

**The Origins of Reservoir Liquids and Vapors from
The Geysers Geothermal Field, California (USA)**

Jacob B. Lowenstern and Cathy J. Janik

U.S. Geological Survey
Mail Stop 910
345 Middlefield Road
Menlo Park, CA 94025

Jlwnstrn@usgs.gov

Short Title: *ORIGINS OF LIQUIDS AND VAPORS FROM THE GEYSERS*

Abstract

In this paper, we consider the primary controls on gas and liquid geochemistry at The Geysers geothermal field (California, USA) prior to significant development and re-injection programs. Well discharges vary considerably in steam/gas ratio, gas composition and δD and $\delta^{18}O$ of steam. Many of the variations can be linked to the degree of liquid saturation within the reservoir. Discharged fluids from the Northwest Geysers have low steam/gas and are produced from reservoir vapor, as little condensed liquid appears to exist in that part of the system. The gas is relatively uniform in composition, and is interpreted to represent a mixture of connate and metamorphic gases derived from high-temperature breakdown of carbon and nitrogen-bearing meta-sediments either within or below the geothermal reservoir. Input of volcanic gas from underlying intrusions appears to be present, but minor. The gas-rich endmember is less evident in the Southeast and Central Geysers where discharged fluids consist primarily of steam boiled from condensed reservoir liquid. Reservoir gases are diluted by the greater input of meteoric waters, which disguises the connate/metamorphic signature of the gas. This is consistent with the pattern of δD and $\delta^{18}O$ of steam across the field.

Introduction

The Geysers steam field is one of the two largest vapor-dominated geothermal reservoirs in the world, and currently produces about 1000 MW of electricity. Well discharges consist almost entirely of superheated steam flowing from the vapor-dominated reservoir below. Within the field, the noncondensable gas fraction varies widely, from < 0.1 mole percent in the Southeast and Central Geysers to > 4 mole

percent of the emitted fluid in the Northwest Geysers (Truesdell et al., 1987; Lowenstern et al., 1999a). These variations result from differences in temperature, saturation and recharge to the geothermal reservoir (Goff et al., 1977; Truesdell et al., 1987; Walters et al., 1992; Truesdell et al., 1993). Besides their high non-condensable gas fractions, the Northwest Geysers well fluids also have higher relative N_2 , CH_4 , CO_2 , HCl and $\delta^{18}O$ of H_2O than the Central and Southeast Geysers (Truesdell et al., 1987; Walters et al., 1992; Lowenstern et al., 1999a). These differences are well documented, but their origins remain unclear. Various workers have argued for meteoric, sedimentary, metamorphic and igneous sources of gases to the Northwest Geysers (Haizlip, 1985; Walters et al., 1992; D'Amore and Bolognesi, 1994; Kennedy and Truesdell, 1996; Lowenstern et al., 1999a). An understanding of the sources of the gases is important in interpreting geochemical changes in the geothermal reservoir and their relationship to production, injection and ongoing natural processes.

Despite the prominence of The Geysers, and the considerable literature on its gas and fluid geochemistry, there exists only one published dataset with complete geochemical analyses of samples from individual wells (Lowenstern et al., 1999a). Herein, we use these data together with methods developed by two pioneering gas geochemists, Werner Giggenbach and Franco D'Amore, to characterize The Geysers reservoir prior to significant development and reinjection programs. We account for the effects of liquid saturation and non-equilibrium processes to estimate the influence of reservoir wallrock on gas chemistry and oxidation state, and to determine the ultimate origin of many of the gas species from The Geysers.

Vapors and Liquids in Geothermal Reservoirs

Interpretations of geothermal gas abundances are complicated by processes such as boiling, condensation and mixing, which can result in non-equilibrium distributions of gas species. Many geothermal reservoirs contain a separate vapor phase, which may be H₂O-dominated or can consist mostly of gas. Liquid-dominated systems may have relatively little vapor present, whereas vapor-dominated systems may contain minimal liquid, mostly found adsorbed in pores and small fractures (White et al., 1971).

In vapor-dominated geothermal reservoirs such as The Geysers, California (USA) and Larderello (Italy), steam is the pressure-supporting medium and liquid is present only because of processes that lower vapor-pressure, such as adsorption (White et al., 1971) or increased liquid salinity. If adequate heat is available, liquid remaining in pores and cracks within the reservoir can be extracted and boiled prior to or during ascent to the wellhead, where it generally emerges as superheated steam. Therefore, measurements of wellhead enthalpies may indicate the presence of steam, but not the reservoir liquid that was recently boiled. Gas concentrations are thus a mixture of species from the two different phases. This mixing can cause misinterpretation of reservoir processes, undermining the effectiveness of some gas geothermometers and confusing interpretations of the oxidation state of the reservoir.

Werner Giggenbach (1980) was the first worker to quantify how gas discharges from geothermal reservoirs are affected by differences in steam fraction (Y : the molar ratio of vaporized H₂O to total H₂O within a geothermal reservoir). Gases boiled off condensed (liquid) H₂O have their compositions controlled by gas solubilities. In contrast, gas ratios in reservoir vapors reflect vapor-phase equilibria. Giggenbach (1980)

provided graphic and analytical methods to estimate the amount of separated vapor within a geothermal reservoir, and the influence of boiled geothermal liquid on measured gas ratios in wellhead discharges. Concurrently, Franco D'Amore and co-workers developed analytical methods to determine Y in vapor-dominated reservoirs (D'Amore et al., 1982; D'Amore and Celati, 1983). Later, D'Amore and Truesdell (1985) applied the model of D'Amore et al. (1982) to The Geysers steam field and found that well discharges from the Southeast Geysers had very low Y relative to the Northwest Geysers. Below, we use these techniques to account for the effect of Y on measured well discharges, and use the results to characterize the sources of gases and liquids to the geothermal system.

Geology of The Geysers

The Geysers is located in the Mayacamas Range in northern California, about 150 km north of San Francisco (Fig. 1). The Geysers is the most obvious manifestation of a large heat-flow anomaly associated with the adjacent Clear Lake volcanic field, a late Pliocene to Holocene aged magmatic system (Hearn et al., 1981, 1995; Donnelly-Nolan et al., 1981). The field lies within the central belt of the Franciscan Complex, an assemblage of deep oceanic deposits formed in the Mesozoic Era and early Tertiary Period. In this region, the Franciscan assemblage consists primarily of regionally metamorphosed graywacke, argillites, greenstones, and cherts. The Franciscan Complex, within and around the Clear Lake volcanic field, is host to scores of small Hg and Au deposits, where mineralization is often associated with accumulations of bitumen and

other organic residues believed to be mobilized from organic materials desposited with the local graywackes (Peabody and Einaudi, 1992; Hulen and Walters, 1993).

The Colloyami and Mercuryville strike-slip faults form the northeast and southwest edges of The Geysers field, respectively, creating a geometry for the steam field that is elongate parallel to the faults of the San Andreas system. Apparently, these faults and associated lithology changes act as permeability barriers that contain the geothermal system (Goff et al., 1977). The steam field is also coaxial with a large intrusion, informally known as “the felsite” (Schriener and Suemnicht, 1981). This composite intrusion of granite, granodiorite and microgranite porphyry was emplaced about 1.1-1.2 Ma (Dalrymple et al. 1999), and is thought to be an intrusive equivalent of Cobb Mountain dacite and rhyolite, which is part of the Clear Lake volcanic field (Hulen and Walters, 1993; Hulen et al., 1997a). The productive portion of the geothermal reservoir is primarily located in weakly metamorphosed Franciscan rocks, but extends down into the felsite intrusion and its surrounding biotite-hornfels-grade aureole (Fig. 2).

It appears that the geothermal system was created by intrusion of “the felsite” to create a liquid-dominated reservoir about a million years ago (Sternfeld, 1981; Moore and Gunderson, 1995; Hulen and Nielson, 1996). The liquid-dominated reservoir was characterized by studies of fluid inclusions and oxygen isotopes (Moore and Gunderson, 1995) and appears to have persisted until 0.28-0.25 Ma when catastrophic depressurization and consequent boiling produced the present-day vapor-dominated reservoir (Shook, 1995; Hulen et al., 1997a, b). More recent, underlying, unsampled intrusions are believed to provide the heat that is being “mined” by the current

geothermal system (Hearn et al., 1981; Truesdell et al., 1987; Walters et al., 1992; Donnelly-Nolan et al., 1993; Stimac et al., 2001).

The Geysers Reservoir

Liquid saturation in the reservoir

As noted above, The Geysers is a vapor-dominated reservoir and is thus underpressured with respect to a hydrostatic pressure gradient. Though well discharges are primarily superheated steam withdrawn from large fractures, the existence of adsorbed liquid water within the rock matrix of the reservoir can be readily demonstrated. Williamson (1992) argued that if the geothermal reservoir contained solely water vapor, the available pore volume could hold only about 30 percent of the H₂O mass that had been withdrawn from The Geysers prior to 1987. He also discussed how liquid saturations (the mass of liquid relative to total H₂O) in the SE Geysers may approach 25 percent within fractures, relative to much lower saturations in the NW Geysers. This explains the relatively rapid production-related pressure declines in the NW Geysers relative to the Central and SE parts of the field (Williamson, 1992).

Geochemical evidence has also been used to infer the presence of liquid within The Geysers reservoir (D'Amore et al., 1982; D'Amore and Truesdell, 1985). Because the reservoir contains both steam and liquid water droplets, the compositions of well discharges are a function of the relative amounts of the two phases available for transport to the surface (Truesdell and White, 1973; Truesdell et al., 1987). The steam fraction, Y , can be estimated by using a combination of gas equilibria and gas solubility equations (D'Amore et al., 1982). D'Amore and Truesdell (1985) estimated that well discharges

from the Southeast Geysers were composed mostly of steam from recently boiled liquid water ($Y = 0.01$ to 0.05), whereas fluids from the Northwest Geysers predominantly sample reservoir vapor ($Y = 0.1$ to 1.0). These fieldwide characteristics can partially be traced to different temperature reservoirs that have been identified.

The Geysers steam field is divided into two principal reservoirs, a normal-temperature reservoir and a high-temperature reservoir (NTR and HTR) which appear to be hydrologically connected. In the NTR, temperatures were originally close to 240°C with a pressure around 35 bars. Pressures in the HTR are only marginally higher, though temperatures normally exceed 300°C and have been measured as high as 342°C (Walters et al., 1992). The host rock for the NTR is normally Franciscan graywacke; though the HTR is found typically in hornfels, no obvious changes in lithology occur as one passes from the NTR to the HTR (Walters et al., 1992). Moreover, the temperature and pressure gradients between the reservoirs are continuous. Wells that extend into the HTR, such as the Prati wells from the Northwest Geysers, pass through the NTR so that sampled fluids represent a mixture of steam and gas from both reservoirs. Though the HTR may reside beneath the NTR throughout The Geysers steam field, it has only been sampled in the Northwest and North-Central Geysers where wells extend below the 1798m (5900 ft.) bsl elevation at which the top of the HTR is located (Fig. 2).

Origin of Geysers gases and steam: Previous work

Geochemically, there are a number of obvious trends that differentiate the Southeast Geysers from the Northwest Geysers. Well discharges from the Southeast Geysers contain mostly steam, and have an isotopic signature of slightly oxygen-exchanged meteoric water

that is similar in deuterium content to present-day local streams and springs (Truesdell et al., 1987). In contrast, fluids from the Northwest Geysers are rich in all non-condensable gases (Truesdell et al., 1987) and have elevated $\delta^{18}\text{O}$ and δD values that show far less influence of present-day meteoric water. Haizlip (1985) suggested that this isotopically enriched water was equivalent to “connate” or formation waters (derived from ancient seawater) that discharge from Franciscan and Great Valley sediments and are found throughout the Clear Lake volcanic field (White et al., 1973). Donnelly-Nolan et al. (1993) noted that the isotopically heavy endmember discussed in The Geysers literature could be created by repeated, near-closed-system boiling of evolved meteoric waters. D’Amore and Bolognesi (1994) noted the similarity of steam from the Northwest Geysers to volcanic gas from arc volcanoes (Giggenbach, 1992a) and concluded that recent magma degassing was contributing most of the H_2O to the Northwest Geysers. Their conclusions were bolstered by workers who found that Northwest Geysers wells have high $^3\text{He}/^4\text{He}$ ratios (R/R_A of 6.3 to 9.6; Torgerson and Jenkins, 1982; Kennedy and Truesdell, 1996), similar to those of MORB. Kennedy and Truesdell (1996) interpreted these values to indicate modern magma degassing beneath the Northwest Geysers, possibly extending south underneath the entire geothermal field. It remains unclear how much magma-derived gas (other than He) is contributed to The Geysers.

Gas Analyses from The Geysers

In this paper, we consider 81 high-quality analyses of The Geysers well discharges published by Lowenstern et al. (1999a). The samples were collected between 1978 and 1991. Some wells, including most of those in the Northwest Geysers and all in

Unit 15 have ceased production due to their high gas content or appreciable HCl (e.g., Haizlip and Truesdell, 1989). All data represent bulk analyses of steam and non-condensable gases collected at the wellhead. Temperatures typically correspond to those of superheated steam, though many samples are only a few degrees above their condensation temperatures and a few were not superheated. Table 1 lists 45 fluids representative of the early stage of development of different parts of the geothermal field. Many were sampled within the first few years after drilling and they show few of the effects expected due to pressure declines and re-injection programs. Even so, it is important to recognize that well discharges may sample heterogeneous fluids. They can originate from multiple steam entries below the level of cement casing. In the Northwest Geysers, they may contain considerable steam from the HTR and additional input from the NTR.

Terminology

Steam: Vaporized H₂O.

Reservoir Vapor: The non-condensed (non-liquid) phase within the geothermal reservoir, including steam and gas.

Reservoir Liquid: The condensed phase within the geothermal reservoir, including liquid H₂O and any dissolved gases.

Fluid: Any combination of the above.

Non-condensable gases (NCG): All measured components of well discharges other than H₂O.

Steam/gas ratio: The molar ratio of H₂O vapor to the sum of all other reported gas components (CO₂, H₂S, H₂, CH₄, N₂, Ar, O₂, He, NH₃).

Y (steam fraction): The molar ratio of steam to total water in the sampled discharge (other gas and liquid constituents are ignored). Calculated Y may not correspond precisely to the molar liquid-to-steam ratio within the reservoir (Arnórsson et al., 1990; Grant et al., 1996), but should be a good approximation. Because the liquid may boil either within the reservoir or in the wellbore, a sample with low Y can still emerge as superheated steam. Two methods for calculating Y are described herein (*Y1* and *Y2*).

Other definitions and descriptions of the data and their acquisition may be found in Lowenstern et al. (1999a).

Well Discharges from The Geysers

In this section, we demonstrate that observed gas ratios result from variations in the relative amounts of reservoir liquid and vapor that are sampled. We use equations developed by Giggenbach (1980) and summarized by Chiodini and Marini (1998) to model the gas ratios expected for various mixtures of reservoir vapor and liquid.

As illustrated in Figure 3, R_H [$\log (H_2/H_2O)$] of bulk well discharges varies between -4.7 and -2.4 . The data could represent heterogeneous oxidation conditions, ranging from around Ni/NiO to the magnetite-hematite buffer, or variable Y values. Figures 4 and 5 help discriminate between the two options by demonstrating how theoretical variations in Y and oxidation state would affect well discharges. With a few reasonable assumptions, one can calculate a hypothetical vapor phase in the geothermal reservoir, as

well as the amounts of gases dissolved in any equilibrium liquid. Along the liquid-vapor saturation curve, the fugacity of H₂O is fixed by its temperature. The fugacity of CO₂ can be estimated by assuming full equilibrium with calcite, and common rock forming minerals such as K-feldspar and K-mica (Giggenbach, 1984, 1988). Oxygen fugacity can be set to a variety of mineral buffers. Given the above constraints, the relative concentrations of H₂, CH₄ and other C-O-H gases can be calculated with the thermodynamic data of Stull et al. (1969). Figure 4 displays the R_H and log (CH₄/CO₂) that would be present in the reservoir vapor at 250°C for three different redox conditions: the rock buffer, quartz-fayalite-magnetite, and magnetite-hematite. The “rock buffer” assumes the presence of ferric and ferrous iron (Giggenbach, 1987). Data from The Geysers lie close to the “rock buffer” but with R_H extending to lower values at constant log(CH₄/CO₂). If well discharges reflect different oxidation states within the reservoir, the data would lie along a diagonal trend connecting the buffers.

Instead the data appear consistent with varying Y. Figure 5 illustrates the same variables as Figure 4, but shows the effect of varying Y under conditions with a fixed oxidation state. It allows one to look at the effect of adding recently boiled reservoir liquid into the vapor discharged at the wellhead. By using vapor-liquid distribution coefficients listed in Giggenbach (1980), one can calculate the concentrations of dissolved gases in reservoir liquid, allowing modeling of isothermal mixing lines between the two phases equilibrating along the “rock buffer”. Overlain are the highly variable values of well discharges from The Geysers. Part of their variation is likely due to the range of temperatures in the geothermal reservoir, but even along individual isotherms, there remains considerable variation in gas ratios from The Geysers wells, consistent with

addition of liquid H₂O and Y values ranging from 1 down to 0.01. The few high-Y samples with R_H above the vapor equilibrium of Figure 5 (R_H = -2.82) suggest that conditions in the HTR may be slightly more reducing than the “rock buffer”, but significantly more oxidizing than the quartz-fayalite-magnetite buffer [Figs. 3, 4; R_H = -1.63 at ~ 250°C].

The results are compatible with a reservoir containing variable proportions of steam and liquid with redox similar to the “rock buffer”. This is consistent with other evidence mentioned above; i.e., the large mass of H₂O removed from The Geysers during its history (Williamson, 1992), and with the relatively uniform and reduced mineralogy of the Franciscan graywacke that hosts most of the reservoir (Moore and Gunderson, 1995; Hulen et al., 1997b).

Assessing Reservoir Y Values:

Having demonstrated that The Geysers well discharges are characterized by varying contributions from reservoir liquid and vapor, we now use two different methods to calculate Y for each sample from Lowenstern et al. (1999a). Though the techniques are quantitative, their results should be used only as qualitative indicators of the amount of condensed liquid adsorbed in the geothermal reservoir. Any individual sample will consist of fluids from multiple steam entries at multiple temperatures. The physics of multiphase flow may contribute to vapor loss or gain during movement of fluid toward the well bore (Arnórsson et al., 1990 Grant et al., 1996). Nevertheless, it is useful to estimate Y, so that one may re-calculate the composition of the vapor phase within the reservoir, adjusting the abundances of H₂O, NH₃ and other soluble gases.

We first use the method of D'Amore et al. (1982), which was developed for vapor-dominated reservoirs and considers C-O-H gases, which are more closely in equilibrium than N-bearing species [as discussed by Giggenbach (1987) and Chiodini and Marini (1998)]. By iterating through equations 1 and 2 (28 and 29 from D'Amore et al., 1982), one can simultaneously solve for temperature (T) and Y,

$$\log\left(\frac{H_2}{H_2O}\right) = -6.355 - \frac{951.6}{T} + 2.076 \log T + \frac{1}{4} \log\left(\frac{CH_4}{CO_2}\right) + \log\left(Y + \frac{1-Y}{B_{H_2}}\right) \quad \text{Eq. 1}$$

$$\log\left(\frac{H_2S}{H_2O}\right) = 2.122 - \frac{2542}{T} - 0.098 \log T + \frac{1}{12} \log\left(\frac{CH_4}{CO_2}\right) + \log\left(Y + \frac{1-Y}{B_{H_2S}}\right) \quad \text{Eq. 2}$$

where T is in Kelvin, the gas ratios are the measured molar proportions, and B_{H_2} and B_{H_2S} are liquid-vapor partitioning expressions from Giggenbach (1980). These equations distribute the amounts of H_2O , CO_2 , CH_4 and H_2S between liquid and vapor as a function of T and Y. The coefficients imply an fO_2 intermediate between that of D'Amore and Panichi (1980) and D'Amore and Truesdell (1980), and similar to Giggenbach's "rock buffer" (1987). Herein, the calculated values are denoted as *YI*, and range from .01 to 1 (no attempt was made to calculate *YI* values less than 0.01). The results, shown in Table 1, are very similar to what can be graphically estimated from Figure 5. Twenty-four of the 81 well discharges have calculated *YI* of 1 (no liquid added to the discharge); most of these are from the Northwest Geysers. Estimated temperatures range from 200 to 260°C, consistent with measured downhole temperatures, but less than is present in parts of the HTR. As discussed above, using the vapor-liquid distribution coefficients from

Giggenbach (1980) and values of $Y1$, the gas data can be recalculated to account for the effects of addition of reservoir liquid. Re-calculated R_H for the 81 reservoir vapors ranges from -2.37 to -3.34 with a mean value of -2.90 ± 0.17 . The recalculated analyses have limited variation in H_2/H_2O compared with the non-normalized values (Fig. 3).

Another means for estimating Y is to choose the well discharge with the highest value of R_H and to assume that it represents the vapor at an appropriate averaged oxidation state for the reservoir; all other samples being diluted somewhat by boiled reservoir liquid. The highest value is -2.37 , slightly more reducing than the -2.82 of the “rock buffer” (Giggenbach, 1987), but similar to that prescribed by coexisting pyrite and pyrrhotite (Fig. 3), minerals commonly found in the host graywacke (Sternfeld, 1981; Moore and Gunderson, 1995). By assigning an R_H of -2.37 to all vapor within the reservoir, and assuming excess H_2O is from the boiled liquid phase, one can calculate $Y2$. Figure 6a displays the Y values calculated with each method. The two methods qualitatively agree, though method 2 requires that only a single sample can have Y equal to unity. Nearly all $Y2$ values are much less than $Y1$.

Once a value for $Y1$ or $Y2$ is determined, soluble gases can be assigned to the liquid based on the partitioning expressions of Giggenbach (1980). Figure 6b shows the ratio of H_2S to N_2 , a soluble gas divided by a relatively insoluble one, in the calculated reservoir vapor. Samples with high Y yield similar calculated vapors for the two methods. For all low- Y samples, $Y1$ is greater than $Y2$, so that less H_2S is partitioned into the calculated liquid, and H_2S/N_2 for $Y1$ is greater than that for $Y2$. Method $Y2$ is simple and easy to calculate. It is unrealistic in that it assumes a single reservoir temperature and oxidation state. However, temperature should have little effect on Y (see Y isopleths in Fig. 5) and

Figure 4 demonstrates that the reservoir oxidation state indeed has relatively little variation. Moreover, the *Y2* method reasonably requires that nearly all reservoir vapors are equilibrating with some absorbed liquid (*Y1* predicts that 24 samples are vapor-only). As discussed below, the *Y2* calculations demonstrate that high-*Y* samples from the Northwest Geysers have reservoir vapor compositions more homogeneous than low-*Y* discharges from the Central and Southeast Geysers.

End-member Vapor Compositions at The Geysers

The above discussion helps identify the primary controls on steam/gas ratios and oxidation state of The Geysers well discharges. With this information, the data from Lowenstern et al. (1999a) and results from previous work, we now focus on the sources of gas and H₂O to The Geysers.

Low-Y endmember — Southeast Geysers:

In the Southeast Geysers, only H₂O is clearly enriched. Figure 7 displays gas abundances in the calculated reservoir vapor versus *Y2*. The low-*Y* fluids are notably poor in all gas species because H₂O dominates *both* the liquid and vapor phase in these samples. In the low-*Y* discharges of the Southeast Geysers, H₂ and H₂S are correlated and appear enriched if H₂O is excluded (Fig. 8); but these species increase sympathetically with steam/gas, and the mass fraction of these gases in the calculated vapor from the Southeast Geysers is exceedingly small (Fig. 7). In Figure 9, H₂O is excluded, and it is apparent that the gas within the Southeast and Central Geysers is highly variable in composition. Because *Y* is low in that part of the field, the small

portion of reservoir vapor may be strongly affected by mixing with injectate, and varied meteoric, magmatic and connate sources of gas. In effect, there is no discernible low- Y endmember other than H_2O .

The mole fraction of CO_2 in NCG from the Southeast Geysers has increased over time, and steam/gas has decreased. This may be due to increased gas flux into The Geysers reservoir from underlying meta-sedimentary and/or magmatic sources (Beall and Box, 1993). Gas flow would be expected to increase as reservoir pressures decline (Beall and Box, 1993) and would cause some dilution of the H_2O -rich endmember within the steam field.

The source of H_2O to the Southeast Geysers is readily apparent given its isotopic composition. Well samples from the Southeast and Central Geysers have isotopic compositions consistent with reservoir recharge primarily by meteoric H_2O , modified by limited H_2O -rock interaction (Fig. 10). The water likely enters the subsurface through the porous volcanic rocks around Cobb Mountain, which is the topographically highest part of the geothermal field (Goff et al., 1977; Truesdell et al., 1987).

High- Y endmember — Northwest Geysers:

Samples from the Northwest Geysers are notably enriched in all gas species. In Figure 7, non-condensable gases are shown to increase in concentration in the calculated reservoir vapor phase (at the expense of H_2O) as a function of Y_2 . In the Northwest Geysers, there is a higher proportion of vapor to liquid, i.e., Y , and the vapor is distinctly gas-rich. Figure 9 demonstrates that the gas-rich source to the Northwest Geysers is more homogeneous than gas sources to the rest of the field. The composition of vapor

from the Northwest part of the field converges on a relatively consistent endmember that is typified by the sample from Prati 25, the well with the highest R_H , and thus a $Y2$ of one (Table 1). In fact, the seven samples with the highest calculated $Y2$ values are all far more similar in gas composition than those samples with lower $Y2$. On a H_2O -free basis, Prati 25 contains approximately 75 mole percent CO_2 , 10 percent each of CH_4 and H_2 and between 1 and 3 percent of H_2S , NH_3 and N_2 . The similarity between gases from high- Y well discharges relative to gases from the Southeast Geysers holds regardless of whether $Y1$ or $Y2$ is used to calculate vapor composition.

The isotopic composition of H_2O vapor from the Northwest Geysers shows an obvious shift away from meteoric sources toward a component rich in deuterium and ^{18}O (Figure 10). As discussed above, this trend has been noted previously, and its origin is controversial. Below, we explore the origin of gas and steam to the Northwest Geysers by considering all the characteristics of the high- Y discharges from this part of the field.

Origins of the gas-rich endmember

Various groups have interpreted the stable isotopic data for waters and steam as indicative of different sources, ranging from magmatic, to metamorphic to evolved meteoric. Thus, despite the striking trend in δD and $\delta^{18}O$ in the Northwest Geysers, it remains unclear from where the water derives. We agree that the mantle-like 3He -signatures of gases from The Geysers imply that He reaches the geothermal system via ongoing magmatism (Torgerson and Jenkins, 1982; Kennedy and Truesdell, 1996). Moreover, thermal modeling of the region is consistent with input of heat and mass through ongoing silicic plutonism (Dalrymple et al., 1999; Stimac et al.; 2001). However,

we find it unlikely that any of the other reservoir gases are derived *predominantly* from a magmatic source.

Carbon gases: Most of the components of The Geysers gases can be attributed to a sedimentary source, consistent with derivation predominantly from Franciscan graywacke. Allen and Day (1927, p. 70), first noted the high CH₄ and H₂ and low CO₂ of The Geysers fumaroles and well discharges compared with fumaroles from the volcanic-hosted geothermal system at Lassen. Also, when compared to many volcanoes, CO₂ from The Geysers is quite low in $\delta^{13}\text{C}$, with values ranging from about -12 to -15 per mil PDB (Lowenstern et al., 1999a; Bergfeld et al., 2001; cf. Janik et al., 1983). Such values are lower than would be expected for CO₂ derived directly from magma, and imply a significant contribution from reduced organic carbon (Allard, 1979; Ohmoto and Rye, 1979; Janik et al., 1983; Rollinson, 1993; Ohmoto and Goldhaber, 1997; Bergfeld et al., 2001). Janik et al. (1983) noted that CO₂ from geothermal fumaroles at Lassen average about -10.5 per mil, and the original magmatic values may be lowered somewhat by addition of organic carbon. Evans et al. (1981) found similar values at Mt. St. Helens, and it appears that most Cascades volcanoes have $\delta^{13}\text{C}$ of CO₂ less than expected for most mantle-derived magmas (-11 per mil PDB vs. -5 per mil; C.Janik and W.C. Evans, unpublished data). At The Geysers, carbon isotopic values of CO₂ are yet lower by 1 to 3 per mil. Moreover, the $\delta^{13}\text{C}$ of CO₂ is similar to that found in hydrothermal carbonate veins found throughout the Franciscan metasediments of the reservoir, which presumably predate the current vapor-dominated reservoir (Bergfeld et al., 2001). The CO₂ in present-day well discharges is likely derived from a mixture of organic-rich sediments and

carbonate from Franciscan rocks and Quaternary hydrothermal veins in and below the reservoir (Bergfeld et al., 2001).

Methane, the next most abundant gas in the high-Y discharges is likely derived from thermal breakdown of complex hydrocarbons, as implied by values for $\delta^{13}\text{C}$ of CH_4 from -30 to -40 (Bergfeld et al., 2001). The methane is unlikely to come directly from any magmatic source, as its equilibrium abundance at temperatures above 500°C is extremely low (Gerlach, 1980; Symonds et al., 1994). If igneous-derived CO_2 were partially converted to CH_4 during low temperature equilibration (Gerlach, 1980), isotopic fractionation would cause the remaining CO_2 to become higher in $\delta^{13}\text{C}$. This means that if both CO_2 and CH_4 have an ultimate magmatic source, the isotopic composition of the original volcanic CO_2 is lighter (more negative) than the already very light values of the present-day gases.

Ammonia: Like CH_4 , NH_3 is normally thought to originate via breakdown of organic material, and is unstable at temperatures above about 400°C (Symonds et al., 1994) at typical crustal oxidation states. And yet, NH_3 concentrations at The Geysers are 1-2 orders of magnitude higher than would be expected under equilibrium reservoir conditions (Lowenstern et al., 1999a). Giggenbach (1987) also found that NH_3 -breakdown reactions were kinetically hindered in a variety of geothermal systems. NH_3 appears to be produced by low- to moderate-temperature breakdown of organic materials in Franciscan graywacke and then lingers in greater-than equilibrium abundances. Due to its relatively high solubility in condensed liquid, NH_3 concentrations can be elevated in parts of the field where discharged geothermal fluids have been cooled and reinjected (Fig. 17 of

Lowenstern et al., 1999a). In such cases, NH_3 can be used as a tracer for the efficiency of the reinjection system (Beall, 1993).

Hydrogen: As discussed above, H_2 concentrations in reservoir vapors are attributable to equilibrium with H_2O at oxidation states near the “rock” (Giggenbach, 1987) and pyrite-pyrrhotite buffers. Variations in $\text{H}_2/\text{H}_2\text{O}$ of the total well discharge correspond to the steam fraction (Y) sampled by the well. Therefore, H_2 concentrations in The Geysers wells appear to reflect equilibrium at reservoir conditions and cannot be traced to external sources. Variations in H_2 concentrations in the calculated vapor phase of low-Y well discharges are mostly a function of increasing dilution by the high-Y endmember gas.

Nitrogen and N_2/Ar : Nitrogen to Ar ratios have also been used to infer magmatic input to The Geysers gases. Moore et al. (2001) argued that N_2/Ar ratios greater than 525 in fluid inclusions from The Geysers were “uniquely magmatic.” Figure 11 shows that 4 samples of gas from The Geysers have N_2/Ar greater than 500, with two of them greater than 525. High N_2/Ar is common in gases from hot springs throughout the Clear Lake volcanic field (Goff and Janik, 1993) and is associated with springs thought to have a large metamorphic component. N_2/Ar has been known to reach values up to 2000 in Central Valley oil wells (Jenden et al., 1988), plausibly due to breakdown of NH_3 -rich materials in Great Valley sediments. Closer to The Geysers, values for N_2/Ar of 602 have been recorded at the Kelseyville gas well, which at 14°C contains 31 percent CH_4 , with most of the rest being CO_2 (C.J. Janik, unpublished data). At the Crabtree gas seep, which emits gas with >90 percent CO_2 , N_2/Ar has been recorded at values ranging from 940 to

2950 (C.J. Janik, unpublished data), but is accompanied by He with low R/R_A (Goff et al., 1995). High N_2/Ar is often found in volcanic gases associated with arc volcanoes (Giggenbach, 1992b). Though volcanism and tectonism in the Clear Lake is broadly related to subduction, the region is far from typical of continental arcs, and it is unclear whether high N_2/Ar should be expected.

Interestingly, N_2/Ar correlates with $1/Ar$, showing that the high N_2/Ar endmember is being diluted by an air-rich meteoric component with N_2/Ar ranging from 38 (air-saturated water) to 84 (air). Only samples with low Ar are high in N_2/Ar . Among those, nearly all are from the Northwest Geysers and Unit 15, the areas within the field least influenced by liquid inflow. And what N_2 is present in those samples is correlated with CH_4 (Fig. 12). This implies that N_2 is derived from the same source as CH_4 , which is unlikely to come directly from underlying magma. Given the correlation of N_2 with CH_4 at The Geysers, it seems reasonable to assign the high N_2/Ar to a meta-sedimentary source that is low in Ar .

Sulfur: Though the $\delta^{34}S$ of H_2S from The Geysers is compatible with a magmatic origin (values between 2 and -3 per mil CDT; Lowenstern et al., 1999a), it is noteworthy that sulfur, usually a major component in volcanic gas, as SO_2 , is conspicuously low in well discharges from the Northwest Geysers (e.g., Fig. 5a, Fig. 6 and Fig. 11c of Lowenstern et al., 1999a). Mole percent H_2S in the reservoir vapor has a negative correlation with N_2/Ar , $\delta^{18}O$ of steam, Y , gas/steam and CH_4 in the reservoir vapor. H_2S in the reservoir likely reflects equilibration of H_2O with pyrite and pyrrhotite.

Total gas composition: A further piece of evidence that adds doubt to a magmatic source for the non-condensable gases from the Northwest Geysers is the relative proportions of gases present in the reservoir discharges. Compared with most volcanic gases or volcano-hosted geothermal systems, CO₂ is relatively low, as is H₂S (cf. Symonds et al., 1994; Giggenbach, 1996). Almost universally, volcanic gases are dominated by H₂O, followed by variable ratios of CO₂, S gases and HCl. At volcano-hosted geothermal systems, such as Lassen, where geothermal vapors are boiled off a ~240°C geothermal liquid, CO₂ makes up more than ~90 percent of the non-condensable gas, followed by H₂S, N₂, and H₂ (C.Janik, unpublished data). Similar data are observed at Alid volcanic center, White Island, and many other geothermal systems (Lowenstern et al., 1999b; Giggenbach, 1987; Goff and Janik, 2000). Systems with low CO₂ and higher H₂S, CH₄, NH₃ and N₂ are usually associated with geothermal reservoirs hosted by argillaceous rocks (Goff and Janik, 2000). Lower CO₂ concentrations at The Geysers are probably not due to absorption in a deep reservoir liquid, because at temperatures >300°C, it is unlikely that CO₂ will be reactive and easily removed from rising volcanic gas (Bischoff and Rosenbauer, 1996). In sum, the low concentrations of CO₂ and high concentrations of CH₄ and NH₃ in well discharges from The Geysers are inconsistent with a dominant volcanic gas source to the geothermal system.

Summary

In assessing the compositions of well discharges from The Geysers, we can make the following conclusions:

- 1) Total well discharges represent a combination of reservoir vapor and recently boiled liquid present in cracks within the reservoir (D'Amore and Truesdell, 1985).
- 2) H_2/H_2O ratios of reservoir vapors are consistent with equilibration near the Giggenbach (1987) "rock buffer". Variations in H_2/H_2O in bulk well discharges are likely due to differing steam fractions tapped by the well and sampled at the wellhead.
- 3) Geographic variations in gas composition reflect two primary endmembers. The first is dominated by condensed H_2O and enters the NTR through natural recharge and injection. There is no unique gas composition associated with this endmember. The second is a gas-rich, H_2O -poor endmember associated with the HTR and found most notably in the Northwest Geysers. The gas composition becomes more uniform as steam fraction increases. Most well discharges represent a mixture of these two endmember components.
- 4) The gas-rich endmember is predominantly derived from thermal decomposition of Franciscan rocks within and beneath the geothermal reservoir. Overall gas composition, stable isotopes, N_2/Ar ratios and the abundance of organic gases are consistent with this interpretation. Nevertheless, a significant volcanic input to the system is permissible with the data, and is indeed likely given the 3He isotopic evidence and the continuing high heat flux of the region. Most likely, recent (though unsampled) intrusions beneath the Northwest Geysers have increased heat flow and thermal maturation of organic materials in the thick sequence of Franciscan graywacke in and below this part of the reservoir.

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Figure Captions

Fig. 1. Map of the Geysers steam field, California. Sampled well locations indicated as diamonds. Bold dashed lines denote informal region boundaries that separate the field into Southeast, Central, Northwest and Unit 15 sectors. They may not be precisely consistent with terminology used in other studies. The outline of the steam field is from California Division of Oil and Gas (1992). Detailed well and sample information available in Lowenstern et al. (1999a).

Fig. 2. Schematic cross section of The Geysers geothermal field based on data from McLaughlin (1981), Unocal Corporation et al. (1992), Walters et al. (1992), Kennedy and Truesdell (1996) and Lowenstern et al. (1999a). The illustrated well depths demonstrate the general trend of increasing well depth towards the northwest. The felsite intrusion has been sampled only in the Southeast and Central Geysers. The placement of the post-felsite intrusion to the northwest is speculative.

Fig. 3. Log H_2/H_2O vs. T for bulk well discharges from The Geysers steam field. For simplicity, all samples are plotted at $250 \pm 50^\circ C$. Mineral and gas buffers from Giggenbach (1987: Figure 4). Analyses of samples from production wells plot throughout the gray box. The figure demonstrates great heterogeneity of H_2/H_2O for bulk well discharges from The Geysers. Variations in H_2/H_2O likely reflect differing Y (steam fractions). By accounting for Y (see text) the composition of the equilibrium vapor can be calculated, and has a much more limited H_2/H_2O (values calculated with YI). The location of the arrows has no temperature implications.

Fig. 4. Log (CH_4/CO_2) vs. log ($\text{H}_2/\text{H}_2\text{O}$) of well discharges from The Geysers. The closed circles denote the compositions of total fluid flowing through the well and collected at the wellhead. The three gray squares represent the calculated compositions of reservoir vapor assuming boiling conditions in equilibrium with calcite, K-feldspar and K-mica and three different oxidation states: Mt-Hm (magnetite-hematite), the “rock buffer” of Giggenbach (1987), and QFM (quartz-fayalite-magnetite). Samples from The Geysers do not follow the trend expected for varying oxidation state at relatively constant temperature.

Fig. 5. Log (CH_4/CO_2) vs. log ($\text{H}_2/\text{H}_2\text{O}$) of well discharges from The Geysers. As in Fig. 4, the data represent total steam plus condensate flowing through the well and collected at the wellhead. As explained in the text, the bold lines represent the theoretical composition of reservoir liquid and vapor under saturated conditions in equilibrium with calcite, K-feldspar and K-mica at an oxidation state similar to that of the “rock buffer” (Giggenbach, 1980; Chiodini and Marini, 1998). The dashed lines represent the compositions of isothermal mixing lines between liquids and vapors under the above-stated conditions. The Geysers samples appear to represent mixtures of reservoir steam and an equilibrium liquid that boils either during flow to the well or during ascent to the wellhead.

Fig. 6. **A)** $Y1$ versus $Y2$ as defined in the text. $Y1$ is calculated by the method of D'Amore et al. (1982), whereas $Y2$ arbitrarily fixes the oxidation state of reservoir vapor as equal to the well discharge with the highest H_2/H_2O . **B)** H_2S/N_2 in the calculated reservoir vapor as estimated using $Y1$ and $Y2$. The trendline represents perfect agreement between H_2S/N_2 calculated with $Y1$ and $Y2$. There is general agreement between the two methods except for samples with low Y .

Fig. 7. Mole percent H_2S , NH_3 and CO_2 in the computed reservoir vapor (including H_2O) versus $Y2$. All three gases increase in relative abundance in samples with the highest steam fraction. High total concentrations of all gases are emitted from the high Y wells because they contain more reservoir vapor, and thus more gas.

Fig. 8. Mol percent H_2S versus H_2 , each relative to all non-condensable gas from calculated reservoir vapor. Throughout the geothermal field, these two gases are positively correlated. The bubble area is proportional to $Y2$. Samples from the Southeast Geysers are low in Y and highest in H_2S and H_2 , on an H_2O -free basis.

Fig. 9. **(A)** Mol percent N_2 , **(B)** H_2S and **(C)** CH_4 versus $Y2$ steam fraction. Each gas computed relative to all non-condensable gases in the calculated reservoir vapor. For each gas, values converge around a single typical gas concentration at high $Y2$. In contrast, the low $Y2$ samples have extremely variable vapor compositions. This implies a relatively homogeneous source of gas to The Geysers reservoir.

Fig. 10. δD vs. $\delta^{18}O$ of steam from The Geysers well discharges. Samples from wells of the Southeast Geysers plot close to the global meteoric water line (Craig, 1961) and local meteoric water (gray ellipse; Gunderson, 1992), as do some samples from the Central Geysers. Some of these wells plot on a trend toward injection-derived condensate. Samples from the Northwest Geysers form a trend toward an isotopically heavy end-member similar to connate waters of the Clear Lake region (Wilbur Springs and Sulphur Bank; White et al., 1973) or volcanic/igneous waters (Taylor, 1979; Giggenbach, 1992a).

Fig. 11. N_2/Ar versus $1/Ar$ for total well discharges. Nearly all samples have N_2/Ar greater than air or air-saturated meteoric water. However, N_2 is correlated with $1/Ar$, demonstrating that the high- N_2/Ar gases are not particularly N_2 -rich.

Fig. 12. Mol percent CH_4 versus N_2 relative to non-condensable gases within the calculated reservoir vapor from the Northwest Geysers and Unit 15.

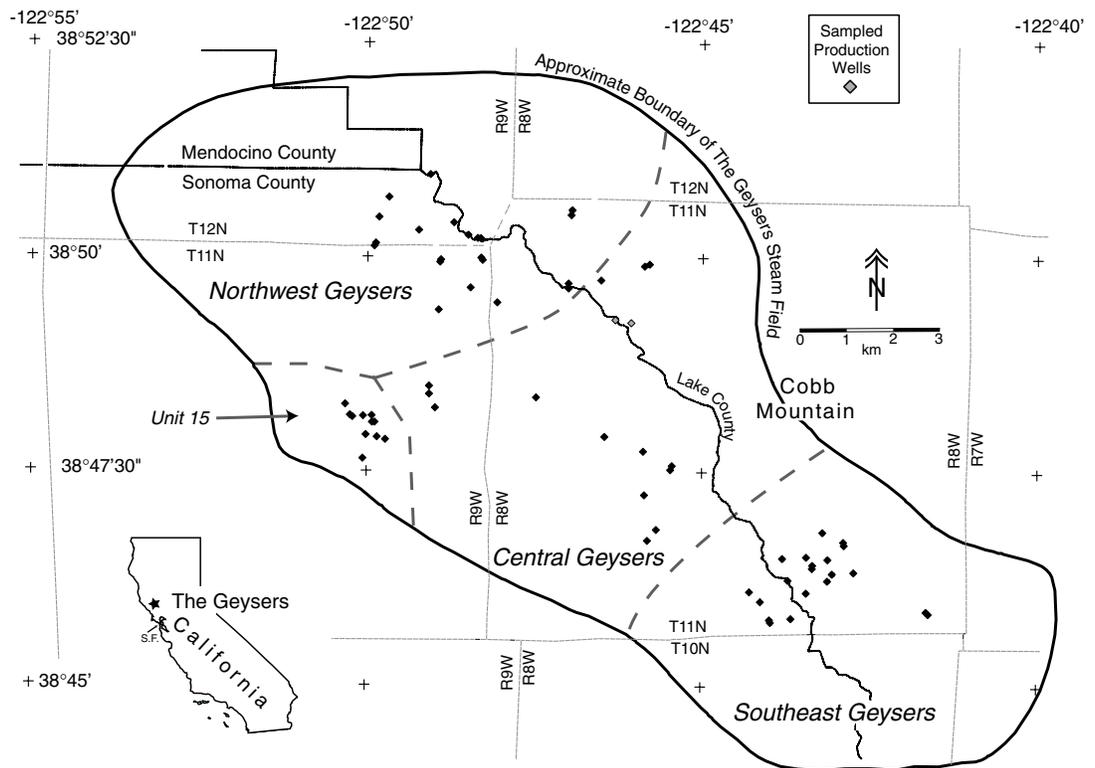


Figure 1: Lowenstern and Janik

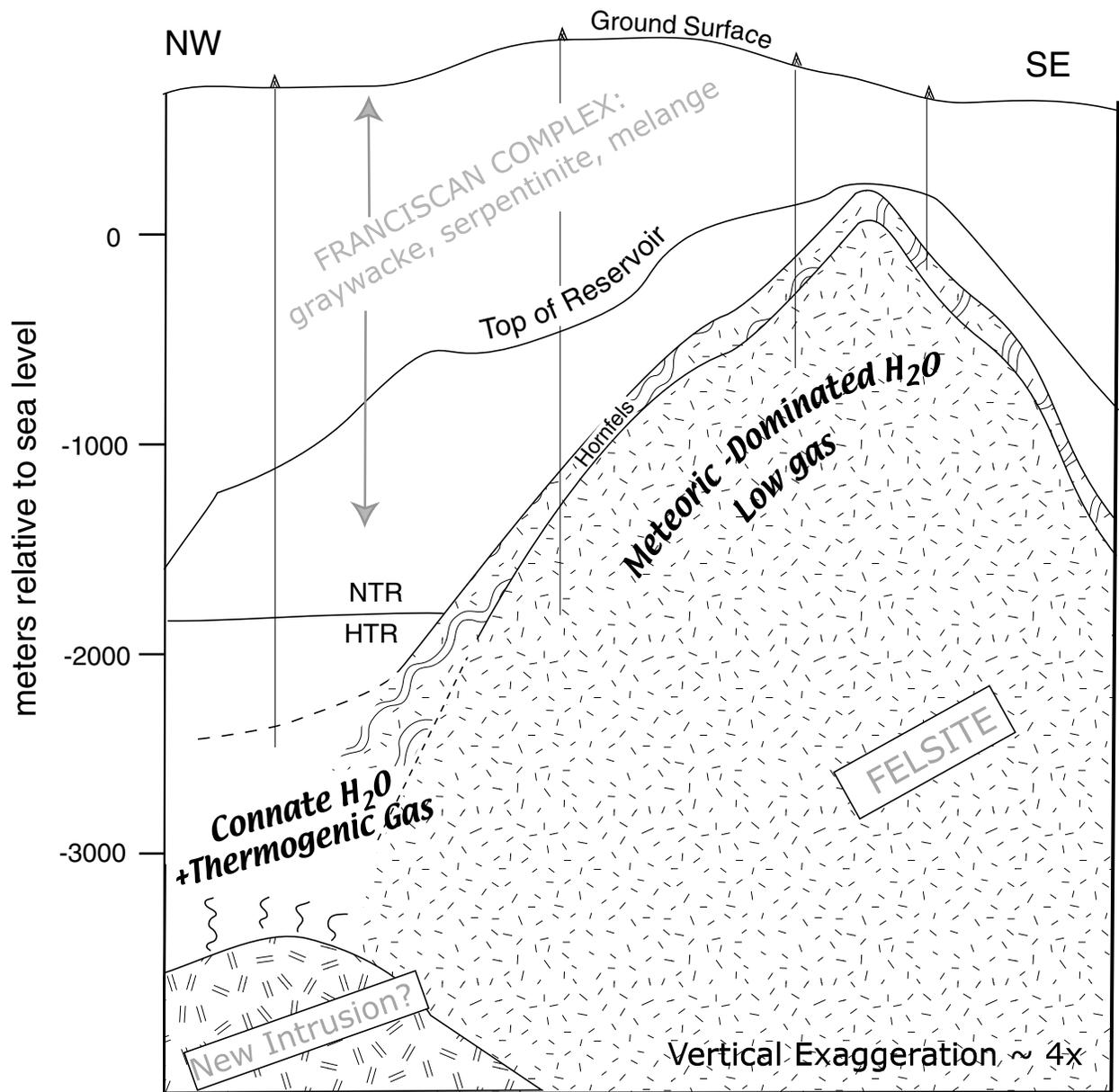


Figure 2: Lowenstern and Janik

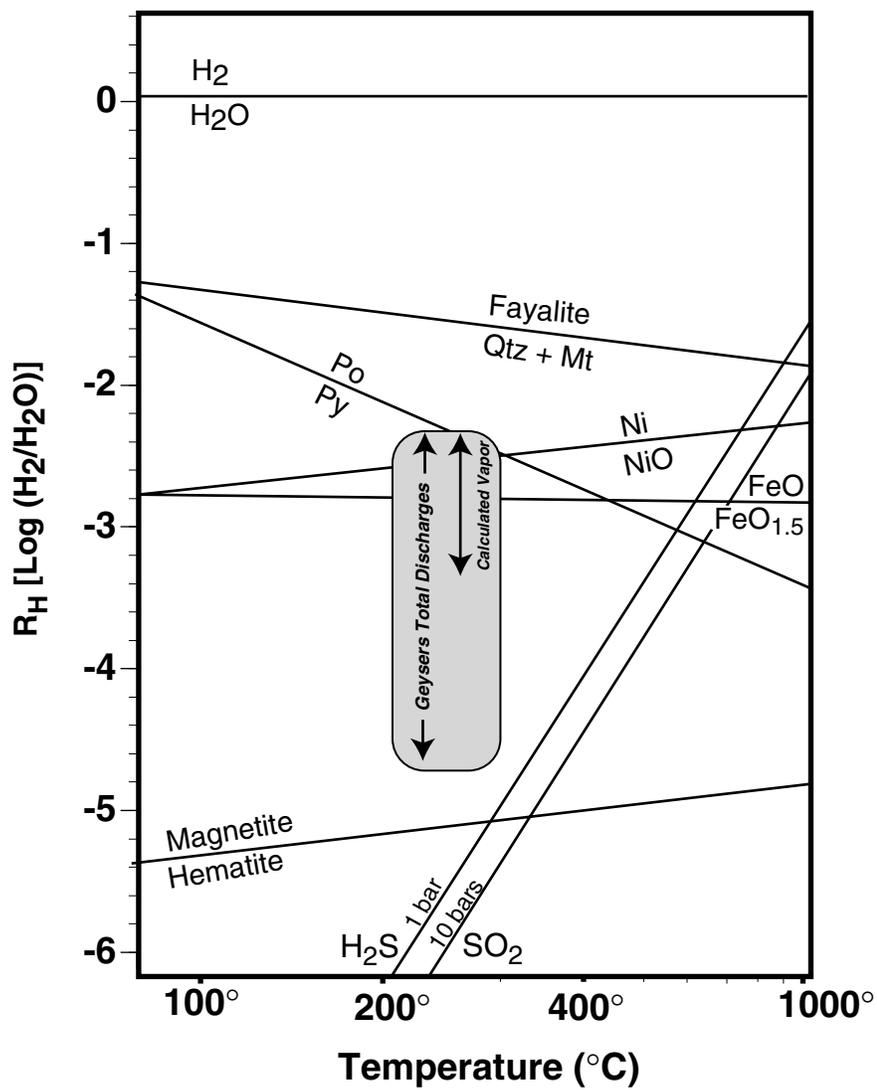


Figure 3: Lowenstern and Janik

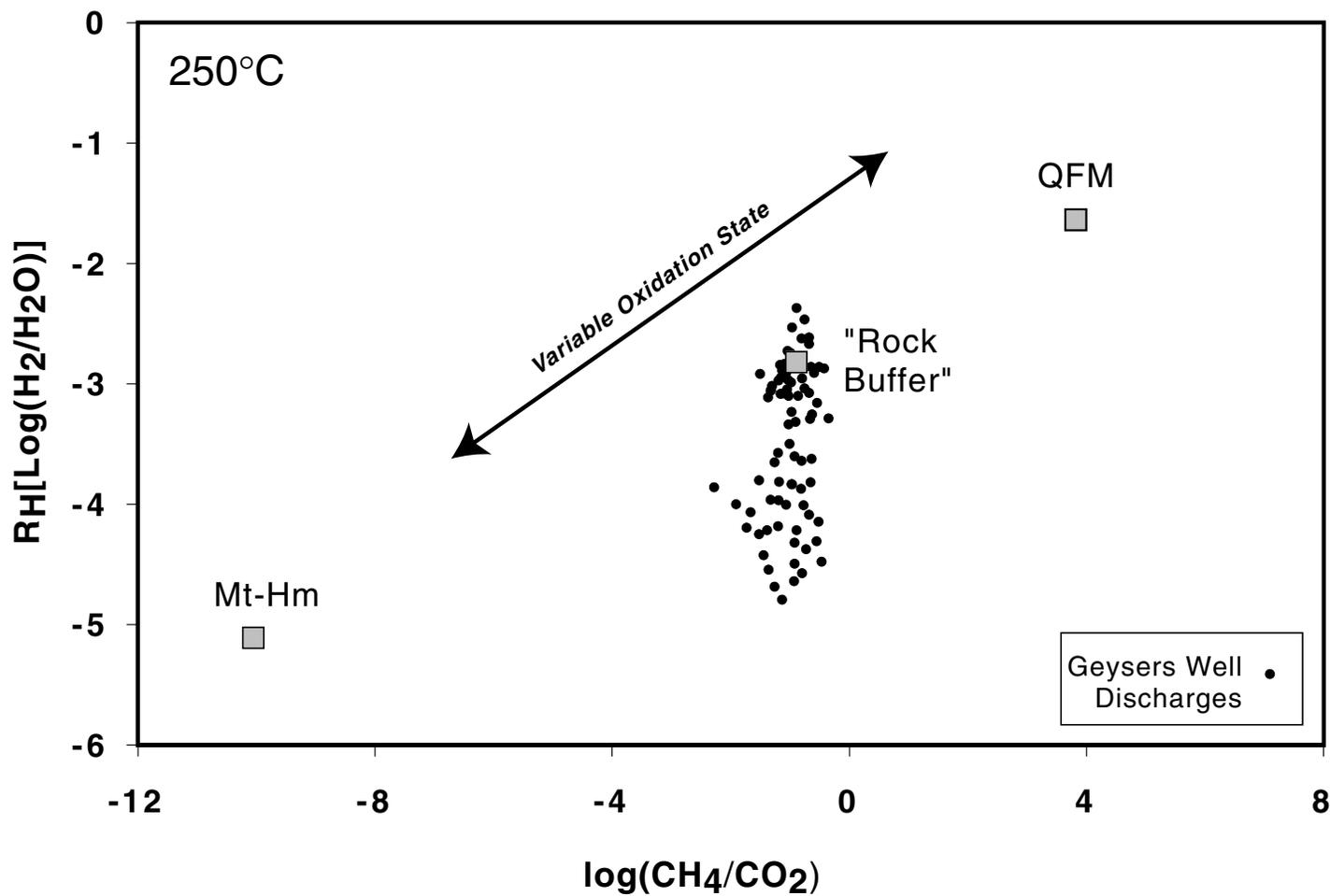


Figure 4: Lowenstern and Janik

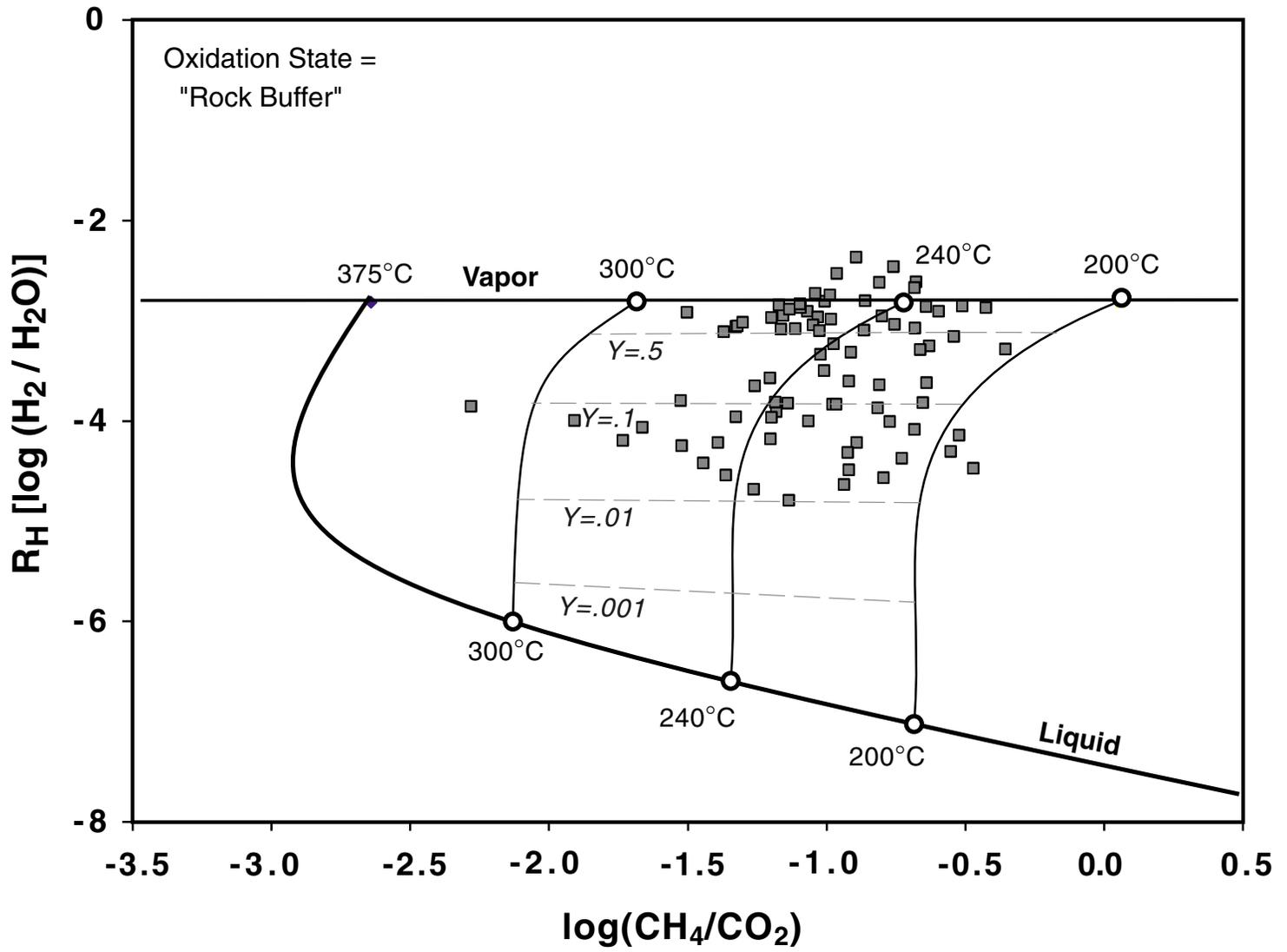


Figure 5: Lowenstern and Janik

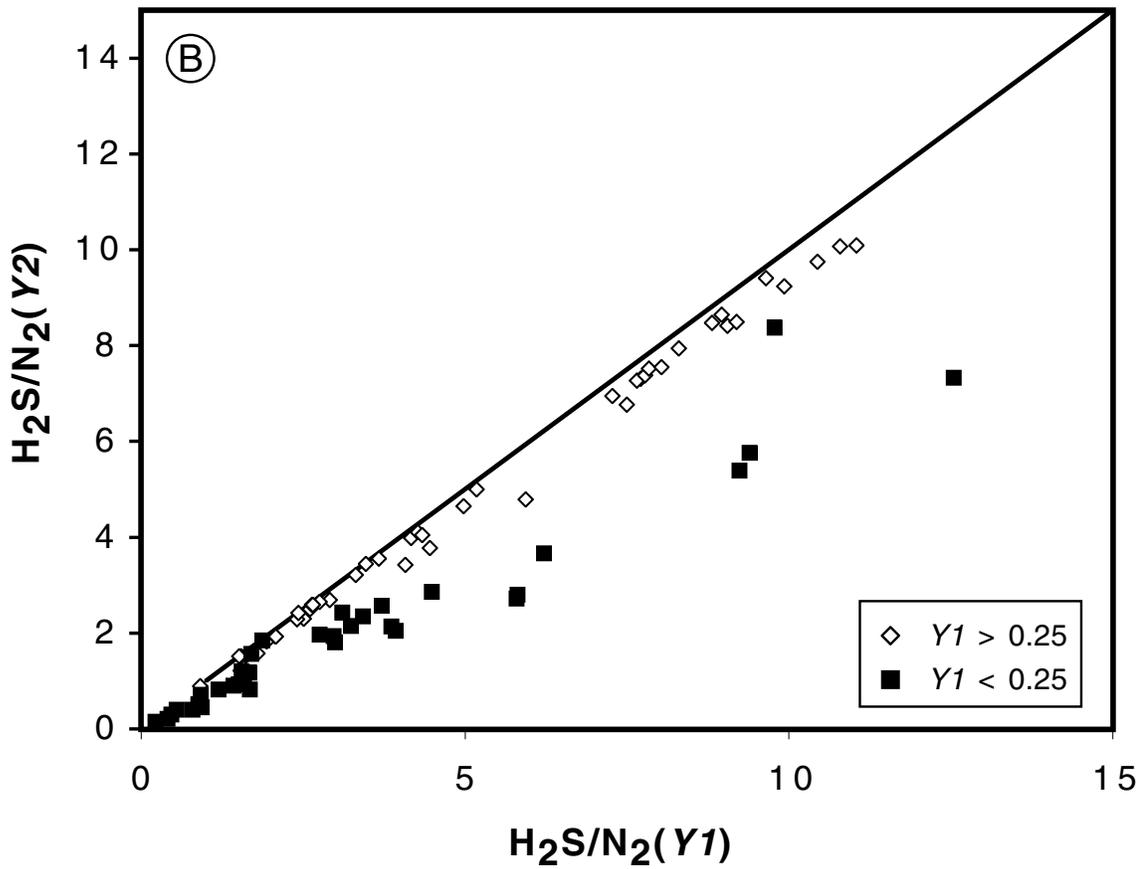
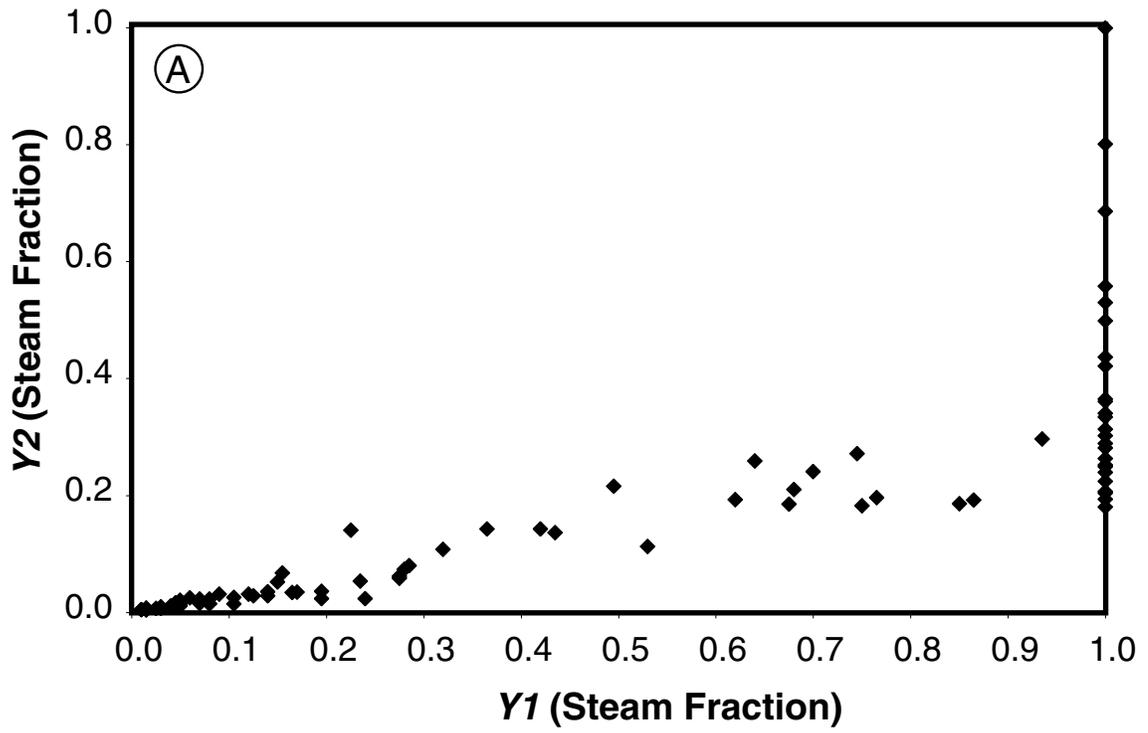


Figure 6: Lowenstern and Janik

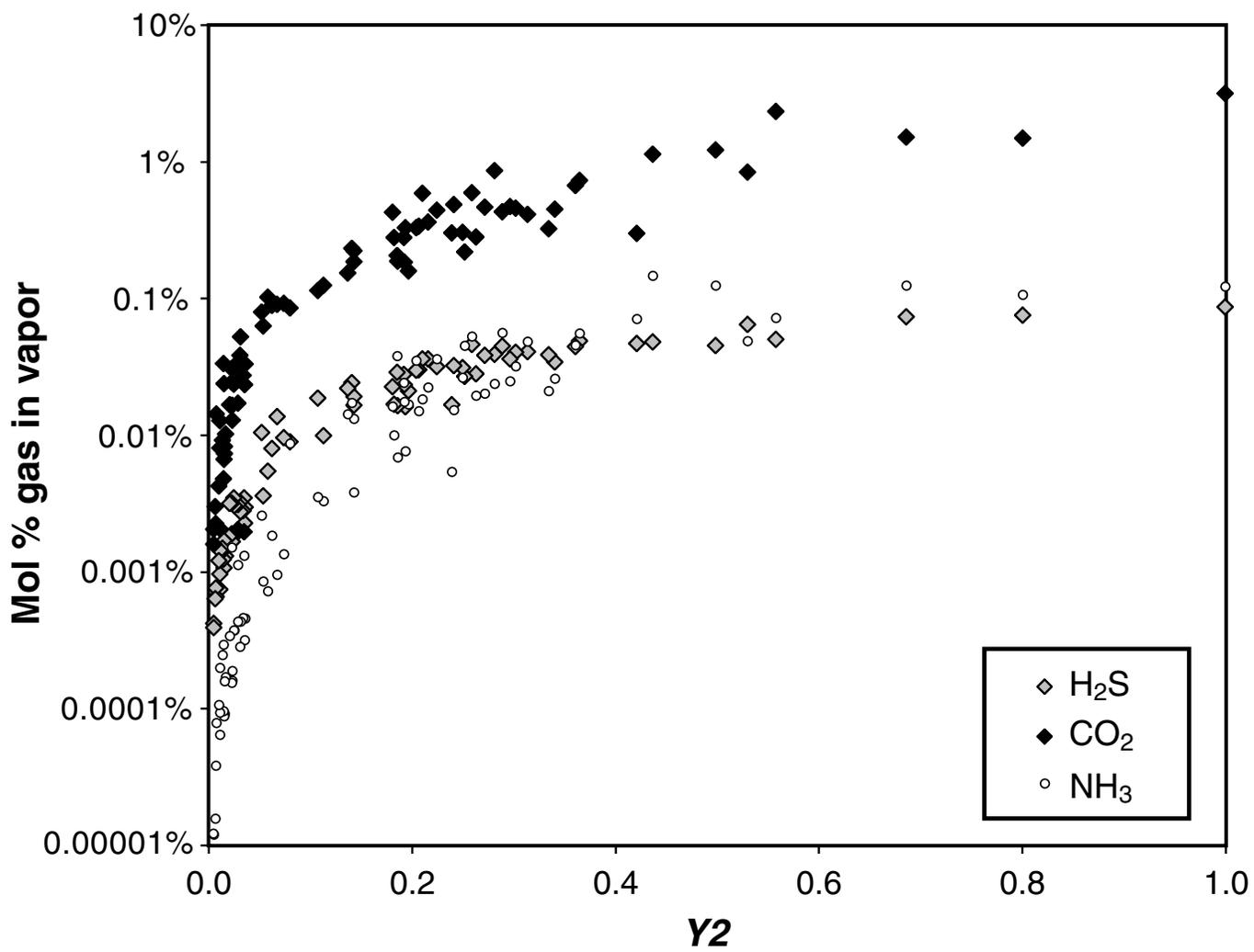


Figure 7: Lowenstern and Janik

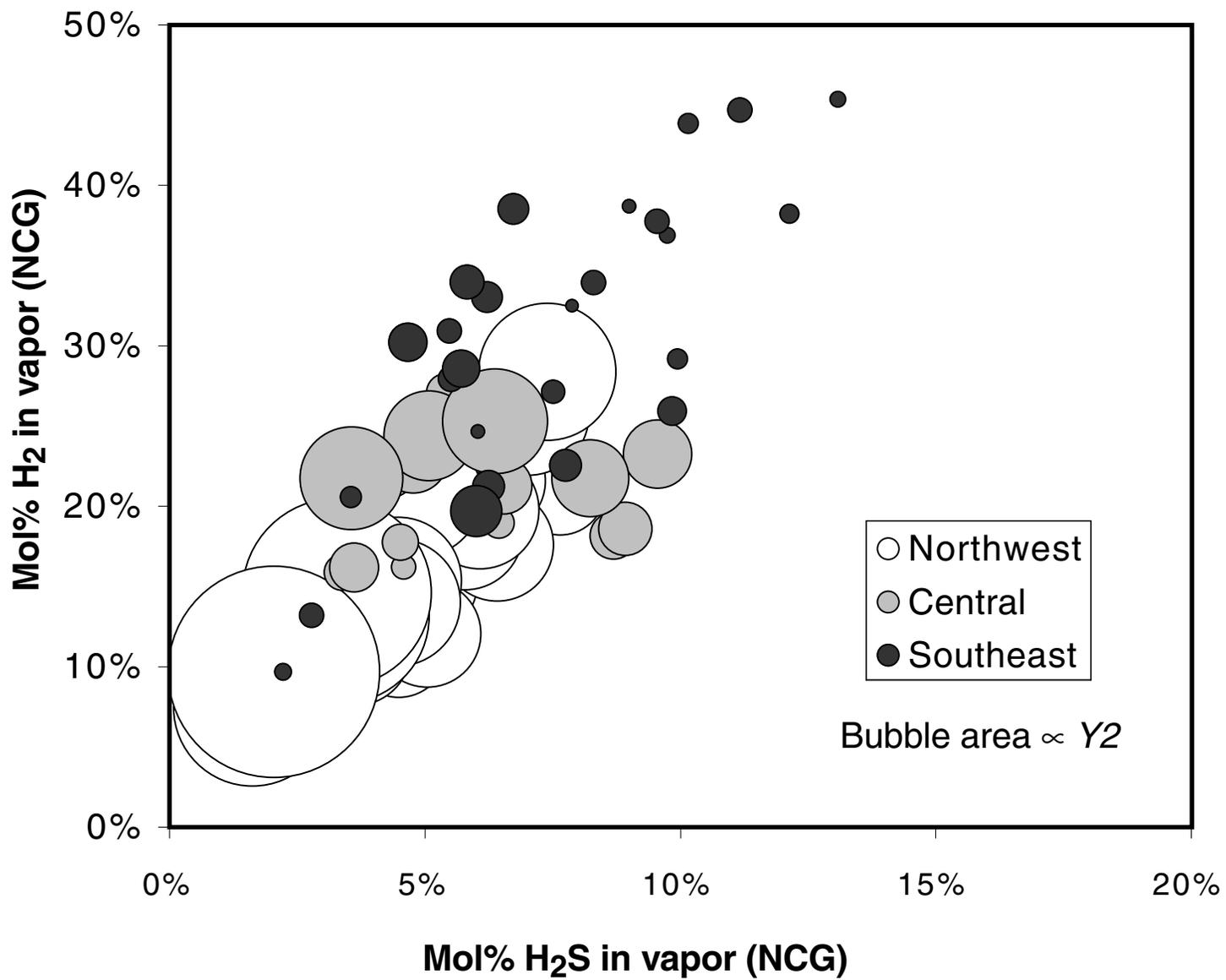


Figure 8: Lowenstern and Janik

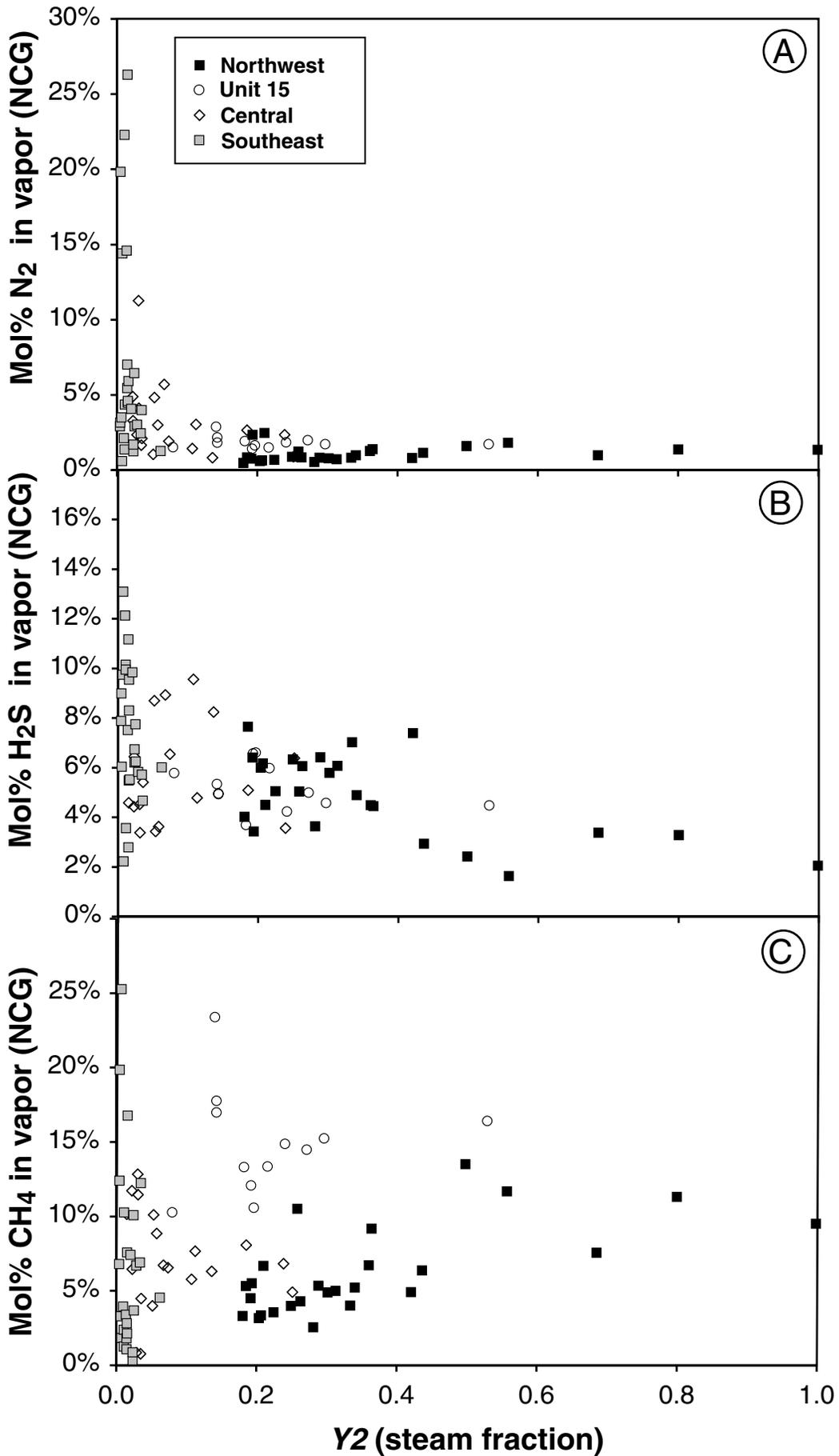


Figure 9: Lowenstern and Janik

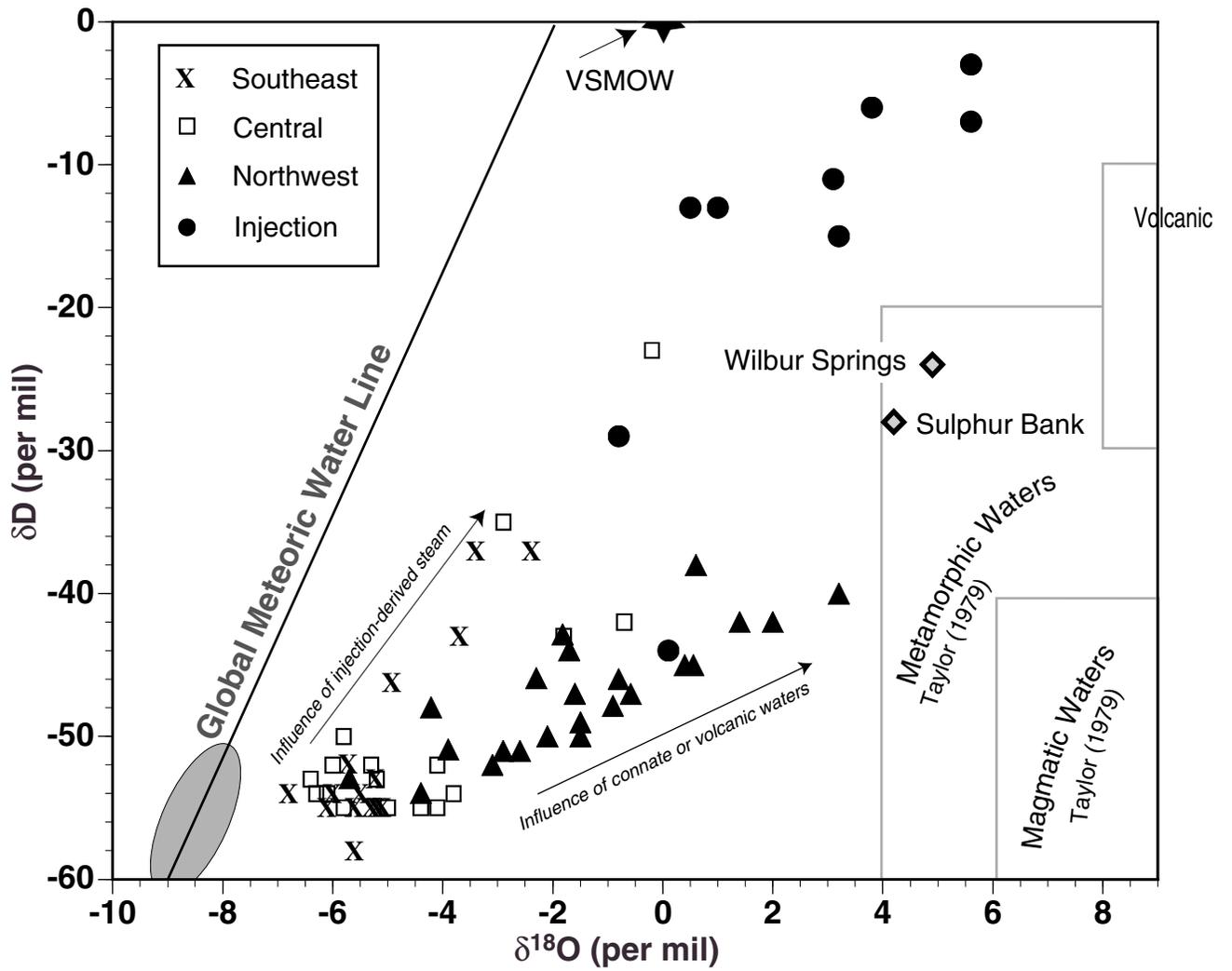


Figure 10: Lowenstern and Janik

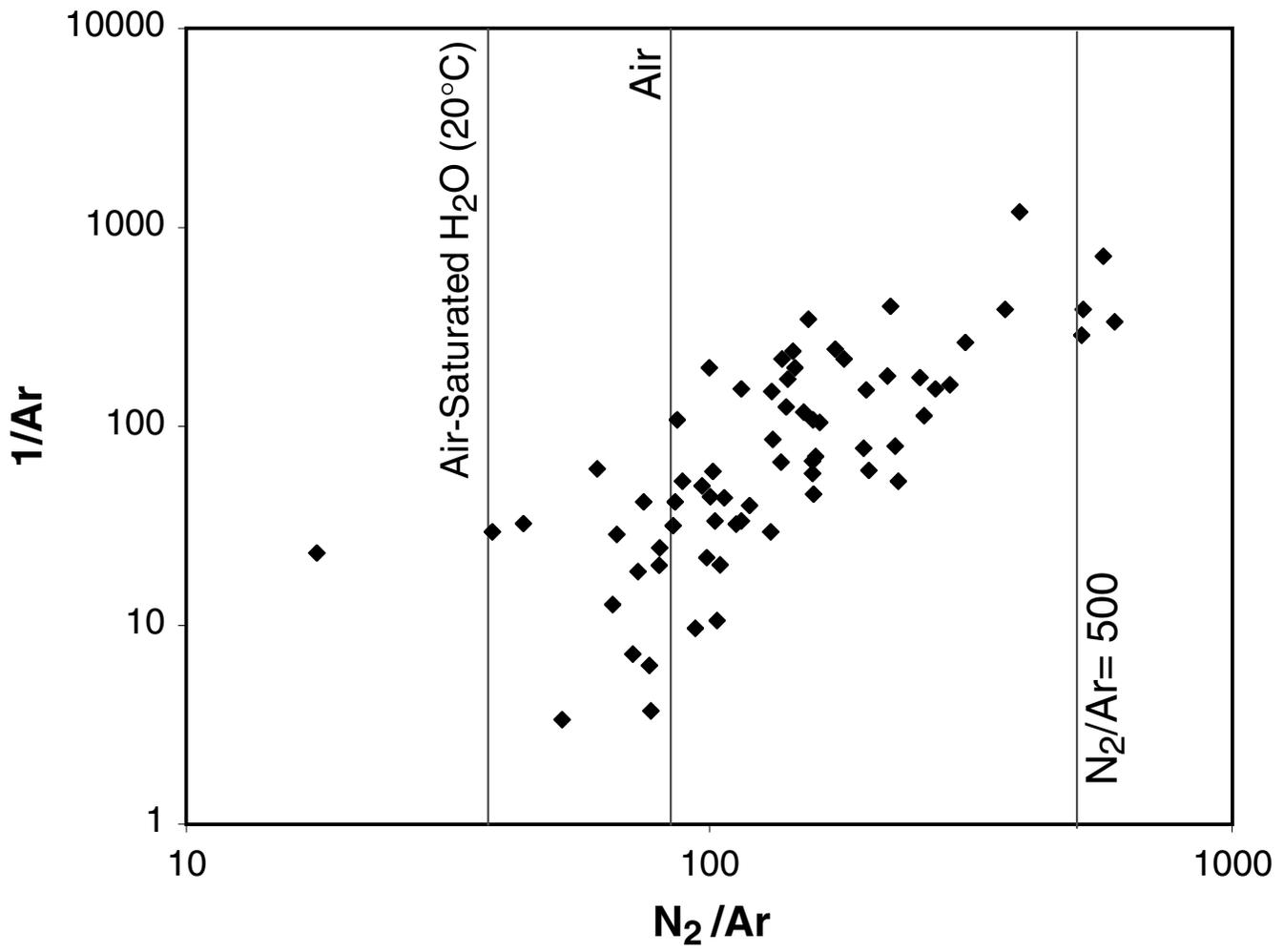


Figure 11: Lowenstern and Janik

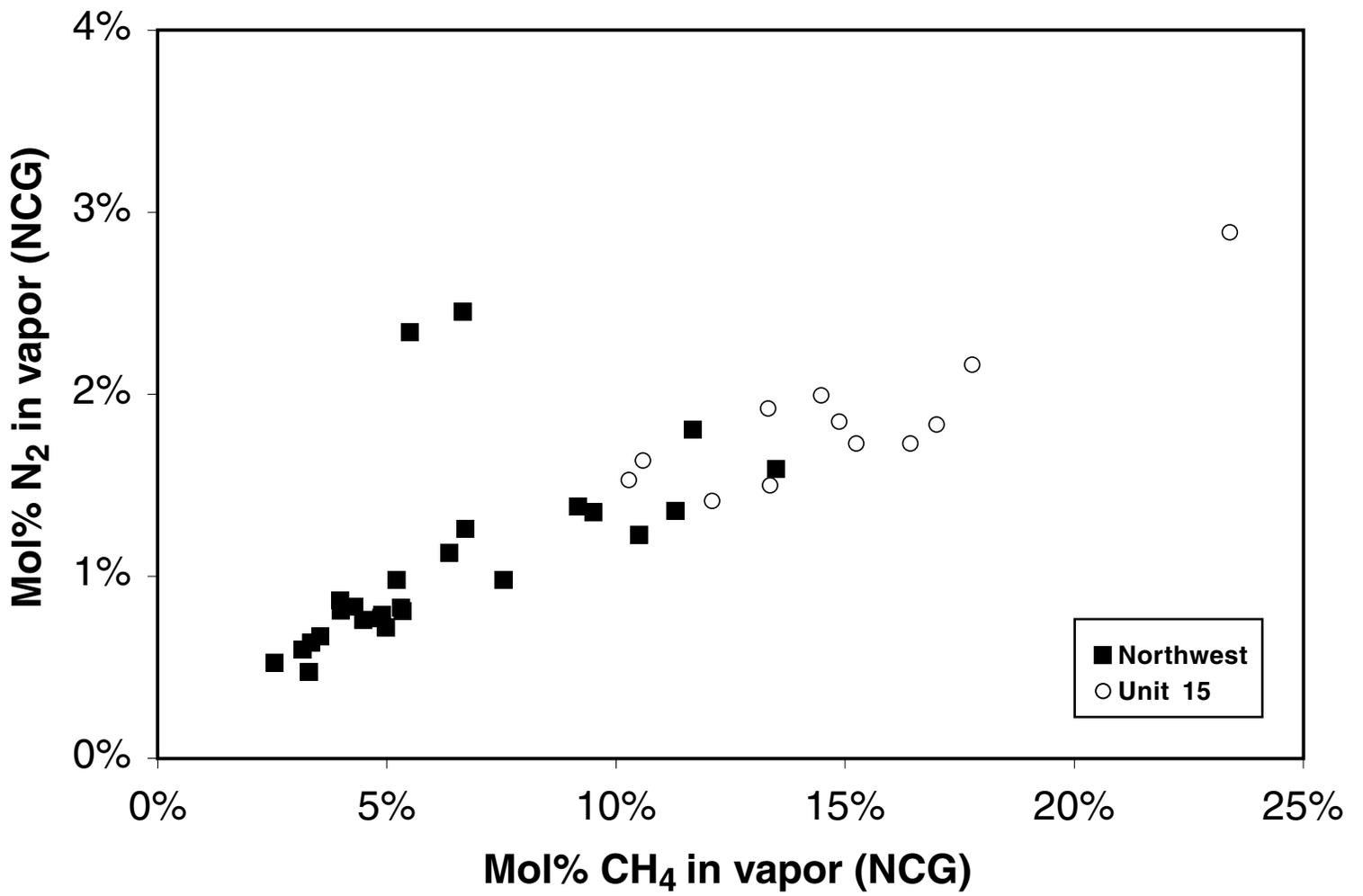


Figure 12: Lowenstern and Janik

Table 1. Gas geochemistry of representative samples from The Geysers

Sample#	Well	Region	Steam/Gas * (molar ratio)	CO2 mol% [†]	H2S mol%	H2 mol%	Ar mol%	N2 mol%	CH4 mol%	NH3 mol%	N2/Ar	Y1	Y2	δD H2O (per mil)	δ ¹⁸ O H2O (per mil)	δ ¹³ C CO2 (per mil)
G78-05	LF State 4597-18 (Lakoma Fame)	C	593	59.2	10.3	17.2	0.050	5.23	6.24	2.06	105	0.15	0.068	-54	-6.1	-12.4
G78-07	LF State 4597-16 (Lakoma Fame)	C	1915	66.3	7.31	12.5	0.017	3.37	7.96	2.23	202	0.04	0.015	-55	-5.0	-13.2
G81-01	D&V-A1 (Dillingham & Vought)	S	3870	51.1	15.3	18.3	0.006	0.82	1.54	13.90	141	0.04	0.011	-54	-6.0	
G81-03	CA 958-37-34 (956#3)	S	9311	54.3	17.8	17.9	0.009	1.47	3.97	4.92	158	0.01	0.004	-55	-5.6	
G81-04	CA 958-37A-34	S	11138	43.2	21.4	23.8	0.006	1.79	8.06	0.37	289	0.01	0.005	-55	-5.1	
G81-05	D&V-A3 (Dillingham & Vought)	S	5647	40.8	20.0	24.4	0.009	1.29	2.59	11.90	152	0.03	0.010	-58	-5.6	
G81-09	Thorne 6	S	2266	50.4	13.8	20.1	0.030	3.08	5.83	7.76	103	0.05	0.021	-53	-6.8	
G81-13	Thorne 3	S	1724	51.9	10.6	18.4	0.079	5.17	8.33	5.46	65	0.06	0.025	-47	-4.9	
G81-16	McKinley 3	S	5271	37.4	17.7	33.4	0.054	3.95	0.81	7.02	73	0.08	0.015	-53	-6.1	
G81-17	MLM1	S	3894	46.6	13.2	26.3	0.030	3.46	5.98	4.64	115	0.05	0.016	-53		
A86-4	Rorabaugh A-7 (Unit 15)	U	158	59.1	6.14	14.7	0.01	1.44	12.9	6.01	253	0.49	0.216			-12.5
A86-6	Rorabaugh A-10 (Unit 15)	U	126	63.4	4.37	13.1	0.00	1.81	14.6	3.10	516	0.70	0.241			-12.4
A86-8	Rorabaugh A-18 (Unit 15)	U	205	49.8	5.55	12.4	0.03	2.70	22.0	7.63	85	0.22	0.141			
A86-9	Rorabaugh A-22 (Unit 15)	U	239	55.6	5.14	14.7	0.02	1.72	16.0	6.75	102	0.36	0.143			-12.2
A86-10	Rorabaugh A-27 (Unit 15)	U	211	61.3	3.87	16.5	bdl	1.86	12.9	3.93		0.75	0.182			-13.3
A86-11	Filley1	U	68	58.3	4.53	15.5	bdl	1.72	16.3	3.95		1.00	0.530			
A87-1	McKinley-3	S	3143	52.7	9.50	31.5	0.0164	1.00	0.28	5.36	61	0.24	0.023			
A87-2	Abel 1	S	2276	48.5	7.68	28.2	0.0230	2.460	5.62	7.35	107	0.14	0.029			
G88-6	Prati State 24	N	193	60.4	6.41	20.7	0.0046	0.83	3.83	8.10	181	1.00	0.250	-49	-1.5	-12.9
G88-7	Prati 38	N	87	65.1	4.48	13.7	0.0026	1.35	8.98	6.56	519	1.00	0.365	-51		-12.1
G88-8	Prati 25	N	31	74.8	1.63	7.4	0.0030	1.79	11.58	2.65	597	1.00	0.558	-49		-11.8
G88-13	CA 956A 56-34 (956#2)	S	3093	44.9	8.70	22.1	0.046	4.55	13.51	6.49	99	0.04	0.017	-54		-14.2
G88-16	Davies Est. 5	S	1351	65.6	3.79	8.6	0.034	4.460	1.21	5.3	131	0.11	0.015	-58		-12.8
G90-02	Ottoboni St.4596 -15	N	207	59.6	6.17	23.4	bdl	0.806	4.17	6.25		1.00	0.263	-48	-0.9	-12.4
G90-03	Ottoboni St.4596-14	N	214	61.8	6.48	17.6	0.004	0.7144	4.23	9.38	174	0.86	0.192	-43	-1.8	-12.7
G90-04	D.X. (Delta Xagon) 4596 -45	N	167	74.1	4.13	13.0	0.003	0.45	3.16	5.05	155	1.00	0.181	-51	-3.9	-11.8
G90-05	L'Esperance 2 (LESP-2)	N	204	69.4	3.58	17.0	0.014	2.27	5.36	2.82	160	1.00	0.194	-48	-4.2	-12.3
G90-06	GD Horner State 4596-9	C	849	60.0	4.12	19.5	0.019	4.37	9.30	3.17	230	0.23	0.054	-55	-4.4	-13.3
G90-07	NE Geysers Unit (NEGU) 15	C	598	68.3	4.29	14.9	0.017	2.73	8.2	1.76	158	0.27	0.058	-54	-3.8	-13.1
G90-10	Sulphur Bank -15	C	339	54.5	8.39	19.9	0.005	0.744	5.78	10.75	146	0.43	0.137	-42	-0.7	-13.1
G90-12	CA State 92-6	N	119	72.2	4.63	10.7	0.015	2.368	6.46	3.74	158	0.68	0.210	-53	-5.7	-11.8
G90-14	NE Geysers Unit (NEGU) 17	C	208	64.5	3.70	21.4	0.009	2.30	6.70	1.82	258	1.00	0.239	-52	-6.0	-13.0
G90-15	GD Horner State 4596-7	C	297	57.3	5.31	23.6	0.013	2.55	7.82	3.8	198	0.85	0.186	-53	-5.2	-13.3
G90-17	D.X. (Delta Xagon) State 4596-87	C	450	59.5	5.2	21.8	0.013	2.86	7.29	3.71	227	0.53	0.113	-55	-4.1	-13.2
G90-19	Angeli 3	C	622	62.4	7.42	19.7	0.007	1.76	6.1	2.86	271	0.28	0.074	-55	-5.8	-13.1
G90-21	Beigel 3	C	1850	59.0	6.43	18.1	0.050	4.02	9.99	2.61	80	0.08	0.023	-50	-5.8	-13.1
G91-01	Prati 37	N	42	64.8	3.29	14.6	bdl	1.356	11.29	4.87		1.00	0.800	-42	1.4	-12.5
G91-05	Prati State 12	N	142	59.8	6.09	19.1	bdl	0.691	4.82	9.80		1.00	0.313	-45	0.4	-12.5
G91-07	Prati State 54	N	138	64.6	5.85	17.9	bdl	0.746	4.74	6.37		1.00	0.302	-50	-1.5	-12.4
G91-08	Prati 27	N	58	68.1	2.92	10.9	bdl	1.098	6.21	10.78		1.00	0.437	-46	-0.8	-12.3
G91-09	Prati 39	N	45	69.0	3.38	13.1	bdl	0.973	7.51	6.15		1.00	0.686	-40	3.2	-12.2
G91-10	Prati 25	N	23	74.6	2.04	9.7	bdl	1.351	9.51	2.88		1.00	0.999	-42	2.0	-12.3
G91-11	Prati State 01	N	186	63.0	6.00	16.2	0.003	0.556	2.96	11.36	222	1.00	0.204	-51	-2.6	-12.5
G91-13	Prati 14	N	149	67.7	5.09	14.4	0.005	0.634	3.37	8.96	138	1.00	0.224	-51	-2.9	-12.6
G91-14	Prati 50	N	139	63.9	4.96	20.3	0.003	0.959	5.12	4.96	369	1.00	0.341	-47	-1.6	-12.4

*C=Central, N= Northwest, S=Southeast, U= Unit 15

†All gases reported as mol % of non-condensable gases in the total well discharge.