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THE QUESTION OF RECHARGE TO THE GEYSERS AND HOT SPRINGS OF YELLOWSTONE NATIONAL PARK

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ABSTRACT

The extraordinary number, size and unspoiled beauty of the geysers and hot springs of Yellowstone National Park make them a national treasure. The hydrology of these special features and their relation to cold waters of the Yellowstone area are poorly known and in the absence of extensive, deep drillholes are only available indirectly from isotope studies. The δD - $\delta^{18}O$ values of precipitation and cold surface and ground water samples fall close to the global meteoric water line (Craig, 1961). δD values of monthly samples of rain and snow collected over the period 1978 to 1981 at two stations in the Park show strong seasonal variations, with average values for winter months close to those for cold waters near the collection site. δD values of over 300 samples of cold springs, cold streams, and rivers collected during the fall since 1967 show consistent N-S and E-W patterns throughout and outside of the Park although values at a given site may vary by as much as 8‰ from year to year. These data along with hot spring data interpreted earlier (Truesdell et al., 1977; Pearson and Truesdell, 1978), show that recharge to the Yellowstone thermal waters occurs at different levels. Near geyser basins, shallow recharge waters dilute ascending deep thermal waters particularly at basin margins. Deep recharge is heated to ≥350°C to become the major deep thermal reservoir fluid that supplies steam and hot water to all (?) geyser basins on the western side of the Park. This water (δD = -148 to -150‰) is isotopically lighter than all but the farthest north, highest-elevation, cold springs and streams. The most likely area of recharge for the deep thermal water in the western part of the Park is in the Gallatin Range where major N-S faults connect with the caldera. This recharge area for the deep thermal water is at least 20 kilometers and possibly as much as 70 kilometers from outflow in the thermal areas. Volumetric and flow models based on published chloride flux studies of thermal waters suggests that in a 0.5 to 4 km deep reservoir the residence time of most of the thermal water should be less than 1900 years. The amount of isotopically light water infiltrating in the Gallatin Range during our sampling period may not be enough to provide the present outflow of deep water suggesting that some recharge may have occurred during a slightly cooler time with a greater amount of winter precipitation.

INTRODUCTION

Extraordinary geysers, hot springs, and fumaroles occur widely in Yellowstone National Park (YNP) and constitute one of its major attractions. Public law [The Geothermal Steam Act of 1970 (30 U.S.C. 1001-1025) as amended by Section 28 in 1988] requires that significant thermal features in the Park be protected from the effects of exploration and exploitation for geothermal energy outside of the park with determination of possible effects to be based on scientific evidence from monitoring studies by the U.S. Geological Survey. For the purposes of this act Yellowstone Park is considered a single significant geothermal system and is protected in its entirety.

Extensive scientific study of the thermal areas of YNP began with the Hayden Expedition of 1871 (Hayden, 1872; 1883) and continued with the geochemical studies of Gooch and Whitfield (1880) and Allen and Day (1935). From 1960 the U.S. Geological Survey has been active in the study of Yellowstone with topographic and geological mapping and geophysical, geothermal and volcano hazard studies (for a bibliography of these studies from 1965 to 1986 see Bargar and Dzurisin, 1986; also see review by Fournier, 1989 and investigations reported in Sorey, 1991). Initial studies of the hydrothermal system(s) of Yellowstone have concentrated on the surface thermal features, their character, chemistry and output. In 1967, as part of a study to understand the geochemistry and hydrology of the thermal areas, we began isotopic studies of cold waters around the various geyser basins in an attempt to locate the recharge for their thermal waters. Chemical and isotopic modeling (Truesdell et al., 1977) indicated that the hot spring and geyser basins on the western side of the Yellowstone caldera are underlain by a deep meteoric water of constant isotopic and chemical composition. This deep water is modified isotopically and chemically as it cools by boiling and mixing with local cold waters. The recharge area or areas of meteoric water for the deepest levels of the Yellowstone system have not been located. The purpose of this paper is to compare the isotopic compositions of deep thermal reservoir waters indicated by analyses of hot spring, geyser and research well waters (Truesdell et al., 1977), with the compositions of meteoric waters in possible recharge areas. From these comparisons and considerations of geologic and hydrologic factors we suggest the likely area for meteoric water recharge into the deep levels of the Yellowstone geothermal system.

THE THERMAL FEATURES OF YNP

The distribution of active thermal areas in YNP and their relationship to surface drainage and major geologic and topographic features is shown in Figure 1. Most active thermal areas are located: 1) close to the outer ring fracture of the 0.6 Ma Yellowstone caldera (e.g., Hot Spring Basin, Washburn Hot Springs), 2) in the topographically low area near the margins of two resurgent domes within the caldera (e.g., Upper and Lower Geyser Basin), or 3) along N-S trending faults that extend outside of the caldera (e.g., Norris, Heart Lake). Geophysical evidence indicates that an active magma system underlies much of the Yellowstone caldera at depths ranging from about 5 to 6 km and currently produces inflation and deflation of the area (Eaton et al., 1975; Dzurisin and Yamashita, 1987).

A variety of thermal features occurs in individual basins. In general, alkaline-chloride hot springs occur in basins on the western side of the caldera located where one would expect to find cold water springs. The springs near the western resurgent dome in the geyser basins fall on crosscutting fault trends that parallel the fractures in the dome near the western inner ring fracture of the caldera (Figure 1). Springs outside of the caldera such as those at Norris and Heart Lake Geyser Basins occur on N-S faults that extend outward from the caldera. These alkaline-chloride springs deposit thick mounds and terraces of silica on glacial till, welded tuff and rhyolite. In areas where boiling water does not emerge at the surface, H_2S in the steam that separates from the water may oxidize to H_2SO_4 at the surface and produce acid-sulfate pools and mud pots. Small travertine-producing springs occur at the margins of the geyser basins where CO_2-charged waters cool by mixing with cold ground water before they have a chance to boil. The thermal features in the eastern side of the park have little liquid water discharge. In this part of the park, activity consists typically of fumaroles surrounded by sulfur and steam-heated pools of acid-sulfate water containing little chloride. This area is elevated relative to the adjacent valleys and the water table seldom intersects the surface. Large travertine deposits such as those at Mammoth Hot Springs and on the Snake River occur outside the caldera at the low temperature margins of the entire Yellowstone system where the thermal fluids flow through thick limestone sequences.

RECOGNITION OF A DEEP WATER COMPONENT IN THE THERMAL SYSTEM-COMPARISON OF δD OF WATER FROM DRILLHOLES AND THERMAL SPRINGS

Early isotope studies showed that essentially all thermal water at Yellowstone and elsewhere were derived from meteoric water (Craig et al., 1956). After hundreds of additional analyses at Yellowstone and other thermal areas throughout the world this conclusion still holds with few exceptions. In 1967 in order to better understand the geochemistry and hydrodynamics of the thermal areas we began a search for the recharge areas for the thermal water in the various geyser basins. At that time we assumed that the hot springs in each basin were recharged locally by water from the surrounding rhyolite plateaus. Analyses of water collected from shallow (65 to 332 meters depth) research holes drilled in 1967-1968 required us to change that assumption. The δD values of waters from the shallow drill holes, nearby hot water springs and local meteoric water from Lower, Norris and Shoshone Geyser Basins are summarized in Table 1. The striking feature of the data in Table 1 is that δD values of waters from hot springs and drill holes are more negative than those of local meteoric waters. For example, the δD values of water from the drillholes at Norris and Lower Geyser Basin were -146 to -151‰ while those of local meteoric water were -140 to -145‰. Recognition of this difference lead to modeling of the δD of thermal waters in terms of isotope effects due to boiling and mixing (Truesdell et al., 1977). The results of this modeling for Norris Geyser Basin is illustrated in Figure 2. This boiling and mixing model enabled interpretation of the measured δD of spring waters in terms of δD of deep water prior to boiling and or mixing. The deep thermal waters mix with cool water from local sources in shallow reservoirs and these mixtures boil to give the chemical and isotopic compositions of the surface thermal waters. Because most boiling and mixing occurs in shallow aquifers, the δD of waters recovered from drill holes approximate the primary composition of thermal water prior to boiling and mixing. This modeling indicated that hot springs in the Norris Geyser Basin have a deep water component that must have been derived from a meteoric water having a δD significantly lower than that of present local meteoric waters. Truesdell et al. (1977) showed that the compositions of thermal waters at Lower and Shoshone Geyser Basins are also consistent with derivation from the same deep water of δD = -148 to -150‰.

A single deep source water for Yellowstone surface thermal water discharges is also indicated by chemical arguments. Chloride compositions and geothermometer temperatures of the thermal waters when plotted on enthalpy-chloride diagrams (Figure 3) show that the temperatures and chloride concentrations of all major thermal waters in the Park are consistent with derivation from a single deep fluid of 320 ppm chloride and 360°C (Truesdell and Fournier, 1976). Research wells do not exist for West Thumb and Heart Lake Geyser Basins and δD values of their thermal waters are complicated by mixing with partially-evaporated water from Yellowstone and Heart Lakes. However, a $\delta^{18}O$ versus chloride plot (Figure 4), which shows the expected mixing line for Cl and $\delta^{18}O$ in Norris, Upper, Lower and Shoshone Geyser Basin waters, also shows that some Heart Lake and West Thumb springs have $\delta^{18}O$-Cl compositions similar to waters from other basins (although other springs have $\delta^{18}O$ values which lie about 2‰ above the mixing line for most other Park waters showing near surface dilution with evaporated lake waters). The fact that the compositions of some thermal waters at Heart and West Thumb fall on the same mixing line as other spring waters suggests that they also may have evolved from the same deep water. All of the data that we have on Yellowstone is consistent with the possibility that an isotopically and chemically homogeneous fluid underlies all of the thermal areas in the western side of the caldera. Possibly the same deep water underlies the steam dominated thermal areas in the eastern part of the caldera as in the western part but the chemical and isotopic compositions of deep water in the eastern side of the caldera are poorly known. The conclusions in this paper are limited, therefore, to the thermal areas on the western side of the caldera that discharge into the Madison and Snake Rivers.

METHODOLOGY FOR TRACING RECHARGE SOURCES

The use of δD in hydrology studies of geothermal areas

Hydrogen and oxygen isotopic compositions of water show variations related to the source of the water and the physical processes it has undergone. For most cold water systems these isotopes may be used interchangeably because processes of evaporation and condensation affect both isotopes similarly, and for geothermal systems both are affected by subsurface processes of mixing, boiling and steam separation as discussed and modeled in our earlier paper emphasizing thermal waters (Truesdell et al., 1977). In geothermal systems such as Yellowstone, however, oxygen isotopes in water exchange with those in rock so that $\delta^{18}O$ values of water depend on the temperature and duration of rock-water interaction, on the ratio of water to rock, and on the character of the rock as well as on mixing and evaporation-condensation processes. This exchange, called the "oxygen isotope shift", complicates the interpretation of the $\delta^{18}O$ values as indicators of recharge. In contrast hydrogen isotope exchange between water and rock minerals is not significant (except at very low water/rock ratios) and the interpretation of δD values of water is more straightforward. For this reason we have concentrated our study of Yellowstone recharge on the deuterium contents of possible infiltrating waters in relation to those of the thermal source water described earlier.

Determining the recharge area for the deep thermal water requires samples which are representative of infiltrating waters. As will be discussed, possible infiltrating waters are best sampled during dry periods in the fall at a time when most streams and rivers at YNP are fed largely by springs and seeps. These springs and seeps receive most of their recharge from snow melt during the previous spring. Over 300 δD analyses were made of possible infiltrating waters from cold springs, wells, streams, and rivers over a 15,000 km^2 region in and adjacent to the Park. These samples were collected largely in the fall during the period from 1967 to 1990. The remainder of this section will focus on validating the use of δD analyses of these samples as an indicator of the composition of infiltrating waters. For this purpose $\delta^{18}O$ analyses were also made on some of these samples.

The $\delta^{18}O$ and δD values of precipitation and cold waters in YNP

The δD and $\delta^{18}O$ values for precipitation samples collected at YNP during May and June and November and December between 1970 and 1977 are given in Table 2 and plotted in Figure 5 along with values of cold water samples from streams, rivers, cold springs and lakes collected in May and June and September and October between 1967 and 1982. The data for the precipitation samples plot very close to the Global Meteoric Water Line (Craig, 1961) with δD values from -64 to -168‰. These data establish the local meteoric water line (LMWL) in the Yellowstone region as similar to the GMWL. Similar results were obtained by Thordsen et al. (1992) on snow core samples.

The δD and $\delta^{18}O$ values of the stream, river and spring samples straddle the GMWL with δD values from -126 to -153‰. These samples are typical of those analyzed only for δD throughout the study and the conformity of their compositions to the GMWL indicates that our surface water samples have not undergone evaporation during precipitation, infiltration or inflow into streams. The δD - $\delta^{18}O$ values of lake samples, however, plot off of the GMWL in a fashion typical of evaporated waters. Our data on streams, rivers, and springs contrast with those of Thordsen et al. (1992) for springs which show increased isotope spread for higher $\delta^{18}O$ values typical of evaporation trends. Many of their samples show values similar to values we observed for lakes in Figure 5 or streams flowing from lakes. Their study differed from ours in including many low altitude samples from springs and seeps collected during summer months. Water from seeps and small springs is likely to undergo evaporation in the summer, and summer rainfall in the low lying valleys of Yellowstone which recharges these seeps and small springs is also likely to undergo evaporation during precipitation. Such waters will not have compositions typical of infiltrating waters derived from melting snow in the spring.

The δD of precipitation at YNP and relationship to δD of infiltrating water

Precipitation in a given drainage area can have a wide range of δD values depending on the temperature, and the source and history of air masses responsible for individual storms. Samples collected monthly by Park rangers from rain and snow gauges at Mammoth and Old Faithful from May 1977 to January 1983 allow us to study the variation of δD of precipitation at these locations over a several year period. The δD values of the precipitation along with amounts of precipitation for the collection period are summarized in Table 2. The δD values range from -206‰ for a single storm of 0.8 cm precipitation at Mammoth January 12, 1979 to -68‰ for 1.5 cm of precipitation during the month of September in 1979. The δD values of precipitation at Mammoth are similar to those at Old Faithful for the few months that collections were made at both sites. The data for Old Faithful where precipitation samples were available for nearly every month over a two year period are plotted in Figure 6. The δD values of the monthly precipitation collections at Old

Faithful show cyclic seasonal variations in which the most negative values are observed in the winter and the least negative are observed in the summer months.

The weighted average δD for the precipitation for winter months (September-May) of -134‰ (Table 2) is close to the average value observed for the water supply at Old Faithful (Table 4 and next section). Thus, it is likely that groundwaters receive most of their recharge from melting snow during spring runoff. Since precipitation in a given drainage area can have a wide range of δD values, the problem of determining the δD of the recharge for the thermal water involves locating cold waters that have the δD value of average infiltrating waters.

In 1967 we assumed that water from wells and cold springs which have steady discharge from groundwater reservoirs in which water has a relatively long residence time should give the best average values for water available for recharge. Unfortunately, there are very few such cold springs in the geyser basins where most subsurface water at low elevations is thermal. Collection of cold springs outside of geyser basins is difficult because they are seldom located on maps and are likely to be small and ephemeral so that the δD of discharging water may reflect the most recent precipitation rather than a long term average value. Much of the drinking water in the Park is not from wells but from surface water that is held in reservoirs where evaporation is likely. In view of the relatively few accessible cold springs and wells, most of our samples collected after 1967 are from fast-moving cold streams and rivers.

Relationship of δD of groundwaters to δD of streams and rivers

Because sampling of Yellowstone streams was largely limited to fall, the isotope systematics of individual streams throughout the year and the relationship of the δD values of stream samples to average values for groundwater must be predicted by analogy from studies of small cold streams that have been sampled frequently over a period of several years (reviewed by Fritz, 1981). In alpine basins with small groundwater storage capacity, the inflow of groundwater was found to cause small sinosoidal annual changes of about ± 5 ‰ in δD with summer values isotopically heavy and winter values light (Hermann et al., 1978). Only the δD of streams during the dry period at the end of summer showed the composition of groundwater with a value near that of the average for winter precipitation. Such studies suggest that stream samples collected in the early fall after the end of summer thunderstorms and before the start of winter storms are probably representative of groundwaters that were recharged largely the previous spring. Supporting this assumption is the observation that at Yellowstone δD values of streams in the fall are mostly within ±4‰ of the value recorded for the previous spring (Table 4). We would not expect perfect agreement between the values for the spring run off and fall stream discharge because the groundwater storage capacity of the reservoirs for springs that feed individual streams probably varies considerably and some may retain water from several previous years.

Sampling of streams for δD analyses

Ideally, sampled streams (and rivers) should undergo little isotopic change during flow and closely reflect the average δD for local groundwater feeding the streams through springs and seeps. Ideal streams are those which are fed exclusively from large subsurface reservoirs in which water has a relatively long residence time and have flowed short distances with minimum evaporation. These streams are likely to have temperatures only slightly above that of the groundwater. Even on warm days at Yellowstone temperatures of streams were seldom observed to reach more than 10°C above temperatures recorded in local cold springs and the δD of the streams does not change during the day as their temperatures rise. Such streams are the most likely to have fairly uniform δD values from year to year when sampled in the fall at times that specifically avoid major storms.

Isolating the effect of possible evaporation on the δD of stream water is hard in mountainous regions because the inflow is from numerous inconspicuous sources along the course of the streams. Where gradients are steep the water may come from a range of elevations possibly with different isotopic compositions. However, evaporation would be expected to be very limited at the low temperatures and short average distances of flow from springs to our sampling points. This is supported by the clustering of data around the GMWL in Figure 5 and by isotope studies of rivers (Friedman et al., 1964; Fritz, 1981) that have shown that flowing water in temperate climates normally undergoes very little change in δD due to evaporation. Even the Nile River undergoes a δD increase of only 3‰ during its 2900 km journey from the source to ocean (Friedman et al., 1964). Thus, it is not surprising that we observed no change in δD of the Stillwater River over sampling sites 65 km apart (Table 4).

Lake water, however, with a long residence time usually shows significant increases in δD and $\delta^{18}O$ due to evaporation (Friedman et al., 1964; Gat, 1981). The compositions of lake waters in Figure 5 plot on a typical evaporation trend. The difference in δD values between Yellowstone Lake (-128 to -133‰) and the average of accessible inflowing streams (-135‰) is largely due to evaporation. The isotopic change may occur over the 10 year average residence time (Pearson and Truesdell, 1978) of water in Yellowstone Lake. In order to minimize possible effects of evaporation, we avoided streams that traversed standing bodies of water such as lakes or that received significant inflow from swampy meadows.

THE δD VALUES OF SURFACE WATER IN AND OUTSIDE OF YNP

The δD values of nearly 300 waters from cold springs, wells, cold creeks and rivers from 1967 to 1990 and their locations are listed in Table 4. More detailed locations on USGS Yellowstone National Park or quadrangle topographic maps can be obtained from the information in Table 4. Elevations are given in feet as well as meters because the USGS topographic maps are contoured in feet. General locations of sampling points and δD values are shown in Figure 7 with locations of mountains, rivers, etc. inside the Park are shown in Figure 1.

Areas to the north of the park

In 1979 streams draining Precambrian to Mesozoic volcanic, igneous and sedimentary rocks of the Gallatin and Madison Ranges to the north and west of the park were sampled from Highway 191 along the Gallatin River drainage for nearly 40 km north of the park. The highest peaks are over 3350 meters (11,000 feet) elevation and steams flowing into the Gallatin River have steep gradients to the sampling points at 1525 to 1825 meters (5000 to 6000 feet) elevation. The δD values of most streams range from -144 to -147‰. A spring just outside of the park has a δD value of -152‰ and a spring 40 km north of the park boundary has a value of -149‰, differing considerably from those of adjacent streams. These springs have not been sampled over time to determine whether their lower δD values reflect recharge at higher elevations than the inflow for the streams, or ephemeral recharge from the last storm in the area.

The Absarokas to the north of the Park lie in volcanic and Precambian terrain between the Yellowstone and Boulder/Stillwater Rivers. This area was sampled in a road traverse in 1978. Much of the area is above 3050 meters (10,000 feet) elevation and samples were collected from elevations of 1525 to 2450 meters (5000 to 8000 feet) elevation from streams with steep gradients. The δD values of most sampled streams near the Park range from -144 to -149‰. The δD value of water in the Stillwater River and its tributaries did not vary significantly over a distance of nearly 65 kilometers and over 1225 meters (4000 feet) of elevation change before it merged with the Yellowstone River suggesting that for this stream, typical of those we studied, evaporation and mixing of water from somewhat different elevations had minimal effect on δD values. In 1978 the Montanapolis warm spring had a δD value of -152‰. This spring may have been recharged during a colder climate or from a higher elevation than the nearby cold streams and warmed by deep circulation. This spring may carry groundwater representative of deeper aquifers with minimal influence of local precipitation.

The area to north of the park between the Stillwater River and U.S. highway 212 contains the Beartooth wilderness area with peaks over 3650 meters (12,000 feet) in Precambrian terrain. Suitable sampling sites are limited along a road traverse because many drainages have glacial lakes in the high country. However, the sampled streams and rivers surrounding the Beartooth Range have a remarkably narrow range of δD value of -137 to -141‰. The single spring sampled has a lower δD of -144‰. The δD values of streams in the Beartooth region are higher (less negative) than those farther west in the Absaroka and Gallatin Ranges.

Gallatin Range

The Gallatin Range in the northwestern part of the park is bounded by the Gallatin River on the west, the Gardiner River on the northeast and the Madison River on the South. The Range contains some of the highest elevations and the largest area of high mountains in the Park. On the north side δD values of the Gardiner River range from -140 to -147‰ while δD values of Glen Creek (sampled almost yearly from 1970 to 1990) range from -147 to -153‰. In 1990 the δD value of (east) Fawn Creek was -141‰ while those of springs along the north and south side of the creek were -146 to -147‰. On the west side δD values of Daly, Black Butte, Specimen, Fan, and (west) Fawn Creeks range from -139 to -151‰. In 1990 the δD values of springs along the south side of (east) Fawn Creek were -142 to -145‰. The δD value of cold streams on the southern part of the range are less negative, based on data from Duck, Cougar, Panther, and Indian Creeks (-135 to -142‰). A small spring with variable flow near Grayling Creek has δD values of -136 to -147‰. It appears that for a given year the δD values of the fall stream discharge from the northern Gallatins are lower than those from the southern part of the range by an average of about 5 ‰.

Washburn Range

The Washburn Range lies north of the caldera and includes the area surrounded by the northern loop of the Yellowstone highway, and a watershed that drains into the Gardiner, Gibbon and Yellowstone Rivers. This area includes Mount Washburn with an elevation of over 3100 meters (10,200 feet). On the north side of the range Lava, Blacktail Deer, Elk and Tower Creeks have δD values from -143 to -148‰, while on the east side Antelope Creek, which is probably recharged at higher elevations on Mount Washburn, has lower δD values from -147 to -153‰. This is one of the few cases where we have observed clear variation of δD with elevation for inflow in a given basin. The δD values of the Gibbon River above Virginia Meadows range from -140 to -143‰, consistent with a increase in the δD values of surface waters to the south.

Buffalo Plateau

The Buffalo Plateau lies to the north of the Yellowstone and Lamar Rivers and Slough Creek and extends outside of the Park. Highest elevations are over 3050 meters (10,000 feet) largely in Precambrian terrain. A small but fast moving cold stream draining the high plateau area had a δD value of -150 ‰ in 1977. Slough Creek, Little Cottonwood Creek, and Buffalo Creek had δD values of -140 to -146 ‰ during 1977 to 1990.

Absaroka Range

The Absaroka Range is a large N-S trending chain of mountains that extends along the entire eastern boundary of the park and to the north where it joins the Beartooth wilderness area on the east and the Gallatin National Forest region in the west. Along the eastern margin of the park, the Absaroka Range consists of intermediate-silica volcanics, the remnants of Eocene stratovolcanos. Topography is steep and peaks along the ridge of the range are usually over 3050 meters (10,000 feet). The δD values of streams along the Lamar River-Soda Butte drainage range from -149 to -144‰ with an average value of -142‰. In the area near Sylvan pass, δD values of Cub Creek range from -133 to -142‰

with an average value of -139‰. The streams near Sylvan pass were sampled at an elevation of over 2600 meters (8500 feet) versus less than 2200 meters (7200 feet) in the Lamar River-Soda Butte drainage. It is clear that δD values of small streams decreases from south to north as in the Central Plateau to the west.

Madison Plateau

The Madison Plateau lies along the rim of the Yellowstone caldera in Plateau rhyolites just above 2550 meters (8400 feet) elevation. Discharge from this Plateau was sampled at three locations from 1971 to 1990. These locations were a cold spring at the base of rhyolite cliffs about 3 kilometers west of Old Faithful Geyser, the Little Firehole River above Mystic Falls, and a cold spring on the old road to Lonestar Geyser. The total range of δD values over 11 years for these waters is only -139 to -143 ‰. The cold spring at Grants pass on the Howard Eaton trail to Shoshone Lake which could be recharged on the Madison Plateau or to the east in the hills north of Shoshone Lake had δD values of -135‰ in 1973 and -143‰ in 1976. Cold springs in the area of Shoshone Geyser Basin range from -135 to -138‰. The δD of the subsurface discharge appears to decrease slightly from south to north in the plateau area.

Central Plateau

The Central Plateau area borders the major geyser basins and covers the region centered around the western resurgent dome of the Yellowstone caldera. The highest elevations in the Central Plateau are about 2625 meters (8600 feet) and much of the plateau is above 2550 meters (8400 feet). Nez Perce Creek which drains the largest watershed in the Central Plateau was sampled at an elevation of about 2200 meters (7200 feet). δD values of -143 to -147‰ were measured from 1971 to 1990. The values are within the -143 to -148‰ range observed from 1975 to 1982 for Arnica Creek which has a much steeper gradient near the southeastern margin of the Central Plateau. δD values of -140 to -148‰ were also obtained for unnamed creeks with steep gradients draining the 2625 meter (8600 foot) Elephant Back Mountain on the eastern side of the plateau between 1971 and 1990. The δD values of the Gibbon River, which has some tributaries on the north margin of the Central Plateau, ranged from -140 to -144‰ in the years 1967 to 1990. The δD values of cold streams and wells at the western margins of the Central Plateau are slightly less negative. On the western margin of the plateau the δD values of water from cold wells for water supplies at the Midway picnic ground in Lower Geyser Basin, Old Faithful, and Norris range from -138 to -143‰. Substantially higher δD values are noted for streams on the south margin of the plateau. DeLacy Creek has a small drainage starting at 2550 meters (8400 feet). δD values of DeLacy Creek ranged from -136 to -142‰ over an 20 year period. Even less negative values of -133 to -137‰ were obtained for Little Thumb Creek which drains similar elevations about 8 kilometers to the east of DeLacy Creek. The δD values of all discharge from the central, northern and eastern margins of the Central Plateau range from -138 to -148‰ and average about -143 to -145‰ while the δD values of discharge in the south margin are higher by about 5-7 ‰.

Yellowstone Lake and Yellowstone River

The δD values of Yellowstone Lake water at the outlet to Yellowstone river near Fishing Bridge, and at Pumice, and Steamboat Points was measured between 1975 and 1990 at -128 to -133‰. The δD value of the Yellowstone River at Buffalo Ford is -125 to -130‰. The enrichment of this water in D over inflow streams reflects evaporation in the lake, which is not surprising considering the residence time of water in the lake is about 10 years (Pearson and Truesdell, 1978).

Mirror Plateau

The Mirror Plateau area borders the fumarolic thermal areas that lie east of the Yellowstone caldera. The highest elevations are above 2900 meters (9600 feet) and much of the plateau area is above 2675 meters (8800 feet). Most of the streams sampled are from steep drainages and δD values should be representative of discharging springs in the area. Streams from the Mirror Plateau and Specimen Ridge had δD values of -143 to -145‰ between 1975 and 1990. These values are similar to those noted from the streams and rivers draining the Absaroka Range to the east and north and the central plateau to the west over a longer period of time. Most of the Mirror Plateau drainage flows north into the Yellowstone River along its Grand Canyon.

Pitchstone Plateau and areas south and west of the park

The Pitchstone Plateau lies to the southwest of the caldera at an elevation of about 2675 meters (8800 feet). Springs probably recharged on the plateau were sampled in 1982 during a single traverse along the trail on the east side of the Bechler River at elevations below 2050 meters (6800 feet). δD values of the water from the springs range from -132 to -135‰, consistent with values observed for the Bechler River (-134‰).
The δD values of streams and rivers areas south (Boone, Calf and Glade Creeks) and west (Strong, Rock, Beaver, and Robinson Creeks) of the Pitchstone Plateau outside of the Park that were also sampled in 1982 have essentially the same range of δD from -131 to -137‰. These values are clearly less negative than those observed for streams in the Central and Madison Plateaus to the north.

Snake River drainage

We have not been able to sample the Two Ocean Plateau area between the Snake and Yellowstone Rivers. However, δD values increase southward in the Park and no cold streams or springs with δD values lower than -144 ‰ have been observed south of Latitude 44° 30'. Cold springs in the Shoshone Geyser Basin ranged from -135 to -138‰ in 1973. Witches Creek above the thermal springs at Heart Lake had a δD value of -140‰ in 1978. The cold spring at Grants pass on the Howard Eaton trail to Shoshone which could be recharged on the Madison Plateau or to the east in the hills north of Shoshone Lake had a δD value of -135‰ in 1973 and -143‰ in 1976. The Snake River at Flagg Ranch had δD values of -131 to -136‰ from 1978 to 1990.

DISCUSSION

δD values of the cold water samples for YNP and the surrounding areas given in Table 4 are summarized in Figure 7. Where samples were taken over several years, average values are shown in italics; data for springs and wells are shown in boldface. δD contours are drawn through the most negative values in the area and are guided by values for samples that are most representative of infiltrating waters. A number of points are evident from the data in Figure 7: 1) δD values of the surface water become more negative from south to north and from east to west north of the park and in the northern part of the park, 2) δD values of surface water more negative than -144‰ are not found in the southern half of the Park. 3) Except for a two small cold streams (both of which are easily influenced by local storms) surface waters with δD values of -148 to -150‰ are not found near the geyser basins. 4) Localities where the δD values of streams or springs are ≤ -150‰ are found exclusively north of the caldera and are relatively scarce.

Yearly variations in δD values at individual sites

The pattern of δD distribution for cold waters of the Park developed in the course of our study is dependent in part on analyses of samples collected once or twice. In order to see if the individual δD values were consistent from year to year and if the same relative differences between waters from various locations were found in different years, we made repeated collections at certain accessible sites.

The maximum variation in δD for an individual stream over the collection period from 1967 to 1990 is 8‰. Although there are some exceptions, δD values of most streams vary by about the same amount from year to year. This pattern is illustrated in Figure 8 which shows similar patterns for δD variations of 9 representative streams at various locations within the park from 1967 to 1990. The important point is that the average δD value for each locality will give a valid picture of the spatial variations in δD of possible infiltrating waters.

Our data base is not sufficiently complete to understand all of the factors controlling the detailed δD of precipitation in the area. Such detailed understanding must await data on individual storms collected over an extended period of time and information on the residence times of infiltrating precipitation that recharges the streams. As indicated in Figure 8 the least negative δD values are for streams collected in 1990 while the most negative values are for streams sampled in 1976. The late 1980's were characterized by below normal amounts of winter precipitation while the early 1970's were characterized by above normal amounts of winter precipitation, as indicated by the yearly average discharge of major rivers (Norton and Friedman, 1991). Although most of the fall stream flow is recharged during the previous spring run off, there may be a substantial component that remains from previous years. Much more detailed studies are needed, but it seems that the average δD values of the streams for a given year correlate with the amount of winter precipitation in the preceding years.

The climatic significance of the regional distribution of the δD of cold waters in the area

The increase in δD values in all directions away from the mountainous Yellowstone Plateau is consistent with the results of a recent study of over 4800 δD values of surface waters in the conterminous US which shows Yellowstone within a large area with δD values lower than -130‰ in which δD contours closely match topographic contours (Kendall and Coplen, 1991). Yellowstone lies in a part of North America affected by Arctic, Gulf of Mexico and Pacific air masses (Bryson and Hare, 1974). The general distribution of δD values of cold waters in the YNP area reflects the influence of both complex weather patterns and altitude.

Precipitation records at Yellowstone have been summarized by Dirks and Martner (1982), river run off records have been summarized Norton and Friedman (1991), and weather patterns have been interpreted by Despain (1987). According to NOAA Climatological Data Annual Summary Records, precipitation in the region is fairly well distributed throughout the year with the exception that the large storms occur in mid winter and dry periods may occur in the fall. As much as 75 percent of the total precipitation at Yellowstone falls during winter snow storms from October through May. The remainder falls primarily during local warm-season thunderstorms. Since the valleys at Yellowstone tend to be dry, seasonal river flow measurements for the major drainage basins such as the Madison indicate that most precipitation is concentrated in the higher elevations and accumulates there as snow causing high river volumes during spring snow melt. The largest amount of precipitation falls in the high plateaus in the southwestern part of the Park with the central plateau in the rain shadow of the higher areas to the southwest (Dirks and Martner, 1982; Norton and Friedman, 1991).

The largest storms are from the Pacific and enter the Park region from the Snake River Plain to the southwest. Winter weather in Yellowstone usually depends upon the relative strengths and positions of Arctic and Pacific air masses. The increase in δD values in all directions away from the mountainous Yellowstone Plateau reflects the influence of high altitudes and complex weather patterns in the region involving Pacific, Arctic and Gulf air masses. The northerly decrease in δD values reflects both increases in elevation and the general S to N path of storm trajectories as well as the rain shadow produced by the southwestern mountains. The trend to less negative δD values for cold water in the northeastern part of mountainous region may reflect the importance Gulf air masses in the eastern part of the region.

The source of recharge of the deep thermal water

Possible recharge areas are constrained by low δD values (-148 to -150‰) comparable to that of the deep thermal waters. It is clear that if deep thermal water was recharged under the present climatic cycle the location of recharge must have been in the mountainous areas to the north and northwest of the caldera. These include: 1) the Gallatin Range in the northwest part of the Park and in the area north of the park between the Gallatin and Yellowstone Rivers, 2) the Washburn Range, 3) the Buffalo Plateau, and 4) the Absarokas to the north of the park.

From geologic considerations (Figures 9 and 10) the most likely recharge area for deep thermal water underlying the geyser basins on the western side of the caldera is the Gallatin Range between Highway 191 and 89 in the northwestern part of the Park and probably extensions of this range to the north of the Park. This elevated area is bounded by several major N-S trending faults which parallel regional faults that are known from earthquake data to be active (Christiansen, 1984). Large sections of these faults are covered by glacial tills and river gravels which are excellent aquifers for the recharge of water to deep levels along the faults. Runoff from snow melt in the spring keeps the gravels saturated with water which in turn can infiltrate along the faults to deep levels of the Yellowstone thermal areas. This area also has large areas of fractured Precambrian basement, Paleozoic and Mesozoic sediments with karstic topography in limestones and Eocene volcanics which may have permeable contacts. Recharge water may also flow along some NW-SE faults in the northwestern part of the Park that parallel major active faults to the west of the park. Additional recharge could come from the Washburn Range but, as faults in the Yellowstone tuff are also N-S, water from this area is more likely to recharge the gas-rich thermal areas in the eastern side of the caldera. Tectonic and sedimentary structures on the east slide of the caldera do not favor recharge from the Absorokas to the east. The recharge area for deep thermal waters in the Gallatin Range is at least 20 km from outflow at Norris Geyser Basin, 30 km from out flow at Lower Geyser Basin and as much as 60 and 70 km from outflow at Shoshone and Heart Lake Geyser Basins, respectively.

We need to consider whether or not the amount of precipitation on the Gallatin Range is sufficient to recharge the deep reservoir supplying the geyser basins on the western side of the caldera. Measured discharge rates of the rivers and chloride concentrations in river waters have been used to calculate the rate of total discharge of the deep component of the hot spring waters (Fournier, 1989; Norton and Friedman, 1991). The amount of deep water (i.e. that heated to ≥350 °C and having 360 ppm Cl) from the west side of the caldera measured by the chloride flux (Norton and Friedman, 1991) in the Madison and Snake Rivers averages about 7.5 x 10^{10} kg of water yr^{-1} with nearly 90% from the Madison. The map area of the Gallatins within Park boundaries between Highways 191 and 89 is about 1000 km^2 of which about 400 km^2 is above 2550 meters (8400 feet). The annual mean precipitation at West Yellowstone and Old Faithful is about 75 cm per year judging from NOAA Climatological Data Annual Summary records and precipitation summaries by Dirks and Martner (1982). Much more precipitation would be expected at the elevations above 2550 meters (8400 feet) elevation of the Gallatin Range. Indeed, precipitation summaries quoted by Dirks and Martner (1982) place the annual mean precipitation in the Gallatin Range close to 150 cm most of which is winter snow. Thus, probably 6 x10^{11} kgs yr^{-1} of precipitation falls on the high elevations of the Gallatin Range within the Park. The amount of run off from just the elevated areas of the Gallatin Range within the Park is approximately eight times the amount of deep water estimated to be discharged from the thermal basins on the western side of the caldera each year. Additional recharge could be received from the extension of this range to the north and northwest of the Park. However, it is not possible to determine exactly where most of the recharge enters the system nor is it possible to determine how much if any recharge comes from outside of the Park boundaries.

The watershed where δD of cold waters is -150‰ is rather limited and does not appear to be large enough to recharge the deep levels of the thermal areas on the western side of the caldera. Furthermore the δD of much possible infiltrating cold water in the southern part of the Gallatin Range is less negative than -148‰ so that there may not be enough presently infiltrating cold waters of the right composition in the Gallatin Range to account for all of the deep thermal water on the western side of the caldera. This may indicate that some recharge is received from ranges to the east of the Gallatins or, more likely, that the deep thermal water was recharged during a colder period that resulted in greater winter snow accumulations and lower δD values of precipitation. Judging from variations noted in Figure 8 we would expect δD values of precipitation to be quite sensitive to increases in snowfall. High snowfall accumulations are recorded for the Yellowstone region near the turn of the 19th century (Dirks and Martner, 1982) and would also be expected during any prolonged cold period such as those observed in Europe in the 15th and 17th and 18th Centuries (Ferronsky et al., 1983).

The volume of the deep thermal water in the western side of the caldera

Figure 10 is a cartoon N-S cross section through the western side of the caldera showing hypothetical hot spring activity and recharge of local shallow and deep thermal waters. According to R.L. Christainsen (written communication, 1990) the caldera consists of a cylindrical core that originally collapsed and later formed the resurgent dome with shallow tensional faults. The resurgent dome is surrounded by thick zone of steeply dipping concentric faults which form the main ring fracture zone of the caldera. The outer part of the caldera consists of large slump blocks extending along shallow faults to the structural wall of the caldera. The location of hot spring activity at Yellowstone is probably largely controlled by the major ring fracture faults related to the formation of the caldera and to later N-S faults within and outside of the caldera. Individual springs such as those at Upper and Lower Geyser Basins, however, may be located along shallow faults that parallel those in the resurgent dome to the east. The shallow structures at the margins of the caldera probably permit a wedge cold water to mix with deep thermal water at various levels within the caldera.

The maximum volume of the deep thermal fluid reservoir in the western side of the caldera can be assumed to be the volume of a cylinder approximately the 30 km diameter of the outer ring fracture of the caldera. The bottom of the reservoir is the lower limit of circulation of meteoric water at which seismic activity maintains permeability in the rocks. This depth is probably about 4 km as indicated by the lowest focal depth of earthquakes beneath the caldera (Fournier and Pitt, 1985). Deeper circulation of water may have taken place in the past and may have circulated into the magma (Friedman et al., 1974; Lipman and Friedman, 1975). However this deep circulation probably only happens during recurrent explosive activity during and immediately after the formation of the caldera (Hildreth et al., 1984; Taylor 1986). Today the circulation depth of meteoric water is probably limited by the depth at which rock deformation changes primarily from brittle fracture to quasi-plastic flow (Fournier, 1989; 1991). This transition probably coincides with a thin zone of thermal cracking that migrates inward toward the magma with time as the rocks are cooled. (Lister, 1974; 1980; 1983). Recharge of cold water along active faults would result in thermal cracking of intrusive rocks at depth creating a continuous supply of permeable rocks in the deep levels of the thermal areas (Christiansen, 1984). The top of the deep reservoir (defined as thermal water not influenced by shallow recharge) may extend in some areas as shallow as 0.5 km as indicated by the depth to the unmixed deep thermal water indicated from modeling (Truesdell et al., 1977) of the isotopic and chemical composition of hot spring water. Thus the maximum thickness of the reservoir for deep thermal water is probably about 4 km.

The maximum amount of water in this reservoir can be calculated with assumptions about average porosity of the reservoir. The rocks in the caldera are a heterogeneous mixture of porous rhyolite, and dense welded tuff and some sediment from the latest and earlier volcanic episodes. Studies of intracaldera volcanics for the smaller caldera at Long Valley, California, indicate porosities between 1 and 10 % (Sorey et al., 1978). The larger figure for is probably not realistic for the Yellowstone caldera as the Yellowstone tuff is dense and the deep thermal water is almost certainly concentrated in highly fractured and permeable rhyolite and is not uniformly distributed throughout the entire caldera. The maximum average porosity for the intracaldera volcanics at Yellowstone can assumed to be about 5% (R. L. Christiansen, oral communication, 1991). Assuming an average porosity between 1 and 5% the amount of thermal water in the deep reservoir is between 28 and 141 x 10^{12}kg.

Age of the deep water

There are few constraints on the age of the deep water. Pearson and Truesdell (1978) determined from tritium measurements that most thermal waters are mixtures of two waters- one containing tritium from an open, well-mixed reservoir of relatively short residence time, the other containing no detectable tritium presumably derived from a deep source. The fact that the deep water contains no detectable tritium means that the deep water is at least 60 years old based on the 12.3 year half life for tritium. Carbon-14 was not detected in CO_2 from fumarolic steam as to be expected for CO2 of igneous or sedimentary origin (F.J. Pearson, Jr, unpublished data, 1978).

A maximum age of the deep water can be estimated from the discharge rate for deep water of about 7.5×10^{10} kg yr^{-1} as measured from Cl inventory considerations (Norton and Friedman, 1991) and the above assumptions for the minimum and maximum volume of the deep water reservoir. The reservoir would be emptied in every 370 to 1900 years assuming a piston flow model in which water does not mix within the reservoir and there is only one point of recharge. These times are consistent with the maximum time (1150 years) for water-rock reaction estimated from a solution and recoil model for radium isotope supply to the hydrothermal system (Clark and Turekian, 1990).

However, if the deep reservoir is well mixed, the oldest water component could exceed 10,000 years raising the possibility that some of the deep water could have been recharged under a different climate regime in which precipitation was isotopically much lighter than at present. However, the amount of recharge during the last glacial period may have been very low because most of Yellowstone, particularly the elevated northern areas, was under a thick ice layer (Pierce, 1979) and recharge channels would have been frozen. Although the presence of thermal kames indicate that certain hot springs were flowing during the last glacial period, hot spring activity was probably greatly reduced. Furthermore the uniformity of temperature, chloride and δD in the deep thermal water probably indicates that the deep water has a uniform source of heat and chloride which is indeed likely for a magmatic system. This uniform source could be produced by thermal stress cracking and contribution of heat and chloride from the freshly exposed rock (Lister, 1974; Christainsen, 1984) or by contribution from a magma across a brine meteoric water interface (Fournier, 1989). It appears probable, therefore, that the time required to flush the entire deep reservoir of the hydrothermal system is considerably less than the 14,000 years since the end of the last glaciation and we can reasonably assume that the recharge of the deep aquifer was under the present hydrologic cycle with variable warm and cold periods (c.f., Vance et al., 1992; Feng and Epstein, 1993) producing small but significant variations in the δD of precipitation. This time spand would also allow for an effect on the volume of flow from the Little Ice Age (15th Century) which would have likely resulted in recharge water of lower δD.

CONCLUSIONS

An extensive park-wide collection and analysis of cold water samples was undertaken to determine the sources of recharge to the geyser and hot spring basins of Yellowstone National Park. Earlier chemical and isotopic modeling of boiling and mixing processes, along with composition of waters from 200-300 meter deep drillholes, show that δD of deep thermal water (-148 to -150‰) is significantly lower that of local cold waters which enter thermal reservoirs only near the surface. Cold waters in the central, southern and eastern parts of the Park are isotopically too heavy (generally δD = -130 to -144‰) to provide deep recharge. Only in the Gallatin Range in the NW part the Park are cold water δD values sufficiently low and geologic structures appropriate to carry recharging water into the deep caldera reservoir. The source of recharge for the deep thermal water is at least 20 km and possibly as much as 70 km from outflow areas. The deep water is at least 60 years old from tritium measurements but probably less than 1900 years as estimated from volume and flow calculations. The quantity of high altitude infiltration with δD ≤-148‰ in this area may not be sufficient at present to match measured thermal outflow as determined from chloride flux studies and some infiltrating waters may have been recharged during a somewhat cooler climate with more winter snowfall such as would be expected to have occurred during the Little Ice Age (15th Century).

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FIGURES

FIGURE 1. Sketch map of Yellowstone National Park showing locations of geyser basins (gray) and their relation to the Yellowstone caldera (heavy black), important N-S faults (thin black), resurgent domes (dashed pattern), surface drainage and topographic features. Also shown are the Continental Divide (dotted line) roads (heavy dots) and state boundaries (thin dashed lines). Caldera outline resurgent domes and faults after Christainsen (1984).

FIGURE 2. Generalized mixing and boiling model for Norris waters from Truesdell et al. (1977). Solid straight line shows compositions and temperatures for mixture of deep thermal water and surface water. Wide dark gray line shows evolved composition of deep waters that undergo single stage or continuous steam separation from 360 to 93 °C without mixing. Dashed lines show compositions at 93°C for various mixed waters after undergoing single stage or continuous steam separation from mixtures having the indicated starting temperatures as shown in parentheses. Gray field shows compositions of Norris neutral chloride hot spring waters. Similar diagrams using the same deep water compositions can explain the compositions of hot springs at Upper and Lower and Shoshone Geyser Basins (Truesdell et al., 1977).

FIGURE 3. Enthalpy-chloride diagram for Lower and Upper, Norris, Heart, and Shoshone Geyser Basins from (Truesdell and Fournier, 1976). Pattern areas outline composition for hot neutral chloride waters in each geyser basin. Since very little heat is lost by conduction and chloride is conservative, all enthalpy and chloride compositions must be a result of mixing and boiling. Diagram shows that all compositions for all basins can be explained as a result of mixing and boiling combinations of single deep thermal water having about 320 ppm chloride at 360°C and dilute cold waters.

FIGURE 4. $\delta^{18}O$-chloride relations for neutral chloride hot spring waters from the Heart Lake, Upper and Lower, Norris, Shoshone and West Thumb Geyser Basins. The less negative $\delta^{18}O$ values for hot waters and Heart Lake and West Thumb reflect the mixing of evaporated waters from Heart and Yellowstone Lakes, respectively. The fact that the compositions of the all of the hot waters fall on a trend suggests they may have evolved from the same thermal water deep water. Different isotopic compositions of hot waters in various basins reflect in large part mixing of the deep thermal water with local shallow water of different compositions.

FIGURE 5. δD - $\delta^{18}O$ of precipitation, streams, rivers, cold springs, wells, and lakes showing relationship to the global meteoric water line (Craig, 1961). Insert shows same data set with two additional precipitation samples with extreme compositions.

FIGURE 6. δD of monthly precipitation collections from rain gauges at Old Faithful from August 1978 to January 1981.

FIGURE 7. Sketch map of YNP and surrounding area showing the δD of cold waters at each sample site. Bold numbers indicate samples of springs. Italics indicate average value for several years. Contours are drawn artistically around the most negative δD values and include samples believed to be most representative of infiltrating waters .

FIGURE 8. δD in early fall discharge of eight Yellowstone streams sampled repeatedly in the fall from 1967 to 1990.

FIGURE 9. Geologic sketch map of YNP showing possible recharge area for the deep thermal waters for the geyser basins based on the δD values of cold waters in Figure 7.

Also shown is location of cross section in Figure 10. The indicated area is the likely source of recharge for thermal waters at Norris, Lower, and Upper Geyser Basins. The possibility of this area as a source of recharge to more distal geyser basins at West Thumb, Shoshone, and Heart Lake is less certain .

FIGURE 10. Cartoon N-S cross section through the western side of YNP showing possible recharge for deep thermal water and shallow mixing waters at Lower and Shoshone Geyser Basins. Caldera structure based on sketch from R.L. Christiansen (written communication, 1990).

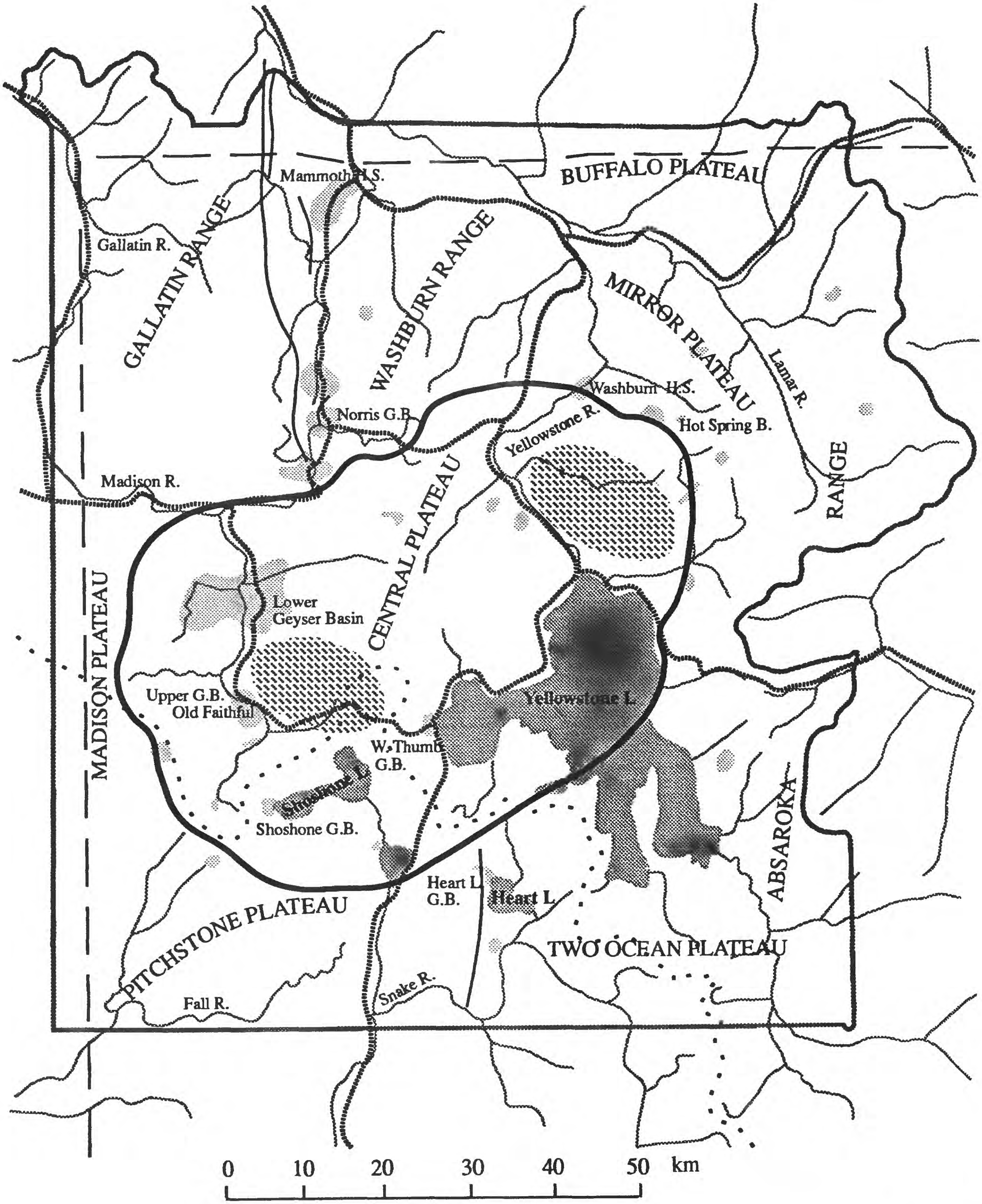

BUFFALO PLATEAU
Mammoth H.S.
Gallatin R.
GALLATIN RANGE
WASHBURN RANGE
MIRROR PLATEAU
Lamar R.
Washburn H.S.
Hot Spring B.
Norris G.B.
Yellowstone R.
RANGE
Madison R.
CENTRAL PLATEAU
MADISON PLATEAU
Lower
Geyser Basin
Upper G.B.
Old Faithful
Yellowstone L.
W. Thumb
G.B.
Shoshone L.
Shoshone G.B.
ABSAROKA
Heart L.
G.B.
Heart L.
PITCHSTONE PLATEAU
TWO OCEAN PLATEAU
Fall R.
Snake R.
0
10
20
30
40
50
km

Figure 1

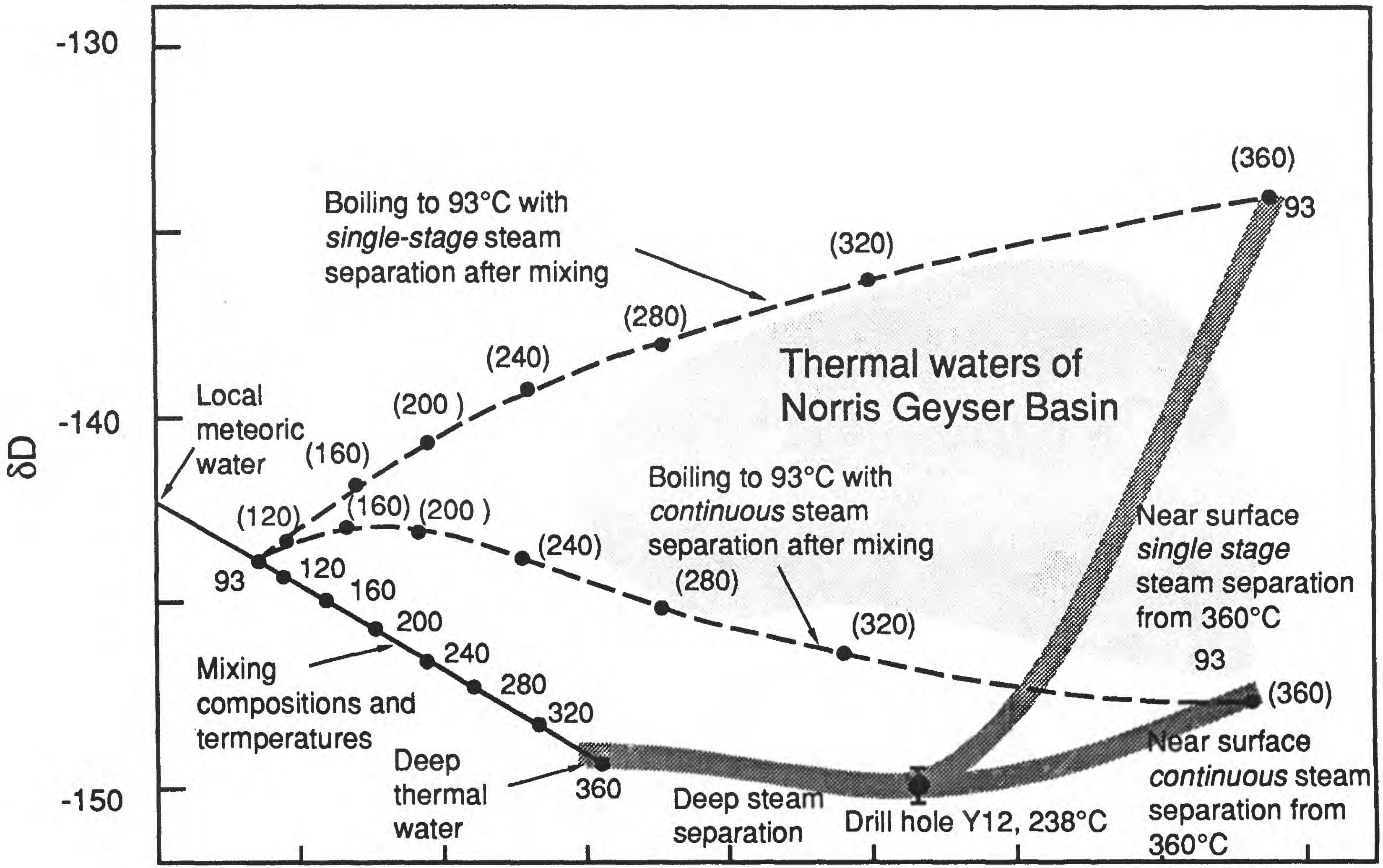

-130
-140
-150
δD
100
200
300
400
500
600
700
800
Chloride, ppm
Thermal waters of Norris Geyser Basin
Boiling to 93°C with *single-stage* steam separation after mixing
Boiling to 93°C with *continuous* steam separation after mixing
Near surface *single stage* steam separation from 360°C
Near surface *continuous* steam separation from 360°C
Local meteoric water
Mixing compositions and termperatures
Deep thermal water
Deep steam separation
Drill hole Y12, 238°C
93
120
160
200
240
280
320
360
(120)
(160)
(200)
(240)
(280)
(320)
(360)

Figure 2

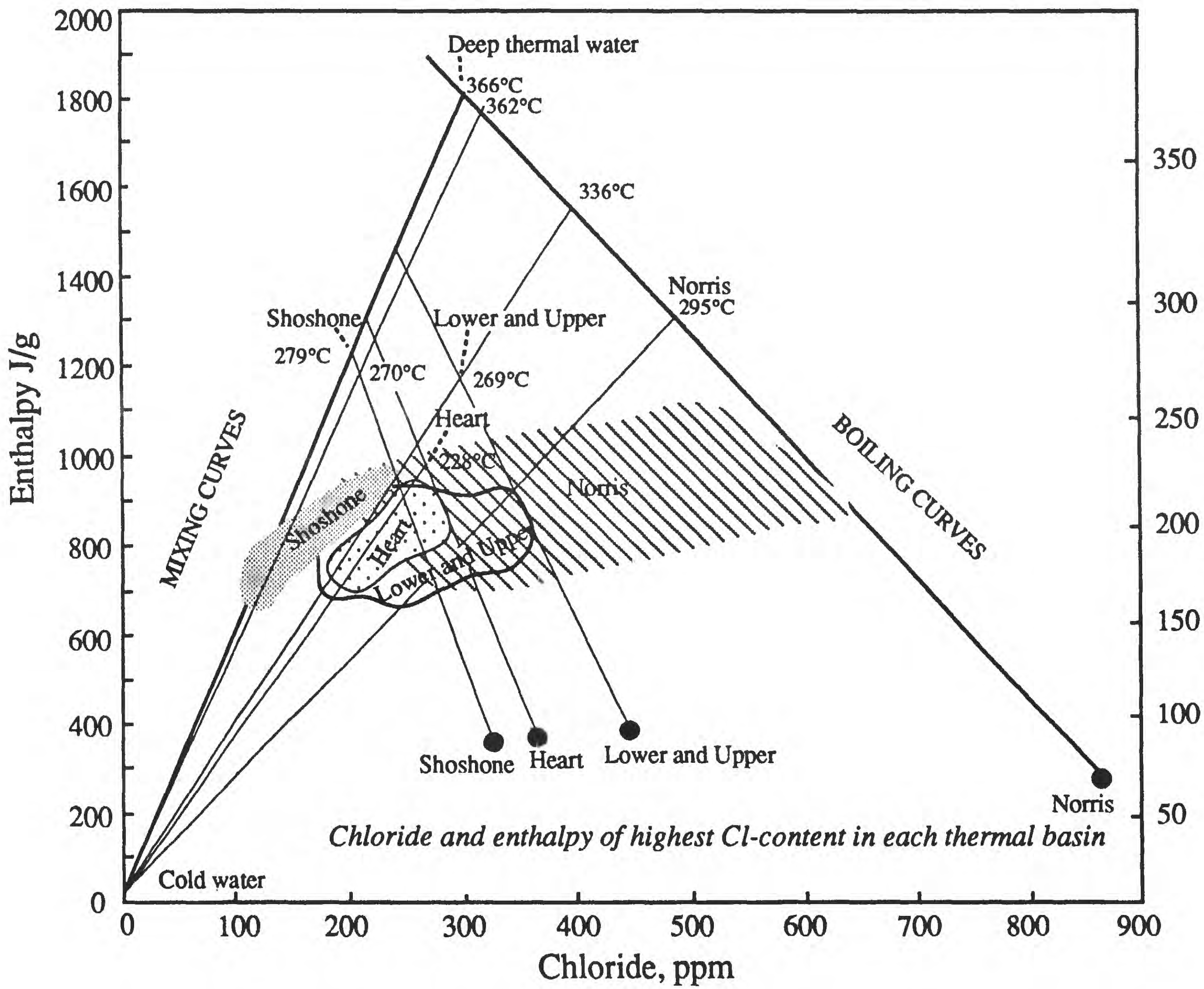
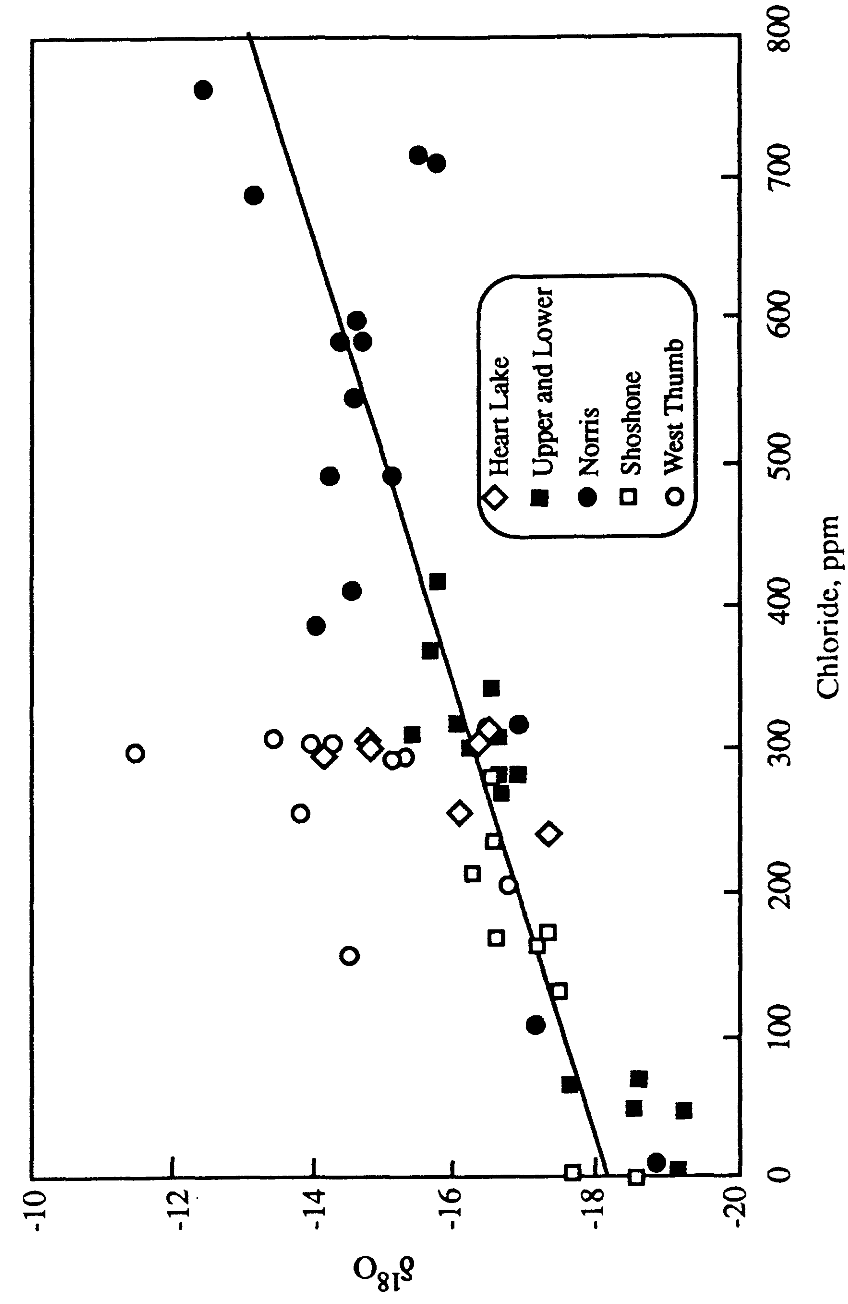

Enthalpy J/g
Chloride, ppm
Temperature °C
Deep thermal water
366°C
362°C
336°C
Norris
295°C
Shoshone
279°C
270°C
Lower and Upper
269°C
Heart
228°C
Norris
Shoshone
Heart
Lower and Upper
MIXING CURVES
BOILING CURVES
Shoshone
Heart
Lower and Upper
Norris
Chloride and enthalpy of highest Cl-content in each thermal basin
Cold water
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
100
200
300
400
500
600
700
800
900
50
100
150
200
250
300
350

Figure 3



Heart Lake
Upper and Lower
Norris
Shoshone
West Thumb
Chloride, ppm
0
100
200
300
400
500
600
700
800
$\delta^{18}O$
-10
-12
-14
-16
-18
-20

Figure 4

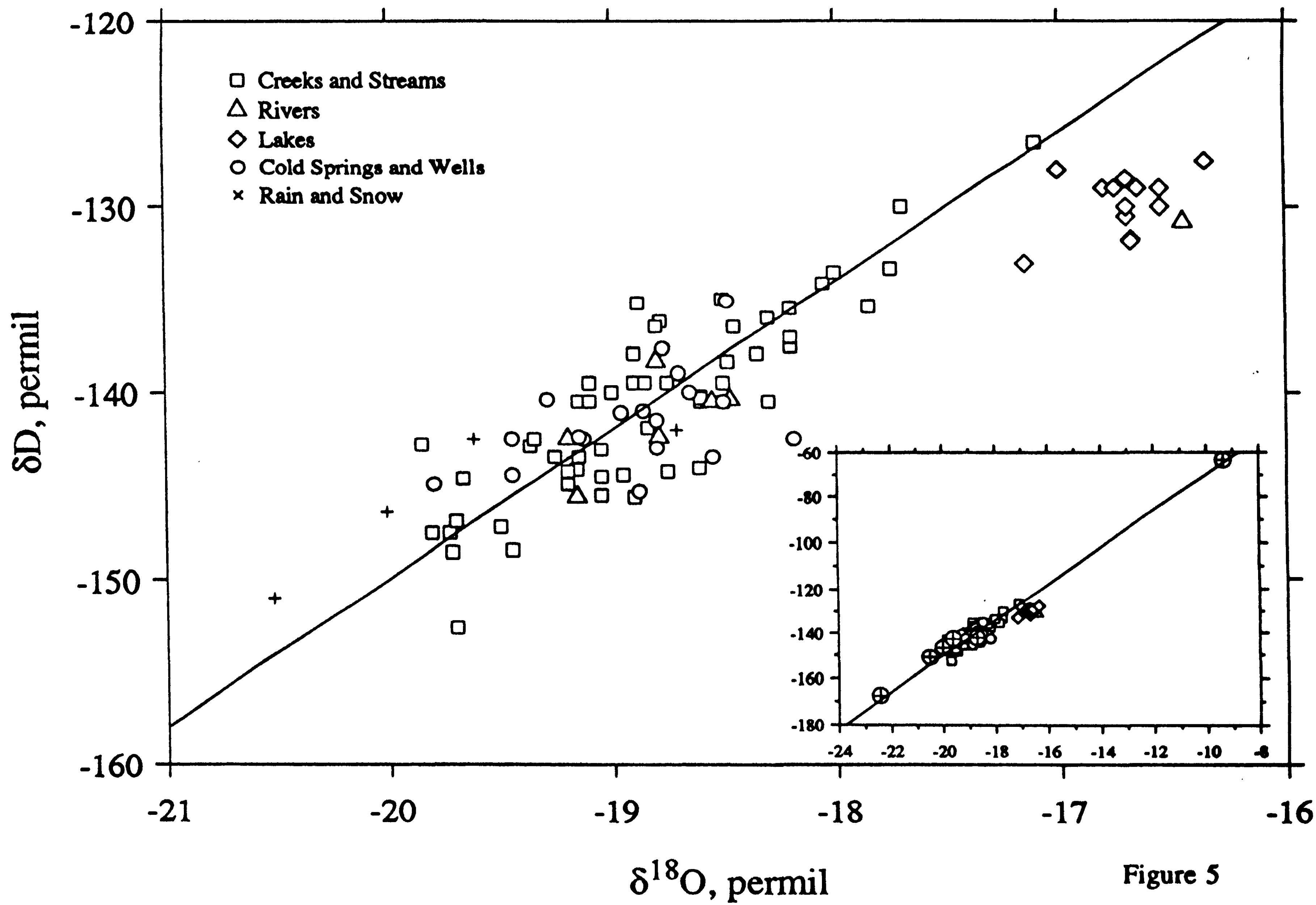

Creeks and Streams
Rivers
Lakes
Cold Springs and Wells
Rain and Snow
δD, permil
δ18O, permil
-120
-130
-140
-150
-160
-21
-20
-19
-18
-17
-16
-60
-80
-100
-120
-140
-160
-180
-24
-22
-20
-18
-16
-14
-12
-10
-8

Figure 5

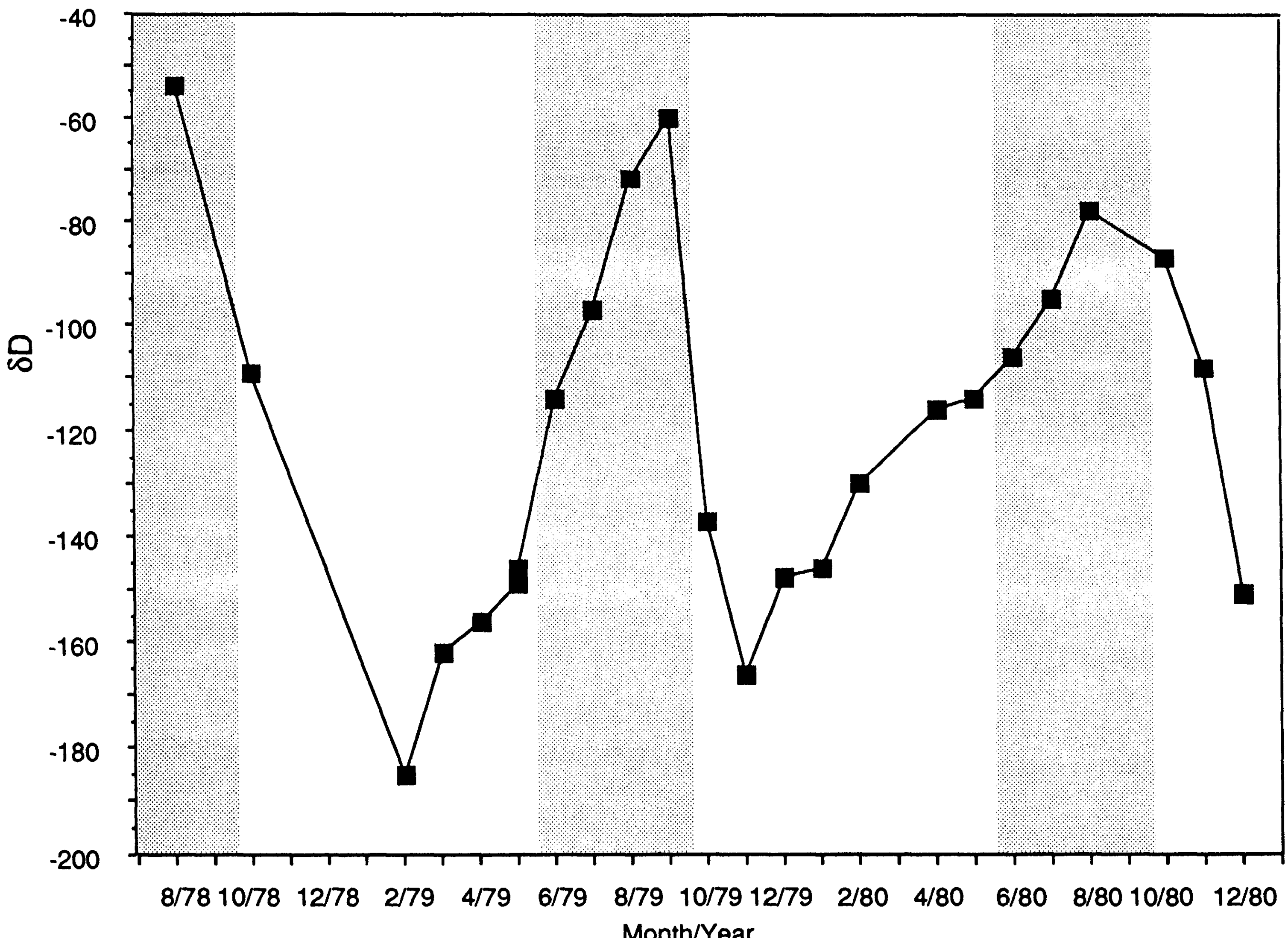

δD
-40
-60
-80
-100
-120
-140
-160
-180
-200
8/78
10/78
12/78
2/79
4/79
6/79
8/79
10/79
12/79
2/80
4/80
6/80
8/80
10/80
12/80
Month/Year

Figure 6

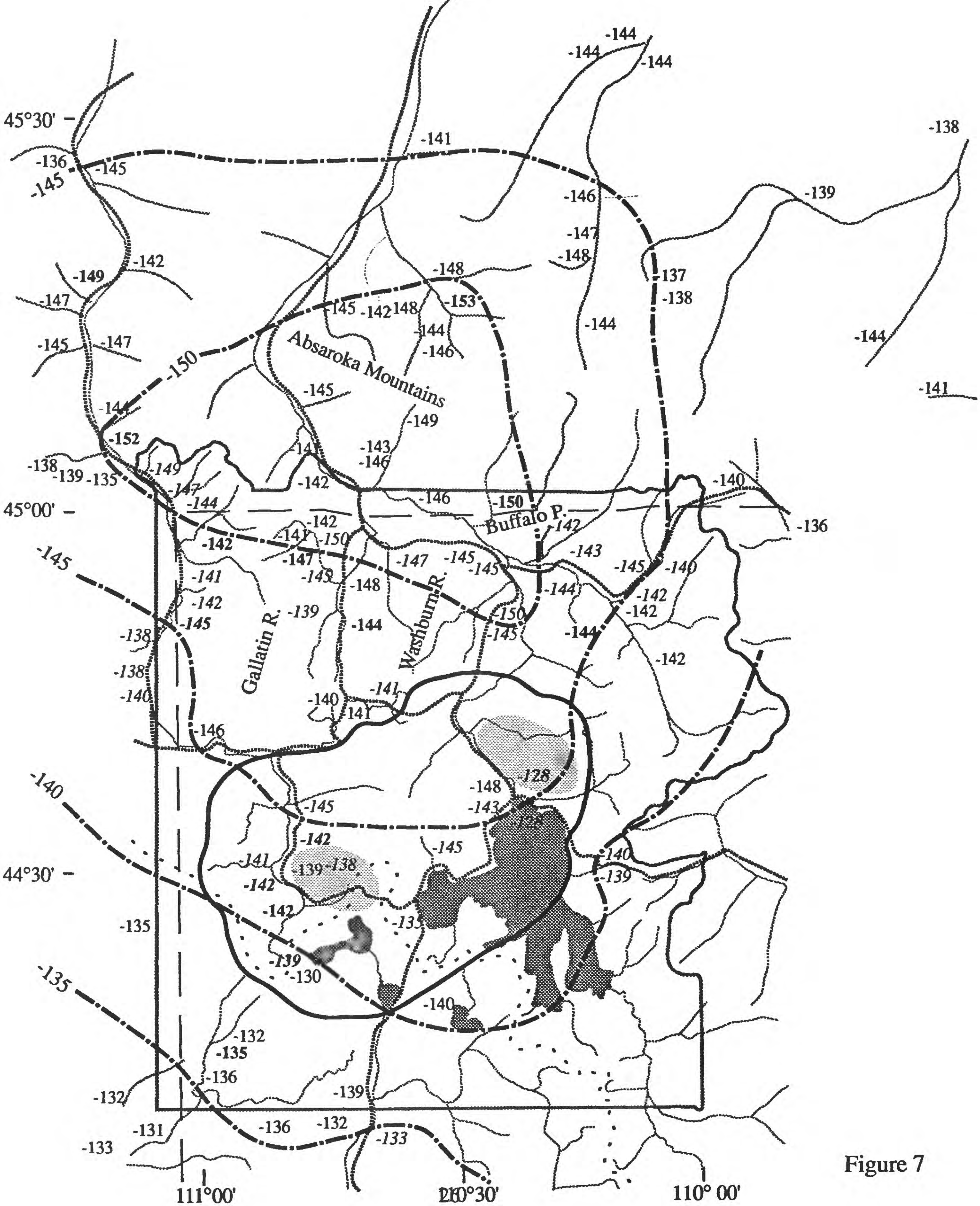

45°30'
45°00'
44°30'
111°00'
110° 00'
Absaroka Mountains
Gallatin R.
Washburn R.
Buffalo P.
-150
-145
-140
-135
-128
-138
-139
-141
-144
-146
-153

Figure 7

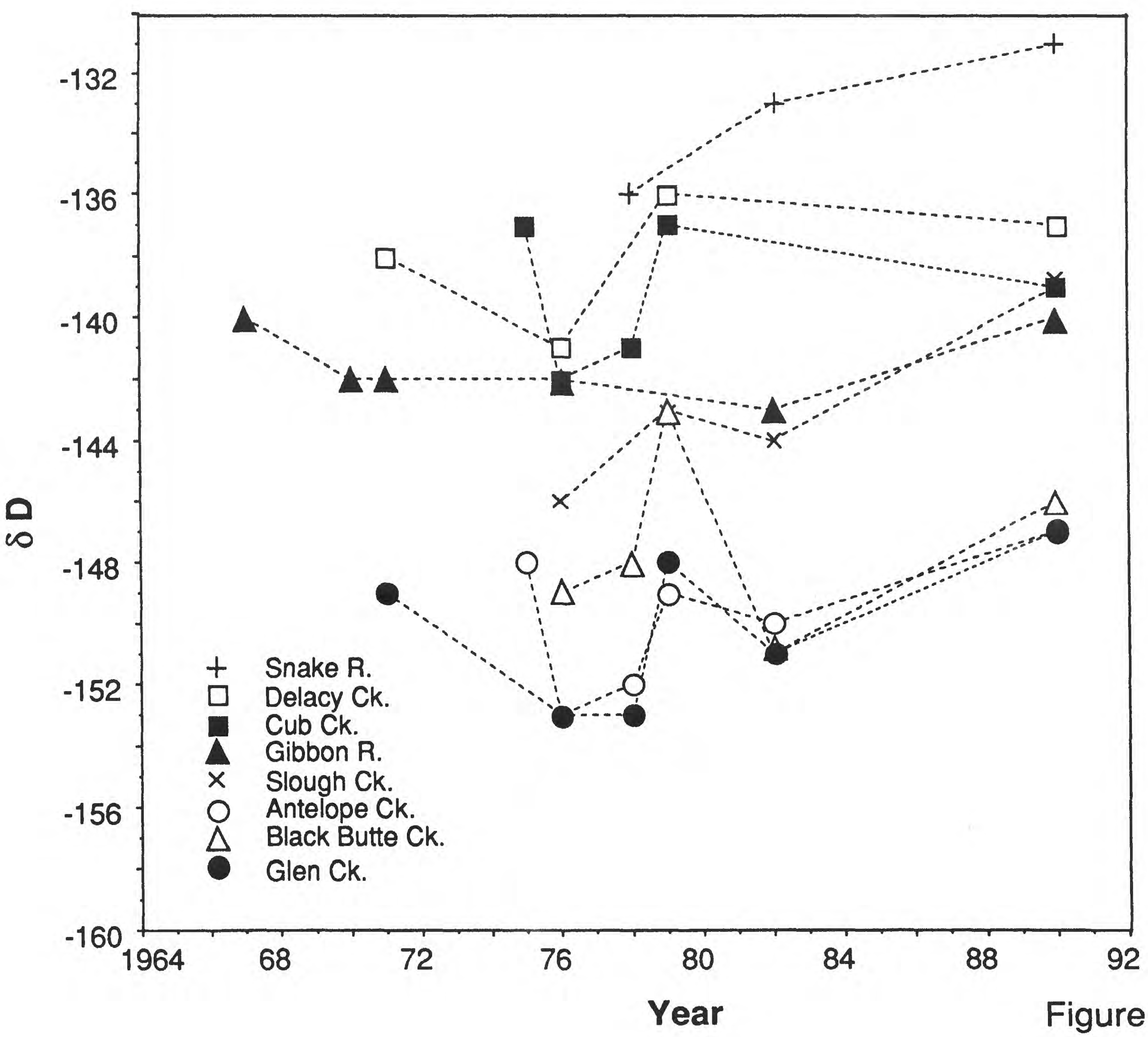

δ D
-132
-136
-140
-144
-148
-152
-156
-160
1964
68
72
76
80
84
88
92
Year
Snake R.
Delacy Ck.
Cub Ck.
Gibbon R.
Slough Ck.
Antelope Ck.
Black Butte Ck.
Glen Ck.

Figure 8

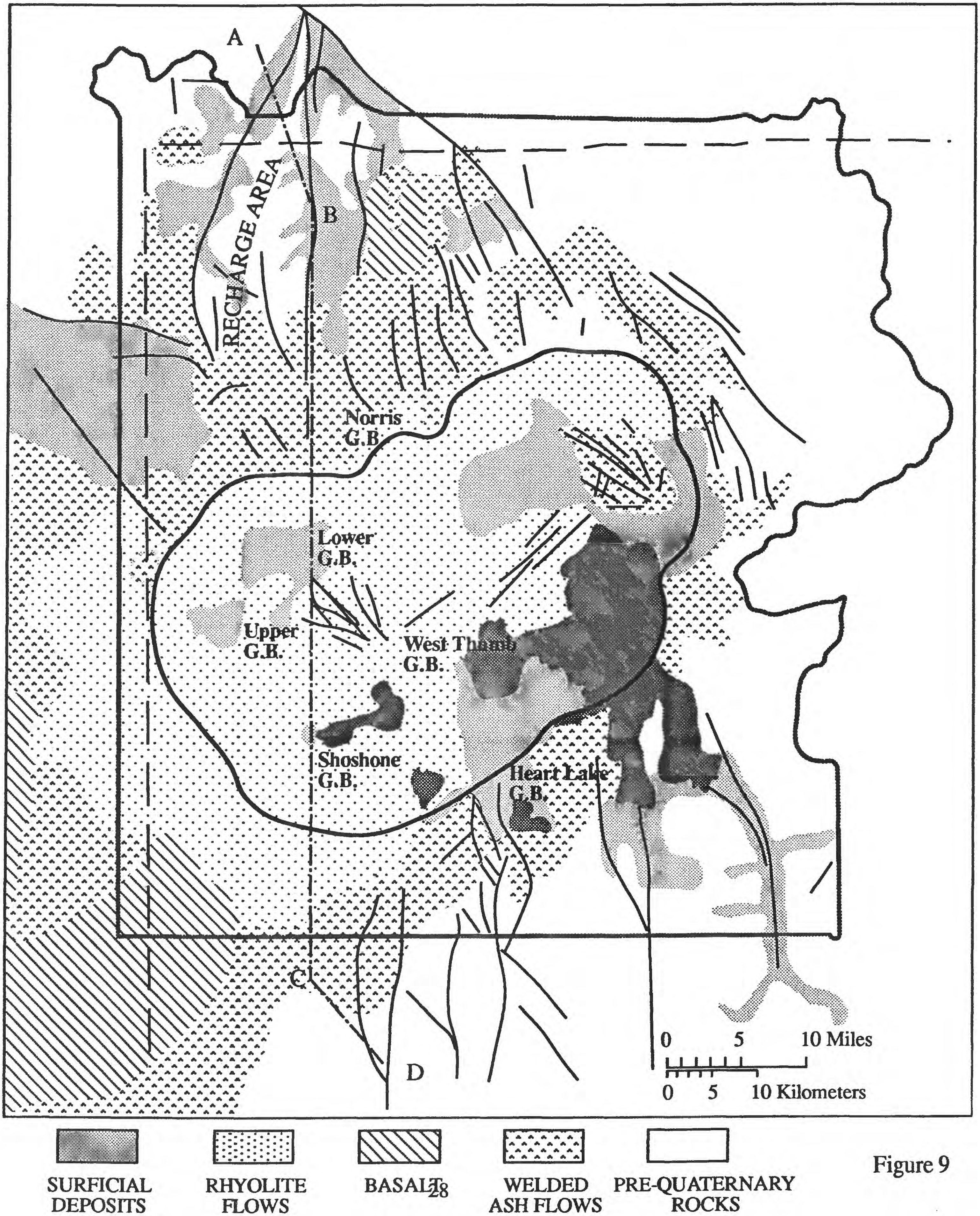
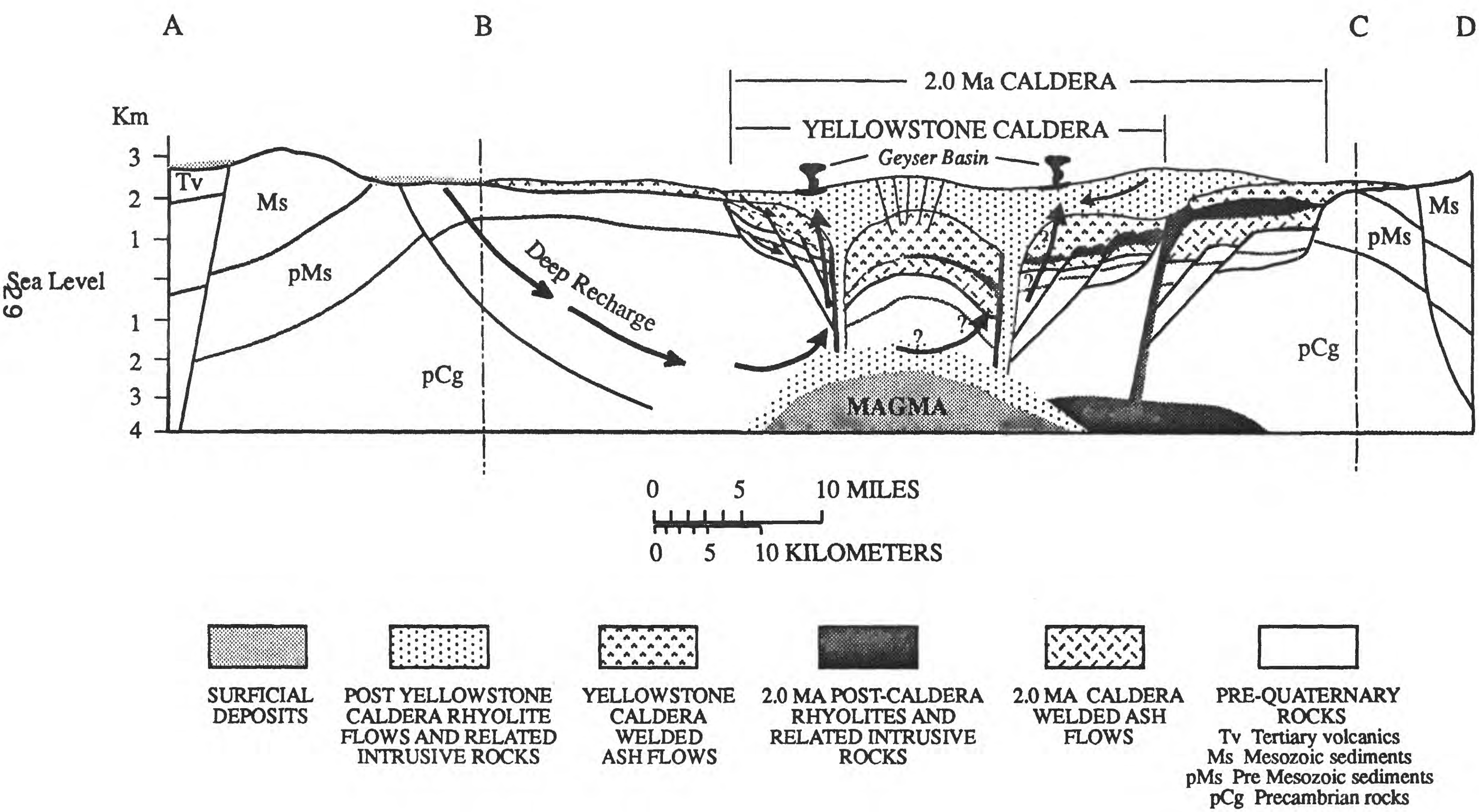

A
B
C
D
RECHARGE AREA
Norris G.B.
Lower G.B.
Upper G.B.
West Thumb G.B.
Shoshone G.B.
Heart Lake G.B.
0 5 10 Miles
0 5 10 Kilometers
SURFICIAL DEPOSITS
RHYOLITE FLOWS
BASALT
WELDED ASH FLOWS
PRE-QUATERNARY ROCKS

Figure 9



A
B
C
D
2.0 Ma CALDERA
YELLOWSTONE CALDERA
Geyser Basin
Km
3
2
1
Sea Level
1
2
3
4
Tv
Ms
pMs
pCg
Deep Recharge
MAGMA
0 5 10 MILES
0 5 10 KILOMETERS
SURFICIAL DEPOSITS
POST YELLOWSTONE CALDERA RHYOLITE FLOWS AND RELATED INTRUSIVE ROCKS
YELLOWSTONE CALDERA WELDED ASH FLOWS
2.0 MA POST-CALDERA RHYOLITES AND RELATED INTRUSIVE ROCKS
2.0 MA CALDERA WELDED ASH FLOWS
PRE-QUATERNARY ROCKS
Tv Tertiary volcanics
Ms Mesozoic sediments
pMs Pre Mesozoic sediments
pCg Precambrian rocks

Figure 10

TABLE 1 δD of Drillhole, Hot Spring, and Cold Water Samples from Yellowstone National Park Geyser Basins

Basin	Drillholes	Hot Springs	Cold Waters
Norris	-149 to -151	-139 to -149	-140 to -144
Lower	-146 to -149	-140 to -146	-140 to -145
Shoshone		-135 to -139	-130 to -135

TABLE 2 δD of Precipitation Yellowstone National Park

Date sampled	Collection	Amount cm.	δD (‰)
	MAMMOTH		
	May-77		-118
1/26/78	Jan-78	1.9	-152
10/23/78	Jun 78 Oct 78		-90
1/12/79	Jan 12,79	0.8	-206
3/7/79	Mar 1-7,79	6.1	-184
7/30/79	Jul-79	3.3	-94
8/31/79	Aug-79	5.2	-73
10/15/79	Oct 15,79	1.3	-83
11/12/78	Oct1-Nov 12, 79		-163
	OLD FAITHFUL		
8/31/78	Aug-78		-61
10/31/78	Oct-78	1.0	-115
3/4/79	Feb-79	6.5	-189
3/31/79	Mar-79	6.3	-167
5/1/79	Apr-79	4.1	-160
5/1/79	Apr-79	4.1	-161
5/31/79	May-79	3.1	-154
6/31/79	Jun-79	3.3	-120
7/31/79	Jul-79	1.3	-103
8/30/79	Aug-79	5.8	-79
9/30/79	Sep-79	1.5	-68
11/2/79	Oct-79	5.6	-142
12/2/79	Nov-79	1.7	-171
1/2/80	Dec-79	2.4	-153
1/31/80	Jan-80	7.8	-151
3/2/80	Feb-80	5.2	-135
4/3/80	Mar-80	1.7	-151
5/1/80	Apr-80	2.5	-122
6/1/80	May-80	11.2	-120
7/1/80	Jun-80	3.2	-112
8/1/80	Jul-80	8.5	-102
9/4/80	Aug-80	4.7	-85
11/4/80	Oct-80	5.6	-93
12/4/80	Nov-80	1.7	-114
1/1/81	Dec-80	8.0	-156
7/30/82	Jul-82	5.6	-124
9/1/82	Aug-82		-113
10/1/82	Sep-82	3.3	-186
11/30/92	Nov-82	6.9	-143
12/31/82	Dec-82	7.7	-188
1/31/83	Jan-83	3.1	-138

TABLE 3 δD and $\delta^{18}O$ of Streams, Rivers, Springs, Lakes, and Precipitation at Yellowstone National Park

Sample	Description	Date sampled yr/mth/day	Temp (°C)	$\delta^{18}O$ (‰)	δD (‰)
		STREAMS			
R-25	Trib. of Solfatara Ck.	67/09/00	38	-18.6	-144
W-3	Glenn Ck.	71/09/21		-19.7	-149
W-4	Nez Perce Ck.	71/09/24		-19.2	-144
W-13	Glenn Ck.	71/10/11	7	-19.8	-148
W-18	DeLacy Ck.	71/10/11	7	-18.5	-138
W-25	Ck. N. of Lake 2 miles	71/10/12	7	-19.7	-145
W-33	Nez Perce Ck.	72/10/04	13	-18.8	-144
W-2	Little Ck.	75/10/10		-18.8	-136
W-3	Arnica Ck.	75/10/10		-19.3	-144
W-4	Cub Ck.	75/10/10		-18.9	-135
W-5	Antelope Ck.	75/10/10		-19.7	-148
W-6	Tower Ck.	75/10/10		-19.4	-143
W-7	Crystal Ck.	75/10/10		-18.8	-142
T73-87	Fall Ck.	73/09/00		-17.7	-130
T76-14	Ck. near Plat. Rd. x-ing Gibbon R.	76/09/00	5	-19.4	-142
T76-15	Ck. near Dunraven picnic area	76/09/00	5	-19.1	-140
T76-16	Antelope Ck.	76/09/00	6	-19.7	-147
T76-17	Trib. of Soda Butte Ck.	76/09/00	6	-17.1	-126
T76-18	Soda Butte Ck.	76/09/00	6	-18.7	-140
T76-19	Ampitheater Ck	76/09/00	5	-18.6	-141
T76-20	Pebble Ck.	76/09/00	5	-19.2	-141
T76-??	DeLacy Ck.	76/09/00		-18.4	-138
T76-28	Trib. of Clear Ck.	76/09/00		-18.9	-138
T76-29	Cub Ck.	76/09/00		-18.8	-136
T76-40	Glen Ck.	76/09/30	8	-19.7	-153
T76-43	Trib to Grayling Ck.	76/09/30		-18.6	-140
T76-44	Trib. to Grayling Ck.	76/09/30		-19.8	-143
T76-45		76/09/30		-19.5	-148
T76-46		76/09/30		-19.5	-147
T76-47	Grayling Ck.	76/09/30		-18.6	-140
W-1002	Delacy Ck.	77/06/14		-18.1	-134
W-1003	Grayling Ck.	77/06/14		-17.8	-133
W-1004	Cub Ck.	77/06/14		-19.1	-146
W-1008	Trib. of Grayling Ck.	77/06/14		-18.2	-136
W-1009	Pebble Ck.	77/06/14		-19.0	-144
W-1010	Glenn Ck	77/06/14		-18.2	-138
W-1012	Ck. near Virginia Meadows	77/06/14		-18.3	-141
W-1013	Antelope Ck.	77/06/14		-19.0	-140
W-1014	Trib. of Barronette Ck.	77/06/14		-17.9	-135
W-1015	Dunraven Peak Ck.	77/06/14		-18.9	-146
W-1017	Trib. of Clear Ck.	77/06/14		-19.1	-143
W-1018	Black Butte Ck.	77/06/14		-19.1	-145
W-1019	Trib. of Grayling Ck.	77/06/14		-18.2	-137
W-1020	Soda Butte Ck.	77/06/14		-19.2	-144
H78-1	Grayling Ck.	78/05/09	3	-18.5	-136
H78-2	Grayling Ck.	78/05/09	4	-18.5	-135
H78-5	Black Butte Ck.	78/05/09	6	-19.2	-145
H78-7	Cub Ck.	78/05/10	2	-19.1	-141
H78-10	Glenn Ck.	78/05/10	4	-19.2	-144
H78-11	Apollinaris Ck.	78/05/10	8	-18.5	-141
H78-13	Ck. N. of Soda Butte	78/05/11	1	-18.5	-140

H78-14	Soda Butte Ck.	78/05/11	3	-18.9	-140
H78-15	Pebble Ck.	78/05/11	3	-18.9	-140
SH86-11	Shoshone Ck.	86/09/00		-18.3	-136
SH86-12	Shoshone Ck.	86/09/00		-18.0	-134
		RIVERS			
R-41	U. Gibbon R. above Va. Cascades	67/09/00		-18.5	-140
W-2	U. Gibbon R. above Va. Cascades	71/09/21		-18.8	-142
W-12	Gardiner R.	71/10/11	8	-19.2	-146
W-17	Little Firehole R.	71/10/11	14	-18.8	-138
W-43	Yellowstone R.	72/10/04	10	-16.5	-131
W-8	Lamar R.	75/10/10		-19.2	-143
T76-13a	Gibbon R.	76/09/00		-18.6	-141
		LAKES			
T75-23	Yellowstone Lake, Fishing Bridge	75/10/06		-16.7	-132
T75-24	Yellowstone Lake, Pumice Pt.	75/10/06		-16.7	-132
T76-30	Yellowstone Lake, Steamboat Pt.	75/10/08		-16.6	-130
T76-31	Yellowstone Lake, Fishing Bridge	75/10/08		-16.7	-131
T76-32	Yellowstone Lake, Pumice Pt.	75/10/08		-16.7	-130
W-1005	Yellowstone Lake, Pumice Pt.	77/06/14		-16.7	-129
W-1006	Yellowstone Lake, Steamboat Pt.	77/06/14		-17.0	-128
W-1011	Yellowstone Lake, Fishing Bridge	77/06/14		-16.8	-129
W-1016	Yellowstone Lake, Fishing Bridge	77/06/14		-16.8	-129
H78-6	Yellowstone Lake, Pumice Pt.	78/05/10		-16.7	-129
H78-8	Yellowstone Lake, Steamboat Pt.	78/05/10		-16.6	-129
H78-9	Yellowstone Lake, Fishing Bridge	78/05/10		-17.2	-133
T81-20	Shoshone Lake	81/09/19		-16.4	-128
		SPRINGS			
F-381	Midway Picnic area spring	67/10/19		-18.9	-145
W-1	Midway Picnic area water supply	71/09/29		-19.2	-142
W-6	Midway Picnic area spring	71/09/29		-19.0	-141
W-9	Above Black Sand	71/10/10		-19.1	-142
W-10	New Old Faithful	71/10/10		-18.8	-138
W-11	Apollinaris	71/10/10		-18.9	-141
F571	W. of Sylvan	72/09/00		-19.3	-140
T73-20	Grant's pass	73/09/07		-18.5	-135
T74-49	Apollinaris	74/08/00		-18.8	-143
T74-59	Apollinaris	74/10/00		-18.8	-143
T75-73	Apollinaris	74/10/00		-18.2	-142
T76-37	Grant's pass	76/09/00		-18.7	-139
W-1007	Apollinaris	77/06/14		-18.6	-140
W1022	Cold Spring	77/06/14		-19.4	-142
H78-3	Spring of trib. of Grayling Ck.	78/05/09		-19.8	-145
H78-4	East of culvert	78/05/09		-19.4	-144
H78-11	Apollinaris	78/05/10		-18.5	-141
T82-5	W. of Emerald pool	82/10/01		-18.8	-142
T82-19	Apollinaris	82/10/04		-18.6	-144
		PRECIPITATION			
F-486	Near Gibbon	70/05/27		-18.7	-142
T75-87	Mammoth	75/12/00		-22.4	-168
T75-85	Mammoth	75/11/00		-20.0	-146
T75-86	Old Faithful	75/12/00		-20.5	-151
T75-84	Old Faithful	75/11/00		-19.6	-142
W-1021	Old Faithful	77/06/14		-9.4	-64

TABLE 4 δD of Cold Waters in Yellowstone National Park and Adjacent Areas

SAMPLE	NAME	ELEV. (meters)	LAT.	LONG.	DATE	LOCATION	Temp °C	δD (‰)
				GALLATIN RANGE NW of YNP				
	Spanish Ck.	1620	45°29'	111°16'	10/1/78	before Gallatin R. along US 191		-136
	Squaw Ck.	1650	45°26'	111°14'	10/1/78	before Gallatin R. along US 191		-145
	Portal Ck.	1670	45°19'	111°11'	10/1/78	before Gallatin R. along US 191		-142
	Dudley Ck.	1830	45°15'	111°14'	9/7/78	before Gallatin R. along US 191	9	-147
	Dudley Ck. Spg.	1830	45°15'	111°14'	9/7/78	N. of Dudley Ck.	14	-149
	Porcupine Ck	1860	45°13'	111°15'	9/7/78	before Gallatin R. along US 191	13	-147
	Beaver Ck.	1860	45°13'	111°11'	9/7/78	before Gallatin R. along US 191		-145
	Buck Ck.	1920	45°10'	111°15'	9/7/78	before Gallatin R. along US 191		-147
	Elkhorn Ck.	1920	45°9'	111°15'	9/7/78	before Gallatin R. along US 191	7.5	-148
	Buffalo Horn Ck.	1950	45°6'	111°13'	9/6/78	before Gallatin R. along US 191	15	-144
	Taylor Fk.	2040	45°4'	111°16'	9/7/78	before Wapati Ck.	15	-138
	Wapiti Ck.	2040	45°4'	111°16'	9/7/78	N. of Taylor Ck.	15	-139
	Taylor Fk. Spg.	2010	45°4'	111°10'	9/8/78	at rockpile near Taylor Fk.	17	-135
	Sage Ck.	2010	45°4'	111°11'	9/7/78	before Big Spring Ck.	15	-137
	Snowflake Spg.	2010	45°4'	111°11'	9/9/78	1/4 mi south of US 191	12	-152
				ABSAROKA-BEARTOOTH RANGE -*WEST*				
R78-28	Pine Ck.		45°30'	110°21'	10/2/78	at quarry 3 Mi E of US 89		-141
R78-29	Mill Ck.	1980	45°16'	110°29'	10/2/78	1/2 mi E of Anderson Ck.		-143
R78-30	**Montanapolis Spg.**	1800	45°17'	110°31'	10/2/78	Warm w/gas and sinter N. of Mill Ck. Ranch		-152
R78-31	West Fork Mill Ck. trib.	1980	46°14'	110°34'	10/2/78	1/2 mi S Coffee Pot Ck. on rd. along W. Mill		-147
R78-32	W. Mill Ck.	1860	45°16'	110°35'	10/2/78	before Arrastra Ck.		-144
R78-33	Arrastra Ck.	2100	45°16'	110°36'	10/2/78	at rd. to Barbara Ann mine		-148
R78-34	E. Fk. Mill Ck.	1740	45°19'	110°31'	10/2/78	at Snowy Range Ranch		-148
R78-35	Emigrant Ck.	1830	45°18'	110°41'	10/2/78	end of rd. in Emigrant Gulch		-142
R78-36	Six Mile Ck.	1620	45°17'	110°46'	10/2/78	at fork in rd. to Dailey Lk.		-144
R78-37	Cedar Ck.	1740	45°9'	110°47'	10/2/78	at rd. crossing W of Ranch		-145
R78-38	Pine Ck.	2100	45°5'	110°37'	10/2/78	at rd. crossing N of Jardine		-145
R78-39	N. Fork Bear Ck.	2120	45°5'	110°38'	10/2/78	at Bear Ck. Trail W of Jardine		-149
R78-40	Bear Ck.	1980	45°5'	110°38'	10/2/78	at Jardine		-146
				ABSAROKA-BEARTOOTH RANGE -*CENTRAL*				
R78-19	Stillwater R.	1560	45°21'	109°54'	9/30/78	at campground .5 mi W of Beartooth Ranch		-138
R78-20	Woodbine Ck.	1560	45°21'	109°53'	9/30/78	below falls trail before Stillwater R.		-137

R78-21	Stillwater R.	1100	45°39'	109°18'	9/30/78	before Yellowstone R. near Columbus		-138
R78-22	Boulder R.	2040	45°16'	110°15'	10/1/78	at Box Canyon Guard Station		-148
R78-23	Four Mile Ck.	1860	45°20'	110°14'	10/1/78	before Boulder R.		-147
R78-24	Speculator Ck.	1710	45°23'	110°12'	10/1/78	before Boulder R.		-147
R78-25	E. Chippy Ck.	1680	45°26'	110°11'	10/1/78	E. Trib. before Boulder R. (near Weasel Ck.)		-146
R78-26	Boulder R.	1460	45°40'	110°6'	10/1/78	before E. Boulder River on state hwy. 298		-144
R78-27	W. Boulder R.	1490	45°37'	110°15'	10/1/78	before Boulder R. on at Rd to Livingston		-145

ABSAROKA-BEARTOOTH RANGE -*EAST*

R78-12	Cook City Ck.	2350	45°1'	109°55'	9/29/78	on east side of Cooke City on US 212		-139
R78-13	Clarks Fork R.	2130	44°57'	109°48'	9/29/78	below Pilot Ck. at US 212 bridge		-136
R78-14	Rock Ck.	2130	45°4'	109°24'	9/29/78	before Lake Fk. on US 212		-140
R78-15	W. Fork Rock Ck.	2350	45°10'	109°29'	9/29/78	at Camp Senia		-141
R78-16	East Rosebud Ck.	1890	45°12'	109°39'	9/30/78	at outlet from E. Rosebud Lake		-138
R78-17	**E. Rosebud Ck. spg.**	1770	45°13'	109°38'	9/30/78	N. side of E. Rosebud 1 mi E. of lake		-145
R78-18	W. Rosebud ck.	1370	45°27'	109°30'	9/30/78	before Fishtail Ck. at Highway near Fishtail		-139

GALLATIN RANGE YNP

W-12	Gardiner R.	2260	44°54'	110°45'	10/11/71	at US 89 near Indian Ck. campgd.		-146
R82-31	Gardiner R.		44°54'	110°45'	9/22/82	at US 89 near Indian Ck. campgd.	5.5	-145
R82-32	Gardiner R.		44°54'	110°45'	9/28/82	on ser. rd. before Panther and Indian Cks.	5	-147
R78-6	Gardiner R.		44°54'	110°45'	9/29/78	at bridge on Grand Loop Rd.		-140
R90-35	Gardiner R.		44°54'	110°45'	9/12/90	at Fawn Pass trail crossing	15	-142
F-478	Glen Ck.	2230	44°56'	110°44'	5/25/70	N. of Rustic Falls on US 89		-147
W-3	Glen Ck.		44°56'	110°44'	9/29/71	N. of Rustic Falls on US 89		-149
W-13	Glen Ck.		44°56'	110°44'	10/11/71	N. of Rustic Falls on US 89		-148
T76-40	Glen Ck.		44°56'	110°44'	9/30/76	N. of Rustic Falls on US 89		-153
W-1010	Glen Ck.		44°56'	110°44'	6/14/77	N. of Rustic Falls on US 89		-138
T78-66	Glen Ck.		44°56'	110°44'	9/29/78	N. of Rustic Falls on US 89		-153
R79-23	Glen Ck.		44°56'	110°44'	9/24/79	N. of Rustic Falls on US 89		-148
R82-33	Glen Ck.		44°56'	110°44'	9/28/82	N. of Rustic Falls on US 89 (after storms)	5	-152
R82-14	Glen Ck.		44°56'	110°44'	9/28/82	N. of Rustic Falls on US 89	9	-151
R90-25	Glen Ck.		44°56'	110°44'	9/12/90	N. of Rustic Falls on US 89 (10:50 AM)	7	-147
R90-37	Glen Ck.		44°56'	110°44'	9/12/90	N. of Rustic Falls on US 89 (6:00 PM)	13	-148
R90-26	E. Fawn Ck.	2410	44°57'	110°49'	9/12/90	on Fawn Pass trail at 7880'	12	-141
R90-27	**E. Fawn Ck. spg.**	2530	44°57'	110°49'	9/12/90	spg. north of Fawn at west end of marshes	7	-147
R90-32	**E. Fawn Ck. spg.**	2410	44°57'	110°48'	9/12/90	middle spring S of above	4.5	-147
R90-33	**E. Fawn Ck. spg.**		44°57'	110°48'	9/12/90	eastern most spring S of above	5	-146
	Indian Ck.		44°53'	110°45'	9/29/78	at Indian Ck. campgd. below Panther Ck.		-140

R90-39	Indian Ck.		44°53'	110°45'	9/14/90	at trail X-ing before Panther Ck. (11:00 AM)	9	-138
R90-42	Indian Ck.		44°53'	110°45'	9/14/90	same location (3:00 PM)	13	-138
R90-41	Indian Ck.		44°52'	110°48'	9/14/90	before gravel filled flats at 7600 '	8	-135
R90-40	Panther Ck.	2380	44°53'	110°49'	9/14/90	on Bighorn Pass trail at 7800 '	6. 5	-139
	Apollinaris Spg.	2230	44°51'	110°44'		E. of US 89		-144
R82-4	Daly Ck.	2070	45°04'	111°08'	9/22/82	before Gallatin R. at US 191	14	-151
R90-10	Daly Ck.		45°04'	111°08'	9/12/90	before Gallatin R. at US 191	5	-146
W-807	Black Butte Ck.	2200	45°03'	111°07'	9/30/76	before Gallatin R. at US 191		-149
W-1018	Black Butte Ck.		45°03'	111°07'	6/14/77	before Gallatin R. at US 191		-145
	Black Butte Ck.		45°03'	111°07'	9/30/78	before Gallatin R. at US 191		-148
R79-8	Black Butte Ck.		45°03'	111°07'	9/23/79	before Gallatin R. at US 191	6	-143
R82- 5	Black Butte Ck.		45°03'	111°07'	9/22/82	before Gallatin R. at US 191	9	-151
R90-11	Black Butte Ck.		45°03'	111°07'	9/12/90	before Gallatin R. at US 191	4	-146
	Speciman Ck.	2200	45°01'	111°05'	9/30/78	before Gallatin R. at US 191		-147
R79-7	Speciman Ck.		45°01'	111°05'	9/23/79	before Gallatin R. at US 191	6	-144
R82-6	Speciman Ck.		45°01'	111°05'	9/22/82	before Gallatin R. at US 191	9	-146
R90-12	Speciman Ck.		45°01'	111°05'	9/12/90	before Gallatin R. at US 191	4	-139
R79-6	Fan Ck.	2230	44°57'	111°04'	9/23/79	before Gallatin R. at US 191	6	-139
R90-17	Fan Ck.		44°57'	111°04'	9/12/90	before Fawn Ck. on Fawn Pass trail	15	-144
R90-13	**Fawn CK. trail spg.**		44°57'	111°04'	9/12/90	western most spring south of Fawn Ck.	5.5	-145
R90-15	**Fawn CK. trail spg.**		44°57'	111°04'	9/12/90	eastern most spring south of Fawn Ck.	5.5	-142
R90-16	**Fawn CK. trail spg.**		44°57'	111°04'	9/12/90	just above Fan Ck. on Fawn Pass trail	12	-142
	Gallatin R.	2200	44°56'	111°04	9/30/78	at Bighorn Pass trail head at U.S. 191		-143
R79-9	Gallatin R.		44°56'	111°04	9/23/79	at Bighorn Pass trail head at U.S. 191	6	-139
T76-47	Grayling Ck.	2160	44°53'	111°03'	9/30/76	before main ck. turns S at US 191		-140
W-1003	Grayling Ck.		44°53'	111°03'	6/14/77	before main ck. turns S at US 191		-133
	Grayling Ck.		44°53'	111°03'	9/30/78	before main ck. turns S at US 191		-139
R90-18	Grayling Ck.		44°53'	111°03'	9/12/90	before main ck. turns S at US 191	11	-138
R79-5	Grayling Ck.		44°53'	111°03'	9/23/79	before main ck. turns S at US 191	6	-135
T76-46	**Grayling Ck. spg.**	2160	44°52'	111°03'	9/30/76	Spring near US191 between above and below		-147
	Grayling Ck. spg.		44°52'	111°03'	10/1/78	Spring near US191 between above and below		-143
R79-4	**Grayling Ck. spg.**		44°52'	111°03'	9/23/79	Spring near US191 (v. little flow)	6	-136
T76-44	Grayling Ck. trib.	2100	44°51'	111°03'	9/30/76	E trib. at state boundary and US 191		-143
W-1019	Grayling Ck. trib.		44°51'	111°04'	6/22/77	E trib. at state boundary and US 191		-137
T76-43	Grayling Ck. trib.		44°51'	111°04'	9/30/76	S. trib 1 mi SW of state boundary on US 191		-140
W-1008	Grayling Ck. trib.		44°51'	111°04'	6/14/77	S. trib 1 mi SW of state boundary on US 191		-136
R79-3	Grayling Ck. trib.		44°51'	111°04'	9/23/79	S. trib 1 mi SW of state boundary on US 191	6.5	-139
R82-7	Grayling Ck. trib.		44°51'	111°04'	9/22/82	S. trib 1 mi SW of state boundary on US 191		-145
	Duck Ck.	2040	44°47'	111°07'	9/30/78	at US 191		-141
R79-1	Duck Ck.		44°47'	111°07'	9/23/79	at US 191	9.5	-137

R90-19	Duck Ck.		44°47'	111°07'	9/12/90	at US 191	18	-136
	Cougar Ck.		44°45'	111°07'	9/30/78	at US 191		-142
R79-2	Cougar Ck.		44°45'	111°07'	9/23/79	at US 191	9	-138
R90-21	Pipe Ck.				9/11/90	trib. of Mol Heron Ck. .5 mi N. of Park.	6	-141
R90-24	Reese Ck.				9/11/90	1.5 mi. sw of US 89.	7	-143
					WASHBURN RANGE			
R78-1	Lava Ck.	2070	44°56'	110°38'	9/29/78	before Lupine at Lava Ck. Campgnd.		-146
R82-15	Lava Ck.		44°56'	110°38'	9/22/82	before Lupine at Lava Ck. Campgnd.	9.5	-148
R82-34	Lava Ck.		44°56'	110°38'	9/28/82	before Lupine at Lava Ck. (after storm)	6	-150
R90-3	Lava Ck.		44°56'	110°38'	9/10/90	before Lupine at Lava Ck. Campgnd.	15	-146
R90-4	Lupine Ck.	2070	44°56'	110°38'	9/10/90	before Lava Ck.	15	-147
R78-2	Blacktail Ck.	2070	44°56'	110°36'	9/29/78	after Deer Ck.		-145
R82-16	Blacktail Ck.		44°56'	110°36'	9/22/82	after Deer Ck.	11	-144
R82-35	Blacktail Ck.		44°56'	110°36'	9/28/82	after Deer Ck. (after storms)	5	-149
R90-5	Blacktail Ck.		44°56'	110°36'	9/10/90	after Deer Ck.	16	-145
R90-6	Deer Ck.	2070	44°57'	110°36'	9/10/90	E of Blacktail Ck.	14	-141
R78-3	Elk Ck.	2040	44°56'	110°27'	9/29/78	at Grand Loop highwy. (after storms)		-147
R82-17	Elk Ck.		44°56'	110°27'	9/22/82	at Grand Loop highwy.	6.5	-147
R90-7	Elk Ck.		44°56'	110°27'	9/10/90	at Grand Loop highwy.	12	-143
W75-6	Tower Ck.	2040	44°55'	110°25'	11/5/75	above Tower falls		-144
R78-4	Tower Ck.		44°55'	110°25'	9/29/78	above Tower falls		-144
R82-18	Tower Ck.		44°55'	110°25'	9/22/82	above Tower falls	11	-146
R82-41	Tower Ck.		44°55'	110°25'	9/28/82	above Tower falls (after storms)	6	-150
R90-8	Tower Ck.		44°55'	110°25'	9/10/90	above Tower falls	13	-144
W75-5	Antelope Ck.	2130	44°54'	110°23'	11/5/75	at Grand Loop highwy.		-148
W-785	Antelope Ck.		44°54'	110°23'	9/27/76	at Grand Loop highwy.		-153
	Antelope Ck.		44°54'	110°23'	6/14/77	at Grand Loop highwy.		-147
R78-5	Antelope Ck.		44°54'	110°23'	9/29/78	at Grand Loop highwy.		-152
R79-10	Antelope Ck.		44°54'	110°23'	9/24/79	at Grand Loop highwy.		-149
R82-19	Antelope Ck.		44°54'	110°23'	9/22/82	at Grand Loop highwy.		-150
R90-9	Antelope Ck.		44°54'	110°23'	9/10/90	at Grand Loop highwy.	13	-147
W-784	Dunraven Peak Ck.	2590			9/27/76	at Grand Loop highwy.		-144
W-1015	Dunraven Peak Ck.				6/14/77	at Grand Loop highwy.		-146
	Dunraven Peak Ck.				9/29/78	at Grand Loop highwy.		-143
					BUFFALO PLATEAU			
R77-7	**Buffalo Plat. ck.**	1950	44°59'	110°26'	10/00/77	at Hellroaring Ck. .5 mi S of state bndry.		-150
R77-10	Little Cottonwood Ck.	1770	45°00'	110°19'	10/00/77	at Black Canyon Yellowstone trail		-146

R77-11	Black Canyon Trail spg.				10/00/77	Small spg on Black Canyon Yellowstone trail		-159
R78-11	Slough Ck.	1920	44°57'	110°31'	9/29/78	above Buffalo Ck.		-142
R82-24	Slough Ck.		44°57'	110°31'	9/22/82	below Buffalo Ck. at campgrnd.	12	-142
R82-36	Slough Ck.		44°57'	110°31'	9/28/82	below Buffalo Ck. at campgrnd. (after storm)		-146
R90-48	Slough Ck.		44°57'	110°31'	9/12/90	below Buffalo Ck. at campgrnd.	16	-140
R82-38	Slough Ck. cpgrnd. well		44°57'	110°31'	9/28/82	**well at Buffalo Ck. campgrnd.**		-143
R90-49	Slough Ck. cpgrnd. well		44°57'	110°31'	9/12/90	**well at Buffalo Ck. campgrnd.**	18	-141
R82-37	Buffalo Ck.	1920	44°57'	110°31'	9/28/82	above Slough Ck. (after storm)	6	-143

MADISON PLATEAU

R78-41	Little Firehole R.	2380	45°29'	110°52'	10/5/78	just above Mystic Falls		-139
	Little Firehole R.		45°29'	110°52'		just above Mystic Falls		-142
R82-26	Little Firehole R.		45°29'	110°52'	9/23/82	just above Mystic Falls	11	-141
R90-56	Little Firehole R.		45°29'	110°52'	9/15/90	just above Mystic Falls	14	-141
W-9	**Black Sand bsn. spg.**	2320	45°27'	110°52'	10/10/71	base of Rhyolite cliffs above Black Sand bsn		-143
R78-42	**Black Sand bsn. spg.**		45°27'	110°52'	10/5/78	base of Rhyolite cliffs above Black Sand bsn	4	-139
R82-25	**Black Sand bsn. spg.**		45°27'	110°52'	9/23/82	base of Rhyolite cliffs above Black Sand bsn	10	-143
R90-38	**Black Sand bsn. spg.**		45°27'	110°52'	9/13/90	base of Rhyolite cliffs above Black Sand bsn	11	-141
W-5	**Lonestar rd. spg.**	2320	45°26'	110°48'	9/29/71	by rd. to Lonestar geyser		-142
R82-27	Madison R.	2040	45°39'	111°01'	9/29/32	at Madison Range overlook	17	-145
R82-42	Madison R.		45°39'	111°01'	9/28/82	at Madison Range overlook	11	-146
R82-72	Boundary Ck.				9/30/82	1/2 mi before Bechler R. on Bechler trail	11	-136
R82-73	Snow Ck.				10/1/82	at Park boundary rd. 509	7	-135
R82-74	S. Fk. Partridge Ck.				10/1/82	1 mi N of Snow Ck. at park bnd.	3	-135

CENTRAL PLATEAU

R67-41	Gibbon River	2380	44°43'	110°39'	9/1/67	Just above Virginia Cascades	7	-140
F-486	Gibbon River		44°43'	110°39'	5/25/70	Just above Virginia Cascades		-142
W-2	Gibbon River		44°43'	110°39'	9/29/71	Just above Virginia Cascades		-142
W-782	Gibbon River		44°43'	110°39'	9/27/76	Just above Virginia Cascades		-142
R82-9	Gibbon River		44°43'	110°39'	9/21/82	Just above Virginia Cascades	10	-143
R90-20	Gibbon River		44°43'	110°39'	9/11/90	Just above Virginia Cascades	15	-140
W-783	Gibbon River	2380	44°43'	110°38'	9/27/76	Virginia Meadows area		-144
W-1012	Gibbon River		44°43'	110°38'	6/14/77	Virginia Meadows area		-142
	Gibbon River		44°43'	110°38'	10/5/78	Virginia Meadows area		-143
W-27	**Gibbon Hill Str.**	2320	44°43'	110°41'	10/2/72	Small unnamed stream on Gibbon Hill		-141
T78-63	Norris Geyser Basin	2290	44°44'	110°42'	10/5/78	**cold water supply**		-140
W-33	Nez Perce Ck.	2200	44°35'	110°47'	10/4/72	at gate to service Rd.		-144
W-4	Nez Perce Ck.		44°35'	110°47'	9/29/71	at gate to service Rd.		-144

R82-29	Nez Perce Ck.		44°35'	110°47'	9/25/82	1 mi E. of gate to service Rd.	19	-149
R90-43	Nez Perce Ck.		44°35'	110°47'	9/14/90	100 yds. E. of US 89	16.5	-145
W-6	**Midway Gys. Bsn. spg.**	2260	**44°32'**	**110°50'**	9/29/71	**at Lower Basin picnic grnd.**		-141
W75-1	**Midway Gys. Bsn. spg.**		**44°32'**	**110°50'**	10/10/75	**at Lower Basin picnic grnd.**		-142
W-18	Delacy Ck.	2440	44°26'	110°41'	10/11/71	about 100 Yds. north of US 89		-138
W-792	Delacy Ck.		44°26'	110°41'	9/28/76	about 100 Yds. north of US 89		-141
W-1002	Delacy Ck.		44°26'	110°41'	6/21/77	about 100 Yds. north of US 89		-134
	Delacy Ck.		44°26'	110°41'	10/5/78	about 100 Yds. north of US 89		-136
R79-16	Delacy Ck.		44°26'	110°41'	9/24/79	about 100 Yds. north of US 89		-138
R90-55	Delacy Ck.		44°26'	110°41'	9/15/90	about 100 Yds. north of US 89	8	-137
R90-54	Dry Ck.	2440	44°26'	110°41'	9/15/90	N of bridge on highway	6	-138
W-10	Old Faithful drink. water		**44°26'**	**110°48**	10/10/71	**cold water supply**		-138
	Old Faithful drink. water		**44°26'**	**110°48**	10/5/78	**cold water supply**		-134
W-25	**Lake Junction area ck.**	2380	44°35'	110°23'	10/12/71	small ck. 2 mi. S Lake Junctn.		-145
R90-44	**Lake Junction area ck.**		44°35'	110°23'	9/14/90	small ck. 2 mi. S Lake Junctn.	9	-140
R82-11	**Ystone L. area ck.**	2380	44°33'	110°25'	9/21/82	small ck. 2 miles N. Yellowstone L.	10	-148
W-43	Yellowstone R.	2380	44°36'	110°22'	10/4/72	near Cascade campground		-125
R82-10	Yellowstone R.				9/21/82	near Cascade campground		-130
	Yellowstone R.				10/5/78	at Fishing bridge		-130
R79-21	Yellowstone R.				9/24/79	at Fishing bridge		-127
R90-45	Yellowstone Lake	2380			9/14/90	at Fishing bridge	20	-128
W75-3	Arnica Ck.	2380			10/10/75	N of Grand Loop Rd.		-144
	Arnica Ck.				10/5/78	N of Grand Loop Rd.		-148
R79-17	Arnica Ck.				9/24/79	N of Grand Loop Rd.		-143
R82-12	Arnica Ck.				9/21/82	N of Grand Loop Rd.	14	-146
R90-2	Arnica Ck.				9/10/90	N of Grand Loop Rd.	16	-146
W75-2	Little Thumb Ck.	2350	44°27'	110°52	10/10/75	W of US 89		-137
R79-22	Little Thumb Ck.		44°27'	110°52	9/24/79	W of US 89		-133

MIRROR PLATEAU

R76-13	**Specimen Ridge trl.**	2680	44°49'	110°14'	9/30/76	on Specimen trail		-144
R76-14	Amethyst Ck.	2010	44°53'	110°14'	9/30/76	on Specimen trail		-145
W75-7	Crystal Ck.	1890	44°55'	110°18'	10/5/75	above Lamar R. on US 212		-143
R90-52	Crystal Ck.		44°55'	110°18'	9/14/90	above Lamar R. on US 212	10	-145

ABSAROKA RANGE

R76-5	Lamar R.	2130			9/30/76	at trail before Lamar R.		-142
R76-6	Miller Ck.	2130			9/30/76	at end of hike along Lamar R.		-143
R76-7	Calfee Ck.	2100			9/30/76	at trail before Lamar Riv.		-142

R76-10	Cache Ck.	2040			9/30/76	at trail before Miller Ck.		-140
W75-8	Larmar River	2010			10/5/75	after Soda Butte		-142
R78-7	Larmar River				9/29/78	after Soda Butte		-141
R82-23	Larmar River				9/22/82	after Soda Butte		-143
R82-40	Larmar River				9/28/82	after Soda Butte (very muddy after storm)		-157
R82-21	Larmar River				9/22/82	after Soda Butte	7	-142
R90-51	Larmar River				9/14/90	after Soda Butte	10	-139
W-789	Pebble Ck.	2070			9/27/76	at Pebble Ck. campground		-146
W-1009	Pebble Ck.				6/14/77	at Pebble Ck. campground		-144
R78-9	Pebble Ck.				9/29/78	at Pebble Ck. campground		-142
R79-13	Pebble Ck.				9/24/79	at Pebble Ck. campground		-143
R82-22	Pebble Ck.				9/22/82	at Pebble Ck. campground	10	-144
R90-50	Pebble Ck.				9/14/90	at Pebble Ck. campground	13	-139
R78-11	Soda Butte Ck.	2200	45°00'	110°00'	9/29/78	at park entrance		-140
W-1020	Soda Butte Ck.	2010	44°55'	110°06'	6/14/77	above Ampitheater		-144
W-787	Soda Butte Ck.		44°52'	110°11'	9/27/76	above Lamar		-142
R82-20	Soda Butte Ck.		44°52'	110°11'	9/22/82	above Lamar		-142
R82-39	Soda Butte Ck.		44°52'	110°11'	9/28/82	above Lamar (after storm)	8	-147
W-788	Ampitheater Ck.	2100	44°55	110°06'	9/27/76	above Soda Butte		-136
R79-14	Ampitheater Ck.		44°55	110°06'	9/24/79	above Soda Butte		-142
R82-21	Ampitheater Ck.		44°55	110°06'	9/22/82	above Soda Butte		-142
W75-4	Cub Ck.	2560	44°30'	110°12	11/5/75	at US 20		-137
W-1004	Cub Ck.		44°30'	110°12	6/14/77	at US 20		-146
W-795	Cub Ck.		44°30'	110°12	9/28/76	at US 20		-142
W-796	Cub Ck.		44°30'	110°12	10/1/76	at US 20		-142
	Cub Ck.		44°30'	110°12	10/5/78	at US 20		-141
R79-18	Cub Ck.		44°30'	110°12	9/26/79	at US 20		-137
R90-46	Cub Ck.		44°30'	110°12	9/14/90	at US 20	16	-139
W-795	Clear Ck.	2560	44°29'	110°10	10/1/76	at US 20		-142
W-1017	Clear Ck.		44°29'	110°10	6/14/77	at US 20		-143
R79-20	Clear Ck.		44°29'	110°10	9/26/79	at US 20		-133
R82-75	Clear Ck.		44°29'	110°10	10/3/82	at US 20		-142

PITCHSTONE PLATEAU AND SNAKE R. DRAINAGE -*PITCHSTONE PLATEAU*

R82-45	North Boone Ck.	1950	44°06'	110°56'	9/29/82	at Reclamation rd. (snowing)	4	-137
R82-46	Calf Ck.	2200	44°08'	110°53'	9/29/82	at Reclamation rd. 1 ft snow on grnd	3	-136
R82-49	Glade Ck.	2200	44°07'	110°47'	9/29/82	at Reclamation rd. (Lakes in Drainage)	3	-132
R82-58	Rock Ck.	1930	44°07'	111°06	9/29/82	at Cave Falls rd.	6	-131
R82-59	Beaver Ck.	1800	44°07'	111°08	9/29/82	at Cave Falls rd.	6.5	-133
R82-60	Robinson Ck.	1740	44°08'	111°10'	9/29/82	at end of Sawmill Ck. rd.	10	-133

R82-61	Porcupine Ck.	1710	44°05'	111°13'	9/29/82	at Cave Falls rd.		-132
R82-73	Snow Ck.	2070	44°15'	111°06'	10/1/82	at Park boundary rd. 509	7	-135
R82-74	N. Fk. Partridge Ck.	2290	44°20'	111°09'	10/1/82	1 mi N of Snow Ck. at park bnd.	3	-135
				PITCHSTONE PLATEAU AND SNAKE R. DRAINAGE -*BECHLER RIVER*				
R82-62	Bechler River	2130	44°15'	110°56'	9/30/82	at stock crossing of river	7	-134
R82-63	**Bechler R. area spgs.**	2130	44°15'	110°56'	9/30/82	Small ck. 100 yards from stock ford	5	-131
R82-64	**Bechler R. area spgs.**	2100	44°15'	110°56'	9/30/82	**Spring 30-40 gpm on Bechler trail**	6	-134
R82-65	**Bechler R. area spgs.**	2040	44°15'	110°56'	9/30/82	**14 gpm spring Bechler trail**	4	-132
R82-66	**Bechler R. area spgs.**	2010	44°15'	110°56'	9/30/82	**3 gpm spring Bechler trail**	3.5	-134
R82-69	**Bechler R. area spgs.**	1980	44°14'	110°57'	9/30/82	**Spg. near fall tree fishing hole**	4	-135
R82-72	Boundary Ck.	1890	44°11'	111°00'	9/30/82	Boundary Ck. at S edge of Bechler meadow		-136
				PITCHSTONE PLATEAU AND SNAKE R. DRAINAGE -*SHOSHONE LAKE AREA*				
T73-20	**Grants Pass Spg.**	2410	**44°23'**	**110°49'**	9/00/73	**at grant pass on Howard Eaton trl.**		-135
W-804	**Grants Pass Spg.**		**44°23'**	**110°49'**	10/4/76	**at grant pass on Howard Eaton trl.**		-143
T73-87	Shoshone Fall Ck.		44°23'	110°47'	9/00/73	above thermal area		-130
				PITCHSTONE PLATEAU AND SNAKE R. DRAINAGE -*HEART LAKE AREA*				
T78-38	N. Fork of Witch Ck.				10/4/78	at Fissure grp.		-137
T78-39	S. Fork of Witch Ck.				10/4/78	at Fissure grp.		-142
T78-44	Witch Ck.	2320	44°17'	110°32'	10/4/78	above all thermal spgs.		-140
				PITCHSTONE PLATEAU AND SNAKE R. DRAINAGE -*SNAKE RIVER AREA*				
R78-43	Snake River	2070	44°06'	110°40'	10/6/78	at bridge on US 89		-136
R82-1	Snake River		44°06'	110°40'	9/21/82	at bridge on US 89	11	-133
R82-50	Snake River		44°06'	110°40'	9/29/82	at bridge on US 89	8	-132
R90-1	Snake River		44°06'	110°40'	9/9/90	at bridge on US 89	17	-131
R82-51	Crawfish Ck.	1950	44°09'	110°41'	9/29/82	above Moose Falls on US 89	14	-139
R82-52	Polecat Ck.	2070	44°07'	110°42'	9/29/82	1 mi W of Flagg Ranch	14	-126