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Distribution of minor elements in the Rodeo Creek Northeast Welches Canyon quadrangles, Eureka County, Nevada

by

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Abstract

The Rodeo Creek NE and Welches Canyon quadrangles include the Lynn Window of the Roberts Mountains thrust. The area is noted for the disseminated gold deposits at the Carlin mine, along the northeast margin of the window. Distributions of 13 elements (Ag,As,Au,Ba,Cu,Hg,Mn,Mo,Pb,Sb,Sn,W and Zn) in 877 rock samples from the two quadrangles were studied. Major gold deposits occur in a northwest-trending zone of hydrothermally altered rock, which may coincide with a Paleozoic or Proterozoic structure, near and along which Cretaceous and early Oligocene intrusions were emplaced. Hydrothermal activity asociated with each of the intrusions may have had a part in development of the zone of hydrothermally altered rock, although gold mineralization may not have occurred during each episode of alteration.

The thirteen elements studied seem to be segregated geographically into two groups: (1) Au, As, Hg, Sb, Cu and Pb, principally in the Rodeo Creek NE Quadrangle around the Carlin deposit; and (2) Ag, Ba, Mo, Mn, W, Sn and Zn in both quadrangles, in the Carlin mine area and in southern Lynn Window. This element distribution may be due to one or more ore controls, including possible element zoning in a geothermal system.

Mass balance calculations suggest that the gold at the Carlin deposit could have been leached largely from the country rock, but magmatic sources cannot be ruled out. The gold could have been transported to the depositional site during the life of a single geothermal system. Geologic evidence, however points to as many as three geothermal systems in the area, suggesting that the hydrothermal processes for forming the deposit may have had low efficiency.

Gold placer deposits, probably subeconomic, may occur in Tertiary and Quaternary sediments east and west of the Carlin and Big Six lode deposits and downstream from gold-bearing quartz veins in the Hanson Creek Formation.

Exploration guides for Carlin-type deposits include (1) a permeable lithology, especially, but not exclusively, the silty dolomitic limestone of Roberts Mountains and Popovich Formations; (2) broad intersecting fault zones, especially ones of regional extent; (3) Mesozoic and Tertiary intrusions; (4) broad zones of hydrothermally altered rock, especially if these zones coincide with (2); and (5) mercury anomalies in soil gas.

Introduction

Location and interest

The Rodeo Creek NE and Welches Canyon quadrangles are located in the southern Tuscarora Mountains, northernmost Eureka County, Nev. (fig. 1). The area is significant because of the completeness of an autochthonous section of predominantly carbonate rocks of Cambrian to Late Devonian age exposed in the

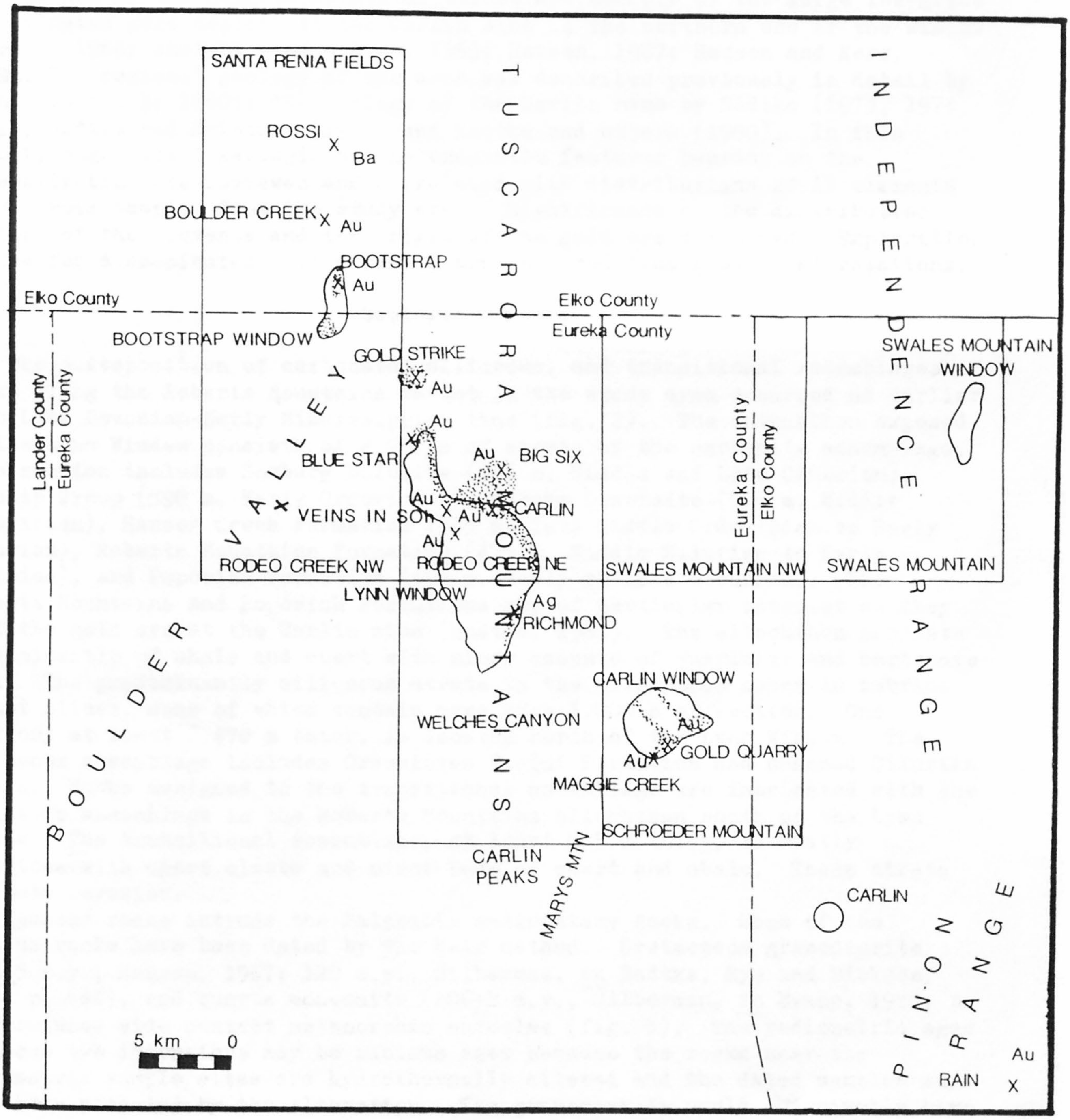

Figure 1. Index map showing location of Rodeo Creek NE and Welches Canyon quadrangles and adjacent areas.

Lynn Window of the Roberts Mountains thrust and because of the large low-grade disseminated gold deposit at the Carlin mine in the northern end of the window (Hardie, 1966; Akright, and others, 1969; Hausen, 1967; Hausen and Kerr, 1968). The regional geology of the area was described previously in detail by Evans (1974a, b; 1980); the geology of the Carlin mine by Radtke (1973, 1974, 1981), Radtke and Scheiner (1970) and Radtke and others (1980). In this report, significant geologic and aeromagnetic features bearing on the mineralization are reviewed and correlated with distributions of 13 elements in 877 rock samples from the study area. Significance of the distribution pattern of the elements and the origin of the gold are discussed. Exploration guides for disseminated gold deposits are inferred from geological relations.

Geologic summary

The juxtaposition of carbonate, siliceous, and transitional assemblages of rocks along the Roberts Mountains thrust in the study area occurred no earlier than Late Devonian-Early Mississippian time (fig. 2). The autochthon exposed in the Lynn Window consists of 2,572 m of strata of the carbonate assemblage. This section includes Hamburg Dolomite (246 m, Middle and Late Cambrian), Pogonip Group (598 m, Early Ordovician), Eureka Quartzite (508 m, Middle Ordovician), Hanson Creek Formation (325 m, late Middle Ordovician to Early Silurian), Roberts Mountains Formation (473 m, Middle Silurian to Early Devonian), and Popovich Formation (424 m, Early to Late Devonian). The Roberts Mountains and Popovich Formations are of particular interest as they host the gold ore at the Carlin mine (Radtke, 1981). The allochthon consists predominantly of shale and chert with minor amounts of quartzite and carbonate rock. The predominantly siliceous strata in the allochthon occur in imbricate thrust slices, some of which contain more than 1,000 m of section. One section, at least 2,470 m thick, is located north of the Lynn Window. The siliceous assemblage includes Ordovician Vinini Formation and unnamed Silurian strata. Rocks assigned to the transitional assemblage are imbricated with the siliceous assemblage in the Roberts Mountains allochthon south of the Lynn Window. The transitional assemblage, at least 915 m thick, is mostly limestone with chert clasts and minor beds of chert and shale. These strata are Late Devonian.

Igneous rocks intrude the Paleozoic sedimentary rocks. Some of the igneous rocks have been dated by the K-Ar method. Cretaceous granodiorite (121±5 m.y., Hausen, 1967; 128 m.y., Silberman, in Radtke, Rye and Dickson, 1980, p. 644), and quartz monzonite (106±2 m.y., Silberman, in Evans, 1980, p. 57) produced wide contact metamorphic aureoles (fig. 3). The radiometric ages of these two intrusions may be minimum ages because the rocks near the radiometric sample sites are hydrothermally altered and the dated samples may have been affected by the alteration. The granodiorite could conceivably have been emplaced earlier than Cretaceous (Jurassic?).

Narrow contact aureoles were formed by granodiorite (37±0.8 m.y.,Silberman, in Evans, 1980, p. 62) and quartz latite (36.6±0.7, McKee and others, 1971, p. 41) emplaced south of the Lynn Window (fig. 3) in early Oligocene. Dikes of intrusive breccia contain fragments resembling quartz latite and may, therefore, be younger than quartz latite. Andesitic dikes of unknown age intrude the siliceous assemblage.

Cretaceous, Tertiary, and Quaternary strata were deposited on older rocks. Cretaceous or early Tertiary rhyodacite flows were deposited on the siliceous assemblage south of the Lynn Window. Rhyolitic welded tuff (14.2 ± 3 m.y., McKee and others, 1971, p. 41) was deposited just west of the window at about the same time as part of the Miocene-Pliocene Carlin Formation was deposited on the east side of the Tuscarora Mountains. Unnamed late Tertiary and Quaternary alluvial deposits occur on both sides of the mountains.

The Antler Orogeny in Late Devonian to Early Mississippian time was probably the earliest episode of deformation recorded in the study area (chert clasts in upper Devonian Limestone of the transitional assemblage). During this orogeny the allochthonous siliceous and transitional assemblages were imbricated in the upper plate of the Roberts Mountains thrust and were brought into the area from the west. Large and minor folds, chiefly plunging at low angles north-northeast and south-southwest, developed in the allochthon during transport (Evans and Theodore, 1978). The autochthonous carbonate assemblage underwent complex faulting, including thrusting. New interpretations of the geology of northern Nevada suggest that post-Paleozoic thrusting may also have had an impact on the structural development of the southern Tuscarora Range (Ketner and Smith, 1982; Coats and Riva, 1983). In late Paleozoic or Mesozoic time, the carbonate assemblage was folded into a broad asymmetric anticline plunging 20° N. 15° W. The west limb of the anticline is overturned and thrust over the siliceous assemblage along the West Lynn thrust. Development of the large north-northwest-trending fold and elongation of the Lynn Window in that direction may be connected with emplacement of Cretaceous granitic rocks. Relatively minor steep faults postdate the Antler Orogeny, and faulting occurred throughout the Mesozoic and Tertiary. The longest post-Antler fault is the Tuscarora fault along the east side of the Tuscarora Mountains. This fault is partly Pliocene in age and may have been involved in development of the basin in which the Carlin Formation was then deposited.

Geology of the deposits

The following geologic sketch of the deposits is taken from the geologic map of the Rodeo Creek NE and Welches Canyon Quadrangles (Evans, 1974a, b). More details of the Carlin and Blue Star deposits are available in geologic interpretations of those areas by Radtke (1973, 1974). The Carlin deposit occurs along the northeast margin of the Lynn Window where the north-northeast striking Lynn fault intersects a zone of steep faults that strike northwest and northeast (fig. 2). The deposit lies in the predominantly silty laminated dolomitic limestone of the Roberts Mountains and Popovich Formations, just below the chert and shale of the upper plate of the Roberts Mountains thrust. The original sedimentary characteristics of much of the host rock have been destroyed by brecciation and hydrothermal alteration, which includes silicification of carbonate rock, leaching of carbonate minerals, argillic alteration, oxidation of carbonaceous material and sulfide minerals, and local enrichment of the rock in carbonaceous material. In places, as in some of the silicified rock, bedding laminae are preserved even though the mineralogy of the rock has been drastically altered by hydrothermal processes. Intensely altered dikes occur throughout the deposit.

The Blue Star deposit is located about 6 km northwest of the Carlin deposit, at the northern end of the Lynn Window (figs. 1, 2). The ore body is along a steep north-striking fault which lies between intensively hydrothermally altered carbonate rocks presumed to have been originally part of the Roberts Mountains and (or) Popovich Formations, and hydrothermally altered chert and shale of the siliceous assemblage. A thick zone of adularia-quartz-calc-silicate occurs near the deposit.

The Gold Strike mine is 3 km north of the Blue Star deposit. In the mine area rocks of the siliceous assemblage are intruded by a Cretaceous granodiorite stock and by latite dikes. Pods of calc-silicate hornfels present along the border of the stock are probably pieces of the carbonate assemblage brought up during intrusion. The stock has a broad (3 km) contact metamorphic aureole. Hydrothermal alteration and gold mineralization occur in all the rock types in the mine area and are intensely developed along faults and breccia zones.

The Big Six group of deposits is about 3 km north-northeast of the Carlin deposit, in brecciated chert along and near the Lynn fault (figs. 1, 2). The gold-quartz veins that comprise the lode deposits supplied gold to placer deposits in the area. One view of the Big Six deposits is that they are due to leakage through the Roberts Mountains thrust and along the Lynn Fault of the same mineralizing fluids that were involved in forming the Carlin deposit.

The defunct Richmond camp shown on a map of Emmons (1910, pl. 2) centers around the Cretaceous quartz monzonite in southeastern Lynn Window (figs. 1, 2). Prospect pits and tunnels are up to 3 km from exposures of the quartz monzonite pluton. Analyses of rocks from the area (fig. 15, this report) suggest that silver was the chief exploration target.

Tunnels and prospect pits dug prior to 1960 occur along quartz veins rich in orpiment and realgar that are in Hanson Creek Formation in northwest Lynn Window. Some of these workings may date from mining activity in the area early in this century. Analyses indicate high gold and silver concentrations in these veins.

Igneous rocks, aeromagnetic anomalies, and hydrothermal alteration

Concealed granitic rocks underlying parts of the study area are inferred from the broad contact metamorphic aureoles around the small Cretaceous intrusions and from the narrower aureoles around the Tertiary intrusions (Evans, 1974a, b; 1980). Visible contact metamorphic effects include bleaching, recrystallization, and neomineralization. Three aeromagnetic highs occur over the inferred concealed intrusions (fig. 3): (1) over the Cretaceous granodiorite at the Gold Strike Claims (1,944 gammas max); (2) over the Cretaceous quartz monzonite in southeast Lynn Window (2,072 gammas max); and (3) over the Tertiary granodiorite and quartz latite intrusions in the Welches Canyon area, south of the window (2,074 gammas max). The magnetic highs reflect concentrations of ferromagnetic minerals and strongly suggest that igneous rocks are far more widespread at depth than at the surface.

The large aeromagnetic low along the northeast flank of the window is of interest because the Carlin gold deposit lies on its southern edge. The low coincides with part of the large northwest-trending zone of hydrothermally altered rock. Alteration effects are listed above in the description of the Carlin deposit. Possible explanations of the low include (1) the occurrence of rock less magnetic than the surrounding rock, (2) oxidation of ferromagnetic minerals (3) a topological configuration occurring between two aeromagnetic highs (1,944 and 2,072 gammas), or (4) magnetic rocks polarized in a reverse sense. Because the low occurs over hydrothermally altered (oxidized) and unaltered sedimentary rock, hypotheses (1) and (2) are most favored. The effect of hypothesis (3), however, cannot be ruled out. Magnetic properties of the rocks would have to be measured to determine the effect of rock magnetization in development of the aeromagnetic low.

The broad northwest-trending zone of hydrothermally altered rock cuts across the southern edge of the contact metamorphic aureole associated with the Cretaceous (or Jurassic?) granodiorite. The hydrothermal alteration is clearly younger than the contact metamorphic effects, because rock which has been bleached and recrystallized, apparently as a result of contact metamorphism, has been partly oxidized, leached of carbonate minerals, argillically altered, and silicified. Projected northwest, the zone of hydrothermally altered rock alines with hydrothermally altered Roberts Mountains Formation at the south end of the Bootstrap Window (fig. 1; Evans and Mullens, 1976). The Bootstrap and Boulder Creek gold deposits lie close to the zone. Projected southeast, the zone alines with hydrothermally altered Silurian and Devonian rocks in the Carlin Window (fig. 1; Evans and Cress, 1972), with the Gold Quarry and Maggie Creek gold deposits at the south edge of the Carlin Window and with the Rain deposit southeast of the town of Carlin (fig. 1). These relations suggest that the northwest-trending zone of hydrothermally altered rock is nearly continuous in the subsurface for about 58 km. This zone coincides with part of the Lynn-Pinyon Belt (of mineralization) proposed by Roberts (1960, p. B18-B19). Roberts extends the belt 12 km farther southeast to include the Railroad district in the Pinyon Window.

The Cretaceous quartz monzonite and the Tertiary granodiorite intrude along steep northwest-striking faults (fig. 2). The South Richmond fault, which is intruded by quartz monzonite, has a stratigraphic separation of a few thousand meters. The Cretaceous granodiorite lies north-northwest of the other two intrusions, but no steep northwest-striking faults are mapped in its vicinity. The three intrusions lie near a line trending N. 25° W that may reflect a major fault in the subsurface. Roberts and others (1971, p. 20) consider the northwest-trending Lynn-Railroad and other mineral belts in north-central Nevada to reflect probable Proterozoic structures (faults?). These belts, however, are drawn trending N. 45° W. The zone of hydrothermally altered rock also has a trend of N. 45° W. This zone intersects the lineament defined by the intrusions at a point just northwest of the Blue Star mine.

Age of Mineralization

Radtke and others (1980, p. 646) and Radtke (1981, p. 40) postulated that mineralization at the Carlin deposit was late Tertiary and suggested that the igneous activity responsible for the middle Miocene rhyolitic welded tuff (called rhyolite and rhyodacite flows by Radtke and others) may have been the heat source for the hydrothermal activity. The present study revealed no evidence of mineralization in the tuff. Geologic mapping (Evans, 1980, p. 70-71) indicates that the Carlin deposit is located near the east edge of the welded tuffs, suggesting that the Miocene igneous activity is not close to the Carlin deposit and may have had no influence on the northwest-trending alteration zone.

Analyses of rock samples in this study indicate that the latest mineralization affected the early Oligocene quartz latite and must be post-early Oligocene. However, this may have been only one stage of mineralization that affected the area. At least three other intrusions were emplaced in the study area, each of which could have supplied heat to drive a geothermal system capable of altering rock and depositing gold.

A multi-episodic history of the kind we suggest for the Carlin deposit may be difficult or impossible to unravel by studying a small part of the zone of altered rock, for example, the Carlin deposit. Vigorous late stages of hydrothermal activity affecting previously hydrothermally altered rock may obliterate evidence of an earlier event. If the kinds of alteration in two or more episodes are similar, some of the effects of the earlier event (such as changes in mineralogy or stable isotope distributions) may be indistinguishable from the effects of the later event. Superposition of differing alteration phenomena could also yield intermediate values for some parameters (such as K-Ar dates of altered rock). Under such circumstances, evidence for the early episodes of alteration may be found only in the areas away from the major altered zones and outside the area involved in the latest hydrothermal event.

Mesozoic disseminated gold deposits are known in other parts of Nevada and a history of multistage intrusion and mineralization is not unique to the Lynn Window. A Cretaceous age of mineralization has been inferred for the Gold Acres deposit (Wrucke and Armbrustmacher, 1975, p. 5), 70 km southwest of the Carlin mine and for the Getchell deposit (Berger and Taylor, 1980, p. 597), 160 km southwest of the Carlin mine. In the Cortez-Buckhorn area the mineralization is complex. According to Wells and others, (1971, p. C134), the mineralization can be explained in two ways: (1) three periods of mineralization coinciding with Jurassic, Oligocene, and Miocene episodes of intrusion; or (2) formation of all deposits at one time, in Miocene or later, with variations in mineralization associated with differences in host rocks and (or) depth of formation of the deposit. Multistage mineralization in the Cortez deposit itself may have occurred, as Wells and others mention that Oligocene quartz porphyry occurs at the deposit and a Jurassic quartz monzonite and granodiorite intrusion is projected under the mine. Rye and others (1974) conclude that at Cortez stable isotopes point to mineralization in the Jurassic (galena; sulfur and lead isotopes) and Tertiary (gold; δD).

History

Gold was discovered in the Lynn district in 1907 in placers in intermittent stream channels draining terrain underlain by siliceous rocks immediately north of the Lynn Window (Johnson, 1973, p. 27). Shortly thereafter, lode mining commenced in quartz veins in chert and shale of the siliceous assemblage in the source area. Total reported gold production of the Lynn District from 1932 to 1961 was 6,644 ounces, (Roberts and others, 1967, p. 93) principally from placers and lode deposits in the siliceous assemblage.

In 1965, the Carlin gold mine, the most important mine of the district, began production from low-grade disseminated deposits in intensely fractured Roberts Mountains and Popovich Formations below the Roberts Mountains thrust at the northeast margin of the Lynn Window. By 1975 production was obtained from siliceous assemblage rocks in the Blue Star and Bootstrap areas. Gold production for the years 1965-82 (table 1) emphasizes the significance of the Carlin deposit.

Present study

During the course of geologic mapping in the Lynn Window and vicinity in 1968-71, 877 samples of mineralized, hydrothermally altered and unaltered sedimentary, igneous, and metamorphic rocks, ranging in age from Cambrian to Tertiary were collected for chemical analysis by J. G. Evans. The analyses were published by Evans and Peterson (1980). All of the samples were analyzed for 29 elements (Ag, As, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, La, Mg, Mn, Mo, Nb, Ni, Pb, Sb, Sc, Sn, Sr, Ti, V, W, Y, Zn, and Zr) by spectrographic methods (Grimes and Marranzino, 1968) and for Au and Hg by atomic absorption methods (Thompson and others, 1968; Vaughn and McCarthy, 1964). Occurrences of Ag, As, Au, Sb, Sn, W, and Zn are considered significant in the study area because the concentrations of them are well above crustal abundance. Concentrations at or above the following threshold values are also considered significant in the study area: Ba, 1,000 ppm; Cu, 200 ppm; Hg, 1 ppm; Mo, 50 ppm; Mn, 1,000 ppm; Pb, 100 ppm. Distributions of these elements in relation to geologic features are described and discussed in this report.

Locations of the sample sites are shown in figure 4. The density of sample sites is contoured in figure 5 using a counting circle with an area equal to 1 percent of the study area. The contours, in percent-per-1-percent area, represent sampling densities of 0, 1.5, 3, 6, 9, 12, 15, 18, 21, 24, and 27 samples per square kilometer. Sample sites tend to cluster in areas of known gold deposits in northern Lynn Window and vicinity. The sampling density also reflects the degree of natural and man made exposures and general visibility of alteration and mineralization. The southern and northern parts of the study area have a relatively low sample density which reflects generally poor exposures and lack of visibly altered and mineralized rock. Sample density in north-central Welches Canyon and west-central Rodeo Creek NE quadrangles are about the same (2 percent). Small isolated areas of relatively high sample density (1 percent) occur in the northeast and southeast corners of the study area owing to locally greater degree of outcrop. Inferences regarding element distributions as drawn from the analytical data are concluded to be largely independent of the sample density because (1) geological field observations supply additional information bearing on continuity of element distributions, (2) both the elements found and their quantity in the samples are independent of sample density, and (3) a hypothetical reduction in the number of sample sites in a uniform manner across the study area is judged to have little effect on determining locations of anomalous concentrations of the elements. If fewer samples had been taken, however, the confidence in and the size of areas of anomalous concentrations may have been reduced. If more samples had been taken, some areas of anomalous concentrations may have been increased and, in some cases, some of the areas may have merged.

The samples were divided for this report into 23 rock units, listed on table 2. Certain units have a greater sample density than others; for example, jasperoid and quartz latite have high sample densities, while shale of the siliceous assemblage has a very low sample density.

Threshold values were determined by finding the nickpoints of log-log cumulative frequency diagrams, or by the analytical value of the 97.5

Table 1.--Production of gold at the Carlin mine 1965-1977 the Blue Star area 1975-1976, and the Bootstrap area 1975-1977

Year	Number of troy ounces	Source of production figures
1965 ----------------	128,500	Ryan, 1966, p. 435
1966 ----------------	205,600	Davis, 1967, p. 507
1967 ----------------	337,000	Ryan, 1968, p. 525
1968 ----------------	280,000	Ryan, 1969, p. 531
1969 ----------------	166,000	Hoyt, 1971, p. 522
1970 ----------------	201,000	Hoyt, 1972, p. 536
1971 ----------------	199,000	West, 1973, p. 541-542
1972 ----------------	194,000	West, 1974, p. 571
1973 ----------------	150,000	West, 1975, p. 560
1974 ----------------	160,500	West, 1976, p. 607
1975		
Main pit area -----	191,657	West, 1977, p. 673
Blue Star area ----	7,570	Do.
Bootstrap area ----	10,773	Do.
1976		
Main pit area -----	183,222	West and Butterman, 1979, p. 594
Blue Star area ----	12,716	Do.
Bootstrap area ----	12,062	Do.
1977		
Main pit area		Butterman, 1980, p. 429
Bootstrap area	215,100	
1978---------------------	152,300	Butterman, 1980b. p. 387
1979---------------------	133,000	do
1980---------------------	110,000	Lucas, 1981, p. 358
1981		
Three open pits -------	136,000	Lucas, 1982
1982		
Main pit area		
Maggie Creek		
Blue Star--------------	145,100	Lucas, 1983
Total:	3,331,100	

Table 2.--Distribution of samples by rock unit

Rock unit	Number of samples
Siliceous assemblage	
chert	255
quartzite	22
shale	34
limestone	21
quartz veins	22
Hamburg Dolomite	40
Pogonip Group	18
Eureka Quartzite	18
Hanson Creek Formation	
dolomite	40
quartz veins	28
Roberts Mountains Formation	79
Jasperoid	108
Silurian and Devonian limestone	28
Popovich Formation	45
Transitional assemblage	12
Cretaceous granodiorite	21
Cretaceous quartz monzonite	7
Cretaceous or Tertiary rhyodacite flows	7
Andesitic rocks of unknown age	13
Eocene-Oligocene granodiorite	9
Oligocene quartz latite	35
Intrusive breccia	10
Miocene rhyolitic welded tuff	5
Total	877

percentile of the sample population, where subpopulations were not determinable by the former method (Lepeltier, 1969, p. 544-546).

Strengths of associations between elements were determined by Spearman's rank correlation techniques (Siegel, 1956; Lovering, 1963). In this report, correlation coefficients greater than 0.50 are significant at a 99 percent confidence level. Elements having statistically significant correlations are given in table 3.

Distributions of elements

Gold

The lower limits of detection used for gold in this study are 0.02 ppm (parts per million) for some groups of samples and 0.05 ppm for other groups. For consistent treatment of the analytical data, a lower limit of 0.05 ppm is adopted here for all samples. Because crustal abundance of gold is estimated to be 0.003 to 0.005 ppm (Jones, 1968, p. 3; Jones, 1969; Lee and Yao, 1970, p. 782), gold in amounts greater than or equal to 0.05 is considered anomalous in this study.

Gold greater than or equal to 0.05 ppm occurs in 176 or 20 percent of the samples (table 4) studied. Gold is most abundant in quartz veins in Hanson Creek Formation, although the Carlin gold deposit is in hydrothermally altered rock of Roberts Mountains and Popovich Formations; 75 percent of the quartz vein samples, 25 percent of the samples of Roberts Mountains Formation, and 22 percent of the samples of Popovich Formation contain greater than or equal to 0.05 ppm gold. Radtke (1981, p. 107) found that the average gold content of oxidized ore at the Carlin deposit is 9 ppm (rock units not differentiated). The proportion of samples with greater than or equal to 0.05 ppm in rocks from the siliceous assemblage is only slightly less than for the Roberts Mountains and Popovich Formations, reflecting sampling near gold deposits in the Big Six and Blue Star areas.

Gold statistically is associated with arsenic in quartz veins in siliceous assemblage (0.78) and quartz veins in Hanson Creek Formation (0.73); with molybdenum in quartz veins in Hanson Creek Formation (0.75); with mercury in Roberts Mountains Formation (0.69); and with scandium in Popovich Formation (0.70) (see table 3). The reason for the statistical association of gold and scandium in Popovich Formation is not known. Scandium is not discussed further in this report because analytical values of the element range from less than 5 to 70 ppm, consistent with its crustal abundance (Adams, 1973, p. 567-568).

According to the results of our sampling, gold is concentrated along the northeast edge of the Lynn Window below a segment of the Roberts Mountains thrust and in the Big Six mine area north of the mine (fig. 6). Rocks near the northeast-striking Lynn fault (Mill fault of Radtke and others, 1980, fig. 3), which cuts through the Carlin and Big Six deposits, contain greater than or equal to 0.05 ppm gold. These relations suggest that the Lynn fault was a major conduit for mineralizing fluids for the two deposits. No gold was found in rocks near the fault north of the Big Six area. High gold concentrations (greater than or equal to 1 ppm) were found in a few quartz veins in Hanson Creek Formation 2 to 3 km southwest of the Carlin mine. Relatively high grade gold-bearing quartz veins in Hanson Creek Formtion may underlie Roberts

Table 3.--Spearman correlation coefficients for the elements that are statistically correlated with one another directly or indirectly at a confidence level of 99 percent

Rock unit	Element	Correlation coefficient	Degrees of freedom	Student's t test
		Gold		
Quartz veins, siliceous assemblage ------------------	As	.78	10	3.97
Quartz veins, Hanson Creek Formation ------------------	As	.73	12	3.68
	Mo	.75	11	3.84
Roberts Mountains Formation ---	Hg	.69	39	5.99
Popovich Formation ------------	Sc	.70	16	3.93
		Silver		
Quartz veins, Hanson Creek Formation -------------------	As	.75	16	4.51
	Cu	.63	21	3.69
		Copper		
Pogonip Group -----------------	Hg	.66	12	3.02
	Pb	.85	10	5.06
Hanson Creek Formation				
dolomite -----------------	Pb	.62	19	3.42
quartz veins -------------	As	.63	17	3.32
	Pb	.77	9	3.56
	Sb	.86	12	5.74
	Zn	.64	15	3.26
Roberts Mountains Formation ---	As	.67	12	3.11
	Sb	.57	23	3.29
		Lead		
Hanson Creek Formation quartz veins -------------	Sb	.84	8	4.43
		Arsenic		
Jasperoid ---------------------	Mo	.66	15	3.43

Table 4.--Distribution of gold in rock units
[Units with no samples containing ≥ 0.05 ppm gold are omitted]

Rock unit	Number of samples with ≥0.05 ppm	percent of subpopulation	Number of samples with ≥1 ppm	Maximum value (ppm)
Siliceous assemblage				
chert ----------------------	49	19	9	20.0
quartzite ------------------	3	14	0	.1
shale ----------------------	6	18	0	.96
quartz veins ---------------	7	32	2	7.0
Eureka Quartzite -------------	1	6	0	.1
Hanson Creek Formation				
dolomite -------------------	8	20	0	.5
quartz veins ---------------	21	75	8	18.0
Roberts Mountains Formation ---	20	25	4	118.0
Jasperoid ---------------------	33	31	7	32.0
Silurian and Devonian limestone	2	7	0	.1
Popovich Formation ------------	9	22	2	1.4
Cretaceous granodiorite -------	4	19	0	.6
Quartz monzonite --------------	1	14	0	.1
Quartz latite -----------------	12	34	4	8.0
Totals	176	20	36 (4 percent)	

Mountains Formation at the Carlin deposit. Gold concentrations greater than or equal to 1 ppm occurs at several localities in the Roberts Mountains allochthon. These appear to be isolated occurrences not clearly indicative of economic gold potential. However, they could be due to gold leakage through the allochthon from more potentially favorable host rock (i.e. limestone) at depth.

The Carlin deposit lies on the south edge of an aeromagnetic trough and within the northwest-trending zone of hydrothermally altered rock (fig. 3). The genetic relation of the aeromagnetic trough to gold mineralization is uncertain, but the hydrothermally altered rock is clearly enriched in gold. Ore bodies smaller than the Carlin deposit occur southeast and northwest of the Carlin mine in the zone of altered rock. Similar ore bodies may be present below the Roberts Mountain thrust northwest of the mine and below the alluvium of Little Boulder Basin.

Arsenic

Arsenic is a relatively rare crustal element constituting about 2 ppm of igneous rocks, 4 ppm of bottom sediments of the Atlantic Ocean, but as high as 65 to 650 ppm in Proterozoic sedimentary iron ores (Gualtieri, 1973, p. 53). Average arsenic concentrations in most of the rock units of the study area are likely to be much less than the 200 ppm lower limit of detection. Therefore, any concentrations of arsenic in amounts detectable by the spectrographic method is considered to be anomalous. Analyses range to 7,000 ppm, the upper limit of detection.

Arsenic greater than or equal to 200 ppm occurs in 190 or 22 percent of the samples (table 5). It occurs most commonly in quartz veins in Hanson Creek Formation (68 percent) and quartz veins in siliceous assemblage (59 percent), and less abundantly in quartz latite (43 percent) and jasperoid (33 percent). The highest concentrations of arsenic (greater than 7,000 ppm) occur in quartz veins in Hanson Creek Formation, jasperoid, and quartz latite. Arsenic occurs much less commonly and in lower concentrations in Roberts Mountains and Popovich Formations, the two rock units in which the Carlin deposit occurs. Radtke (1981, p. 109) reported an average arsenic content of 506 ppm for unoxidized ore and 405 ppm for oxidized ore at the Carlin deposit. Arsenic has a positive correlation with gold in quartz veins in Hanson Creek Formation (0.73) and in quartz veins in siliceous assemblage (0.78); with silver in quartz veins in Hanson Creek Formation (0.75); with copper in quartz veins in Hanson Creek Formation (0.63) and in Roberts Mountains Formation (0.67); and with molybdenum in jasperoid (0.66) (see table 3).

Geographical distribution of arsenic in concentrations greater than or equal to 200 ppm coincides with the distribution of gold in the Carlin and Big Six areas and with the small gold deposits west and northwest of the Carlin mine (fig. 7). Most arsenic occurs in and near the aeromagnetic trough (fig. 3). Exceptionally high concentrations occur in quartz veins in Hanson Creek Formation south and west of the Carlin mine and in a quartz latite dike south of the window.

Table 5.--Distribution of arsenic in rock units
[Units with no samples containing ≥ 200 ppm arsenic are omitted]

Rock unit	Number of samples with ≥200 ppm	percent of subpopulation	Number of samples with ≥1,000 ppm	Maximum value (ppm)
Siliceous assemblage				
chert	67	26	20	5,000
quartz	6	27	1	1,000
shale	7	21	2	7,000
quartz veins	13	59	4	3,000
Hamburg Dolomite	3	8	0	300
Eureka Quartzite	1	6	0	300
Hanson Creek Formation				
dolomite	1	3	0	700
quartz veins	19	68	11	>7,000
Roberts Mountains Formation	15	18	5	3,000
Jasperoid	36	33	10	>7,000
Popovich Formation	3	9	1	2,000
Cretaceous granodiorite	2	10	1	2,000
Quartz monzonite	2	29	0	500
Quartz latite	15	43	7	>7,000
Totals	190	22	62 (7 percent)	

Mercury

Mercury greater than or equal to 0.01 ppm (lower limit of detection) occurs in 98 percent of the samples collected for this study. Background values (geometric means) for mercury in most rock units in the area range from 0.07 to 0.2 ppm (table 6). These values are consistent with crustal abundance, calculated at about 0.08 ppm (Bailey and others, 1973, p. 407). Higher background values, in the 0.45 to 8 ppm range occur in quartz veins, jasperoid, and Roberts Mountains Formation, all rock units which have undergone extensive mineralization. Threshold values of mercury vary from one rock unit to another. In general, concentrations greater than or equal to 1 ppm seem anomalous. This general threshold is 100 times the limit of detection and about 10 times crustal abundance and the background values of many of the rock units.

Mercury greater than or equal to 1 ppm occurs in 207 or 24 percent of the samples (table 6). It is most abundant in quartz veins in Hanson Creek Formation (75 percent) and in jasperoid (52 percent), both of which are rock units closely associated with mineralization. (Jasperoid is included in the zone of hydrothermally altered rock shown as SDa on figure 2 and by light stippling in figure 3.) About one-third of the samples of Roberts Mountains Formation and quartz latite contain greater than or equal to 1 ppm. A little more than one-quarter of the samples of quartzite (siliceous assemblage) and quartz veins (siliceous assemblage), Popovich Formation, and quartz monzonite have anomalous mercury concentrations. High mercury concentrations (greater than 10 ppm) occur locally in all the rock units named above, as well as in chert, in limestone of the siliceous assemblage and in Hanson Creek Formation. At the Carlin deposit average mercury content of unoxidized ores is 21 ppm; of oxidized ores, 18 ppm (Radtke, 1981, p. 80, 108). Mercury has a positive correlation with gold in the Roberts Mountains Formation (0.69) and with copper in Pogonip Group (0.66) (see table 3).

Our samples showed that mercury greater than or equal to 1 ppm occurs in the Carlin and Big Six areas and vicinity and in association with gold in the northwest-trending zone of hydrothermally altered rock (fig. 8). High concentrations (greater than 10 ppm) occur in and near the aeromagnetic trough (fig. 3) and are associated with large gold and silver concentrations south and southwest of the Carlin mine. A few localities with greater than 10 ppm occur in southern Lynn Window near rocks relatively rich in molybdenum, tungsten, and zinc.

Antimony

Antimony greater than or equal to 70 ppm (lower limit of detection) occurs in 164 or 19 percent of the samples collected in the area (table 7). This concentration is much greater than crustal abundance, estimated to be 0.2 to 0.5 ppm, with basalts and deep-sea clays containing as much as 1 ppm (Miller, 1973, p.47). Therefore, samples with detectable amounts of antimony are considered anomalous. Some samples have concentrations of antimony greater than 5,000 ppm, the upper limit of detection. Precise antimony contents were not determined for these samples.

Table 6.--Distribution of mercury in rock units

Rock unit	Background (ppm)	Number of samples with ≥1 ppm	percent of subpopulation	Number of samples with ≥5 ppm	Maximum value (ppm)
Siliceous assemblage					
chert	0.10	46	18	12	>10
quartzite	.20	6	27	2	6.0
shale	.20	5	15	0	3.0
limestone	.10	3	14	1	>10
quartz veins	.45	6	27	2	7.0
Hamburg Dolomite	.20	4	10	0	3.5
Pogonip Group	.1	1	6	0	1.6
Eureka Quartzite	.2	0	0	0	.7
Hanson Creek Formation					
dolomite	.2	7	18	3	>10
quartz veins	8.00	21	75	15	>10
Roberts Mountains Formation	.45	26	33	4	>10
Jasperoid	1.00	56	52	16	>10
Silurian and Devonian limestone	.05	0	0	0	.9
Popovich Formation	.15	12	26	3	>10
Transitional assemblage	.10	0	0	0	.26
Cretaceous granodiorite	.08	1	5	1	10.0
Quartz monzonite	.12	2	29	1	>10
Rhyodacite flows	.08	0	0	0	.65
Andesite	.08	0	0	0	.24
Tertiary granodiorite	.08	0	0	0	.35
Quartz latite	.20	11	31	3	>10
Intrusive breccia	.09	0	0	0	.40
Rhyolitic welded tuff	.07	0	0	0	.12
Totals		207	24	63 (7 percent)	

Table 7.--Distribution of antimony in rock units
[Units with no samples containing ≥ 70 ppm antimony are omitted]

Rock unit	Number of samples with ≥70 ppm	percent of subpopulation	Number of samples with ≥1,000 ppm	Maximum value (ppm)
Siliceous assemblage				
chert ----------------------	20	8	0	300
quartzite ------------------	1	5	0	200
shale ----------------------	1	3	1	10,000
quartz veins ---------------	1	5	0	500
Hamburg Dolomite --------------	3	8	0	200
Pogonip Group -----------------	1	6	0	150
Eureka Quartzite --------------	3	17	0	300
Hanson Creek Formation				
dolomite -------------------	9	23	2	1,500
quartz veins ---------------	26	93	15	>10,000
Roberts Mountains Formation ---	25	32	1	1,000
Jasperoid ---------------------	59	55	1	3,000
Silurian and Devonian limestone	3	11	0	100
Popovich Formation ------------	4	7	1	2,000
Cretaceous granodiorite -------	1	5	0	500
Andesite ----------------------	1	8	0	100
Quartz latite -----------------	6	17	0	150
Totals	164	19	21 (2 percent)	

Antimony in detectable quantities occurs in 16 of the rock units in the area (table 7). It is proportionally most common in quartz veins in Hanson Creek Formation (93 percent). About one-half of the jasperoid samples (55 percent) and one-third of the samples of the Roberts Mountains Formation (32 percent) contain greater than or equal to 70 ppm. Less than one-quarter of the samples of all other rock units contain detectable amounts. High concentrations (greater than 5,000 ppm) occur primarily in quartz veins in Hanson Creek Formation; one sample with more than 5,000 ppm occurs in shale. Average content of antimony in unoxidized Carlin ores is 126 ppm; in oxidized ores, 95 ppm (Radtke, 1981, p. 83, 109). Antimony is statistically associated with copper (0.86) and lead (0.84) in quartz veins in Hanson Creek Formation and with copper (0.57) in Roberts Mountains Formation (table 4).

The distribution of samples with greater than or equal to 70 ppm antimony coincides with the occurrence of gold and other elements in the Carlin mine and with gold occurrences in the zone of hydrothermally altered rock northwest and southeast of the mine (fig. 9). Most of these occurrences are less than 1,000 ppm. Concentrations greater than 5,000 ppm are associated with arsenic and barium in the Blue Star area, and with gold, silver, arsenic, and lead in several combinations south and southwest of the Carlin mine in quartz veins in Hanson Creek Formation. Samples containing very large concentrations of antimony are generally distant from the Carlin mine, although a few occur in the vicinity of the aeromagnetic trough.

Copper

Copper greater than or equal to 5 ppm (lower limit of detection) is present in 85 percent of the samples obtained during this study. Twenty-one of the rock units have background less than 50 ppm (table 8), concentrations consistent with the 50 ppm crustal abundance (Cox and others, 1973, p. 167). The other two units with higher background values are quartz veins in Hanson Creek Formation (700 ppm) and quartz latite (100 ppm). Threshold values of copper in the study area vary by rock unit from less than 100 ppm to more than 200 ppm. In this study a general threshold of 200 ppm was adopted.

Copper greater than or equal to 200 ppm occurs in 76, or 9 percent, of the samples (table 8). Thirteen of the rock units have no samples showing this much copper. Of the rock units with anomalous amounts of copper, quartz veins in Hanson Creek Formation contain copper greater than or equal to 200 ppm most commonly (61 percent). Copper concentrations greater than or equal to 10,000 ppm (upper limit of detection) occur in chert and quartz veins in siliceous assemblage, in jasperoid, and in quartz latite. All analyzed samples from the Roberts Mountains and Popovich Formations, both gold hosts in the Carlin mine, show concentrations less than or equal to 150 ppm. Unoxidized ore at the Carlin deposit averages 33 ppm copper; oxidized ore, 22 ppm (Radtke, 1981, p. 89, 111). Copper is positively correlated with arsenic in quartz veins in Hanson Creek Formation (0.63) and in Roberts Mountains Formation (0.67); with antimony in the same two rock units (0.63 and 0.57, respectively); with lead in Pogonip Group (0.85), Hanson Creek dolomite (0.62) and quartz veins in Hanson Creek Formation (0.77); and with zinc in the quartz veins (0.64) (see table 4).

Samples with copper greater than or equal to 200 ppm are concentrated in the general vicinity of the Big Six gold deposit (fig. 10). Locally high

Table 8.--Distribution of copper in rock units

Rock unit	Background (ppm)	Number of samples with ≥200 ppm	percent of subpopulation	Number of samples with ≥1,000 ppm	Maximum value (ppm)
Siliceous assemblage					
chert	50	29	11	10	>10,000
quartzite	15	0	0	0	100
shale	30	2	6	0	300
limestone	7	0	0	0	50
quartz veins	50	5	23	3	10,000
Hamburg Dolomite	15	7	18	1	3,000
Pogonip Group	5	0	0	0	150
Eureka Quartzite	5	0	0	0	30
Hanson Creek Formation					
dolomite	5	1	3	0	500
quartz veins	700	17	61	13	7,000
Roberts Mountain Formation	10	0	0	0	150
Jasperoid	10	4	4	1	>10,000
Silurian and Devonian limestone	15	1	4	0	200
Popovich Formation	5	0	0	0	150
Transitional assemblage	<5	0	0	0	20
Cretaceous granodiorite	15	0	0	0	100
Quartz monzonite	5	0	0	0	30
Rhyodacite flows	<5	0	0	0	10
Andesite	15	2	15	1	7,000
Tertiary granodiorite	10	0	0	0	30
Quartz latite	100	8	23	3	10,000
Intrusive breccia	30	0	0	0	50
Rhyolitic welded tuff	<5	0	0	0	5
Totals		76	9	32 (4 percent)	

copper concentrations occur in the Blue Star mine area, in association with gold, silver, and arsenic, and in the siliceous assemblage northeast of the Carlin mine.

Lead

Lead greater than or equal to 10 ppm (lower limit of detection) occurs in 59 percent of the samples collected for this study. Background values of 22 of the rock units in the area are less than 10 to 30 ppm (table 9). These are in accord with the 5- to 20-ppm range in igneous rocks, the 7- to 20-ppm average for sedimentary rocks and a crustal abundance of 15 ppm (Morris and others, 1973, p. 317). Quartz veins in Hanson Creek Formation have a much higher background (3,000 ppm). At the Carlin deposit average lead content of oxidized ores is 25 ppm and, for oxidized ores, ranges from 20 to 51 ppm. Radtke, 1981, p. 86, 111). These values are not much greater than background for samples of the Roberts Mountains Formation in this study. However, samples of unoxidized ores range to 1,500 ppm, and oxidized ores to 200 ppm. Threshold values are near 100 ppm in most rock units in this study, and, therefore, a general threshold of 100 ppm is adopted here. Some samples contain an undetermined amount of lead greater than 20,000 ppm (upper limit of detection).

Lead greater than or equal to 100 ppm occurs in 66, or 8 percent, of the samples from the study area (table 9). Quartz veins in Hanson Creek Formation contain proportionally more lead in anomalous amounts than any of the other rock units (75 percent). Less than one-seventh of the samples of the other units contain greater than or equal to 100 ppm. Nine of the units contain less than 100 ppm. Lead has a positive correlation with copper in Pogonip Group (0.85), Hanson Creek dolomite (0.62) and in quartz veins in Hanson Creek Formation (0.77); and with antimony in the quartz veins (0.84) (see table 4).

The distribution of samples with anomalous lead values coincides in part with samples high in gold and other elements at the Carlin mine but is areally more restricted. Other samples with anomalous lead values are geographically associated with high gold, silver, arsenic, and mercury concentrations south to northwest of the mine (fig. 11). The greatest lead concentrations, in quartz veins in Hanson Creek Formation, are located away from the Carlin area.

Barium

Barium greater than or equal to 20 ppm (lower limit of detection) is present in 96 percent of the samples studied. Background values of the rock units in the area vary from a low of 10 ppm in Popovich Formation to a high of 1,500 ppm in Tertiary granodiorite (table 10). Fifteen of the rock units have background values less than or comparable to crustal abundance, estimated to be 300 to 500 ppm (Brobst, 1973, p. 77). Of the eight rock units with greater than or equal to 700 ppm background, seven are igneous rocks. Threshold values for the rock units are greater than or equal to 1,000 ppm, which is adopted as a general threshold. Some samples have barium concentrations greater than 5,000 ppm (upper limit of detection).

Barium greater than or equal to 1,000 ppm occurs in 180 or 21 percent of the samples collected (table 10). The intrusive rock units have proportionally more samples with greater than or equal to 1,000 ppm than the

Table 9.--Distribution of lead in rock units

Rock unit	Background (ppm)	Number of samples with ≥100 ppm	percent of subpopulation	Number of samples with ≥1,000 ppm	Maximum value (ppm)
Siliceous assemblage					
chert	10	14	6	0	200
quartzite	<10	1	5	0	100
shale	10	0	0	0	50
limestone	<10	0	0	0	70
quartz veins	<10	2	9	0	100
Hamburg Dolomite	20	5	13	1	1,000
Pogonip Group	<10	1	6	0	100
Eureka Quartzite	10	1	6	0	100
Hanson Creek Formation					
dolomite	20	5	13	2	7,000
quartz veins	3,000	21	75	18	>20,000
Roberts Mountains Formation	15	8	10	2	3,000
Jasperoid	10	4	4	1	2,000
Silurian and Devonian limestone	<10	0	0	0	—
Popovich Formation	<10	2	4	2	7,000
Transitional assemblage	<10	0	0	0	<10
Cretaceous granodiorite	10	0	0	0	20
Quartz monzonite	20	0	0	0	30
Rhyodacite flows	15	1	14	0	100
Andesite	10	0	0	0	50
Tertiary granodiorite	20	0	0	0	30
Quartz latite	15	1	3	10	100
Intrusive breccia	10	0	0	0	20
Rhyolitic welded tuff	30	0	0	0	70
Totals		66	8	26 (3 percent)	

Table 10--Distribution of barium in rock units

Rock unit	Background (ppm)	Number of samples with ≥1,000 ppm	percent of subpopulation	Number of samples with ≥5,000 ppm	Maximum value (ppm)
Siliceous assemblage					
chert ----------------------	700	56	22	9	>5,000
quartzite ------------------	300	5	23	1	>5,000
shale ----------------------	500	7	21	0	2,000
limestone ------------------	100	1	5	0	1,000
quartz veins ---------------	300	4	18	1	>5,000
Hamburg Dolomite -------------	70	1	3	0	2,000
Pogonip Group ----------------	30	0	0	0	700
Eureka Quartzite -------------	50	1	6	0	3,000
Hanson Creek Formation					
dolomite -------------------	30	3	8	1	>5,000
quartz veins ---------------	20	2	7	1	>5,000
Roberts Mountains Formation ---	200	11	13	2	>5,000
Jasperoid --------------------	20	27	25	8	>5,000
Silurian and Devonian limestone	200	8	29	0	3,000
Popovich Formation -----------	10	6	15	1	>5,000
Transitional assemblage -------	500	2	17	0	1,500
Cretaceous granodiorite -------	700	8	38	0	1,500
Quartz monzonite -------------	700	3	43	0	3,000
Rhyodacite flows -------------	700	1	14	0	1,000
Andesite ---------------------	700	6	46	1	5,000
Tertiary granodiorite ---------	1,500	7	78	1	5,000
Quartz latite ----------------	700	14	40	0	3,000
Intrusive breccia -------------	1,000	7	70	2	>5,000
Rhyolitic welded tuff ---------	200	0	0	0	700
Totals		180	21	28 (3 percent)	

other rock units (78 percent max Tertiary granodiorite; 38 percent min Cretaceous granodiorite). The average barium content of unoxidized ores at the Carlin deposit is 400 ppm; unoxidized ores average 1,100 to 1,600 ppm (Radtke, 1981, p. 90, 112).

Samples with barium greater than or equal to 1,000 ppm are abundant in areas of high gold and arsenic concentrations in the Carlin and Big Six areas (vicinity of aeromagnetic trough) and in the Blue Star area (vicinity of aeromagnetic high 1044) (see fig. 12). Zones of relatively abundant barium also occur in the vicinity of the two aeromagnetic highs south of the Carlin mine.

Barium-strontium relations

Barium-strontium relations were studied at the Highland Valley porphyry copper deposits in British Columbia by Olade and others (1975), who found that Ba/Sr greater than one outline mineralized zones in the igneous rocks. Although the geologic setting at the Lynn Window is very different from the porphyry copper deposits at Highland Valley, Ba/Sr in the study area were obtained in order to determine if they define areas of hydrothermal mineralization. Barium/strontium ratios could be calculated for all samples by assuming an average strontium content of 50 ppm for samples with less than 100 ppm (lower limit of detection) and an average barium content of 10 ppm of samples with less than 20 ppm (lower limit of detection). The range in geometric mean values of Ba/Sr ratios for the rock units of the area varies from 0.5 to 7, with the means of 19 of the rock units greater than or equal to 1. A geographic plot (not included here) of localities with Ba/Sr ratios greater than or equal to 10 exhibits clusters of sites which closely match the areas of high barium concentrations. High Ba/Sr ratios, therefore, reflect the relatively high barium concentrations in the study area.

Manganese

Manganese greater than or equal to 10 ppm (lower limit of detection) occurs in 98 percent of the samples (table 11) collected. Background concentrations for most of the 23 rock units in the area are less than or equal to 1,000 ppm, the estimated crustal abundance (Dorr and others, 1973, p. 387). Background exceeds crustal abundance in Hamburg Dolomite (2,000 ppm). Manganese greater than or equal to 1,000 ppm occurs in 138, or 16 percent, of the samples, suggesting that the terrain sampled may be below normal in its manganese content with respect to crustal abundance although not clearly below normal with regard to average manganese content for certain sedimentary and igneous rocks. Because of the small proportion of samples with manganese at and above crustal abundance, 1,000 ppm was chosen as a general threshold in this study. Some of the samples have more than 5,000 ppm (upper limit of detection).

Manganese greater than or equal to 1,000 ppm is most common in Tertiary granodiorite (67 percent), and nearly as common in Hamburg Dolomite (55 percent) and Pogonip Group (56 percent). Among the other 20 rock units, quartz latite (40 percent) and limestone in siliceous assemblage (38 percent) have anomalous amounts of manganese in more than one-third of the samples. One-third or less of the other 18 rock units have manganese greater than or equal to 1,000 ppm.

Table 11.--Distribution of manganese in the rock units

Rock unit	Background (ppm)	Number of samples with $\geq$1,000 ppm	percent of subpopulation	Maximum value (ppm)
Siliceous assemblage				
chert	100	21	2	5,000
quartzite	100	2	9	1,500
shale	100	9	26	2,000
limestone	700	8	38	>5,000
quartz veins	150	6	27	>5,000
Hamburg Dolomite	2,000	22	55	>5,000
Pogonip Group	300	10	56	>5,000
Eureka Quartzite	150	0	0	700
Hanson Creek Formation				
dolomite	200	8	20	>5,000
quartz veins	200	2	7	1,000
Roberts Mountains Formation	200	9	11	5,000
Jasperoid	70	3	3	>5,000
Silurian and Devonian limestone	300	5	18	3,000
Popovich Formation	150	2	4	2,000
Transitional assemblage	150	0	0	300
Cretaceous granodiorite	700	7	33	2,000
Quartz monzonite	300	2	29	1,000
Rhyodacite flows	700	2	29	1,000
Andesite	700	4	31	1,500
Tertiary granodiorite	1,000	6	67	1,500
Quartz latite	200	5	14	3,000
Intrusive breccia	500	4	40	1,500
Rhyolitic welded tuff	500	1	20	5,000
Totals		138	16	

Anomalous concentrations of manganese occur in diffuse clusters close to centers of intrusion and of hydrothermal alteration (fig. 13). The main cluster, in and near the Cretaceous quartz monzonite intrusion, is partly coincident with areas of anomalous molybdenum, tin, tungsten, and zinc to be described below. A small cluster in the vicinity of the Cretaceous granodiorite is partly coincident with areas of anomalous arsenic and barium. Anomalous manganese values in the vicinity of the Tertiary granodiorite and quartz latite intrusions are close to occurrences of anomalous amounts of barium. Manganese greater than or equal to 1,000 ppm also occurs in the Carlin and Big Six areas and in some rocks near the Lynn fault between the two deposits. However, manganese is not closely associated with quartz veins and jasperoid, which are linked to gold mineralization. At one locality in siliceous rocks northeast of the Carlin mine, large amounts of copper and manganese occur together.

Molybdenum

Molybdenum greater than or equal to 5 ppm (lower limit of detection) occurs in 246 or 28 percent of the samples (table 12) studied. Background values for rocks in the area are less than 5 ppm, consistent with crustal abundance, estimated to be 1 to 1.5 ppm (King and others, 1973, p. 427). Average concentrations of molybdenum at the Carlin mine are of similar magnitude or higher: oxidized ores, 3 ppm; unoxidized ores 6 ppm (Radtke, 1981, p. 90, 112). Estimated threshold values of the rock units vary from 5 to 2,000 ppm, or the entire range of analytical values from the sample population. A threshold of 50 ppm was selected for all samples.

Molybdenum greater than or equal to 50 ppm occurs in 36 or 4 percent of the samples collected. It is most common and in greatest concentrations in Hamburg Dolomite and Pogonip Group. Molybdenum and gold are statistically associated in quartz veins in Hanson Creek Formation (0.75) (see table 3).

Anomalous concentrations occur in southeast Lynn Window close to the aeromagnetic high 2072 which is associated with quartz monzonite (fig. 14). A zone of anomalous molybdenum occurrences also lies along a northeast-striking fault southeast of the Carlin mine. Few high molybdenum occurrences are in the Carlin and Big Six area.

Silver

As the crustal abundance of silver is estimated to be 0.07 ppm (Vinogradov, 1962), amounts of silver greater than or equal to 0.5 ppm (lower limit of detection) are considered anomalous in this study. Silver in detectable quantities occurs in 216, or 25 percent, of the samples collected (table 13). It is most abundant and in greatest concentrations in quartz veins in Hanson Creek Formation; 82 percent of these samples contain detectable silver and three-fourths of these contain greater than or equal to 5 ppm to a maximum of 1,500 ppm. A little more than one-third of the samples of chert and Roberts Mountains Formation contain greater than or equal to 0.5 ppm silver, reflecting mineralization in the Carlin and Big Six areas. In this study silver does not exceed 10 ppm in chert and 3 ppm in Roberts Mountains Formation. A little less than one-third of the samples of Hamburg Dolomite, quartz veins in siliceous assemblage and jasperoid

Table 12.--Distribution of molybdenum in the rock units

Rock unit	Number of samples with $\geq$50 ppm	percent of subpopulation	Maximum value (ppm)
Siliceous assemblage			
chert ----------------------	15	6	150
quartzite ------------------	1	5	50
shale ----------------------	2	6	70
limestone ------------------	0	0	10
quartz veins ---------------	2	9	70
Hamburg Dolomite --------------	4	10	1,000
Pogonip Group -----------------	3	17	2,000
Eureka Quartzite --------------	0	0	7
Hanson Creek Formation			
dolomite -------------------	1	3	200
quartz veins ---------------	1	4	200
Roberts Mountains Formation ---	1	1	50
Jasperoid ---------------------	4	4	70
Silurian and Devonian limestone	0	0	10
Popovich Formation ------------	2	4	70
Transitional assemblage -------	0	0	10
Cretaceous granodiorite -------	0	0	10
Quartz monzonite --------------	0	0	<5
Rhyodacite flows --------------	0	0	<5
Andesite ----------------------	0	0	<5
Tertiary granodiorite ---------	0	0	5
Quartz latite -----------------	0	0	10
Intrusive breccia -------------	0	0	5
Rhyolitic welded tuff ---------	0	0	10
Total	36	4	

Table 13.--Distribution of silver in rock units
[Units with no samples containing ≥0.5 ppm silver are omitted]

Rock unit	Number of samples with ≥0.5 ppm	percent of subpopulation	Number of samples with ≥5 ppm	Maximum value (ppm)
Siliceous assemblage				
chert	88	35	3	10.0
quartzite	14	18	0	1.5
shale	6	18	0	1.5
quartz veins	6	27	0	2.0
Hamburg Dolomite	10	28	6	15.0
Pogonip Group	2	11	0	1.0
Eureka Quartzite	1	6	0	.5
Hanson Creek Formation				
dolomite	11	28	2	7.0
quartz veins	23	82	17	1,500.0
Roberts Mountains Formation	29	36	10	3.0
Jasperoid	23	21	4	500.0
Silurian and Devonian limestone	1	4	0	.5
Popovich Formation	5	13	0	3.0
Rhyodacite flows	1	14	0	1.0
Tertiary granodiorite	1	11	0	.5
Quartz latite	4	11	2	5.0
Intrusive breccia	1	10	0	.5
Totals	216	25	34 (4 percent)	

contain greater than or equal to 0.5 ppm. Of these units, jasperoid contains a maximum of 500 ppm; Hamburg Dolomite, of 7 ppm; and the quartz veins, of 2 ppm. The youngest rock unit definitely affected by silver mineralization is quartz latite. Although intrusive breccia contains silver and may be younger than quartz latite, the silver may be in previously mineralized quartz latite fragments incorporated in the breccia. Unoxidized ores in the Carlin deposit average 0.4 ppm; oxidized ores average 0.7 ppm (Radtke, 1981, p. 88, 111). Silver has a positive correlation with arsenic (0.75) and copper (0.63) in quartz veins in Hanson Creek Formation (see table 4).

Disseminated deposits of the Carlin type contain very small amounts of silver and very large gold/silver ratios. At Carlin the average silver content in unoxidized ores is 0.4 ppm and the gold/silver ratio is about 20:1 (Radtke, 1981, p. 88). Ratios in other disseminated gold deposits may differ widely from this figure. At Gold Acres the ratio is 10:1 (Wrucke and Armbrustmacher, 1975, p. 23). Also, gold and silver are not statistically associated in our sample population. Nevertheless, the geographic distributions of the two metals suggests a close spatial association (fig. 15). Silver occurrences are common in the Big Six and Carlin areas and near the Lynn fault between the two mines as well as north of the Big Six mine. This distribution supports the hypothesis that the Lynn fault was a main conduit for mineralizing fluids. Silver contents of 500 to 1,500 ppm occur in quartz veins in Hanson Creek Formation south and west of the Carlin mine, coinciding with scattered relatively high gold concentrations in that area. Analyses of these rocks show that their gold/silver ratios are very different from the Carlin deposit, with, in some places, ratios less than 1. Silver is much more abundant than gold in southern Lynn Window where the rocks have undergone contact metamorphism due to the largely concealed quartz monzonite intrusion. Scattered occurrences of silver are in siliceous assemblage immediately south of the window.

Tin

Tin greater than or equal to 10 ppm (lower limit of detection) occurs in 45, or 5 percent, of the samples in 7 of the rock units (table 14) sampled in this study. Therefore, background values of tin for most of the rock units are less than 10 ppm, consistent with crustal abundance estimated at 2 to 3 ppm, although some kinds of rock average 10 or more parts per million tin (Sainsbury and Reed, 1973, p. 641). Threshold for tin in this study is taken to be 10 ppm.

Tin greater than or equal to 10 ppm occurs most commonly in quartz veins in Hanson Creek Formation (53 percent), in Hamburg Dolomite (40 percent), less frequently in dolomite of the Hanson Creek Formation (18 percent), and in Pogonip Group (17 percent).

Tin in detectable quantities occurs primarily in an area north of exposures of the quartz monzonite (fig. 16). This area is coincident with areas rich in molybdenum, manganese, tungsten, and zinc. High values of tin (greater than or equal to 1,000 ppm) coincide with high values of gold, silver, lead, antimony, and zinc at three localities south of the Carlin mine. Two of these localities are high in arsenic and two are high in mercury. A locality rich in tin west of the Carlin mine is also rich in lead, silver, and zinc.

Table 14.--Distribution of tin in the rock units
[Units with no samples containing ≥10 ppm tin are omitted]

Rock unit	Number of samples with ≥0.05 ppm	percent of subpopulation	Maximum value (ppm)
Siliceous assemblage			
limestone -------------------	2	10	50
Hamburg Dolomite --------------	16	40	200
Pogonip Group -----------------	3	17	200
Hanson Creek Formation			
dolomite --------------------	7	18	100
quartz veins ----------------	15	53	>1,000
Roberts Mountains Formation ---	1	1	10
Jasperoid ---------------------	1	1	100
Total	45	5	

Tungsten

Tungsten greater than or equal to 50 ppm (lower limit of detection) occurs in 40, or 5 percent, of the samples (table 15) collected. This value is much greater than the 1 to 1.3 ppm estimated crustal abundance (Hobbs and Elliott, 1973, p. 669). Therefore, all samples with detectable amounts of tungsten are considered anomalous in this study.

No tungsten was found in samples of 11 of the rock units studied. Of the other units, tungsten greater than or equal to 50 ppm occurred most commonly in Hamburg Dolomite (25 percent). Although only two samples of Pogonip Group contain tin in amounts greater than or equal to 50 ppm, both samples have high concentrations (2,000 and 10,000 ppm). Less than one-seventh of the samples of the remaining rock units have greater than or equal to 50 ppm to a maximum of 200 ppm. Unoxidized ores at the Carlin mine average 12 to 18 ppm; oxidized ores average 8 to 12 ppm (Radtke, 1981, p. 90, 112).

Samples with high tungsten concentrations (200-10,000 ppm) are grouped in southeastern Lynn Window in the contact metamorphic aureole associated with the aeromagnetic high 2072 and coincide with areas high in molybdenum, manganese, tin, and zinc (fig. 17). Samples with generally low tungsten content (less than or equal to 200 ppm) occur in the Carlin and Big Six areas where they are associated with gold and other elements in the northwest-trending zone of hydrothermally altered rock. A diffuse cluster of tungsten-bearing samples occurs in the Blue Star area near the aeromagnetic high 1944 which is related to the Cretaceous granodiorite.

Zinc

Zinc greater than or equal to 200 ppm (lower limit of detection) occurs in 207 or 24 percent of the samples (table 16) obtained for this study. This concentration is greater than the 65 to 94 ppm estimated for crustal abundance, but not greater than zinc concentrations in some carbonaceous shales and dolomites (Wedow and others, 1973, p. 700). Background values of 21 of the rock units in the study area are less than 200 ppm. However, Hamburg Dolomite has a background of 200 ppm and quartz veins in Hanson Creek Formation, of 1,500 ppm. Occurrences of zinc greater than or equal to 200 ppm may be significant although actual threshold values are probably greater than 200 ppm. In this study, all samples with detectable amounts of zinc are considered anomalous, and some samples contain zinc in amounts greater than 10,000 ppm, the upper limit of determination.

Zinc in detectable quantities was found most commonly in quartz veins in Hanson Creek Formation (86 percent). Zinc is less abundant in Hamburg Dolomite (53 percent) and in quartz veins in siliceous assemblage rocks (50 percent). These three rock units and Popovich Formation locally contain zinc in amounts greater than 10,000 ppm. Igneous rocks contain little zinc. The relatively high zinc content of Hamburg Dolomite may be of sedimentary or diagenetic origin, as in the zinc-rich dolomites mentioned by Wedow and others (1973). Unoxidized ores in the Carlin deposit average 165 to 185 ppm; oxidized ores average 90 ppm (Radtke, 1981, p. 111). Zinc is statistically associated with copper (0.64) in quartz veins in Hanson Creek Formation (see table 4).

Clusters of samples with greater than or equal to 200 ppm zinc occur in the Carlin and Big Six areas and along the Lynn fault (fig. 18). A few high

Table 15.--Distribution of tungsten in rock units
[Units with no samples containing $\geq$50 ppm tungsten are omitted]

Rock unit	Number of samples with $\geq$50 ppm	percent of subpopulation	Maximum value (ppm)
Siliceous assemblage			
chert ----------------------	5	2	150
quartzite -----------------	1	5	50
shale ----------------------	2	6	70
quartz veins --------------	3	14	100
Hamburg Dolomite ----------------	10	25	200
Pogonip Group -------------------	2	11	10,000
Hanson Creek Formation			
dolomite -------------------	1	3	200
quartz veins --------------	2	7	70
Roberts Mountains Formation ----	4	5	70
Jasperoid -----------------------	6	6	100
Cretaceous granodiorite --------	1	5	70
Quartz latite -------------------	5	14	200
Total	40	5	

Table 16.--Distribution of zinc in rock units
[Units with no samples containing ≥200 ppm zinc are omitted]

Rock unit	Number of samples with ≥200 ppm	percent of subpopulation	Number of samples with ≥1,000 ppm	Maximum value (ppm)
Siliceous assemblage				
chert	68	27	9	5,000
quartzite	2	9	0	300
shale	10	29	1	1,500
limestone	3	14	1	1,000
quartz veins	11	50	5	>10,000
Hamburg Dolomite	21	53	12	5,000
Pogonip Group	4	22	3	5,000
Hanson Creek Formation				
dolomite	8	20	3	10,000
quartz vein	24	86	16	10,000
Roberts Mountains Formation	18	23	6	2,000
Jasperoid	21	19	5	>10,000
Silurian and Devonian limestone	5	18	0	500
Popovich Formation	8	18	1	>10,000
Transitional assemblage	1	8	0	200
Tertiary granodiorite	1	11	0	200
Quartz latite	4	11	0	500
Totals	207	24	62 (7 percent)	

concentrations (greater than or equal to 5,000 ppm) occur in that area. Local high concentrations occur in jasperoid northwest of the mine and in quartz veins in Hanson Creek Formation south and southwest of the mine. These high zinc concentrations are associated with large concentrations of gold, silver, mercury, lead, and antimony. A broad cluster of zinc-rich rocks lies in an area of southeast Lynn Window north of the Cretaceous quartz monzonite intrusion and is partly coincident with zones rich in manganese, molybdenum, tin, and tungsten. Southwest of the quartz monzonite, partly in siliceous assemblage, a diffuse cluster of zinc-rich samples is partly coincident with clusters of silver-rich and barium-rich samples. Scattered occurrences of zinc greater than or equal to 500 ppm with no clear relation to other elements or structures are in siliceous assemblage nearly to the north edge of the study area. Other occurrences in the southeast corner of the area are close to high concentrations of barium, mercury, and silver.

Discussion

Areas containing anomalous concentrations of each of the 13 elements studied were outlined on figures 19 and 20 by drawing lines around clusters of sample sites having anomalous concentrations. The elements were divided into two groups based on the geographic similarity of the areas in which they occur in anomalous concentrations. Areas anomalous in gold, arsenic, mercury, antimony, copper, and lead occur in the Rodeo Creek NE quadrangle along with some localities rich in gold, arsenic, antimony, mercury, and lead in both quadrangles (fig. 19). Areas anomalous in silver, barium, molybdenum, manganese, tungsten, and zinc occur in both quadrangles (fig. 20). Tin, most of which occurs in the Welches Canyon Quadrangle, is included in this suite. The partial geographic segregation of the two suites of elements may be due to the occurrences of different hydrothermal systems, or to structural and (or) physico-chemical controls, but is not likely to be fortuitous. The segregation of the element suites suggests the kind of element zoning described by White (1981) for active geothermal systems, and suggested by him for epithermal deposits: an upper zone with gold dominant, characterized by mercury, antimony and arsenic and containing minor silver (includes thallium and boron); and a lower zone containing much silver and base metals (includes selenium, tellurium and bismuth). The two zones may be separated in places by a barren zone. In the Lynn Window, this kind of zoning, with complications, may be present. The geographic separation of the zones in the window may be due to tilting and erosion during late Mesozoic to Tertiary, or, more likely, due to the configuration of isotherms or conduits of the hydrothermal fluids.

The source of the gold in the Carlin deposit is not known. Dickson and others (1978) suggested that ore fluids could have leached some or all of the gold, as well as other elements, from sedimentary carbonate rocks that occur below the deposit. Based on relations of stable isotopes, Radtke (1981, p. 134) suggested that gold and gangue components were hydrothermally leached from the carbonate assemblage of the southern Tuscarora Range, from shale and sandstone believed to underlie the carbonate section and from igneous rocks. Doe (in Radtke, 1981, p. 133) concluded from lead isotope ratios in barite veins from the Carlin deposit that all or at least part of the lead in the veins was derived from the Roberts Mountains Formation. Similarly, lead and sulfur isotope relations determined for the Cortez deposit by Rye and others

(1974) were interpreted to favor a gold source in the country rock. The reasoning behind these conclusions should be examined briefly in order to see whether the conclusions are justified.

Radtke and others (1980) and Radtke (1981, p. 123, 133) concluded from studies of certain stable isotopes that the hydrothermal fluids at the Carlin deposit were largely of meteoric origin and did not contain significant amounts of CO_2, sulfur or barite from sources other than marine carbonate rocks, because the isotope ratios in certain gangue minerals and in altered rock are like the isotope ratios in fresh carbonate rock. The problem with jumping from these conclusions to the hypothesis that the gold was also leached from the marine carbonate rock is that the stable isotopes mentioned above do not bear directly on the origin of the gold (see discussion in Anderson, 1980). Gold from a magmatic source could be carried by the hydrothermal fluids while the fluids scavenge gangue components from and equilibrate stable isotope ratios with the country rock. Therefore, with regard to gold origin, stable isotope studies are intrinsically inconclusive, if not irrelevant.

Another approach to the origin of the gold would be to show by calculation whether or not all the gold at the Carlin deposit could be obtained by leaching from the local sedimentary rocks. The gold that could not be derived from the sedimentary rocks would have to have a magmatic source. Radtke (1981, p. 135) stated that all the gold at the Carlin deposit could have been leached from 3,000 t of carbonate rock, implying an unreasonably high gold concentration of at least 3.3 percent in the source rock. Estimates of volume of rock, presumably largely from the Roberts Mountains Formation, needed as a source for amounts of As, B, Cu, Hg, Pb, Sb and Tl found in the Carlin deposit were calculated by Dickson and others (1979, p. 107) but are not directly relevant to the origin of the gold. To some extent calculations of this nature are inconclusive because of the number of unknown factors. Some of these factors are discussed briefly below prior to presenting some trial calculations.

Figure 3 suggests that, at least at the surface, hydrothermal alteration is concentrated in the Roberts Mountains and Popovich Formations. Hydrothermal effects, which may reflect subsurface alteration in these two formations, are found in the siliceous rocks of the upper plate of the Roberts Mountains thrust. The extent of surficial alteration does not seem consistent with the model of leaching gold from a great thickness of sedimentary rock beneath the deposit unless the zone of hydrothermal alteration is narrowly focused along steep faults. The calculations below are made for three models: (1) leaching of gold only from the Roberts Mountains and Popovich Formations (897 m total thickness); (2) leaching of gold from the entire carbonate section of the window (2,572 m); and (3) leaching of gold from a vertical block of rock of unspecified lithology, having dimensions determined by surface exposures of hydrothermally altered and mineralized rock.

Radtke (1981, p. 135) assumed that the Carlin deposit contained 100 t of gold, an amount also mentioned by Henley and Ellis (1983, p. 29). An over-estimate of production of 4 million ounces was given by Dickson and others (1979, p. 101). An estimate of the gold content is obtained here by adding production and reserves. Production through 1982 (table 1) was 103.6 t of gold. Published reserves, as of 1982 (Lucas, 1983) are 6,988,000 tons (English) of ore containing 0.165 troy ounces per ton, or 35.9 t (metric). A total of 139.5 t of gold can be accounted for in this way. Some of this amount is from the nearby Blue Star and Bootstrap deposits (fig. 2). Submarginal gold deposits peripheral to the main deposit may account for an additional quantity of gold that is irretrievable at present. For purposes of the following calculations, a total of 140 t of gold is used.

Radtke and others (1972) reported gold to 0.06 ppm in two samples of fresh carbonate hosts rock (formation not indicated) at the Carlin deposit. However, these values, as well as the values of other elements from this class of rock at the deposit are suspect because of the difficulty in visually determining what rocks have been completely unaffected by mineralizing fluids in a terrain in which broad halos of hydrothermally altered rock are characteristic. Most of the samples of unaltered host rock studied by Radtke and others, actually contained less than 0.02 ppm gold (lower limit of detection) but a more exact concentration was not determined. The rock volumes estimated by Dickson and others (1979) from which it is necessary to leach the amounts of As, B, Cu, Hg, Pb, Sb and Tl found in the Carlin deposit range from 0.004 to 6 km^3. These figures imply average source rock gold concentrations of 0.0086 to 13 ppm. Radtke (1981, p. 135) later estimated the gold content of possible source rocks at 0.03 ppm. This figure is much larger than most gold analyses of modern seawater, equals the largest gold content found in marine organisms (Jones, 1970), and is much greater than average gold content for carbonate rock (0.002-0.003 ppm, Jones, 1969, p. 23). Wells and others (1969, p. 532-536), who proposed a sedimentary origin for the gold at the Cortez deposit, found gold-bearing pyrite in "unaltered" Roberts Mountains Formation near the deposit. They obtained 0.6 ppm gold in pyrite, which was recalculated to 0.006 ppm for the rock as a whole, given one percent pyrite in the rock. This amount of gold is of the same order as some of larger concentrations of gold found in modern seawater and in certain marine organisms (Jones, 1970), and two to three times the average for carbonate rocks (Jones, 1969). Mullens (1980, p. 41-42), however, pointed out the difficulty in obtaining unaltered host rock near epithermal deposits in Nevada, and maintained that the amount of pyrite in unaltered Roberts Mountains Formation is 0.3 percent. More pyrite than that, he suggests, would be of hydrothermal origin. This conclusion impies that the "unaltered" Roberts Mountains Formation studied by Wells and others (1969) had been slightly mineralized. Assuming uniform distribution of gold in the pyrite, the gold concentration of unaltered rock in the Cortez area should be closer to the 0.002 ppm value for average carbonate rock. In the calculations below, original gold values of 0.002, 0.006 and 0.03 ppm are used.

Although previous workers cited above have suggested the origin of the gold in leaching from rocks below the Roberts Mountains Formation, they have not suggested what gold values these rocks may have had originally. This matter is not addressed here as most rock types have gold values which fall close to the range 0.002 to 0.03 ppm (Jones, 1969).

Radtke (1981, p. 135) assumes a 90 percent efficiency in leaching of gold from the source carbonate rocks, but does not indicate how this level of efficiency was determined. In the calculations below, 100 percent efficiency in leaching, transporting and depositing the gold is assumed, although the hydrothermal processes are not likely to be that efficient. The volume calculations below would have to be increased by an amount that depends on the level of efficiency one wishes to assume.

Densities of carbonate rocks range from about 2.6 to 2.84 in Heiland (1951, p. 84). A value of 2.7 is assumed for the carbonate and for the non-carbonate rocks of the Lynn Window, including rocks below the exposed section. This density may be a little high for parts of the section like the Eureka Quartzite, and for some of the granitic rocks which may underlie the window.

Assuming a gold concentration of 0.002 ppm in unaltered carbonate rock, 7 x 10^{10}t of fresh rock would have to be leached to supply 140 t of gold. If this amount of leached rock was entirely in the Roberts Mountains and Popovich Formations, an area underlain by leached rock of the two formations would total 29 km^2. This compares favorably with the 25 km^2 estimated area of hydrothermally altered rock in the Rodeo Creek NE Quadrangle (includes exposed areas and assumed extent of hydrothermal alteration concealed by alluvium in Little Boulder Basin). However, most of that gold has to be concentrated in an area of about 3 km^2 around the main pit at the Carlin mine, suggesting that intensive leaching may have been more restricted.

If the gold concentration of the unaltered source rocks was 0.006 ppm, 2.3 x 10^{10} t of rock would have to be leached of gold. Deriving the gold from Roberts Mountains and Popovich Formations would result in at least 9.5 km^2 of ground underlain by hydrothermally altered rock of the two formations. If the gold concentration of the source rocks was 0.03 ppm, 4.7 x 10^9 t of rock would have to be leached, resulting in 1.9 Km^2 of hydrothermally altered terrane underlain by the two formations. Although the two larger gold concentrations for source rocks result in figures for the surficial extent of hydrothermally altered rock that are more in line with the geological evidence, as discussed above, these gold values are probably too high for the fresh rock.

Performing the same calculations utilizing a model requiring leaching of gold from strata equivalent to the entire exposed section of the Lynn Window reduces the lateral extent of hydrothermal alteration to be expected. With an initial gold concentration of 0.002 ppm in the source rocks, hydrothermal alteration need underlie only 10 km^2; with 0.006 ppm initial gold concentration, only 3.3 km^2; and with 0.03 ppm, only 0.7 km^2. The 10 km^2 figure is nearly consistent with the geologic evidence and can be reduced by including leaching of gold from rock units which may underlie the exposed carbonate section. In this case it would not be necessary to resort to geologically unlikely gold values in the source rocks. The only possible problem with including rocks below the exposed section as part of the gold source is that one cannot be sure whether these rocks are sedimentary or igneous (or metamorphic), as there are shallow intrusions north and south of the Carlin deposit, and possibly also beneath it. In addition, it is not known whether one or more intrusions has shouldered aside a substantial part of the carbonate section not far below the deposit. Further, the question is left unresolved as to whether the gold has a magmatic source or was derived by lateral secretion, because either hypothesis could be consistent with a shallow intrusion.

By trying to leach the gold from a vertically-bounded block of ground irrespective of lithology, one can calculate the depth to which the rock would have to be leached of gold. Using an initial gold concentration of 0.002 ppm and assuming that the entire 1.6 x 16 km (25.6 km^2) alteration zone from the east side of the Tuscarora Range to the Bootstrap deposit is a potential source region, leaching would have to extend downward at least 1 km, a reasonable depth for a hydrothermal system. However, as noted above, most of the gold may have come from a column of rock, with a 3 km^2 cross section, extending downward in the vicinity of the main pit. Using the figure of 3 km^2 for the area of the column of leached rock, the zone of leaching would extend to a depth of 8.6 km. This is close to, but slightly exceeds, the lower limit suggested for hydrothermal systems (Henley and Ellis, 1983). Changing initial assumptions like the initial gold concentration of the source rock and cross-sectional area of the rock column would decrease the depth of the alteration zone. Given the possibility of shallow intrusions in the area, it seems likely that the zone of leaching would intersect a concealed pluton. The origin of the gold would then be indeterminate because the gold could have had a magmatic source or have been leached from the plutonic rock.

Seward (1973) suggested that a significant proportion of gold could be transported by thio complexes in hydrothermal ore solutions. Using his experimentally determined solubility of 0.0225 ppm, 6.22 km^3 of water would be needed to tranport 140 t of gold in solution. Weissberg (1969, p. 104) found gold concentrations of 0.00004 ppm in certain thermal waters in New Zealand that were forming ore-grade precipitates. This low concentration is not necessarily the same as would be found in all other thermal environments. However, this figure can be used as a lower limit for purposes of comparison. If the hydrothermal fluids that formed the Carlin deposit carried no more than 0.00004 ppm, about 3,500 km^3 of water would have to pass through the site of the deposit. To determine whether this amount of water can reasonably flow through the Carlin deposit in a single geothermal cycle requires examination of the duration of geothermal systems in general and discharge rates of known goethermal systems.

Silberman and others (1979) examined geological evidence for the duration of geothermal and ore-forming epithermal systems. The time spans range on the order of 1 to 3 million years. Cathles (1981) constructed cooling curves for plutons and concluded that, for the conductivities he selected, no intrusion at 800° C can maintain an anomaly greater than 200°C within 5 km of the surface for more than 4 m.y. For purposes of this report, two cases are examined: (1) that the gold was deposited during one geothermal system which lasted for 3 million years, the maximum duration based on geologic evidence; and (2) that gold was deposited at least three times, twice in the Cretaceous and once in the Tertiary, coincident with the three intrusive episodes for which geological evidence is available in the study area. (The two Tertiary intrusions overlap in time and, for purposes of these calculations are considered to be a single intrusive episode.) Each of the episodes is assumed to have resulted in a geothermal system lasting 3 million years.

It is not known whether the geothermal system or systems which occurred in the Carlin area vented at the surface. Radtke and others (1980, p. 646) suggest that 305 to 518 m of overburden have been eroded away in late Tertiary since the latest episode of mineralization, and no evidence of surface springs remains. However, the fluids carrying the gold must have flowed generally upward toward the paleosurface and may be considered as discharge whether or not the water was ultimately recycled to the convective geothermal system. Natural discharges from identified convection systems range from less than 0.001 to 5.7 m^3/min (Renner and others, 1975, p. 5-57; Brook and others, 1979, p. 18-85). Discharges from Steamboat Springs, Nevada and Sulphur Bank, California are of particular interest. The Steamboat Springs geothermal area is 5 km northwest of the Comstock Lode District (Thompson and White, 1964). Also, siliceous mud precipitated in fissures below the water table contain as much as 10 ppm Au (White, 1967, p. 594). White (1968, p. C87) estimated discharge for the Steamboat Springs area at 4.3 m^3/min. However, 36 percent of this discharge is from geothermal wells. The Sulphur Bank mine is the most productive mineral deposit in the world that is closely related to hot springs (White and Roberson, 1962, p. 398). Sims and White (1981, p. 238) estimate discharge from the Sulphur Bank mercury mine area at 1.1 m^3/min. These discharge rates must be used cautiously as standards of comparison because there is no way of knowing if these are close to averages for their systems. At least these discharge rates can be used to indicate possible magnitudes of natural discharges.

If the gold at the Carlin mine was deposited during a geothermal cycle lasting 3 million years, average discharge of water would have to be at least 2,073 m^3/yr if the water carried as much as .0225 ppm Au. This is very low compared to the yearly natural flow of 1.45 million m^3/yr at Steamboat Springs and 0.6 million m^3/yr at Sulphur Bank. Even if the hypothetical Carlin geothermal system lasted only 1 million years, the flow required to deposit the gold would be many orders of magnitude smaller than many natural discharges. The hydrothermal system responsible for deposition of the gold, however, may have been a subsystem of a much more extensive geothermal system with a total discharge much greater than needed to form the Carlin deposit. If the work was done by all three of the geothermal systems that may have affected the area, the efficiency in concentrating the gold by the three systems could have been very low. If the thermal waters that circulated through the Carlin deposit carried 0.00004 ppm gold, annual discharge would have to be at least 1.2 million m^3/yr over a 3 million year-long geothermal system, and 0.39 million m^3/yr for three geothermal systems, each lasting 3 million years. The greater discharge rate is still less than the one at Steamboat Springs, suggesting that even with very low gold concentrations in solution, one geothermal system may have been able to do the work of transporting the gold to the depositional site.

Although the calculations outlined above are inconclusive they suggest: (1) that the gold at the Carlin deposit could have been leached from the country rock, although magmatic sources cannot be ruled out: and (2) that the work of leaching and transporting the gold to the deposit could have been performed by a single, relatively inefficient, geothermal system, even though geologic evidence suggests that at least three systems could have developed in the area.

Because gold-bearing rock, was eroded from the upper part of the Carlin deposit and nearby areas, including the Big Six deposit, gold placer deposits should occur near the present lode deposits. Gold placers are present in Lynn, Rodeo, Sheep and Simon Creeks and in Quaternary fanglomerate where Lynn Creek leaves the siliceous assemblage on the east flank of the range (Johnson, 1973, p. 26-27). That gold placers are not known from drainages below the Carlin deposit is probably due to the micron-size gold particles from Roberts Mountains and Popovich Formations being too small to recover by panning. The Carlin deposit had been recently (in geological terms) uncovered by erosion prior to discovery (see Evans, 1980, pl. 1, cross section CC'). Gold-bearing gravels from this upper plate source have subsequently been mixed with and (or) buried by alluvium derived from the carbonate assemblage. Therefore, unexploited gold placers of limited potential may underlie present alluvium in streams draining east and west from the Carlin deposit and from parts of the northwest-trending zone of hydrothermally altered rock. Placers could occur in the alluvium of southern Little Boulder Basin and along the east flank of the range in the southeast corner of the Rodeo Creek NE quadrangle. This alluvium and the fanglomerate to the north are underlain by the middle Miocene-early Pliocene Carlin Formation, some of which could also contain gold placers. Minor gold placers in southwest Rodeo Creek NE quadrangle may be present downstream from gold-bearing quartz veins in Hanson Creek Formation. Gold in any of these Tertiary and Quaternary units, especially if it originated from the carbonate assemblage, may be present in small amounts in very fine sediment fractions and may not comprise economic deposits by present-day standards.

Some of the geologic, aeromagnetic, and geochemical features associated with the Carlin deposit may be unique and other features may be useful as guides for exploration for disseminated gold deposits, at least in Nevada. Among characteristics that may be useful as exploration guides is the well-known lithological association of principal gold deposits in the Roberts Mountains and Popovich Formations, particularly the silty laminated dolomitic limestone common to both formations. Gold is also deposited in chert and shale of the siliceous assemblage, but these deposits do not comprise the major ore body in the study area. Large reserves of gold have been found in the Coast Ranges of California in a geological setting very different from north-central Nevada (Vredenburgh, 1982). The deposits may be associated with altered serpentinite, and assemblages that may include a wide variety of marine sedimentary rocks, mafic volcanic rocks and metamorphic rocks (zeolite and blueschist facies), and are associated with relatively high concentrations of mercury and antimony. These occurrences suggest that lithology may not be as important as other kinds of ore controls on a regional basis.

Steep, generally north trending faults are associated with the Carlin, Big Six, Blue Star, and Bootstrap deposits, although a regional northwest-trending structure may have been important in localizing alteration and gold deposition. Gold was deposited in the brecciated rock and the faults served as conduits of mineralizing fluids. These relations suggest that another guide to exloration would be broad preferably intersecting fracture zones, the trends of which may be important if they are related to Paleozoic or Proterozoic structures which are inferred to control the orientations of mineral belts. Gold occurrences in the study area further suggest that many lithologies may be favorable ore hosts provided they are brecciated or hydrothermally altered enough to be permeable to ore fluids.

As the deposits in the Lynn Window and vicinity seem related to Mesozoic and Tertiary intrusions, Paleozoic rocks in the vicinity of other such intrusions should be examined for metalliferous deposits. These intrusions may be concealed below sedimentary rocks where their presence may be suggested by broad contact metamorphic aureoles surrounding minor intrusive bodies and aeromagnetic highs, especially over terrain exhibiting contact metamorphism and intrusion. Ore deposits may be closely associated with intrusions, as at the Gold Strike mine. Alternatively, deposits may be several kilometers from visible portions of intrusions. In the Lynn Window, the major gold deposit, at Carlin, is about 5 km from the outcrops of the quartz monzonite, 8 km from the Cretaceous granodiorite at Gold Strike mine and even farther from the main Tertiary granodiorite and quartz latite intrusions. One or more of these intrusions may have been associated with the gold mineralization at Carlin.

Absence of contact metamorphic aureoles or aeromagnetic highs does not rule out the presence of concealed intrusions. Aureoles could be concealed beneath unmetamorphosed or hydrothermally altered rock. Aeromagnetic highs over concealed intrusions may be absent if the ferromagnetic minerals are oxidized, were lacking initially, or are overprinted by ferromagnetic surficial lavas. The highs also may be absent if the intrusions are deep below surficial rocks poor in ferromagnetic minerals. In this case, ore deposits may also be inaccessible to surficial exploration techniques. The aeromagnetic trough in the study area does not appear to be significant regionally, as the gold deposits at the Bootstrap and Carlin Windows (U.S. Geol. Survey, 1967), at Gold Acres (Wrucke and others, 1968, fig. 7), and at Cortez (Gilluly and Masursky, 1965, pl. 3) occur on aeromagnetic gradients.

The Carlin deposit is within a broad zone of hydrothermally altered rock which may be part of an extensive mineral belt (see p. 6) at least 70 Km long. The origin of this zone is complex; in the study area it may be the product of as many as three episodes of hydrothermal activity. Other broad alteration zones of this kind may have potential for gold deposits, regardless of orientation.

Because gold is statistically associated with mercury in Roberts Mountains Formation, the principal ore host at the Carlin deposit, mercury analyses of soil gas may be a particularly valuable exploration tool in disseminated gold deposits (McCarthy and others, 1969). Brooks and Berger (1978) however, have found that detected mercury anomalies may not be directly related to gold mineralization at depth.

Conclusions

(1) The Carlin gold deposit occurs in a northwest-trending zone of hydrothermally altered rock 30 km long to 3 km wide that may be part of a 70 km long belt of mineralization.

(2) Geologic evidence suggests that the zone of hydrothermally altered rock, including the Carlin deposit, developed as a consequence of Mesozoic and Tertiary intrusions.

(3) Partial geographical segregation of element suites may be due to one or more or controls including element zoning in a geothermal system: (1) Au, As, Hg, Sb, Cu and Pb in the Rodeo Creek NE Quadrangle around the Carlin mine: and (2) Ag, Ba, Mo, Mn, Sn, W and Zn in both quadrangles.

(4) Mass balance calculations suggest that the gold in the Carlin deposit could have been concentrated during one geothermal cycle by hydrothermal fluids scavenging gold at concentrations of the order of crustal abundance from carbonate sedimentary rocks in the lower plate of the Roberts Mountain thrust. However, a magmatic source for part of the gold cannot be ruled out.

(5) Gold placer deposits of limited potential may occur in Tertiary and Quaternary sedimentary units east and west of the Carlin and Big Six deposits and downstream from gold-bearing quartz veins in Hanson Creek Formation.

(6) Guides for exploration for Carlin-type disseminated gold deposits include (a) a lithology, such as the silty dolomitic limestone in Roberts Mountains and Popovich Formations, which is permeable to hydrothermal fluids, or any lithology which has had its permeability enhanced by hydrothermal action and (or) brecciation; (b) broad intersecting fault zones, especially ones which may be regional structures of great age; (c) Mesozoic and (or) Tertiary intrusions in Paleozoic rocks; (d) broad zones of hydrothermally altered rock, especially ones coincident with (b); (e) mercury anomalies in soil gas.

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