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Becky — file or toss

Application of Structural Geology to Mineral and Energy Resources of the Central and Western United States

Edited by CHARLES H. THORMAN

Papers presented at a workshop sponsored by the U.S. Geological Survey, October 9–10, 1990, Colorado School of Mines, Golden, Colorado

Jon — Just out. Best regards! Pete

(All our work is done despite Mitch Reynolds!)

1992

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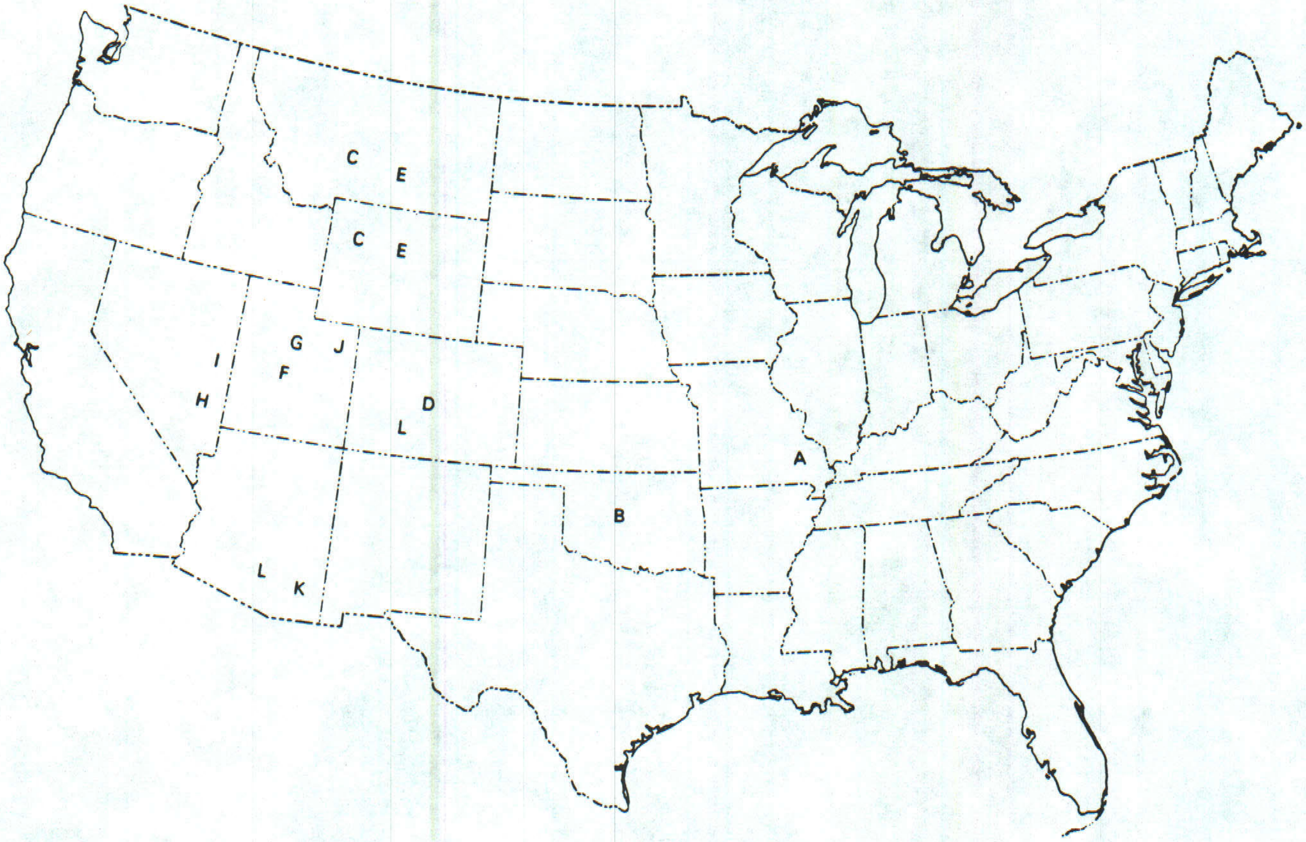
[Letters designate chapters]

PREFACE

This volume includes some of the papers presented at a workshop sponsored by the U.S. Geological Survey and held October 9–10, 1990, at the Green Center, Colorado School of Mines, Golden, Colorado. The workshop presented current research by U.S. Geological Survey scientists who are using structural geology in their investigations into the mineral and energy resources of the United States. The figure below shows the areal distribution of the 12 chapters included herein; the papers are lettered on the figure according to their position in the text of this report.

One of the most important aspects of this workshop was a demonstration of the integrating of many disciplines in unraveling the structural evolution of an area, regardless of scale. The application of structural geology by itself provides only a limited amount of information and leaves many aspects of the evolution of an area unresolved.

Integration of geophysical techniques (gravity, seismic, and audio-magneto-telluric) with detailed and regional geology in sedimentary and volcanic terranes establishes the basis for new approaches to exploration for hydrocarbons in Arizona, Colorado, Utah, Wyoming, and Montana (chapters D, E, J, K). Field studies at detailed to regional scales (chapters A, C, F, G, H, I, L) present data that call for moderate to major revision of thinking in areas often thought to be well understood. These studies emphasize the continuing need to remap so-called well-understood areas, as well as the need to map those areas for which only limited data are available. Detailed petrologic studies in Missouri and Arizona (chapters A, L) of both carbonate and volcanic rocks cause us to reconsider our concepts of the origin of well-established rocks units and thus their implications regarding the structural evolution of those areas. Depositional patterns can be key indicators of the tectonic control of paleotopographic highs, a major factor in basin evolution, as suggested for the Anadarko Basin (chapter B). The application of isotopic dating in structurally complex areas has greatly increased our knowledge of the relative timing and duration of events that influenced the migration of mineralizing and hydrocarbon fluids and gases (chapters G, H). With a better grasp of the time involved, we can better correlate the various deformational and migrational events in Utah and eastern Nevada.



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Item 11

Structural Setting of the Chief Mining District, Eastern Chief Range, Lincoln County, Nevada

By Peter D. Rowley[1], Lawrence W. Snee[2], Harald H. Mehnert[2], R. Ernest Anderson[3], Gary J. Axen[4], Kelly J. Burke[5], F. William Simonds[1], Ralph R. Shroba[1], *and* Stephen D. Olmore[6]

Abstract

The Chief Mining District produced at least 2,000 ounces of gold, 11,000 ounces of silver, and minor amounts of lead and copper between 1870 and the 1960's. The production was from fissure-vein precious-metal deposits containing highly oxidized mineral aggregates within breccia zones of mostly low-angle faults. The main veins consist of scorodite and related minerals that replaced arsenopyrite and of barite, galena, quartz, and iron- and manganese-oxide minerals. The deposits probably represent the lower part of an epithermal gold-silver system that was subsequently deeply eroded. The likelihood of finding additional precious-metal economic orebodies is not good, but the district has potential for a porphyry-copper deposit.

Most veins are in Proterozoic and Cambrian quartzite (Stirling Quartzite, Wood Canyon Formation, Zabriskie Quartzite) and Cambrian limestone (Highland Peak Formation). A large shallow intrusive body of quartz monzonite porphyry, the Cobalt Canyon stock, underlies the district and was the source of the mineralizing fluids, perhaps from convective cells of heated meteoric water. $^{40}Ar/^{39}Ar$ dates for minerals in the stock average 24.8 Ma; the stock may represent an early phase of igneous activity in the Caliente caldera complex, whose boundary is about 4 km south of the mining district.

The Chief Mining District is near the western end of the east-trending Delamar–Iron Springs mineral belt. This belt may have resulted from igneous activity along early Tertiary east-striking faults, which also may have defined other east-striking structural features in the area including the Timpahute Lineament, which intersects the mining district. Other epithermal gold districts in and near the Caliente caldera complex also contain east-striking features that suggest that younger (reactivated) faulting, igneous activity, and mineralization were all locally controlled by east-striking faults.

Recent detailed geologic mapping demonstrates at least three episodes of Tertiary extensional faulting in the district. The oldest episode of faulting was along the low-angle Stampede Detachment Fault Zone, a major east-dipping structure of pre–late Oligocene age (pre-32 Ma), with upper plate movement to the east, that separates Zabriskie Quartzite in the lower plate from Highland Peak Formation in the upper plate. Faults of this episode provided sites for fissure-vein orebodies. The second episode of extensional faulting took place in the Miocene (by at least 19 Ma and continuing to less than 12 Ma) and is characterized by high-angle strike-slip, oblique-slip, and normal faults and, outside the district, by detachment faults. An early phase of this episode may have controlled emplacement of the Cobalt Canyon stock and thus epithermal mineralization. The youngest episode, basin-range faulting, formed much of the present topography; the faults strike north, postdate basalts of 12 Ma, and also cut basin-fill sedimentary rocks of the Panaca Formation (as young as 3 Ma) and Quaternary deposits.

INTRODUCTION

The Chief Mining District in Lincoln County, Nevada, also known as the Caliente Mining District, produced at least 2,000 ounces of gold, 11,000 ounces of silver, and minor amounts of lead and copper between 1870 and the 1960's. The metals came from a cluster of mines (fig. 1) in a 6-km^2 area on the eastern side of the Chief Range, about 8 km north of Caliente, Nevada. Orebodies are in quartzite of Late Proterozoic and Early Cambrian age and limestone and dolomite of Early and Middle Cambrian age; the ore resulted from emplacement of a quartz monzonite porphyry stock of

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Oligocene age. This report summarizes the structural control on the orebodies based on data collected during detailed bedrock mapping. It also includes preliminary $^{40}Ar/^{39}Ar$ dates that constrain the timing of faulting and mineralization.

The Chief Mining District is in the eastern Great Basin (fig. 2) at the western end of the east-trending Delamar–Iron Springs mineral belt of Shawe and Stewart (1976). The Chief Range is a basin range bounded on the east by the deep Panaca fault-block basin. The main locus of igneous activity in the area is the large Tertiary Caliente caldera complex of Nevada and Utah; the northern rim of this complex is as close as 4 km to the mining district.

Prior to our studies, the only geologic information published on the Chief Mining District was a report based on a reconnaissance study of the orebodies by a master geologist, Eugene Callaghan, that was written in 1936 while production in the district was declining. As far as we know, production ceased in the 1960's and the mining district was subsequently abandoned; few buildings remain standing (fig. 1), and, because most shafts, adits, and tunnels have collapsed, few orebodies are accessible. Even where freshly exposed, most orebodies are extensively oxidized and the ore minerals are complex hydrous oxides that are difficult to identify without extensive microscopic and geochemical study, which we have not done. Thus we cannot contribute much additional information on the orebodies, except for chemical analyses of grab samples (table 1). Much later than Callaghan's study, the geologic setting of the area was established by milestone reconnaissance 1:250,000-scale geologic maps of Lincoln County, Nevada, by Tschanz and Pampeyan (1970) and Ekren and others (1977).

The new data in this report result from two 1:24,000-scale geologic mapping projects. The first, beginning in 1985, involved structural studies by G.J. Axen (University of Northern Arizona and Harvard University) and his students in the Highland Range and nearby areas about 10–15 km north of the Chief Mining District and their collaboration with J.M. Bartley (University of Utah), W.J. Taylor (University of Utah), and D.R. Lux (University of Maine at Orono) who worked in the North Pahroc Range, southern Schell Creek Range, and southern Fairview Range, about 30 km west and north-northwest of the mining district. The purpose of this work was to define geometry, timing, and mechanisms of Tertiary extension in the area, the products of which include two major detachment fault zones, the older Stampede Detachment and the younger Highland Detachment (Axen and others, 1988). In order to understand these fault zones, the Paleozoic stratigraphy of the area was refined. Mapping progressed southward, the most recent being that of Burke (1991) in the northern Chief Range. The second project, beginning in 1986, involved quadrangle mapping by the U.S. Geological Survey (USGS) near Caliente in an effort to understand the evolution of the Caliente caldera complex. This project was later incorporated into a major USGS mapping project that encompasses the Basin and Range–Colorado Plateau (BARCO) transition zone in southeastern Nevada and southwestern Utah. Mapping of the Caliente caldera complex started along its northwestern margin in the Indian Cove quadrangle (Rowley and Shroba, 1990, 1991), just east of the mining district, and in the Eccles (R.E. Anderson, unpub. data, 1988) and Caliente quadrangles (P.D. Rowley, unpub. data, 1988), southeast and south of the mining district. Later mapping of the Chief Mountain quadrangle (Rowley and others, 1991), which embraces the mining district and most of the Chief Range, as well as mapping of the Pahroc Spring SE quadrangle (Swadley and Rowley, 1992) and mapping in progress of the Caliente NW, Delamar, and Dow Mountain quadrangles, provides additional geologic framework for this report.

Six new $^{40}Ar/^{39}Ar$ mineral dates from three samples and one K-Ar mineral date from one sample help to constrain temporal relationships in the Chief Mining District. These data are part of a larger K-Ar and $^{40}Ar/^{39}Ar$ geochronologic study being done within the context of the BARCO project. The $^{40}Ar/^{39}Ar$ isotopic dating method is a variant of the conventional K-Ar method; for $^{40}Ar/^{39}Ar$ analysis, samples are irradiated in a nuclear reactor to produce ^{39}Ar from ^{39}K. In this study, 50–100 mg of sanidine and biotite and about 300 mg of hornblende were irradiated in the USGS Denver TRIGA reactor for 30 hours at 1 megawatt. Each sample was irradiated adjacent to an aliquant of standard MMhb–1 hornblende for which K=1.555 percent, $^{40}Ar_K=1.624\times10^{-9}$ mol/g, and K-Ar date=520.4 Ma (Samson and Alexander, 1987). Samples were experimentally degassed in a double-vacuum resistance furnace via step heating in 12–15 steps under ultra-high vacuum for about 20 minutes at each temperature step. The mass 40, 39, 38, 37, and 36 isotopes of argon were analyzed using a Mass Analyser Products series 215 rare-gas mass spectrometer. Raw isotopic data were corrected for volume, mass discrimination, trap current, radioactive decay of ^{37}Ar and ^{39}Ar, and interfering isotopes of argon. Decay constants of Steiger and Jäger (1977) were used to recalculate dates of any cited samples that were analyzed before 1977. Our preliminary ages were first reported in Rowley, Snee, and others (1990) and Snee and others (1990). Isotopic data are available from the authors.

Classifications of volcanic and plutonic rocks are those of the International Union of Geological Sciences (Le Bas and others, 1986, and Streckeisen, 1976, respectively). Relative offset on some faults that contain slickensides was determined using the methods of Angelier and others (1985) and Petit (1987).

Acknowledgments.—We gratefully acknowledge numerous helpful discussions with R.B. Scott concerning the structural setting and regional stratigraphy, with G.B. Allen and S.P. Bingham (both of Alma American Mining Corporation), J.E. Elliott, and E.B. Ekren regarding epithermal mineral deposits, and with W C Swadley pertaining to surficial deposits. We thank R.B. Blakestad and R.R. Kern (both of Homestake Mining Company) for access to company-

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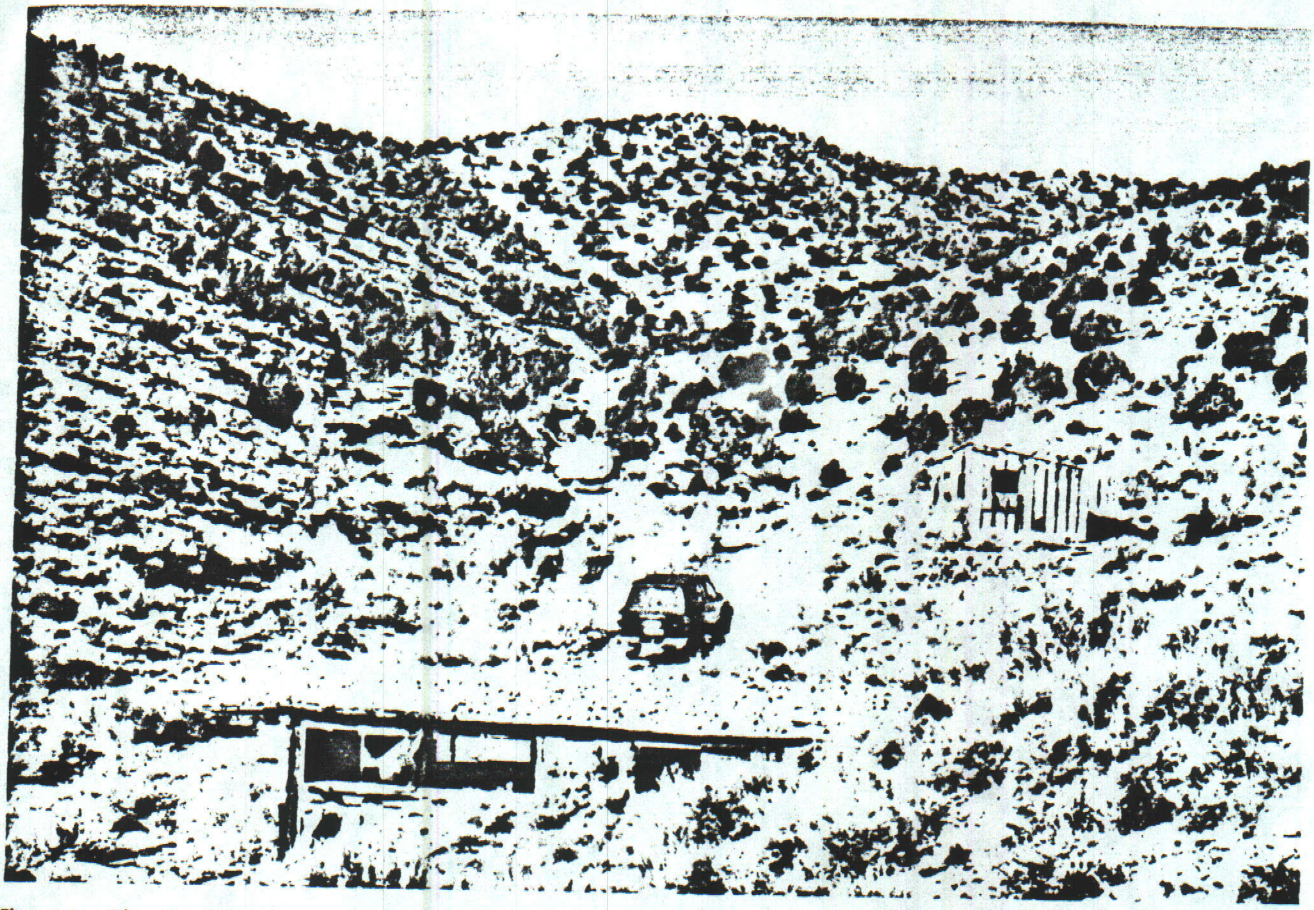


Figure 1. Photograph, looking west, showing mines in upper Cobalt Canyon, Chief Mining District, Lincoln County, Nevada. Building to right of car was a former boarding house, and building farther up the canyon and to left is at entrance to tunnel of the Contact Mine; both are underlain by Highland Peak Formation, beyond which are Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite. A dump at the Gold Stake Mine is farther up canyon. The Advance Mine is in gulch left of central hill on horizon, and the Old Democrat Mine is at bottom of gulch to right of central hill.

confidential data on the Chief Mining District, and we are grateful to these geologists and to Homestake for permission to publish some of those data, as identified in the text. We thank J.L. Askey and J.B. Harlan (both of FMC Gold Company), Charley Martin (Worldwide Resources), and R.R. Kern for information on the Taylor (Easter) Mine. Inclusion of chemical analysis of mineralized and altered rock samples (table 1) would not have been possible without the kind cooperation and rapid work of B.M. Adrian, R. Hill, D.E. Detra, R.M. O'Leary, R.W. Leinz, and C.M. McDougal of the USGS, and dating could not have been done without mineral separations by D.M. Cheney. Mapping in the northern Chief Range and adjacent areas by Axen and Burke was partly funded by grants to them from Texaco, Marathon, and Mobil oil companies, by grants to Burke from Sigma Xi and Northern Arizona University, and by National Science Foundation Grant EAR-14455-AC2 to J.M. Bartley (University of Utah). Editorial assistance was provided by C.H. Thorman and K.S. Kellogg. We thank C.H. Thorman for technical review of the manuscript and Ron, Betty, Chad, and Brenda Young of Caliente for help and many kindnesses during our field work.

HISTORY AND PRODUCTION

The date when the first ore deposits in the Chief Mining District were found is unknown, but it probably was shortly after the initial discoveries in 1868 in the Pioche Mining District, 27 km to the north (Callaghan, 1936). The Chief district was organized in 1870 and had an estimated production of $25,000 during the next few years. Production records for the district are incomplete. The first recorded shipment of ore was in 1896, followed by shipments of unknown value in subsequent years (Callaghan, 1936). An estimated 2,000 ounces of gold, 11,000 ounces of silver, 45,000 pounds of lead, and 2,000 pounds of copper, with a total value of about $70,000, were tabulated for the period 1907–1953 (Callaghan, 1936, table 1; Tschanz and Pampeyan, 1970, table 28). There is little information on production from individual

Table 1. Chemical analyses of grab samples of hydrothermally altered and mineralized rocks from the Chief Mining District, Lincoln County, Nevada

[Flame atomic absorption analyses of Te, Tl, and Au by R. Hill, R. O'Leary, and B.H. Roushey; DC-ARC AES analyses of other elements by B.M. Adrian, D. Detra, and R.T. Hopkins. Ca, Fe, Mg, Na, and Ti in percent, all other values in parts per million. Lower limit of determination of each element given in parentheses. N, not detected at limit of detection; H, interference; <, detected, but below limit of detection; >, greater than. P at or below limit of detection except in samples 777 (0.5 percent) and 812 (0.2 percent); Bi not detected except in sample 781 (15 ppm); Ge, Sn, and Th not detected; Nb at or below limit of detection except in sample 812 (20 ppm); W only detected in sample 781 (20 ppm)]

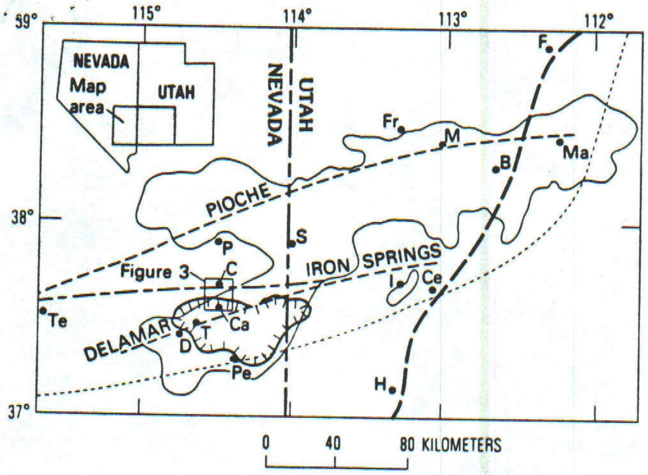
Sample number	378a	469b	751	765	777	778	781	793	794	802	812	866	1121c	1122a
						Chemical analyses of samples								
Te (0.05)	N	N	N	0.4	1.4	3.6	0.9	1.7	0.2	<	N	0.1	N	N
Tl (0.05)	<	0.35	0.15	0.35	0.95	0.2	0.3	0.2	2.2	3.1	0.5	2.8	0.55	0.45
Au (0.05)	N	N	N	N	N	N	1.1	N	1.1	N	N	0.05	N	N
Ca (0.05)	0.2	>20	0.2	0.15	0.5	0.05	<	15	10	7	0.2	1	1.5	5
Fe (0.05)	2	1	0.7	2	3	20	7	7	2	7	0.3	7	5	7
Mg (0.02)	0.3	1.5	0.1	0.7	0.1	0.03	0.1	0.3	2	2	0.3	0.3	1	3
Na (0.2)	N	<	<	2	N	<	0.2	N	<	<	0.2	0.5	>5	5
Ti (0.002)	0.3	0.07	0.02	0.5	0.07	0.02	0.2	0.03	0.007	0.1	1	0.02	0.5	0.7
Ag (0.5)	N	N	N	<	1	5	20	1	10	<	<	100	N	N
As (200)	N	N	N	N	500	10,000	10,000	300	500	200	N	300	N	N
B (0.10)	N	10	10	70	50	10	2,000	15	15	50	150	70	<	<
Ba (20)	70	30	70	300	1,000	700	100	200	5,000	2,000	150	500	1,000	1,000
Be (1)	2	<	2	<	5	<	2	<1	<1	<	2	1.5	<1	1
Cd (20)	N	N	N	N	70	N	N	N	N	N	N	70	N	N
Co (10)	10	N	<	<	15	N	15	10	<	N	N	10	15	20
Cr (10)	100	10	10	<	<	10	150	<	<	15	70	20	50	50
Cu (5)	20	5	5	5	500	50	100	15	30	7	5	150	30	30
Ga (5)	5	15	N	70	N	H	20	N	7	15	50	7	50	50
La (50)	<	N	N	70	100	N	50	N	N	N	100	N	100	100
Mn (10)	150	700	200	100	>5,000	50	2,000	5,000	5,000	5,000	200	5,000	300	1,000
Mo (5)	N	N	N	N	15	10	50	<	10	15	N	N	N	N
Ni (5)	20	5	5	<	70	<	7	10	7	5	<	5	15	20
Pb (10)	20	10	N	30	20	10,000	20,000	500	10,000	100	50	15,000	50	50
Sb (100)	N	N	N	N	<	200	700	<	<	N	N	150	N	N
Sc (5)	7	10	<	10	N	N	10	7	<	5	10	5	7	15

Table 1. Chemical analyses of grab samples of hydrothermally altered and mineralized rocks from the Chief mining district, Lincoln County, Nevada—Continued

Sample number	378a	469b	751	765	777	778	781	793	794	802	812	866	1121c	1122a
Sr (100)	<	200	<	200	500	150	1,000	100	1,000	200	N	100	300	700
V (10)	100	<	20	100	100	100	100	20	15	50	150	500	100	150
Y (10)	15	15	<	20	30	N	10	20	15	15	20	15	20	30
Zn (200)	N	N	N	N	700	300	15,000	500	3,000	500	N	10,000	N	N
Zr (10)	150	50	10	150	100	10	200	10	<	50	300	70	200	200

Lithology and location of samples

378a	Fault zone between Zabriskie Quartzite and Cobalt Canyon stock, lat 37°40'09" N., long 114°31'31" W.
469b	Metamorphosed limestone at contact with Cobalt Canyon stock, lat 37°39'33" N., long 114°30'51" W.
751	Hydrothermally altered and quartz veined Cobalt Canyon stock, lat 37°40'36" N., long 114°30'14" W.
765	Hydrothermally altered local lava flows and tuffs near contact with Cobalt Canyon stock, lat 37°41'11" N., long 114°30'58" W.
777	Quartz veins, mineralized rocks in Zabriskie Quartzite from prospect pit 250 m east of Gold Stake vein, lat 37°41'19" N., long 114°31'38" W.
778	Quartz veins and mineralized rocks in Wood Canyon Formation from a shaft on Gold Stake vein, lat 37°41'16" N., long 114°31'46" W.
781	Mineralized quartz veins on north side of a shaft of Republic Mine, lat 37°41'17" N., long 114°32'03" W.
793	Mineralized rocks in Highland Peak Formation brecciated by Stampede Detachment, from dump of SOA Mine, lat 37°41'56" N., long 114°31'17" W.
794	Mineralized vein in Highland Peak Formation at entrance to Gold Chief Mine, lat 37°41'50" N., long 114°31'20" W.
802	Mineralized vein in fault zone in Highland Peak Formation at Lucky Chief No. 3 Pit, lat 37°41'51" N., long 114°32'01" W.
812	Hydrothermally altered Cobalt Canyon stock, lat 37°42'17" N., long 114°32'05" W.
866	Mineralized rocks in fault zone of Lucky Hobo Mine, lat 37°41'42" N., long 114°31'51" W.
1121c	Hydrothermally altered Cobalt Canyon stock, lat 37°40'29" N., long 114°30'04" W.
1122a	Sulfide minerals in hydrothermally altered chilled contact of Cobalt Canyon stock, lat 37°40'34" N., long 114°30'16" W.



EXPLANATION

- Caliente caldera complex
- Boundary of aeromagnetic ridge; from Zietz and others (1976, 1978)
- Axes of Pioche and Delamar–Iron Springs Mineral Belts of Shawe and Stewart (1976)
- Timpahute Lineament of Ekren and others (1976)
- Axis of Intermountain Seismic Belt (Smith and Sbar, 1974)
- Colorado Plateau–Great Basin boundary

Figure 2. Tectonic setting of Chief Mining District, Lincoln County, Nevada. B, Beaver; C, Chief Mining District; Ca, Caliente; Ce, Cedar City; D, Delamar; F, Fillmore; Fr, Frisco; H, Hurricane; M, Milford; Ma, Marysvale; P, Pioche; Pe, Pennsylvania Mining District; S, Stateline Mining District; T, Taylor (Easter) Mine; Te, Tempiute Mining District.

mines other than some records that show that the Gold Chief Mine was by far the principal producer and the largest mine in the district. By 1911, the Gold Chief had an inclined shaft about 130 m long and drifts totalling about 300 m in length (Callaghan, 1936). Production was insignificant after 1941, and mining probably ceased in the 1960's. As a result of renewed interest in heap-leach processing of disseminated gold ore, claims recently were staked throughout the district as well as in the area adjacent to the main mass of the Cobalt Canyon stock (described below), which is centered about 1.5 km south of the district. An area north of the Lucky Hobo Mine was apparently drilled by Texas Gulf International in 1982 (Tingley, 1984). Homestake Mining Company did a geologic and geochemical study, authored by S.D. Olmore, of the district in 1985, including 12 reverse-circulation drill holes.

Prospects on the northern town limits of Caliente are considered to be part of the Chief Mining District (Tingley, 1984), but, because no production records are known for the area near these prospects and no orebodies are exposed there, they are not discussed in this report.

GEOLOGY

Stratigraphy

Most rocks in the Chief Mining District (fig. 3) consist of resistant, reddish-brown, pink, gray, and white, mostly thin-bedded, planar and crossbedded, dense, vitreous orthoquartzite correlated by Callaghan (1936) with the Prospect Mountain Quartzite of Late Proterozoic and Early Cambrian age (details on regional stratigraphy of this and other Paleozoic units in the area are in Merriam, 1964, and Tschanz and Pampeyan, 1970). Stewart (1974, 1984) measured a stratigraphic section through this continental and near-shore marine quartzite sequence in Antelope Canyon, 6 km south of the district, and correlated it with Stirling Quartzite of Late Proterozoic age, Wood Canyon Formation of Late Proterozoic and Early Cambrian age, and Zabriskie Quartzite of Early Cambrian age. We followed Stewart's stratigraphy in our mapping. The Stirling Quartzite is composed of light-colored, unfossiliferous, generally pure quartzite that is typically coarser grained than the two younger formations and is at least 600 m thick (base not exposed); a prominent basalt lava flow is in its upper part. The Wood Canyon Formation is a dark-colored sequence of interbedded quartzite, siltstone, and shale that is about 320 m thick and that contains animal tracks, burrows, and a thin basalt flow in its upper part. The Zabriskie Quartzite is mostly white, pure quartzite that is as thick as 140 m and that contains local animal tracks and burrows.

The Lower and Middle Cambrian Pioche Shale conformably overlies the Zabriskie Quartzite and is well exposed in an incomplete section in and north of Antelope Canyon. It consists of a soft, green, locally fossiliferous, micaceous marine shale and subordinate siltstone, sandstone, and limestone and is as thick as 250 m in the Pioche area. Conformably overlying the Pioche in the Antelope Canyon area are two thin Middle Cambrian marine units, the Lyndon Limestone, a resistant medium- and dark-gray limestone about 20 m thick, and the Chisholm Shale, a soft brown nonmicaceous shale about 30 m thick.

Lower parts of Middle and Upper Cambrian Highland Peak Formation are exposed in the Antelope Canyon area. This formation consists of resistant, light- to dark-gray, black, and white, marine limestone and dolomite that has a maximum thickness of about 1,500 m in the Pioche area (Merriam, 1964). Numerous members have been mapped north and west of the Chief Range, where they are well

Figure 3 (facing page). Generalized geology of Chief Mining District and vicinity, Lincoln County, Nevada. A, Advance Mine; C, Contact Mine; G, Gold Chief Mine; H, Lucky Hobo Mine; L, Lucky Chief Mine; O, Old Democrat Mine; R, Republic Mine; S, Gold Stake Mine; So, SOA Mine.

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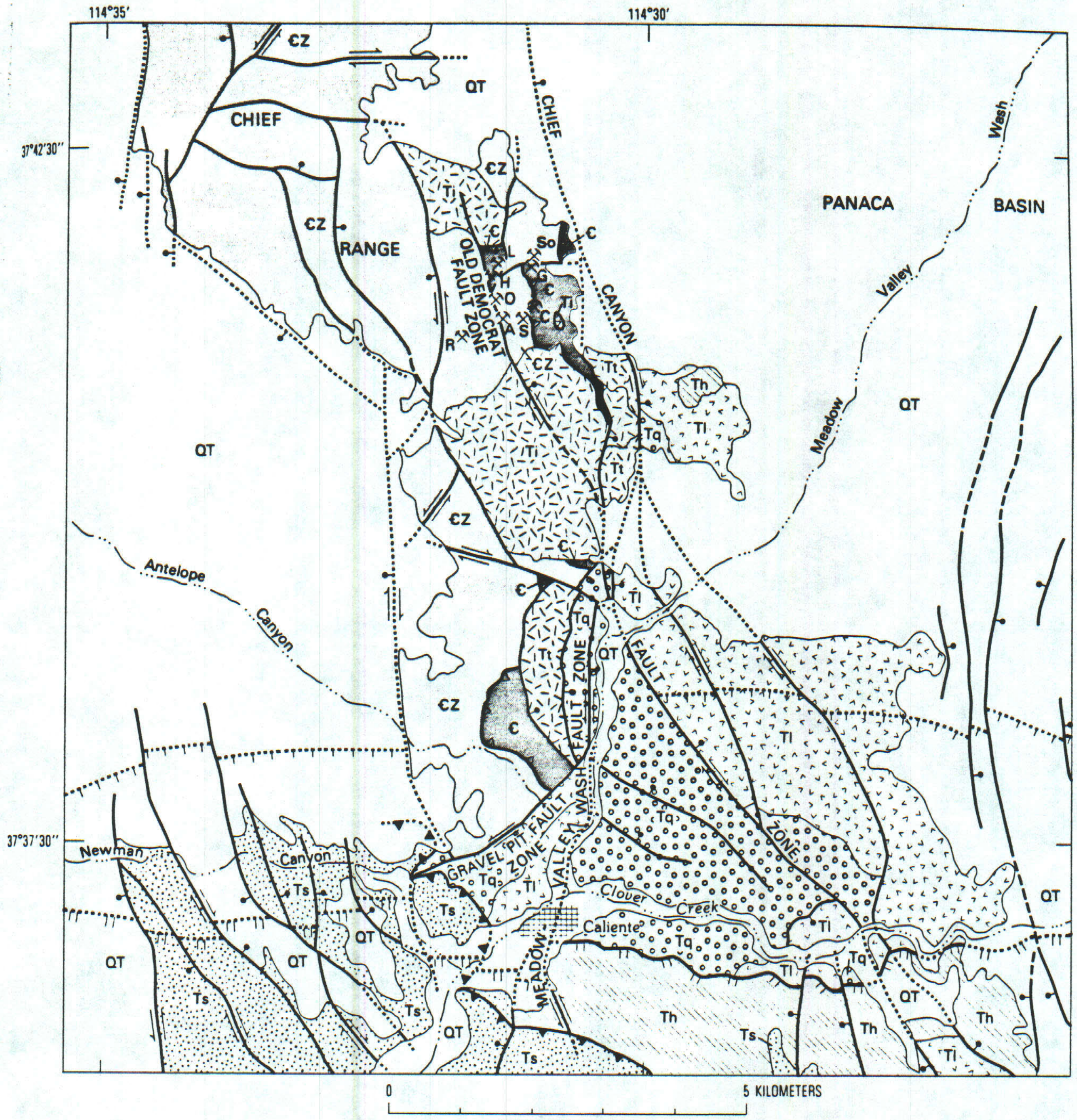

EXPLANATION

Cenozoic:

- QT — Surficial and basin-fill sediments
- Ts — Tuffs and sedimentary rocks of 14–12 Ma
- Th — Hiko Tuff
- Tl — Lava flows of Indian Cove
- Tq — Quichapa Group
- Ti — Cobalt Canyon stock
- Tt — Oligocene tuffs and lava flows

- € — Cambrian limestone and shale
- €Z — Cambrian and Proterozoic quartzite
- High-angle fault—Dashed where approximately located, dotted where concealed
- Newman Canyon Detachment—Teeth on upper plate
- Stampede Detachment—Teeth on upper plate
- Delamar caldera—Dotted where concealed
- Clover Creek caldera—Concealed

exposed (Axen, 1986; Lewis, 1987; Axen and others, 1988; Sleeper, 1989; Burke, 1991), but in the Antelope Canyon area only the basal Peasley Member and overlying Burrows Member (Merriam, 1964) are exposed. In the mining district, light-gray limestone only about 50 m thick is exposed; it is contact metamorphosed by the underlying Cobalt Canyon stock (see below) and can only be assigned tentatively to the Highland Peak Formation.

Tertiary volcanic rocks unconformably overlie Proterozoic and Cambrian units in an area north of Antelope Canyon that is within 3 km of the southern margin of the mining district. Most of the volcanic rocks here are complexly faulted by a series of oblique-, normal-, and strike-slip faults; these same rocks are better exposed west of the Chief Range. The lowest volcanic unit (Oligocene) in the faulted area north of Antelope Canyon consists of hydrothermally altered local lava flows and tuffs intertongued and overlain by the Isom Formation, which consists of a series of mostly brown, crystal-poor, trachytic, regional ash-flow tuffs with a probable caldera source on the northern side of Escalante Valley north of Modena, Utah, and has a $^{40}Ar/^{39}Ar$ date of about 27 Ma (Best, Christiansen, and Blank, 1989).

The overlying Quichapa Group contains, in ascending order, regional ash-flow sheets of the Leach Canyon Formation, Swett and Bauers Tuff Members of the Condor Canyon Formation, and Harmony Hills Tuff (Anderson and Rowley, 1975). The Leach Canyon Formation is a soft, pink, poorly to moderately welded, crystal-poor, rhyolite ash-flow tuff; it has an average age of 24.0 Ma based on three K-Ar dates on biotite, sanidine, and plagioclase by Armstrong (1970) and two fission-track dates on zircon by Kowallis and Best (1990), but there is significant variation in these dates (26.7–21.6 Ma). The Swett and Bauers Tuff Members are resistant, reddish-brown and light-purple, densely welded, crystal-poor, rhyolitic ash-flow tuff; the Bauers has two $^{40}Ar/^{39}Ar$ dates averaging 22.8 Ma (Best, Christiansen, and others, 1989, table R3). The Harmony Hills Tuff is a resistant, greenish-gray, moderately welded, crystal-rich, andesitic ash-flow tuff that has a probable age of about 22.5–22 Ma based on isotopic dates on overlying (Rowley and others, 1989) and underlying rocks.

A sequence of resistant, fresh, mostly gray, red, and brown lava flow rocks and subordinate flow breccia and volcanic mudflow breccia and minor fluvial sandstone rests unconformably on the Harmony Hills or older rocks 2.5 km southeast of the mining district. This sequence was named the lava flows of Indian Cove (Rowley and Shroba, 1991) for the area where it attains its greatest thickness (about 500 m) 5 km southeast of the mining district. It probably formed as isolated or coalesced volcanic domes composed of high-alkali andesite and trachyandesite and subordinate high-alkali dacite and trachydacite. A lava flow from the unit yielded a Miocene plateau $^{40}Ar/^{39}Ar$ date on sanidine of 21.9±0.1 Ma (L.W. Snee, preliminary unpub. data, 1990; Snee and others, 1990). Pinching out against this dome complex, but locally exposed on its northern flank about 2.5 km southeast of the mining district (Rowley and Shroba, 1991), is resistant, tan, poorly to moderately welded, crystal-poor, rhyolite ash-flow tuff of the Hiko Tuff (Dolgoff, 1963), which has an average $^{40}Ar/^{39}Ar$ date of 18.6 Ma (Taylor and others, 1989). Locally derived sedimentary rocks and interbedded ash-flow tuff of the Kane Wash Tuff (14 Ma; Novak, 1984) overlie the Hiko Tuff south and west of Caliente and are in turn overlain by the tuff of Etna (which we earlier miscorrelated with the Ox Valley Tuff of Cook, 1960); these units are included in unit Ts of figure 3.

The youngest rocks in the area (unit QT of fig. 3) are fluvial and lacustrine sedimentary rocks exposed in areas surrounding the Chief Range. Most of these sedimentary rocks are basin-fill deposits associated with the youngest (basin-range) episode of extensional faulting, but sandstone, conglomerate, and air-fall tuff at least 200 m thick (sedimentary rocks of Newman Canyon of Rowley and others, 1991) that predate basin-fill sedimentary rocks south of the Chief Range and overlie the tuff of Etna have yielded a K-Ar date on sanidine of 13.8±0.9 Ma (H.H. Mehnert, preliminary unpub. data, 1990; Snee and others, 1990). Among the basin-fill deposits, the most extensive unit fills the Panaca Basin east of the mining district. This unit consists of soft, tan, salmon, and light-green sandstone, limestone, siltstone, mudstone, and claystone of the upper Miocene and Pliocene Panaca Formation. Only the upper part, about 400 m thick, of the formation is exposed (Rowley and Shroba, 1991) and based on vertebrate fossils it is as young as the Blancan III mammalian age of 3.7–3.2 Ma (Repenning, 1987). Overlying the Panaca Formation are mostly coarse grained surficial deposits ranging in age from Pliocene to Holocene. Chief among these deposits is a series of alluvial-fan deposits of different ages that underlie five or more well-expressed geomorphic surfaces. In contrast to the fine-grained sediments of the Panaca Formation that were deposited in a closed basin, these coarse sands, gravels, and fanglomerates, as well as rounded fluvial gravels, are interpreted to represent deposition following the development of through-flowing drainage in the Panaca Basin via Meadow Valley Wash to the Colorado River, which is about 170 km south of the mining district.

Intrusive Rocks

A large, irregular, discordant intrusive mass of quartz monzonite porphyry, herein called the Cobalt Canyon stock, underlies most of the Chief Mining District at shallow depth and is exposed as plutons, plugs, dikes, sills, and faulted slivers within and near the district. Hydrothermal solutions from the stock and (or) circulating meteoric groundwater heated by the stock are believed to be the source of most metals in the district. Callaghan (1936) was the first to map parts of the stock and to recognize its association with the orebodies.

Ekren and others (1977) mapped the main mass of the stock, which is centered about 1.5 km south of the district. Our mapping reveals separate plutons, plugs, dikes, and sills (fig. 3) and interprets these bodies to be apophyses of one stock at depth. In addition to the plutonic rocks shown in figure 3, dikes, small plugs, and faulted slivers of the same lithology have been noted in several mines and prospects. From north to south, these bodies include (1) a plug 250 m northeast of the entrance to the Gold Chief Mine (Callaghan, 1936, fig. 2) and drill-hole cuttings (Homestake Mining Company) of quartz monzonite porphyry on the road (from a drill hole sited on the road) 100 m southeast of that mine, which indicate the presence of plutonic rock at depth; (2) a silicified dike in "the fault west of the Gold Chief Mine" (presumably the Stampede Detachment, which is exposed here) and a sill in limestone just south of the mine (Callaghan, 1936, p. 10); (3) drill-hole cuttings of pyrite-bearing porphyry on the road 450 m southeast of the entrance to the Gold Chief Mine; (4) several plugs near the Lucky Hobo Mine (Callaghan, 1936, fig. 2, p. 29) and an altered dike along the Stampede Detachment exposed in a prospect trench about 200 m west of the mine; (5) a "lens" exposed in the main shaft and samples from the dump of the Old Democrat Mine (Callaghan, 1936, p. 24); (6) chips of porphyry next to a vertical shaft along the road in the bottom of Cobalt Canyon less than 100 m east down the canyon from the Old Democrat Mine and drill-hole cuttings of fresh porphyry along the same road another 100 m down the canyon; (7) several plugs and dikes between the Advance and Contact Mines (Callaghan, 1936, fig. 2); (8) a plug on the ridge just south of the Contact Mine and an altered dike in the mine itself (Callaghan, 1936, p. 10, 21–23); and (9) a 1-m-wide dike in the Stampede Detachment exposed in a trench on top of the ridge just south of the Contact Mine.

Rock of the Cobalt Canyon stock is gray, tan, green, and khaki, locally grusy, quartz monzonite porphyry that consists of 35–55 percent phenocrysts of plagioclase, subordinate clinopyroxene, and minor biotite and iron-titanium oxide minerals in a fine-grained, holocrystalline groundmass of sanidine, subordinate to minor quartz, and minor clinopyroxene, iron-titanium oxide minerals, and biotite. The intrusive mass has fine-grained holocrystalline chilled margins and, in northwestern exposures, includes a large body of black, coarse-grained pyroxenite. Locally the intrusion is deuterically and hydrothermally altered at and near intrusive and fault contacts. The Cobalt Canyon stock is of Oligocene age, based on a 24.8-Ma average of two $^{40}Ar/^{39}Ar$ plateau dates on mineral separates, 24.9±0.1 Ma on sanidine and 24.7±0.1 Ma on biotite (L.W. Snee, preliminary unpub. data, 1990; Snee and others, 1990), from a sample collected from the chilled margin of the main mass about 1 km east-southeast of the district (Rowley and others, 1991).

A second variety of intrusive rock is named the porphyry of Meadow Valley Wash (Rowley and Shroba, 1990, 1991). The unit consists of widely scattered dikes and plugs, too small to be shown in figure 3, of high-alkali dacite that was intruded along major oblique-slip and strike-slip faults in the area. The light-gray and pink, locally grusy rock is characterized by large (as long as 2 cm) feldspar phenocrysts. The rock consists of about 35 percent phenocrysts of plagioclase, subordinate biotite, subordinate to minor sanidine, quartz, and hornblende, minor iron-titanium-oxide minerals, and traces of clinopyroxene, all in a glassy groundmass. It is named for exposures in the canyon of Meadow Valley Wash about 5 km south-southeast of the mining district, but the same rock has been mapped along a fault about 3 km south-southwest of the district, where it crops out along the Meadow Valley Wash and Chief Canyon Fault Zones. It also is present along the Gravel Pit Fault Zone and at several other locations in the northern Caliente caldera complex. Plugs of similar lithology were noted along a northwest-striking fault zone just east of Panaca Summit, about 30 km northeast of the mining district (unit Tp of Best and others, 1991), and in a major north-northwest-striking fault zone (Swadley and Rowley, 1992) on the northern side of the Delamar Mining District, about 30 km southwest of the Chief Mining District (P.D. Rowley, unpub. mapping, 1990). A sample from a dike of the porphyry of Meadow Valley Wash intruded along the Chief Canyon Fault Zone in the canyon of Meadow Valley Wash is Miocene in age, based on a 19.4-Ma average of two $^{40}Ar/^{39}Ar$ plateau dates on mineral separates, 19.3±0.1 Ma for a well-defined spectrum on sanidine and 19.5±0.1 Ma for a slightly less defined spectrum on hornblende; 22.5 Ma for a disturbed spectrum on biotite from the same sample was discounted (L.W. Snee, preliminary unpub. data, 1990; Snee and others, 1990).

Caliente Caldera Complex

The Caliente caldera complex contains two small epithermal gold districts and may control the large nearby Delamar epithermal gold district (see later discussion). The caldera complex is also the source of several ash-flow tuffs exposed near the Chief Mining District. Williams (1967) was the first to suggest, on the basis of regional stratigraphy and isopach data, that the Leach Canyon and Condor Canyon Formations were derived from centers in the Caliente-Panaca area. Noble and others (1968) and Noble and McKee (1972) did the first geologic reconnaissance study in this area and proposed that the Caliente depression, which they defined as a circular volcano-tectonic basin at least 32 km in diameter that extends from about 7 km east of Caliente eastward almost to the Utah State line, was the source of regional ash-flow sheets of the Harmony Hills, Racer Canyon, Hiko, and Ox Valley Tuffs. Reconnaissance mapping by Ekren and others (1977), combined with Bouguer gravity data, much refined the extent and location of the feature, which they called the Caliente caldron complex. Instead of being circular, they determined that it is elongated east-west (64 km by

29 km), extending from 25 km west of Caliente to almost the Utah State line, and that it is centered farther south than previously inferred; they recognized that the Hiko Tuff was derived from the western part of the complex.

Our detailed mapping in the north-central and northwestern parts of the complex and our reconnaissance studies in the northeastern part, combined with aeromagnetic and Bouguer gravity data (Blank and Kucks, 1989), indicate that the Caliente caldera complex extends into Utah and thus is somewhat larger (at least 80 km east-west by 35 km north-south) than was previously thought. The complex consists of several inset calderas of widely different ages, four of which we have named (Rowley and Siders, 1988). The oldest is the Clover Creek caldera, the source of the Bauers Tuff Member (22.8 Ma; Best, Christiansen, and others, 1989) and perhaps the source of the petrologically similar Swett Tuff Member, both of the Condor Canyon Formation. The Clover Creek caldera, although complexly faulted and mostly covered, is 4 km south-southeast of the mining district and underlies the north-central part of the Caliente caldera complex. The Delamar caldera, the source of the Hiko Tuff (18.6 Ma; Taylor and others, 1989), is 8 km south of the mining district and makes up the western part of the caldera complex. The other two named calderas produced unnamed ash-flow tuffs that are not known to crop out outside the caldera complex; these tuffs are as young as about 15 Ma (Mehnert and others, 1989). The tuff of Etna and at least one other ash-flow sequence probably also were derived from the Caliente caldera complex. The Delamar and younger calderas clearly formed during an episode of major faulting (described later) and thus are characterized by a complex combination of faults and structural and topographic caldera walls (Rowley, Anderson, and others, 1990). The Clover Creek caldera may have formed during the same episode of faulting.

Although the southern exposed margin of the Cobalt Canyon stock (24.8 Ma) is almost adjacent to the Clover Creek caldera (22.8 Ma), the difference between the two ages of these bodies argues against a genetic tie. Nonetheless, the stock may have been synchronous with an early, as yet undocumented, phase of magmatism in this long-lived caldera complex. In fact, isopach data led Williams (1967) to suggest that the source of the Leach Canyon Formation (24.0? Ma) was the northern part of the Caliente caldera complex, but this hypothesis has not been verified because this part of the complex is only partly mapped and is mostly buried by much younger rocks.

STRUCTURE

Mineral Belts

Mineralization in the Chief Mining District probably was controlled by both regional tectonic features and local structures. Numerous mineral belts have been proposed for many years to describe alignments of mining districts in the Great Basin. Bagby (1989) summarized some of this literature and showed two major provinces of mineral belts, one in central and western Nevada in which precious metals are the most significant products and in which districts are aligned along northwest-trending zones and one in eastern Nevada and western Utah in which base metals are the most significant products and in which districts are aligned along generally east-trending zones.

The Chief Mining District is within the Delamar–Iron Springs mineral belt of Shawe and Stewart (1976), which also includes the Tempiute, Delamar, and Iron Springs mining districts and is south of the Pioche mineral belt (fig. 2). It might be more appropriate to call these alignments igneous belts because they contain most of the volcanic and intrusive rocks in southwestern Utah and southeastern Nevada and are well delineated by aeromagnetic anomalies (fig. 2) (Zietz and others, 1976, 1978). Cenozoic and perhaps older east-trending alignments of structures and igneous centers also are well known in this part of the Great Basin (Ekren and others, 1976; Rowley and others, 1978). One of these, the Timpahute Lineament (fig. 2) of Ekren and others (1976), intersects the Chief district; Ekren and others (1976, 1977) suggested that it controlled emplacement of the Cobalt Canyon stock, the northern side of the Caliente caldera complex, and numerous other features. Stewart and others (1977) also called attention to the east-trending grain of the geology of the Great Basin, especially patterns of Tertiary igneous activity. Other, mostly older (Oligocene to early Miocene), east-trending topographic alignments, dikes, and other features were noted by Best (1988) in southeastern Nevada and southwestern Utah. Also noteworthy is the fact that most faults strike east in the Bull Valley Mountains of Utah (Hintze, 1980) and Clover Mountains of Nevada, which are east and southeast of the Chief district, and that the Intermountain Seismic Belt (Smith and Sbar, 1974) swings southwest through southern Utah and Nevada (fig. 2), centered at about the latitude of the Caliente caldera complex. The probable control of the belts, lineaments, and other aligned features is the same, namely old, deep-seated, east-striking faults or basement flaws, some of which have been reactivated during the Tertiary (Rowley and others, 1978). In stark contrast, almost all major younger (post–middle Miocene) faults strike north, northeast, and northwest.

Pre–Upper Oligocene Detachment Faults

Recent geologic mapping demonstrates at least three episodes of Tertiary extensional faulting in the Chief district. These episodes were recognized also by Bartley and others (1988), Taylor and others (1989), and Taylor (1990) in an east-west transect north of the district. The oldest episode involves a north-striking, east-dipping, low-angle fault, first recognized by Callaghan (1936), that separates Zabriskie

Quartzite on the west from Highland Peak Formation on the east; Callaghan also recognized that the fault is a major structure because the entire thickness of the Pioche Shale is faulted out. He called it a "probable" thrust fault and noted that it is better exposed in Antelope Canyon than in the mining district and that many orebodies are in the wide breccia zones developed along the structure. Tschanz and Pampeyan (1970, plate 3) traced this structure northward along the eastern side of the Chief Range and correlated it with a west-dipping low-angle fault on the western side of the Highland Range, which is north of the Chief Range; they named the structure the "Highland thrust fault" and considered it to be of "Laramide" age. In a brief discussion of thrust faults in Lincoln County, however, Tschanz and Pampeyan (1970, p. 82–83) cited field relations, especially in the northern Bristol Range about 50 km north of the Chief district, that suggest that this fault may be Tertiary in age and may not be a thrust. The name "Stampede detachment" was proposed by Axen and others (1988) for outcrops near Stampede Gap in the northwestern Highland Range that Tschanz and Pampeyan correlated with their Highland thrust; Axen and colleagues mapped the east-dipping Stampede Detachment along the eastern Chief Range and southwestern Highland and Bristol Ranges and in the Pioche area (Bartley and others, 1988, fig. 2). Axen and others (1988) recognized that the low-angle normal fault is related to extension that predates the oldest (late Oligocene) volcanism in the area; movement of the upper plate of the Stampede Detachment was to the east. The detachment is primarily a bedding-parallel fault in the Pioche Shale or, less commonly, in the Chisholm Shale or lower Highland Peak Formation, and the rocks in this part of the section are generally attenuated and locally cut out. The age of the Stampede Detachment is poorly constrained, but Axen and others (1988) and we consider it to be Tertiary; the geometry of the detachment resembles faults mapped by Nutt and Thorman (this volume) in the Drum Mountains of western Utah that they consider to be of Sevier(?) age. Throw on the Stampede Detachment decreases southward, and the fault has not been recognized at the latitude of the Caliente caldera complex. The fault is well exposed in the Chief District despite having been contact metamorphosed. Gouge and fault breccia as thick as 20 m along the fault are favorable sites for mineralized rocks.

Miocene Faults

The major episode of faulting in and near the Chief Mining District is Miocene in age (at least as old as 19–12 Ma). Faults of this episode consist of low-angle normal (detachment) faults and high-angle strike-slip, oblique-slip, and normal faults (fig. 3). Those faults that strike east or northwest tend to have right slip or oblique (right) slip, whereas those that strike north or northeast tend to have left slip or oblique (left) slip. An example of a major high-angle oblique-slip-fault zone is the Chief Canyon Fault Zone (fig. 3). Where exposed about 2 km southeast of the district, the fault zone strikes north and is almost vertical; we consider it to be an oblique-slip fault based both on strike-slip and dip-slip slickensides and on reidel shears (see Angelier and others, 1985; Petit, 1987) that indicate its eastern side was offset down and to the right. Farther south, it veers south-southeast and requires the same sense of oblique slip to explain slickensides and geologic relations. The amount of movement on this part of the fault is constrained by outflow Bauers Member to the north and intracaldera Bauers Member to the south; on the basis of this poorly constrained margin of the Clover Creek caldera, we estimate right slip of 1 km or more. Where the Chief Canyon Fault Zone cuts the Delamar caldera, west of lower Barnes Canyon about 10 km south-southeast of the district, the zone is expressed as a narrow, complex horst of propylitically and argillically altered rocks in which the predominant offset is normal (R.E. Anderson, unpub. data, 1989). The northern part of the Chief Canyon Fault Zone, east and northeast of the district, is not exposed but was inferred on the basis of a steep Bouguer gravity gradient (Blank and Kucks, 1989); considering that the fault here strikes north and separates the 700-m-high Chief Range from the Panaca Basin, it is likely that this segment of the fault zone is younger than the southern part of the fault zone and that it is a basin-range fault (see next section).

Other faults west of the Chief Canyon Fault Zone and 4–6 km south of the mining district confirm that major deformation occurred during this Miocene episode (fig. 3). The Meadow Valley Wash Fault Zone strikes north along the western side of the canyon of Meadow Valley Wash; a 2-km-long wedge of the Clover Creek caldera on the east against Bauers outflow tuff and Oligocene volcanic rocks on the west indicates at least 2 km of left slip and probable displacement down to the east. The fault zone is joined on the east, just north of Antelope Canyon, by the north-northeast-striking Gravel Pit Fault Zone that separates another 2-km-long wedge of the Clover Creek caldera on the east from Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite on the west. Field evidence argues against the Clover Creek caldera having been west of the fault, so we interpret the Gravel Pit Fault Zone as an oblique-slip fault of at least 2 km of left slip and probable downthrow to the east; limited slickenside data, including reidel shears, support this interpretation. Dikes and plugs of the porphyry of Meadow Valley Wash, as much as 300 m across, have been intruded along the Meadow Valley Wash, Gravel Pit, and Chief Canyon fault zones. Preliminary $^{40}Ar/^{39}Ar$ dates on the porphyry indicate that most deformation on these faults had taken place by 19 Ma. Other nearby faults having the same attitude and throw and interpreted to belong to the same Miocene episode are younger, whereas still others may be older.

High-angle faults are abundant in the Chief Range, but, because most rocks are Proterozoic and Cambrian quartzite, the age of faulting and amounts of slip are not well constrained. Abundant slickensides in the brittle quartzite indicate mostly oblique, normal, right, and left slips on these faults. Probably most date to the Miocene episode of faulting, but we cannot rule out the possibility that some faults in the Chief Range predate the Miocene episode and thus may be of the same age as the Stampede Detachment or perhaps older; because of their unusual strike, a series of east-striking faults, some shown on figure 3, are particularly suspect as older features. In addition, some faults in the interior of the Chief Range, like those that bound it, must be younger basin-range faults (see next section). The age of faults is somewhat better constrained in the mining district because most faults there offset Tertiary volcanic rocks and the Cobalt Canyon stock. Unfortunately, few shears were found in the grus of the stock, but mapping indicates that the southwestern and northern sides of the stock are bounded by faults. The Old Democrat Fault Zone (fig. 3) is typical of the deformation along faults in the Chief Range. It is a significant fault zone that has several splays, local fault-breccia zones as wide as a few meters, and opposing dips to strata on opposite sides of the zone. The fault plane locally dips steeply east and in other places dips steeply west; quartzite east of the fault zone is younger than quartzite to the west. Slickensides on several splays at the Old Democrat Mine indicate oblique slip on east-dipping fault planes and right slip and reverse slip on west-dipping fault planes. The Old Democrat, Advance, and perhaps Lucky Hobo mines, as well as several unnamed prospects, are along the Old Democrat Fault Zone and its splays; apparently these mines were developed in old (24.8 Ma) orebodies offset by the fault zone, although metals are present along some faults and may indicate remobilization of metals by groundwater during or after deformation. The earliest phase of high-angle faulting of the Miocene episode probably is in fact Oligocene in age and synchronous with emplacement of the Cobalt Canyon stock and epithermal mineralization, as in the Walker lane of western Nevada (see, for example, John and others, 1989; Hardyman and Oldow, 1991).

A major low-angle normal fault, the Highland Detachment of Axen (1986), is exposed at the northwestern end of the Chief Range (Burke and Axen; 1990; Burke, 1991). From here it can be traced northward as a fairly continuous feature along the western sides of the Highland and northern Bristol Ranges. Parts of it were mapped as the "Laramide" Highland Thrust Fault and other parts were mapped as the "post-Laramide" Bristol Thrust Fault (Tschanz and Pampeyan, 1970). Axen (1986), Lewis (1987), Axen and others (1988), Bartley and others (1988), Sleeper (1989), and Burke and Axen (1990) interpreted exposures of the Highland Detachment along the Chief, Highland, and Bristol Ranges to be the breakaway of the detachment. In contrast to the much older Stampede Detachment, the Highland Detachment dips west and movement of its upper plate was to the west. These geologists have not identified the Highland Detachment to the east, and they interpreted that it continues in the subsurface under ranges to the west.

The hanging wall of the Highland Detachment, on the western sides of the Chief and Highland Ranges, contains a complex sequence of intertongued, mostly soft, coarse-grained landslide deposits and mudflow breccia, minor alluvial deposits, and rhyolitic air-fall and possibly ash-flow tuff that comprise the McCullough Formation of Axen and others (1988). These rocks are syntectonic, having been deposited contemporaneously with movement on the detachment (Axen and others, 1988; Sleeper, 1989; Burke and Axen, 1990; Burke, 1991). One of the air-fall tuff beds in the McCullough Formation, perhaps from a source in the Caliente caldera complex, has a $^{40}Ar/^{39}Ar$ date of 15.3 Ma (Axen and others, 1988; Taylor and others, 1989), thereby giving a minimum age for detachment faulting. Andesitic volcanic mudflow breccia, andesitic flow breccia, and small andesitic lava flows, called the volcanic rocks of Klondike Spring (Rowley and others, 1991), that underlie the McCullough Formation may also be syntectonic with the Highland Detachment.

In the Caliente caldera complex south of the mining district, north-northwest-striking high-angle right-slip, oblique-slip, and normal faults are abundant and one low-angle detachment fault (Newman Canyon Detachment) is exposed (Bowman, 1985; R.E. Anderson and P.D. Rowley, unpub. mapping, 1986–1990; Angelier and others, 1987; Mehnert and others, 1989; Michel-Noël and others, 1990; Rowley and others, 1990). In places caldera margins are a complex combination of faults and topographic and structural margins, arguing that these faults were active during formation of the Delamar caldera (18.6 Ma; Taylor and others, 1989) and younger calderas (as young as 15 Ma; Mehnert and others, 1989). Fault offsets that decrease upward in the stratigraphic section ("growth faults" of Bowman, 1985) indicate that the faults were also active during deposition of postcaldera tuffs of the Kane Wash Tuff (14 Ma; Novak, 1984) and the overlying tuff of Etna (also 14 Ma). These tuffs are unconformably overlain by the conglomerate of Ash Canyon (Rowley and Shroba, 1990, 1991) and intertongued basalt lava flows that have K-Ar dates of about 12 Ma (Mehnert and others, 1989) in exposures about 12 km south-southeast of the Chief Mining District. Although our early mapping indicated that the conglomerate and basalt also unconformably overlie faults of the Miocene episode (Mehnert and others, 1989), later mapping indicates that some of these faults cut rocks at least as young as the conglomerate and basalt (Snee and others, 1990). The similar ages of many of the faults, whether detachment or high angle, in the Caliente caldera complex, Chief Range, and Chief district indicate that the faults formed in a major Miocene eposide, from at least 19 to 12 Ma, the main extensional episode in this part of Nevada.

Upper Miocene and Pliocene Basin-Range Faults

Displacements on Neogene faults have strongly influenced development of much of the present-day large-scale topography in the eastern Great Basin, especially imprinting this topography with a prominent north-south grain. These Neogene faults are known as basin-range faults and are generally younger than about 10 Ma (Anderson and others, 1983). They may have formed under an extension direction (with least principal stress oriented west-northwest) that had been rotated clockwise about 60° from the Miocene extension direction (with least principal stress oriented west-southwest) (Anderson and Ekren, 1977; Zoback and others, 1981; Anderson and others, 1983; Anderson, 1989). Near the Chief Mining District, most basin-range faults strike north, such as those in the Panaca Basin (fig. 3). The oldest exposed basin-fill deposits, the conglomerate of Ash Canyon and intertongued 12-million-year-old basalts, are cut by mostly north-striking basin-range faults. Younger Tertiary basin-fill sedimentary rocks, including the Panaca Formation, are also cut by such faults. Some basin-range faults in the area are Quaternary in age, such as north-striking faults in Delamar Valley about 20 km west of the Chief Mining District (Tschanz and Pampeyan, 1970; Ekren and others, 1977). Similar faults control the position of some north-trending streams about 15 km south-southeast of the mining district (R.E. Anderson, unpub. mapping, 1989).

Old basin-range faults are not as easy to identify as younger ones, but many old faults have greater displacement than younger ones. The north-trending Chief Range is probably a basin range, bounded by basin-range faults whose displacements must be at least that of the 700-m height of the range above the adjacent Panaca Basin. Faults on the western and southern sides of the range (upper left part of fig. 3) are locally well exposed and consist of high-angle faults containing slickensides that indicate normal slip. The buried northern part of the Chief Canyon Fault Zone, extending north from just east of the mining district, is interpreted to be the range-bounding fault that separates the Chief Range from the Panaca Basin. If so, it is much younger than the southern part and perhaps is a reactivated part of the Miocene oblique-slip fault zone that is farther to the south.

ORE DEPOSITS

Epithermal fissure-vein precious-metal deposits are common in and adjacent to calderas (see, for example, Hayba and others, 1986; Heald and others, 1987; Lipman, this volume). Most such deposits are related to the plumbing systems of calderas, in which late-forming intrusions produce convection cells of meteoric water. Orebodies form in the upper parts of these plumbing systems, and thus younger, less eroded calderas are generally better sites for exploration than are older buried ones. The Caliente caldera complex is poorly known geologically and has not been adequately explored for epithermal gold; however, it contains relatively young calderas, suggestive of good exploration potential.

The Chief Mining District, near the northern edge of the complex, and the major Delamar Mining District (Callaghan, 1937; Tchanz and Pampeyan, 1970; Tingley, 1984), near the southwestern edge of the complex (fig. 2), are both deeply eroded epithermal gold systems. In both districts, most orebodies are in brittle quartzite of the Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite, which must have shattered like glass during faulting, preparing the rocks for mineralization, which took place during intrusive activity that apparently was synchronous with faulting. Both districts probably are of the adularia-sericite type (Heald and others, 1987) of epithermal deposits. Analyses of grab samples (Tingley, 1984, appendix B, samples 1740–1755) from the Delamar district show gold values of as much as 22 ppm, silver values of as much as 300 ppm, and anomalous values of copper, lead, and zinc. East-striking structures, including rhyolite dikes associated with some orebodies, are common in the district (Callaghan, 1937). The Delamar district has recently (1990–91) been explored and studied by Alma American Mining Company and Fischer-Watt Gold Company (S.P. Bingham and G.B. Allen, written commun., 1990).

Another known adularia-sericite type of epithermal system underlies the Taylor (or Easter) Mine, located within the caldera complex 13 km east-northeast of Delamar and 15 km southwest of Caliente (fig. 2). Tingley (1984, appendix B, sample 579) reported values of gold of 18 ppm and of silver of 70 ppm from a grab sample from the mine. Sparse slickenside data suggest that the structure is simple, namely a normal fault zone in Hiko intracaldera tuff (Delamar caldera) that strikes N. 80° E. and dips 50° to the north; this fault may be a dilational response to right slip along a nearby concealed east-striking fault (R.R. Kern, oral commun., 1990). Banded quartz veins that contain comb structure and follow the fault have low base-metal contents but relatively high gold contents, and locally the tuff is intensely hydrothermally altered within a zone that is at least 100 m wide on either side of the fault. The orebodies are in a high-level epithermal system (G.B. Allen and S.P. Bingham, oral commun., 1990) that has been previously drilled and explored by Homestake Mining Company and other firms (Charley Martin, oral commun., 1990) and in 1990–91 by FMC Gold Company (J.L. Askey and J.B. Harlan, oral common., 1990).

In addition, the small, poorly known Pennsylvania mining district on the southern margin of the caldera complex (fig. 2) is probably an epithermal gold system (Tchanz and Pampeyan, 1970; Tingley, 1984); values of gold of as much as 180 ppm and of silver of as much as 1,500 ppm, as well as anomalous values of copper, lead and zinc, were reported from grab samples (Tingley, 1984, appendix B, samples 1701–1707).

Orebodies in the Chief Mining District are deeply eroded epithermal fissure-vein deposits that occupy breccia and low-angle faults of the Stampede Detachment Fault and high-angle faults and joints within quartzite. Most of the following descriptions of the ore deposits are those of Callaghan (1936). Callaghan noted evidence for replacement of some country rocks by ore minerals—for example, quartzite in the Old Democrat Mine (fig. 3) and limestone or dolomite in the Lucky Chief Mine. He found that all ore is oxidized, except for some sulfide minerals (galena) in the Republic and Gold Chief mines. He recognized three types of vein deposits. The first, which has the highest amounts of gold and silver in the district, is the arsenian type, which is found in the Advance, Old Democrat, Republic, and Lucky Hobo mines. Typically, the ore in these veins is a green to brown, vuggy aggregate of supergene scorodite that replaced arsenopyrite and is locally replaced in turn by a brown micaceous mineral (arsenosiderite?) and by iron-oxide minerals; quartz, jarosite, cerussite, descloizite, mimetite, beudantite, and manganese-oxide minerals also are present. The second type of vein deposit, which is the most economically productive in the district although it contains relatively low proportions of gold and silver, is characterized by a network of tabular barite crystals and scattered grains of galena; chalcedonic quartz is present as veins in barite, and cavities between barite crystals locally contain quartz, calamine, mimetite, and manganese- and iron-oxide minerals. This type of deposit is present along the Stampede Detachment in the Gold Chief and Lucky Chief mines. The third type of vein deposit, from which most of the lead was produced, includes irregular and pipelike masses of cerussite in the Republic and Lucky Chief mines; in addition to cerussite, ores contain fine-grained quartz, opal, plumbojarosite, and manganese- and iron-oxide minerals. A fourth type of vein, which is barren or contains low amounts of gold and silver but is exposed in many prospect pits, consists of lenses and small bodies of red iron oxide in quartzite resulting from fault breccia cemented by iron oxide and comb quartz. In addition, Tingley (1984) noted fine-grained disseminated sulfide minerals and silicified quartzite wallrock in the Advance Mine. Furthermore, in 1985, Homestake Mining Company discovered, by reverse-circulation drilling, a large body of disseminated pyrite (2–10 percent by volume) and phyllically altered rock of the Cobalt Canyon stock at about 110 m depth below, east, and south of the Gold Chief Mine. Although chemical analyses reveal anomalous amounts of arsenic and several other elements, the body does not contain appreciable amounts of gold or silver, but it is suggestive of a porphyry copper deposit (data from a 1986 report by S.D. Olmore of Homestake Mining Company that was made available for publication courtesy of Homestake Mining Company in 1990).

The only published chemical analyses of orebodies in the Chief District are by the USGS and include atomic absorption analyses of As, Au, Sb, and Zn and semiquantitative spectrographic analyses of other elements for 12 grab samples (Tingley, 1984, appendix B) and flame atomic absorption analyses of Te, Tl, and Au and direct-current arc and alternating-current spark emission spectrographic field analyses of other elements for 14 grab samples that we collected (table 1). The analyses suggest that the various veins are not much different geochemically from each other except for those in mines in the Stampede Detachment, which contain somewhat less arsenic. There is no evidence from these meager geochemical data that the veins are of more than one age. The different vein types of Callaghan (1936) cannot be discerned using the geochemical data, although those veins that are high in arsenic (arsenian type) are in the Advance, Republic, Lucky Hobo, and Gold Stake mines, as he noted; these veins, however, contain some of the highest values of lead and other base metals, in contrast to his descriptions of the minerals in these veins. Overall, the analyses show that veins contain gold and silver as well as relatively high values of other indicator elements (As, B, Sb, Te, Tl; samples were not analyzed for Hg or U) typical of epithermal precious-metal deposits (Silberman and Berger, 1986). Anomalous values of gold and silver are in veins in the Gold Chief (highest overall gold value, at 3.9 ppm; sample 120 of Tingley, 1984), Lucky Hobo (highest overall silver value, at 2,000 ppm; sample 123 of Tingley, 1984), Republic, Advance, Lucky Chief, SOA, and Gold Stake mines and in a prospect (sample 126 of Tingley) southwest of the Contact Mine. Even more anomalous values are those of lead and zinc and, to a much lesser extent, of copper; high values of iron, magnesium, and manganese also are characteristic. These higher values of base metals and silver, in fact, provide evidence of vertical geochemical zoning in the Chief district (Silberman and Berger, 1986) and indicate, along with the field evidence, that the district has been deeply eroded. It is likely that the veins containing the highest amounts of gold and silver were removed by erosion long ago.

CONCLUSIONS

The Chief Mining District is a minor mining district, but the lessons it provides may help in finding ore deposits elsewhere in and near the Caliente caldera complex. The district contains deposits of a deeply eroded epithermal fissure-vein system. The heat source that led to the transportation of most metals was provided by the Cobalt Canyon stock (24.8 Ma), which underlies the district. Metals most likely were leached from country rocks, then precipitated during convective overturn of groundwater heated by the stock; some metals, however, may have been derived from hydrothermal solutions from the intrusion itself. The stock may represent an early magmatic event in the adjacent Caliente caldera complex, although it predates the known main episode of magmatism (23–14 Ma) in the complex, which has controlled mineralization of three other epithermal gold districts. The tectonic control on the location of the stock and the caldera complex is not well constrained but may result partly from an east-trending grain in underlying rocks, perhaps the result of pre–middle Tertiary east-striking faults, some of which were reactivated, and partly from the Miocene episode of faulting.

Most orebodies in the district are in brecciated fault zones of the Tertiary Stampede Detachment system, an east-dipping bedding-parallel normal fault that separates quartzite below the detachment from limestone and dolomite above it; the detachment was active prior to late Oligocene volcanism, well before mineralization. As in the major Delamar Mining District to the southwest, brittle quartzite was extremely shattered in and near faults, providing sites for mineralization. At some of these sites, ore was localized along high-angle faults and joints in quartzite. Some of these structures probably formed during emplacement of the Cobalt Canyon stock, which may also have localized a porphyry copper ore deposit. Structures of the Miocene episode of high-angle oblique-slip faulting that began before 19 Ma may have localized some metals. Early phases of the Miocene episode of faulting in fact may have been synchronous with, and provided control on, emplacement of the Cobalt Canyon stock. Some ore could have resulted from younger igneous activity such as the porphyry of Meadow Valley Wash or from remobilization of existing orebodies by groundwater heated during deformation. The history and structure of the Chief District have many similarities to those of epithermal gold districts in the Walker lane of western Nevada (John and others, 1989; Hardyman and Oldow, 1991). Evidence for geochemical zoning in which amounts of gold decrease with depth and evidence for deep erosion that removed most of the roof over the Cobalt Canyon stock indicate that the likelihood is low for discovering new gold orebodies in the district. The possibility of finding other gold deposits in and near the Caliente caldera complex, however, is probably much better.

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