Lewis, 1966; Sharp, 1970; and Pearl, 1972. Most of the hot wells are used for heating homes, greenhouses, bathing and drinking (fig. 3).

The area contains at least six thermal wells and two thermal springs (Table 1), including Hortense Hot Spring, reportedly the hottest spring in Colorado. Many other thermal seeps issue directly into Chalk Creek, and cannot be counted. Several low-pressure, steam fumeroles are present, about 100 m. (368.3 ft.) to the west of Hortense Hot Spring, in a talus slope at the base of the Chalk Cliffs. The approximate heat discharge for the thermal features of the area, computed as the product of the volume rate and enthalpy of the water in excess of ambient temperature, is seen in Table 1. All the thermal features combine to produce 4×10^6 cal/sec. or enough heat to supply approximately 200 average sized houses.

Table 1. Thermal features of the Mount Princeton area.

Sample Name	T°C	Flow l/m	Heat Discharge cal/sec.
Hortense Hot Spring	85	38	4.9×10^4
Younglife Hot Well East	85	379	4.9×10^5
Younglife Hot Well West	67	379	3.7×10^5
Greenhouse Hot Well	68	379	3.8×10^5
Chalk Creek Greenhouse Hot Well	65	1892	1.8×10^6
Jump Steady Hot Well	59	568	5.0×10^5
Mt. Princeton Hot Spring	56	265	2.1×10^5
Deer Ranch Hot Well	38.5	379	1.9×10^5
			4.0×10^6 cal/sec.
			1.6×10^4 BTU/sec .

Analyses of thermal and non-thermal waters of the Mount Princeton area are given in Table 2. Non-thermal waters of the Mount Princeton area generally contain less than 150 mg/l of dissolved solids. Water pH is generally neutral to slightly basic. Bicarbonate is the principle ion followed by silica, calcium, sodium and magnesium. Cold waters contain an average of 22 mg/l of silica. Ice Pond Cold Spring, about 1 mi. (1.6 km) to the northeast of Buena Vista, was chosen to represent background water chemistry.

Thermal waters exhibit basic to very basic pH. Four types of thermal water are recognized:

1. Sulfate-sodium waters, with less than 12 mg/l chloride, may represent steam condensate that has reached equilibrium with quartz monzonite of the Mount Princeton batholith. The

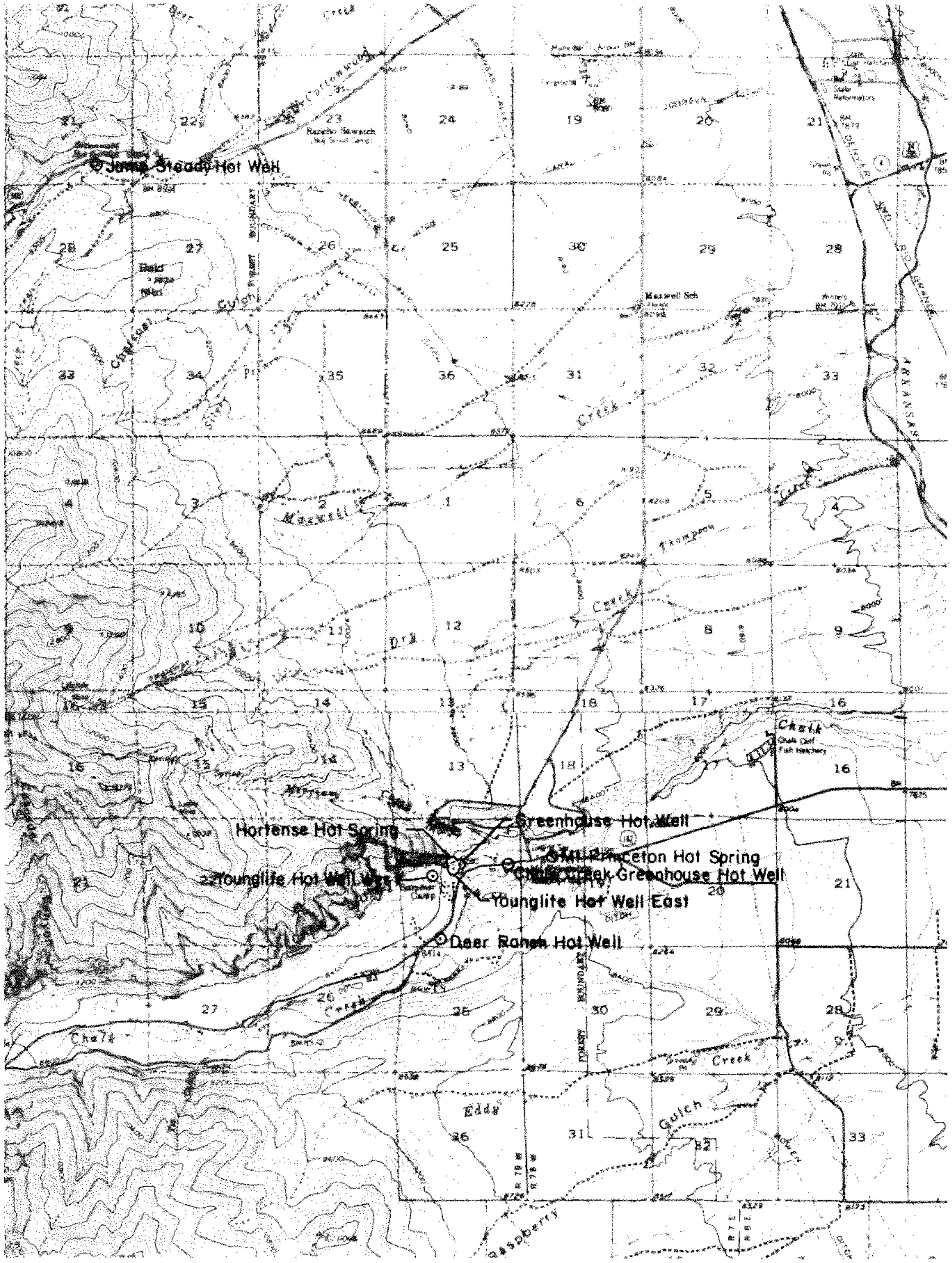

Figure 3. Location of the thermal features of the Mount Princeton area.

Table 2. Chemical analysis of the thermal features of the Mount Princeton area. Units are mg/l unless otherwise noted.

	Hortense Hot Spring	Younglife Hot Well East	Greenhouse Hot Well	Younglife Hot Well West	Chalk Creek Greenhouse Hot Well	Jump Steady Hot Well	Mt. Princeton Hot Spring	Deer Ranch Hot Well	Ice Pond Cold Spring
pH	9.6	9.2	9.1	9.1	8.8	9.2	8.6	8.8	7.6
Cl	8.8	11	6.6	2.2	6.6	28	5.5	4.4	3.0
F	16	15	13	9.3	10	14	9.4	6.2	0.2
HCO_3	46	43	79	44	52	31	59	64	68
CO_3	16	18	20	10	0	24	0	0	0
SO_4	100	90	80	60	70	110	60	40	6
SiO_2	85	80	75	75	65	60	60	45	25
Na	100	80	80	60	60	110	50	40	7
K	4.0	2	2	2	2	2	2	2	1
Ca	15.0	12	7	17	10	50	20	20	18
Mg	0.1	<0.1	<0.1	0.4	0.1	0.3	0.4	0.9	4
Li	0.2	0.1	NA	0.1	NA	0.2	0.1	0.1	NA
B	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
NH_3	0.4	0.3	<0.1	<0.1	NA	<0.1	<0.1	<0.1	<0.1
TDS	392	351	363	280	276	430	266	223	132
T°C	85	85	68	67	65	59	56	38.5	9
Flow (gpm)	10	100	100	100	500	150	70	100	75
$TSiO_2$°C	125	125	122	122	115	110	111	97	72
TNa/K°C	97	74	64	84	84	45	97	115	230*
TNa-K-Ca°C	75	55	67	47	57	34	43	41	12
Cl/SO_4	0.2	0.3	0.2	0.1	0.3	0.7	0.3	0.3	1.4
Cl/F	0.3	0.4	0.3	0.1	0.1	1.1	0.3	0.4	8.0
Cl/HCO_3+CO_3	0.5	0.6	0.2	0.1	0.4	1.7	0.3	0.2	0.2
Resistivity ohm-m	21.4	24.2	NA	NA	NA	19.2	32.6	36.2	63.7

NA = not analysed

+ = Does not represent true subsurface conditions, i.e. $\frac{\sqrt{Ca}}{Na} > 1$

Hortense and Mt. Princeton Hot Springs, and three hot wells, located south of the Chalk Cliffs, are included in this category.

2. Sulfate-sodium waters with greater than 25 mg/l of chloride probably represent low temperature, low salinity, hot water systems, derived through deep circulation. These waters are saturated with calcium carbonate minerals and deposit varying amounts of travertine. The Jump Steady Hot Well (Cottonwood Hot Spring) characterizes this category.
3. Bicarbonate-sodium waters with less than 7 mg/l of chloride may represent dilutions of sulfate-sodium waters by bicarbonate rich groundwaters. Greenhouse Hot Well and Deer Ranch Hot Well represent this group.
4. Groundwater, as is found at the Ice Pond Cold Spring, is generally rich in bicarbonate.

Chemical analyses of hot spring systems may be used to estimate subsurface temperatures of active geothermal areas. The assumptions made in applying geochemical indicators are summarized by Fournier, White, and Truesdell (1974); Fournier and Truesdell (1973) suggest criteria for selecting the most probable temperature. These techniques, used in determining the subsurface equilibrium temperatures given in Table 2, indicate temperatures on the order of 125°C.

Waters in the Mount Princeton area were analysed for oxygen-18, deuterium, and tritium. In the analysis of the data, deuterium and oxygen-18 have been normalized, relative to standard mean ocean water (SMOW), and are noted as δD and δO^{18}.

Figure 4 shows the variation between δD and δO^{18}, relative to SMOW, for several

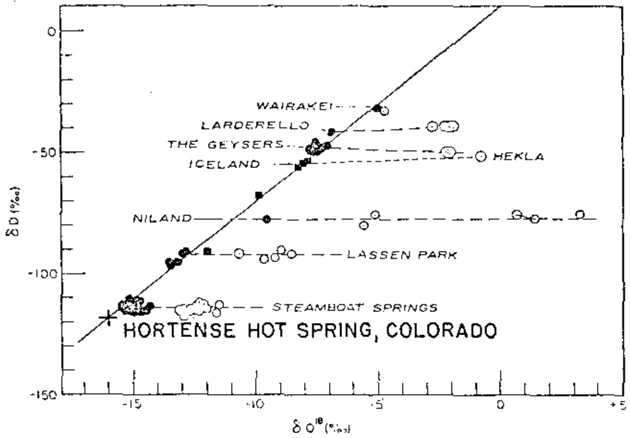

Figure 4. Observed isotopic variations in near-neutral chloride type geothermal waters and in geothermal steam. Solid points are local meteoric waters, or slightly heated near-surface groundwaters. Open circles are hot springs or geothermal water, crinkled circles are high temperature, high pressure, geothermal steam (after Craig 1963).

geothermal areas. The straight line represents the almost world-wide slope for meteoric waters plotted in this way. Deuterium concentrations are constant and equal to local meteoric water. On the other hand, 0^{18} concentrations show a characteristic enrichment or shift. The 0^{18} shift is due to an isotopic oxygen exchange between groundwater and carbonates and silicates in the rocks. Silicate and carbonate rocks contain 0^{18}, ranging from +6 to +30 per mil greater than SMOW. Deuterium generally does not vary from the meteoric concentration because rocks contain negligible hydrogen or deuterium. A strong shift in 0^{18} implies a long storage time and/or a large reservoir capacity. A very small shift implies one of two situations: first, temperature-pressure conditions are too low to allow waters to exchange 0^{18} with rocks within a relatively short time period, and second, descending meteoric waters are heated and rise so quickly that insufficient time is available for an 0^{18} exchange to occur. As shown on fig. 4, Niland waters, which have mingled over a long period of time with carbonate-rich Colorado River sediments, show the greatest shift. On the other end of the scale, Wairakei shows negligible shift which implies that waters descend quickly, stay in storage for only a short time, and then ascend.

Figure 5 is a plot of δD-$\delta 0^{18}$ for selected waters of the Mt. Princeton area. The hot waters show no apparent 0^{18} shift. This implies that these hot waters have been in residence with the reservoir rocks only a short time and have not exchanged oxygen isotopes as at Niland.

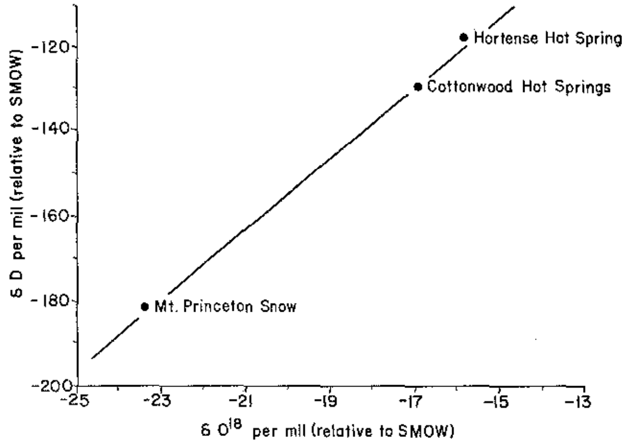

Figure 5. δD versus $\delta 0^{18}$ for waters of the Mount Princeton area.

Tritium analyses indicate an age of 20 to 51 years for Hortense Hot Spring, and 21 to 56 years for the Jump Steady Hot Well. These ages are in good agreement with the suggested youth of the same waters by 0^{18} analysis.

Heat Source

The youngest igneous rock in the Mount Princeton area is Raspberry Gulch Rhyolite 22 m.y. old - too old to be the heat source for the Mount Princeton area hot springs - and it is doubtful that any younger igneous intrusions are present at shallow depths. The youngest rocks in the northern part of the Rio Grande rift system are 4.5 - 3.6 m.y. - old olivine tholeiitic basalts in the southern portion of the San Luis Valley. According to Lipman (1969), these basalts were derived from depths of 15-20 km (9.3 - 12.4 mi.). This suggests that a portion of the rift is underlain by an upward protrusion of hot, mantle rocks that forms a zone of abnormally high heat flow. Heat flow measurements along the rift show values of two to three times the average crustal value (Gross 1974). White (1957) states that meteoric water in fractured rocks can circulate to depths of 3,000 m. (10,000 ft.) and the active faulting within the past 30,000 years could have permitted the fracture system at Mount Princeton to remain open to considerable depths. Circulation of meteoric waters to these depths would be more than adequate to produce the hot springs at Mount Princeton and the indicated subsurface temperatures.

Although igneous intrusion into faults of the rift system cannot be completely ruled out, the most likely heat source for the thermal manifestations in the Mount Princeton area is the abnormally high geothermal gradient associated with the Rio Grande rift.

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