

FLUID-INCLUSION GAS CHEMISTRY OF THE DIXIE VALLEY (NV) GEOTHERMAL SYSTEM

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ABSTRACT

Hydrothermally altered samples from outcrops along the eastern Stillwater Range (NV), and scale and vein samples from Dixie Valley geothermal wells were collected for fluid-inclusion analyses. Fluid-inclusion microthermometry and gas analysis by quadrupole mass spectrometry were applied to establish the chemistry of the fluids trapped during alteration. Relationships between CO₂/CH₄, N₂/Ar, and H₂S were used to evaluate the origins of the inclusion fluids. Most geothermal vein samples from the wells are interpreted as mixtures of shallow meteoric and evolved meteoric ("crustal") fluids. Fluid-inclusion gases from epidote-bearing fault gouge appear to have a strong crustal signature (with low CO₂/CH₄ ratios). Hematite-bearing vein assemblages exhibit gas compositions that are oxidized (with high CO₂/CH₄ ratios), and meteoric (N₂/Ar = 50-100) in origin. Analyses with high N₂/Ar ratios (up to 300) indicate a magmatic origin for some fluid-inclusion gases. Actinolite-bearing veins associated with Miocene-age basaltic dikes contain mixtures of magmatic and meteoric gases. There also appears to be a small magmatic component to the gases in quartz-calcite veins from production wells. This result was unexpected because the Dixie Valley system is thought to be a deep-circulation, nonmagmatic geothermal system. However, vapor-rich fluid inclusions in production well scales and production fluids also contain some magmatic helium, and have slightly higher N₂/Ar ratios than gases with a purely meteoric origin.

INTRODUCTION AND GEOLOGIC SETTING

The Dixie Valley geothermal system in west-central Nevada is a typical deep-circulation, fault-related geothermal system. Wells a few kms south of the geothermal field produce the hottest (265- 275°C) fluids in the entire Basin and Range Province (Benoit, 1994; Blackwell et al., 2000). Permeable zones in production wells in the field are associated with the Dixie Valley fault, a large-displacement normal fault with a long history of activity. In the

southern Stillwater Range, up to 6 km of vertical displacement has been recorded along this fault system since the mid-Miocene (Parry et al., 1991). The Dixie Valley fault continues to be one of the most active fault systems in the Basin and Range Province (Bell and Katzer, 1987; Caskey et al., 1996; 2000a; Caskey and Wesnousky, 2000b). The fluids in the Dixie Valley geothermal system are dominantly meteoric in origin, and the source of the heat for the geothermal system is thought to be the deep circulation of fluids in an area of above average geothermal gradients (Williams et al., 1997; Blackwell et al., 2000). Isotopic studies of Dixie Valley production fluids have demonstrated that the fluids are essentially unexchanged meteoric water of late Pleistocene age (Nimz et al., 1999). However, gases collected at the wellheads appear to contain a small component of magmatic fluid. Elevated helium contents and helium isotopic signatures suggest that as much as 7.5 % of the helium may have a magmatic source. Therefore, at least some of the heat in the Dixie Valley geothermal system may be magmatic in origin (Kennedy et al., 1996).

In this paper, we examine the sources and chemistry of fluids trapped in alteration minerals and wellbore scales associated with the geothermal system and recorded by the fluid-inclusion gas compositions. The samples collected for analysis represent a variety of depth intervals, mineralogies, and alteration types. Outcrop samples collected from the Stillwater range front include silicified gouge from the Dixie Valley fault, corrensite-rich clay from range front fault splays, geothermal veins with variable amounts of quartz, calcite, dolomite, barite and hematite, fumarolic encrustations (gypsum), and fossil hot spring sinters and quartz breccias from the Dixie Comstock Mine (Vikre, 1994; Fig. 1). For comparison, actinolite-bearing veins associated with Miocene-age basaltic dikes were also sampled. In all, thirteen outcrop samples were analyzed, resulting in 133 fluid-inclusion gas analyses. Subsurface samples consist of vein fragments hand-picked from the cuttings of three geothermal wells and carbonate

scales from four production wells. These eleven samples yielded 93 gas analyses. The objectives of this study were to determine the importance and distribution of magmatic, crustal or meteoric derived volatiles during the evolution of the geothermal system.

METHODS

Major and minor gases, including H₂O, CO₂, CH₄, H₂S, H₂, N₂, Ar, and C₂₋₇ organic species contained in inclusions in alteration minerals and calcite scale deposits were analyzed with a Balzers QME 125 quadrupole mass spectrometer after being released from the inclusions by crushing (crush-fast-scan (CFS) method). Norman et al. (1996) have presented the details of this analytical technique.

The CFS method involves opening inclusions with a swift crush in a vacuum chamber housing the mass spectrometer. The volatiles are removed by the vacuum pumping system in 1 or 2 seconds and recorded by operating the quadrupole in a fast-scan mode with measurements taken every 150 to 225 milliseconds. Opening a 10-20 micron inclusion, or group of smaller inclusions of equivalent volume, provides the ideal amount of volatiles for CFS analysis. Five to 20 crushes can be made on a 0.2 g sample. Species routinely recorded are H₂, He, CH₄, H₂O, N₂, O₂, H₂S, Ar, C₃H₈, H₂, CO₂, and SO₂. The precision of the CFS analyses is <5 % for major gaseous species and about 10% for the minor species.

ALTERATION MINERALOGY

A long history of hydrothermal alteration is recorded in mineral assemblages exposed along the surface trace of the Dixie Valley fault. In southern Dixie Valley, alteration minerals and fluid-inclusion characteristics record over 25 my of hydrothermal alteration and the presence of a variety of different fluids along the fault, with salinities ranging from 0.1 to 39.2 wt % NaCl equivalent, homogenization temperatures from 120° to 400°C, and variable CO₂ contents (Parry et al., 1991). In northern Dixie Valley, hydrothermal alteration along the fault appears to be much younger. Here, the fluid inclusions record temperatures up to 325°C (but mostly below 250°C) and contain low salinity (<1.9 wt % NaCl equivalent), gas-poor liquids (Fig. 2, Lutz et al., 1998). Production fluids that power the 62 MW geothermal plant have temperatures near 240°C and salinities of 0.1-0.2 wt %. Based on isotopic and geochemical analyses, these geothermal fluids appear to be less than 13,000 years old (Nimz et al., 1999). Six hydrothermal alteration assemblages can be recognized in the production well cuttings samples. These assemblages consist of (from oldest to youngest): 1) epidote-chlorite-calcite; 2) illite

(sericite); 3) wairakite-quartz-calcite; 4) mixed-layer illite/smectite and calcite-quartz; 5) chalcedony-dolomite-calcite-barite-chlorite/smectite-hematite; and 6) quartz-calcite (Lutz et al., 1997; 1998). The variety of mineral assemblages suggests that chemically-distinct fluids from different sources have been active along the fault system at different times.

In general, four geothermal alteration assemblages are found in outcrops along the eastern Stillwater range front adjacent to the geothermal field: 1) calcite-dolomite-hematite-barite veins and travertine deposits; 2) quartz-rich fault breccias and sinter deposits; 3) travertine and calcite veins, and 4) gypsum-kaolin-halite fumarole encrustations. The sinters are fossil hot spring deposits that occur along the surface trace of the Dixie Valley fault in an area where fumaroles are now active (see Section 10/15 area in Fig. 1; Lutz et al., this volume). The mineralogy of the Stage 1 travertine and Stage 2 sinter deposits is similar to vein assemblages 5 and 6, respectively, in the geothermal reservoir (see previous discussion) and suggests that these are surface-subsurface expressions of the same hydrothermal event at different depths along the Dixie Valley fault. It can be difficult to tie individual calcite vein fragments in the well cuttings to these stages of alteration. However, samples from well 52-18 at 8030 and 9300 ft (2450 and 2835 m) contain dolomite, hematite and barite and probably represent Stage 1 veins. Prismatic quartz from well 73B-7 at 8783 and 8876 ft (2677 and 2705 m) may represent Stage 2 veins; these veins occur in a currently productive splay of the fault system in this production well.

The alteration assemblages represent two major stages of hydrothermal activity related to the present geothermal system. The oldest is the calcite-dolomite-hematite-barite assemblage that appears to predate strong quartz alteration at the Dixie Comstock Mine (Vikre, 1994), the Mirrors locality, and in geothermal well cuttings (Lutz et al., 1997; 1998). Radiocarbon dating of organic material in the travertine and sinter deposits suggests that the calcite-dolomite-hematite-barite assemblage may be about 5040 years old, whereas young opaline sinters (and associated subsurface quartz veins) may range in age from modern to 3450 years old (Lutz et al., this volume).

FLUID-INCLUSION GAS CHEMISTRY

Fig. 3 shows the results of fluid-inclusion gas analyses for selected outcrop and well cuttings samples. The data are plotted on a diagram developed by Norman et al. (1998) that uses CO₂/CH₄ vs. N₂/Ar to differentiate fluid inclusion gases into fields that include magmatic, shallow

meteoric, evolved meteoric (crustal), and crustal-organic zones.

CO₂/CH₄ - N₂/Ar Relationships

Norman et al. (1996) demonstrated that the ratios of CH₄, N₂, and Ar are useful indicators for tracing the sources of gases trapped in fluid inclusions. They argued that hydrothermal fluids derived from meteoric waters will have N₂/Ar ratios between those of air (84) and air-saturated water (36) although boiling will expand this range slightly because of differences in the solubilities of the two gases. Meteoric fluids that have boiled can have N₂/Ar ratios that range from about 100 to 15, depending on whether the inclusions trapped the gas-depleted liquid or the steam (Norman et al., 1997). Fluids from active Basin and Range geothermal systems have N₂/Ar ratios up to about 100 or 150 (Welhan et al., 1988). Crustal fluids (those which are not involved in the meteorological cycle) are typically enriched in CH₄ and other hydrocarbons. Hydrothermal fluids may accumulate CH₄ through thermal degradation of organic material, and/or oxidation-reduction reactions involving iron-bearing minerals and CO₂ (Giggenbach, 1992). Magmatic gases are distinguished by low CH₄ contents, high ³He/⁴He isotopic ratios, and N₂/Ar ratios exceeding 100 (Giggenbach, 1986; Norman and Musgrave, 1995; Norman et al., 1996).

The fluid-inclusion gas chemistry of the Dixie Valley samples in Figure 3 indicates the mixing between three end-member fluids; shallow meteoric, evolved meteoric, and magmatic. Most vein samples from the geothermal wells are interpreted as mixtures of shallow meteoric and evolved meteoric ("crustal") fluids that have N₂/Ar ratios between 40 and 100. Hematite-bearing vein assemblages exhibit gas compositions that are oxidized (with CO₂ contents of 4.4 mol % and high CO₂/CH₄ ratios), and meteoric (N₂/Ar = 50-100) in origin (Fig. 4). Fluid-inclusion gases from epidote-bearing fault gouge appear to have the strongest crustal signature with high methane contents (up to 2.2 mol % CH₄) and low CO₂/CH₄ ratios (Fig. 5). Actinolite-bearing veins associated with Miocene-age basaltic dikes contain mixtures of magmatic and meteoric gases (Fig. 6). Analyses with high N₂/Ar ratios (up to 300) indicate a magmatic origin for these fluid-inclusion gases.

Gases from several of the samples from the geothermal wells record mixing between crustal and magmatic fluids. Quartz veins from 9750 ft (2972 m) in well 52-18 and quartz-calcite veins from 8783 ft (2677 m) in well 73B-7 (Fig. 7) show a mixing trend between evolved meteoric fluids with high CH₄ contents (as much as 1 mol %) and magmatic fluids with high N₂/Ar ratios (up to 276). The vein sample from well 73-7 consists of very fine prismatic quartz

that appears to have been deposited in a productive fault which is parallel to the main range front fault. The fluid inclusions in these quartz crystals may represent modern geothermal gases.

In the following sections we relate the differences in gas compositions to the effects of mixing between fluids of different origins.

He- N₂ -Ar Relationships

The helium compositions of geothermal and volcanic systems have been studied by Giggenbach (1992, 1995). In these studies, the end-member compositions for various types of volcanic gases were related to their geological setting (e.g. andesitic or basaltic volcanoes and their associated geothermal systems). Basaltic systems are characteristic of rift (New Zealand, Iceland) and hot spot (Hawaii) tectonic settings. The andesitic systems are from a variety of continental and oceanic convergent plate environments associated with subduction complexes. Giggenbach attributes a large range in andesite gas compositions and high N₂ contents to assimilation of marine sedimentary crust during ascent of the magma. In both andesitic and basaltic systems, geothermal fluids (both liquid and gases) mix with air-saturated groundwaters (ASW in Fig. 8).

Welhan et al. (1988) studied the gas compositions of Basin and Range geothermal systems and basaltic to andesitic volcanoes from western North America. The study revealed that the gases from Basin and Range hot-spring systems follow the basalt or continental line that ranges from predominantly meteoric in origin, to more evolved fluids that have high He contents (Fig. 8). An analysis of the Beowawe (NV) geothermal field was included. This analysis plots near the He corner of the He-N₂-Ar diagram, but with much lower helium contents than most magmatic or volcanic-related geothermal systems (e.g., Coso; Lutz et al., 1999; Adams et al., 2000).

Because He can be produced both as primary emissions from the mantle and radiogenically in the crust, ³He/⁴He isotopic ratios can be used to distinguish between a mantle or crustal origin. Ratios normalized to atmospheric abundances that are greater than 5 are generally considered to have a significant amount of mantle He. In general, helium isotope ratios of geothermal systems within the central Basin and Range vary from 0.1 to 2.5 R_a and reflect the non-magmatic nature of these geothermal systems. For example, the helium isotopic ratio for fluids from the Beowawe geysers is 0.46 R_a, compared to a ratio of 7.08 R_a for the Devil's Kitchen fumaroles at the Coso geothermal field (Welhan et al., 1988).

A survey of noble gas abundances and isotopic compositions of Dixie Valley production fluids was conducted by Kennedy et al. (1996). Their study determined that the helium component of production fluids has an isotopic composition of 0.70 to 0.76 R_a , which suggests that ~7.5 % of the helium in the reservoir fluid may be mantle derived. Kennedy et al. suggested two mechanisms for the modest enrichment of mantle He in the Dixie Valley geothermal system: 1) fluid circulation through an aged and non-active magma chamber (perhaps the source chamber for local Miocene basalts), and 2) fluid transport along the range front fault from deep mantle sources.

Dixie Valley Reservoir Gas Compositions

The gas composition of fluids from Dixie Valley production well 76-7 (data from T. DeRocher, 2002) is plotted on the CO_2/CH_4 vs. N_2/Ar diagram in Figure 3 and on the He- N_2 -Ar diagram in Figure 8. The analysis falls in the shallow meteoric portion of Figure 3 and in the basaltic or continental area near the Beowawe analysis in Figure 7. In Figure 3, the analysis of the produced gas plots near fluid-inclusion gases from various carbonate vein assemblages but with a slightly higher CO_2 content.

Fluid-inclusion Gas Geothermometry

The proportions of CO_2 , CH_4 , and H_2S in the fluid-inclusions can be used as a gas geothermometer as long as several assumptions are held. The assumptions are: the gases are in equilibrium at the time of trapping, homogeneous trapping of a single fluid, no boiling has occurred, that species have not reacted nor were lost after trapping, and that the fluid salinity is known (Blamey and Norman, this volume). The salinities of Dixie Valley geothermal fluids are generally very low (see Fig. 2), and this method of gas thermometry can be applied. Figure 9 illustrates the fluid-inclusion gas equilibria for selected Dixie Valley alteration samples. In this low-sulfur system, most of the geothermal veins plot in the magnetite stability field at temperatures below about 200°C. The gases in actinolite-bearing veins from the Miocene dike are in equilibrium with magnetite and pyrite at about 230°C. For geothermal veins, the gas fluid-inclusion equilibrium temperatures are about 50° less than both fluid-inclusion homogenization temperatures (see Fig. 2), and present production temperatures (~240°C).

Another application of fluid-inclusion gas thermometry is in the interpretation of equilibrium conditions during alteration. The gases in the geothermal veins appear to have approached equilibrium from the cool side of the diagram (in other words, these veins were deposited from fluids

undergoing heating; see Norman et al., 1998 for a more complete discussion). This interpretation is consistent with a deep-circulation model for the heating of Dixie Valley geothermal fluids.

SUMMARY

The compositions of fluid-inclusion gases indicate that fluids of different origins were involved in the formation of alteration minerals during the evolution of the Dixie Valley geothermal system.

Epidote-bearing assemblages are characterized by fluid-inclusion gases with high methane contents and low CO_2/CH_4 ratios. This assemblage appears to record reduced conditions along the Dixie Valley fault at depths greater than 2-3 km. The source of the methane in these crustal fluids may either be from the pyrolysis of sedimentary organic compounds or the result of Fisher-Tropsch reactions. N_2/Ar ratios of 61 to 104 suggest that fluids along the fault have evolved from meteoric fluids, and are not related to either mantle gases or magmatic fluids associated with Miocene basaltic dikes.

Most of the carbonate vein assemblages appear to have formed from the heating of shallow meteoric fluids. The presence of vein minerals with retrograde solubilities, such as calcite, dolomite and barite, is consistent with this interpretation. The high CO_2/CH_4 ratios are also consistent with the deposition of hematite from oxygenated groundwaters. The presence of minor amounts of chalcedonic quartz and the occurrence of dolomite indicates formation of these veins below 180°C (Fournier, 1985; Browne, 1993), which is consistent with the equilibrium fluid-inclusion gas geothermometry.

Prismatic quartz veins contain inclusions that are most similar to fluids in the Dixie Valley geothermal reservoir. The gas chemistry of the quartz veins suggests mixing between two distinct fluid sources, an evolved meteoric fluid and a magmatic fluid. Most of the quartz-bearing vein assemblages from outcrop and well cuttings samples have N_2/Ar fluid-inclusion gas ratios that are above 100 and appear to contain a small component of magmatic gas.

The source of this magmatic component is not completely understood; no shallow magmatic bodies have been identified seismically or by other means in the Dixie Valley region. The youngest volcanic rocks in the area are late Miocene basalts (K-Ar age of ~8.5 my; Weibel, 1987) that are unlikely to have retained any radiogenic helium. Kennedy et al. (1996) have modeled the migration of helium from a deep (~30 km) mantle source up along the Dixie Valley fault. However, the fluids associated with

epidote-bearing fault gouge at 2.8 km appear to be entirely non-magmatic. Kennedy et al. have suggested that an isolated, aged magma chamber may possibly supply magmatic gases from U and Th decay. The fluid-inclusion gas chemistry seems to imply that Miocene basalt could be the source of magmatic gas in the geothermal veins.

ACKNOWLEDGEMENTS.

We would like to thank Caithness Energy and the Caithness-Dixie Valley staff for their support during fieldwork sessions. Thanks also to Ted DeRocher for permission to use data from his PhD dissertation. We also appreciate Mike Adams' help with interpreting the gas data and drafting by Doug Jensen. Funding for this study was provided by the U.S. Department of Energy, for SJL and JNM under Contract DE-AC07-95ID13274, and for DIN and NB under Contract DE-FG07-00ID13953.

REFERENCES

- Adams, M.C., Moore, J.N., Bjornstad, S., and Norman, D.I., 2000, Geologic history of the Coso geothermal system: Proceedings, World Geothermal Congress, Kyushu-Tohoku, Japan, May 28-June 10, 2000, p. 2463-2469.
- Bell, J.W. and Katzer, T., 1987, Surficial geology, hydrology, and late Quaternary tectonics of the IXL Canyon area, Nevada as related to the 1954 Dixie Valley earthquake: Nevada Bureau of Mines and Geology, Bulletin 102, 52p.
- Benoit, D., 1994, Review of geothermal power generation projects in the Basin and Range Province 1993: GRC Bulletin, May, p. 173-178.
- Blackwell, D.D., Golan, B., and Benoit, D., 2000a, Thermal regime in the Dixie Valley geothermal system: Proceedings World Geothermal Congress, Kyushu-Rohoku, Japan, May 28-June 10, 2000, p. 991-996.
- Blackwell, D.D., Golan, B., and Benoit, D., 2000b, Temperatures in the Dixie Valley, Nevada geothermal system: Geothermal Resources Council Transactions, v. 24, p. 223-228.
- Blamey, N., and Norman, D.I., 2002, New interpretations of geothermal fluid inclusion volatiles: Ar/He and Ne/Ar ratios- a better indicator of magmatic volatiles, and equilibrium gas geothermometry: Twenty-seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, in press.
- Browne, P.R.L., 1993, Application of mineralogic methods to access the thermal stabilities of geothermal reservoirs: Eighteenth Annual Workshop on Geothermal Reservoir Engineering, Stanford University, p. 73-78.
- Caskey, S.J., Wesnousky, S.G., Zhang, P., and D.B. Slemmons, 1996, Surface faulting of the 1954 Fairview Peak (Ms7.2) and Dixie Valley (Ms6.9) earthquakes, central Nevada, Bulletin of the Seismological Society of America, v. 86, n. 3, p. 761-787.
- Caskey, S.J., Bell, J.W., D.B. Slemmons, and A.R. Ramelli, 2000a, Historical surface faulting and paleoseismology of the central Nevada seismic belt: Geological Society of America, Field Guide 2, p. 23-44.
- Caskey, S.J., and S.G. Wesnousky, 2000b, Active faulting and stress redistribution in the Dixie Valley, Beowawe, and Brady's geothermal fields: implications for geothermal exploration in the Basin and Range: Proceedings, Twenty-fifth Workshop on Geothermal Reservoir Engineering, Stanford Geothermal Workshop, Stanford University, 16p.
- DeRocher, T., 2002, The hydrogeochemistry of Nevada's productive geothermal resources: PhD dissertation draft, Department of Hydrologic Sciences, University of Nevada-Reno, in review.
- Fournier, R.O., 1985, The behavior of silica in hydrothermal solutions: Reviews in Economic Geology, Volume 2: in B.R. Berger and P.M. Bethke, eds., Geology and Geochemistry of Epithermal Systems, Society of Economic Geologists, p. 45-61.
- Giggenbach, W.F., 1986, The use of gas chemistry in delineating the origin of fluid discharges over the Taupo Volcanic Zone: a review: International Volcanological Congress, Hamilton, New Zealand, Proceedings Symposium, v. 5, p. 47-50.
- Giggenbach, W.F., 1992, The composition of gases in geothermal and volcanic systems as a function of tectonic setting: in Kharaka and Maest, eds., Proceedings of the International Symposium of Water-rock Interaction, Balkema, Rotterdam, v. 7, p. 873-878.
- Giggenbach, W.F., 1995, Magmatic components in hydrothermal fluids, in J.F.H. Thompson, ed., Magmas, Fluids and Ore Deposits: Mineralogical Association of Canada Short Course Volume 23, p. 247-261.
- Jarchow, C.M., Thompson, G.A., Catchings, R.D., Mooney, W.D., 1993, Seismic evidence for active magmatic underplating beneath the Basin and Range Province, Western United States: Journal of Geophysical Research, v. 98, p. 22095-22108.

- Kennedy, B.M., Benoit D., and Truesdell, A.H., 1996, A preliminary survey of noble gases at Dixie Valley, Nevada: Transactions Geothermal Resources Council, v. 20, p. 815-820.
- Lutz, S.J., Moore, J.N., and Benoit, D., 1997, Geologic framework of Jurassic reservoir rocks in the Dixie Valley geothermal field, Nevada: Implications from hydrothermal alteration and stratigraphy: Proceedings, Twenty-second Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 27-29, p. 131-139.
- Lutz, S.J., Moore, J.N., and Benoit, D., 1998, Integrated alteration mineralogy and fluid-inclusion study at the Dixie Valley geothermal field, Nevada: Proceedings, Twenty-third Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 26-28, p. 315-321.
- Lutz, S.J., Moore, J.N., Adams, M.C., and Norman, D.I., 1999, Tracing fluid sources in the Coso geothermal system using fluid-inclusion gas chemistry: Twenty-fourth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, p.188-195.
- Lutz, S.J., Caskey, S.J., Mildenhall, D.D., Browne, P.R.L., and Johnson, S.D., 2002, Dating sinter deposits in northern Dixie Valley, Nevada- the paleoseismic record and implications for the Dixie Valley geothermal system: Twenty-seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, in press.
- Nimz, G., Janik, C., Goff, F. Dunlap, C., Huebner, M., Counce, D., and S.D. Johnson, 1999, Regional hydrology of the Dixie Valley geothermal field, Nevada: preliminary interpretations of chemical and isotopic data: Geothermal Resources Council Transactions, v. 23, p. 333-338.
- Norman, D.I., and Musgrave, J., 1995, N₂, Ar, and He in fluid inclusions: tracers of hydrothermal fluids: *Geochimica et Cosmochimica Acta*, v. 58, p. 119-131.
- Norman, D.I., Moore, J.N., Yonaka, B., and Musgrave, J., 1996, Gaseous species in fluid inclusions: A tracer of fluids and indicator of fluid processes: Proceedings, Twenty-first Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford California, January 22-24, 1996, p. 233-240.
- Norman, D.I., Moore, J.N., and Musgrave, J., 1997, More on the use of fluid-inclusion gaseous species as tracers in geothermal systems: Proceedings, Twenty-second Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 27-29, 1997, p. 419-426.
- Norman, D.I., Chomiak, B.A., and Moore, J.N., 1998, Approaching equilibrium from the hot and cold sides of the FeS₂-FeS-Fe₃O₄-H₂S-CO₂-CH₄ system in the light of fluid inclusion gas analysis; *in* Arehart, G.B., and Hulston, J.R., eds, Proceedings of the 9th International Symposium of Water-Rock Interaction: Rotterdam, A.A. Balkema, p. 565-568.
- Parry, W.T., Hedderly-Smith, D., and Bruhn, R.L., 1991, Fluid inclusions and hydrothermal alteration on the Dixie Valley fault, Nevada: *Journal of Geophysical Research*, v. 96, n. 12, p. 19733-19748.
- Vikre, P.C., 1994, Gold mineralization and fault evolution at the Dixie Comstock Mine, Churchill County, Nevada: *Economic Geology*, v. 89, n. 4, p. 707-719.
- Weibel, A.F., 1987, An overview of the geology and secondary mineralogy of the high temperature geothermal system in Dixie Valley, Nevada: *Geothermal Resources Council, Bulletin*, Sept/Oct, p. 5-11.
- Welhan, J.A., Poreda, R.J., Rison, W., and Craig, H., 1988, Helium isotopes in geothermal and volcanic gases of the western United States, 1. Regional variability and magmatic origin: *Journal of Volcanology and Geothermal Research*, v. 34, p. 185-199.
- Williams, C.F., Sass, J.H., and Grubb, F.V., 1997, Thermal signature of subsurface fluid flow near the Dixie Valley geothermal field, Nevada: Proceedings, Twenty-second Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 27-29, 1997, p. 161-168.

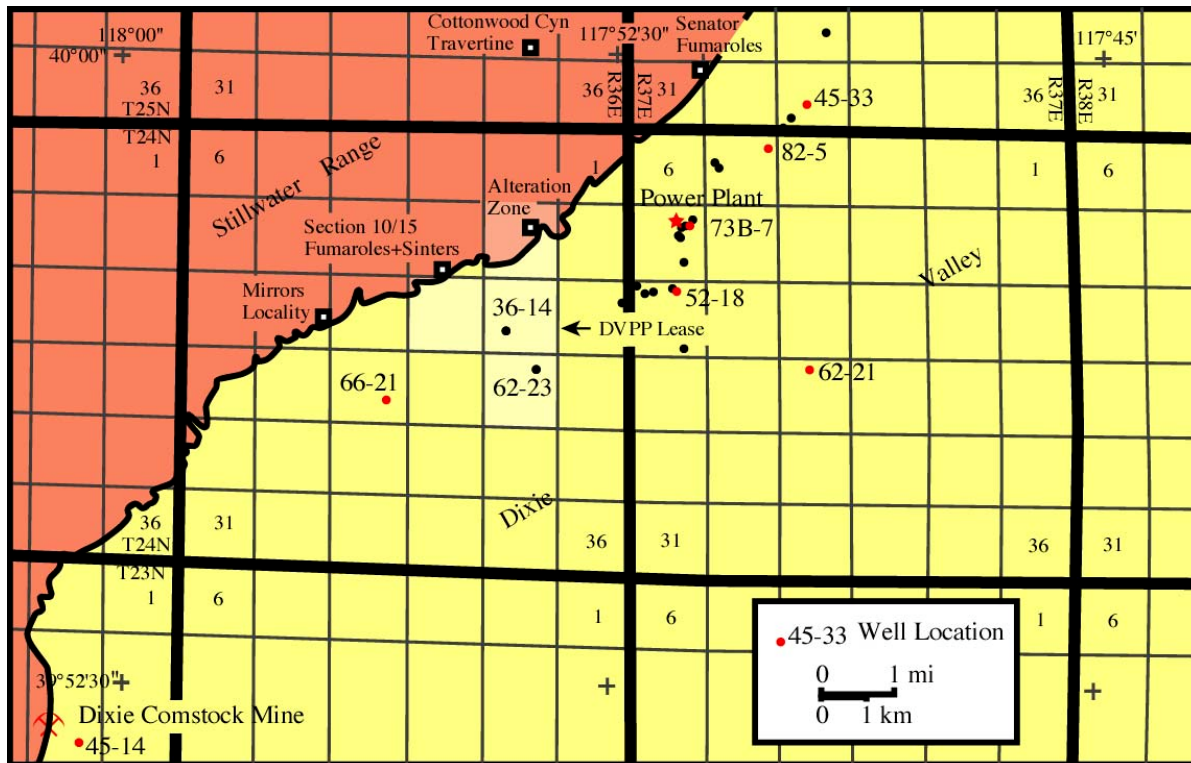


Fig. 1. Location of selected wells in the Dixie Valley geothermal field, and outcrop and sample localities along the Stillwater range front in northern Dixie Valley, Nevada. Sample locality for Miocene basaltic dikes is along the range front about 3 km NE of the Senator Fumaroles.

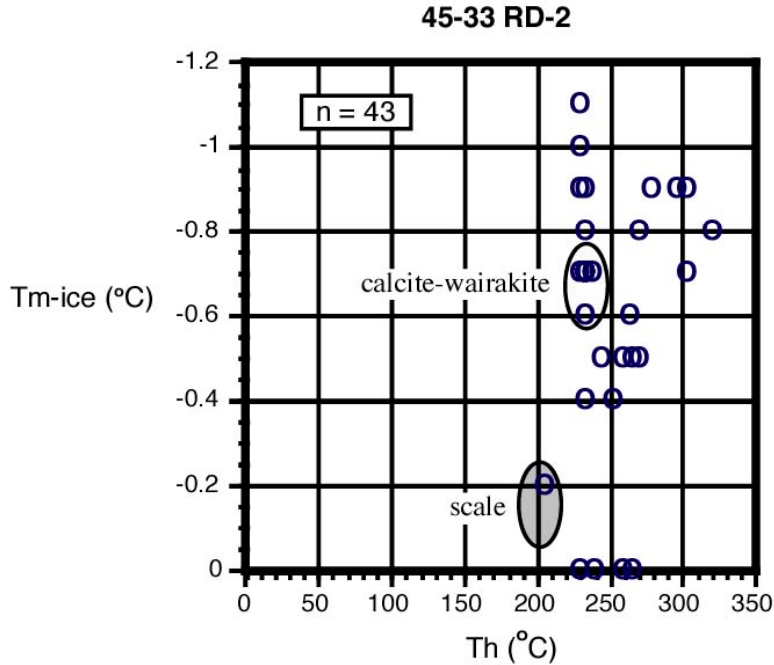


Fig. 2. Fluid inclusion data for the lower portion of well 45-33 RD-2. The open circles are fluid inclusions in vein calcite and may represent many different alteration events. The fluid inclusions in calcite from wairakite veins are related to early stages of alteration of the modern geothermal system. These inclusions have an average homogenization temperature (Th) of 235°C and an apparent salinity of about 1.2 wt % NaCl (temperature of ice melting Tm-ice of about -0.7°C). For reference, the conditions of scale formation of well 76-7 are displayed as a shaded oval. Modern production fluids have salinities of 0.1 to 0.2 wt % and temperatures up to 248°C.

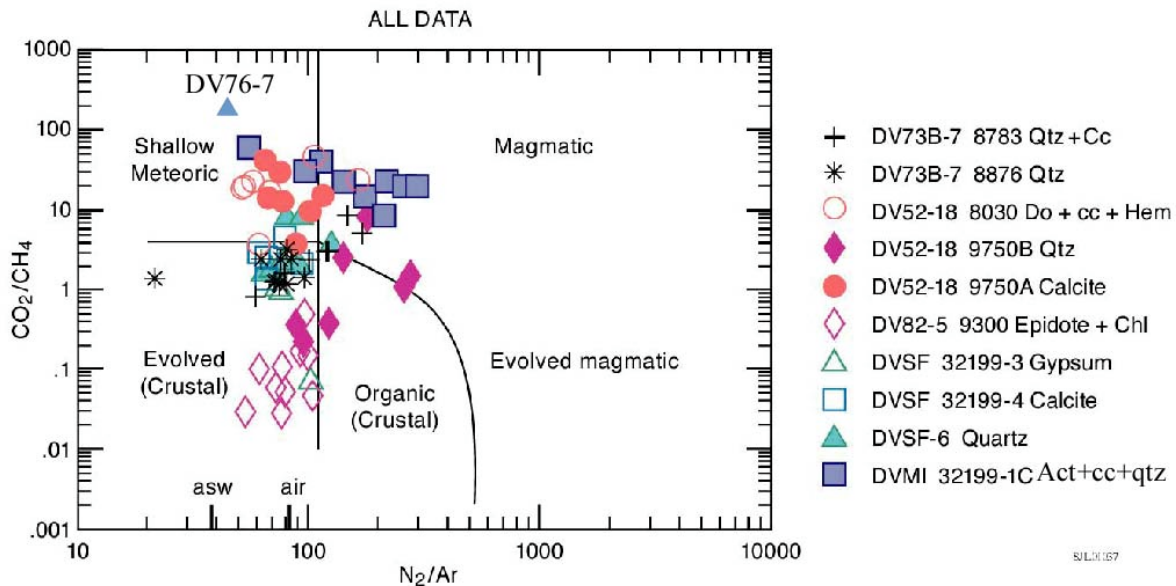


Fig. 3. Dixie Valley fluid-inclusion gas data for selected alteration samples plotted on a CO₂/CH₄ vs. N₂/Ar diagram. Geothermal vein samples are from wells 73B-7, 82-5 and 52-18. The analysis for gas in production fluids from well 76-7 falls in the shallow meteoric field (data from T. DeRocher, 2002). Outcrop samples are from the Senator Fumarole area (DVSF), and from actinolite-bearing veins associated with Miocene basaltic dikes (DVMI).

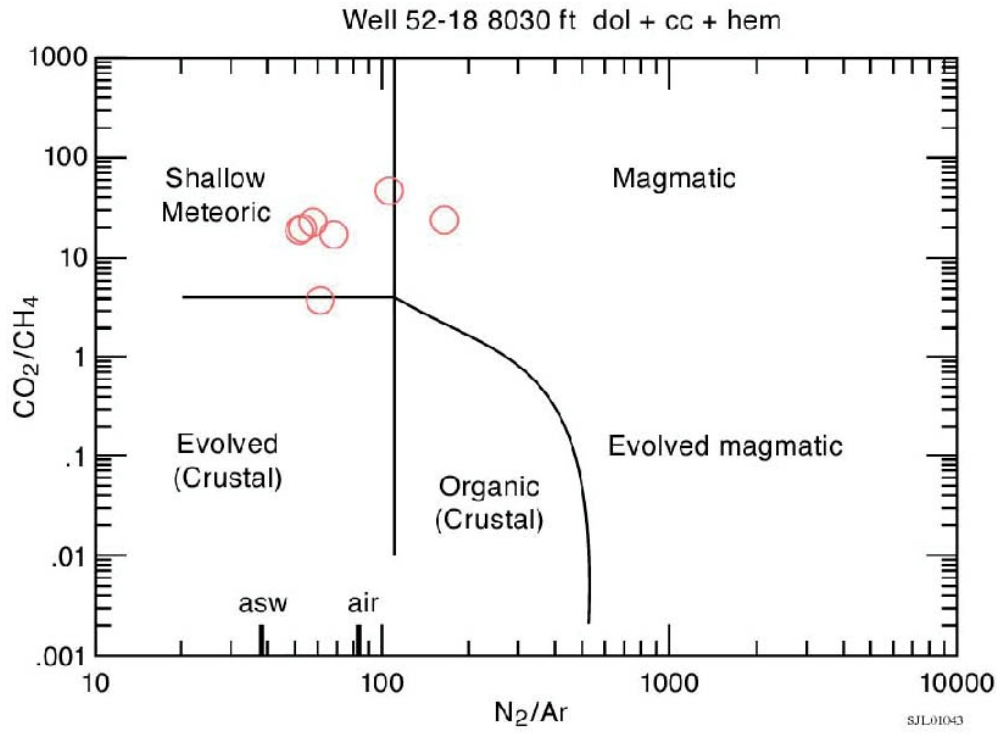


Fig. 4. Fluid-inclusion gas data for dolomite-calcite-hematite veins at 8030 ft (2450m) in well 52-18. The gases in this vein represent a shallow, meteoric fluid source.

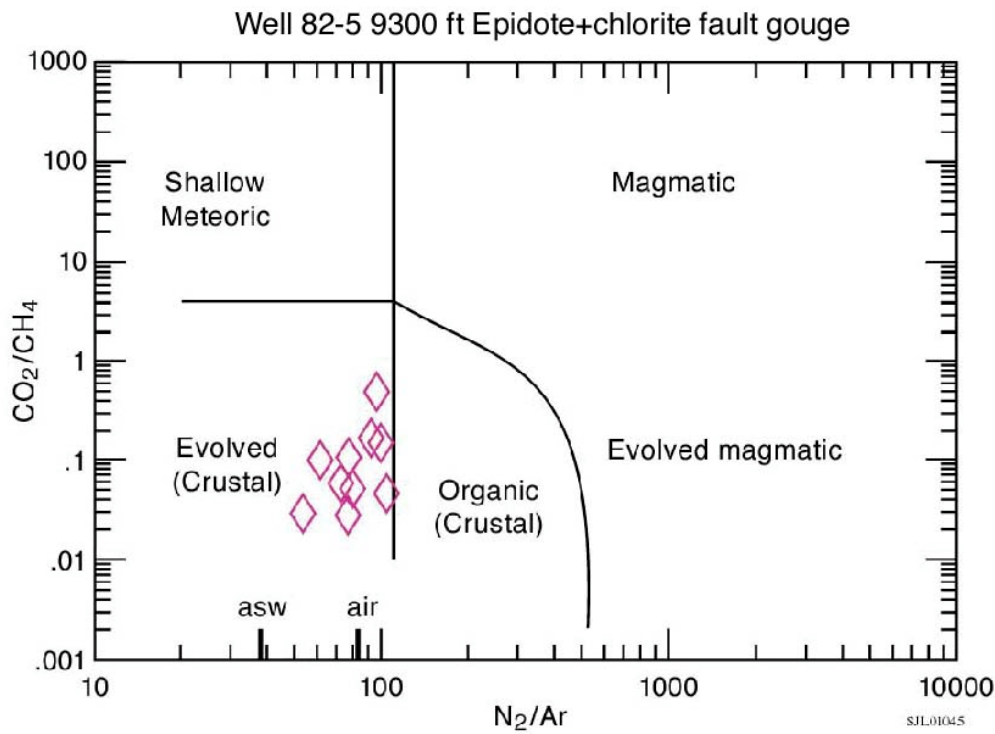


Fig. 5. Fluid-inclusion gas data for epidote-chlorite fault gouge along the Dixie Valley fault at 9300 ft (2835m) in well 82-5. The gases in this sample represent an evolved meteoric or crustal fluid source.

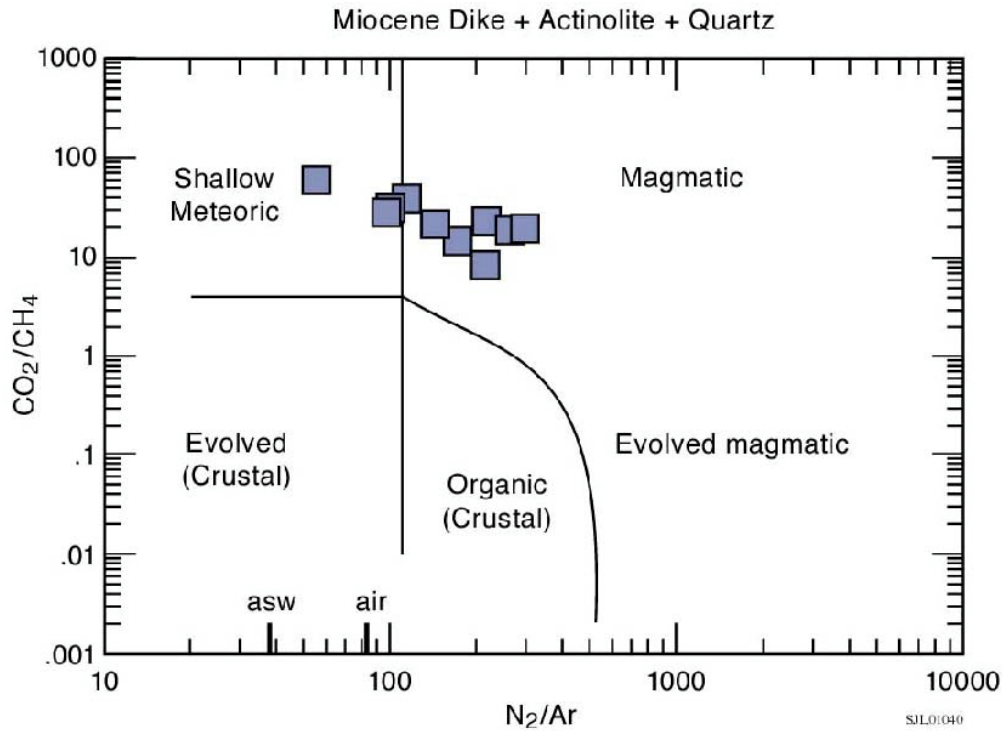


Fig. 6. Fluid-inclusion gas data for actinolite-quartz-calcite veins along a Miocene-age basaltic dike. This sample was collected from a dike swarm complex along the eastern Stillwater range front, in an area approximately 3 km north of the Senator Fumarole. The gases in this sample represent a mixture of shallow meteoric and magmatic fluid sources.

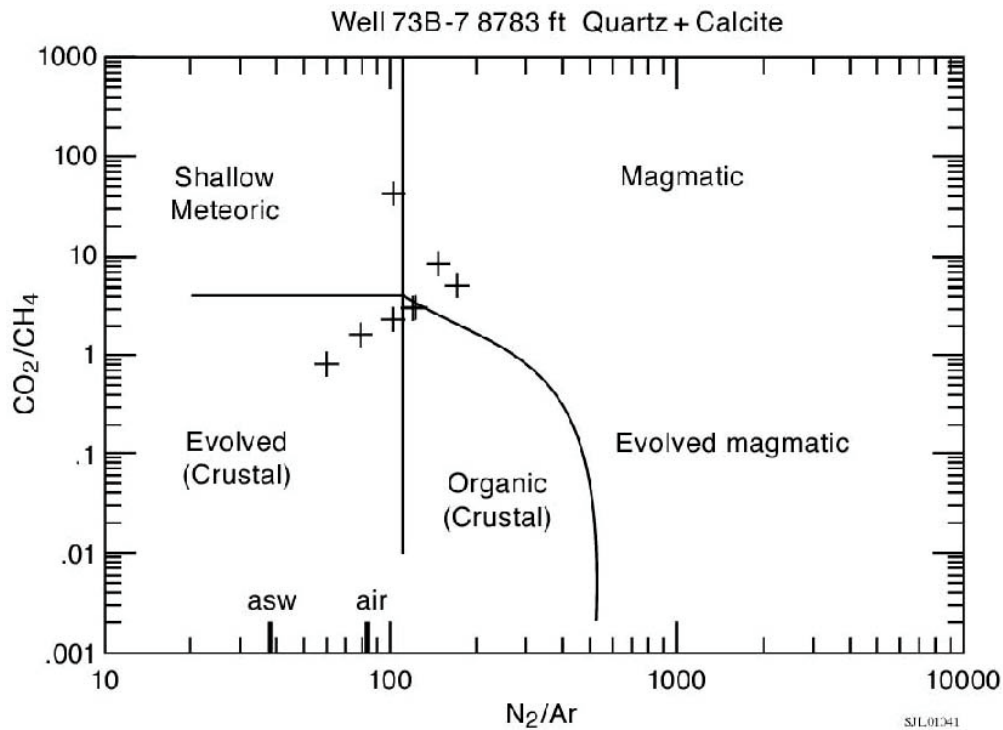


Fig. 7. Fluid-inclusion gas data for prismatic quartz-calcite veins at 8783 ft (2677m) in production well 73B-7. The gases in this vein represent a mixture of evolved meteoric and magmatic fluid sources.

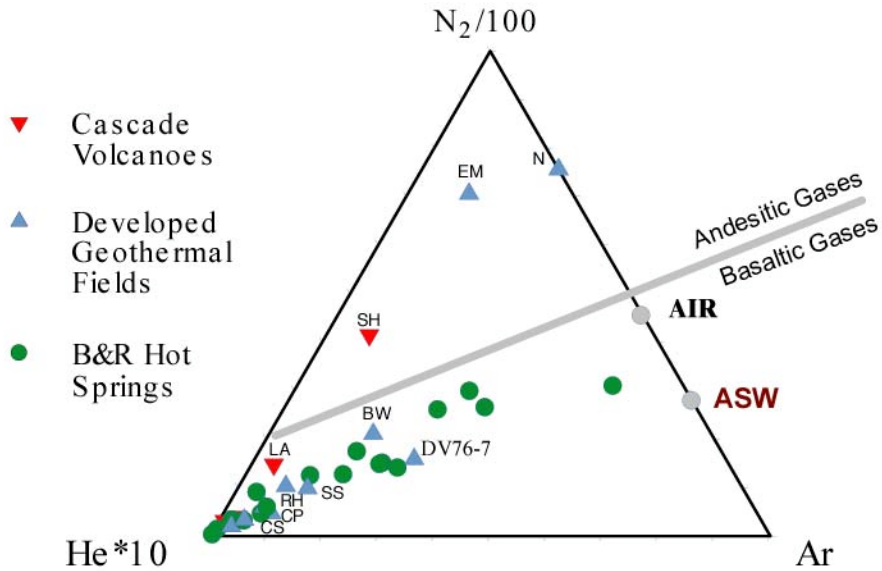


Fig. 8. Gas data from Basin and Range hot springs and fumaroles, Cascade volcanoes, and geothermal wells in the western United States plotted on a He*10-N₂/100-Ar ternary diagram (data from Welhan et al., 1988). The analysis for gas in production fluids from Dixie Valley well 76-7 (data from DeRocher, 2002) is in the basaltic gas field (as defined by Giggenbach, 1992; 1995) along an evolved or continental trend. Abbreviations: AIR= air, ASW= air-saturated water, DV=Dixie Valley Well 76-7, BW=Beowawe Well, SS=Steamboat Springs, RH=Roosevelt Hot Spring, CP=Cerro Prieto, CS=Coso Devil's Kitchen Fumarole, LA=Lassen Peak, SH=Mt. Shasta Hot Spring, EM=East Mesa, N=Niland.

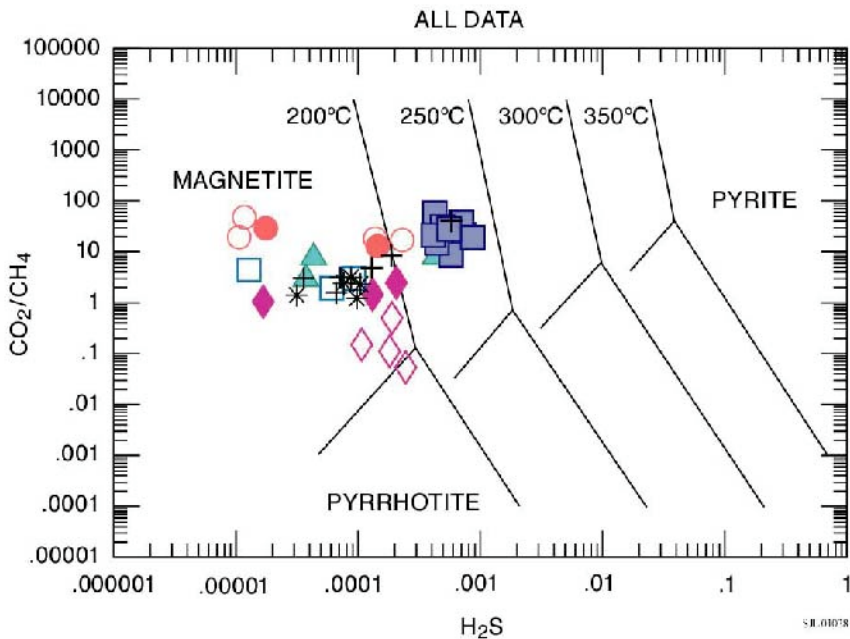


Fig. 9. Geothermometry of Dixie Valley alteration samples based on fluid-inclusion gas equilibria. Dixie Valley fluid-inclusion gas data for selected alteration samples plotted on a CO₂/CH₄ vs. H₂S diagram. Key for symbols in Figure 3.