# SOIL GAS STUDIES ALONG THE CARLIN TREND, EUREKA AND ELKO COUNTIES, NEVADA

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## ABSTRACT

Soil gases were sampled at 175 sites along widely-spaced traverses that crossed the Carlin Trend in north-central Nevada. Inorganic and organic soil gases including $H_2$, $O_2$, $CO_2$, and hydrocarbon gases, were analyzed using a truck-mounted mass spectrometer. The objective of these measurements was to test the possibility that gases might reveal faults that controlled the localization of gold deposits along this linear trend. Soil gases were sampled at 1-1.5 km intervals along traverses that extended 16-31 km on both sides of the hypothetical center line of the Carlin Trend, and for about 80 km in a north-south direction from Carlin on the south to the Willow Creek drainage on the north. $CO_2$ and $H_2$ soil-gas anomalies were found 8-11 km west of the hypothetical center line of the Carlin Trend. $H_2$ and more limited $CO_2$ gas anomalies were also found 3-11 km east of the trend line on two of the traverses. These gas anomalies may result from leakage along faults that have genetic significance in localization of the Carlin Trend. Both $CO_2$ and $H_2$ are produced in the deep crust or mantle, and deep-seated regional faults may be indicated by these gas anomalies. The anomalies extend as far north as the Willow Creek drainage suggesting that the trend may continue northward, beyond the known gold deposits.

## INTRODUCTION

Many geologists have attempted to explain the linear pattern of gold deposits that occur along the Carlin Trend (Roberts, 1960; Roberts, 1966; Shawe, 1991). Shawe (1991) stated “The linearty of the gold trends and concentration of igneous rocks along them suggest that deep-penetrating regional structures controlled the emplacement of magmas generated in the lower part of the crust or upper mantle.” Based on Pb and Sr isotope ratios, Wooden and others (1997) infer that both the Carlin and Battle Mountain mineral belts were localized along crustal scale regional faults. The considerable length of the Carlin Trend (about 185 km from the Dee Mine on the north to the Alligator Ridge Mine on the south) suggests deep-seated structural control. Northwest-striking faults of limited extent have been mapped along the Carlin Trend (Roberts and others, 1967); however, through-going faults of regional extent have not been identified.

Gases produced at depth migrate to the surface, commonly along faults, because the faults are usually more permeable than the surrounding rock. Gases measured at the surface have been used to map concealed faults (Kasimov and others, 1979; Scherbakov and Koslova, 1986; McCarthy and Hardyman, 1996). Linear, narrow gas anomalies are found over high-angle faults and linear, broad or asymmetric gas anomalies over low-angle faults (Fridman, 1990). Assuming that deep-seated structures may exist along the Carlin Trend, the soil gas studies reported here were undertaken to test the possibility that they might be revealed by surface gas measurements. Although considerable thicknesses of Quaternary sediments and Tertiary volcanic rocks overlie the basement Paleozoic rocks that host the gold deposits on the Carlin Trend, gases have been found to migrate from depth to the surface through similair types of overburden (McCarthy and others, 1968; Kasimov and others, 1979).

## SAMPLING AND ANALYTICAL PROCEDURES

Gases were sampled along traverses that followed roads crossing the Carlin Trend (figs. 1-3). Sample intervals were 1 to 1.5 km and some traverses extended 16-32 km on both sides of the north-northwest-striking line shown on figures 1-3, which represents the approximate center of the Carlin Trend. These traverses extended from the town of Carlin on the south to the Willow Creek drainage on the north, a distance of about 80 km. Gases were sampled by driving a hollow steel probe into the ground to a depth of 75 cm and extracting soil air from that depth. The samples were analyzed at each site using a truck-mounted mass spectrometer (McCarthy and Bigelow, 1990). Analytical reproducibility is ± 30 percent. A paper copy of the analytical data is printed, and along with the latitude and longitude of the site location, recorded on a floppy disk to permit plotting of individual gas species.

Individual atomic or molecular gas species are analyzed in the mass spectrometer and converted to concentration by comparison with standard gases of known composition. The concentration of the gases are expressed as volume of gas per volume of air (v/v). A detailed description of the mass spectrometer and its operation is given by McCarthy and Bigelow (1990).

The intervals selected for contours on figures 1-3, are based on concentrations that are considered anomolous. For

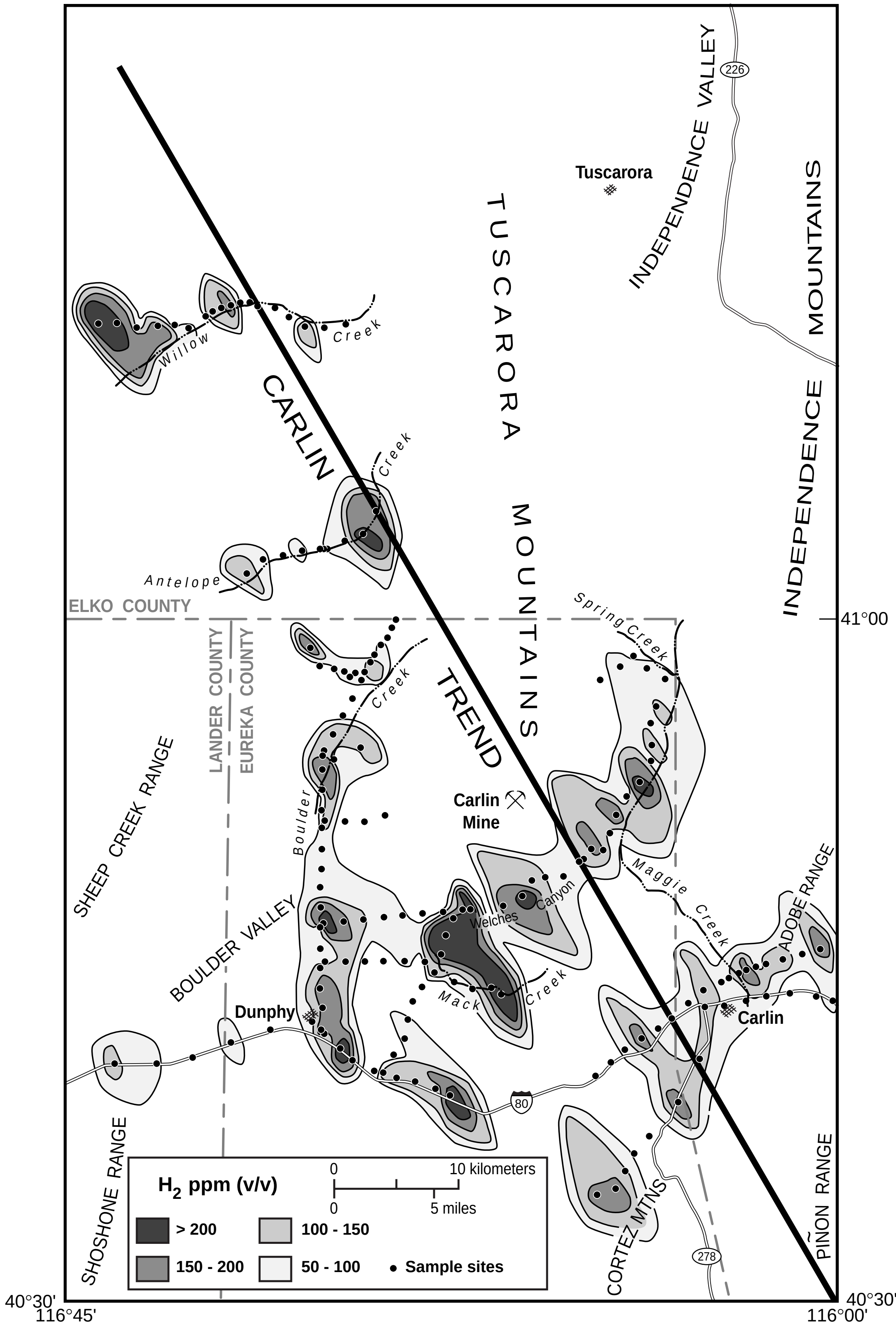


**Figure 1**. Contour map of $H_2$ in soil gas samples along the Carlin trend, Eureka and Elko Counties, Nevada.

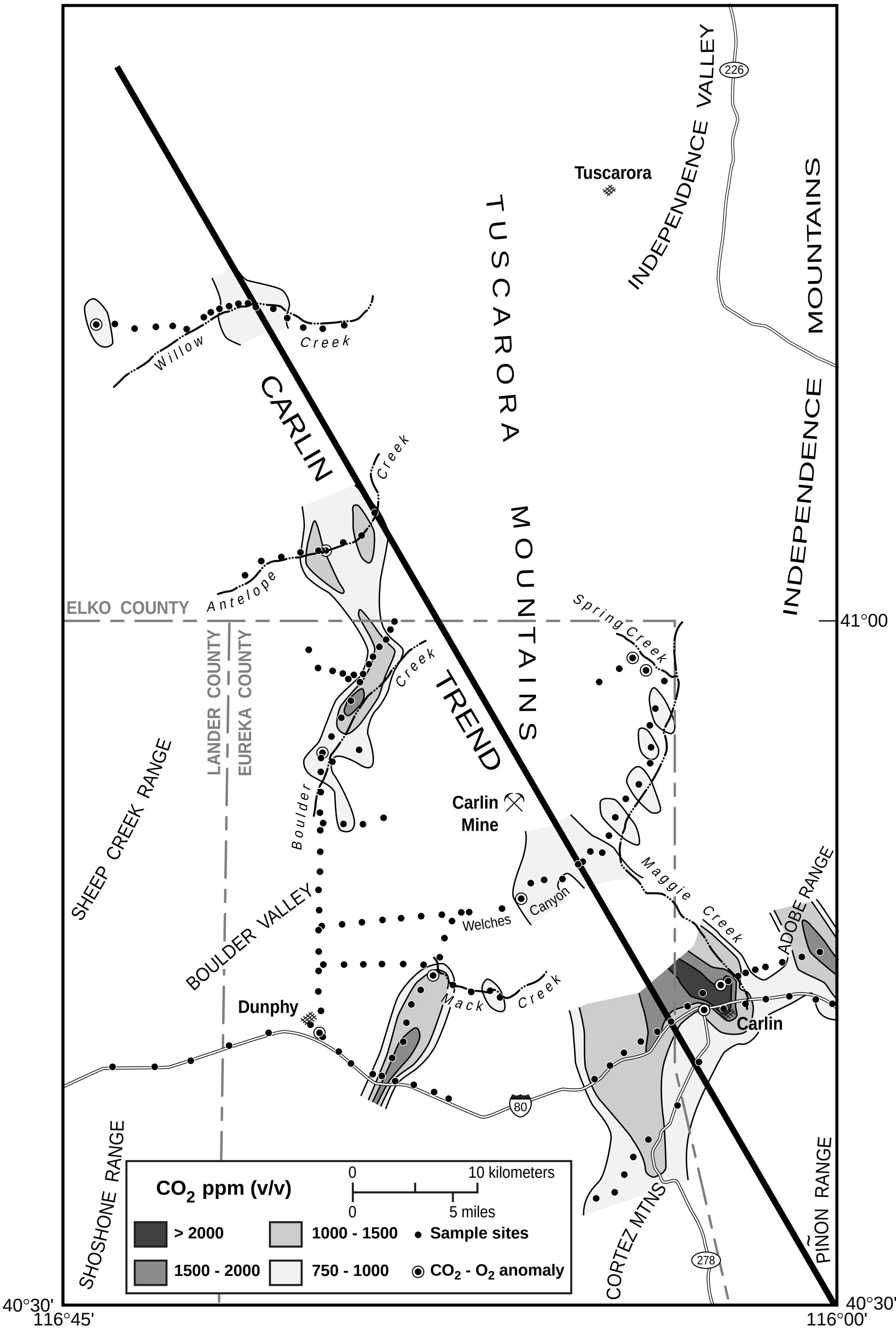


**Figure 2.** Contour map of $CO_2$ in soil gas samples along the Carlin trend, Eureka and Elko Counties, Nevada.

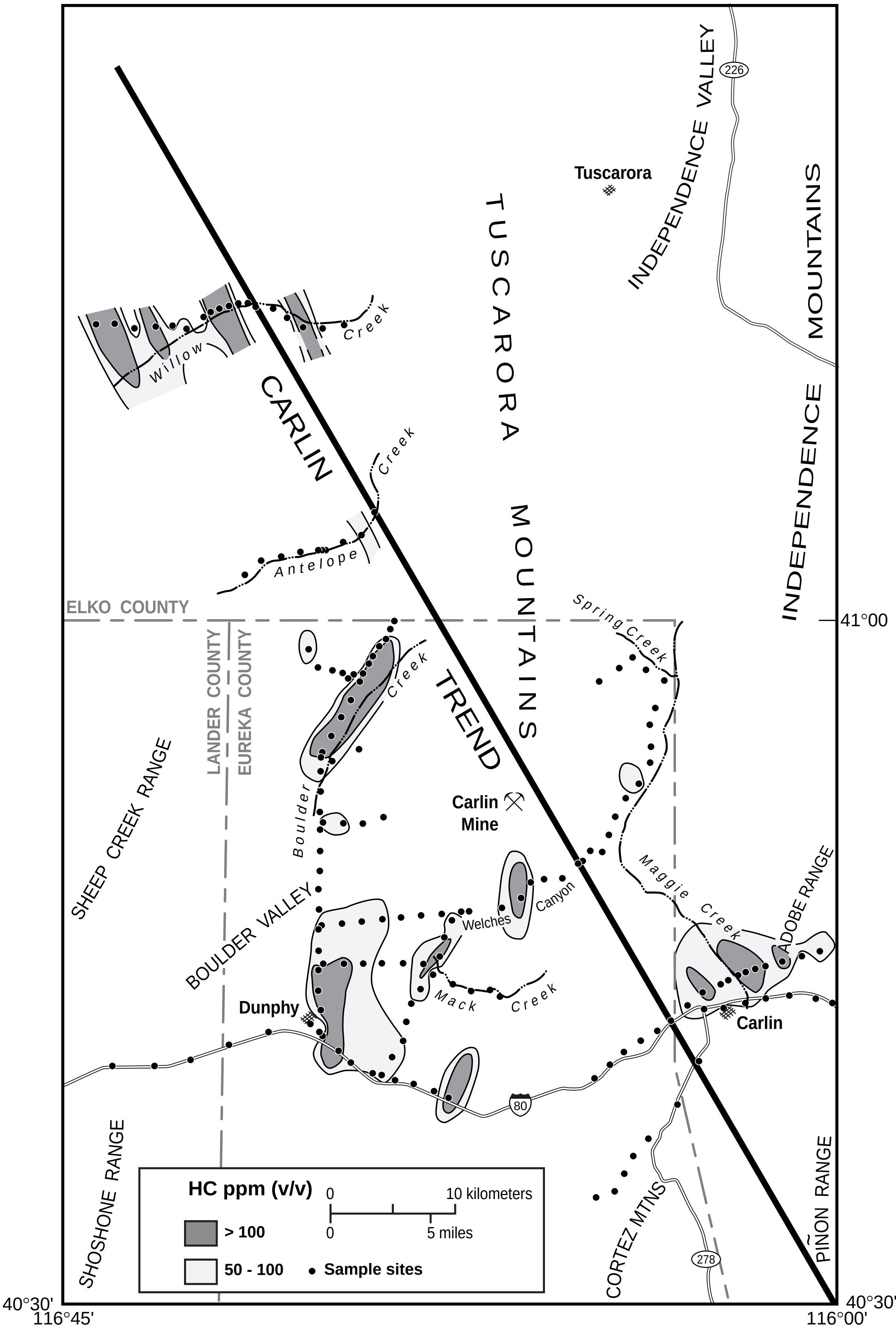


**Figure 3**. Contour map of hydrocarbon gases (HC) in soil gas samples along the Carlin trend, Eureka and Elko Counties, Nevada.

example, the background concentration of $CO_2$ in air is 350 ppm (Rose and others, 1979); approximately twice that concentration was selected as anomalous, and is the minimum contour shown on figure 2. The minimum concentration considered anomalous for $H_2$ and contoured on figure 1 is 50 ppm, and for the combined hydrocarbon gases (HC on figure 3) is 50 ppm.

## RESULTS

Two of the gases measured in this study, $H_2$ and $CO_2$, are of particular interest because both of these gases can be derived from the deep crust and mantle (Krauskopf, 1967; Neal and Stanger, 1983; Shcherbakov and Kozlova, 1986; Barnes and others, 1978). Thus, these gases could indicate deep-seated faults.

The results for $H_2$, $CO_2$, and $C_2H_5^+$ (an ion fragment that represents both propane and butane) were plotted on maps and contoured to show patterns of anomalous concentrations (figs. 1-3). Individual $H_2$ gas anomalies were connected by contours based on levels of concentration (fig. 1) and suggest possible northwest-striking linear alignments; however, northeast-striking alignments are also possible; the latter alignments may only reflect the sampling along roads. The linear continuity of any of these anomalies can only be confirmed (or negated) by additional sampling traverses between those reported in this study.

As shown by the data, $H_2$ gas anomalies were found 8 to 11 km west of the line on the figures indicating the approximate center of the Carlin Trend. A similar, but less continuous, alignment of $CO_2$ and $H_2$ gas anomalies were found about 3 to 11 km east of the trend line. If connected, these anomalies would reflect linear alignments that are approximately parallel to the Carlin Trend line. Two anomalies for both $H_2$ and $CO_2$ cross the Carlin Trend line; one is just north of the town of Carlin and the other extends from Welches Canyon on the west to the Maggie Creek drainage on the east. The latter anomaly coincides with a north-northeast-striking fault zone as mapped by Peters (this volume).

At several sites, high concentrations of $CO_2$ coincide with low concentrations of $O_2$, a combination that is commonly associated with oxidizing sulfide minerals (Lovell and others, 1983). In field studies cited by Lovell and Hale (1983) up to 9 percent $CO_2$ (v/v) and corresponding low levels of $O_2$ were found in soil gas samples over massive sulfide mineralization in Ireland, Scotland, Spain, and the United States. This process results from oxidation of sulfide minerals (in the cases cited above sphalerite, galena, chalcopyrite, and pyrite) producing acid solutions that react with carbonate minerals producing $CO_2$. McCarthy and others (1986) found similar high $CO_2$ and low $O_2$ anomalies in soil gases over the Crandon massive-sulfide ore deposit in northern Wisconsin. Carlin-type disseminated gold deposits commonly contain only 4 to 5 percent sulfide minerals (mostly pyrite), and consequently have less pronounced $CO_2$ and $O_2$ anomalies (McCarthy and others, 1989). East of the trend line, this combination of $CO_2$ and $O_2$ anomalies are found near the town of Carlin, and along Spring Creek near its confluence with Maggie Creek. West of the trend line they occur at six sites: along Mack Creek, in Welches Canyon, 1.6 km southeast of Dunphy, 22 km north of Dunphy where the road heading north from Dunphy crosses Boulder Creek, along Antelope Creek 5 km west of the Trend line, and along Willow Creek 5 km west of the trend line. These anomalous sites (circled on fig. 2) may reflect oxidizing sulfide minerals in bedrock.

Anomalous concentrations of volatile hydrocarbons in soil gas samples (fig. 3) are found: at several sites in Boulder Valley north and east of Dunphy, at several sites extending 8 km east-northeast from the town of Carlin, at several sites 8 to 11 km west of the Carlin Trend line in the Boulder Creek drainage, and at several sites along the Willow Creek drainage. Hydrocarbon gas anomalies are associated with base metal deposits (Disnar, 1990) and with gold deposits (Ilchik and others, 1986; McCarthy and others, 1989). Carbonaceous material is a common constituent of Carlin-type gold deposits (Percival and others, 1988), and maturation of this organic matter could produce hydrocarbon gases. These gases may be used as exploration guides to gold and other types of mineral deposits.

All of the gas anomalies noted above probably result from gases migrating along faults in Paleozoic basement rocks. The inferred depth to Paleozoic bedrock based on modeling of gravity data (Saltus and Jachens, 1995) varies from about 1.8 km in the Antelope Creek basin to 4.5 km in the Maggie Creek basin. The depth to basement in Boulder Valley is about 3 km in the south and decreases to 1.6 km in the north. Studies have shown that gases migrate to the surface from such depths through valley-fill sediments (McCarthy and Hardyman, 1996) and through volcanic rocks (McCarthy and others, 1968).

In a study conducted in the Sheep Creek Range, north of Battle Mountain, Nevada, mercury vapor was detected through 300 m of volcanic rocks overlying mineralized Paleozoic basement rocks. Here, sphalerite and galena from a prospect pit in the underlying Paleozoic rocks contained several ppm of Hg, which appears to be the source of the Hg vapor detected at the surface. The Hg anomalies were found along faults in the volcanic rocks indicating that the Hg migrated as a vapor along the faults. These studies demonstrate that gases can migrate to the surface through volcanic or alluvial overburden.

## DISCUSSION

The linear alignment of anomalous concentrations of $H_2$ and $CO_2$ as contoured on figures 1 and 2 probably result from leakage along faults that could have genetic significance in localization of the Carlin Trend. Both $H_2$ and $CO_2$ (as well as other gases) are common constituents of the following mantle-derived fluids-(**1**) volcanic emanations (Mason and Moore, 1981); (**2**) submarine rift zones (Welhan and Craig, 1979); (**3**) continental rift zones (Coveney and others, 1987); and (**4**) ophiolites (Neal and Stanger, 1983). Both $CO_2$ and $H_2$ could reflect faults that penetrate to the deep crust or mantle. But, both can also have shallow sources (Sugisaki and others, 1983, Lovell and others, 1983).

## HYDROGEN

According to Kasimov and others (1979), hydrogen emanating from faults in Kazakhstan came from great depth. However, Sugisaki and others (1983) have found several volume percent $H_2$ in both shallow and deep faults with historical movement, which they attribute to the reduction of water by reactive rock surfaces along the faults.

## CARBON DIOXIDE

According to Barnes and others (1978), "$CO_2$ is thought generally to come from three different sources: (1) organic material, (2) metamorphism of marine carbonate rocks, and (3) the mantle." Carbon dioxide is a significant constituent of volcanic emanations and mid-ocean ridge gases, and isotopic measurements indicate that some of this $CO_2$ is derived from the mantle (Hoefs, 1997). Faults are commonly more permeable than the surrounding rock and provide conduits for fluids to migrate from depth (Shcherbakov and Kozlova, 1986). It is possible that the gases measured in this study migrate along faults that extend to the mantle.

Methane is commonly produced along with $CO_2$ when organic matter decomposes (Tan, 1994); however, anomalous concentrations of both methane and $CO_2$ are found in only 5 of the 175 soil gas samples in this study. We therefore conclude that most of the $CO_2$ anomalies reported here do not result from the decomposition of organic matter.

It is possible that the $CO_2$ found in the soil gas samples is produced by metamorphism of carbonate rocks. Although carbonate rocks do not crop out where $CO_2$ anomalies are found, they do crop out in the Tuscarora Mountains near the Carlin Mine (Roberts and others, 1967), and they underlie the volcanic rocks and the upper plate siliciclastic rocks of the Roberts Mountains allochthon. Thus, $CO_2$ in the soil gas samples may result from prior or continuing metamorphism of carbonate rocks.

A fourth possible source of $CO_2$ is reaction of acid solutions with carbonate rocks or minerals. Sulfuric acid is formed when oxygenated ground waters react with sulfide minerals, such as pyrite, which commonly is present in Carlin-type gold deposits. The resulting acidic fluid reacts with carbonate host rock, and $CO_2$ is produced. Oxygen is consumed in this reaction, and when lowered concentrations of $O_2$ are found in soil gas samples that have increased concentrations of $CO_2$, oxidizing sulfide minerals in rocks below surficial deposits are indicated. The $CO_2$ generated in this reaction process has been documented by several investigators (Lovell and others, 1983, McCarthy and others, 1986).

## OTHER GASES

Hydrocarbon gases are also associated with base and precious metal mineral deposits (Disnar, 1990; McCarthy and others, 1989; Taylor and others, 1981). It has been known for some time that hydrocarbons are associated with sediment-hosted gold deposits (Kesler and others, 1990; Ilchik and others, 1986). According to some investigators, volatile hydrocarbons are produced by thermal maturation of organic matter in the host or wall rock, with heat provided by ore-bearing hydrothermal solutions. However, evidence from Carlin-type deposits elsewhere indicates that hydrocarbons were present before the gold-bearing fluids were introduced, as at Alligator Ridge (Ilchik and others, 1986). Even if petroleum hydrocarbons were present before the introduction of gold-bearing fluids, the hydrocarbons would be subject to further maturation and production of gases by hydrothermal solutions that were introduced later. Volatile hydrocarbons (alkanes) have been found in soil gases at all Carlin-type gold deposits investigated (McCarthy, 1989; and unpublished data). The hydrocarbon gases (HC) plotted in figure 3 are combined $C_3$ and $C_4$ alkanes.

These and other $C_{2+}$ alkanes are of thermogenic origin (Hunt, 1979), and could have been produced by thermal maturation of organic matter by hydrothermal solutions (Welhan, 1988). Although methane ($CH_4$) is also produced thermogenically, about 80 volume percent of methane in air is biogenic (Enhalt, 1974), hence it may be misleading as a guide to hydrothermal ore deposits. Hydrocarbon gas anomalies were found at several sites in the study area and these sites may indicate concealed gold deposits. Six of the sites with hydrocarbon gas anomalies also have $CO_2$-$O_2$ anomalies.

These gas studies compliment geophysical studies in the area. A northwest-trending $H_2$ anomaly near the foot of Welches Canyon corresponds with the location of a deep crustal fault as interpreted from magnetotelluric measurements (Rodriguez,1997).

## CONCLUSIONS

Linear patterns of $H_2$ and $CO_2$ in soil gas were found 8 to 11 km both east and west of the hypothetical center line of the Carlin Trend, and are parallel to it. This alignment probably results from leakage of gases along faults. If so, these faults may represent regional structures that influenced the localization of the Carlin Trend and the gold deposits along it.

These gas anomalies extend to the northwest about 10 km beyond the known gold deposits along the Trend. Anomalies typical of oxidizing sulfide minerals (high $CO_2$ and low $O_2$) are found at two sites north of the known gold deposits, one on Antelope Creek and one on Willow Creek. The Willow Creek anomaly has a coincident hydrocarbon gas anomaly. The gas anomalies reported here may also be produced by volcanic-hosted gold or base-metal deposits. These findings indicate that the Carlin Trend may extend to the northwest and perhaps contain additional mineral deposits.

## REFERENCES CITED


Barnes, I., Irwin, W.P., and White, D.E., 1978, Global distribution of carbon dioxide discharges, and major zones of seismicity: U.S. Geological Survey Open-File Report 78-39, 12 p.

Coveney, R.M., Jr., Goebel, E.D., Zeller, E.J., Dreschhoff, G.A.M., and Angino, E.E., 1987, Serpentinization and the origin of hydrogen gas in Kansas: American Association of Petroleum Geologists Bulletin, v. 71, no. 1, p. 39-48.

Disnar, J.R., 1990, Volatile hydrocarbons in Ba-Zn-Pb ore genesis: analysis and use in mineral exploration: Journal of Geochemical Exploration, v. 38, p. 205-224.

Enhalt, D.H., 1974, The atmospheric cycle of methane: Tellus, v. 26, p. 58-70.

Fridman, A.I., 1990, Application of naturally occurring gases as geochemical pathfinders in prospecting for endogenetic deposits: Journal of Geochemical Exploration, v. 38, nos. 1-2, p. 1-11.

Hoefs, J., 1997, Stable isotope geochemistry: New York, Springer-Verlag, 201 p.

Hunt, J.M., 1979, Petroleum geochemistry and geology: San Francisco, W.H. Freeman and Company, 617 p.

Ilchik, R.P., Brimhall, G.H., and Schull, H.W., 1986, Hydrothermal maturation of indigenous organic matter at the Alligator Ridge gold deposits: Nevada, Economic Geology, v. 81, p. 113-130.

Kasimov, N.S., Kovin, M.L., Proskurykov, Y.V., and Shmel'kova, 1979, Geochemistry of the soils of fault zones (exemplified by Kazakhstan): Soviet Soil Science, v. 11, p. 397-406.

Kesler, S.E., Gerdenich, M.J., Steininger, R.C., and Smith, C., 1990, Dispersion of soil gas around micron gold deposits: Journal of Geochemical Exploration, v. 38, nos. 1-2, p.117-132.

Krauskopf, K., 1967, Introduction to geochemistry: New York, McGraw Hill, Inc., 721 p.

Lovell, J.S. and Hale, M., 1983, Application of soil-air carbon dioxide and oxygen measurements to mineral exploration: Transactions of the Institute of Mining and Metallurgy, v. 92, p. 28-32.

Lovell, J.S., Hale, M., and Webb, J.S., 1983, Soil air carbon dioxide and oxygen measurements as a guide to concealed mineralization in semi-arid and arid regions: Journal of Geochemical Exploration, v. 19, p. 305-317.

Mason, Brian and Moore, C.B., 1981, Principles of Geochemistry: New York, John Wiley and Sons, 344 p.

McCarthy, J.H., Jr., Vaughn, W.W., Learned, R.E., and Meuschke, J.L. 1968, Experiments with mercury in soil gas and air applied to mineral exploration: Mining Engineering, v. 20, no. 12, p. 46-47.

McCarthy, J.H., Jr., and Bigelow, R.C., 1990, Multiple gas analyses using a mobile mass spectrometer: Journal of Geochemical Exploration, v. 38, p. 233-245.

McCarthy, H. and Hardyman, R., 1996, Mapping concealed faults in basins by measurement of naturally occurring gases, *in* Coyner, A.R. and Fahey, P.L., eds., Geology and Ore Deposits of the American Cordillera: Geological Society of Nevada Symposium Proceedings, Reno/Sparks, Nevada, April 1995, p. 757-768.

McCarthy, J.H., Jr., Lambe, R.N., and Dietrich, J.A., 1986, A case study of soil gases as an exploration guide in glaciated terrain: Economic Geology, v. 81, p. 408-420.

McCarthy, J.H., Jr., Erdman, J.A., Lovering, T.G., and Bettles, K.H., 1989, Evaluation of multiple geochemical sample media at the Betze gold deposit, Eureka County, Nevada: U.S. Geological Survey Circular 1035, p. 45-46.

Neal, C. And Stanger, G., 1983, Hydrogen generation from mantle source rocks in Oman: Earth and Planetary Science Letters, v. 66, p. 315-320.

Percival, T.J., Bagby, W.C., and Radtke, A.S., 1988, Physical and chemical features of precious metal deposits hosted by sedimentary rocks in the western United States, *in* Schafer, R.W., Cooper, J.J., and Vikre, P.G., eds., Bulk mineable precious metal deposits of the western United States: Geological Society of Nevada, p. 11-34.

Peters, S.G., this volume, Evidence for the Crescent Valley-Independence lineament, north-central Nevada, *in* Tosdal, R.M., ed., Contributions to the gold metallogeny of northern Nevada: U.S. Geological Survey Open-File Report.

Roberts, R.J., 1960, Alinements of mining districts in north-central Nevada: U.S. Geological Survey Professional Paper 400-B, p. B17-B19.

Roberts, R.J., 1966, Metallogenic provinces and mineral belts in Nevada: Nevada Bureau of Mines and Geology, Report 13, p. 47-72.

Roberts, R.J., Montgomery, K.M., and Lehner, R.E., 1967, Geology and mineral resources of Eureka County, Nevada: Nevada Bureau of Mines and Geology Bulletin 64, 152 p.

Rodriguez, B.D., 1997, Deep regional resistivity structure across the Carlin trend, *in* Vikre, P., Thompson, T.B., Bettles, K., Christensen, O., and Parratt, R., eds., Carlin type gold deposits: Society of Economic Geologists, Guidebook Series, Volume 28, p. 39-45.

Rose, A.W., Hawkes, H.E., and Webb, J.S., 1979, Geochemistry in mineral exploration: New York, Academic Press, 657 p.

Saltus, R.W. and Jachens, R.C., 1995, Gravity and basin-depth maps of the Basin and Range province, western United States: U.S. Geological Survey, Map GP-1012, 1:2,500,000 scale.

Shcherbakov, A.V. and Kozlova, N.D., 1986, Occurrence of hydrogen in subsurface fluids and the relationship of anomalous concentrations to deep faults in the USSR: Geotectonics, v. 20, p. 120-128.

Shawe, D.R., 1991, Structurally controlled gold trends imply large gold resources in Nevada, *in* Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W. Geology and Ore Deposits of the Great Basin, Symposium Proceedings: Geological Society of Nevada, v. 1, p. 199-212.

Sugisaki, R., Ido, M., Takeda, H., Isobe, Y., Hayashi, Y., Nakamura, N., Satake, H., and Mizutani, Y., 1983, Origin of hydrogen and carbon dioxide in fault gases and its relation to fault activity:

Journal of Geology, v. 91, no, 3, p. 239-258

Tan, K.H., 1994, Environmental soil science: New York, Marcel Dekker, Inc., 304 p.

Taylor, C.H., Kessler, S.E., and Cloke, P.L., 1981, Sulfur gases produced by the decomposition of sulfide minerals: application to geochemical exploration: Journal of Geochemical Exploration, v. 17, p. 165-186.

Welhan, J.A. and Craig, H., 1979, Methane and hydrogen in East Pacific Rise hydrothermal fluids: Geophysical Research Letters, v. no. 11, p. 829-831.

Welhan, J.A., 1988, Origins of methane in hydrothermal systems: Chemical Geology, v. 71, no. 1/3, p. 183-198.

Wooden, J.L., Tosdal, R.M., and Kistler, R.W., 1997, Pb and Sr isotopic mapping of crustal structure in the Northern Great Basin, *in* Vikre, P., Thompson, T.B., Bettles, K., Christensen, O., and Parratt, R., eds., Carlin-type gold deposit: Society of Economic Geologists, Guidebook Series, Volume 28, p. 47-51.