

Results Of Weekly Chemical And Isotopic Monitoring Of Selected Springs In Norris Geysir Basin, Yellowstone National Park During June-September, 1995.

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ABSTRACT

Each year at Norris Geyser Basin, generally in August or September, a widespread hydrothermal "disturbance" occurs that is characterized by simultaneous changes in the discharge characteristics of many springs, particularly in the Back Basin. During the summer season of 1995, water samples from eight widely distributed hot springs and geysers at Norris were collected each week and analyzed to determine whether chemical and isotopic changes also occurred in the thermal waters at the time of the disturbance. In addition, Beryl Spring in Gibbon Canyon, 5.8 km southwest of Norris Geyser Basin, was included in the monitoring program.

Waters discharged by four of the monitored hot springs and geysers appear to issue from relatively deep reservoirs where temperatures are at least 270 °C and possibly higher than 300 °C. At the time of, and for several days after, the onset of the 1995 disturbance, the normally neutral-chloride waters discharged by these four features all picked up an acid-sulfate component and became isotopically heavier. The acid-sulfate component appears to be similar in composition to some waters discharged in 100 Spring Plain that issue from subsurface regions where temperatures are in the range 170–210 °C. However, the two monitored springs that discharge acid-chloride-sulfate waters in the 100 Spring Plain region did not show any significant chemical or isotopic response to the annual disturbance. Beryl Spring, and two neutral-chloride hot springs at Norris that appear to draw their water from reservoirs where temperatures are 250 °C or less, also did not show any significant chemical or isotopic response to the annual disturbance.

After the start of the annual disturbance, chloride concentrations in water sampled from Double Bulger Geyser in the Back Basin increased from about 800 ppm to about 1500 ppm, nearly twice as high as any previously reported chloride concentration in a thermal water at Yellowstone. The isotopic composition of that water precludes an origin of the high chloride by evaporation at atmospheric pressure. One way to account for the unique chemical and isotopic composition of this highly concentrated water

is by recirculation of water that had gone through one cycle of adiabatic cooling during upflow (decompressional boiling) back down into the hydrothermal system, where it is reheated to greater than 220 °C. This previously boiled water then undergoes additional cycles of decompressional boiling during subsequent upflow. Another way the unique chemical and isotopic composition of Double Bulger water might evolve is by excess boiling in the formation that results from a decrease in fluid pressure within the channels of upflow.

The annual disturbance at Norris Geyser Basin generally appears to be triggered by a cyclic up and down movement of the boiling-point curve within the hydrothermal system in response to changes in the potentiometric surface of the cold water that is adjacent to, and interconnected with, that hydrothermal system. Annual disturbance phenomena that are easily recognized at Norris Geyser Basin may not be easily recognized elsewhere in Yellowstone National Park because (1) the neutral-chloride waters at Norris ascend directly from higher-temperature and higher-pressure reservoirs (270 to >300 °C at Norris compared to 180–215 °C at Upper and Lower Geyser Basins) that are capable of producing massive amounts of high-pressure steam, and (2) the clay that makes hot spring and geyser waters become turbid at Norris, heralding the start of the disturbance, comes from acid altered rocks that are widely distributed at intermediate depths at Norris, and that are rare in other geyser basins.

INTRODUCTION

At Norris Geyser Basin, Yellowstone National Park (YNP), an annual hydrothermal "disturbance" occurs, generally in late August or September, that is characterized by increased turbidity in many hot springs, increased discharge of water and steam, extreme fluctuations in temperatures of pools, and sometimes small hydrothermal explosions (White and others, 1988). Chemical changes at the time of the annual disturbance also have been observed in waters collected from Cistern Spring in the Back Basin of Norris (Fig. 1) (Fournier and others, 1986). Long-term monthly collections and chemical analyses of water from Cistern Spring during 1976–1985

showed a yearly cycle in which there was a general increase in concentrations of all dissolved constituents over the course of each summer. This is indicative of increased boiling leading up to the disturbance (Fournier and others, 1986; 1992). In contrast, immediately following the onset of these disturbances, Cistern Spring waters have lower chloride and pH, and increased sulfate, indicative of subsurface mixing of neutral-chloride and acid-sulfate waters at the time of the disturbance and for several weeks thereafter (Fournier and others, 1986; 1992).

Prior to our 1995 study only one other hydrothermal feature at Norris (recently informally named "Wistful" Geyser) was known to behave in a similar manner. It normally issues water that has pH \approx 7.0, Cl \approx 675 mg/kg, and SO₄ \approx 25 mg/kg. By chance it was sampled on the first day of the 1990 annual disturbance. That sample had pH = 2.82, Cl = 527 mg/kg, and SO₄ = 133 mg/kg (Fournier and others, 1994). Four days later its pH had increased to 5.36, its Cl was 634 mg/kg, and SO₄ was 99 mg/kg (Fournier and others, 1994). These results clearly show that subsurface mixing of neutral-chloride and acid-sulfate waters occurs in at least two regions of Norris at the time of the disturbance. The present study was undertaken to determine the extent of subsurface mixing and discharge of different thermal waters during these disturbances, and the duration of "mixed" discharge.

MONITORED HYDROTHERMAL FEATURES

The approximate locations of the eight hydrothermal features that were monitored at Norris Geyser Basin are shown in Figure 1, along with the locations of some other well-known springs and geysers. In addition, one spring (Beryl Spring) that is located in Gibbon Canyon about 5.8 km to the southwest of Norris Geyser Basin was included in the monitoring program to see whether the annual disturbance extends to that region of the park. We limited our monitoring activities to a total of nine springs because of constraints on the time that could be devoted to sample collection activities, and because of a limited budget to carry out the supporting chemical and isotopic analyses.

Eight springs at Norris were selected to achieve as widespread a geographic distribution as possible. A major limiting factor in their selection was the distribution of flowing springs at the start of the sampling period in 1995. In the Porcelain Terrace region we monitored "Wistful" Geyser, Perpetual Spouter, and "Carnegie" Spring, the latter issuing at the site of the second Carnegie drill hole (Fenner, 1936); in the Back Basin we monitored Cistern Spring, Double Bulger Geyser, and Porkchop Geyser; in the 100 Spring Plain we monitored Sulfur Dust Spring and "Black" Spring. Quotation marks indicate that a particular spring or geyser has recently been given an informal name that has not yet been officially recognized by the National Park Service.

The nine hydrothermal features selected for monitoring were divided into four groups as follows:

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|---------|---|
| Group 1 | a. Beryl Spring
b. Cistern Spring |
| Group 2 | a. Perpetual Spouter
b. "Black" Spring
c. Sulfur Dust Spring |
| Group 3 | a. "Carnegie" Spring at the Carnegie drill site #2
b. "Wistful" Geyser |
| Group 4 | a. Cistern Spring
b. Double Bulger Geyser
c. Porkchop Geyser |

Each of the springs in a given group were sampled on the same day, and the different groups generally were sampled on four successive days. Three days then passed with no sampling. Note that Cistern Spring is in two groups, so it was sampled twice a week. This was done because we intended to use its compositional variations as a key indicator of the onset and progress of the annual disturbance. The dates of sample collection are given in Table 1.

COLLECTION AND ANALYSIS PROCEDURES

Waters for use in all the chemical analyses, except for silica, were collected without filtration into 500 ml plastic bottles. For silica analyses, 10 ml of spring water were pipetted into 80 ml of silica free water that had previously been measured into a 125

ml plastic bottle. Standard analytical procedures were used for the chemical analyses (Trujillo, and others, 1987). Samples for isotopic analyses were collected in 60 ml glass bottles, with the water completely filling the bottles.

Values for pH were determined in the field using a portable pH meter and combination glass electrode calibrated before each measurement with pH 4, pH 7, and pH 9 buffer solutions. The field pH readings for the thermal waters were made with the combination electrode immersed in the hot spring and geyser pools. Except for the interval from June 22 (Julian day 173) to July 21 (Julian day 202), a thermister probe that also served to make automatic temperature corrections for pH measurements was used to measure the temperatures of the hydrothermal features. On June 22 (Julian day 173) the thermister probe for the pH meter was damaged and a replacement was not obtained until July 22 (Julian day 203). Therefore, during that time interval, a different thermister meter and probe, separate from the pH meter, was used to measure water temperature. This necessitated making manual temperature corrections for the pH measurements. Subsequent calibration indicated that the interim thermister equipment gave readings in the field about 2°C lower than other temperature probes.

On July 15 (Julian day 196), the combination pH electrode that had been used up to that time was accidentally broken; it was replaced with a new electrode on July 16 (Julian day 197). It will be shown subsequently that some of the field pH readings were anomalously high (especially for Sulfur Dust Spring) between the time that the pH meter temperature probe broke on June 22 (Julian day 173), and the time when a new pH electrode was installed on July 16 (Julian day 197). Coincident with installation of the new combination pH electrode the anomalously high field pH readings returned to normal readings. We suspect that the original pH electrode began to malfunction at about the time that the pH meter temperature probe was damaged on June 22 (Julian day 173), and that unreliably high pH readings were obtained thereafter from that electrode, especially for the more acid waters. However, because we now have no way to

verify this, in Figs. 2a–10a all our field pH data are plotted even though we believe that only the data before June 22 (Julian day 173) and after July 16 (Julian day 197) are likely to be reliable. The interval in doubt is bracketed by vertical dashed lines on these figures and pH is indicated by small diamonds.

The recorded temperatures of the springs and geysers were measured in the deepest and hottest parts of their pools that could be accessed using a temperature probe with a 1-meter reach. For Beryl Spring, Cistern Spring, and Porkchop Geyser, the deepest, and probably hottest, parts of the pools could not be reached with our equipment. However, care was taken always to measure temperature at the same location within each pool so that variations are likely to be significant even if the recorded temperature was less than the maximum temperature. Note that at the elevation of Norris Geyser Basin dilute water boils at about 92 °C.

RESULTS AND DISCUSSION

The results of the chemical and isotopic analyses are given in Table 1 and summarized in Figs. 2–10. The onset of the hydrothermal event that we set out to study, the 1995 annual disturbance at Norris Geyser Basin, occurred relatively early in that year, on July 29 (Julian day 210). It was marked by the usual widespread increase in hydrothermal activity and the appearance of turbidity in many spring waters.

Two of the monitored springs, "Black" Spring and Sulfur Dust Spring, usually discharge acid-chloride-sulfate waters, typical of the 100 Spring Plain region and Porcelain Basin. The other monitored hydrothermal features usually discharge near neutral, chloride-rich and sulfate-poor waters. Four of these hydrothermal features, Cistern Spring, Double Bulger Geyser, Porkchop Geyser, and "Wistful" Geyser, apparently draw most of their water from a relatively deep reservoir at Norris where temperatures are at least 270 °C, and possibly as high as 310 °C according to Fournier and others (1976), Fournier (1989), and Fournier and others (1994). The three remaining monitored hydrothermal features, Beryl Spring, "Carnegie" Spring, and Perpetual Spouter, apparently draw most of their water

from cooler reservoirs where temperatures are 250 °C or less (Table 2). The estimation of reservoir temperatures is discussed below.

Estimation Of Reservoir Temperatures

Subsurface reservoir temperatures at Norris Geyser Basin previously have been estimated using a variety of chemical geothermometers and mixing models (Fournier et. al. 1976; Fournier, 1989; Fournier and others 1991; Fournier and others 1994). We have used the silica and Na/K data of Table 1 to estimate last temperatures of water-rock equilibration (presumably reservoir temperatures) that are shown in Table 2.

The silica (quartz) geothermometer (Fournier and Rowe, 1966; Fournier and Potter, 1982) works best for near neutral waters issuing from reservoirs where temperatures are in the range 180 °C to about 230 °C (Fournier, 1985). Where reservoir temperatures are above 230 °C, some amorphous silica is likely to precipitate underground during upflow from the reservoir to the surface. In this case, quartz geothermometry gives too low an estimated reservoir temperature. An exception is for acid waters because polymerization and precipitation of amorphous silica are inhibited when pH is less than about 4 (Fournier 1985). When using silica geothermometry to estimate a reservoir temperature it is necessary to make assumptions regarding which silica mineral is controlling dissolved silica (usually quartz is assumed when the temperature is > 180 °C), and whether there has been mainly conductive cooling or mainly cooling by adiabatic decompressional boiling during ascent (Fournier, 1985, Fournier, 1991). Table 2 shows the range of possible results with different assumptions.

Many different Na/K geothermometers have been proposed for hydrothermal systems (Fournier, 1979; 1981; 1991 and references therein). The most widely ones now in use are by Truesdell (1976), Fournier (1979), Arnórsson (1983), and Giggenbach (1988). Which of these works best in a given area appears to depend on the mineral suite and the structural states of the alkali feldspars that are present in the reservoir rocks (Fournier, 1991). Results using the

Giggenbach (1988), Fournier (1979), and Truesdell (1976) Na/K geothermometers are given in Table 2. The Arnórsson (1983) geothermometer gives results that are very similar to those of the Truesdell (1976) geothermometer.

Figure 11 is a plot of temperatures estimated using the Giggenbach (1988) Na/K geothermometer versus temperatures estimated using the quartz geothermometer (Fournier and Potter, 1982). The straight line shows where there is agreement between temperatures estimated by the two geothermometers. Only waters from Beryl Spring and "Carnegie" Spring, which are assumed to have cooled adiabatically, lie on this line. Adiabatic cooling for waters discharged by these springs is reasonable, as they discharge a lot of steam with their waters. All the other spring and geyser waters yield silica temperatures that are significantly lower than the Na/K temperatures. The estimated temperature of the reservoir supplying water to Perpetual Spouter is about the same as that of the "Carnegie" Spring reservoir, based on the quartz geothermometer. However, Na/K geothermometry puts the Perpetual Spouter reservoir at about 210 °C using the Truesdell (1976) equation and at about 250 °C using either the Fournier (1979) equation or the Giggenbach (1988) equation (Table 2 and Fig. 11). We conclude that silica is likely to have precipitated during upflow and prefer the 250 °C estimated reservoir temperature because of the excellent agreement of the Giggenbach (1988) Na/K geothermometer with the silica geothermometer for Beryl Spring and "Carnegie" Spring waters. Similarly, silica is likely to have precipitated from the Cistern Spring, Double Bulger Geyser, Porkchop Geyser, and "Wistful" Geyser waters before reaching the surface. Again, we prefer the estimated reservoir temperatures obtained using the Giggenbach (1988) Na/K geothermometer. The Na/K geothermometer of Fournier (1979) gives temperatures which are much higher than the maximum likely temperature of the reservoir at Norris, estimated using enthalpy-chloride relations (Fournier, 1989).

The waters issuing from Sulfur Dust Spring have silica temperatures (quartz conductive) of about 200 °C and those

issuing from "Black" Spring have silica temperatures ranging up to 205 °C (quartz adiabatic) or to about 230 °C (quartz conductive). In contrast, Na/K gives temperatures in excess of 300 °C (Table 2 and Fig. 11). These are acid waters, so amorphous silica is not likely to have precipitated during upflow. We conclude that the reservoir temperatures for these two springs are likely to be about equal to the silica temperatures, and that Na/K gives estimated reservoir temperatures that are much too high, as is usual for acid waters that are equilibrating with clay minerals in the absence of feldspars (Fournier, 1991). Note that the lower-temperature acid-chloride-sulfate waters at Norris have Na/K ratios similar to those in the high-temperature, near-neutral, chloride-rich waters. Therefore, subsurface mixing of these two water types during upflow will markedly affect Cl/SO₄ ratios while Na/K ratios remain almost unchanged.

Geochemical Response To The Annual disturbance

The chemical and isotopic response exhibited by hot-spring and geyser waters to the annual disturbance ranged from insignificant for the initially acid-chloride-sulfate waters discharged by Sulfur Dust Spring and "Black" Spring (Figs. 2 and 3) in the 100 Spring Plain area, to very pronounced for the generally near-neutral waters that issue from the high-temperature reservoirs feeding Cistern Spring, Double Bulger Geyser, Porkchop Geyser, and "Wistful" Geyser (Figs. 4–7). Near-neutral waters issuing from the lower-temperature reservoirs feeding "Carnegie" Spring, Perpetual Spouter, and Beryl Spring (Figs. 8–10) showed little response to the disturbance.

The large upward spike in pH exhibited by Sulfur Dust Spring over the period June 23–July 14 (Julian days 174–195) shown in Figure 2a is contrary to what would be expected from the nearly constant Cl and SO₄ concentrations measured in the waters collected at the same time from this spring (Fig. 2b). It also is contrary to the pH measurements made in the laboratory (Fig. 2a and Table 1). As discussed above, we

believe that the anomalously high field pH measurements are in error. However, an argument can be made that the high field pH readings for Sulfur Dust Spring might be accurate (not the result of a faulty electrode reading). During the period that anomalously high pH readings were made in Sulfur Dust's pool there was no detected problem with the 3-buffer calibration of the electrode before each pH reading. Also, with the exception of two anomalously high pH readings in "Black" Spring (Fig. 3a), and one anomalously high reading in Cistern Spring (discussed below), consistently "reasonable" pH readings were made in other thermal pools on the same day, and over the same time span that anomalously high pH readings were made for Sulfur Dust waters. If the anomalous high field pH readings for Sulfur Dust and "Black" are real (not the fault of a malfunctioning electrode) the pH of the samples will have had to change (become lower) in the sample bottles after collection. One way for this to occur would be for the deep Sulfur Dust Spring water (and "Black" also) to carry a nearly constant concentration of colloidal sulfur which usually is completely converted to sulfuric acid by bacteria activity before reaching the surface pool. If, for some unexplained reason, for a period of about three weeks, this colloidal sulfur was not converted to sulfuric acid underground, it could have been converted to sulfuric acid in the sample bottle by bacterial activity between the time of collection and the time of laboratory analyses because the water samples were not filtered. Again, we stress that we do not advocate this latter explanation because the return to "normal" pH readings in both Sulfur Dust Spring and "Black" Spring was coincidental with the replacement of the original pH electrode with a new electrode.

Like the Sulfur Dust results, Cl, SO₄ and pH in "Black" Spring's waters, measured in the laboratory, remain essentially constant even though some pH readings were anomalously high (Fig. 3). Again, we believe that the best explanation for the pH anomaly is a malfunctioning pH electrode that was used with the portable pH meter. It is puzzling, however, why the upward pH spike for Sulfur Dust Spring was so much greater and started sooner than that for

"Black" Spring. Sulfur Dust Spring normally has a slightly lower pH and much lower temperature than "Black" Spring. Perhaps the higher temperature of "Black" Spring allowed a faulty pH electrode to come closer to equilibrium during the relatively short time of the in-pool measurement than occurred for Sulfur Dust Spring.

The waters from "Black" Spring are slightly lower in Cl and are isotopically heavier than those collected from Sulfur Dust Spring (Table 1 and Figs. 2d, 3d, and 12). The isotopically heavy nature of "Black" Spring relative to Sulfur Dust can be explained in part by different degrees of mixing of isotopically light and Cl-rich waters with isotopically heavy and Cl poor waters, and in part by a greater degree of evaporative steam loss from "Black" Spring. A relatively high degree of evaporation from "Black" Spring, compared to Sulfur Dust Spring, seems reasonable because of its much greater surface area, higher temperature (compare Figs. 2a and 3a), and, during our sampling campaign, very low rate of discharge. Prior to evaporation "Black" Spring waters would have contained even less Cl than our reported values. Our data show that, in general, the thermal waters at Norris which contain less Cl generally have heavier δD values.

Water collected from the Y-12 drill hole probably provides the best indication of the chemical and isotopic composition of the deepest and hottest fluid beneath the Norris Geyser Basin. It has $\delta D \approx -148 \text{ ‰}$, $\delta^{18}O \approx -16.5 \text{ ‰}$, and $Cl \approx 548 \text{ ppm}$ (unpublished data, U. S. Geological Survey files, sample YJ93-17, collected July 29, 1993). During upflow from the deep reservoir, this water apparently mixes with water in shallower reservoirs, generally becoming more dilute in Cl and isotopically heavier. Sulfur Dust Spring water is about 6 ‰ heavier in δD and about 1.5 ‰ heavier in $\delta^{18}O$ than the Y-12 water. On a plot of $\delta^{18}O$ versus δD , Sulfur Dust Spring water has about the same δD as local meteoric water, but is about 4 ‰ heavier in $\delta^{18}O$ (Fig. 12a). In contrast, the δD of "Black" Spring water is about 17 ‰

heavier than local meteoric water (about 23 ‰ heavier than Y-12) while its $\delta^{18}O$ is about 8 ‰ heavier than local meteoric water (about 6 ‰ heavier than Y-12) (Fig. 12b). For comparison, in Figure 12 the data point labeled "Vermilion Spg" shows a typical isotopic composition of a low-chloride, acid-sulfate water in a steam-heated, non-overflowing pool.

Cistern Spring (Fig. 4) exhibited a slow decrease in pH and Cl/SO_4 for about 15 days prior to the start of the annual disturbance (Figs. 4a and 4c). This trend of changing composition abruptly became much more pronounced on the day of the disturbance and continued for 30 days thereafter. Similar precipitous changes in Cl/SO_4 and pH had been noted at the times of other annual disturbances (Fournier and others, 1986). There also was a small and short-lived mixing event 20 days prior to the start of the disturbance (day 190), during which Cistern Spring's water exhibited decreased Cl and increased SO_4 (Fig. 4b). This event was accompanied by a decrease in Na/K (Fig. 4c). We expected to see an accompanying decrease in pH at the time of this small event, but instead recorded an anomalously high pH reading (Fig. 4a). As noted above, we suspect that this high pH on day 190 may be erroneous, the result of a malfunctioning electrode.

Isotopic changes in Cistern Spring's waters generally parallel the variations in Cl and SO_4 . Both δD and $\delta^{18}O$ become heavier as Cl decreases and SO_4 increases (compare Fig. 4d with 4b and 4c). This clearly shows that the sulfate-rich component of the mixed water is isotopically relatively heavy. We suspect that the upward spike in $\delta^{18}O$ on day 176 (Fig. 4d) is not real because it is not accompanied by any other chemical anomaly. In contrast, the small $\delta^{18}O$ spike on day 190 probably is real because it is accompanied by distinct δD , Cl/SO_4 and Na/K anomalies (Fig. 4c). The decreasing trend in δD from day 173 to 180 is not accompanied by other major chemical changes, and, at this time, we can offer no explanation for this anomaly.

On a diagram showing $\delta^{18}\text{O}$ versus δD for all Norris waters, Cistern Spring waters show considerable variation, but all plot with the heavier waters (Fig. 12c). These isotopic variations probably result in part from different amounts of mixing of different waters, and in part from different degrees of boiling with steam separation during upflow.

Double Bulger Geyser's waters exhibited dramatic and unexpected changes over the monitored period. Prior to the annual disturbance chloride values were very irregular, ranging up and down from a minimum of 665 ppm to a maximum of 849 ppm (Fig. 5b and Table 1). Other dissolved constituents, including Br, Na, K, and SO_4 , show similar peaks and valleys when plotted versus Julian day (Fig. 13), so we conclude that those ups and downs in Cl concentration were real, and probably resulted from different degrees of steam separation during flow to the surface. However, there was a general trend of decreasing Cl/ SO_4 prior to the annual disturbance (Fig. 5c), so some subsurface mixing of different waters was occurring. On the day of the annual disturbance there was an increase in Cl and Cl/ SO_4 (Figs. 5b and 5c). This is contrary to what was observed in the Cistern Spring and "Wistful" Geyser waters (Figs. 4b and 4c and Figs. 7b and 7c). Shortly after the start of the annual disturbance, the water level in Double Bulger dropped to a level too low to sample, although discharge of steam continued, and upward splashing of water from deep within the vent could be seen. By eleven days after the start of the annual disturbance the water level once again was high enough to sample. By then Double Bulger Geyser's Cl had attained a value of 1444 ppm, which was about twice as high as any previously recorded in a Yellowstone thermal water (extensive tabulations of chemical analyses are given in Gooch and Whitfield, 1888; Allen, and Day, 1935; Rowe and others, 1973; Thompson and others, 1975; Thompson and Yadav, 1979; and Thompson and DeMonge, 1996). However, at the same time the Cl/ SO_4 ratio and pH both decreased (Figs. 5a and 5c), indicating addition of an H_2SO_4 component to the water. The addition of an H_2SO_4

component after the start of the disturbance also is evident in Figure 13, which shows a dramatic increase in SO_4 while the major cations, Na and K, continue to reflect mainly variations in Cl and Br.

Figures 14 and 15 are plots of δD and $\delta^{18}\text{O}$ respectively versus Cl for Double Bulger Geyser's waters compared with data for the other springs collected in 1995. Also shown are data for Echinus Geyser which discharges the largest volume of acid-sulfate-chloride water of any feature at Norris. For comparison, Y-12 drill hole water (condensed total flow) and local meteoric water also are plotted in Figures 14 and 15. In these figures the labeled diamonds show expected compositions of the residual liquid at atmospheric pressure after adiabatic decompressional boiling of water fed by reservoirs at 300 °C, 325 °C and 350 °C. For computational purposes, the isotopic composition and Cl concentration of the water in the deep reservoir before boiling were assumed to be similar to that of the condensed water-steam mixture discharged from the Y-12 drill hole. The above two figures show that the isotopic compositions and Cl concentrations in the waters discharged by Double Bulger Geyser 11 and 16 days after the start of the annual disturbance cannot be explained by a simple adiabatic decompressional model with single-step steam loss at atmospheric pressure. The isotopic changes accompanying single-step steam loss at atmospheric pressure were calculated using methods outlined in Truesdell and others (1977). Figures 16 and 17 are similar plots of δD and $\delta^{18}\text{O}$ respectively versus SO_4 . The Cl and SO_4 versus isotopic composition plots all show widely ranging anionic concentrations while the isotopic compositions show relatively little variation. These observations preclude evaporation at atmospheric pressure of standing water in a non-discharging pool as a way to explain the high concentration of Cl that was obtained after the start of the annual disturbance because that process would produce residual water that becomes progressively heavier as Cl and SO_4 concentrations increase.

One way to explain the data would be by a refluxing of some of the cooled and relatively dense boiled water back underground where it would again be heated to high temperature. This would occur during the non-discharging period just after the annual disturbance, when the water level in the vent was too low to sample. The previously boiled water, which had counter-flowed downward, then undergoes additional decompressional boiling during subsequent upflow. In this model, the refluxed water must be re-heated to greater than 220 °C in order to minimize the partitioning of lighter isotopes into the vapor phase during subsequent "reboiling". Note that above 220 °C, boiling causes the residual liquid water to become lighter in δD and only slightly heavier in $\delta^{18}O$ (Truesdell and others, 1977).

Another way to attain the anomalously high concentrations of non-volatile dissolved constituents, and the isotopically heavy water, would be by non-adiabatic evaporation utilizing excess heat in the reservoir rock. For example, if the discharge up the main channel of flow occurred at a faster rate than fluid could migrate into that relatively open channel from the surrounding rock, there would have been a drop in fluid pressure at all depths within, and immediately adjacent to, the main channel of upflow. This would result in boiling-point temperatures in the neutral-chloride and acid-chloride-sulfate reservoirs becoming less than the prevailing reservoir temperatures. Boiling of water "in place" would then occur in the reservoirs, producing steam in excess of that obtained by adiabatic decompressional boiling, until rock temperatures declined to a point where rock temperature-fluid pressure conditions were again compatible with a new, adiabatic "boiling-point" curve.

According to the above models, Double Bulger Geyser's waters should have become isotopically heavier in $\delta^{18}O$, and perhaps lighter in δD (if boiled in place above 220 °C), as the Cl concentration increased. However, the first sample taken after the start of the annual disturbance was lighter in $\delta^{18}O$, but heavier in δD relative to the

preceding sample (Fig. 5d). But, it was not lighter in $\delta^{18}O$ relative to the composition of Y-12 water (Fig. 15). We suggest that soon after the start of the annual disturbance the main source of the discharged water shifted slightly to produce fluid isotopically more closely related to Y-12 water. Subsequently, as subsurface pressures declined further, a SO_4 -rich water with a still different isotopic composition began to enter the discharge channel and mix in various proportions with the Cl-rich water (Fig. 18). We suspect that SO_4 -rich water enters the channel of upflow at a shallower depth than the Cl-rich water entry.

On a diagram showing $\delta^{18}O$ versus δD for all Norris waters, Double Bulger Geyser's waters, like Cistern Spring's waters, plot with the isotopically heavier waters (Fig. 12d). However, most (but not all) of Double Bulger Geyser's waters plot along the right side of the data cluster, while most (but not all) of Cistern Spring's waters plot toward the left side of the data cluster (Fig. 12c).

On a plot of Cl versus SO_4 , most waters collected from Double Bulger Geyser before the start of the annual disturbance fall along line B, which is radial from the origin, and which passes slightly above the Y-12 water data point (Fig. 18). However, the first two samples of water collected from Double Bulger Geyser have the lowest SO_4 concentrations and plot close to line A, which passes through the Y-12 water data point. We note that the two data points that lie closest to line A also have the lightest δD values of any of the waters collected from Double Bulger Geyser, and also are among the three lightest in $\delta^{18}O$ (Table 1). The only Double Bulger Geyser sample that is lighter in $\delta^{18}O$ was the first sample collected after the start of the disturbance (Table 1 and Fig. 18). Thereafter, the $\delta^{18}O$ of waters sampled from Double Bulger Geyser became progressively heavier as SO_4 increased (Fig. 18). For comparison, Cl- SO_4 relations for waters from Cistern Spring and Porkchop Geyser also are shown in Figure 18.

In striking contrast to the Double Bulger Geyser waters, variations in composition of Cistern Spring waters in the summer of 1995 lie along a single mixing trend with one end-member water having about 550 ppm Cl and 60 ppm SO₄, and the other about 350 ppm Cl and 110 ppm SO₄ (Fig. 18). There is no sign in the Cistern Spring waters of the evaporative concentration of non-volatile components that is exhibited by Double Bulger Geyser waters. On the other hand, most of the compositional variations in the Porkchop Geyser waters seem to be related to differences in the degree of vapor or steam loss from water that is compositionally similar to Y-12 water (the data points plot near line A in Fig. 18). However, there is no indication in the Porkchop Geyser waters of the high degree of high-temperature evaporation that appears to be occurring in the Double Bulger Geyser waters.

Porkchop Geyser waters exhibited a small increase in temperature and Cl/SO₄, a small decrease in Na/K, and a significant change in isotopic composition (δD and $\delta^{18}O$ became lighter) leading up to the annual disturbance (Fig. 6). After the disturbance there was a decrease in Cl/SO₄ and pH, indicating that a small increase in an acid-sulfate component was being incorporated into the discharge. The water also became isotopically heavier. At the same time the Cl concentration and Na/K ratio increased, and discharge temperature decreased. The increase in Cl concentration and trend toward an isotopically heavier water after the start of the annual disturbance were probably mainly the result of a significant decrease in the rate of discharge. The slower rate of discharge allowed evaporation from the surface of the pool to affect water compositions. However, on a graph of $\delta^{18}O$ versus δD the Porkchop Geyser waters show only about a 2 ‰ range in $\delta^{18}O$ and about an 8 ‰ range in δD (Fig. 19a), suggesting that atmospheric evaporation effects were not extreme.

Previously, Fournier and others (1991) proposed a model in which two reservoirs of alkaline-chloride water at different temperatures contribute water to Porkchop Geyser's discharge. A decrease in Na/K and

increase in the enthalpy of the discharged water-steam mixture over a span of several years resulted from drawing a larger proportion of water from the deeper and hotter reservoir. Our 1995 data do not show the extreme variations in Na/K reported by Fournier and others (1991) (Fig. 20). Apparently most of the water discharged by Porkchop Geyser in the summer of 1995 came from the deeper and hotter reservoir, with the proportion of deeper and hotter water becoming even larger (more K-rich water) leading up to the annual disturbance. After the annual disturbance the proportion of the deep component again decreased slightly.

"Wistful" Geyser showed little chemical or isotopic variation leading up to the annual disturbance (Fig. 7). On the day of the disturbance there was an immediate drop in pH and Cl/SO₄ (Figs. 7a and 7c). Cl continued to decrease and SO₄ to increase for another 10 days, reaching respective minima and maxima on day 220 (Fig. 7b). By day 240 the concentration of Cl was larger, and the Cl/SO₄ was about the same as prior to the start of the annual disturbance. The pH change was as expected, generally decreasing in proportion with increasing sulfate (Figs. 7a and 7b). As was the case for Cistern Spring waters, in the "Wistful" Geyser waters both δD and $\delta^{18}O$ became heavier as Cl decreased and SO₄ increased (compare Fig. 7d with 7b). On the other hand, the Na/K data showed little variation except for two anomalously low values on days 218 and 220 that also had the highest SO₄ values (compare Fig. 7c with 7b).

Isotopically, "Wistful" Geyser waters became heavier in both δD and $\delta^{18}O$ as Cl/SO₄ decreased (Figs. 7c and 7d). On a diagram showing $\delta^{18}O$ versus δD for all Norris waters, "Wistful" waters exhibit almost the full range in isotopic compositions found in these waters (Fig. 19b). Prior to the start of the annual disturbance all the data plot with the isotopically lighter waters (Fig. 19b). In contrast, during the disturbance and for a few days thereafter, "Wistful" waters plot with the isotopically heavier waters, generally trending toward the isotopic composition of Vermilion Spring, a typical

low-chloride, acid-sulfate, steam-heated, non-overflowing pool. Like the results for Double Bulger Geyser, the data points for "Wistful" Geyser plot at the right side of the data cluster. There is a general mixing trend that extends from the Y-12 composition toward an isotopically heavy acid-chloride-sulfate water.

The response of "Carnegie" Spring water to the annual disturbance was very slight. There was a general trend of increasing temperature, Cl, and Cl/SO₄ prior to the start of the disturbance (Figs. 8a, 8b and 8c). These trends reversed immediately after the start of the disturbance. The relatively large variations in Na/K ratios (Fig. 8c) are more apparent than real because the "Carnegie" Spring waters contain relatively little K. Therefore, small analytical differences of less than 1 ppm (within the analytical uncertainty) result in relatively large differences in Na/K. Compared to pre-disturbance values, δD became slightly lighter after the disturbance, while $\delta^{18}O$ became slightly heavier.

The "Carnegie" Spring waters have δD values close to that of the local meteoric water, and $\delta^{18}O$ values about 1.5 ‰ heavier than Y-12 water (Fig. 19c). Even though the "Carnegie" waters apparently issue from a relatively low-temperature reservoir at about 190°C (Table 2 and Fig. 11) they appear to have attained isotopic as well as chemical equilibration with the reservoir rock. However, the δD values close to that of the local meteoric water may be coincidental. Isotopic exchange with rock may have occurred mainly in a deeper and hotter reservoir before the water moved up into the shallower and cooler 190°C reservoir, where chemical, but not isotopic, re-equilibration occurred.

Perpetual Spouter waters behaved very similarly to the "Carnegie" Spring waters in that there was very little isotopic and chemical response to the annual disturbance. Relative to the pre-disturbance composition, δD recovered to slightly lighter values after the disturbance while $\delta^{18}O$ remained nearly constant. Like the "Carnegie" Spring waters,

Perpetual Spouter waters have δD values close to those of the local meteoric water, and $\delta^{18}O$ values about 1.5 ‰ heavier than Y-12 water (Fig. 19d). Na/K and Cl/SO₄ variations probably reflect the analytical uncertainty in the measurements.

Over the course of the monitoring period Beryl Spring showed minor chemical and $\delta^{18}O$ variations, but significant δD changes both before and after the disturbance (Fig. 10). However, like "Carnegie" Spring waters, Beryl Spring waters issue from a relatively low temperature reservoir (discussed above). This reservoir is probably relatively shallow and may not be sensitive to changes that trigger annual disturbance responses in the deep, high-temperature reservoirs beneath Norris Geyser Basin.

TRIGGERING OF THE ANNUAL DISTURBANCE

Fournier and others (1986) noted that several factors may be important in triggering the annual disturbance, including self-sealing by mineral deposition, clogging of channels by clay suspended in flowing waters, large geyser eruptions, seasonal changes in water table, deformation and fracturing induced by tectonic forces, and hydrofracturing. Of these, for most years seasonal variations in fluid pressure within the hydrothermal system are probably most important. Fournier (1983) pointed out that fluid pressures measured at the bottoms of shut-in wells drilled in thermal areas of YNP (White and others, 1975) generally are close to the pressures that would be exerted by overlying columns of cold water. This strongly suggests that there are relatively open hydraulic connections between the hydrothermal systems and the surrounding low-temperature groundwater systems. Accordingly, a possible explanation of the annual disturbance involves changes in reservoir pressure brought about by changes in the potentiometric surfaces of the regional cold water systems.

Temperature-depth curves in the central part of the hydrothermal system, where upward convective flow rates are greatest, come to define boiling-point curves

appropriate for the fluid pressure profile. While fluid pressures within the hydrothermal "plumbing system" remain high (controlled by the cold-water system adjacent to the Norris hydrothermal system), waters in shallower, relatively low-pressure reservoirs are essentially held in check (unable to enter the channels of upflow and mix with the waters of deeper origin) because there is no pressure gradient to drive this entry. However, this situation is very unstable because a drop in pressure in the cold-water part of the system results in a drop in pressure in the hydraulically interconnected hot-water part of the system. In turn, this decrease in pressure requires that boiling temperatures at given depths decrease. But, rock temperatures do not decrease as rapidly as does the boiling-point curve. Liquid water vigorously flashes to steam (non-adiabatic evaporation at high pressure), energized by the heat stored in rock. The boiling "in place" and temporary increase in pressure within relatively shallow, acid-water reservoirs (rich in clay minerals) cause "muddy" water and steam to be ejected from these reservoirs into the main channels of upflow. The annual disturbance is initiated. The immediate, but temporary upward surge in pressure at the top of the system is followed shortly thereafter by a decline in pressure deeper in the system. This is because water from the deep reservoirs does not enter the channels of upflow at as fast a rate as water is propelled upward by expansion of "excess" steam, and because the increased proportion of steam to water lightens the "load" exerted by the overlying column of fluid. Where temperatures in shallow reservoirs are less than the prevailing boiling temperature, the general decline in pressure within the hydrothermal system allows waters in these initially lower-pressure reservoirs to enter the main channels of upflow without violent steam propulsion. There they mix with waters ascending from the deeper reservoirs, producing the mixed waters seen in some Norris springs and geysers.

The annual disturbance generally does not occur in the spring of the year because then the water table (potentiometric surface) is generally high as a result of the melting of thick covers of snow. At this time fluid

pressure at given depths, both outside and inside the hydrothermal system, is higher than average. This situation allows the boiling point curve to rise slightly, and there is a heating of rock adjacent to the main channels of convective upflow in the heart of the hydrothermal system. As the summer progresses, the water table drops slightly, the rate of recharge of cold water decreases, groundwater temperature adjacent to the hydrothermal system increases slightly, and the density of the pressure-controlling column of "cold" water decreases. The boiling-point within the hydrothermal system drops in response to these changes and, in some places, previously heated rock gives up that heat by causing excess evaporative boiling (flashing to steam) of ascending fluids, as discussed above.

Beneath Double Bulger, evaporative boiling is probably occurring simultaneously in the shallower acid-chloride-sulfate and the deeper neutral-chloride reservoirs as a result of a drop in fluid pressure along the flow path. Elsewhere, as at Cistern Spring and "Wistful" Geyser, the main effect of a slight drop in fluid pressure along the flow path seems to be to allow larger proportions of waters from shallower reservoirs (the acid-chloride-sulfate waters) to enter the channels of upflow and mix with the waters of deeper origin.

Annual disturbance phenomena may not occur in other geyser basins in YNP because the thermal waters in those basins are fed by shallower, lower-temperature reservoirs (180–215 °C at Lower and Upper Geyser Basins compared to 270–310 °C at Norris according to Fournier and others (1976) and Fournier (1989)). It is also possible that annual disturbance phenomena do occur in other Geyser Basins, but have not been recognized because widespread shallow reservoirs of acid waters are not present in those basins to furnish the clay which makes hot spring and geyser waters murky at Norris Geyser Basin, heralding the onset of the disturbance there.

SUMMARY AND CONCLUSIONS

At the time of the annual disturbance there is widespread subsurface mixing of shallow, acid-chloride-sulfate water (reservoir temperature probably in the range

about 180–220 °C) with near-neutral, chloride-rich water ascending from higher-temperature (270 °C to >300 °C), and presumably deeper, reservoirs beneath Norris Geyser Basin. In contrast, hot springs that discharge near-neutral, chloride-rich waters that have equilibrated with rock in reservoirs where temperatures are 250 °C or less show little chemical response to the annual disturbance. Acid-sulfate-chloride water, similar in composition to waters discharged in Porcelain Basin and 100 Spring Plain, underlies much of the Back Basin, but is discharged there only after mixing with the neutral-chloride water. Generally, this occurs only for short periods of time after annual disturbances.

The large volume of acid-chloride-sulfate water discharged by Echinus Geyser in the Back Basin is distinctly different chemically and isotopically compared with the Porcelain Basin and 100 Spring Plain acid-chloride-sulfate waters (Figs. 14–17). The low chloride and isotopically relatively light Echinus Geyser-type waters do not appear to be mixing in significant amounts with the neutral-chloride waters in the Back Basin.

In contrast with the acid-sulfate-chloride waters discharged by Echinus Geyser, most of the acid-chloride-sulfate waters at Norris are isotopically relatively heavy in both δD and $\delta^{18}O$ (Figs. 14–18). To date, all of the waters collected from non-discharging, steam-heated, acid-sulfate pools at Norris and elsewhere in YNP have been found to be isotopically heavy (for example, the Vermilion Spring pool shown in Figs. 12 and 19). Some of this type of water is likely to percolate into the ground and mix with other subsurface waters.

The extremely high concentrations of Cl and SO_4 in waters collected from Double Bulger Geyser after the start of the 1995 annual disturbance are probably the result of excess boiling (more steam loss than can be accounted for by adiabatic decompressional boiling of a "once-through" fluid). Excess boiling may have occurred as a result of counter flow of previously boiled fluid back underground where it was re-heated to over 220 °C. This water then boiled adiabatically a second time during subsequent convective upflow; the cycle may have been repeated

more than once. Alternatively, and more likely, a drop in fluid pressure all along the channel of upflow resulted in excess boiling of water in neutral-chloride and acid-chloride-sulfate reservoirs that supply water to Double Bulger Geyser.

Triggering of the annual disturbance probably is caused mainly by annual changes in elevation of the potentiometric surface of the cold-water system that surrounds the Norris hydrothermal system, although seismicity may be important sometimes. In the spring the water table is high and rate of downward percolation of cold water adjacent to the Norris hydrothermal system is greatest. At this time fluid pressures within the interconnected cold-and hot-water systems are highest. While high fluid pressure prevails along paths or channels of upward hydrothermal convective fluid flow, the flow of acid-chloride-sulfate waters from relatively shallow, low-pressure reservoirs into the main channels of upflow is prevented because there is no pressure gradient driving that entry. Generally, by the end of the summer months, there is a decrease in the elevation of the local potentiometric surface (the water table) sufficient to result in a decrease in fluid pressure within that hydrothermal system. In reservoirs at various depths excess evaporative boiling is induced which initially produces an upward pressure surge at shallow depths, followed by a rapid decline in pressure deeper in the hydrothermal system. The drop in pressure allows acid-chloride-sulfate waters to enter the channels of upflow and mix with the neutral-chloride waters of deeper origin.

Annual disturbance phenomena that are easily recognized at Norris Geyser Basin may not be easily recognized elsewhere in Yellowstone National Park because (1) the neutral-chloride waters that are fed from relatively shallow, and lower-temperature reservoirs in other geyser basins may not react as vigorously in their steam production as do the waters in the very high-temperature Norris reservoirs in response to small pressure changes outside of the hydrothermal system, and (2) the clay that makes hot spring and geyser waters become turbid at Norris, heralding the start of the disturbance, comes from acid altered rocks that are widely

distributed at intermediate depths at Norris, and that are rare in other geyser basins.

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Figure Captions

Figure 1. Sketch map of Norris Geyser Basin, Yellowstone National Park, showing topographic features, locations of features that were monitored, U.S. Geological Survey drill holes Y-9 and Y-12, and other selected hot springs and geysers. Contours show equal altitude in feet.

Figure 2. Chemical and isotopic variations versus Julian day for Sulfur Dust Spring.

- a) temperature and pH versus Julian day.
- b) Cl and SO₄ versus Julian day.
- c) Na/K and Cl/SO₄ versus Julian day.
- d) δD and $\delta^{18}O$ versus Julian day.

Figure 3. Chemical and isotopic variations versus Julian day for "Black" Spring.

- a) temperature and pH versus Julian day.
- b) Cl and SO₄ versus Julian day.
- c) Na/K and Cl/SO₄ versus Julian day.
- d) δD and $\delta^{18}O$ versus Julian day.

Figure 4. Chemical and isotopic variations versus Julian day for Cistern Spring.

- a) temperature and pH versus Julian day.
- b) Cl and SO₄ versus Julian day.
- c) Na/K and Cl/SO₄ versus Julian day.
- d) δD and $\delta^{18}O$ versus Julian day.

Figure 5. Chemical and isotopic variations versus Julian day for Double Bulger Geyser.

- a) temperature and pH versus Julian day.
- b) Cl and SO₄ versus Julian day.
- c) Na/K and Cl/SO₄ versus Julian day.
- d) δD and $\delta^{18}O$ versus Julian day.

Figure 6. Chemical and isotopic variations versus Julian day for Porkchop Geyser.

- a) temperature and pH versus Julian day.
- b) Cl and SO₄ versus Julian day.
- c) Na/K and Cl/SO₄ versus Julian day.
- d) δD and $\delta^{18}O$ versus Julian day.

Figure 7. Chemical and isotopic variations versus Julian day for "Wistful" Geyser.

- a) temperature and pH versus Julian day.
- b) Cl and SO₄ versus Julian day.
- c) Na/K and Cl/SO₄ versus Julian day.
- d) δD and $\delta^{18}O$ versus Julian day.

Figure 8. Chemical and isotopic variations versus Julian day for "Carnegie" Spring.

- a) temperature and pH versus Julian day.
- b) Cl and SO₄ versus Julian day.
- c) Na/K and Cl/SO₄ versus Julian day.
- d) δD and $\delta^{18}O$ versus Julian day.

Figure 9. Chemical and isotopic variations versus Julian day for Perpetual Spouter.

- a) temperature and pH versus Julian day. b) Cl and SO₄ versus Julian day.
- c) Na/K and Cl/SO₄ versus Julian day. d) δD and $\delta^{18}O$ versus Julian day.

Figure 10. Chemical and isotopic variations versus Julian day for Beryl Spring.

- a) temperature and pH versus Julian day. b) Cl and SO₄ versus Julian day.
- c) Na/K and Cl/SO₄ versus Julian day. d) δD and $\delta^{18}O$ versus Julian day.

Figure 11. Temperatures of reservoirs estimated using the Na/K geothermometer of Giggenbach (1988) compared with estimated reservoir temperatures using the silica (quartz) geothermometer of Fournier and Potter (1982). Circles plot at silica temperatures estimated assuming adiabatic cooling and x's plot at silica temperatures estimated assuming conductive cooling.

Figure 12. δD versus $\delta^{18}O$ for all Norris waters compared with a) Sulfur Dust Spring waters, b) "Black" Spring waters, c) Cistern Spring waters, and d) Double Bulger Geyser waters.

Figure 13. Variations in Cl, Na, K, SO₄, and Br versus Julian day for Double Bulger Geyser waters.

Figure 14. δD and Cl relations in Double Bulger Geyser, Sulfur Dust Spring, Echinus Geyser, and Y-12 waters compared with all other data for Norris waters. Diamonds show calculated compositions of Y-12 waters after adiabatic decompressional boiling from the indicated initial reservoir temperatures with single stage steam separation at atmospheric pressure.

Figure 15. $\delta^{18}O$ and Cl relations in Double Bulger Geyser, Sulfur Dust Spring, Echinus Geyser, and Y-12 waters compared with all other data for Norris waters. Diamonds show calculated compositions of Y-12 waters after adiabatic decompressional boiling from the indicated initial reservoir temperatures with single stage steam separation at atmospheric pressure.

Figure 16. δD and SO_4 relations in Double Bulger Geysers, Sulfur Dust Spring, Echinus Geysers, and Y-12 waters compared with all other data for Norris waters.

Figure 17. $\delta^{18}O$ and SO_4 relations in Double Bulger Geysers, Sulfur Dust Spring, Echinus Geysers, and Y-12 waters compared with all other data for Norris waters.

Figure 18. SO_4 versus Cl for Double Bulger Geysers, Cistern Spring, and Porkchop Geysers waters. $\delta^{18}O$ values are shown for selected waters. See text for discussion.

Figure 19. δD versus $\delta^{18}O$ for all Norris waters compared with a) Porkchop Geysers waters, b) "Wistful" Geysers waters, c) "Carnegie" Spring waters, and d) Perpetual Spouter waters.

Figure 20. K versus Na for Porkchop Geysers waters. Waters collected prior to 1985 all plot below the dashed line.

Table 1. Results of chemical and isotopic analyses

Table 2. Estimated reservoir temperatures using silica and Na/K geothermometers

Appendix 1 - Field notes

- June 11 (day 162) Double Bulger Geyser - Heavier than previous boils \approx 2-3 ft
- June 22 (day 173) Temperature probe on the Orion combination temperature-pH meter broke - Now using a different electronic thermometer made by Keithly. Must manually enter temperature to get an accurate pH reading.
- June 23 (day 174) Sulfur Dust Spring- Surprised by higher pH. Pipette slipped so the accuracy of the 10 ml sample for silica analysis is off. Question the accuracy of the electronic thermometer now being used. Will check it against the new probe when it becomes available. The present probe seems to give slightly cooler readings than the previous probe.
- There were new hydrothermal breakouts near Amethyst - continuous boils 3-4 ft. Ledge Spring boiling 2-3 ft.
- June 30 (day 181) Ledge Spring is overflowing. Mudpots are active. Rock Springs are empty with steam discharge. Lots of new hot areas east of Sulfur Dust Spring at the Black and White Springs. Many new springs at old hydrothermal area west of Ragged Hills.
- July 2 (day 183) Double Bulger Geyser water level is lower by a few inches, but splash seems higher.

Cistern Spring run-off seems more significant to the east - less to the west.

- July 15 (day 196) The pH probe broke. Must cool the water below 80°C to get a pH reading with a different probe. No pH readings were measured on this date.
- July 21 (day 202) Sulfur Dust Spring temperature measured with the Keithly electronic thermometer used since June 23rd is 44.2°C. For comparison, the Orion thermometer with maximum temperature limit of 80°C is 46.0°C.
- July 22 (day 203) Both temperature probes replaced. Now functioning with just the Orion equipment.
- July 23 (day 204) Significant ground temperature increases between Double Bulger Geyser and the boardwalk, including the western side of the creek running past Porkchop Geyser . A new sink hole with "sizzling" water on the western side of the boardwalk directly across from Double Bulger Geyser . Ground steaming on both sides of the boardwalk beyond Bastille. Bastille still holding water. Pearl in constant eruption with overflow to the north, southeast, and southwest. Splashes reaching 1/2 way between its vent and the boardwalk. Southwest runoff extending under boardwalk towards Porkchop Geyser. Porkchop Geyser having periodic light boils with significant increase of runoff extending north into "second eruptor" and south flowing into the creek. 3 new sputtering vents upstream from the bridge over Tantalus Creek.
- July 26 (day 207) Double Bulger Geyser down 1.0 -1.5 ft with eruptions clearing the rim 1–3 ft. Heavy runoff continues around Pearl Geyser and Porkchop Geyser with more /new runoff flowing directly east from Porkchop. Yellow Funnel Spring's water level is down about 6" to 1'. New sink holes around Bastille on both sides of the boardwalk. Dabble erupting from a pool about 3 ft in

diameter. Hydrophane down 4" to 6" since Saturday (in 4 days). Acidic springs such as Son of Green Dragon, Orbe, "the Cousins", Blue Mud Spring don't seem to have any change (or have only slight change) in water level/activity.

- July 27 (day 208) Cistern Spring's water has become very green - relatively light boils over the vent.
- July 29 (day 210) The "annual disturbance" is clearly underway at Norris.
- Sept. 9 (day 252) Double Bulger Geyser water level is up a few inches, but there is still no overflow from the system.
- Sept. 10 (day 253) Double Bulger Geyser water level now down approximately 4" from rim - lower than last week.
- Sept. 11 (day 254) Orange cyanobacteria mats redeveloping on the terraces. The entire basin has not yet returned to pre-disturbance activity. Cistern Spring's pH continues to slowly rise. Double Bulger Geyser still has low pH and less water in the system compared to pre-disturbance levels. The acidic springs from Crater to Son of Green Dragon still have lower water levels and turbulence. Yellow Mud still is having 3-4' boils. Yellow Funnel's water level has been increasing over the last week and is about 6" to 1' below the pre-disturbance level. Hydrophane and the surrounding area still has lower water levels. Vixen still erupts every 1-4 minutes. Bastille is still in constant eruption and Pearl has remained in a steam phase since the start of the "annual disturbance".

- Sept. 16 (Day 259) Cistern Spring has increased amounts of orange Cyanobacteria mats that are forming. Still, the majority of the previous mats are white. Double Bulger Geyser is erupting from a lower water level approximately 6" to 8" below the rim. Only light spray is periodically erupting from the unnamed geyser between Double Bulger Geyser and Bastille.
- Sept. 21 (day 264) The unnamed geyser between Double Bulger Geyser and Bastille has no water erupting. The water level in Double Bulger Geyser has not changed significantly.
- Sept. 26 (day 269) No water is visible in Double Bulger Geyser
- Sept. 28 (day 271) the water level is again 6–8" below the rim of Double Bulger Geyser

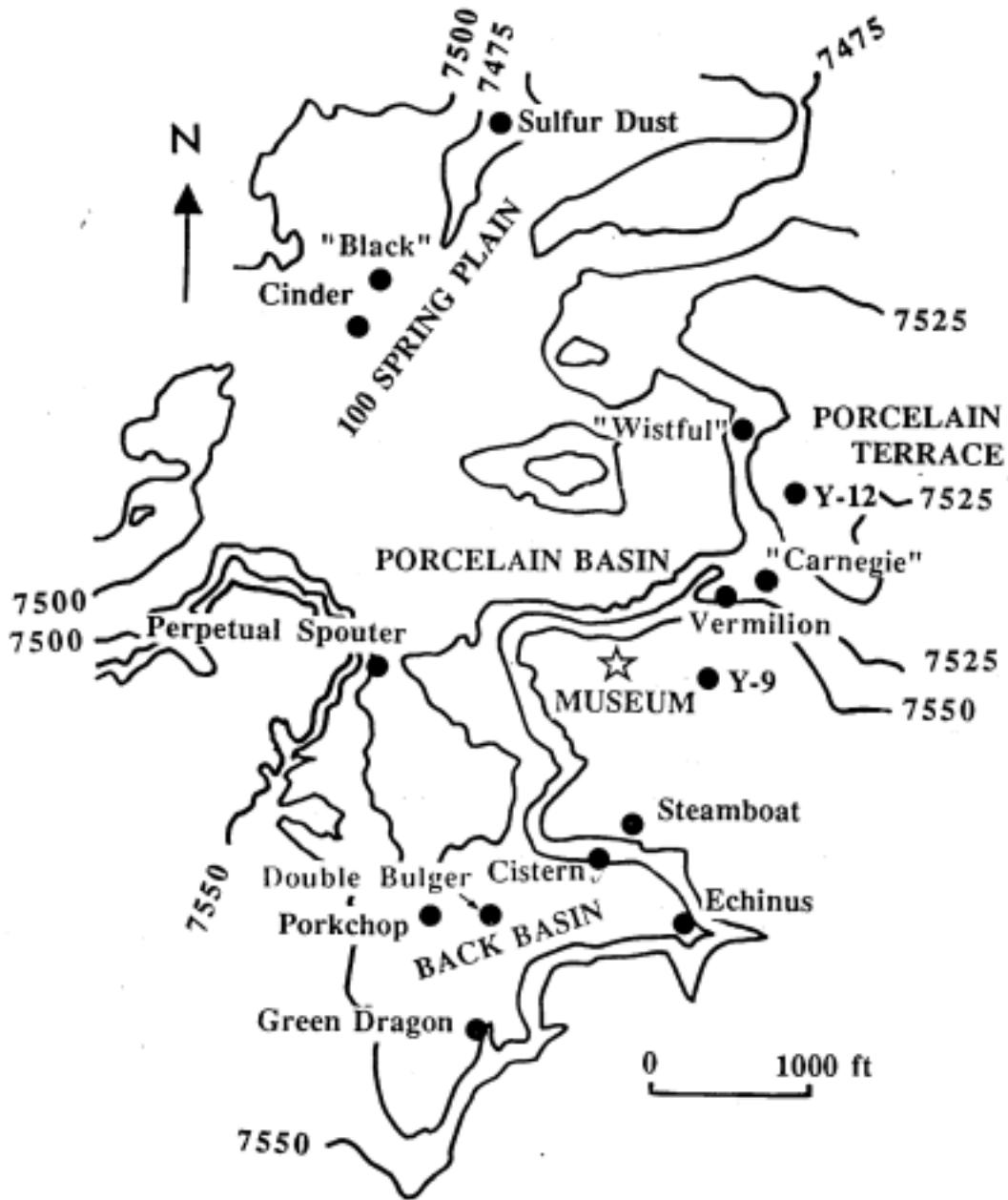


Figure 1

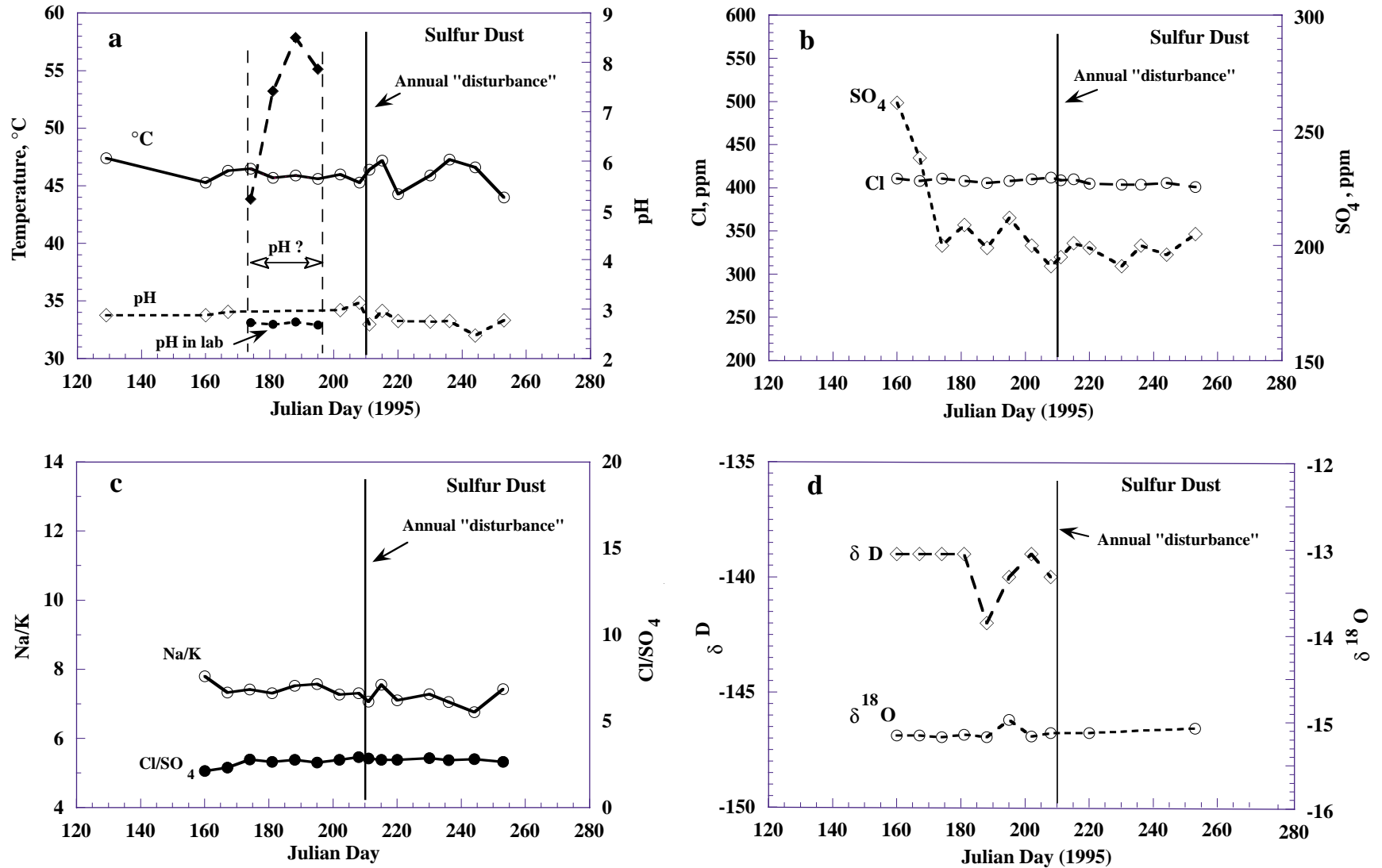


Figure 2

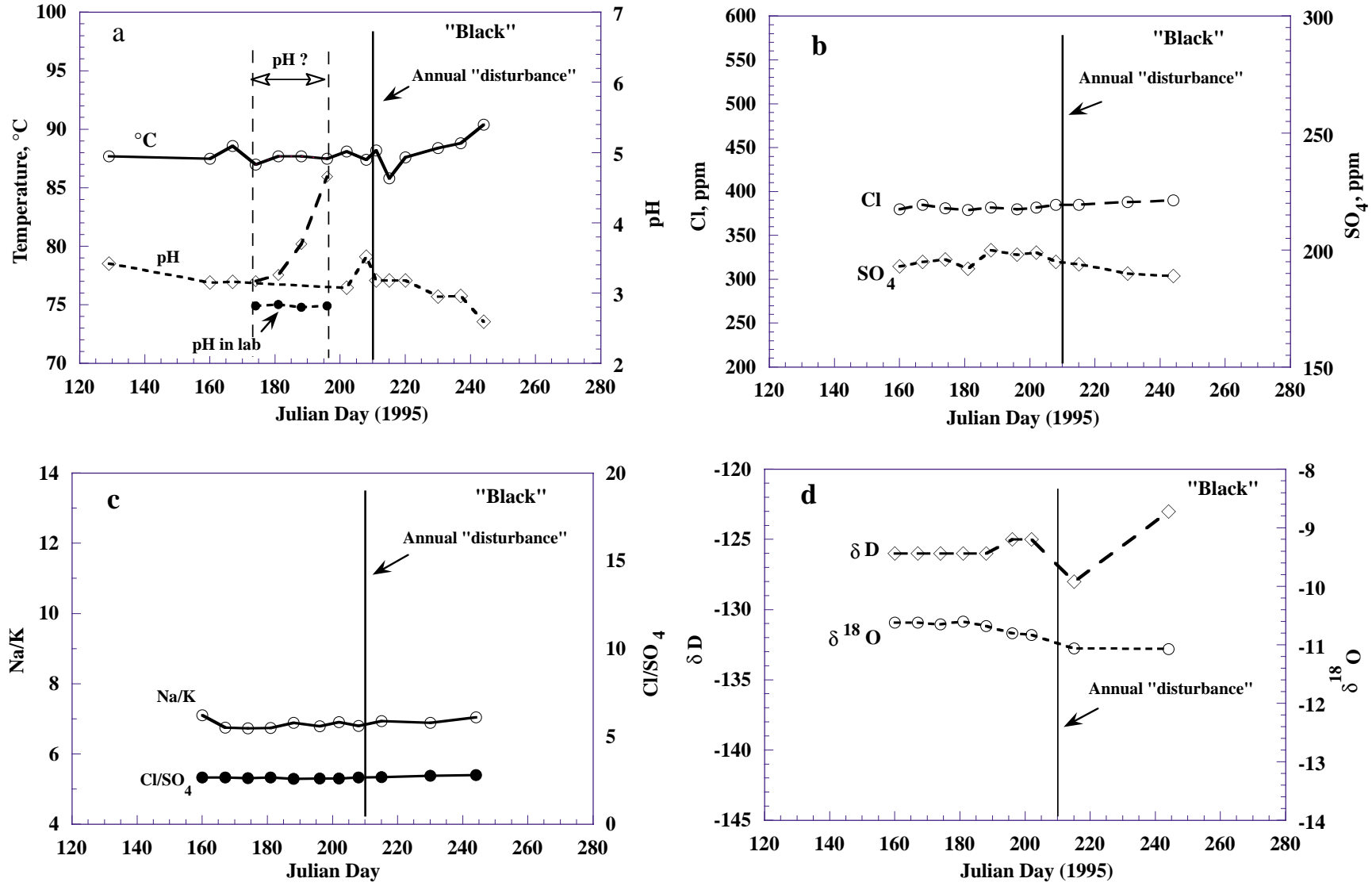


Figure 3

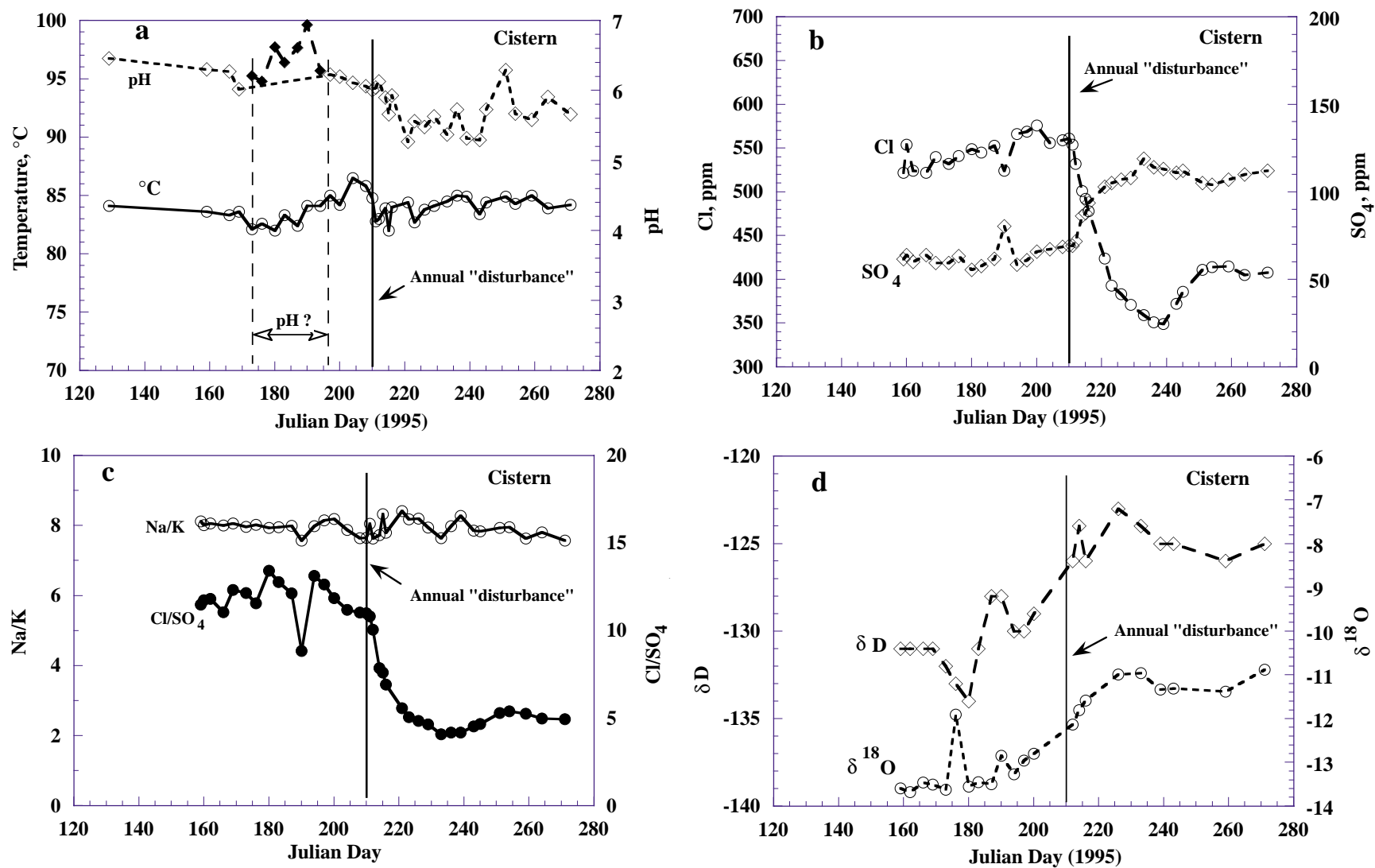


Figure 4

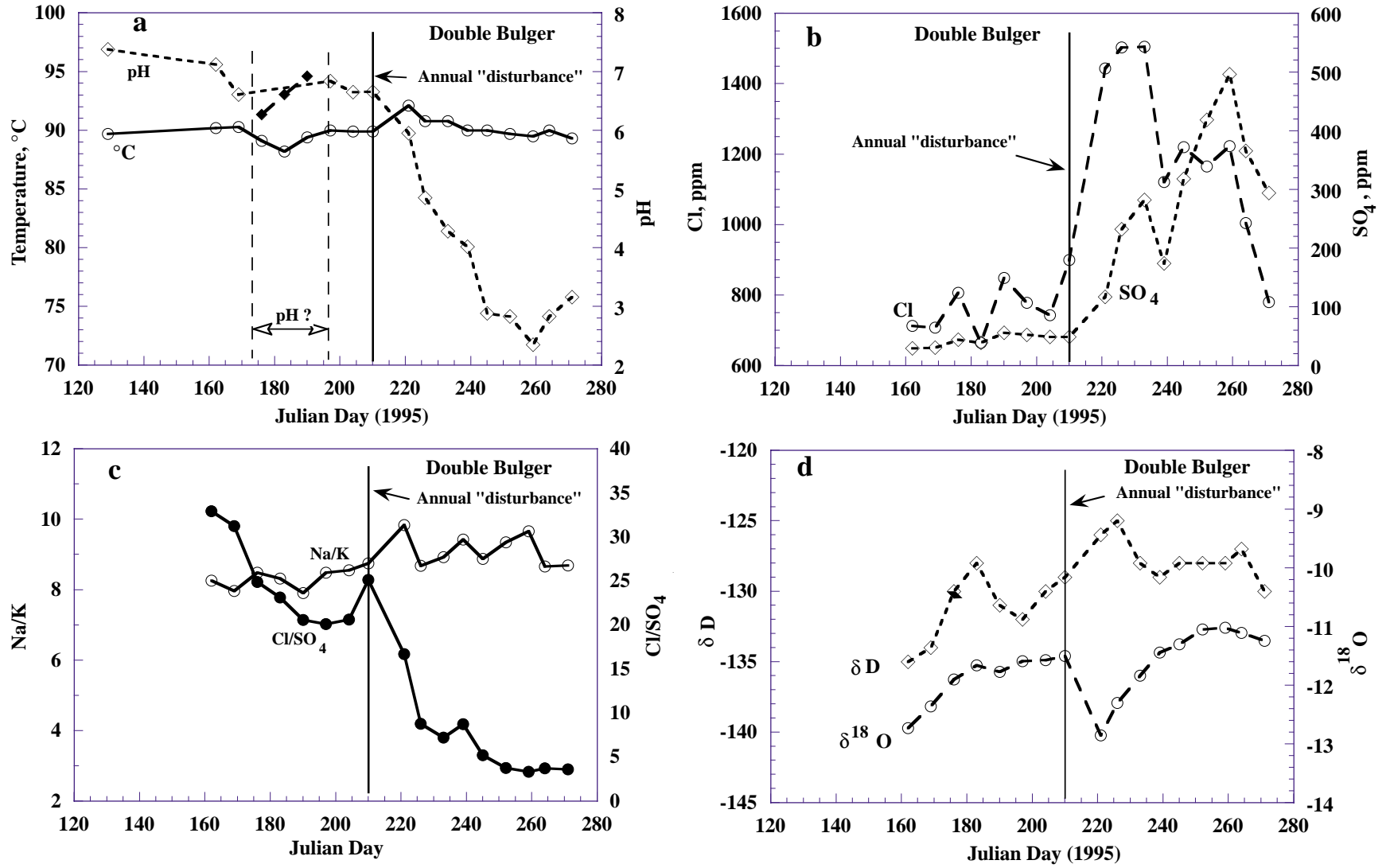


Figure 5

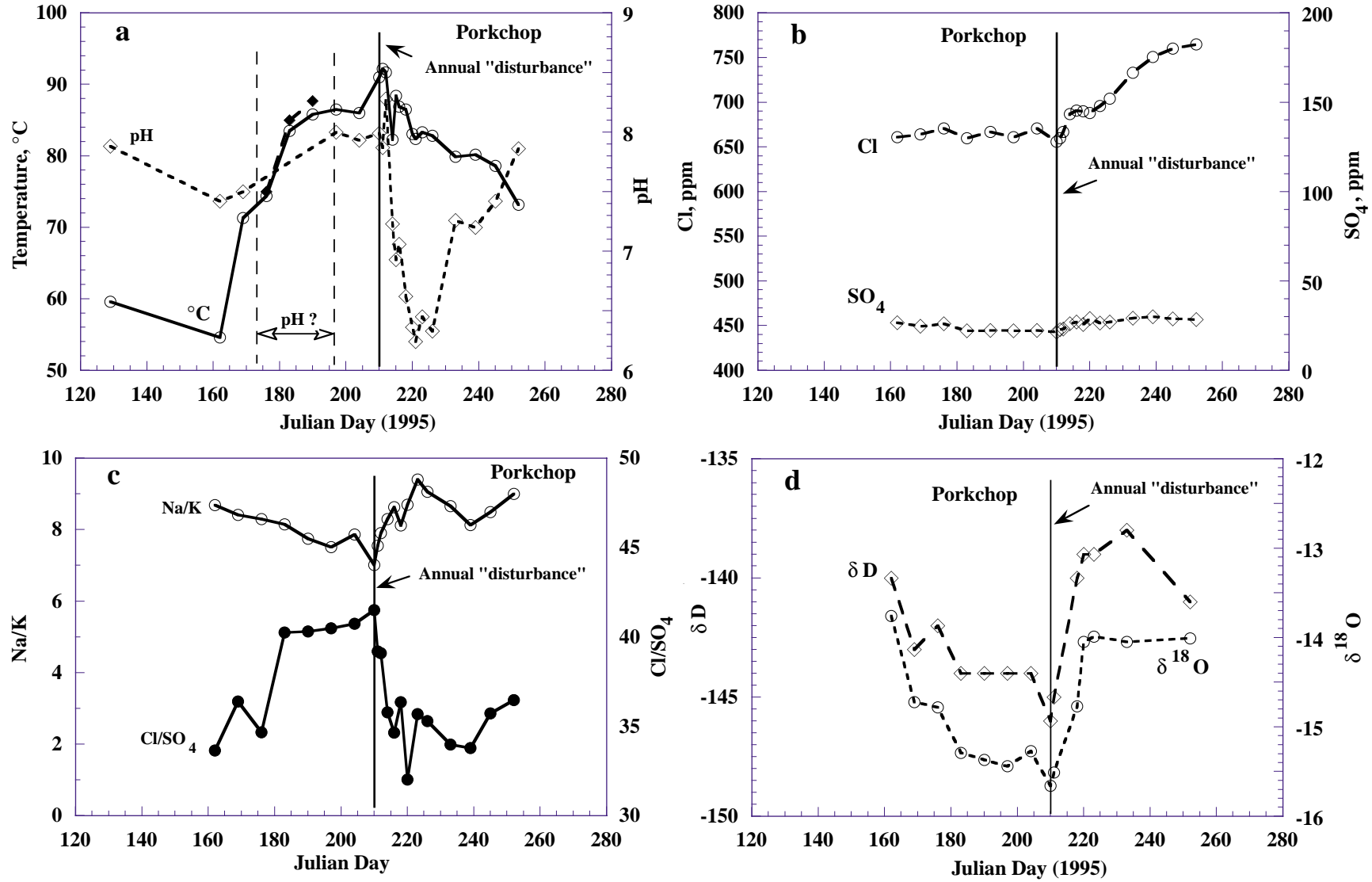


Figure 6

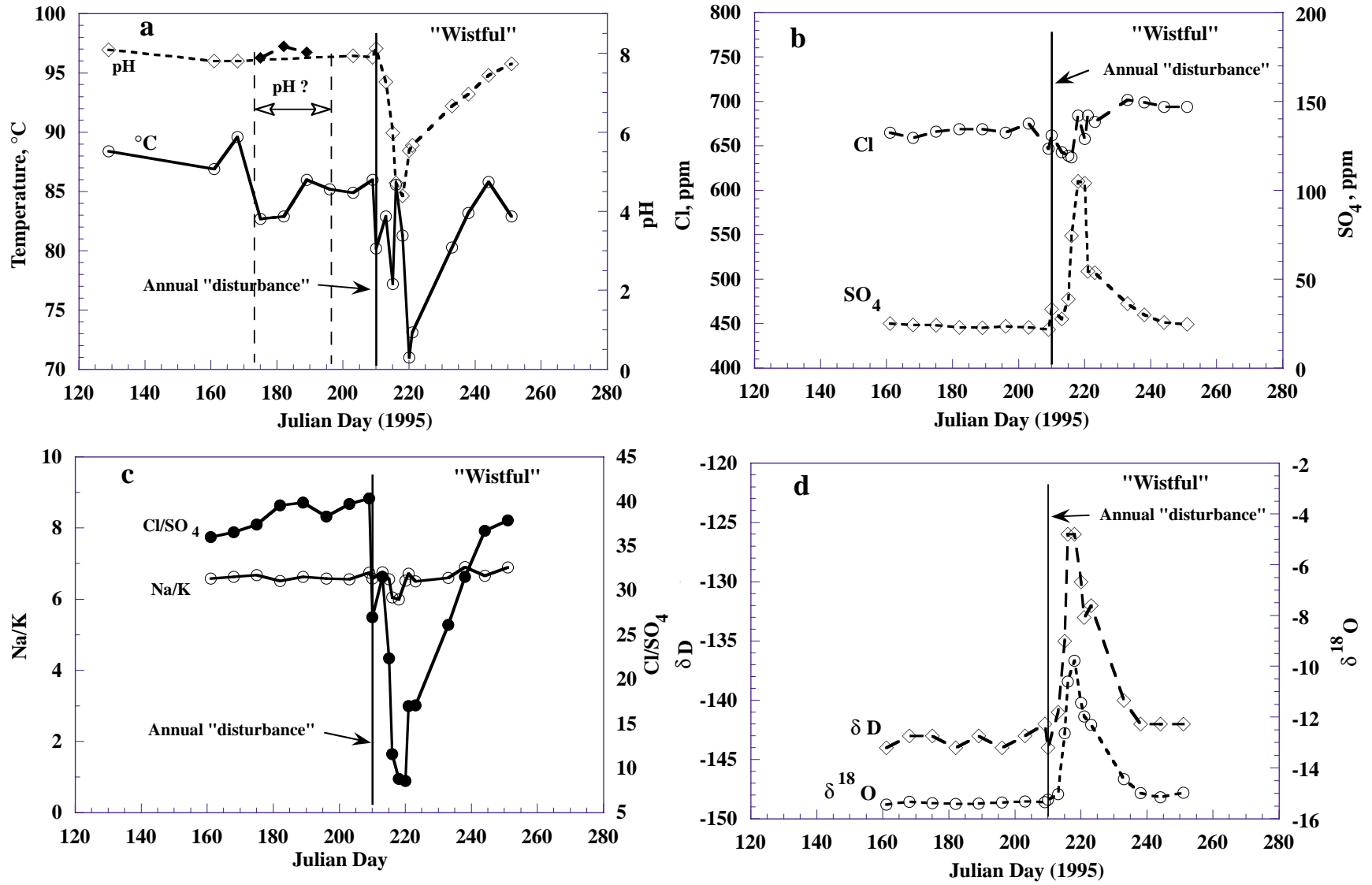


Figure 7

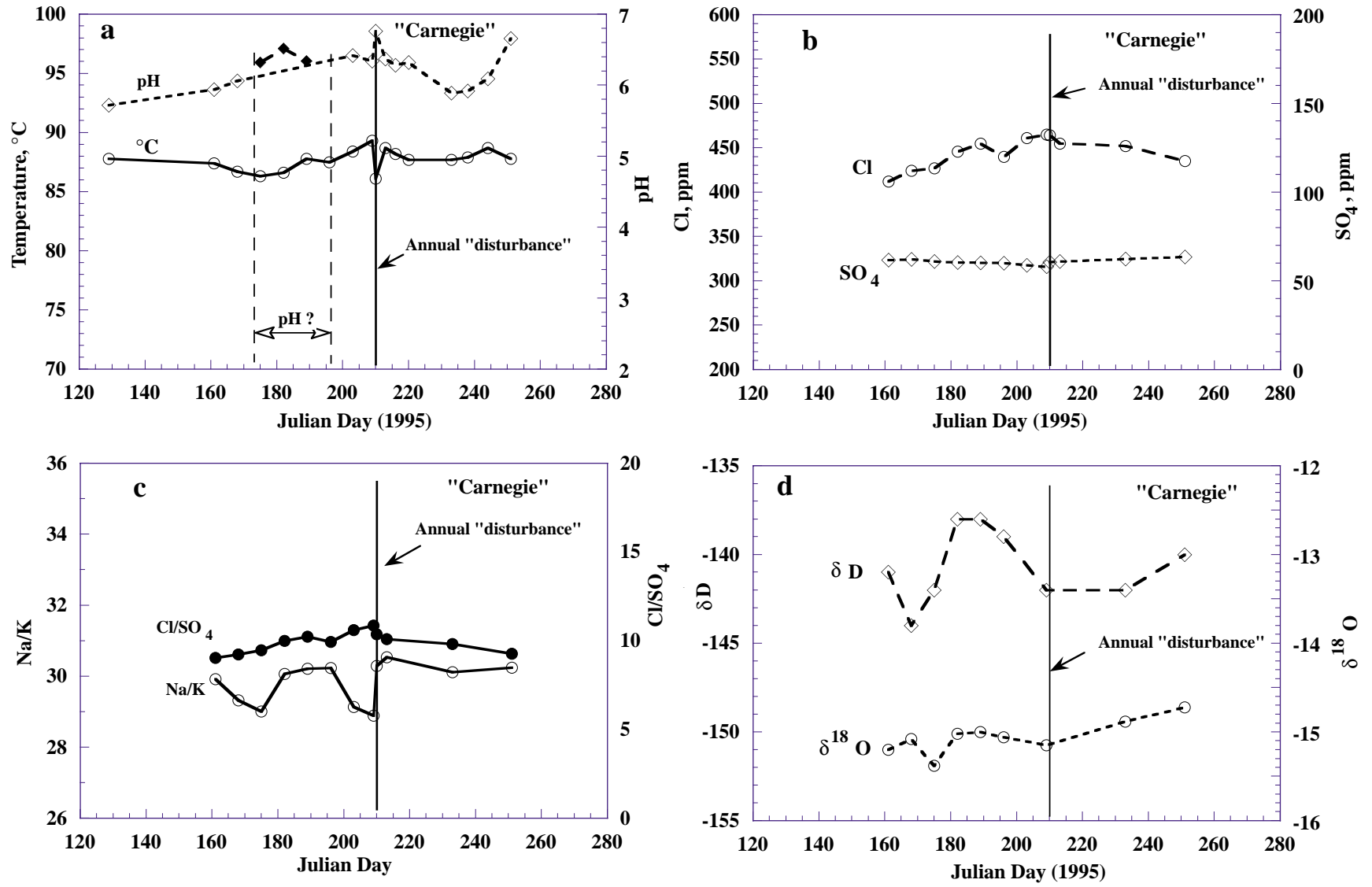


Figure 8

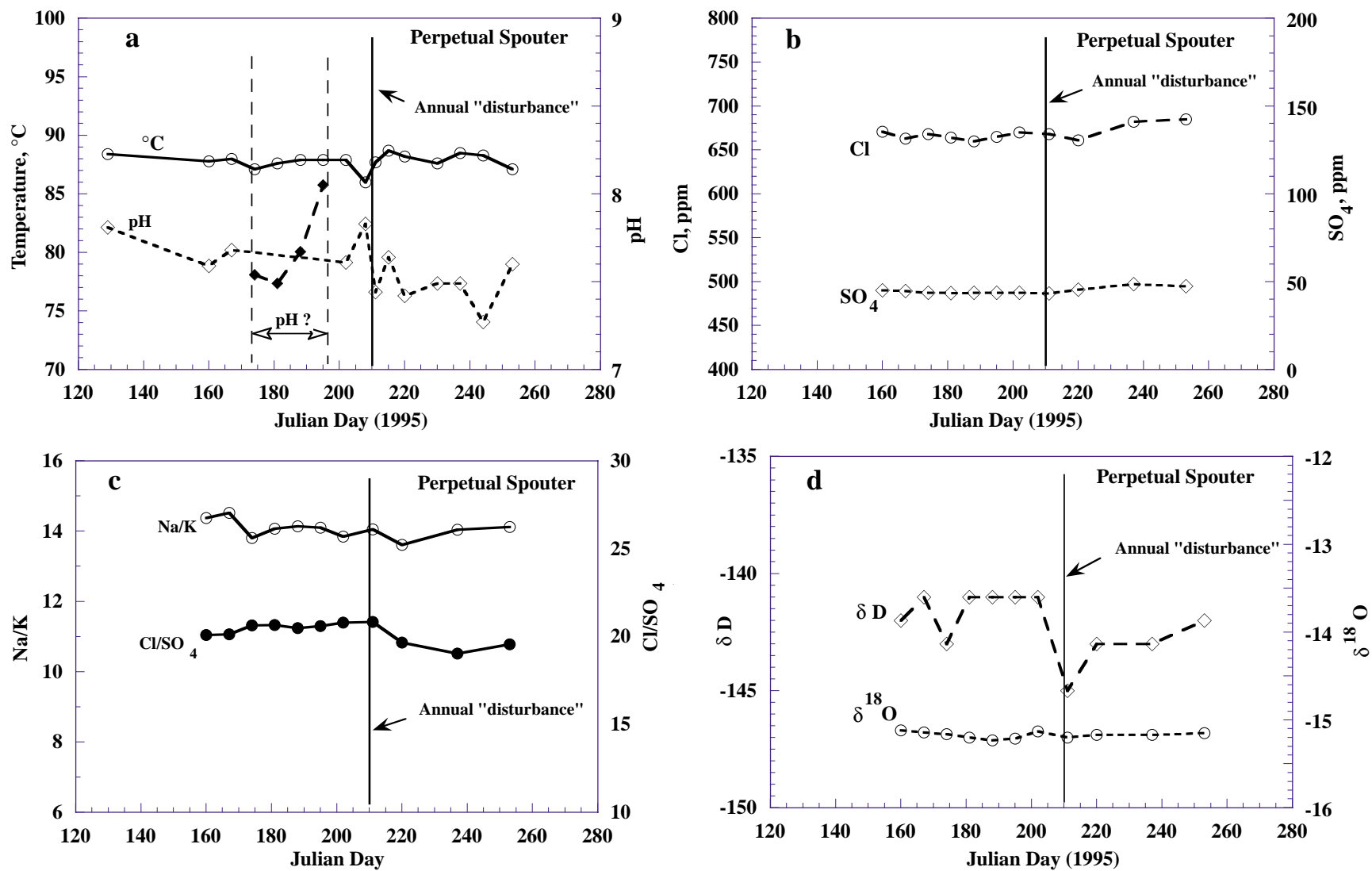


Figure 9

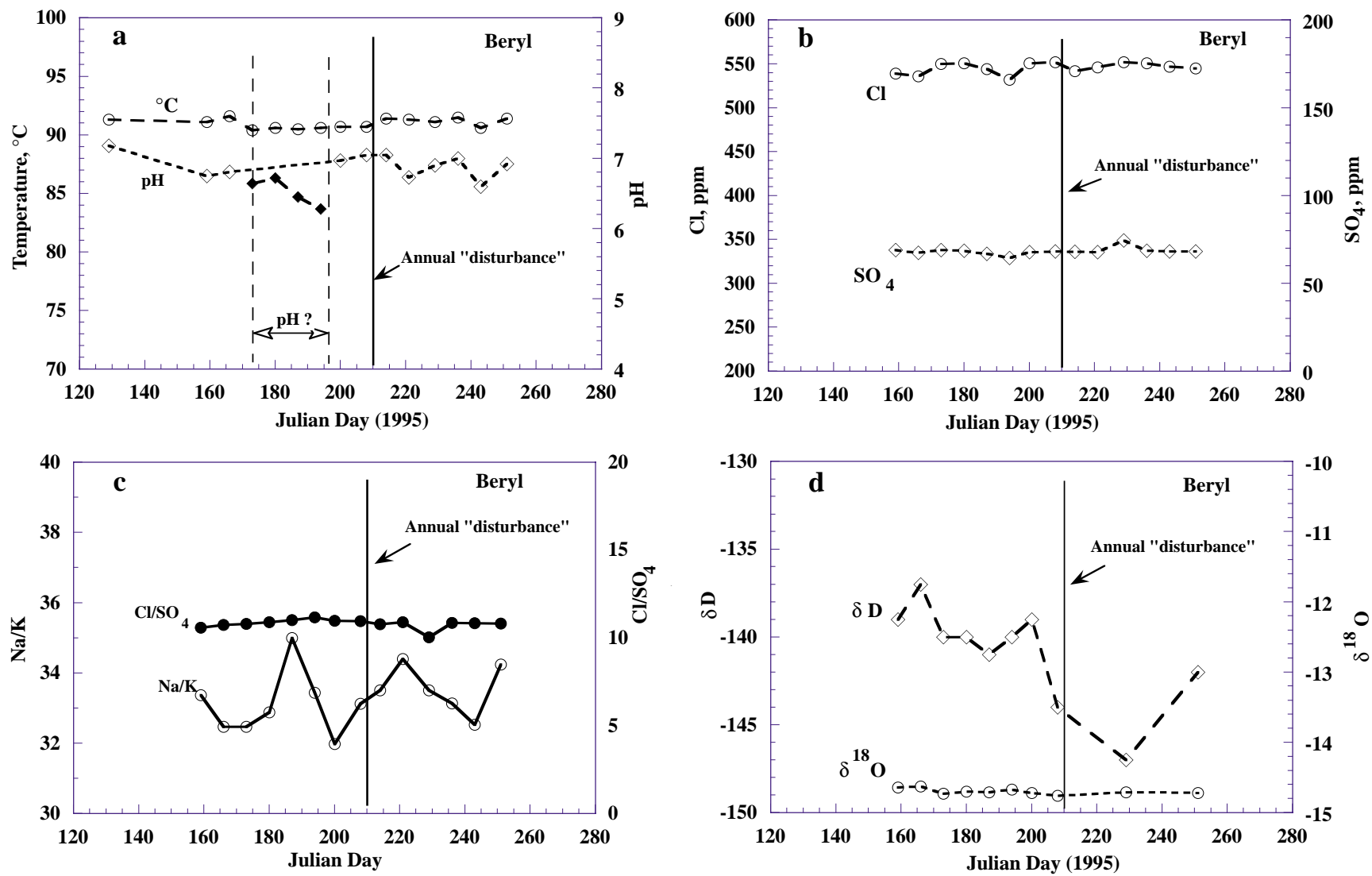


Figure 10

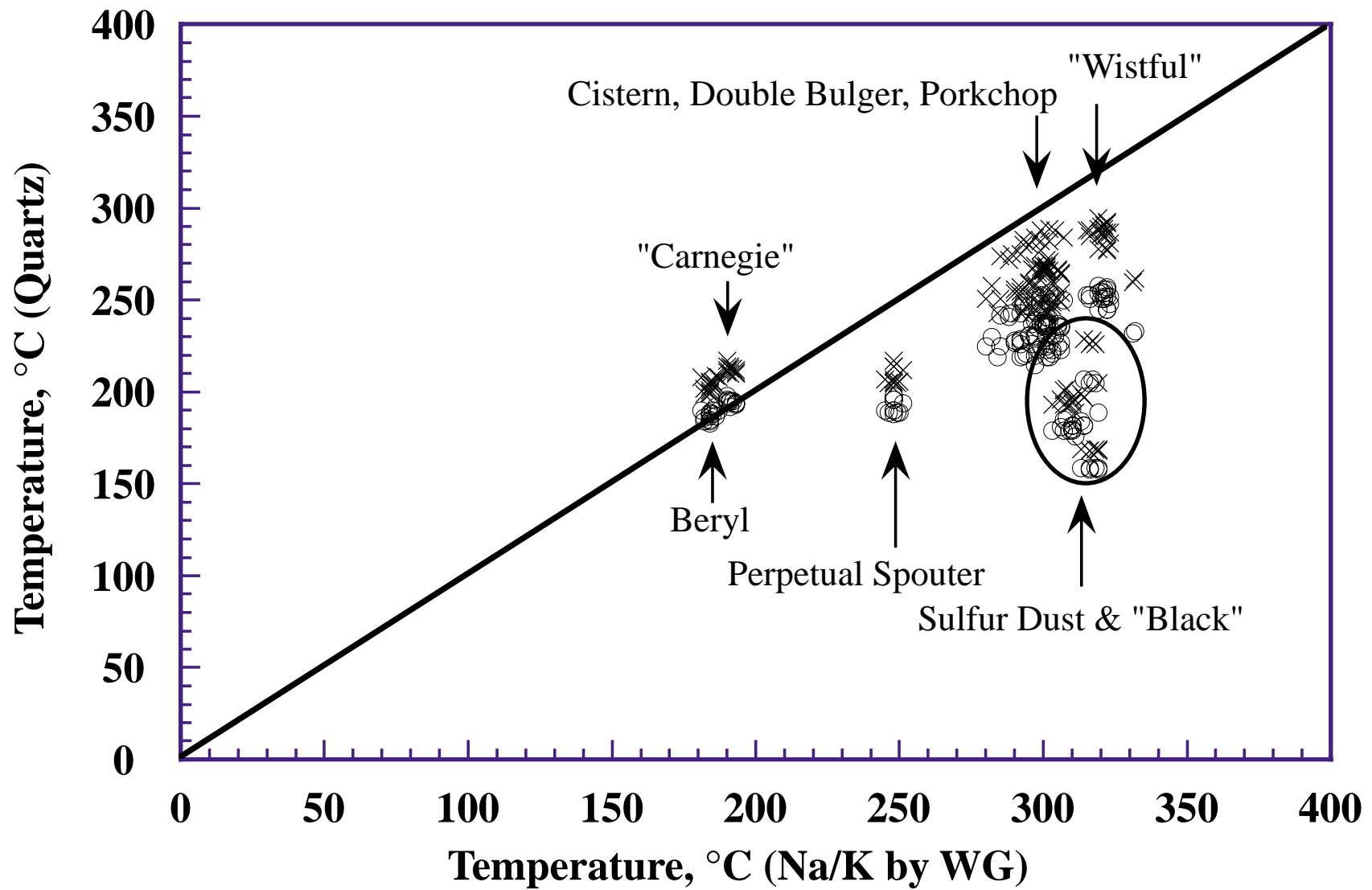


Figure 11

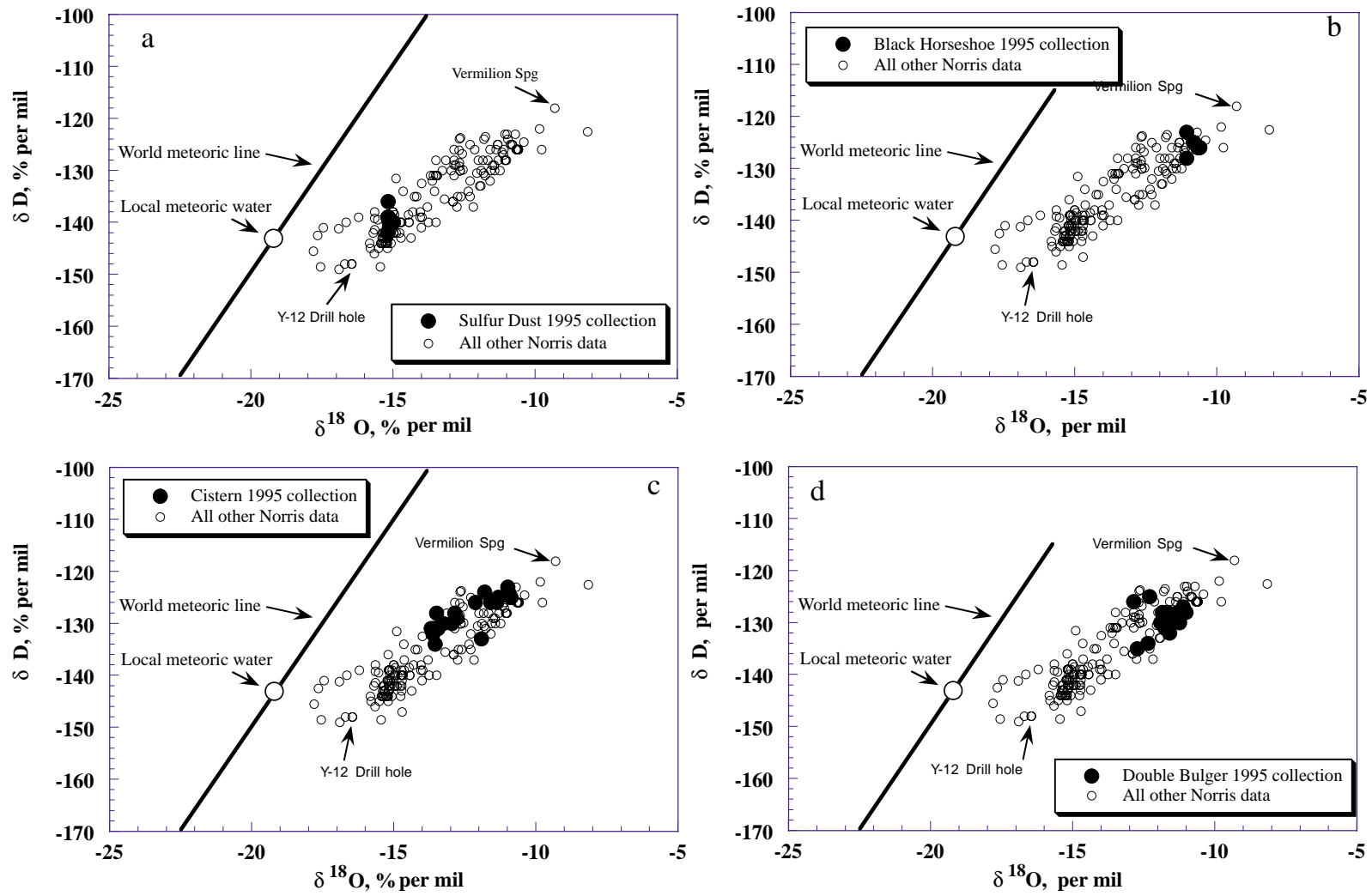


Figure 12

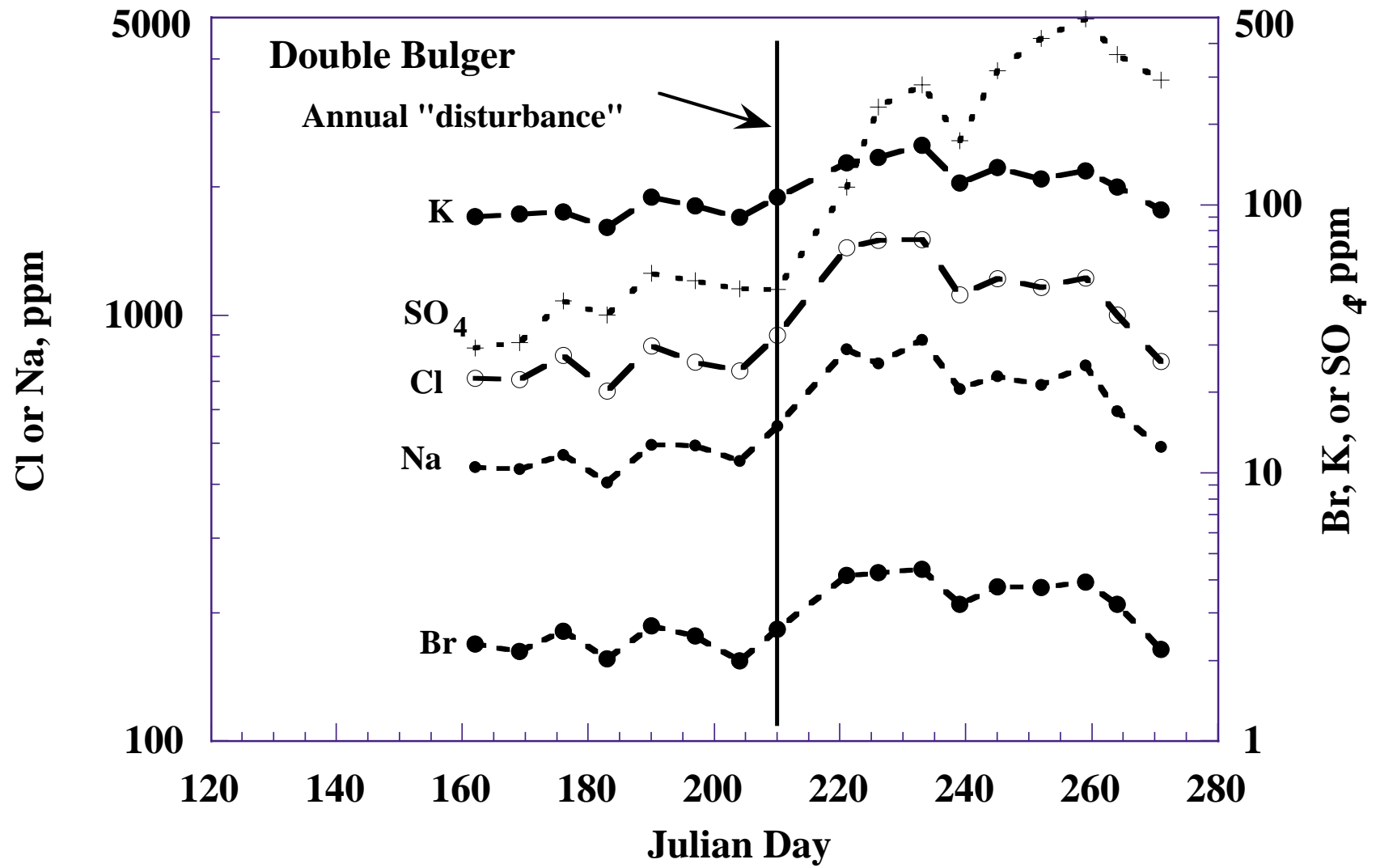


Figure 13

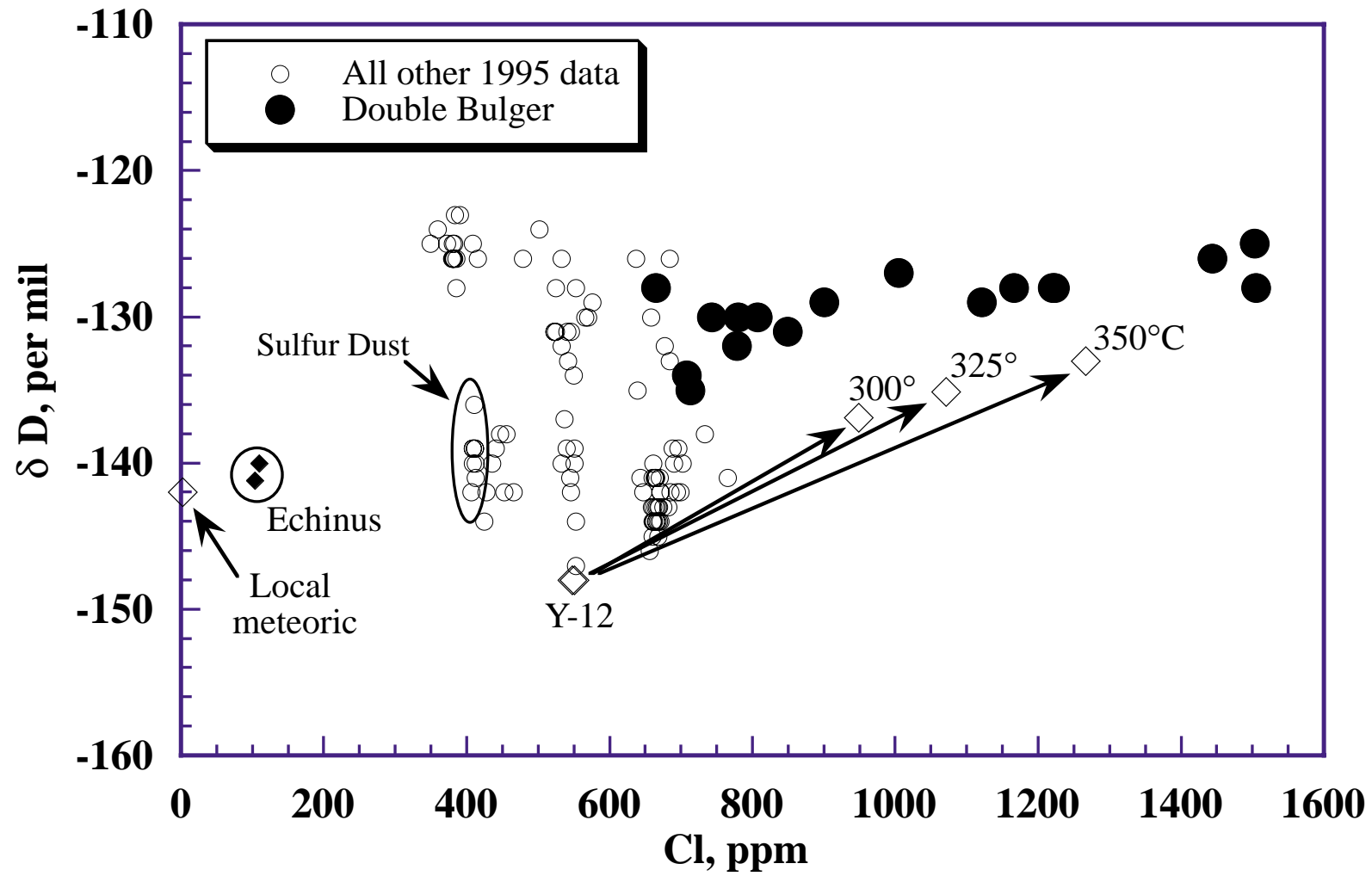


Figure 14

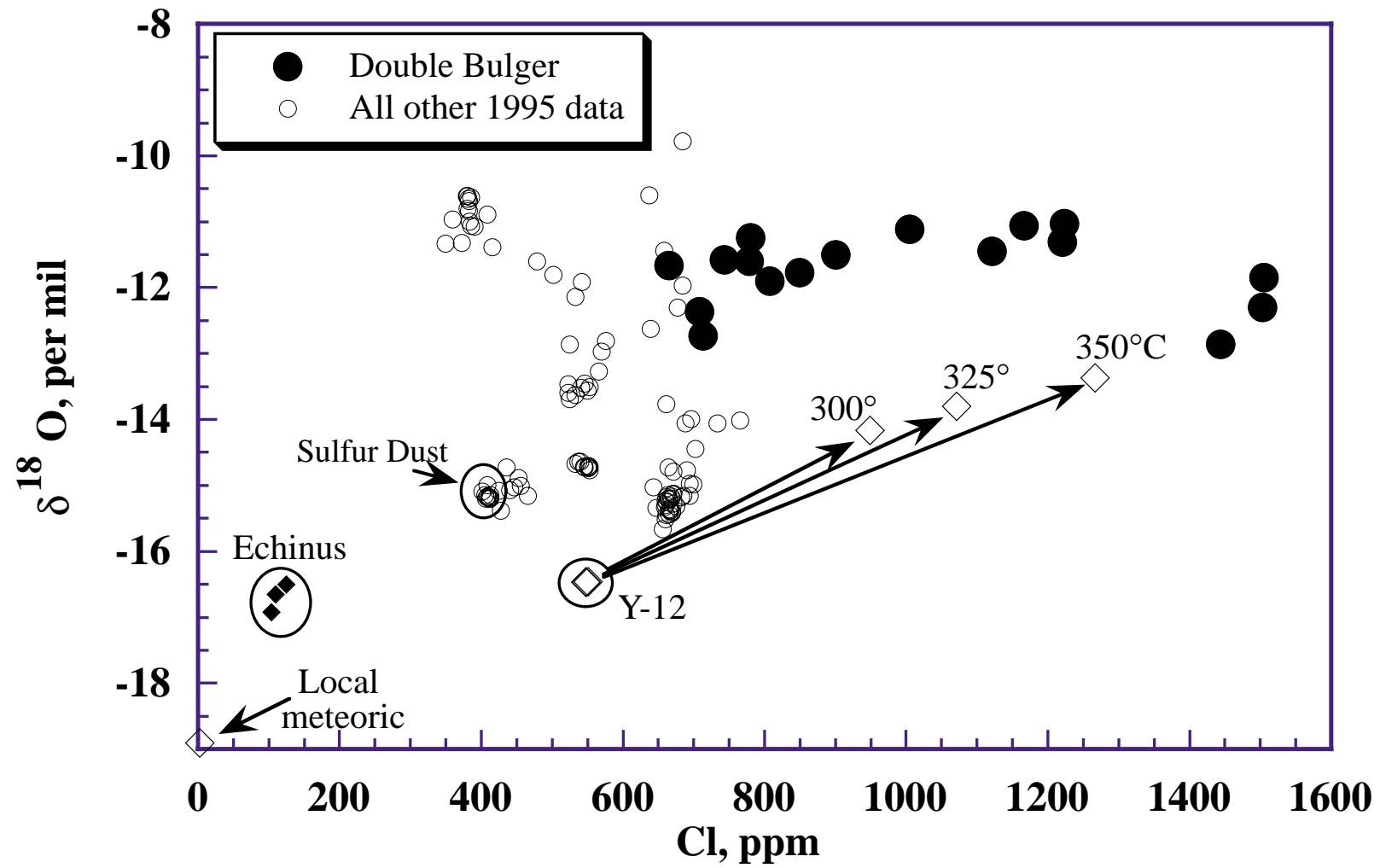


Figure 15

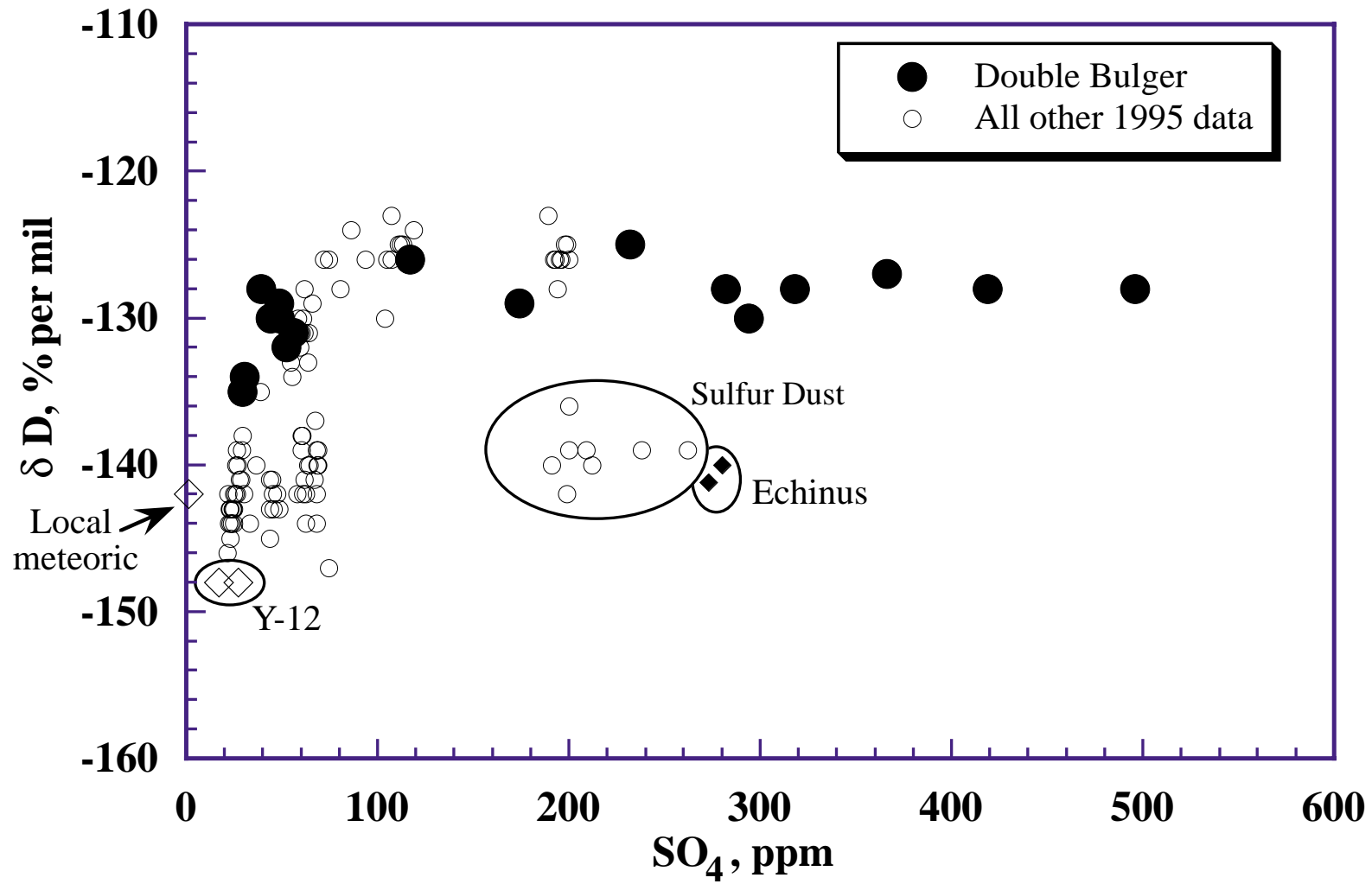


Figure 16

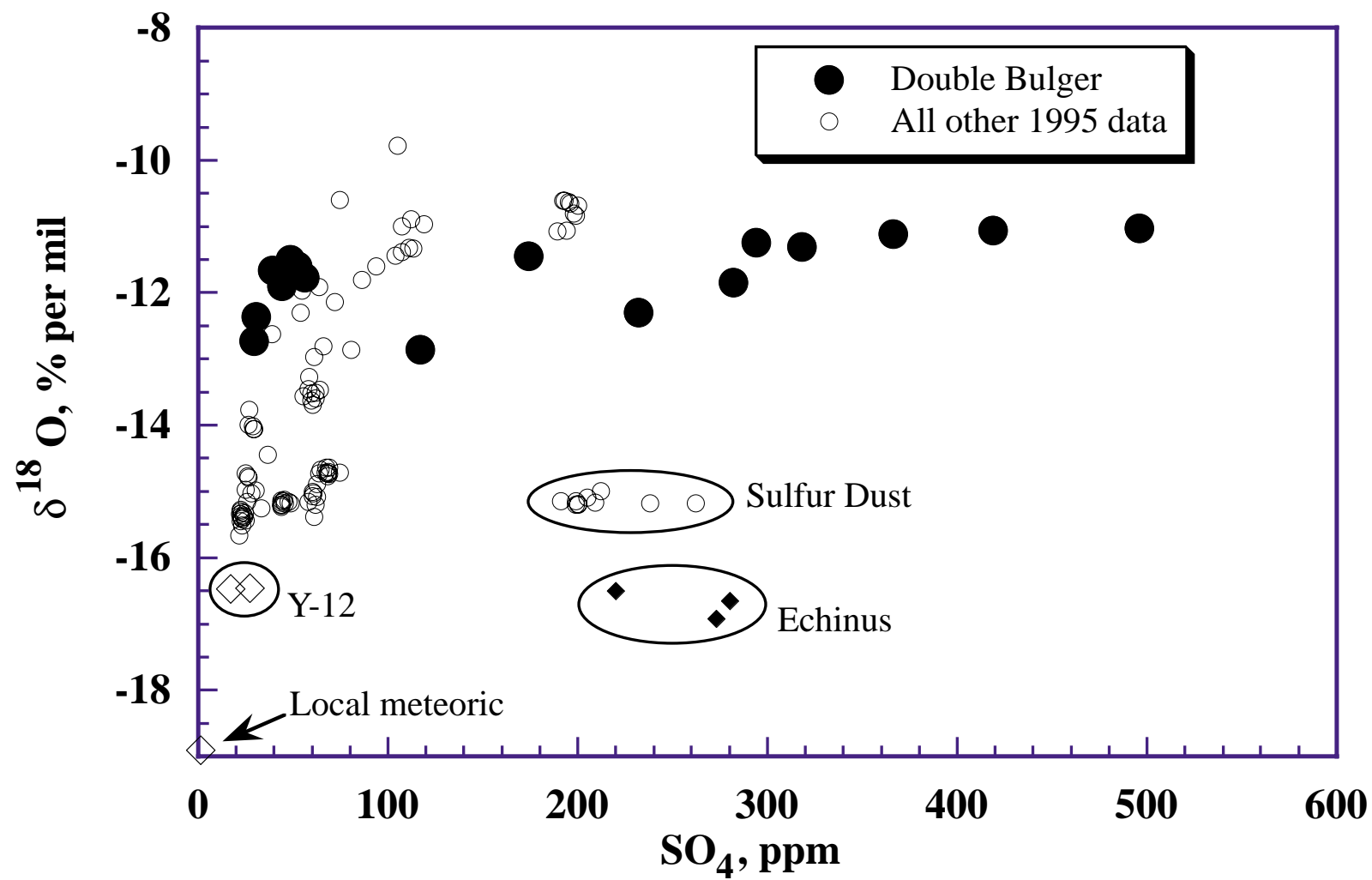


Figure 17

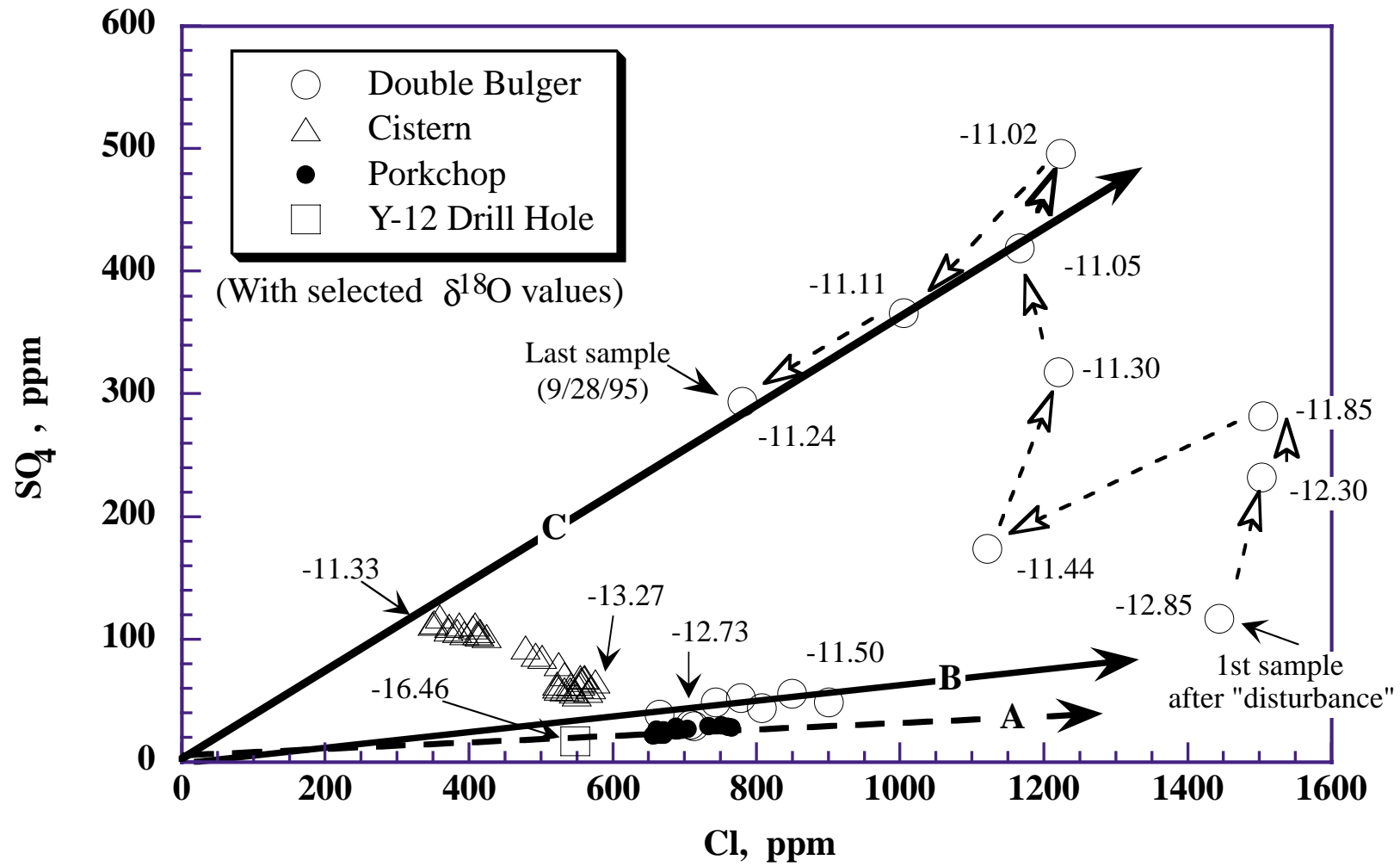


Figure 18

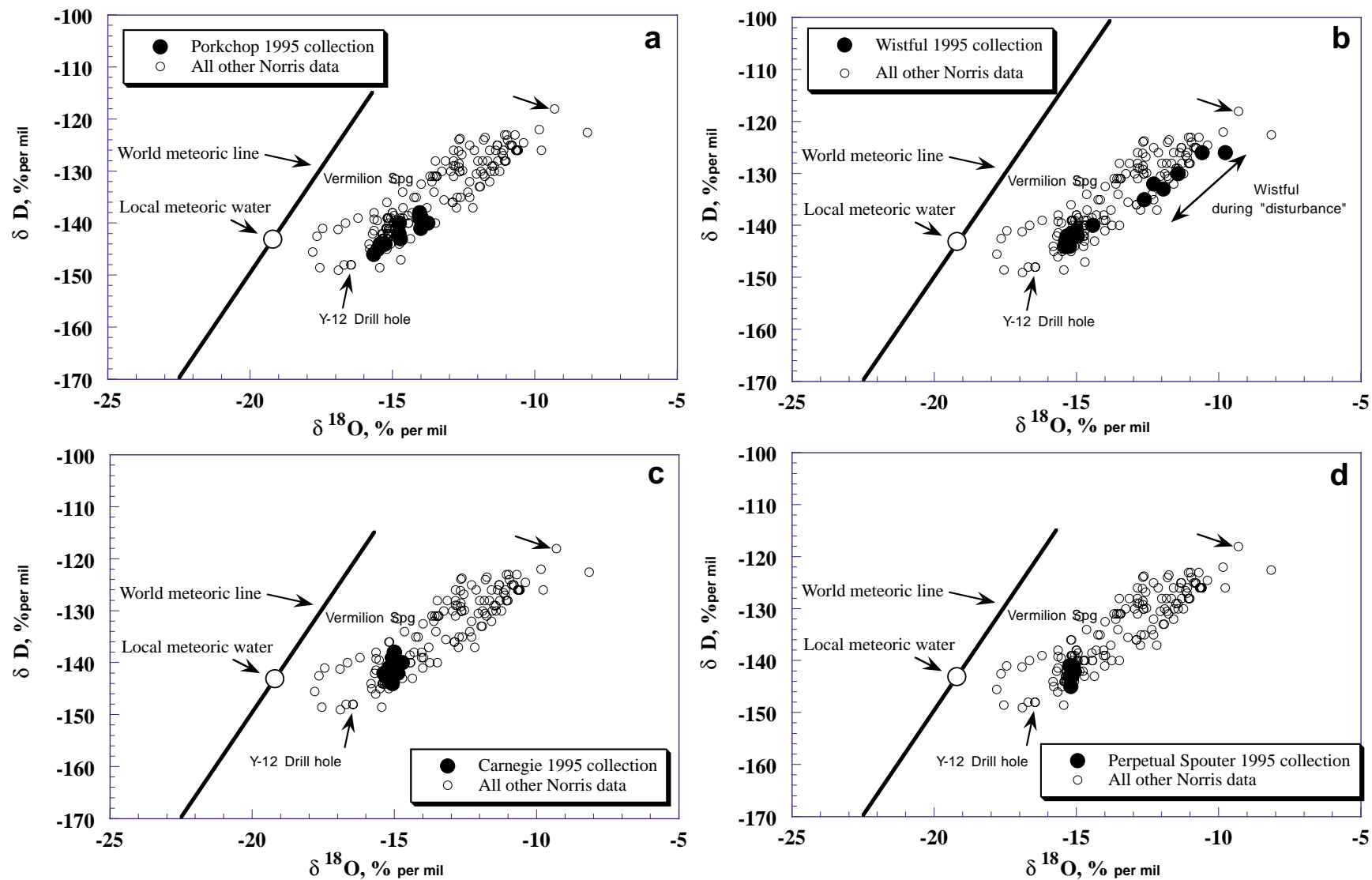


Figure 19

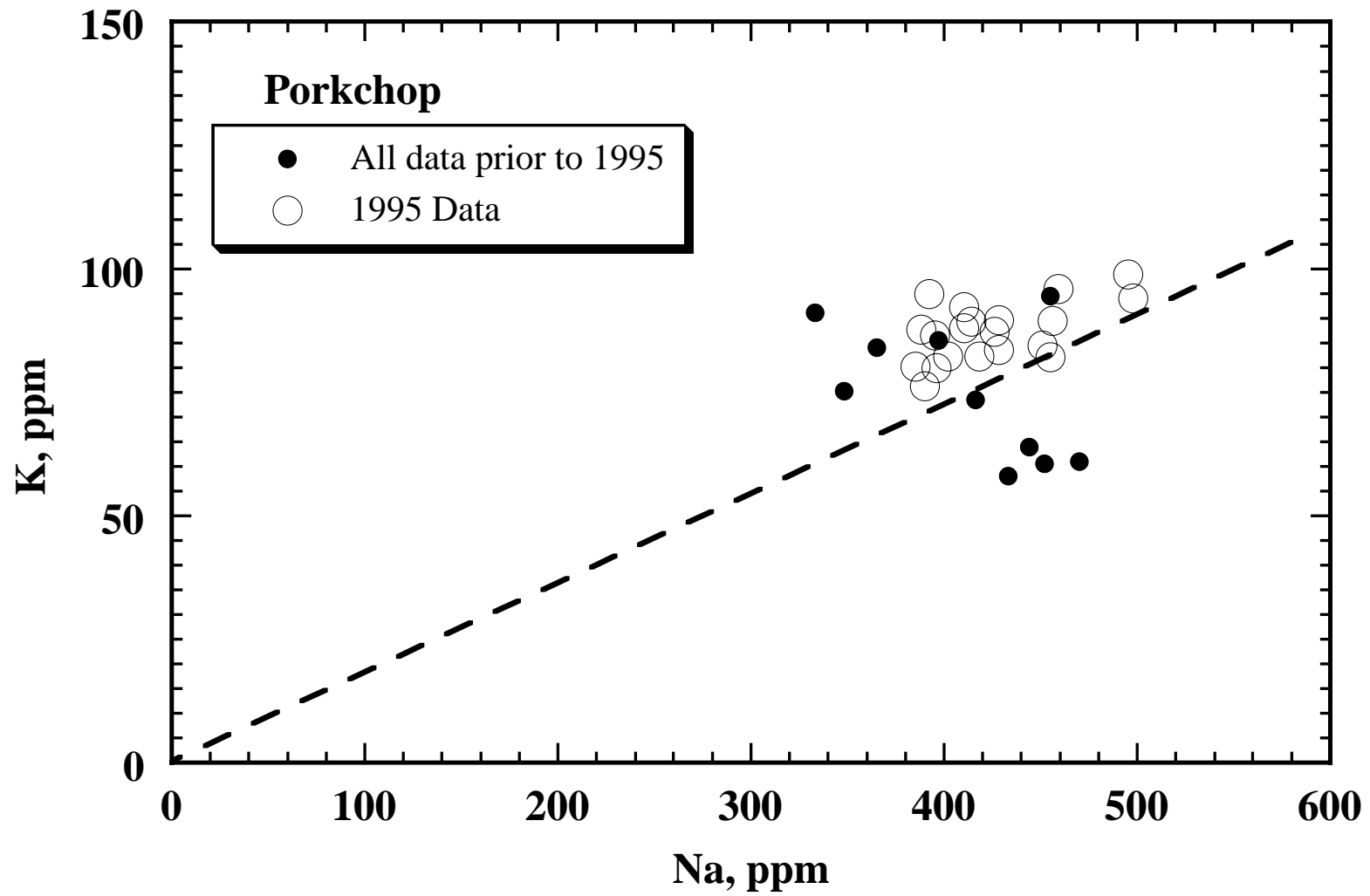


Figure 20

Table 1. Chemical¹ and isotopic² analyses of thermal waters collected at Norris Geyser Basin and Gibbon Canyon in 1995

Name & Lab Number	Date	Julian Day	Temp. ³ °C	pH (field)	pH (lab)	Na ppm	K ppm	Br ppm	Cl ppm	SO4 ppm	F ppm	CO3 ppm	HCO3 ppm	SiO2 ppm	δD ‰	δ ¹⁸ O ‰
Beryl																
	5/9/95	129	91.3	7.18												
BS2	6/8/95	159	91.1	6.75	6.75	422	21.5	1.68	539	68.9	17.70	12.8	99.2	282	-139	-14.64
BS3	6/15/95	166	91.6	6.81	6.81	424	22.2	1.62	536	67.5	17.70	12.1	102	300	-137	-14.63
BS4	6/22/95	173	90.4	6.64	6.64	424	22.2	1.71	550	68.9	17.90	11.7	102	278	-140	-14.73
BS5	6/29/95	180	90.6	6.72	6.72	412	21.3	1.68	551	68.5	18.10	13.1	97.7	289	-140	-14.70
BS6	7/6/95	187	90.5	6.45	6.45	420	20.4	1.62	544	66.8	17.90	11.7	102	293	-141	-14.71
BS7	7/13/95	194	90.6	7.18	7.98	417	21.2	1.69	532	64.5	17.60	11.8	103	287	-140	-14.67
BS8	7/19/95	200	90.7	6.97	6.97	427	22.7	1.79	551	67.9	18.20	12.3	99.7	293	-139	-14.72
BS9	7/27/95	208	90.7	7.05		419	21.5	1.66	552	68.2	18.20			276	-144	-14.76
BS10	8/2/95	214	91.4	7.05		412	20.9	1.55	542	68.0	18.00			268		
BS11	8/9/95	221	91.3	6.73		427	21.1	1.47	546	67.8	17.80			263		
BS12	8/17/95	229	91.1	6.90		412	20.9	1.73	552	74.5	18.50			261	-147	-14.71
BS13	8/24/95	236	91.5	7.00		425	21.8	1.62	551	68.7	18.10			265		
BS14	8/31/95	243	90.6	6.60		421	22.0	1.55	547	68.3	18.10			280		
BS15	9/8/95	251	91.4	6.92		421	20.9	1.75	545	68.2	18.10			274	-142	-14.72
“Black”																
	5/9/95	129	87.7	3.42												
BH2	6/9/95	160	87.5	3.15	2.89	252	60.3	1.25	380	193	3.22	0	0	169	-126	-10.62
BH3	6/16/95	167	88.6	3.16	2.83	252	63.4	1.25	385	195	3.33	0	0	169	-126	-10.62
BH4	6/23/95	174	87.0	3.17	2.82	244	61.6	1.23	381	196	3.29	0	0	166	-126	-10.65
BH5	6/30/95	181	87.7	3.26	2.84	247	62.3	1.28	379	192	3.27	0	0	166	-126	-10.60
BH6	7/7/95	188	87.7	3.70	2.80	243	59.9	1.17	382	200	3.26	0	0	168	-126	-10.68
BH7	7/14/95	195	87.5	4.66	2.82	245	61.3	1.23	380	198	3.24	0	0	169	-125	-10.80
BH8	7/21/95	202	88.1	3.08	2.81	245	60.3	1.27	382	199	3.33	0	0	166	-125	-10.83
BH9	7/27/95	208	87.4	3.52		235	58.7	1.12	385	195	3.31			370		
BH10	7/30/95	211	88.2	3.18												
BH11	8/3/95	215	85.8	3.18		236	57.8	1.08	385	194	3.27			368	-128	-11.06
BH12	8/8/95	220	87.6	3.18												
BH13	8/18/95	230	88.4	2.95		242	59.7	1.14	388	190	3.20			379		
BH14	8/25/95	237	88.8	2.96												
BH15	9/1/95	244	90.4	2.59		255	61.5	1.06	390	189	3.22			381	-123	-11.07
BH16	9/10/95	253	89.9	2.86												
“Carnegie”																
	5/9/95	129	87.8	5.72												
CD2	6/10/95	161	87.4	5.94	6.79	301	17.1	1.34	412	61.7	6.59	0	5.8	302	-141	-15.20
CD3	6/17/95	168	86.7	6.06	6.87	307	17.8	1.48	424	62.2	6.80	0	7.1	315	-144	-15.08
CD4	6/24/95	175	86.3	6.32	6.88	302	17.7	1.44	427	61.0	6.80	0	8.3	312	-142	-15.38
CD5	7/1/95	182	86.6	6.52	6.90	306	17.3	1.50	446	60.4	6.85	0	8.3	315	-138	-15.02
CD6	7/8/95	189	87.8	6.34	6.89	311	17.5	1.35	455	60.2	6.82	0	8.4	312	-138	-15.00
CD7	7/15/95	196	87.5		6.98	297	16.7	1.47	440	60.0	6.72	0	9.1	308	-139	-15.06
CD8	7/22/95	203	88.4	6.42		300	17.5	1.50	461	58.9	6.85			308		
CD9	7/28/95	209	89.3	6.34		311	18.3	1.62	465	58	6.64			304	-142	-15.15
CD10	7/29/95	210	86.1	6.76		310	17.4	1.48	464	60.6	6.50			317		
CD11	8/1/95	213	88.7	6.37		300	16.7	1.38	455	61	6.50			319		
CD12	8/4/95	216	88.2	6.28												
CD13	8/8/95	220	87.7	6.32												
CD14	8/21/95	233	87.7	5.89		287	16.2	1.27	452	62.3	6.43			317	-142	-14.88

Name & Lab Number	Date	Julian Day	Temp. ³ °C	pH (field)	pH (lab)	Na ppm	K ppm	Br ppm	Cl ppm	SO4 ppm	F ppm	CO3 ppm	HCO3 ppm	SiO2 ppm	δD ‰	δ ¹⁸ O ‰
Carnegie (continued)																
CD15	8/26/95	238	87.9	5.92												
CD16	9/1/95	244	88.7	6.09												
CD17	9/8/95	251	87.8	6.66		274	15.4	1.30	435	63.5	6.62			330	-140	-14.72
Cistern																
	5/9/95	129	84.1	6.46												
CS2	6/8/95	159	83.6	6.30	7.76	335	70.1	1.65	522	61.5	4.68	0	47.3	589	-131	-13.59
CS3	6/9/95	160			7.36	332	70.4	1.81	554	63.9	5.34	0	26.2	595		
CS4	6/11/95	162	84.9	6.21	7.51	336	70.8	1.68	524	60	4.85	0	38.5	597	-131	-13.68
CS5	6/15/95	166	83.3	6.27	7.50	332	70.5	1.74	522	63.9	4.83	0	33.8	589	-131	-13.46
CS6	6/18/95	169	83.6	6.02	7.54	334	70.4	1.63	540	59.3	4.84	0	47.5	578	-131	-13.51
CS7	6/22/95	173	82.1	6.21	7.62	335	71.5	1.77	532	59.3	4.88	0	36.9	580	-132	-13.62
CS8	6/25/95	176	82.6	6.13	7.43	332	70.3	1.72	541	63.3	5.18	0	34.1	578	-133	-11.91
CS9	6/29/95	180	82.0	6.62	7.59	338	72.4	1.87	549	55.4	5.35	0	43.5	606	-134	-13.55
CS10	7/2/95	183	83.3	6.40	7.43	333	71.1	1.77	545	57.7	5.16	0	30.0	586	-131	-13.45
CS11	7/6/95	187	82.4	6.61	7.56	331	70.4	1.88	553	61.7	5.27	0	37.3	569	-128	-13.50
CS12	7/9/95	190	84.1	6.94		337	75.6	1.56	524	80.3	5.05			567	-128	-12.85
CS13	7/13/95	194	84.1	6.28	7.40	345	73.5	1.72	566	58.4	5.11	0	41.3	614	-130	-13.27
CS14	7/16/95	197	85.0	6.23	7.24	346	72.1	1.70	569	60.9	5.15	0	25.8	582	-130	-12.96
CS15	7/19/95	200	84.2	6.20	7.10	348	72.2	1.83	576	65.8	5.13	0	20.4	571	-129	-12.80
CS16	7/23/95	204	86.5	6.11		352	76.0	1.73	556	67.3	5.32			578		
CS17	7/27/95	208	85.8	6.06		350	77.8	1.61	559	68.6	5.27			578		
CS18	7/29/95	210	84.8	6.00		366	81.3	1.73	561	69.1	5.26			586		
CS19	7/30/95	211	82.8	6.04		362	76.4	1.70	554	69.3	5.18			584		
CS20	7/31/95	212	83.0	6.13		336	74.8	1.57	532	71.7	5.04			574	-126	-12.13
CS21	8/2/95	214	83.9	5.90		326	71.7	1.61	501	86.2	5.06			535	-124	-11.80
CS22	8/3/95	215	82.0	5.66		325	66.3	1.39	492	87.7	4.90			533		
CS23	8/4/95	216	84.0	5.93		308	67.1	1.50	478	93.6	4.64			535	-126	-11.59
CS24	8/9/95	221	84.4	5.27		302	61.0	1.24	424	103	4.90			505		
CS25	8/11/95	223	82.7	5.56		292	60.7	1.20	393	105	4.64			492		
CS26	8/14/95	226	83.8	5.48		277	57.4	1.16	383	107	4.68			479	-123	-10.99
CS27	8/17/95	229	84.1	5.63		264	56.5	1.11	371	108	4.60			452		
CS28	8/21/95	233	84.5	5.37		272	60.5	1.13	359	119	4.89			492	-124	-10.96
CS29	8/24/95	236	85.0	5.73		249	53.0	1.06	351	114	4.70			484		
CS30	8/27/95	239	84.9	5.32		259	53.2	1.11	349	113	4.73			460	-125	-11.33
CS31	8/31/95	243	83.4	5.29		271	58.6	1.15	372	111	5.00			482	-125	-11.31
CS32	9/2/95	245	84.4	5.73		270	58.6	1.15	386	112	4.97			484		
CS33	9/8/95	251	84.9	6.29		297	63.6	1.19	411	105	4.86			499		
CS34	9/11/95	254	84.3	5.67		298	63.7	1.23	414	104	4.78			496		
CS35	9/16/95	259	85.0	5.58		305	67.9	1.27	415	107	4.54			507	-126	-11.38
CS36	9/21/95	264	83.9	5.91		284	61.8	1.30	405	110	4.71			469		
CS37	9/28/95	271	84.2	5.66		292	65.5	1.21	408	112	4.68			484	-125	-10.88
Double Bulger																
	5/9/95	129	89.7	7.38												
DB2	6/11/95	162	90.2	7.12	7.72	440	90.5	2.31	713	29.3	6.13	0	34.6	535	-135	-12.73
DB3	6/18/95	169	90.3	6.61	7.52	436	93.0	2.17	708	30.7	6.22	0	26.9	533	-134	-12.36
DB4	6/25/95	176	89.1	6.27	6.93	470	94.2	2.57	807	43.9	6.72	0	7.3	535	-130	-11.90
DB5	7/2/95	183	88.2	6.61	7.07	405	82.7	2.03	665	38.9	5.91	0	10.0	428	-128	-11.66
DB6	7/9/95	190	89.4	6.92	6.52	498	107.0	2.69	849	55.8	7.18	0	4.2	456	-131	-11.77
DB7	7/16/95	197	90.0	6.84	6.90	495	99.2	2.47	778	52.4	6.91	0	7.3	541	-132	-11.59
DB8	7/23/95	204	89.9	6.65		455	90.4	2.00	743	48.8	6.18			469	-130	-11.57

Table 1

Name & Lab Number	Date	Julian Day	Temp. ³ °C	pH (field)	pH (lab)	Na ppm	K ppm	Br ppm	Cl ppm	SO4 ppm	F ppm	CO3 ppm	HCO3 ppm	SiO2 ppm	δD ‰	δ ¹⁸ O ‰
Double Bulger (continued)																
DB9	7/29/95	210	89.9	6.66		551	107.0	2.61	900	48.5	7.20			524	-129	-11.50
DB10	8/9/95	221	92.1	5.95		833	144.0	4.16	1444	117	6.90			492	-126	-12.85
DB11	8/14/95	226	90.8	4.85		771	151.0	4.26	1503	232	6.53			501	-125	-12.30
DB12	8/21/95	233	90.8	4.28		877	167.0	4.38	1505	282	4.91			511	-128	-11.84
DB13	8/27/95	239	90.0	4.02		671	121.0	3.24	1121	174	5.11			452	-129	-11.44
DB14	9/2/95	245	90.0	2.88		721	138.0	3.77	1220	318	3.73			518	-128	-11.30
DB15	9/9/95	252	89.7	2.83		687	125.0	3.74	1166	419	3.16			492	-128	-11.05
DB16	9/16/95	259	89.5	2.35		762	134.0	3.91	1223	496	3.61			531	-128	-11.02
DB17	9/21/95	264	90.0	2.83		596	117.0	3.24	1005	366	4.30			458	-127	-11.11
DB18	9/28/95	271	89.3	3.16		491	96.0	2.20	780	294	3.78			452	-130	-11.24
Perpetual Spouter																
	5/9/95	129	88.4	7.81												
PS2	6/9/95	160	87.8	7.59	7.97	405	47.9	2.61	671	45.2	6.19	8.6	3.5	285	-142	-15.12
PS3	6/16/95	167	88.0	7.68	8.02	428	50.1	2.21	663	44.6	6.14	9.3	2.1	291	-141	-15.14
PS4	6/23/95	174	87.1	7.54	8.00	428	52.7	2.05	668	43.8	6.34	9.3	1.9	287	-143	-15.16
PS5	6/30/95	181	87.6	7.49	7.81	419	50.6	2.24	664	43.5	6.38	6.9	6.5	291	-141	-15.20
PS6	7/7/95	188	87.9	7.67	7.99	406	48.8	2.36	660	43.6	6.19	8.8	2.5	282	-141	-15.23
PS7	7/14/95	195	87.9	8.05	8.00	394	47.5	2.47	665	43.7	5.98	9.2	1	289	-141	-15.21
PS8	7/21/95	202	87.9	7.61	7.98	413	50.7	2.19	670	43.6	6.25	9.1	1.2	285	-141	-15.13
PS9	7/27/95	208	86.0	7.83												
PS10	7/30/95	211	87.7	7.44		406	49.1	2.01	668	43.4	5.76			319	-145	-15.20
PS11	8/3/95	215	88.7	7.64												
PS12	8/8/95	220	88.2	7.42		410	51.2	2.04	661	45.5	5.45			312	-143	-15.17
PS13	8/18/95	230	87.6	7.49												
PS14	8/25/95	237	88.5	7.49		432	52.3	2.11	682	48.5	5.79			330	-143	-15.17
PS15	9/1/95	244	88.3	7.27												
PS16	9/10/95	253	87.1	7.60		417	50.2	1.95	685	47.4	6.06			319	-142	-15.15
Porkchop																
	5/9/95	129	59.6	7.88												
PC2	6/11/95	162	54.6	7.42	7.94	390	76.3	2.27	661	26.6	6.59	9	48	516	-140	-13.76
PC3	6/18/95	169	71.3	7.50	8.18	396	80.0	2.09	664	24.7	6.36	13.8	19.6	582	-143	-14.72
PC4	6/25/95	176	74.4	7.50	8.27	402	82.3	2.31	671	26.2	6.76	15.4	12	597	-142	-14.78
PC5	7/2/95	183	83.5	8.10	8.81	385	80.3	2.14	660	22.2	6.37	14.5	0	721	-144	-15.29
PC6	7/9/95	190	85.8	8.26	8.83	395	86.6	2.45	667	22.4	6.32	15.1	0	721	-144	-15.37
PC7	7/16/95	197	86.5	8.00	8.88	388	87.7	2.33	661	22.1	6.14	13.1	0	719	-144	-15.44
PC8	7/23/95	204	86.0	7.93		414	89.4	2.07	671	22.3	5.76			725	-144	-15.27
PC9	7/29/95	210	91.0	7.99		392	95.0	1.66	656	21.4	5.69			717	-146	-15.66
PC10	7/30/95	211	92.2	7.87		410	92.3	2.18	660	22.8	5.74			693	-145	-15.51
PC11	7/31/95	212	91.7	8.28		410	88.1	1.75	667	23.1	5.91			681		
PC12	8/2/95	214	82.3	7.23		426	87.3	1.86	687	26	5.73			693		
PC13	8/3/95	215	88.4	6.93												
PC14	8/4/95	216	86.9	7.06		418	82.3	2.04	691	27	6.12			685		
PC15	8/6/95	218	86.5	6.62		428	89.6	2.20	690	25.7	5.92			646	-140	-14.77
PC16	8/8/95	220	83.1	6.36		428	83.6	2.17	688	29.1	5.92			631	-139	-14.05
PC17	8/9/95	221	82.4	6.24												
PC18	8/11/95	223	83.3	6.45		455	82.2	2.06	696	26.4	6.47			627	-139	-13.99
PC19	8/14/95	226	82.8	6.33		451	84.6	2.11	704	27	7.07			616		

Table 1

Name & Lab Number	Date	Julian Day	Temp. ³ °C	pH (field)	pH (lab)	Na ppm	K ppm	Br ppm	Cl ppm	SO4 ppm	F ppm	CO3 ppm	HCO3 ppm	SiO2 ppm	δD ‰	δ ¹⁸ O ‰
Porkchop (continued)																
PC20	8/21/95	233	79.9	7.26		456	89.5	2.32	733	29.2	7.79			666	-138	-14.05
PC21	8/27/95	239	80.2	7.20		459	96.0	2.14	751	30.1	7.63			678		
PC22	9/2/95	245	78.6	7.42		495	99.0	2.52	760	28.8	7.57			666		
PC23	9/9/95	252	73.2	7.86		498	94.0	2.42	765	28.4	7.01			633	-141	-14.01
Sulphur Dust																
	5/9/95	129	47.4	2.88												
SD2	6/9/95	160	45.3	2.88	2.52	252	54.9	1.25	411	262	3.55			240	-139	-15.17
SD3	6/16/95	167	46.3	2.95	2.58	252	58.4	1.22	408	238	3.53			244	-139	-15.17
SD4	6/23/95	174	46.5	5.23	2.73	267	61.2	1.28	411	200	3.44			242	-139	-15.19
SD5	6/30/95	181	45.7	7.42	2.69	260	60.4	1.26	408	209	3.46			246	-139	-15.16
SD6	7/7/95	188	45.9	8.50	2.74	261	58.9	1.21	406	199	3.48			242	-142	-15.19
SD7	7/14/95	195	45.6	7.86	2.68	263	59.0	1.32	408	212	3.56			250	-140	-14.99
SD8	7/21/95	202	46.0	2.98	2.74	261	61.0	1.38	410	200	3.51			229	-139	-15.18
SD9	7/27/95	208	45.3	3.13		273	63.5	1.21	412	191	3.30			253	-140	-15.14
SD10	7/30/95	211	46.4	2.69		249	59.9	1.17	409	195	3.23			255		
SD11	8/3/95	215	47.2	2.97		274	61.6	1.15	410	201	3.24			270		
SD12	8/8/95	220	44.3	2.76		253	60.5	1.15	405	199	3.25			263	-139	-15.14
SD13	8/18/95	230	45.9	2.75		259	60.4	1.22	404	191	3.26			255		
SD14	8/24/95	236	47.3	2.76		254	61.2	1.29	404	200	3.12			253		
SD15	9/1/95	244	46.6	2.47		257	64.6	1.31	406	196	3.21			285		
SD16	9/10/95	253	44.0	2.78		269	61.5	1.30	401	205	3.10			274	-139	-15.09
“Wistful”																
	5/9/95	129	88.4	8.09												
WF2	6/10/95	161	86.9	7.80	8.66	407	105.0	2.25	665	25	6.11	0	0	702	-144	-15.43
WF3	6/17/95	168	89.6	7.80	8.66	402	103.0	2.23	659	24.4	6.23	0	0	743	-143	-15.32
WF4	6/24/95	175	83.7	7.88	8.65	405	103.0	2.22	666	24.1	6.37	0	0	736	-143	-15.38
WF5	7/1/95	182	82.9	8.18	8.62	410	107.0	2.27	669	22.9	6.33	0	1.4	715	-144	-15.41
WF6	7/8/95	189	86.0	8.02	8.66	406	104.0	2.05	669	22.7	6.35	0	0	713	-143	-15.39
WF7	7/15/95	196	85.2		8.57	422	109.0	1.98	665	23.5	6.27	0	6.1	753	-144	-15.35
WF8	7/22/95	203	84.9	7.94	8.63	413	107.0	2.07	675	23	6.17	0	0	751	-143	-15.31
WF9	7/28/95	209	86.0	7.90		393	99.0	1.93	647	21.7	5.59			770	-142	-15.34
WF10	7/29/95	210	80.2	8.12		391	101.0	2.09	662	33.2	5.70			713	-144	-15.25
WF11	8/1/95	213	82.9	7.28		402	101.0	1.90	643	27.6	5.50			730	-141	-15.02
WF12	8/3/95	215	77.2	5.99		390	101.0	2.18	639	38.7	5.63			646	-135	-12.62
WF13	8/4/95	216	85.6	4.72		374	105.0	2.00	637	74.4	4.86			544	-126	-10.59
WF14	8/6/95	218	81.3	4.39		392	111.0	1.98	684	105	4.98			554	-126	-9.77
WF15	8/8/95	220	71.0	5.54		434	113.0	2.15	658	104	5.64			651	-130	-11.43
WF16	8/9/95	221	73.1	5.67		415	105.0	2.16	684	54.5	6.21			651	-133	-11.96
WF17	8/11/95	223				398	104.0	2.01	677	53.7	6.83			674	-132	-12.29
WF18	8/21/95	233	80.3	6.67		404	104.0	2.25	702	36.4	6.87			728	-140	-14.44
WF19	8/26/95	238	83.2	6.97		435	107.0	2.27	699	30	6.71			698	-142	-14.98
WF20	9/1/95	244	85.8	7.44		423	108.0	2.02	694	25.6	5.83			706	-142	-15.15
WF21	9/8/95	251	82.9	7.73		410	101.0	2.27	694	24.8	8.92			719	-142	-14.97

¹ Laboratory chemical analyses by D. Counce² Isotope analyses by L. D. White³ For Julian days 173 through 202 the listed temperatures are 2 °C higher than those recorded in the field to correct for an instrumental error in calibration.

Table 2. Estimated reservoir temperatures using silica and Na/K chemical geothermometers

Name/Number	SiO2 ppm	Na ppm	K ppm	Na/K (AT) °C	Na/K (RF) °C	Na/K (WG) °C	Quartz (cond.) °C	Quartz (adiab) °C	Chalcedony °C	α -Cristobalite °C
Beryl										
BS2	282	422	21.5	125	153	184	205	188	188	156
BS3	300	424	22.2	127	155	186	209	192	193	161
BS4	278	424	22.2	127	155	186	204	187	186	155
BS5	289	412	21.3	126	154	185	206	190	190	158
BS6	293	420	20.4	121	149	181	208	190	191	159
BS7	287	417	21.2	125	153	184	206	189	189	157
BS8	293	427	22.7	129	157	187	208	190	191	159
BS9	276	419	21.5	126	154	184	203	187	186	154
BS10	268	412	20.9	125	153	184	201	185	183	152
BS11	263	427	21.1	123	150	182	199	184	181	151
BS12	261	412	20.9	125	153	184	199	183	181	150
BS13	265	425	21.8	126	154	184	200	184	182	151
BS14	280	421	22.0	127	155	185	204	188	187	156
BS15	274	421	20.9	123	151	182	202	186	185	154
"Black"										
BH2	169	252	60.3	306	357	313	169	159	146	119
BH3	169	252	63.4	315	367	319	169	159	146	119
BH4	166	244	61.6	315	368	319	168	158	145	117
BH5	166	247	62.3	315	368	319	168	158	145	117
BH6	168	243	59.9	311	363	316	168	159	146	118
BH7	169	245	61.3	314	366	318	169	159	146	119
BH8	166	245	60.3	311	363	316	168	158	145	117
BH9	370	235	58.7	314	366	318	226	205	213	179
BH11	368	236	57.8	310	362	316	226	205	213	178
BH13	379	242	59.7	311	363	317	228	207	216	181
BH15	381	255	61.5	307	359	314	229	207	216	182
"Carnegie"										
CD2	302	301	17.1	134	163	191	210	192	194	162
CD3	315	307	17.8	136	165	192	213	195	198	165
CD4	312	302	17.7	137	166	193	212	194	197	164
CD5	315	306	17.3	134	162	191	213	195	198	165
CD6	312	311	17.5	133	162	190	212	194	197	164
CD7	308	297	16.7	133	162	190	211	194	196	163
CD8	308	300	17.5	136	165	193	211	194	196	163
CD9	304	311	18.3	137	166	193	210	193	194	162
CD10	317	310	17.4	133	162	190	214	195	198	166
CD11	319	300	16.7	132	161	190	214	196	199	166
CD14	317	287	16.2	134	162	191	214	195	198	166
CD17	330	274	15.4	133	162	190	217	198	202	169

Name/Number	SiO ₂ ppm	Na ppm	K ppm	Na/K (AT) °C	Na/K (RF) °C	Na/K (WG) °C	Quartz (cond.) °C	Quartz (adiab) °C	Chalcedony °C	α-Cristobalite °C
Cistern										
CS2	589	335	70.1	284	332	299	268	238	264	224
CS3	595	332	70.4	286	334	301	269	238	266	225
CS4	597	336	70.8	285	333	300	269	239	266	226
CS5	589	332	70.5	286	335	301	268	238	264	224
CS6	578	334	70.4	285	333	300	266	236	262	222
CS7	580	335	71.5	287	336	301	266	236	263	223
CS8	578	332	70.3	286	334	300	266	236	262	222
CS9	606	338	72.4	288	336	302	271	240	268	227
CS10	586	333	71.1	287	336	301	267	237	264	224
CS11	569	331	70.4	287	335	301	264	235	260	221
CS12	567	337	75.6	295	345	306	264	235	260	220
CS13	614	345	73.5	287	335	301	272	241	269	229
CS14	582	346	72.1	284	331	299	267	237	263	223
CS15	571	348	72.2	283	331	298	265	235	261	221
CS16	578	352	76.0	289	338	302	266	236	262	222
CS17	578	350	77.8	294	343	305	266	236	262	222
CS18	586	366	81.3	294	343	305	267	237	264	224
CS19	584	362	76.4	286	334	300	267	237	263	223
CS20	574	336	74.8	294	343	306	265	236	261	222
CS21	535	326	71.7	292	341	304	259	231	253	214
CS22	533	325	66.3	280	328	297	258	230	253	214
CS23	535	308	67.1	291	339	303	259	231	253	214
CS24	505	302	61.0	279	326	296	253	226	246	208
CS25	492	292	60.7	283	331	299	251	225	243	206
CS26	479	277	57.4	283	330	298	248	223	240	203
CS27	452	264	56.5	288	336	301	243	219	234	197
CS28	492	272	60.5	294	343	305	251	225	243	206
CS29	484	249	53.0	287	335	301	249	223	242	204
CS30	460	259	53.2	281	329	297	245	220	236	199
CS31	482	271	58.6	289	338	303	249	223	241	204
CS32	484	270	58.6	290	339	303	249	223	242	204
CS33	499	297	63.6	288	336	302	252	226	245	207
CS34	496	298	63.7	288	336	301	252	225	244	207
CS35	507	305	67.9	294	343	306	254	227	247	209
CS36	469	284	61.8	290	339	303	247	221	238	201
CS37	484	292	65.5	295	345	306	249	223	242	204
Double Bulger										
DB2	535	440	90.5	281	329	297	259	231	253	214
DB3	533	436	93.0	287	336	301	258	230	253	214
DB4	535	470	94.2	277	324	295	259	231	253	214
DB5	428	405	82.7	280	328	297	238	215	228	192
DB6	456	498	107	288	337	302	244	219	235	198
DB7	541	495	99.2	277	324	295	260	231	254	215

Name/Number	SiO ₂	Na	K	Na/K (AT)	Na/K (RF)	Na/K (WG)	Quartz (cond.)	Quartz (adiab)	Chalcedony	α -Cristobalite
	ppm	ppm	ppm	°C	°C	°C	°C	°C	°C	°C
DB8	469	455	90.4	276	323	294	247	221	238	201
DB9	524	551	107	273	319	292	257	229	251	212
DB10	492	833	144	256	300	280	251	225	243	206
DB11	501	771	151	274	320	292	253	226	245	208
DB12	511	877	167	270	316	290	254	227	248	210
DB13	452	671	121	262	306	284	243	219	234	197
DB14	518	721	138	270	316	290	256	228	249	211
DB15	492	687	125	263	308	285	251	225	243	206
DB16	531	762	134	258	302	282	258	230	252	213
DB17	458	596	117	274	321	293	244	220	235	199
DB18	452	491	96.0	274	320	292	243	219	234	197
Perpetual Spouter										
PS2	285	405	47.9	207	244	246	205	189	189	157
PS3	291	428	50.1	206	243	245	207	190	190	159
PS4	287	428	52.7	212	250	250	206	189	189	157
PS5	291	419	50.6	209	247	248	207	190	190	159
PS6	282	406	48.8	209	246	248	205	188	188	156
PS7	289	394	47.5	209	247	248	206	190	190	158
PS8	285	413	50.7	211	249	249	205	189	189	157
PS10	319	406	49.1	209	247	248	214	196	199	166
PS12	312	410	51.2	213	251	251	212	194	197	164
PS14	330	432	52.3	210	247	248	217	198	202	169
PS16	319	417	50.2	209	247	248	214	196	199	166
Porkchop										
PC2	516	390	76.3	274	320	292	255	228	249	211
PC3	582	396	80.0	279	326	296	267	237	263	223
PC4	597	402	82.3	281	328	297	269	239	266	226
PC5	721	385	80.3	284	331	299	288	253	290	247
PC6	721	395	86.6	292	341	304	288	253	290	247
PC7	719	388	87.7	297	346	307			290	247
PC8	725	414	89.4	289	338	302	289	254	291	248
PC9	717	392	95.0	308	360	315	288	253	289	246
PC10	693	410	92.3	296	346	307	284	250	285	243
PC11	681	410	88.1	288	337	302	282	249	283	240
PC12	693	426	87.3	281	328	297	284	250	285	243
PC14	685	418	82.3	275	321	293	283	249	283	241
PC15	646	428	89.6	284	332	299	277	245	276	235
PC16	631	428	83.6	274	320	292	275	243	273	232
PC18	627	455	82.2	262	307	285	274	242	272	231
PC19	616	451	84.6	267	313	288	272	241	270	229
PC20	666	456	89.5	274	321	293	280	247	280	238
PC21	678	459	96.0	284	332	299	282	248	282	240
PC22	666	495	99.0	277	324	295	280	247	280	238
PC23	633	498	94.0	268	314	289	275	243	273	232

Name/Number	SiO ₂ ppm	Na ppm	K ppm	Na/K (AT) °C	Na/K (RF) °C	Na/K (WG) °C	Quartz (cond.) °C	Quartz (adiab) °C	Chalcedony °C	α -Cristobalite °C
Sulphur Dust										
SD2	240	252	54.9	291	339	303	193	179	174	144
SD3	244	252	58.4	301	351	310	194	179	175	145
SD4	242	267	61.2	299	349	309	193	179	174	144
SD5	246	260	60.4	301	351	310	195	180	176	145
SD6	242	261	58.9	296	346	307	193	179	174	144
SD7	250	263	59.0	295	345	306	196	181	177	147
SD8	229	261	61.0	302	353	311	189	176	170	140
SD9	253	273	63.5	301	352	310	197	182	178	148
SD10	255	249	59.9	307	358	314	197	182	179	148
SD11	270	274	61.6	296	345	307	201	185	184	153
SD12	263	253	60.5	306	357	313	199	184	181	151
SD13	255	259	60.4	302	352	310	197	182	179	148
SD14	253	254	61.2	307	359	314	197	182	178	148
SD15	285	257	64.6	315	367	319	205	189	189	157
SD16	274	269	61.5	298	348	308	202	186	185	154
"Wistful"										
WF2	702	407	105	319	372	321	285	251	287	244
WF3	743	402	103	318	371	321	291	256	294	251
WF4	736	405	103	317	369	320	290	255	293	250
WF5	715	410	107	321	375	323	287	252	289	246
WF6	713	406	104	318	371	321	287	252	289	246
WF7	753	422	109	319	373	322	293	257	296	252
WF8	751	413	107	320	373	322	292	256	296	252
WF9	770	393	99.0	315	367	319	295	258	299	255
WF10	713	391	101	319	373	322	287	252	289	246
WF11	730	402	101	315	367	319	289	254	292	249
WF12	646	390	101	320	373	322	277	245	276	235
WF13	544	374	105	335	390	331	260	232	255	216
WF14	554	392	111	336	392	332	262	233	257	218
WF15	651	434	113	321	374	322	278	245	277	235
WF16	651	415	105	316	368	319	278	245	277	235
WF17	674	398	104	322	375	323	281	248	281	239
WF18	728	404	104	319	372	321	289	254	291	248
WF19	698	435	107	311	363	316	285	251	286	243
WF20	706	423	108	317	370	320	286	251	287	245
WF21	719	410	101	311	363	316	288	253	290	247

Na/K (AT) - Temperature estimated using the equation of Truesdell (1976)

Na/K (RF) - Temperature estimated using the equation of Fournier (1979)

Na/K (WG) - Temperature estimated using the equation of Giggenbach (1988)

Quartz (cond) - Temperature estimated using the equation of Fournier and Potter (1982), assuming conductive cooling and silica controlled by the solubility of quartz

Quartz (adiab) - Temperature estimated using the equation of Fournier and Potter (1982), assuming adiabatic cooling and silica controlled by the solubility of quartz

Chalcedony - Temperature estimated using the equation of Fournier (1985), assuming conductive cooling and silica controlled by the solubility of chalcedony

α -Cristobalite - Temperature estimated using the equation of Fournier (1985), assuming conductive cooling and silica controlled by the solubility of α -cristobalite