Text and references for Nevada Bureau of Mines and Geology Map 136

GEOLOGY OF THE WILLOW CREEK RESERVOIR SE QUADRANGLE

ELKO, EUREKA, AND LANDER COUNTIES, NEVADA

by

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INTRODUCTION

The Willow Creek Reservoir SE Quadrangle is in the northeastern Sheep Creek Range in southwestern Elko County and northernmost Eureka and Lander Counties, 60 km northeast of Battle Mountain and 25 km east-southeast of Midas (fig. 1). The quadrangle includes the southern part of the Ivanhoe mining district, from which mercury ores were mined intermittently between 1915 and the mid 1970s and gold ores in the early 1990s. Mapping in the quadrangle is a continuation of a broader study of Tertiary volcanism, extension, and gold-mercury mineralization related to the northern Nevada rift and the Yellowstone hot spot (Wallace, 1991, 1993; Wallace and John, 1998; John and others, 2000). The quadrangle also is near the northwestern end of the Carlin trend of gold deposits. Those deposits formed largely in the late Eocene (Ressel and others, 2000) in Paleozoic sedimentary rocks similar to those that underlie the quadrangle at depth.

Although many exploration companies have mapped in parts of the quadrangle, little has been published on the geology of the study area. The general geology is shown on the Elko County geologic map (Coats, 1987). Bailey and Phoenix (1944) described the mercury deposits in the district, using unpublished mapping and data from J.M. Nelson and R.J. Roberts of the U.S. Geological Survey. During an exploration program for gold in the late 1980s, the geology of parts of the quadrangle were studied and reported by Bartlett and others (1991) and Deng (1991), with an emphasis on the area surrounding the Hollister gold deposit near the north edge of the quadrangle. LaPointe and others (1991) summarized the mining history of the Ivanhoe district. Hollister and others (1992) described the hot-spring nature of the Hollister gold deposit. Gold exploration in the late 1990s and 2000s has produced new unpublished data on the geology of the north-central part of the quadrangle.

The present study shows a complex suite of middle Miocene volcanic and volcaniclastic units that depositionally overlie a basement composed of the Ordovician Vinini Formation and a small Eocene pluton (fig. 2). The oldest volcanic rocks are middle Miocene tuffs and tuffaceous sediments, and, in the northern half of the quadrangle, andesite and various rhyolite flows were erupted during sedimentation. Units in the northern part of the quadrangle were cut and tilted by high-angle, northeast- and north-northwest-striking faults, whereas volcanic and sedimentary rocks in the southern part of the study area are flat lying. Mercury- and gold-bearing hydrothermal solutions rose along some of the high-angle faults, forming mercury deposits in massive silica replacement and sinter bodies in the tuffs, disseminated gold deposits in various Miocene rocks, and high-grade gold-silver veins in Paleozoic and deeply buried rhyolitic rocks. Reactivation of many faults in the late Miocene exposed the mercury deposits, whereas the gold deposits remain concealed.

Geochronologic data for the Ivanhoe district and nearby areas are given in table 1. Major-oxide and trace-element compositions of volcanic rocks in the district are provided in table 2.

PALEOZOIC SEDIMENTARY ROCKS

Quartzite, chert, and argillite of the Ordovician Vinini Formation are the oldest rock units exposed in the quadrangle. Quartzite forms prominent blue-gray to light-brown outcrops, and it is the dominant lithology. Poorly exposed argillite forms broad interbeds with quartzite in the northeast corner of the quadrangle, and minor bedded chert and chert-pebble conglomerate lenses are interbedded with the quartzite. Bartlett and others (1991) reported minor greenstone (presumably mafic flows) in drill cuttings and core of Paleozoic rocks, although none was observed during this study. Drilling to a depth of 1,201 m (3,964 feet) in the eastern part of the quadrangle intersected the Devonian Rodeo Creek formation in thrust contact beneath the Vinini Formation (Tewalt, 1998; also Great Basin Gold Ltd press releases, 2002).

Quartzarenite (orthoquartzite) has been used to differentiate the Valmy from the Vinini, which typically contains more argillite than quartzite (see discussion in Gehrels and others, 2000). Bartlett and others (1991) assigned the Paleozoic rocks in this quadrangle to the Ordovician Valmy Formation, based on limited fossil data that indicated an Ordovician age. Stratigraphic data and paleontological ages from the adjacent Santa Renia Fields Quadrangle (fig. 1; Theodore and others, 1998) indicate that the rocks there, which include abundant quartzarenite (orthoquartzite), are part of the Ordovician Vinini Formation. Some of those exposures are continuous with the exposures in this quadrangle, and the Paleozoic rocks exposed in this quadrangle thus are assigned to the Vinini Formation. Clearly, though, this assignment is tentative, and detailed biostratigraphic data are needed for the Paleozoic rocks exposed in this quadrangle.

Breccia unit

In the northeast part of the quadrangle, a massive to sheeted breccia zone, at least 200 m thick, is conformably associated with bedded, unbrecciated Vinini quartzite and chert. The eastern part of the body dips eastward conformably beneath the quartzite, and it was deformed along with the enclosing quartzite beds during Paleozoic folding and shearing. The western part of the body dips gently to the west, resulting in an overall antiformal geometry for the breccia unit. North-northwest-trending folds in the quartzite beds coincide with and parallel the hinge line between the west- and east-dipping zones. The breccias grade upward into unbrecciated quartzite in the eastern exposures. In addition to the main breccia unit, similar 1- to 2-m-thick beds of breccia are interbedded with massive quartzite, and a small breccia body near the northeast edge of the quadrangle conformably overlies bedded chert with a sharp contact.

Three different breccia units may be present in this northeastern area. In outcrop, the Vinini-related breccias generally resemble the subangular quartzite breccias in the middle Miocene conglomerate and tuff unit (Tct), especially in areas where they were hydrothermally silicified. In unsilicified areas, the Vinini-related breccias were differentiated by the quartzitic instead of tuff matrix, the conformable contacts with both the quartzite and chert beds,

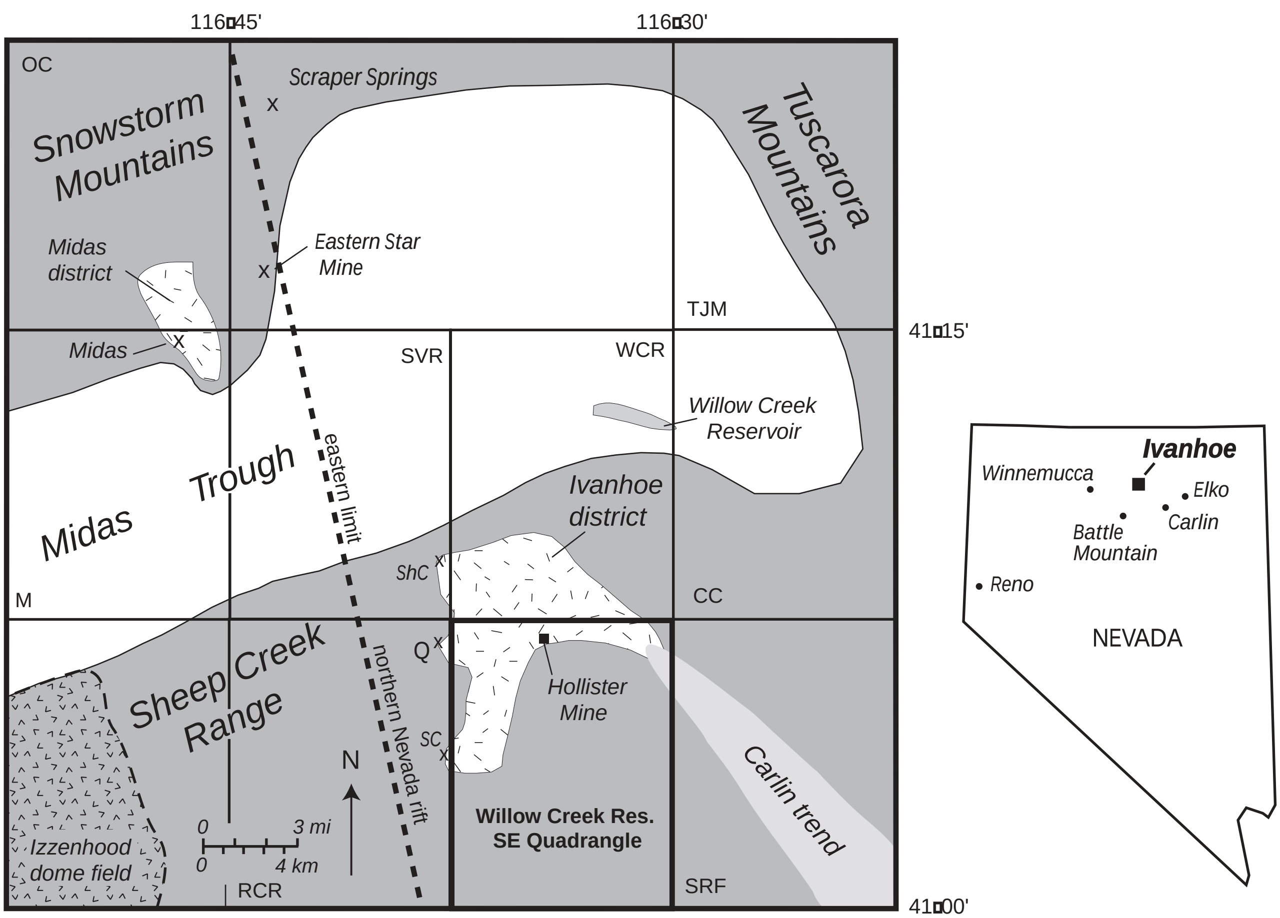

Figure 1. Location of the Ivanhoe mining district, Nevada (right) and Willow Creek Reservoir SE Quadrangle and geographic features mentioned in text (above). Geologic quadrangle maps: M, Midas, OC, Oregon Canyon (both part of Wallace, 1993); SRF, Santa Renia Fields (Theodore and others, 1998); TJM, Toe Jam Mountain (Henry and Boden, 1999); WCR, Willow Creek Reservoir (Wallace, 2003a). CC, China Camp; RCR, Rock Creek Ranch; SVR, Squaw Valley Ranch. Q, Quiver area; ShC, Sheep Corral Mine; SC, Silver Cloud Mine.

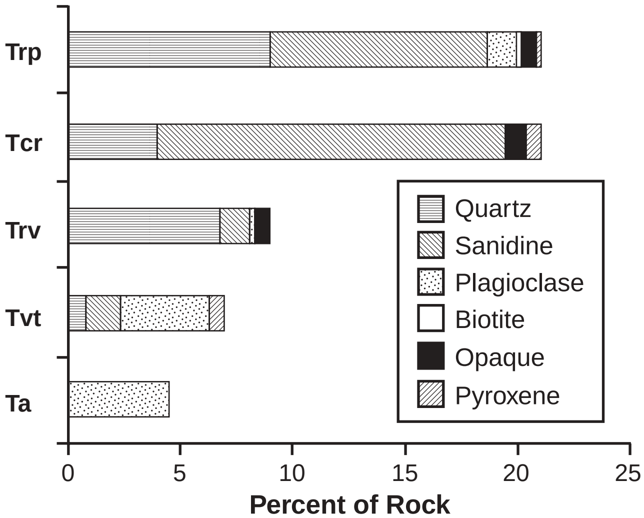

Figure 2. Average modal compositions of Tertiary volcanic rocks in the Willow Creek Reservoir SE Quadrangle. Unit abbreviations from map unit descriptions.

and the presence of Paleozoic-age folds and shears. Some parts of the Vinini-related breccia unit also resemble conglomerate beds in the nearby upper tuff unit, although clasts in the conglomerates generally are more rounded than in the older breccias; some of these beds may be present in the mapped breccia body where the breccia unit and the upper tuff unit are in contact. The upper tuff unit (Ttsu) unconformably overlies the breccia, in places conformably and in others with a strike at right angles to that of the underlying breccia.

Bartlett and others (1991), based on drilling data and minor exposures in the district, identified a fragmental unit at the contact between the Vinini and the overlying Tertiary units. This unit is exposed at the Hollister Mine and a few other places in the district, but it is not shown separately on the map. The unit is composed of angular fragments of quartzite in a red, clay-rich matrix. In the Willow Creek Reservoir Quadrangle, the fragmental unit underlies Eocene tuffs (Wallace, 2003a); in the vicinity of the Hollister Mine, it underlies the middle Miocene tuffaceous and volcanic units; and it is absent in many places where the Tertiary-Paleozoic contact is exposed. Bartlett and others (1991) proposed a Tertiary pre-volcanic "erosional residuum" origin

Table 1. Summary of isotopic ages from the Ivanhoe district and vicinity

Rock type/unit	Material dated	Age (Ma)	Method
Ivanhoe area:			
Carlin Formation (Tcas)[a]	sanidine	14.41±0.04-15.10±0.08	^{40}Ar/^{39}Ar
Rhyolite porphyry (Trp)	sanidine	14.92±0.05	^{40}Ar/^{39}Ar
Craig rhyolite (east) (Tcr)	sanidine	14.99±0.05-15.16±0.05	^{40}Ar/^{39}Ar
Air-fall tuff (Ttsu)	——	15.05±0.25	^{40}Ar/^{39}Ar, chemistry
Craig rhyolite (west) (Tcr)	sanidine	15.07±0.08-15.17±0.05	^{40}Ar/^{39}Ar
Rhyolite of the Velvet area (Trv)	sanidine	15.10±0.05	^{40}Ar/^{39}Ar
Hollister Au deposit	adularia	15.10±0.4	K-Ar
Vitric tuff (Tvt)	sanidine	15.10±0.06	^{40}Ar/^{39}Ar
Ivanhoe Au vein	adularia	15.19±0.05	^{40}Ar/^{39}Ar
Airfall tuff (Ttsl)	plagioclase	≤15.84±0.10	^{40}Ar/^{39}Ar
Trachyandesite flow (Tta)	plagioclase	37.23±0.1	^{40}Ar/^{39}Ar
Big Cottonwood Can. tuff (Tbc)	sanidine	39.22±0.1	^{40}Ar/^{39}Ar
Nelson Creek tuff (Tnc)	sanidine	39.42±0.11	^{40}Ar/^{39}Ar
Snowstorm Mountains area:			
Ken Snyder (Midas) Au	adularia	15.14±0.08	^{40}Ar/^{39}Ar
Sawtooth dike	adularia	15.19±0.023	^{40}Ar/^{39}Ar
Esmeralda Formation (Midas)	sanidine	15.43±0.09	^{40}Ar/^{39}Ar

Craig rhyolite (east) dates are from exposures in the Santa Renia Fields Quadrangle (Theodore and others, 1998). Craig rhyolite (west) dates are from two exposures in Rock Creek Ranch Quadrangle: flows ~200 m west of the Willow Creek Reservoir SE Quadrangle and flows overlying the Rock Creek rhyolite in the Quiver area (fig. 1). Carlin Formation of Theodore and others (1998) equivalent to "upper tuff unit" (Ttsu) in Ivanhoe district (see text). Date on upper tuff (Ttsu) based on tephrochronologic correlations (Perkins and others, 1998) and not direct dating of the unit. All data from Wallace and John (1998) and John and others (2000), except for Fleck and others (1998), Bartlett and others (1991; sample from drill core in Hollister deposit), Henry and Boden (1999), R.J. Fleck, written commun. (1999), Leavitt and others (2000; ave. 3 samples), Perkins and others (1998), Leavitt (2001), Peppard (2002), and C. Henry, written commun. (2001). ^{40}Ar/^{39}Ar ages were determined at geochronology labs at the U.S. Geological Survey, New Mexico Bureau of Mines and Geology, and the University of Nevada, Las Vegas; these ages were standardized (recalculated) to an age of 27.55 Ma for Fish Canyon Tuff.

Table 2. Chemical analyses of Miocene rocks from the Ivanhoe mining district, including the Willow Creek Reservoir SE Quadrangle

Sample ID	97WC-5	97WC-12	98WC-3	00WC-10	97WC-10	97WC-11	98WC-8	98WC-10	96WC-3	96WC-4	96WC-2	97WC-1	97WC-14	97WC-16	97WC-7	97WC-13	96WC-17	96WC-18	96WC-19	96WC-24
Map Unit	Ta	Ta	Ta	Ta	Tcr	Tcr	Tcr	Tcr	Trc	Trc	Trp	Trp	Trp	Trp	Trv	Trv	Ttsl	Tvt	Tvt	Tvt
Latitude	41-07-58	41-05-24	41-06-04	41-06-42	41-07-30	41-04-58	41-03-52	41-04-25	41-10-02	41-09-50	41-10-53	41-12-00	41-11-49	41-07-44	41-07-33	41-07-37	41-14-08	41-14-02	41-09-36	41-13-51
Longitude	116-36-16	116-38-07	116-36-48	116-34-35	116-31-43	116-37-50	116-36-27	116-37-00	116-37-35	116-37-32	116-36-08	116-33-30	116-36-40	116-31-05	116-33-34	116-33-32	116-32-57	116-32-39	116-35-20	116-31-31
Quadrangle	WCR	RCR	WCRSE	WCRSE	WCR	RCR	WCRSE	WCRSE	WCR	WCR	WCR	WCR	WCR	WCR	WCR	WCR	WCR	WCR	WCR	WCR
Major Oxides (percent)																				
SiO_2	56.12	56.42	57.67	58.85	76.08	74.22	78.00	75.45	77.11	72.96	74.26	74.96	77.41	79.42	74.06	76.92	66.98	70.92	70.55	70.31
$Al2O_3$	15.23	13.72	13.42	13.86	13.68	12.22	10.89	12.49	13.30	13.86	13.74	14.23	11.62	11.01	13.96	11.51	16.42	15.08	15.61	14.92
Fe_2O_3	11.53	12.57	12.28	10.13	3.65	3.17	1.94	2.16	1.93	3.61	1.60	1.20	1.69	1.49	1.85	1.96	5.52	2.68	3.06	3.48
MgO	2.82	1.89	0.17	2.75	0.08	0.21	0.03	0.03	0.16	0.18	0.18	0.07	0.05	0.70	0.13	0.07	0.05	0.36	0.40	0.46
MnO	0.09	0.19	2.69	0.178	0.01	0.06	0.15	0.17	0.01	0.03	0.01	0.01	0.02	0.02	0.02	0.03	0.07	0.03	0.03	0.04
CaO	5.55	5.81	6.42	6.48	0.29	0.48	0.64	0.96	0.51	0.51	0.72	0.24	0.28	2.14	0.63	0.38	3.05	1.26	1.08	1.83
TiO_2	1.82	2.24	2.75	2.228	0.15	0.23	3.03	2.51	0.26	0.27	0.06	0.04	0.06	0.08	0.11	0.13	0.57	0.30	0.31	0.33
Na_2O	3.51	3.69	1.70	2.86	1.65	4.03	5.08	5.90	1.86	2.96	4.71	4.74	4.29	1.49	3.82	3.88	2.61	2.90	2.38	2.87
K_2O	2.47	2.70	2.10	1.89	4.44	5.35	0.19	0.23	4.81	5.56	4.65	4.47	4.54	3.63	5.32	5.10	3.27	6.40	6.48	5.69
P_2O_5	0.86	0.77	0.27	†0.77	0.01	0.03	0.01	0.02	0.06	0.05	0.06	0.05	0.04	0.01	0.08	0.03	0.10	0.06	0.09	0.06
Total	97.30	98.46	96.94	98.78	96.25	98.75	98.85	95.47	98.39	99.16	97.42	98.80	98.40	94.20	99.36	98.89	89.60	96.74	95.01	95.09
Trace Elements (ppm)																				
Ag	-0.5	-0.5	-0.5	NA	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
As	5.0	9.0	-5.0	NA	-5.0	-5.0	18.9	-5.0	601.0	54.0	-5.0	-5.0	23.0	-5.0	15.0	21.0	22.0	-5.0	-5.0	9.0
Ba	939	1269	1059	1105	1072	1631	653	723	839	1385	15	21	134	3646	148	90	946	1034	977	2452
Bi	1.9	-0.2	0.2	NA	-0.2	-0.2	-0.2	0.2	0.5	3.1	1.0	0.6	2.5	0.6	0.8	0.5	6.9	0.6	0.3	1.2
Ce	81	109	110	86	116	168	180	179	80	104	78	49	80	94	136	173	74	119	118	105
Co	25	22	23	NA	0	0	1	-1	0	1	0	0	0	0	0	0	3	1	2	2
Cr	7.0	5.0	34.7	7.0	5.0	5.0	53.4	23.2	5.0	1.0	2.0	6.0	6.0	42.0	5.0	7.0	7.0	4.0	4.0	5.0
Cs	1.3	4.2	1.8	5.3	2.7	3.8	4.4	4.4	1.6	3.4	9.1	7.6	7.5	5.9	4.7	5.4	2.7	4.1	4.4	6.2
Cu	-10	-10	16	13	-10	-10	18	15	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
Dy	8.7	8.7	8.7	9.8	6.1	14.0	13.8	13.8	7.3	12.0	22.0	19.0	17.0	15.0	16.0	12.0	8.1	13.0	13.0	12.0
Er	5.1	4.9	5.0	5.2	3.9	9.0	8.9	9.1	4.8	6.8	15.0	13.0	12.0	10.0	10.0	7.9	4.7	7.6	7.8	7.2
Eu	2.4	2.5	2.5	2.7	0.9	1.3	1.1	1.4	0.8	2.0	0.1	0.1	0.1	0.0	0.3	0.3	2.1	1.4	1.4	1.6
Ga	25	22	21	20	21	24	25	24	21	21	31	35	27	21	27	22	23	24	24	22
Gd	10.0	10.0	10.2	10.4	6.5	14.0	17.9	16.2	5.5	13.0	16.0	13.0	12.0	12.0	14.0	12.0	8.8	12.0	13.0	12.0
Ge	2.0	2.0	1.4	NA	2.0	2.0	1.5	1.4	2.0	2.0	2.0	3.0	2.0	2.0	2.0	2.0	1.0	2.0	2.0	1.0
Hf	7.4	7.7	7.1	7.6	9.4	14.0	11.9	12.8	11.0	12.0	9.4	9.1	9.1	7.0	9.3	8.8	8.5	16.0	15.0	15.0
Ho	1.7	1.8	1.7	2.0	1.2	3.0	2.6	2.9	1.6	2.3	4.8	4.1	3.7	3.3	3.3	2.6	1.5	2.5	2.5	2.3
In	-0.2	-0.2	-0.2	NA	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
La	58	50	53	45	55	86	108	96	62	76	51	28	34	40	91	80	57	89	92	89
Lu	0.7	0.7	0.7	0.7	0.8	1.4	1.0	1.3	0.8	1.0	2.3	2.2	1.8	1.5	1.4	1.2	0.7	1.1	1.1	1.1
Mo	1.0	0.7	2.1	NA	2.6	3.1	2.4	3.9	-0.5	1.8	2.1	1.6	2.9	-0.5	2.8	3.0	0.6	2.7	2.4	2.2
Nb	21	25	24	23	32	44	43	45	27	28	46	52	58	42	32	37	18	36	36	32
Nd	54	52	50	50	50	76	92	81	34	67	52	32	38	41	72	66	45	71	73	69
Ni	-10.0	-10.0	67.0	3.0	2.0	5.0	-10.0	13.5	16.0	-10.0	-10.0	-10.0	-10.0	132.0	12.0	0.2	23.0	-10.0	-10.0	17.0
Pb	34	23	38	18	47	52	33	44	53	66	123	95	79	57	86	63	44	53	62	57
Pr	12	13	11	12	14	20	22	19	10	15	12	7	10	11	17	18	10	16	17	16
Rb	84	88	60	65	185	177	186	179	134	171	373	514	444	137	277	311	94	179	191	163
Sb	0.3	0.5	0.3	NA	2.4	1.8	21.2	2.4	2.0	0.6	0.6	0.3	1.8	2.1	0.6	2.4	0.8	0.5	0.9	0.7
Sm	11	11	11	12	10	15	17	16	4	14	15	11	11	11	16	14	9	14	14	14
Sn	3.0	3.0	2.6	NA	4.0	6.0	3.9	5.4	3.0	3.0	16.0	12.0	12.0	12.0	7.0	12.0	3.0	6.0	6.0	6.0
Sr	375	378	372	368	58	59	28	51	89	96	15	8	10	1034	40	15	341	84	73	183
Ta	1.5	1.4	1.4	1.5	2.5	2.4	2.4	2.4	2.1	2.2	6.6	8.3	6.0	4.0	3.7	3.1	1.5	2.8	2.8	2.4
Tb	1.6	1.6	1.3	1.6	1.1	2.4	2.4	2.2	1.3	2.1	3.4	2.9	2.7	2.4	2.8	2.1	1.5	2.2	2.2	2.1
Th	8.2	7.4	7.8	6.0	27.0	18.0	16.7	17.5	17.0	18.0	45.0	50.0	45.0	31.0	35.0	29.0	19.0	27.0	27.0	23.0
Tl	0.4	0.4	0.4	NA	1.2	1.0	0.6	1.9	1.1	1.3	2.0	2.6	1.8	3.6	1.7	1.2	0.7	1.2	1.6	1.1
Tm	0.8	0.7	0.7	0.7	0.7	1.4	1.2	1.3	0.8	1.1	2.6	2.4	2.0	1.7	1.7	1.3	0.7	1.2	1.2	1.1
U	2.7	2.7	2.4	2.5	5.9	4.5	3.5	5.0	4.8	6.0	16.0	14.0	10.0	8.4	9.7	11.0	3.7	6.2	6.6	5.2
V	224	207	232	250	8	-5	9	-5	-5	9	-5	-5	19	6	22	6	1093	-5	10	19
W	0.6	-0.5	1.0	NA	-0.5	-0.5	2.4	1.8	1.9	2.1	5.6	5.1	2.7	2.0	2.6	0.8	0.8	1.5	1.8	1.2
Y	47	51	45	49	27	90	74	82	45	63	120	110	121	109	84	76	43	67	65	64
Yb	4.6	4.8	4.5	4.6	5.0	10.0	6.6	8.5	5.2	6.1	16.0	15.0	14.0	12.0	10.0	8.8	4.4	7.5	7.4	6.6
Zn	170	142	143	142	34	216	130	112	2	161	87	88	58	80	104	67	99	72	81	88
Zr	245	306	286	298	317	536	408	515	364	376	157	134	173	147	217	252	259	464	431	469

Map unit: abbreviations as shown on geologic map and description of map units. Quadrangles (fig. 1): RCR, Rock Creek Ranch; WCR, Willow Creek Reservoir (Wallace, 2003a); WCRSE, Willow Creek Reservoir SE (this map). All analyses by ActLabs, except for 00WC-10 (Geoanalytical Laboratory, Washington State University), major oxide analyses by X-ray fluorescence (XRF); trace element analyses by XRF and ICP-MS. Major oxides are normalized to 100% on a volatile-free basis; total is before normalization. Fe_2O_3 = total Fe, "-" = amount present is less than indicated number; † = amount present is more than indicated number. NA = not analyzed for.

for the fragmental unit. The angularity of the breccia fragments argues against the deposit being a long-lived surficial deposit, and the unit may include both late Eocene and middle Miocene surficial deposits. Bartlett and others (1991) included the eastern outcrops of Vinini breccia (described above) in their Tertiary "Fragmental Unit," but a Paleozoic age for the breccia would preclude this correlation.

Eocene Igneous Rocks

A small, altered, multi-phase rhyodacite to granodiorite pluton was emplaced into Paleozoic sedimentary rocks in the northeastern part of the quadrangle at about 43 Ma (Tewalt, 1998; Hollister and others, 1992). The pluton, known informally as the Hatter stock (Tdh on map and fig. 3; Tewalt, 1998), produces a small but strong positive anomaly that is visible on regional aeromagnetic maps (Hildenbrand and Kucks, 1988). The pluton is one of many late Eocene intrusive bodies along the northwest-trending Carlin trend, many of which produce similar positive magnetic anomalies (fig. 1; Ressel and others, 2000). Surface exposures are limited to scattered float in a several hundred-meters-square area, but drilling delineated a 1- to 2-km-wide pluton that is present at a relatively shallow depth largely west and southwest of the mapped area of float (Tewalt, 1998; Great Basin Gold Ltd, unpub. data, 2000). Sediments of the upper tuff unit were deposited on top of it, indicating a period of post-Eocene, pre-middle Miocene erosion that exposed the pluton.

Miocene Sedimentary and Tuffaceous Units

Most of the volcanic and volcaniclastic rocks within the Willow Creek Reservoir SE Quadrangle are middle Miocene in age. The rocks include andesite and rhyolite flow units, tuffs, and tuffaceous sedimentary rocks. Deposition of the tuffs and tuffaceous sediments began at about 16 Ma and continued to at least 14.4 Ma. Various mafic and felsic flows and domes were erupted episodically onto the tuffaceous units during that time, creating an interleaved sequence of flows and tuffs.

The oldest Miocene rocks consist of poorly exposed tuffs and tuffaceous sedimentary rocks that form a continuous depositional sequence. The interbedded vitric tuff (Tvt) and andesite (Ta) units (described below) provide useful stratigraphic and time divisions in the northern part of the quadrangle, and the tuffs and tuffaceous sedimentary rocks there are divided into lower (Ttsl), middle (Ttsm), and upper (Ttsu) members. In the central and southern parts of the quadrangle, where the vitric tuff is not apparent and the andesite is absent, the tuffaceous units form a continuous sequence. In the Willow Creek Reservoir Quadrangle to the north (Wallace, 2003a, b), the tuffaceous section is more than 200 m thick and deposition began at about 16.5 Ma. The lower tuff unit thins to the south; it locally is absent at the Hollister Mine, and it is totally absent in areas to the east and in the Santa Renia Fields Quadrangle (Theodore and others, 1998). Thus, the base of the Miocene section is younger in this quadrangle than at Willow Creek Reservoir, reflecting progressive southward expansion of the lake (Wallace, 2003b).

Approximately 2 km southwest of the Hollister Mine, small exposures of the base of the middle tuff unit contain ostracode-bearing limestone. The limestone is about a meter thick and is interbedded with water-laid tuffs. Limestone beds at the same stratigraphic position are present in the Quiver area west of the quadrangle (fig. 1), but they are absent throughout the rest of the district. In both of those locations, the limestone is interbedded with finely laminated lacustrine sediments.

At 15.10±0.06 Ma (table1), a dark-gray vitric tuff (Tvt) was deposited on the lower tuffaceous units. The unit is a distinctive marker bed within the otherwise monotonous tuffaceous rock sequence in the northwestern quadrant of the quadrangle. In that area and areas to the north (Wallace, 2003a; Henry and Boden, 1999), the vitric and welded character of the tuff indicates subaerial deposition. However,

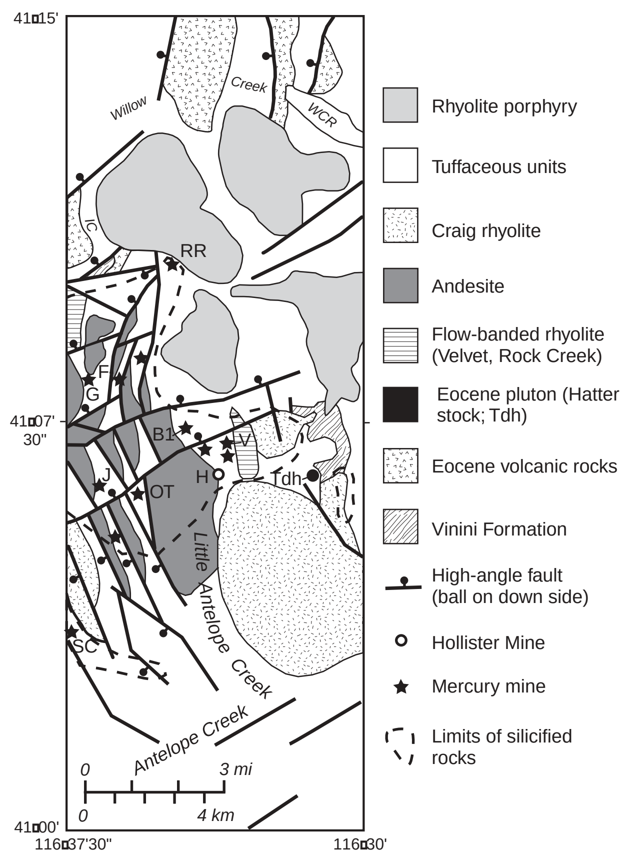

Figure 3. General geology Willow Creek Reservoir (north half of figure) and Willow Creek Reservoir SE (south half) Quadrangles, including the Ivanhoe district. Location shown in figure 1. Mines and prospects: B1, Butte #1; F, Fox; G, Governor; H, Hollister; J, Jackson; OT, Old Timer's; RR, Rimrock; SC, Silver Cloud; V, Velvet. Locations: IC, Ivanhoe Creek; WCR, Willow Creek Reservoir. Geology from this map and Wallace (2003a).

the vitric tuff is not apparent in the rest of the quadrangle, even through the stratigraphic interval in which it should occur is exposed in many places. Typical vitric tuff is exposed 1.5 km northwest of the Hollister Mine, and the same stratigraphic interval exposed in the mine is composed of water-laid tuffaceous material. The vitric tuff likely is part of this water-laid sequence, but subaqueous deposition likely modified the final character of the unit and made it megascopically indistinguishable from the other tuffaceous units. Thus, the vitric tuff likely is present elsewhere in the quadrangle, but in a modified form.

A generally flat-lying sequence of tuffs and tuffaceous sedimentary rocks is exposed south of Antelope Creek and in the northeastern corner of the quadrangle. These units are continuous with middle Miocene units in the Santa Renia Fields Quadrangle to the east, where Theodore and others (1998) equated them to the Carlin Formation. On the basis of lithology and age, the units south of Antelope Creek undoubtedly are continuous with the middle and upper tuff units (Ttsm, Ttsu) exposed to the north. However, the extremely poor exposures in the intervening area preclude direct correlation. The basal Carlin Formation unit (Tcas) is a mixture of thin welded tuff units and thick to thin beds of tuffaceous sediments. The percentage of tuff and thicknesses of tuff beds increase to the west, suggesting a westerly source for the tuffs that possibly include 14.84±0.04 Ma rhyolite domes of the Izzenhood dome field (fig. 1; John and others, 2000). Clastic sediments are relatively more common to the east, and, in the southeastern part of the quadrangle, Tcas contains abundant clasts derived from the nearby 15–15.16 Ma Craig rhyolite (Tcr). This is consistent with 14.4 to 15.1 Ma dates on this unit in the Santa Renia Fields area (table1; Fleck and others, 1998), indicating that the Craig rhyolite was a local highland that shed debris into adjacent lowlands. The upper unit (Tcss) is composed of siltstone and sandstone with little primary tuffaceous material. Depositional textures in both units indicate both subaerial and subaqueous deposition, including diagenetic chert in tuffaceous beds.

Conglomerates in the Hollister Mine area

The tuffaceous units in the Hollister Mine area contain abundant poorly sorted to chaotic conglomerates (Tct) that are not present elsewhere in the district (Wallace, 2003b). These coarse clastic rocks are at the approximate contact between the middle and upper tuff units, based on stratigraphic position above the andesite and exposures of vitric tuff at this interval 1.5 km northwest of the mine. Beds of pebble conglomerates also are present in the upper tuff unit east of Hollister. As exposed in the mine, a gently east-dipping angular unconformity sharply separates thin-bedded lacustrine rocks of the middle tuff unit from overlying coarse clastic rocks; the angular discordance between the conglomerate and the underlying sedimentary rocks is about 5º. The clastic beds range from coarse conglomerate to finer-grained, pebble-rich sandstones, all with a fine-grained tuffaceous matrix. The subangular to angular clasts are composed almost entirely of Vinini quartzite, and sparse imbricate clasts indicate westward transport. Individual beds are internally chaotic, but the overall sheetlike bedding is planar. The coarse clastic beds grade north, south, and west into pebble-bearing sandstones and eventually fine-grained tuffs. Clast size decreases upward in the section into very finely laminated tuffaceous sediments, marking a return to a quiet lacustrine environment. Drilling data indicate that the conglomerate extends at least 2 km east beneath the Velvet rhyolite (Great Basin Gold Ltd, unpub. data, 2000).

The conglomerate indicates a very pronounced and relatively short-lived high-energy clastic environment that temporarily interrupted sedimentation in a low-energy lacustrine environment. At the time of clastic deposition, the Vinini Formation was exposed only to the east (see below), providing an easterly source for the quartzite clasts, and the angularity of the clasts indicates both limited transport and juvenile source areas. The angular unconformity beneath the conglomerate also points to a major change in the lake-bottom environment and may indicate the early stages of fault-related tilting.

MIOCENE FLOW UNITS

Andesite

Red to black andesite flows are widespread in the northwestern part of the quadrangle. The flows were erupted during tuffaceous sedimentation, forming the division between the lower (Ttsl) and middle (Ttsm) tuffaceous units. The thickness varies from a few to 100 m, suggesting an undulating topography at the time of eruption or local eruptive centers. The unit pinches out to the east and south in this quadrangle; overall, it pinches out in all directions, with a central, somewhat thicker area in the northwest part of this quadrangle. Feeder dikes may be present but were not identified.

Throughout most of the area, exposures show no interaction of the flows with water during emplacement, indicating subaerial conditions. As exposed in the Hollister Mine, finely bedded lacustrine sediments were deposited conformably on top of the basalt flows, but most flows show no interaction with water, such as hyaloclastite breccias or hydration. One late flow unit exposed in the mine is composed of a mixture of massive to vesicular flow rock, breccias, and mafic pumiceous material. This reddish-purple hyaloclastic unit both overlies and underlies lacustrine sediments. Mafic, poorly sorted pumiceous tuff is present in several beds exposed slightly higher in this section, indicating continued eruptions during renewed lacustrine sedimentation. Laterally away from but close to the mine, the basal sediments of the middle tuff unit (Ttsm) contain laminated interbeds of mafic tuff. These breccia and mafic tuff beds are at the same stratigraphic position as the limestone beds in other areas, indicating a widespread expansion of the lake at the end of andesite volcanism.

Direct dating of the unit proved unsuccessful due to argon loss from the samples. One $^{40}Ar/^{39}Ar$ dating attempt on a fresh sample collected 2 km west of the Hollister Mine produced a disturbed spectrum that probably resulted from argon loss from glass in the matrix; a probable minimum age of 15.04±0.08 was derived from the highest-temperature step (C. Henry, written commun., 2002). A second dating attempt on a sample collected from just west of the quadrangle boundary also was unsuccessful due to significant argon loss (R. Fleck, written commun., 2001). The overlying, 15.10±0.06 Ma vitric tuff unit indicates a somewhat older age for the andesite, and its stratigraphic position just above possible 15.4 Ma units in the lower tuff unit (Wallace, 2003a) suggests an age of about 15.4 Ma or slightly younger.

Rhyolite of the Velvet area

Flow-banded rhyolite flows were erupted at 15.10±0.05 Ma (table1), and they presently are exposed over several square kilometers east of the Velvet and Clementine Mines and extend less than a kilometer north into the Willow Creek Reservoir Quadrangle (Wallace, 2003a). The flows overlie conglomerate and tuff units to the west, tuff units to the north, and early Craig rhyolite flows to the east; the upper tuff unit overlies the flows to the south. The flows are extremely flow-banded and folded internally, indicating fairly high viscosity. In the northern part of the rhyolite mass, the flows thinned and pinched out as they flowed over the exposed tuffs. In contrast, the western margin of the mass ends abruptly at Little Antelope Creek, suggesting either fault offset or a barrier to westward flow. Drilling data (Bartlett and others, 1991; Great Basin Gold Ltd, unpub. data, 2001) and surface mapping show that the underlying stratigraphy is continuous beneath the margin of the rhyolite mass, thus ruling out fault offset. The conglomerate unit, which was deposited in a depocenter of uncertain origin, parallels and underlies the rhyolite margin, and its northern and southern limits approximate that of the Velvet rhyolite. Given the similar distributions of the conglomerate and rhyolite, it is possible that the flows of Velvet rhyolite were erupted into the same depocenter. Eruption, though, took place after coarse clastic sedimentation ceased, the lacustrine environment was reestablished in the depocenter, and hydrothermal alteration silicified those lacustrine sediments, as described later.

Craig rhyolite

In the eastern and, to a lesser extent, western parts of the quadrangle, a thick series of phenocryst-rich rhyolite flows was emplaced during deposition of the upper tuffs and tuffaceous sedimentary rocks. The flows were named the “Craig rhyolite” by Bartlett and others (1991) for the high survey point in the eastern part of the area. The flows in the eastern part of the quadrangle, and extending east into the Santa Renia Fields Quadrangle (Theodore and others, 1998), were erupted between 14.99±0.05 and 15.16±0.05 Ma (table1). The flows in the western part of quadrangle and areas to the west were erupted between 15.07±0.08 and 15.17±0.05 Ma (table1).

The Craig flows east of Little Antelope Creek are sheet-like to extremely flow-folded, and the numerous rhyolite flows dip radially away from the high central core of the rhyolite mass. Basal vitrophyres are present only locally, mostly in flows at the fringes of the rhyolite mass or in the youngest flows. Most of the flow units show little or no evidence of quenching or chilling at their bases, suggesting that the flows were emplaced in rapid succession. Gas cavities and lithophysae are ubiquitous, and vertical, 1- to 10-cm-wide microbreccia zones extend from the uppermost parts of some flows and feather out into overlying flows. These breccia zones may indicate emplacement of the overlying flow before gas could escape from the older flow, causing gas overpressuring and explosion into the overlying flow. Feeder vents for the flows likely are part of the exposed mass, and some linear zones, such as the southern end of the Craig summit ridge, may represent feeders into still-hot and perhaps semi-molten flows.

The rhyolite flows in the western part of the quadrangle are identical in form to those to the east. The western package of flows extends and thickens to the west, where it forms a large mass of rhyolite exposed over several tens of square kilometers and overlies the Rock Creek rhyolite, the lower and middle tuff units, the vitric tuff, and the andesite (A. Wallace, unpub. mapping, 2001). At the Silver Cloud Mine, at and just west of this quadrangle, the upper tuff unit overlies the Craig rhyolite.

In this quadrangle, the relations between the Craig rhyolite and the tuffaceous units are consistent with effusive rhyolite volcanism at and shortly after 15.1 Ma. The Craig rhyolite both underlies and overlies the 15.10±0.05 Ma rhyolite of the Velvet area east of the Hollister Mine, and it overlies the andesite and the middle and upper tuff units along Little Antelope Creek. In the latter area, basal flows both overlie and are overlain by tuffaceous beds, indicating alternating volcanism and sedimention. Similar relations are exposed in the western part of the quadrangle. There, some flows have hydrated, brecciated, and altered basal vitrophyres, possibly indicating eruption onto wet sediments of the underlying lower tuff unit, and thinly bedded lacustrine sediments of the upper tuff unit were deposited on the Craig rhyolite. South of Antelope Creek, the basal Carlin Formation unit (Tcas) contains abundant clasts of Craig rhyolite, consistent with the 15.1 to 14.4 Ma isotopic ages on the Carlin Formation to the east (Fleck and others, 1998; Theodore and others, 1998).

The Craig rhyolite was part of a more widespread rhyolite event that extended from the western Santa Renia Fields Quadrangle, through the Quiver area (fig. 1) and northwest into the southern Snowstorm Mountains (fig. 1). Craig rhyolite flows were erupted in the Quiver area at 15.17±0.05 to 15.07±0.08 Ma (table1). The Sawtooth dike in the southern Snowstorm Mountains is approximately the same age (15.19±0.023 Ma) as the Craig rhyolite (table1; Wallace, 1993; Zoback and Thompson, 1978), and it fed one or more flows exposed along the side of the Midas trough. These flows are part of an extensive series of rhyolite porphyry flows that chemically and petrographically are similar to those of the Craig rhyolite. All of the Craig and Sawtooth-type rhyolite flows apparently were fed by north-northwest-trending dikes, but the flows and their feeders formed along a northwest-trending belt.

Rhyolite porphyry

A few flows of porphyritic rhyolite (Trp) are exposed in the extreme northeastern part of the quadrangle. These are part of a much larger series of rhyolite porphyry domes and flows that are exposed in the Willow Creek Reservoir Quadrangle to the north. The rhyolite porphyry is compositionally and petrographically similar to the Craig rhyolite. Similar domes and flows are exposed in the Izzenhood dome field to the west (fig. 1) and near the south border of the Santa Renia Fields Quadrangle to the southeast (S. Ludington and R.J. Fleck, written commun., 2001). The eruption of the 14.92±0.05 Ma flows (table1) onto the Vinini Formation indicates that the Paleozoic rocks were exposed at the time of eruption and thus not covered by lacustrine sediments.

Late Tertiary and Quaternary Units

Several unconsolidated sedimentary units are exposed in the quadrangle. The oldest is a coarse, unconsolidated conglomerate (QTgu, QTgm) that was deposited on two extensive pediments surfaces south of Antelope Creek. The upper deposits are approximately 30 m above the lower deposits, and both levels are conformable with the underlying, nearly flat-lying Carlin Formation. Clast lithologies are Paleozoic chert and quartzite, with minor volcanic rocks, and source areas were to the east (Theodore and others, 1998). Theodore and others (1998) included these deposits in the Carlin Formation, but evidence here and reevaluation of the deposits in the Santa Renia Fields Quadrangle (T.G. Theodore, oral commun., 2001) support a younger, late-Cenozoic age. The two pediment-capping units in this quadrangle apparently merge into one to the east. Similar east-derived, pediment-capping gravel deposits are exposed 25 km to the north above Willow Creek (Wallace, 2003a).

Additional terrace gravel deposits are exposed south of Antelope Creek (QTgl), and unmapped, discontinuous gravel deposits vaguely define three terrace levels west of Little Antelope Creek and north of Antelope Creek. These record progressive downcutting of Antelope Creek after deposition of the higher conglomerates. Alluvial sediments (Qal, Qoa) along Antelope Creek, Little Antelope Creek, and minor tributaries are the most recent stream sediments.

Structural Geology

Pre-Miocene structure

Paleozoic tectonism is evident in the limited exposures of the Vinini Formation in the eastern part of the quadrangle, where folding and faulting producing north-northwest-trending folds and related small-scale axial plane faults. These indicate east-northeast-directed compression, consistent with at least the late Devonian-early Mississippian Antler orogeny (Roberts and others, 1958) and possibly later regional compressional events (Theodore and others, 1998). Drilling through the Vinini has encountered the late Devonian Rodeo Creek unit at a depth of 1200 m (Tewalt, 1998) and possibly the Silurian Roberts Mountains Formation below 2000 m (Great Basin Gold Ltd, press release, 2001). These formations underlie the Roberts Mountains thrust of the Antler orogeny and host major gold deposits along the nearby Carlin trend (Teal and Jackson, 1997).

In the Willow Creek Reservoir Quadrangle, late Eocene tuffs and trachyandesite flows were tilted by as much as 20° prior to the deposition of the 16-Ma lower tuff unit (Wallace, 2000, 2003a). The Eocene tuffs are outflow from a distant caldera, and the flows are conformable on the tuffs, so the dips probably are not primary. Similar middle Tertiary tilting that took place east of Battle Mountain (Wallace and John, 1998) and elsewhere in northern Nevada records a deformational event sometime between 34 and 16 Ma. Bartlett and others (1991) defined an arcuate, 150-m-high paleotopographic ridge in the area of the Hollister Mine and areas immediately to the north. The origin of this high is uncertain, but it may be related in part to the middle Tertiary tilting event. It also may have been responsible for the southward thinning of middle Miocene sediments towards the Hollister area.

Middle Miocene structure

The dominant structures in the quadrangle are high-angle normal faults in the northwest quarter of the quadrangle where offset strata are well exposed. There, the faults strike both north-northwest and northeast. They are mutually crosscutting, but movement along the northeast-striking faults continued after movement along the north-northwest faults ceased. Regionally, north-northwest-striking Miocene faults are consistent with the west-southwest extension direction in the middle Miocene (Zoback and Thompson, 1978; Zoback and others, 1994), and the northeast-striking faults are related to younger (<8 Ma) northwest-directed extension (Zoback and Thompson, 1978; Wallace, 1991). The later extension produced large east-northeast-trending grabens, such as the Midas trough northwest of the quadrangle (fig. 1), and northeast-striking normal faults in the Willow Creek Reservoir Quadrangle just to the north (Wallace, 2003a).

Field and geochronologic evidence indicates that fault activity may have begun at depth at about 15.2 Ma, but that faults did not penetrate to the surface until after 15.1 Ma. Gold-silver veins in the Vinini north of the Hollister Mine formed at 15.19±0.05 Ma (table1), and they may indicate that fault activity began at that time. The north-northwest-striking faults offset Miocene rocks that formed between 16 Ma and about 14.4 Ma, which was a period of nearly continuous shallow lacustrine and low-relief subaerial sedimentation (Wallace, 2003b). The faults generally have less than 100 m of normal offset each and produced east-tilted fault blocks. As a result, the stratigraphic section is repeated several times from west to east in the northwestern part of the quadrangle. The continuity of strata and sedimentary textures across the faults indicates that faulting did not noticeably disrupt the paleosurface until about 15.1 Ma. Fault-related tilting also took place after the formation of the replacement silica deposits in the middle tuff unit, as these deposits are offset and repeated along with the enclosing tuffaceous and volcanic units. However, as seen both here and elsewhere in the district (Wallace, 2000), some mercury deposits are along or adjacent to north-northwest-striking faults. Thus, faulting may have penetrated to shallow depths or the surface by about 15.1 Ma. Much of the faulting took place between 15.1 and 14.92 Ma. This is evident near Willow Creek Reservoir (fig. 1), where the 15.1 Ma vitric tuff was tilted about 20° before the eruption of the 14.92 Ma rhyolite porphyry domes (Wallace, 2003a).

Bedding tilts in this quadrangle generally decrease from about 10 to 15° in the north to essentially horizontal along and south of Antelope Creek. This is part of a gradual southward decrease in dip from the Willow Creek area in the Willow Creek Reservoir Quadrangle to Antelope Creek (Wallace, 2000; Wallace 2003a). Offset of the Carlin Formation south of Antelope Creek is minor, consistent with decreasing amounts of offset to the south along the north-northwest-striking faults.

MIDDLE MIOCENE PALEOGEOGRAPHY

The sedimentary units indicate subaerial and subaqueous deposition in an area of low relief, with periodic syn-sedimentary eruptions of volcanic flow units. In the Willow Creek Reservoir Quadrangle (Wallace, 2003a), tuffaceous sedimentation began as early as 16.5±0.5 Ma (fig. 4a). Prior to that time, late Eocene tuffs had been tilted by as much as 20° near Willow Creek Reservoir and possibly stripped away in the central part of the Ivanhoe district. A broad, perhaps east-trending topographic high of about 150–200 m elevation had formed in the general area of the Hollister gold deposit (Bartlett and others, 1991), extending east into the adjacent Santa Renia Fields Quadrangle. Paleozoic rocks east of a general north-south line that runs through the eastern part of this quadrangle, including the area of the Craig rhyolite, remained exposed until about 15.1 Ma. This area includes the late Eocene Hatter stock, which was intruded to an unknown depth and then partially exhumed before 15.1 Ma, and much of the Santa Renia Fields Quadrangle (Theodore and others, 1998).

Early sedimentation was both subaqueous and subaerial, with thinly laminated lacustrine sediments indicating subaqueous deposition and unreworked tuffs indicating subaerial deposition. The lake gradually expanded, extending as far west as Midas by 15.4 Ma and south to the Hollister area by about 15.3 Ma (fig. 4b; Wallace, 2000; Leavitt, 2001). The planar and laterally continuous beds indicate a subdued topography. The presence of clastic sediments coarser than siltstone in only a few marginal areas (Willow Creek Reservoir, Midas area) indicate some distance from a highland source or a subdued source topography that did not generate extensive fluvial systems to transport coarser material. Clast imbrications in conglomerates and known lithologic source areas indicate transport from the northeast.

Andesite flows were erupted subaerially in the western half of the quadrangle, and the flows spread and eventually pinched out to the east and south (fig. 4b). The mafic flows were deposited largely on the lower tuff unit, and variations in the thickness of the unit suggest a slightly undulating but overall subdued topography. At the Hollister Mine, some flows rest directly on the Paleozoic basement, indicating either pre-flow erosion or non-deposition of the lower sediments over a local topographic high.

Throughout much of the quadrangle, fine-grained tuffs and tuffaceous sediments continued to be deposited both subaerially and subaqueously after the eruption of the andesite (fig. 4c). The distribution of the subaerial form of the 15.10±0.06 Ma vitric tuff defines the locations of exposed areas (and, conversely, the lake) at that time (fig. 4d). Near the Hollister Mine, thinly bedded sediments and fresh-water, ostracode-bearing limestone record a rapid expansion of the lake after eruption of the andesite flows. Shortly before the 15.10±0.05 Ma eruption of the rhyolite of the Velvet area, repeated debris flows were shed westward from a Vinini-cored highland into the lake margin in the Hollister area (figs. 4c, d). These debris flows were restricted to a relatively small marginal area of the lake, and they graded laterally into fine-grained lacustrine sediments farther into the lake. This debris flow event was not long lived, and overlying sediments were deposited in a quiet lacustrine environment. At about the same time (stratigraphically the same, and within the resolution of the isotopic dates), lacustrine sediments in the Willow Creek Reservoir area underwent soft-sediment deformation (fig. 4d; Wallace, 2003b). The causes of these sedimentary disruptions are unknown, but possible sources of strong ground motion include volcanic eruptions (Craig, Velvet rhyolites) and seismic activity related to early faulting.

After the local eruption of early Craig rhyolite flows (Tcr) and the rhyolite of the Velvet area (Trv), with the extent of the latter possibly controlled by the conglomerate basin, sedimentation continued with deposition of the upper tuff unit (Ttsu) (fig. 4e). In the northeasternmost part of the quadrangle, these fine-grained to local pebble-bearing tuffaceous sediments were deposited on the early Craig rhyolite, the rhyolite of the Velvet area, and the Vinini Formation. In the rest of the quadrangle, deposition of the middle and upper tuff units was continuous above the andesite. The lateral continuity of and fine grain size in these beds indicate low-energy deposition in an area of little or no topography.

Early Craig rhyolite flows were emplaced east and southeast of the Hollister area beginning at 15.16±0.05 Ma

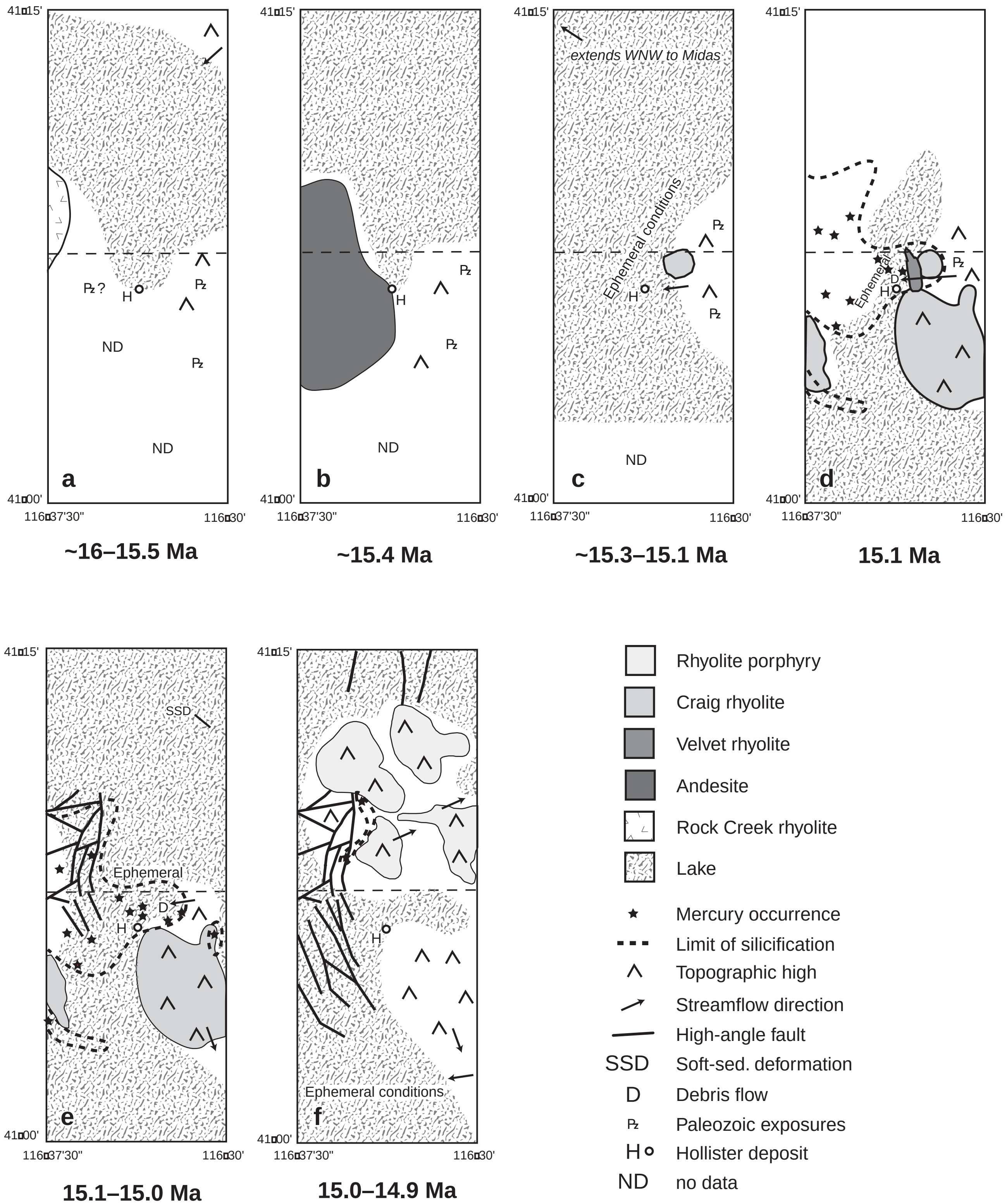

Figure 4. Paleogeographic evolution of the Ivanhoe mining district. Dashed horizontal line is boundary between this quadrangle and Willow Creek Reservoir Quadrangle to north (Wallace, 2003a). Hollister Mine (H) shown as reference point in all figures. From Wallace (2003b).

(fig. 4c). This began a series of eruptions that lasted to 14.99±0.05 Ma and covered sizeable areas in the western and eastern parts of the quadrangle with rhyolite flows (figs. 3, 4e). The rhyolite flows in the western area were erupted at 15.07±0.08 Ma during early upper tuff sedimentation, and they largely flowed over the lower and middle tuff units. Just west of the quadrangle, the thickness of the tuffaceous units between the andesite and the Craig rhyolite decreases to the north from several tens of meters to just a few meters (A. Wallace, unpub. mapping, 2000). These relations indicate some pre-Craig erosion of the sedimentary sequence in that area. The eastern mass of Craig rhyolite eventually formed a dome at least 300 m high that developed on units ranging in age from the upper tuff unit (Ttsu) to the Vinini Formation. Flows along the southwestern and southern margins of the dome complex were erupted during deposition of the tuffs, producing interfingered tuffs and flows. The eruption of the rhyolite porphyry was the last major volcanic event in the district, taking place largely north of this quadrangle (fig. 4f).

The flows of the early Craig rhyolite and rhyolite of the Velvet area effectively prevented continued westward transport of coarse Paleozoic clasts towards the Hollister area after about 15.1 Ma. The main Craig rhyolite also must have disrupted any pre-existing drainage patterns in the area in which it was erupted. Evidence in the southern part of the Santa Renia Fields Quadrangle (Theodore and others, 1998) indicates that a west-flowing drainage pattern developed around the south end of the Craig edifice shortly after eruption of the rhyolite, and those sediments comprise the Carlin Formation south of Antelope Creek in this quadrangle. If, as suggested by the west-flowing transport at Hollister, the pre-15.1 Ma drainage pattern was to the west, then the Craig edifice would have deflected that drainage and diverted it to the south and then west (figs. 4e, f). Indeed, the Carlin Formation sediments (Tcas) just south of the Craig rhyolite contain abundant clasts derived from the Craig rhyolite itself. Higher terrain near the northeast corner of the quadrangle, an area underlain by various rhyolite masses and the Paleozoic basement, may have prevented a northward stream deflection.

MINERAL DEPOSITS

The Willow Creek Reservoir SE Quadrangle includes the southern half of the Ivanhoe mining district. Mineral deposits in the district include: (1) disseminated gold deposits in Miocene rocks, such as the Hollister deposit (Bartlett and others, 1991; Hollister and others, 1992); (2) mercury in extensive near-surface replacement silica zones and more localized sinter deposits (Bailey and Phoenix, 1944); and (3) recently discovered high-grade gold and silver in Paleozoic, Eocene, and Miocene rocks that underlie the Miocene sedimentary rocks. Several mining companies have explored and drilled for gold in the district since the early 1990s. Targets for these gold exploration programs have included Miocene and Paleozoic host rocks, as well as the Eocene Hatter stock.

Mercury was discovered in the Ivanhoe area in 1915. Intermittent mining took place until 1943, with brief periods of mining from 1958–1973. Total mercury production was 2,180 flasks (LaPointe and others, 1991). The district was explored for porphyry molybdenum in the 1960s and 1970s and for uranium in 1980. Gold exploration began in the late 1970s, and U.S. Steel identified a gold resource near the middle of the district. In 1987, Cornucopia purchased the property and entered into a joint venture with Galactic Resources Ltd to form Touchstone Resources. Mining began at the Hollister gold deposit in 1990 and continued through 1992, eventually producing 115,000 ounces of gold through heap leaching. Newmont Gold bought into the property in the early 1990s and has completed reclamation of the open pits and mine dumps. Recent (1996–2003) exploration activity has focused on (1) veins in the Vinini Formation beneath the Hollister area (Price, 2001), (2) high-grade targets in deeply buried Miocene rhyolites, (3) deep targets in lower-plate Paleozoic rocks that structurally underlie the Vinini, and (4) veins related to the Eocene Hatter stock (Tewalt, 1998; Great Basin Gold Ltd press releases, 1999–2001).

Silicification

The most obvious signs of hydrothermal mineralization in the quadrangle are siliceous sinter and replacement deposits. Sinter deposits, with surface vents, mudcracks, and interbedded outflow breccias, are interbedded with sediments of the middle tuff unit. Sinters are exposed at the Butte #1 Mine, and areas northwest of the Hollister Mine and east of the Jackson Mine (fig. 3); younger sediments likely conceal other sinter deposits. The sinters are not laterally extensive, extending less than a hundred meters from the vent. Vertical, semi-concentric breccia zones at the Butte #1 Mine and other locations may indicate hydrothermal upwelling and boiling-related brecciation, and the stratiform breccias in the surface deposits may be the products of these eruptions. The sinters grade downward into massive to vuggy silicified tuffs that, at Hollister, contain hypogene kaolinite, jarosite, apatite and alunite (Deng, 1991; Hollister and others, 1992).

Throughout most of the district, chalcedony replaced a horizon several meters above the base of the middle tuff unit (Ttsm), and chalcedony float and outcrops mark the presence of this interval in areas of poor exposures. Silicification of sediments was complete to partial. Where complete, the replaced interval is composed of massive, featureless chalcedony. Where partial, silicified beds alternate with unsilicified but altered beds, and silicification fronts and margins are sharp. In places, primary bedding can be traced from fresh rocks into silicified rocks, and sedimentary structures and clast shapes are retained in silicified zones. Partially silicified zones commonly overlie a more massive silicified zone, such as above the Velvet Mine and the Silver Cloud Mine just west of the quadrangle. Although silicified zones generally follow bedding planes, they commonly cut across bedding, indicating secondary silicification rather than syn-sedimentary deposition of silica. The andesite and vitric tuff units also show evidence of hydrothermal alteration. However, fresh andesite and vitric tuff commonly both underlie and overlie the replacement deposits in the middle tuff unit, indicating preferential lateral flow of mineralizing fluids along that horizon.

Several other units in the quadrangle were silicified. The conglomerate and tuff unit (Tct) near the Hollister Mine locally was intensely silicified; silica replaced the tuffaceous matrix but preserved the quartzite clasts. East of the Hollister Mine, silicification of the Velvet and Craig rhyolites, rhyolite porphyry, and Vinini took place along the upper surfaces of those units at their contacts with overlying tuffaceous sediments, which also were silicified. The groundmass in the rhyolites was completely silicified, but quartz and sanidine phenocrysts, as well as flow-bands and lithophysal textures, were preserved.

Mercury deposits

Almost all of the mercury mines were inaccessible during this study, and the deposits were not studied in detail. Bailey and Phoenix (1944) provided descriptions of the Ivanhoe mining district mercury deposits and mining operations. Within the quadrangle, the principal mercury deposits include the Butte #1 and #2, Clementine, Velvet, Jackson, Old Timer's, and Rowena deposits. Other mercury deposits in the district include those at the Governor, Fox, Sheep Corral, Silver Cloud, and Rimrock Mines (fig. 3). Most of the silicified zones in the district have been explored by small pits and shallow trenches.

Mercury was deposited during silica replacement of the middle tuff unit. Cinnabar is the only ore mineral, and it is intergrown with massive chalcedony and forms discrete beds within variably silicified tuff. The cinnabar is black on weathered surfaces and red on fresh faces, reflecting a high chlorine content (McCormack, 2000). As exposed in limited open workings, cinnabar forms conformable massive to disseminated zones within altered and silicified tuffs, is intergrown with massive chalcedony, and fills small fractures in silicified tuff. Cinnabar-rich layers are 1–10 cm thick and have sharp contacts with enclosing beds. The cinnabar-bearing horizons preferentially follow thin beds within the host rocks, suggesting possible permeability and porosity influences by the original tuff beds. Other sulfides are not exposed in the mine workings, but pyrite is present in discarded drill cuttings. As seen at the Hollister Mine, the depth of oxidation ranges from ten to more than a hundred meters. This oxidation is both hypogene and supergene (Hollister and others, 1992).

Gold deposits

Gold is disseminated in Miocene volcanic and sedimentary units and forms veins in Paleozoic sedimentary rocks and Miocene rhyolites. Veins also are associated with the Eocene Hatter stock. The principal known gold deposits are in the vicinity of the Hollister Mine. Disseminated gold was identified in altered Miocene rocks beneath the Clementine, Velvet, Rowena, and Butte mercury Mines (Bartlett and others, 1991; Deng, 1991; Hollister and others, 1992), and the Hollister Mine exploited two of those gold-bearing zones. Gold is disseminated in the middle and lower tuffs, the andesite, and locally the Vinini Formation; the lower tuff beneath the andesite is the main host rock (Deng, 1991; Bartlett and others, 1991). The primary ore minerals are electrum and pyrite, with adularia, quartz, and chalcedony (Deng, 1991); the adularia was dated at 15.1±0.4 Ma (table1; Bartlett and others, 1991). The wall rocks were silicified and altered to various clay minerals and chlorite. Much of the upper part of the deposit is oxidized, possibly in part due to hypogene processes (Hollister and others, 1992), and pyrite is abundant in the unoxidized rocks. Limited fluid inclusion data were collected from healed microfractures in the Vinini directly beneath the Hollister deposit (Deng, 1991), but the relation of these veinlets to the Miocene mineralizing system is uncertain.

Recent (1996–2001) exploration drilling has defined a series of high-grade, apparently west-northwest- and north-striking veins in the Vinini Formation 1-2 kilometers north of the Hollister Mine. These veins underlie mercury-bearing silicified zones and a gold geochemical halo in the Miocene rocks (Great Basin Gold Ltd, unpub. data, 2002), and they are not exposed at the surface. Available but limited drill core data (Tewalt, 1998; Price, 2001) indicate that the veins contain banded quartz and adularia, with pyrite, electrum, silver selenides, and bladed calcite; quartz in places pseudomorphically replaced the calcite (Price, 2001). The controlling structures reportedly extend up to the base of the Miocene section, but offset of the Miocene units was minimal (Great Basin Gold Ltd, unpub. data, 2001). A $^{40}Ar/^{39}Ar$ date on adularia from one of the Hollister-area veins produced a 15.19±0.05 Ma age (Peppard, 2002; table1). Considering that one system overlies the other and the overlap in ages of these veins and the Hollister gold deposit (table1), the high-grade veins likely formed from the same hydrothermal system that produced both the Hollister deposit and the overlying mercury deposits.

Deep drilling through silicified Miocene sedimentary rocks in the western part of the Ivanhoe mining district indicates gold in Miocene rhyolites (Rock Creek, Craig), and Paleozoic rocks underlying the rhyolites, to depths of at least 500 m. Further evaluation of these targets is in progress, and results are not yet publicly available.

Drilling has explored the area near the late Eocene Hatter stock, with targets in and around the stock (Tewalt, 1998; Great Basin Gold Ltd, unpub. data and press releases, 2000). Float samples of the stock indicate chlorite-calcite alteration of the mafic minerals, which by their altered shapes appear to have been hornblende and biotite, and drilling data indicate a hornfels contact aureole around the stock in the host Paleozoic sedimentary rocks (Great Basin Gold Ltd, unpub. data, 2000). Drill holes encountered intervals containing 0.1–1.0 ounces per ton or greater gold grades in both the stock and adjacent Vinini Formation (Great Basin Gold Ltd, unpub. data, 2000). Information on vein mineralogy and textures has not been published. Many of the gold deposits along the northwest-trending Carlin trend, which extends to the Hatter area, are related genetically to late Eocene igneous rocks (fig. 1; Henry and Ressel, 2000), and the veins associated with the Hatter stock similarly may be related genetically to that pluton. However, no detailed work has been published on the veins that confirms this relation or shows that the veins are not related to the nearby middle Miocene epithermal systems.

Formation of hot-spring-related deposits

Based on geologic relations and $^{40}Ar/^{39}Ar$ dates on rocks and hydrothermal adularia, the gold and mercury deposits in the Ivanhoe district formed from the same widespread hydrothermal system (Wallace, 2003b). Hydrothermal activity began at 15.19±0.05 Ma ($^{40}Ar/^{39}Ar$ date on adularia; Peppard, 2002), and silicification of the rhyolite of the Velvet area, the Craig rhyolite, and the upper tuff unit, as well as flows of the 14.92±0.05 Ma rhyolite porphyry domes, indicates that mineralization in the district as a whole may have spanned 300,000 years. Throughout the district, the 15.10±0.06 Ma vitric tuff is fresh to weakly to strongly altered in mineralized areas, confirming that mineralization was taking place at or near the surface at that time. During this 300,000-year period, volcanic activity produced the rhyolite of the Velvet area, the Craig rhyolite, and the rhyolite porphyry, and high-angle faulting began and was active (figs. 4e, f).

As described above, the area of the Ivanhoe district at the time of mineralization had little topography, was alternately exposed and covered by shallow lakes (fig. 4), and had a temperate, moist climate (Axelrod, 1956). Thus, meteoric water was abundantly available for recirculation in a shallow hot-spring system. Incipient fault activity provided new vertical conduits to flat-lying, unconsolidated, and possibly water-saturated Miocene tuffs and sediments. In the central and southern parts of the district, the widespread Craig rhyolite was erupted at the same time (table1), likely serving as the principal heat source for the hydrothermal system. In the northern part of the district, small mercury deposits and silicified zones, such as at the Rimrock Mine and west of Big Butte, formed in the upper tuffaceous unit (Ttsu) adjacent to the 14.92 Ma rhyolite porphyry domes (Wallace, 2003a). Silicification and subsequent faulting preceded the dome eruptions, but the high stratigraphic level of the replacement silica indicates an age for silicification that was not much older than dome eruptions. Thus, heat from the ascending but not yet erupted magmas may have produced small hydrothermal systems in those areas. The relatively impermeable andesite unit may have focused fluid flow along its upper surface (fig. 5), or in some way controlled the groundwater table, leading to the almost ubiquitous silicification in tuffs above those flows in this quadrangle. Bartlett and others (1991) argued that the paleotopographic high channeled fluids upward to form the Hollister gold deposit. While that might be the case there, the abundant silicified zones and mercury deposits elsewhere in the district indicate that the high was not an essential element in fluid flow throughout the district.

The stratigraphic positions of the silicified zones in the district suggest that the locus of mineralization may have shifted with time, starting in the central part of the district and then moving or expanding laterally south and east (fig. 5; Wallace, 2003b). Therefore, even though the mineralizing processes spanned 300,000 years for the district as a whole, the duration of mineralization in any one area may have been considerably less. In the western half of the district, early silicification (~15.2–15.1 Ma) took place in the middle tuff unit above the andesite and Rock Creek rhyolite (area A, fig. 5). In the Silver Cloud Mine area (area B, fig. 5), massive chalcedony replaced the Craig rhyolite (dated there at 15.07±0.08 Ma) and the overlying upper tuff unit. East of the Hollister area, silicification above the Vinini, the Craig and 15.10 Ma Velvet rhyolites, and the 14.92 Ma rhyolite porphyry took place after deposition of the upper tuff unit and, locally, the rhyolite porphyry (area C, fig. 5). Similarly, the upper tuff unit in the Rimrock Mine area in the Willow Creek Reservoir Quadrangle was silicified shortly before emplacement of the rhyolite porphyry domes in that area (area D, fig. 5; Wallace, 2003a). The lake was ephemerally present during mineralization (fig. 4).

Hollister and others (1992) proposed that the mercury-bearing silicified zones at Hollister formed above the groundwater table in the vadose zone, and that the Tertiary-hosted gold deposits largely formed beneath that water table. However, Rytuba and Heropoulos (1992) used trace element data from chalcedony-hosted cinnabar at the Governor Mine (fig. 3), similar to the chalcedonic zones in the Hollister area, to indicate that the mercury-silica mineralization took place beneath the groundwater table. As such, the apparent hypogene oxidation described by Hollister and others (1992) may indicate a drop in the water table during late mineralization.

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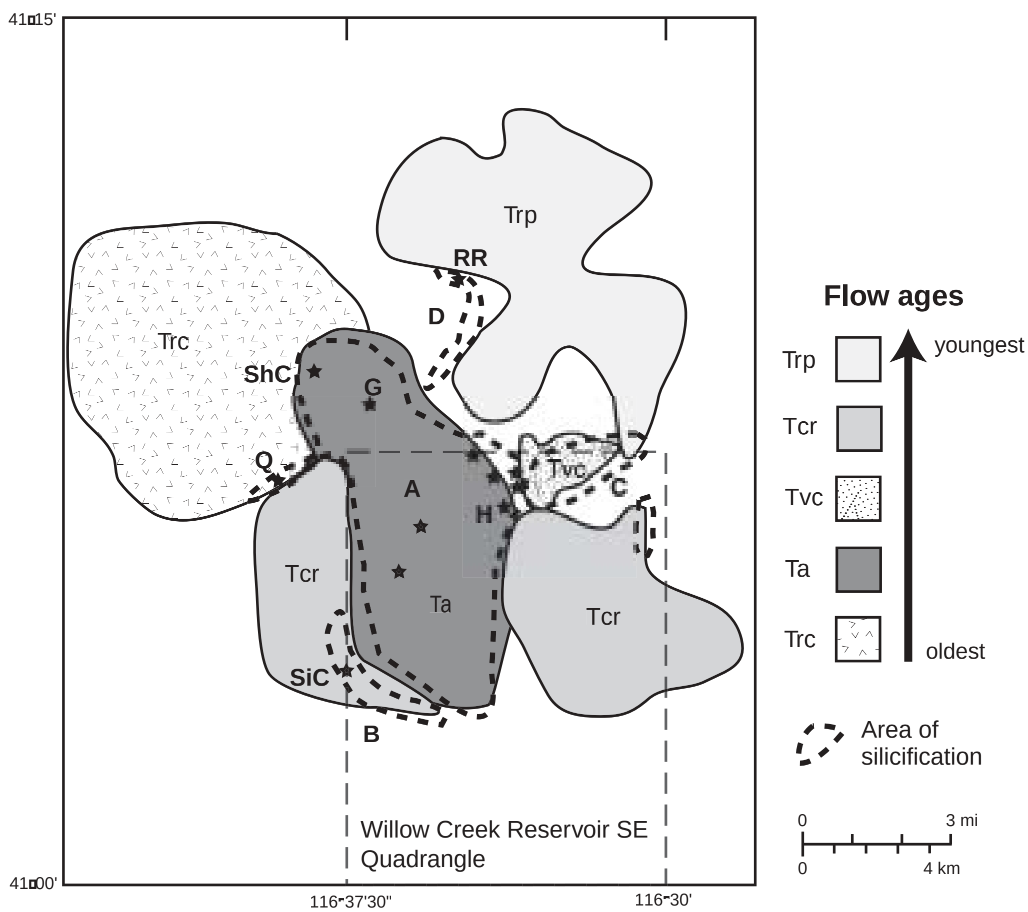

Figure 5. Distribution of major volcanic flow units and areas of silicification (dashed outlines). Willow Creek Reservoir SE Quadrangle shown with dashed rectangle. Units: Trc, Rock Creek rhyolite; Ta, andesite; Tvc, Velvet and early Craig rhyolites; Tcr, Craig rhyolite; Trp, rhyolite porphyry. Mines and prospects (stars): G, Governor; H, Hollister; Q, Quiver; RR, Rimrock; ShC, Sheep Corral; SiC, Silver Cloud. Letters A-D refer to areas described in text. Modified from Wallace (2003b).

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