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**Reconnaissance fluid inclusion study of silver and gold
deposits in the Tonopah 1° x 2° quadrangle, Nevada**

By

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

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INTRODUCTION

Nevada has been the site of active exploration for precious-metal deposits for over a hundred years. Most of the deposits discovered in the past have shown surficial indications of the underlying mineralization, such as quartz veining, jasperoid, outcropping gossan, or other types of alteration. Observations of this variety are still useful today; however, most near-surface deposits have already been discovered. New geologic concepts and geochemical exploration techniques should aid in the discovery of the deeper deposits with more subtle surface expression. The Conterminous United States Mineral Appraisal Program (CUSMAP) was initiated in 1981 to apply modern geologic, geochemical, and geophysical concepts and techniques for mineral resource assessment in the Tonopah 1° x 2° quadrangle. The present study is an attempt to use fluid inclusion data as a means of characterizing the gross ore-forming environment of 18 precious-metal deposits or districts within the Tonopah 1° x 2° quadrangle.

CLASSIFICATION OF PRECIOUS-METAL DEPOSITS

Precious-metal deposits in the Tonopah 1° x 2° quadrangle occur in a variety of geologic settings and have highly variable mineralogic and elemental composition. For the purposes of this study, a classification scheme that emphasizes the geologic association and sulfide mineralogy is used for precious-metal deposits. The general mineralogy is visually evident at the deposits, even where the sulfides have been oxidized, and is also reflected in whole-rock chemistry (Nash, unpublished data). An empirical subdivision based on the relative amount of base-metal sulfides present is employed to distinguish between deposits that are hosted by volcanic rocks. This distinction has also been made by Heald-Wetlaufer and others (1983), but is not necessarily intended to imply genetic differences.

Four types of precious metal deposit have been defined in the Tonopah 1° x 2° quadrangle. Type EHS deposits are epithermal vein deposits with high base metal sulfide content, typically hosted by Tertiary volcanic or hypabyssal rocks. Oxidized parts of these deposits are often rich in cerargyrite (AgCl). ELS deposits are also epithermal, and are typically volcanic hosted, but have a higher ratio of precious to base metals, i.e., have relatively low base metal sulfide content. Several districts, such as Divide and Gilbert, could be placed in either the EHS or ELS category. Within the Divide district, for example, there are veins with very sparse sulfides and others with several percent sulfides including molybdenite. Type C deposits are associated with contact-metamorphic zones around plutonic rocks, as in the Barcelona district. Type M deposits are in low-grade metamorphic rocks, as at the Richmond and Berlin mines. Types C and M generally have a significant amount of base-metal sulfides present.

Table 1 is a classification of the deposits or districts in the Tonopah 1° x 2° quadrangle, from which fluid inclusion data were obtained in the present study, or for which published fluid inclusion data are available. The table also indicates the major elements exploited from each deposit or district, based mainly on production records.

As in any classification scheme, there are deposits which may be transitional between the end-member deposit types. However, this classification is utilized to simplify the discussion of the fluid inclusion data, which generally consist of a limited number of samples for any one deposit or district. By combining the data from different deposits in each

class, some general trends become apparent about the ore-forming fluids in the various deposit classes in the Tonopah 1° x 2° quadrangle.

FLUID INCLUSION DATA

Sample Selection

Samples for fluid inclusion study were collected from mine dumps and workings or outcrops. Sample collection was done in conjunction with geochemical sampling of the ore minerals. Samples of non-opaque minerals (generally quartz) were collected when judged potentially suitable in the field for fluid inclusion studies. Many samples contained both weathered and unweathered sulfides. One sample, no. 859 from the San Antone district (Cimarron Vein), contained visible gold. However, in general, the samples selected for study could not be placed unambiguously in a paragenetic sequence related to the main-stage mineralization of a particular deposit. This was due to the reconnaissance nature of the study and to the general lack of supporting evidence in the field. In general, the fluid inclusion data must be treated as point sources of information relative to the evolving hydrothermal systems which produced the mineralization. Figure 1 shows the location of samples collected for study.

Analytical Procedure

Doubly polished plates, approximately 0.1-0.5 mm thick, were prepared from the samples. The suitability of the samples for fluid inclusion study varied greatly, but most of the plates contained at least some useable inclusions. Homogenization temperature and salinity measurements were made in a U.S. Geological Survey laboratory using a gas-flow heating/freezing stage of USGS design. Salinity was determined from the freezing point depression of ice, which was converted to equivalent weight percent NaCl using the equation of Potter and others (1978). Salinities of CO₂-rich inclusions were determined by recording the melting temperature of clathrate coexisting with CO₂ vapor, liquid CO₂, and water. This temperature was then converted to equivalent weight percent NaCl using the relationships of Chen (1972) and Bozzo and others (1975) as discussed in Collins (1979). Predominantly primary inclusions were used in this study, and criteria for determining the origin of inclusions were based on Roedder (1984a). In general, inclusions located along crystal growth planes, or isolated, regularly shaped inclusions were considered to be primary, i.e., trapped during crystal growth. Inclusions located along curvilinear planes (healed fractures) in the crystals were generally considered to be secondary in origin. However, in a few cases there was evidence that these planes terminated against a growth zone in the crystal, indicating a pseudosecondary origin for the inclusions. Inclusions that had obviously undergone "necking" were not used.

Because of the reconnaissance nature of the study and uncertainties as to the paragenetic significance of the samples, only a limited number of measurements were performed on a single sample. The number of homogenization temperature measurements ranged from 5 to 30 per sample, with an average of 7. Fewer salinity measurements were taken due to optical limitations. However, even with only a limited number of observations, the data were generally tightly clustered, and the value reported represents a modal value. When the data were more variable, the range of values is reported (Table 2).

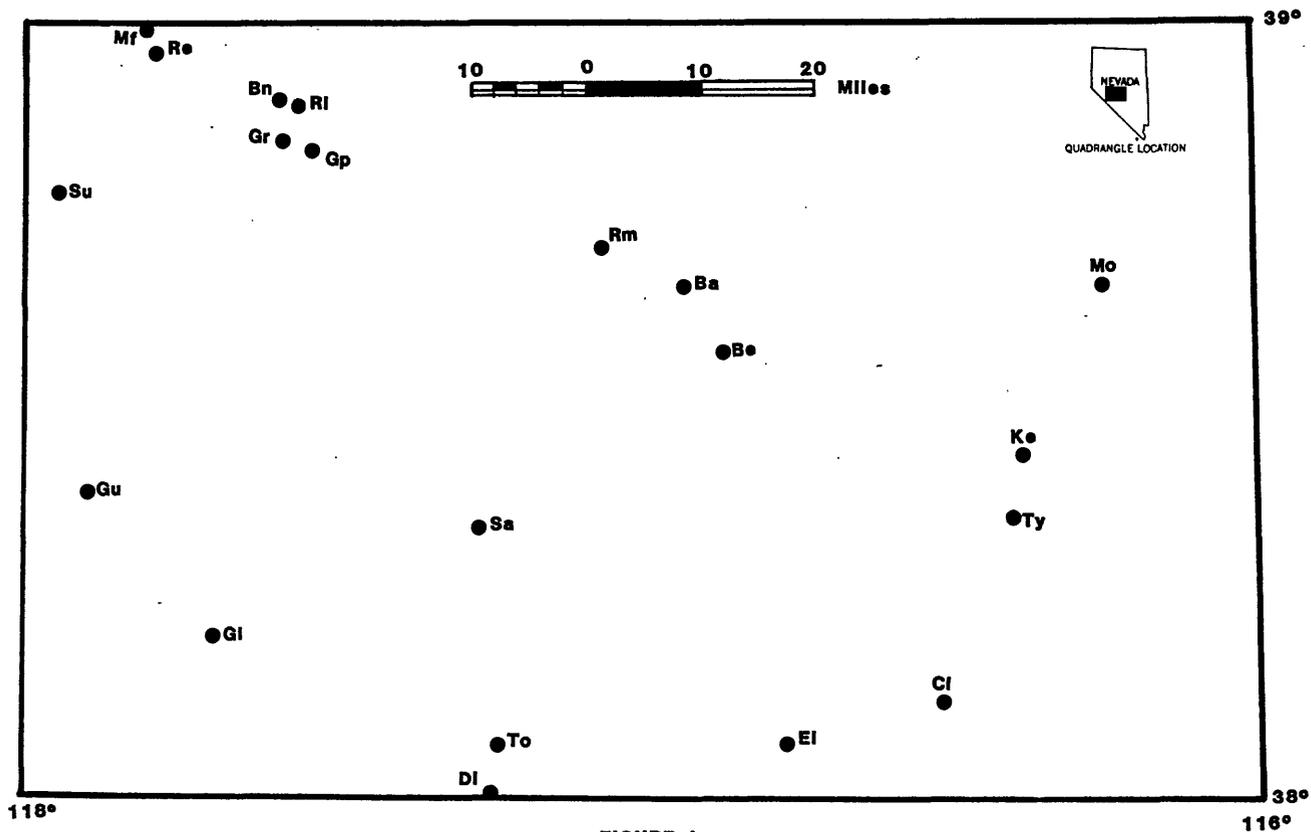


FIGURE 1.

Figure 1. Location of silver and gold deposits and districts within the Tonopah 1° X 2° quadrangle sampled for fluid inclusion studies. Abbreviations of deposit or district names: Ba, Barcelona; Be, Belmont; Bn, Berlin; Cl, Clifford; Di, Divide; El, Ellendale; Gi, Gilbert; Gp, Grantsville Pass; Gr, Grantsville; Gu, Gunmetal (Pilot Mountain); Ke, Keystone; Mf, Marble Falls; Mo, Morey/Red Mountain; Re, Return; Ri, Richmond; Rm, Round Mountain; Sa, San Antone; Su, Sullivan; To, Tonopah; Ty, Tybo.

The homogenization temperatures reported represent a lower bound on the trapping temperature of the fluid. A correction for the effect of pressure should be added to the homogenization temperature (T_h) in most cases. This correction generally ranges from 0°C for boiling fluids to more than 100°C for fluids under moderate geologic pressures. A 100°C pressure correction corresponds to a 3 km burial depth (assuming a 1 kb lithostatic fluid inclusion entrapment pressure at this depth, and an isochoric slope, $(dP/dT)_V=10$ bars/°C, appropriate for moderate salinity aqueous inclusion fluids. However, since many of the deposits investigated in this study are believed to have formed at shallow levels, the pressure correction would be small, probably less than 10°C. Since a range of 10° or more is typical of the distribution of T_h measurements from any of the sample localities, the effect of pressure has been neglected. However, type C and M deposits may have formed at greater depths and would require significant pressure corrections. Determination of fluid pressure during entrapment of an inclusion must be based on geologic reconstruction of the depth and pressure conditions (lithostatic vs. hydrostatic), and is beyond the scope of this report.

Results

Results of the fluid inclusion studies are presented in Table 2. Published fluid inclusion data from other deposits in the Tonopah 1° x 2° quadrangle are included for comparison and completeness.

As can be seen from Table 2, homogenization temperatures range from about 175° to 360°C for the epithermal volcanic-hosted deposits (EHS and ELS). However, the values tend to cluster around 250°-270°C. These temperatures are in accordance with the observations of Heald-Wetlaufer and others (1983) in their compilation of published data on volcanic-hosted precious- and base-metal districts. They report 230°-270°C as the typical range of homogenization temperatures for precious-metal deposition, with almost a complete overlap between deposits with high and low base-metal contents. In addition, they noticed bimodal distribution for the reported salinities of fluid inclusions at 1-3% and 6-8%. As can be seen from Table 2, the epithermal deposits, EHS and ELS, studied in the Tonopah 1° x 2° quadrangle, generally fall into these salinity ranges, with most at the lower end. Although a considerable overlap in temperature and salinity data is evident, the temperature and salinity ranges for the EHS are somewhat higher than for the ELS deposits. These data may or may not be statistically significant, but they are consistent with higher solubilities of base metals as chloride complexes at higher salinities and temperatures.

No evidence of CO₂ was observed in fluid inclusions from the volcanic-hosted deposits, although generally >10 mole percent CO₂ must be present to be observed optically (Roedder, 1984a). Among samples collected for this study, fluid inclusion evidence for boiling conditions in the volcanic-hosted EHS and ELS deposits is rare. However, some apparently primary, unnecked inclusions in samples from the Gilbert, Keystone, and Sullivan districts are vapor dominant, indicating entrapment above the two-phase interface in a boiling system. Due to the lack of paragenetic control, these vapor-dominant inclusions cannot be directly related to precious-metal deposition.

Based on the correspondence of the temperature and salinity data for volcanic-hosted deposits in this study with published data (Table 2), we suggest that the samples collected for this study are generally representative of the ore-forming stages of the hydrothermal systems for these deposit

types. However, sample 456, vein quartz from the Tybo district, is apparently not related to the main-stage mineralization; fluid inclusion measurements suggest that it formed from cooler, low salinity fluids.

Silver, and a minor amount of gold, have been mined from deposits related to contact-metamorphic zones adjacent to Jurassic-Cretaceous plutons (type C deposits). Some of these deposits are calc-silicate skarn-type deposits, such as the Gunmetal tungsten deposit (with minor silver), while others are related to silica alteration zones. In the latter type of deposit, silver is associated with Cu-Pb-Zn-W mineralization, as at the Barcelona mine. Only at the Sullivan mine does gold seem to be more important than silver (Kleinhampl and Ziony, 1984).

Temperatures and salinities of aqueous and CO₂-rich inclusions in the type C deposits (table 2) do not differ greatly from the previously described volcanic-hosted deposits. Homogenization temperatures range from about 240° to 360°C, while the salinities range predominantly between 3.5 and 5.5 wt. percent NaCl equivalent. As mentioned above, the homogenization temperatures of aqueous inclusions from this deposit type could require significant correction for pressure effects. It should be noted, however, that in contrast to the H₂O-NaCl system, H₂O-NaCl-CO₂ homogenization in the 200°-300°C range generally corresponds to pressures above one kilobar (see, for example, Bowers and Helgeson, 1985, fig. 2) for low salinity fluids. The salinities of fluid inclusions from type C deposits are generally higher than the ELS deposits, but are similar to the range for the EHS deposits. Three-phase inclusions indicate the presence of CO₂ in some inclusions from the Sullivan Cu-Au-Ag deposit. Permissive evidence for boiling (immiscibility) was also observed in samples from the Sullivan deposit; this evidence consisted of primary water-rich and CO₂-rich inclusions which homogenized in the same general temperature range. However, there was no concrete evidence that these two types of inclusions were contemporaneous as they were not clearly located along the same growth zone.

Silver-gold vein deposits hosted by regionally metamorphosed, lower greenschist grade Paleozoic-Mesozoic volcanoclastic rocks (type M) occur at Richmond and Berlin (fig. 1). Mineralization is localized in quartz veins, which are characterized by the lack of alteration halos in the host rocks, suggesting that metamorphism may have been important in forming or remobilizing these deposits. Temperature and salinity data from these deposits (table 2) are not significantly different from other deposit types investigated in this study; however, the presence of visible liquid CO₂ at room temperature implies significant (>1 kilobar) pressures at the time of entrapment. Homogenization temperatures were in the range of 215°-275°, with salinities less than 3 wt. percent NaCl equivalent. In addition, fluid inclusions in samples from this type of deposit commonly have a high (>20 mole percent) CO₂, visible as a ring of liquid around the vapor bubble. CO₂ is a major constituent of fluid inclusions in gold deposits hosted by metamorphic rocks elsewhere (Roedder, 1984b), and is a common volatile species liberated by prograde metamorphism. Fyfe and Kerrich (1984) have suggested that prograde metamorphism can: (1) produce volatile species capable of transporting gold (such as the carbonyl ion, CO); and (2) provide the source rocks for the gold. In their model, metals and fluids generated under conditions of the greenschist-amphibolite metamorphic grade transition move up permeable structures and are deposited higher in the sequence in lower metamorphic-grade rocks. Metal precipitation should occur in response to decreases in the temperature. The compatibility of metamorphic-hosted vein deposits in the Tonopah 1° x 2° quadrangle to this type of model cannot be

critically evaluated due to the allochthonous nature of the metamorphic terranes.

Discussion and Conclusions

Boiling, fluid mixing, and cooling are the three principal mechanisms for precipitating metals from solution. Given a suite of samples representative of a system, and containing fluid inclusions suitable for study, the precipitation mechanism can frequently be identified. Fluid mixing may be identified through the spatial distribution of fluid inclusions of distinct temperatures and salinities. A progressive change in composition (salinity, volatile content, etc.) between distinct endmembers is indicative of mixing. Simple cooling may also cause precipitation of metals and may be documented as progressively decreasing inclusion homogenization temperatures away from the heat source, given a knowledge of relative pressure corrections. Fluid inclusion evidence for boiling is frequently more controversial than for the other precipitation mechanisms, and merits discussion since it applies to some of the samples examined in this report.

The most unequivocal evidence of boiling would be a group of coeval vapor-dominant inclusions (Bodnar and others, 1985). Some of the inclusions from the Gilbert, Keystone, and Sullivan deposits fall into this category (Table 2). The absence of liquid-rich inclusions in the group precludes formation by necking of two-phase inclusions. These inclusions can only have been trapped at or above the liquid-vapor interface of a boiling system. Another form of evidence for boiling consists of contemporaneous liquid- and vapor-dominant inclusions for which the liquid/vapor ratios are consistent among the liquid-dominant group and different, but consistent among the vapor-dominant inclusions. Ideally, both the liquid- and vapor-dominant inclusions would homogenize at the same temperature. However, due to the difficulty in observing homogenization to a vapor phase, vapor-dominant inclusions may yield a range of temperatures (Bodnar and Sterner, 1985). Liquid or vapor-dominant inclusions with consistent liquid/vapor ratios represent trapping of the pure endmember phase. Textural observations such as chalcedonic banding within a quartz vein may indicate rapid precipitation, and are consistent with boiling, but are not, by themselves, proof that boiling occurred.

Perhaps the most important point to be made about fluid inclusion evidence for boiling is that the absence of such evidence does not indicate that boiling did not occur (Roedder, 1984b, p. 33-34). For reasons not fully understood, inclusions may preferentially trap either phase present in a two-phase system (Roedder, 1984b, p. 28-31; Bodnar and Sterner, 1985). The more usual case, however, is preferential entrapment of the liquid phase. Caution must be used to avoid erroneously interpreting necking as heterogeneous trapping, or an ambiguous microcrystalline texture as evidence of boiling. On the other hand, instances of boiling will necessarily go unrecognized because the preferential trapping of the liquid phase leaves little or no evidence of the vapor that was present. In addition, microcrystalline phases such as chalcedony invariably trap inclusions that are too small to work with, making it impossible to verify that this phase resulted from boiling.

Despite the relative scarcity of well documented examples, boiling should, from a theoretical standpoint, be a common mechanism for precipitating metals that are present in solution as chloride complexes. Partitioning of "acid" volatile species such as CO_2 and H_2S to the vapor phase during boiling is very effective in raising the solution pH (Drummond and Ohmoto, 1985). An increase in pH destabilizes metal-chloride complexes, causing the metals to

precipitate. Since boiling is dependent on the prevailing hydrostatic or lithostatic pressure, metals deposited by the effect of boiling often show a strong correlation to stratigraphic position. However, little data were available in this study to evaluate the control of depth on metal distribution in the deposits studied.

When metals are carried in solutions as complexes other than chloride, the effects of boiling may not be evident. Drummond and Ohmoto (1985) have shown, for example, that boiling may actually increase the solubility of gold transported as bisulfide complexes. The pH of ore solutions, which carry gold in bisulfide complexes, is generally near neutral (Seward, 1984) and is in the H₂S stability field. Increases in pH due to boiling will increase the solubility of gold unless the amount of H₂S loss to the vapor is greater than the pH increase by a fixed ratio (Drummond and Ohmoto, 1985). Therefore, in certain cases, boiling is less effective than cooling or fluid mixing in causing metal precipitation.

Boiling has been suggested by a number of workers (Berger and Eimon, 1983; Buchanan, 1981) as a primary control for the concentration of precious metals in epithermal deposits. It is not surprising that boiling should have occurred at some point in many of the deposits studied here, given the temperature range indicated by fluid inclusion data and their inferred shallow levels of formation. However, identification of the precipitation mechanism using fluid inclusions often requires a very detailed study of an extensive suite of samples from a given deposit. In many cases, such as the present study, it may not be possible to locate a reasonable number of unnecked inclusions large enough to work with (generally >4 micrometers) and clearly related to mineralization. Heald-Wetlaufer and others (1983), in their compilation of characteristics of volcanic-hosted deposits, found boiling to be unequivocally associated with precious-metal deposition at only a few of the 15 deposits they investigated, and also found that boiling occurred at time intervals not related to precious-metal deposition.

The fluid inclusion data generated in this study suggest that the deposit types described in this study cannot easily be distinguished on the basis of homogenization temperatures, but show significant differences in the salinity and CO₂ content. Homogenization temperature values for the epithermal, volcanic hosted deposits of both high and low base-metal sulfide content (EHS and ELS) fall predominantly between 250° and 270°. There is almost complete overlap in the ranges of values from each category, although there is a slight tendency for the EHS samples to yield higher temperatures. Salinities for the EHS category range up to 8.2 wt. percent NaCl equivalent, while salinities for ELS samples do not exceed 2.5 wt. percent NaCl equivalent. Salinities for type C deposits fall primarily between 3.5 and 5.5 wt. percent NaCl equivalent, while salinities of type M deposits are distinctly lower, ranging from 0.5 to 3.0. CO₂ was observed only in type C and type M deposits.

The data from the volcanic-hosted deposits agree favorably with published data from similar, better documented deposits in Nevada and elsewhere. Evidence of boiling was observed at a few deposits, although its relationship to precious-metal precipitation is not known.

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TABLE 1.--Classification of gold-silver and related deposits studied in the Tonopah 1° x 2° quadrangle, Nevada

[Abbreviations: Au, predominantly a gold deposit; Au-Ag, gold deposit with significant by-product silver; Ag-Au, silver deposit with significant by-product gold; Ag, predominantly a silver deposit; Cu-Pb-Zn-W-Hg, other commodities produced in significant quantities]

EHS (Epithermal, volcanic associated, high base-metal sulfide content)

Tybo, Ag-Pb-Zn	Grantsville, Ag-Pb
Morey (Wist Vein), Ag	Ellendale, Cu-Ag-Au ³
Gilbert, Au-Ag ¹	Keystone, Ag-Au ³

ELS (Epithermal, volcanic associated, low base-metal sulfide content)

Grantsville Pass, Hg-Pb-Cu	Clifford, Ag-Au
Return (Ellsworth), Ag-Au	San Antone (Cimarron Vein), Au-Ag
Tonopah, Ag-Au ²	Round Mountain, Ag-Au ²
Divide, Ag-Au ¹	

C (Associated with contact zones of plutons)

Sullivan, Cu-Au-Ag	Gunmetal, W, Ag ³
Barcelona, Ag-Au	Belmont, Ag-Pb
Marble Falls, Au-Ag	

M (Veins in metamorphic rocks)

Berlin, Ag-Au	Richmond (Union), Ag-Au
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¹Transitional between EHS and ELS.

²Not studied, but published fluid inclusion data are available.

³Historical records report production of an unknown quantity of gold or silver.

TABLE 2.--Fluid inclusion data for gold and silver bearing veins in the Tonopah quadrangle, Nevada.

[Explanation: Deposit type: ELS, epithermal with low associated base metal content; EHS, epithermal with high associated base metal content; M, metamorphic vein; C, contact zone. Host mineral: Q, quartz; F, fluorite. Fluid inclusion type: 1, aqueous, liquid-dominant; 2, aqueous, vapor-dominant; 3, CO₂-rich; P, primary; S, secondary. T_h: mode of temperatures within a 20°C range, unless a larger range is shown; #, number of measurements made. Cp = chalcopyrite; gn = galena; py = pyrite; sphal = sphalerite]

No.	District or mine	Deposit type	Host mineral	F.I. type	T _h (°C) (#)	Salinity wt.% NaCl eq. (#)	Comments
993	Return (Ellsworth)	ELS	Q	1P	252 (2)	1.5-2.3 (3)	
1273	Clifford	ELS	Q	1P	241 (10)	1.3 (2)	
859	San Antone (Cimarron Vein)	ELS	Q	1P	237 (6)	0.8 (2)	coarse Au
959	Grantsville Pass (Hg)	ELS	Q	1P	249 (7)	1.7-2.5 (3)	Hg deposit
N39-68	Round Mtn. ¹	ELS	Q	1P	260	0.2-1.4	assoc. w/ adularia
N69-68	Round Mtn. ¹	ELS	Q	1P	250	0.2-1.0	assoc. w/ adularia
--	Tonopah ²	ELS	Q,F		230-260	0.8-2.0	boiling?
374	Gilbert	EHS	Q	1P	265-365 (5)	2.0 (5)	boiling?
		EHS	Q	1S	265 (15)	1.0 (1)	
		EHS	Q	3P?			
383	Gilbert	EHS	Q	1P	254-277 (4)	0.8-1.3 (4)	
1547	Morey (Wist Vein)	EHS	Q	1P	260-340 (5)	8.2 (3)	dissem. py
1287	Ellendale	EHS	Q	1P	230-267 (4)	0.8-1.0 (3)	Cu-Fe oxides

TABLE 2. (continued)

No.	District or mine	Deposit type	Host mineral	F.I. type	T _p (°C) (#)	Salinity wt.% NaCl eq. (#)	Comments
452	Keystone	EHS	Q	1P	235 (7)		sphal + gn
		EHS	Q	1P	265 (5)		
		EHS	Q	1P	285 (8)		
		EHS	Q	1,2P	325 (9)		boiling
456	Tybo	EHS	Q	1P	173-197 (11)	1.0-1.5 (7)	
297	Divide	EHS	Q	1P	212-241 (12)	6.5-7.5 (6)	
512	Grantsville	C	Q	1P	181-273 (6)		abnt. Fe-oxides + sulfides
		C	Q	1S	220-260 (4)		
514	Grantsville	C	Q	1S	177-207 (11)	3.8 (5)	abnt. Fe-oxides + sulfides
		C	Q	1S		1.0 (5)	
517	Grantsville	C	Q	1P	228 (9)	5.8 (3)	abnt. Fe-oxides + sulfides
920	Grantsville	C	Q	1P	208-234 (5)	3.5-5.3 (3)	veins in jasperoid
900	Barcelona	C	Q	3P	289 (7)	4.8 (2)	
1017	Belmont	C	Q	3	254 (3)	4.7-5.4 (3)	
939	Gunmetal	C	Q	1P	247 (9)	4.8 (3)	
940	Gunmetal	C	Q	1P	231 (2)	3.3-4.8 (5)	

TABLE 2. (continued)

No.	District or mine	Deposit type	Host mineral	F.I. type	T _h (°C) (#)	Salinity wt.% NaCl eq. (#)	Comments
959	Sullivan	C	Q	1P	299 (5)	4.8-5.5 (2)	boiling
		C	Q	2P	350 (2)		
980	Marble Falls	C	Q	1P/S	277-325 (6)	2.5-3.7 (2)	gn, Au
931	Union (Richmond)	M	Q	3	274 (4)	1.0-2.8 (4)	cp
935	Union (Richmond)	M	Q	3	242 (7)	1.8-2.8 (3)	cp
1013	Berlin	M	Q	1P	214 (4)	0.8-1.9 (3)	

¹Nash (1972)²Fahley (1979)