Alteration and Geochemistry of Tertiary Volcanic Rocks in Parts of the Virginia City Quadrangle, Nevada

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ALTERATION AND GEOCHEMISTRY OF TERTIARY VOLCANIC ROCKS IN PARTS OF THE VIRGINIA CITY QUADRANGLE, NEVADA

By Donald H. Whitebread

ABSTRACT

The Virginia City quadrangle, which includes parts of the Virginia and Flowery Ranges in western Nevada, is best known for the Comstock Lode mining district, which produced more than 8 million ounces of gold and about 200 million ounces of silver. Also in the quadrangle is the Jumbo district, which has yielded a small amount of gold and silver; the Castle Peak mine, which produced about 2,500 flasks of quicksilver; and the Washington Hill prospect, which yielded a few flasks of quicksilver. The Alta Formation, of Miocene age, is the main host rock for the gold, silver, and mercury deposits; the overlying Kate Peak Formation, also of Miocene age, is mineralized locally. These formations compose a thick section of dactic and andesitic volcanic rocks that are extensively exposed in the Virginia and Flowery Ranges. Age determinations from adularia in veins in the Comstock district indicate that mineralization took place about 13 million years ago and within the same time interval as emplacement of the Kate Peak Formation.

The effects of alteration were noted early in the history of the Comstock Lode district; it is considered to be the type area for propylitic alteration. Much of the Alta and parts of the Kate Peak have undergone propylitic alteration that has produced varying amounts of chlorite, calcite, epidote, albite, montmorillonite, zeolites, and pyrite. The propylitized rocks locally grade into unaltered rock, but also they are found adjacent to conspicuously bleached rocks. Bleaching is a relatively near-surface feature resulting from supergene alteration of pyrite-bearing altered rocks and is caused by the action of sulfuric acid produced by oxidation of the pyrite. The bleached rocks are composed mainly of clay minerals and quartz, but they also include resistant ledges composed of quartz and alunite.

A small diamond-drilling program supported surface geologic studies and provided information on the rocks beneath the bleached zone. DDH–1 and DDH–2, about 8 km (5 miles) north of Virginia City, were drilled to confirm, if possible, the position of the Comstock fault and to obtain further information about the nature of a strong geophysical anomaly discovered during induced-polarization (IP) traverses across the projected trace of the fault. The anomalous IP values coincide approximately with a zone of relatively unaltered dacite cut by numerous veinlets of pyrite. DDH–3 and DDH–4, 7 and 17 km (4½ and 10½ miles), respectively, north of Virginia City, were drilled to investigate the relation of geochemical anomalies to rock alteration and possible mineralization. The holes are entirely within the Kate Peak Formation except in the bottom part of DDH–3 where some propylitized rocks are tentatively assigned to the Alta Formation.

DDH–1 and DDH–2 penetrated several intervals of argillized rocks containing montmorillonite, cristobalite, pyrite, and zeolites. Drill cores from DDH–3 and DDH–4 revealed a repetitive zonal pattern of alteration. This zonal arrangement, representing a decreasing order of intensity of alteration extending outward from main channelways of hydrothermal solutions, consists of an inner alunitic zone, an intermediate argillic zone, and an outer propylitic zone. The alunitic zone has been subdivided into an alunite-quartz-pyrite assemblage and an alunite-jarosite-quartz assemblage; the argillic zone contains the kaolinite-quartz-pyrite and illite-montmorillonite (mixed layer)-quartz-pyrite assemblages; and the propylitic zone is subdivided into the montmorillonite-calcite-quartz-pyrite and montmorillonite-chlorite-calcite-quartz-pyrite assemblages and a weakly altered chlorite-montmorillonite-calcite-quartz assemblage. The sequence of zones indicates a decrease in acidity of the hydrothermal solutions outward from the alunitic zone. Alteration in a relative low-temperature (<200°C) environment is indicated from a study of fluid inclusions, but temperatures were higher locally, as shown by the presence of pyrophyllite in some areas of bleached rocks.

The increasing extent of hydrogen metasomatism with increasing degree of alteration is reflected in the various mineral assemblages by the progressive depletion of calcium, magnesium, sodium, and potassium ions present in the original dacitic rocks, and a corresponding gain of hydrogen ions. Potassium was introduced in the alunitic zone, however, where it is a component of alunite and jarosite. Silica and aluminum are decreased slightly by weak propylitic alteration, but no extensive changes of these elements occur in the more altered zones except for a further loss of aluminum in the alunite-jarosite-quartz assemblage. Ferrous iron is depleted in the argillic and alunitic zones, but total iron content remains relatively unchanged, as most of the iron freed during alteration combined with sulfur to form pyrite.

Mercury, gold, silver, lead, antimony, bismuth, and molybdenum are enriched in parts of some alunitic zones, and mercury is locally enriched in the kaolinite-quartz-pyrite assemblage. Arsenic, cobalt, and nickel are depleted from the alunitic zone. The highest values for the introduced metals are found mainly in the alunite-jarosite-quartz assemblage. With the possible exception of mercury, however, the concentrations of metals generally are not appreciably above the minimum values considered to be anomalous.

In the bleached rocks, compositional changes resulting from supergene alteration are difficult to separate from changes that took place during the earlier hydrothermal alteration. Comparison of background values for elements in bleached rocks and their unoxidized equivalents beneath the bleached zone shows that mainly cobalt and nickel were removed additionally during bleaching, although barium and copper also were decreased slightly. The porous highly silicified ledges within the bleached rocks have undergone near-surface leaching of aluminum and enrichment of silica, and they represent the greatest cumulative effects of hypogene and supergene alteration.

About 1,100 surface samples of rock, soil, iron-rich fracture fillings,

and vein material were collected and analyzed, and the distribution of anomalous gold, silver, lead, and mercury was plotted. Most of the samples were from areas of bleached rocks, which were considered to be the most promising exploration targets. All samples containing more than 5 parts per million gold or more than 15 parts per million silver are from veins in the Comstock Lode, Flowery, or Jumbo mining districts. Outside the known mineralized areas, anomalous amounts of mercury, silver, arsenic, antimony, lead, and bismuth were found mainly in resistant alunite-quartz ledges within the bleached rocks and locally in bodies of opalite. The ledges that contain anomalous amounts of metals are identical in appearance and mineral composition to many others that are barren.

The zonal pattern of alteration revealed in the drill cores is similar to that associated with epithermal ore deposits in volcanic rocks at Goldfield, Nev., and several other mining districts where rich ores are developed in zones of alunite-quartz alteration. The close relation between faults and the known significant deposits of gold, silver, and mercury in the Virginia City quadrangle suggests that further geochemical sampling of the bleached rocks should concentrate on those silicified ledges developed along or near well-defined faults or brecciated zones or along the projection of such structures into the bleached areas. Extensive geochemical exploration of areas of bleached rocks lacking these structures does not appear to be warranted by the occurrences of anomalous but generally minor concentrations of metals. Geochemical sampling in the vicinity of Virginia City does not suggest wide dispersal through the wallrock of elements that might indicate the presence of the gold-silver deposits.

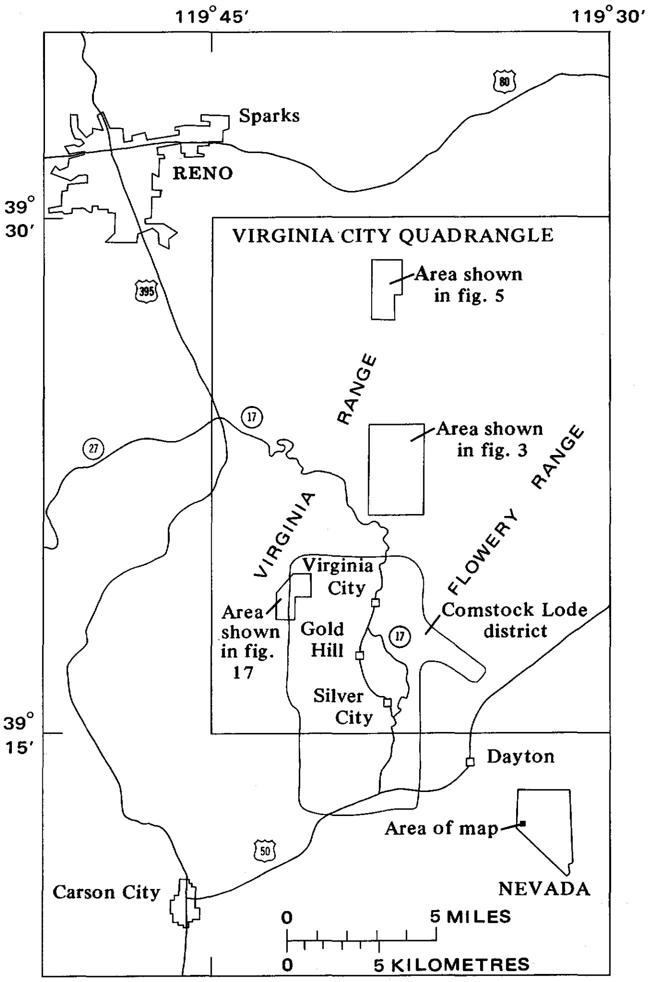


FIGURE 1.—Index map showing location of the Virginia City quadrangle, the Comstock Lode district, and areas mapped in detail.

INTRODUCTION

The Virginia City quadrangle is in the Virginia and Flowery Ranges southeast of Reno and includes the towns of Virginia City, Gold Hill, and Silver City (fig. 1). The Comstock Lode mining district is mainly in the southern part of the quadrangle, although as delineated by the map of Calkins and Thayer (1945), it extends for several kilometres farther south. The Flowery mining district, 5 km (3 mi) east of Virginia City, also is commonly included in the Comstock Lode district. About $400 million worth of silver and gold have been produced in the district since discovery of placer gold in a canyon southeast of Silver City in about 1850. The Jumbo mining district, 5 km (3 mi) west of Gold Hill, has yielded a small amount of gold, and the Castle Peak mine, 10½ km (6½ mi) north of Virginia City, has been one of the more productive quicksilver mines in Nevada. Nearly all the known ore deposits occur in the Alta Formation, of Miocene age, but there are minor deposits in the overlying Kate Peak Formation, also of Miocene age. The Alta and Kate Peak Formations comprise a thick section of dacitic and andesitic volcanic rocks that underlie a large part of the Virginia and Flowery Ranges.

Geologic studies have been conducted intermittently in the Comstock Lode district since shortly after discovery of the rich lode deposits in 1859. The early reports by von Richthofen (1868), King (1870), Becker (1882), and others are summarized in the later detailed reports of Gianella (1936) and Calkins (1944), and the history in mining is thoroughly described by DeQuille (1876), Lord (1883), Smith (1943), and Stoddard and Carpenter (1950). Thompson (1956) and Thompson and White (1964) described the geology within the Virginia City quadrangle, and their geologic maps, which incorporate the earlier map of Calkins and Thayer (1945), were used extensively during the present investigation. The most recent report on the regional geology and mineral deposits was written by Bonham (1969).

Two main types of altered rocks, propylitized and bleached, were recognized by earlier workers in the Comstock Lode district. Propylitized rocks are well exemplified; in fact, the Comstock Lode district is the type locality for propylitic alteration, as the term was derived from the name propylite which was first applied by von Richthofen (1868) to certain altered rocks in the district. Bleaching results from near-surface alteration of pyrite-bearing altered rocks. This supergene alteration is most extensive in the Alta and Kate Peak Formations, but locally it also affects other rocks.

The earlier geologic studies provided the base for the geochemical and alteration studies described here. The main objectives of the present study were to appraise the potential for additional deposits of heavy metals, principally silver, gold, and mercury, and to obtain information on the nature of the widespread alteration and its possible relation to ore deposits. Particular emphasis was directed toward study of the extensive bleached areas outside the Comstock Lode district because of their striking similarity to exposures above the ore bodies near Virginia City and Gold Hill and because of the reported occurrence of anomalous mercury and silver in several of these outlying areas (Cornwall and others, 1967, p. B11).

ACKNOWLEDGMENTS

The cooperation of the Curtiss Wright Corp. and the Carlsberg Financial Corp., on whose properties much of the investigation was conducted, is gratefully acknowledged. Duval Corp. held an option on the Curtiss-Wright lands during part of the studies, and their staff was most cooperative. Lane W. Schultz assisted in the fieldwork in 1966, and Jules A. MacKallor directed the studies during part of the field season in 1968. Will N. Blair assisted in the fieldwork in 1968 and was particularly helpful during the drilling program. Carol Piper Ankunding did much of the X-ray study on surface samples and made several mineral separations for age determination in 1966–67. Randolph Koski assisted with X-ray work and mineral separations in 1970–71.

METHODS OF STUDY

The investigation was begun by widespread sampling of the Alta and Kate Peak Formations, particularly in the bleached areas. About 1,100 samples of unaltered, propylitized, and bleached rock; soil; iron-stained fracture fillings; and vein material were collected and analyzed. Most samples of rock were collected from outcrops or from dumps of prospect pits. Analyses of samples from dumps of the large mines in the Virginia City and Gold Hill areas were not included in the compilations of anomalous sample localities.

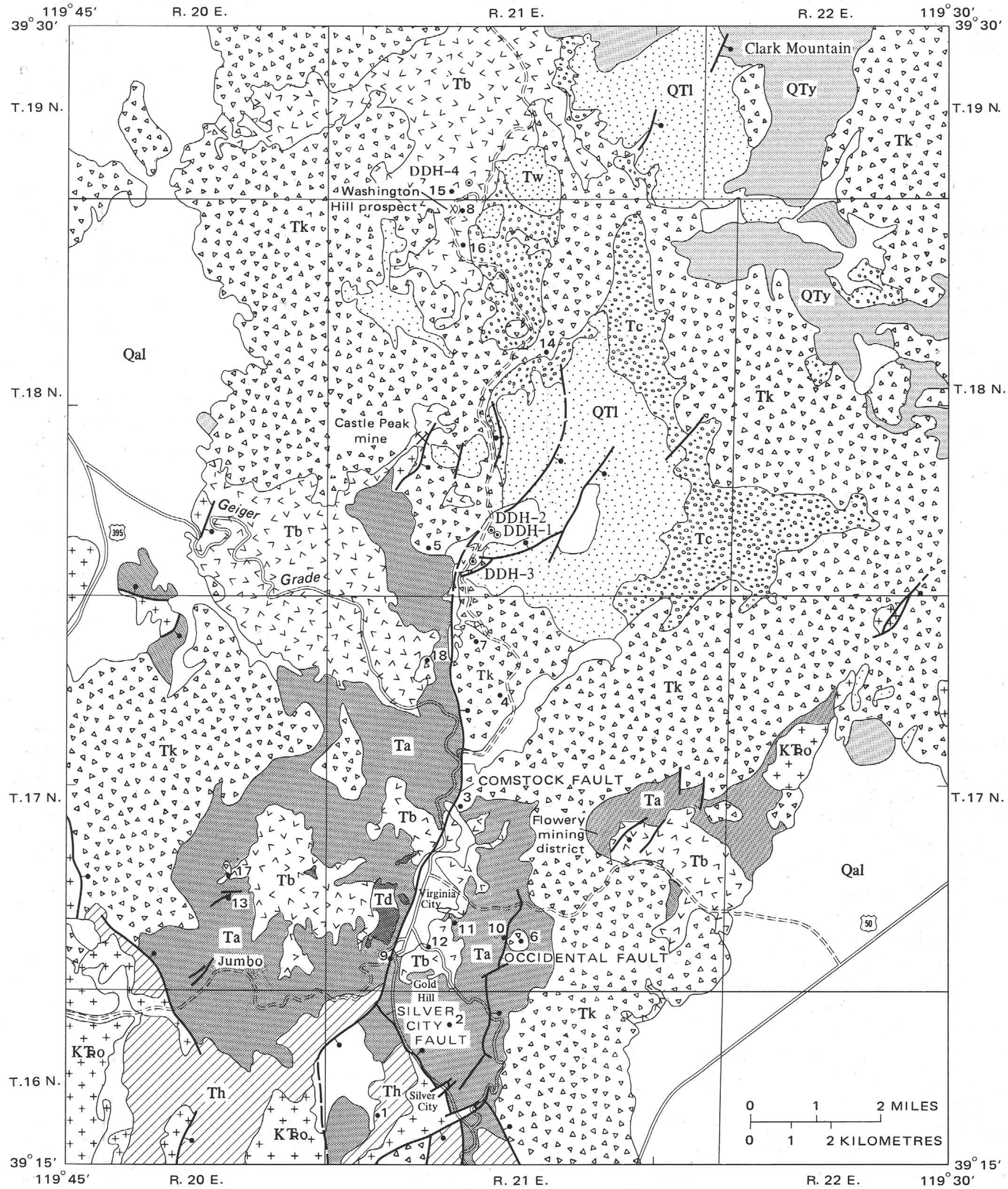
Several areas were selected for detailed mapping on the basis of the geochemical sampling or their geologic setting. These include a strip along the Comstock fault north of Virginia City and an area near the Washington Hill prospect, several kilometres farther north, where Cornwall, Lakin, Nakagawa, and Stager (1967) had reported anomalous mercury in bleached rocks (figs. 1, 2). Preliminary results of these studies and of induced polarization (IP) and electromagnetic geophysical surveys were reported earlier by Whitebread and Hoover (1968).

Four diamond-drill holes (DDH) drilled by the U.S. Geological Survey for additional geologic information provided an opportunity to examine the altered rocks below the bleached zone. DDH–1, DDH–2, and DDH–3 are about 8 km (5 mi) north of Virginia City, and DDH–4 is in the Washington Hill area. Core was recovered from all except 23 m (75 ft) of the total length of the four drill holes, excluding the uppermost parts of each hole that were drilled with a rock bit.

The alteration minerals were determined chiefly by microscopic study of thin sections and by using X-ray diffraction methods. Megascopic examination was of only limited value in determining the type and degree of alteration of those rocks containing a considerable amount of clay. Many of these rocks also were too soft and crumbly for thin sectioning, and they were studied only by X-ray diffraction. X-ray diffraction patterns were obtained first from whole-rock samples broken to -100 mesh, ground for 15 minutes, and packed in aluminum mounts. Concentrations of clay minerals were obtained from selected samples by disaggregating the rock, preparing an aqueous suspension, withdrawing a small amount of the -2μ clay-size fraction, and sedimenting it on a glass slide. The clay minerals therefore are representative of the bulk rock sample. Diffraction data were obtained from the air-dried clays, and, when necessary, additional patterns were made after treating the slide with ethylene glycol, after heating at 400°C for half an hour, and again after heating at 550°C for half an hour.

In this report the term kaolinite is used as a group name and includes both kaolinite and dickite. These two minerals were distinguished on the basis of X-ray diffraction patterns in some of the samples from the drill holes but in only a few samples of bleached rocks on the surface. The term montmorillonite includes those clay minerals in which the (001) spacing ranges from about 14 to 15.5 A and expands to 17 A when the clay is treated with ethylene glycol. It should be recognized that some expandable vermiculite may be included as montmorillonite. The term illite refers to a nonexpanding mica-type clay mineral with a (001) spacing at approximately 10 A (Grim, 1968, p. 42). The term alunite applies to all members of the alunite-natroalunite series, and the term jarosite likewise refers to all members of the jarosite-natrojarosite series.

Samples from surface exposures and chip samples collected from every 1.5-m (5-ft) interval of core from each drill hole were analyzed for 30 elements by emission spectrographic methods (Grimes and Marranzino, 1968). Gold was determined by atomic absorption spectrophotometry (Huffman and others, 1967), mercury was determined by instrumental atomic absorption (Vaughn and McCarthy, 1964), and arsenic and antimony in some samples were determined by wet-



Geology modified after Thompson(1956, pl. 3)

FIGURE 2.—Generalized geologic map of the Virginia City quadrangle showing location of drill holes.

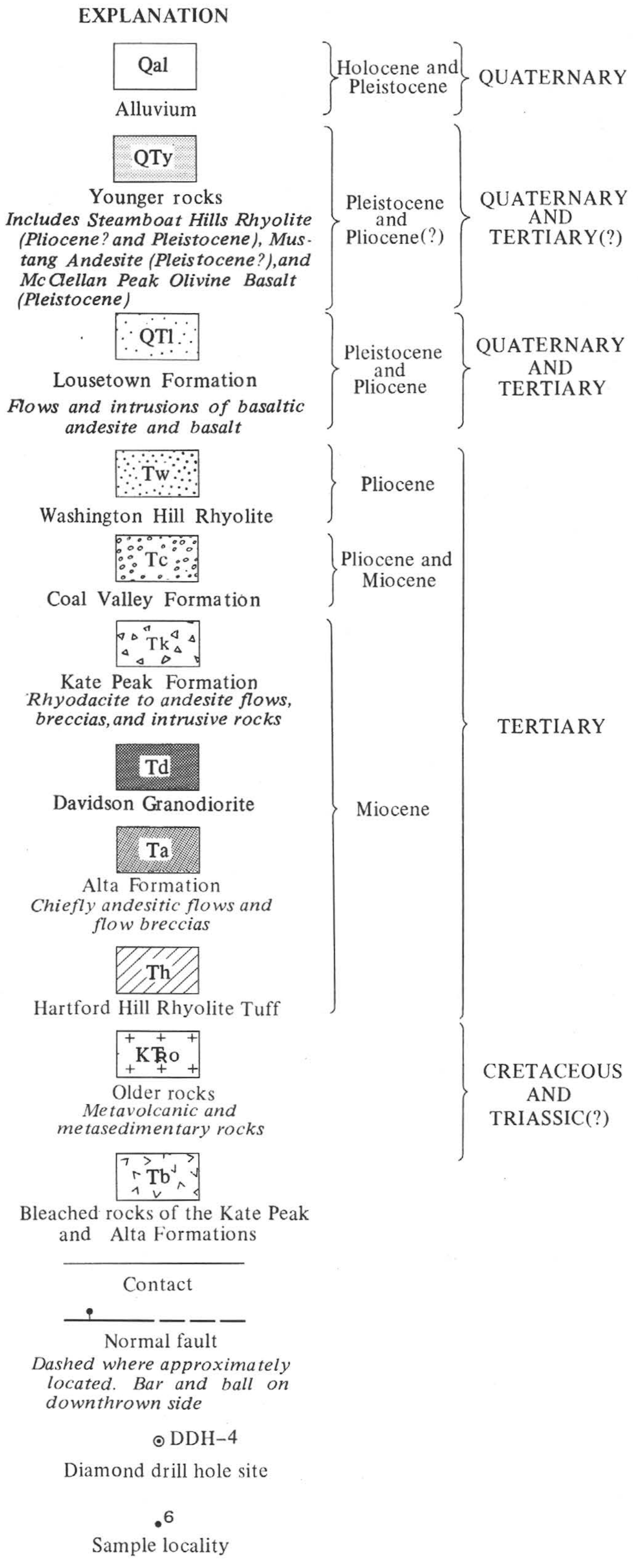


FIGURE 2.—Continued.

chemical techniques (Ward and others, 1963). The analysts for gold were W. W. Campbell, M. S. Rickard, T. A. Roemer, R. F. Hansen, T. G. Ging, G. H. Van Sickle, R. B. Tripp, and T. M. Stein; and for mercury, K. R. Murphy, W. L. Campbell, W. W. Janes, S. L. Noble, and H. D. King. Spectrographic analysts were D. J. Grimes, K. C. Watts, E. L. Mosier, J. M. Motooka, K. J. Curry, and E. E. Martinez.

Analyses of samples from surface exposures and drill cores were evaluated statistically in order to determine average concentration levels and other data. Background values and threshold levels were obtained by plotting cumulative frequency curves of selected analytical data (Lepeltier, 1969).

GEOLOGIC SETTING

The rocks exposed in the Virginia City quadrangle are mostly volcanic rocks of Tertiary and Quaternary age (fig. 2). Pre-Tertiary rocks consist of Triassic metamorphosed sedimentary and volcanic rocks and Cretaceous granodiorite. The Hartford Hill Rhyolite Tuff, the oldest Tertiary unit exposed, is composed of vitric-crystal tuff, tuff-breccia, and welded tuff. The early Miocene age of the Hartford Hill is based on age dates of 22.7 and 22.8 m.y. (million years) obtained from sanidine and plagioclase (Evernden and James, 1964, p. 972) and 22.5 m.y. from biotite (table 1). Above the Hartford Hill are the Alta and Kate Peak Formations, of Miocene age, both of which are composed mainly of flows and flow breccias of dacite, rhyodacite, and andesite. Geologic studies were confined largely to the Alta and Kate Peak Formations, and they are described later in more detail.

The Davidson Granodiorite, the only Tertiary holocrystalline intrusive rock in the quadrangle, intrudes the Alta Formation in the footwall of the Comstock fault near Virginia City. Porphyritic rocks that are possible offshoots of the Davidson cut the Alta in several of the mine workings in the hanging wall (Coats, 1940, p. 9). Chemical analyses and field relations indicate that the Davidson Grandiorite is contemporaneous with part of the Kate Peak Formation (Thompson, 1956, p. 53), and, therefore, it is middle Miocene in age.

Lacustrine and fluviatile deposits that overlie the Kate Peak Formation are composed mainly of tuffaceous siltstone and sandstone with interbeds of diatomite, shale, conglomerate, and tuff-breccia. In the Virginia City quadrangle they were mapped as the Truckee Formation by Thompson (1956) but were included in the Coal Valley Formation by Axelrod (1958, p. 98; 1962, p. 199). The assignment of these rocks to the Coal Valley Formation is based on the conclusions of Bonham (1969, p. 37–38), who examined both the type Truckee and

TABLE 1.—*Potassium-argon age determinations of rocks and veins in the Virginia City quadrangle*

[Locality numbers refer to those shown in fig. 2]

Locality	Sample No.	Rock unit	Mineral	K_2O[1] (weight percent)	$^{40}Ar(rad)$ (moles/g)	$^{40}Ar(rad)/^{40}Ar(total)$	Calculated age[2] (m.y.)
1	6–147	Hartford Hill Rhyolite Tuff	Biotite	8.245	2.753×10^{-10}	0.62	22.5±0.7
2	6–144	Alta Formation	Plagioclase	.3395	7.246×10^{-12}	.46	14.4±0.4
3	6–75	Intrusive rock, Kate Peak Formation	Hornblende	.6065	1.336×10^{-11}	.20	14.9±0.4
			Biotite	8.03	1.684×10^{-10}	.53	14.1±0.4
4	5–267	Kate Peak Formation	do	5.97	1.222×10^{-10}	.601	[3]13.8±0.3
5	5–61	do	Hornblende	.523	1.059×10^{-11}	.081	[3]13.7±1.6
6			do	.580	1.110×10^{-11}	.37	12.9±0.4
	6–153	Intrusive rock, Kate Peak Formation	Biotite	6.54	1.229×10^{-10}	.57	12.7±0.4
7	96–159	do	do	8.20	1.508×10^{-10}	.407	[3]12.4±0.3
8	99–157	Kate Peak Formation	do	7.38	1.347×10^{-10}	.652	[3]12.3±0.2
9	6–93	Comstock vein	Adularia	15.82	3.220×10^{-10}	.91	13.7±0.4
10	6–45	Occidental vein	do	16.14	3.066×10^{-10}	.70	12.8±0.4

[1] Potassium analyses by Lois Schlocker.

[2] Argon analyses and age calculation by Joan Engels and Jarel Von Essen unless otherwise specified.

[3] Argon analyses and age calculation by M. L. Silberman.

Coal Valley Formations during a regional study. Axelrod's (1956, p. 29–30, fig. 2) measured section *A–A′*, considered to be the type section of the Coal Valley, extends from NE¼NW¼ sec. 2 to NW¼SE¼ sec. 1, T. 7 N., R. 27 E., in southeast Lyon County. According to Bonham, the age of the Coal Valley Formation ranges from late Miocene to middle Pliocene. The Washington Hill Rhyolite, an extrusive dome of rhyolitic glass and perlite, represents the end stage of eruptions that supplied tuffaceous material to the Coal Valley ("Truckee") Formation (Thompson, 1956, p. 56).

At many places the Coal Valley Formation is missing, and the Kate Peak is overlain unconformably by the Lousetown Formation. The Lousetown is composed of a series of well-defined flows of basalt and basaltic andesite that came from several local vents. The flows at the type locality, about 10 km (6 mi) north of Virginia City, are Pliocene, on the basis of a potassium-argon age of 6.9 m.y. (Dalrymple and others, 1967, p. 165). From paleomagnetic evidence, however, Heinrichs (1967, p. 3288) believed that the Lousetown flows at Clark Mountain, about 10 km (6 mi) north of the type locality, are significantly younger, and he estimated their age at about 2.4 m.y. or 3.4 m.y. Birkeland (1963, p. 1456–1457) correlated the Lousetown flows in the Virginia Range with flows near Truckee, Calif., that range in age from 1.2 to 2.3 m.y. Rocks assigned to the Lousetown thus range in age from Pliocene to Pleistocene.

Rocks younger than the type Lousetown Formation include the Steamboat Hills Rhyolite, the Mustang Andesite, and the McClellan Peak Olivine Basalt. Potassium-argon ages of 1.15 to 1.52 m.y. for the Steamboat Hills Rhyolite (Silberman and White, 1975) and 1.14 m.y. for the McClellan Peak Olivine Basalt (Doell and others, 1966, p. 534) establish their ages as Pleistocene.

Evidence for two episodes of structural deformation—one during Mesozoic time and a less intense event from Miocene to Holocene time—has been described in the Virginia Range by Thompson (1956, p. 63–68). Mesozoic rocks that were folded, metamorphosed, and intruded by Cretaceous granitic rocks are overlain by Tertiary rocks that have been tilted to the west. Faults that cut the Tertiary rocks are mostly downthrown on the east. The Pliocene and Pleistocene Lousetown flows poured out over an erosion surface of the Coal Valley Formation and older rocks, and subsequently they were also tilted slightly west.

The Comstock fault, along which the Comstock lode was formed, trends about N. 20°E., and mine workings show that it dips about 45°E. The throw on the fault was estimated to be 1,050 m (3,450 ft) by Gianella (1936, p. 85) and 760 m (2,500 ft) by Thompson (1956, p. 66). The fault can be traced with certainty for about 6½ km (4 mi) north of Virginia City; its throw may diminish in that direction. Near Gold Hill it is intersected by the Silver City fault, which trends about N. 35°W. and also dips about 45°E. The Occidental fault, which lies about 2½ km (1½ mi) east of the Comstock fault, dips about 35°E. and has a throw of several hundred feet (Calkins, 1944). Faults in the Lousetown Formation developed later than the main displacement along the Comstock fault, but they follow the trend of the older faults.

Three holes, DDH–1, DDH–2, and DDH–3, were drilled a short distance beyond the northernmost point to which the Comstock fault can be traced with confidence. The geology in the vicinity of these drill holes is shown in greater detail in figure 3. For several kilometres north of Virginia City, the Comstock fault separates the Kate Peak Formation on the east from Alta Formation on the west, but near DDH–3 the trace of the fault is obscured by alluvium and bleached rock. A short distance north of DDH–3, the Kate Peak Formation crops out on both sides of the projected trace of the

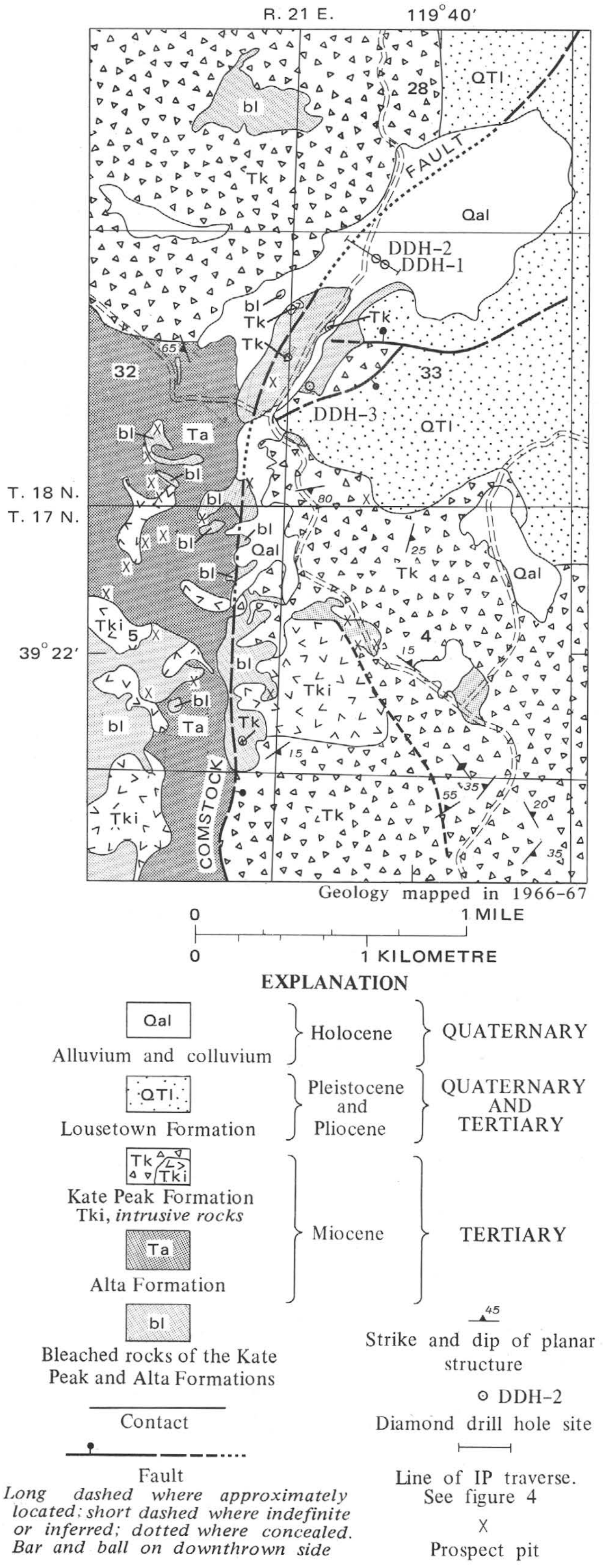


FIGURE 3.—Geologic map of area along northern extension of Comstock fault showing location of DDH–1, DDH–2, and DDH–3.

fault. The projected position of the Comstock fault is limited west of DDH–1 and DDH–2 by nearly continuous outcrops of the Kate Peak. Thompson (1956, p. 68) suggested that the Comstock fault and a fault that borders a pronounced basin in the Lousetown Formation about 1½ km (1 mi) east of DDH–1 and DDH–2 are part of the same major fault zone. Whitebread and Hoover (1968, p. 6) inferred that the Comstock fault continues to the north and possibly joins with another fault in the Lousetown northeast of DDH–1 and DDH–2. According to this interpretation, the Comstock fault would pass near the west edge of the flat alluvial-covered area around DDH–1 and DDH–2, and thus all three drill holes would be in the hanging wall of the fault.

DDH–1 and DDH–2 were drilled to confirm, if possible, the position of the Comstock fault and to explore a strong geophysical anomaly that was discovered during a series of induced-polarization (IP) traverses across the projected trace of the fault (fig. 4; Whitebread and Hoover, 1968, fig. 9). High values in percent frequency effect (PFE) associated with a zone of slightly increased resistivity were interpreted to indicate the fault zone and also to indicate sulfide mineralization. DDH–1 was inclined at an angle of 45° NW. along the line of the anomalous IP readings and was collared at station 9 of the traverse (fig. 4). DDH–1 was drilled to intersect the fault, but verification of its presence by this means was prevented when swelling clay in the lower part of the hole caused drilling to be terminated at 175 m (575 ft). DDH–2 was drilled vertically to a depth of 280 m(917 ft) and was collared 60 m (200 ft) northwest of DDH–1, at station 7 of the IP traverse. The fault was not intersected in DDH–2, and if present west of the drill hole, it must have a dip steeper than 45°.

A study of the drill cores from DDH–1 and DDH–2 indicates that the anomalous IP values shown in figure 4 approximately coincide with a zone of relatively unaltered dacite that is cut by numerous pyrite veinlets. The reliability of the IP data in delineating the Comstock fault at points along its projected trace (Whitebread and Hoover, 1968, p. 6–13) was not confirmed in the drill holes, but the close correlation of the anomalous IP values and the pyrite veinlets indicates the potential value of IP profiles in the search for sulfide ore bodies in the volcanic rocks.

DDH–3 and DDH–4 were drilled to investigate the relation of geochemical anomalies to rock alteration and possible mineralization. DDH–3 was drilled about 1 km (half a mile) southeast of DDH–2. It was collared in an outcrop of bleached rock about 45 m (150 ft) southeast of a resistant outcrop of bleached rock from which a sample containing 24 ppm (parts per million) mercury had been collected. An IP traverse across these outcrops showed a moderate PFE anomaly that correlated with

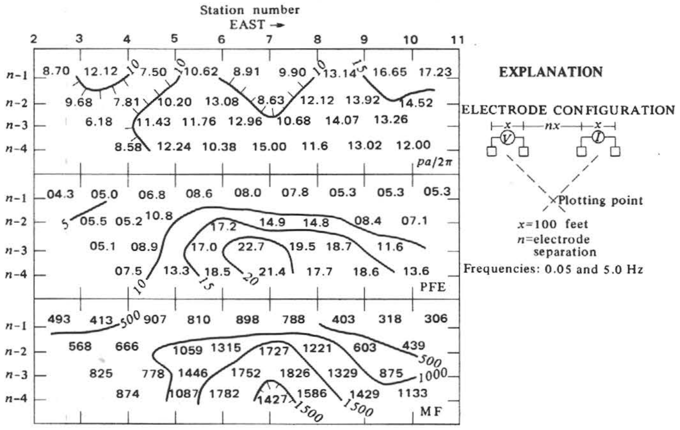


FIGURE 4.—Results of induced-polarization traverse through sites of DDH–1 and DDH–2 (Whitebread and Hoover, 1968, fig. 9). DDH–1 and DDH–2 were collared at stations 9 and 7, respectively. Apparent resistivities are computed in ohm-ft/2π ($\rho a/2\pi$), IP values in percent frequency effect (PFE), and metal factor (MF) in reciprocal ohm-ft. Line of traverse shown in figure 3.

the ledge containing the high mercury values (Whitebread and Hoover, 1968, p. 11–12). DDH–3 was drilled vertically to a depth of 322 m (1,056 ft) and penetrated mostly altered rocks of the Kate Peak Formation, with the exception of the lowermost 24 m (80 ft) that has been tentatively assigned to the Alta Formation. The large thickness of Kate Peak penetrated in the hole is best explained by a fault, here interpreted as the extension of the Comstock fault, that separates the Kate Peak from the Alta Formation to the west.

DDH–4 was located northeast of the Washington Hill prospect, about 8 km (5 mi) north of DDH–2, where anomalous mercury was found in numerous samples of bleached rock (Cornwall and others, 1967, p. B13; Whitebread and Hoover, 1968, p. 18). Figure 5 shows the distribution of bleached rocks and remnants of unaltered Kate Peak in the vicinity of the Washington Hill prospect. The hole was collared in a resistant ledge composed mainly of alunite and quartz and was drilled vertically to a depth of 259 m (850 ft).

The altered rocks penetrated by the drill holes are described in the sections under "Hydrothermal Alteration."

MINERAL DEPOSITS

COMSTOCK LODE DISTRICT

The Comstock Lode district, as defined by Calkins (1944), includes the Comstock, Silver City, and Occidental (Brunswick) lodes. The epithermal silver and gold deposits of the district have been explored over a distance of about 11 km (7 mi) in vein systems developed mainly along and adjacent to the north-trending Comstock fault and the northwest-trending Silver City fault. The vein of the Occidental lode parallels the Comstock fault about 2½ km (1½ mi) farther east. The Flowery mining district, about 5 km (3 mi) northeast of Virginia City, also is often included as part of the Comstock Lode district; gold and silver ores were mined there from a network of northeast-trending quartz veinlets. The Alta Formation is the host rock for the ore bodies in the Comstock Lode district, except those in several mines southwest of Silver City, where the veins also cut the Hartford Hill Rhyolite Tuff and Triassic metavolcanic rocks.

Placer gold was discovered in about 1850 near the mouth of Gold Canyon, which drains southeast from Gold Hill. Continued placer mining in Gold Canyon and in the upper parts of Sixmile Canyon finally led to the discovery of the rich lode deposits in 1859. Mining of the Comstock lode was most active from 1860 to 1878, and the rich ore bodies exploited during that time made the district one of the most famous in the United States. The supply of gold and silver influenced the conduct of the Civil War, and the large population attracted to the territory resulted in Nevada's early admission to statehood. Most deep mining was discontinued in 1878; since then, however, much low-grade ore has been mined from open cuts, and many dumps and tailings piles have been reworked. The ore bodies of the Silver City lode were not as spectacular as those in the Comstock lode, but mining activity has been more continuous. Placer mining has been carried on intermittently since 1850. The largest venture was conducted in the early 1920's, when deposits of gravel in Gold Canyon were worked by dredging (Vanderburg, 1936, p. 112).

Production figures compiled by Bonham (1969, p. 103–104) show that 8,256,179 ounces of gold, 192,010,565 ounces of silver, 76,630 pounds of copper, and 55,504 pounds of lead were mined from 1859 through 1957 in Storey County in the Comstock Lode district. Through 1940, the recorded production of silver and gold was $381,018,965 from the Comstock lode proper, $12,740,785 from the Silver City lode, and $3,686,248 from the Flowery district (Couch and Carpenter, 1943, p. 93–94, p. 133–136). These figures, however, do not include a considerable value of placer gold recovered. Since 1940, about $6 million in gold and silver has been produced mainly by mining low-grade ore from open pits, but mining virtually ceased after 1950. The value of production from the Occidental lode, which is not included in the above figures, was probably about $1,500,000. Smith (1943, p. 295) estimated that silver accounted for about 55 percent of the total value of ore from the Comstock lode, and gold accounted for 45 percent. According to Lincoln (1923, p. 225–227), the average value of all the ore mined in the Comstock lode from 1859 to 1921 was $31.16 per ton; however, the

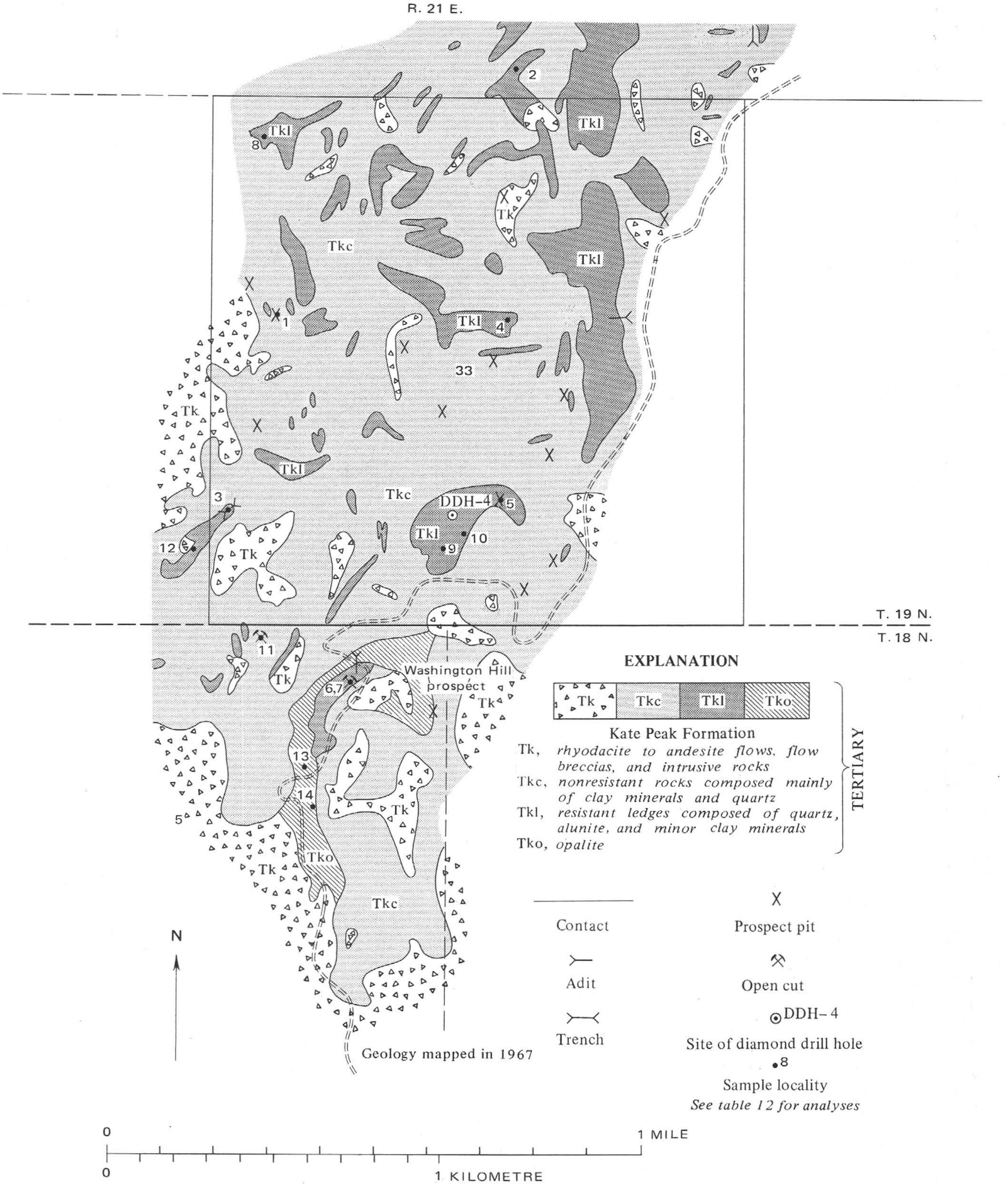


FIGURE 5.—Geologic map of Washington Hill prospect area showing distribution of bleached rocks and remnants of unaltered Kate Peak in vicinity of DDH-4.

bonanza deposits yielded an average of $42.89 per ton, and the famous Big Bonanza yielded $93.35 per ton.

Bastin (1923, p. 44–45) stated that specimens of ore from mines in the Comstock lode contain sphalerite, galena, chalcopyrite, pyrite, argentite, gold, and minor polybasite and stephanite. The gangue is dominantly quartz with some calcite. The ores had the same general character throughout their vertical range except for local supergene enrichment in which native silver replaced argentite to depths rarely exceeding 100 m (350 ft). The ore minerals noted in the Silver City lode by Gianella (1936, p. 92) are pyrite, gold, silver, electrum, some argentite, and a small amount of chalcopyrite; gangue minerals are calcite and quartz. The proportion of sulfides to gangue is lower than in the Comstock lode.

All the major ore bodies were above a depth of 600 m (2,000 ft), but many of the mines were explored to a depth of 900 m (3,000 ft) or more. Several small ore bodies were mined between the 670- and 790-m (2,200- and 2,600-ft) levels of mines near the northern end of the lode, but generally only small amounts of low-grade ore were found in the deeper workings. Becker (1882, p. 5) estimated that the total length of the mine workings on the Comstock lode in 1881 was between 290 and 306 km (180 and 190 mi).

Below a depth of about 300 m (1,000 ft), mining was made more difficult by high temperatures and large quantities of abnormally hot water that required constant pumping to prevent flooding of the lower levels. The temperature increased about 3°F for every additional 30 m (100 ft) of depth (Becker, 1882, p. 3). Temperatures in the mines commonly ranged from 100° to 125°F, and the water had temperatures as high as 170°F (Becker, 1882, p. 230). According to Becker (1882, p. 392), the temperature in the Sutro Tunnel increases geometrically as the lode is approached, and recent data from drill holes (Sass and others, 1971, p. 6394) indicate that heat flow decreases both to the north and south from a high near Virginia City. The Sutro Tunnel was driven to drain the mines and provide a better haulageway for the ore, but it did not reach the workings until 1878, after most of the ore was mined out. Moreover, the tunnel intersected the workings at a depth of about 565 m (1,850 ft), above the level of the deeper workings.

Gianella (1936, 1959) recognized that the Comstock mineralization occurred after the emplacement of the Davidson Granodiorite, but he postulated a considerable time lapse between deposition of the ore and extrusion of the Kate Peak Formation. Thompson (1956, p. 72) believed that the ore deposits are as young as the Kate Peak but older than his Truckee Formation. Age determinations from adularia collected from the Comstock and Occidental veins indicate that mineralization took place during the time spanned by deposition of the Kate Peak Formation. Adularia in quartz veins along the Comstock fault at the Comstock Coalition, Inc., opencut at Gold Hill gave a potassium-argon age of 13.7 m.y. (table 1); adularia from the Occidental vein gave an age of 12.8 m.y., which agrees closely with the age of 12.6 m.y. reported by Bonham (1969, p. 107) for adularia from the same vein. All three ages are within the time range shown for the Kate Peak Formation in table 1. The main significance of the above dates is that the Kate Peak Formation may be a possible host rock for ore deposits equivalent in age to the Comstock deposits, and thus hydrothermal alteration related to mineralization is as significant a guide to ore in the Kate Peak as in the underlying Alta Formation.

OTHER MINES

The only significant mining activity outside the Comstock Lode district has been in the Jumbo district, about 5 km (3 mi) west of Gold Hill, and at the Castle Peak mine, about 11 km (7 mi) north of Virginia City. In the Jumbo district, gold and silver were produced between 1909 and 1948 from several veins in the Alta Formation. Bonham (1969, p. 65) estimated that the total production of the district was less than $200,000. The Castle Peak mine has yielded 2,576 flasks of quicksilver from ore averaging 8.7 lb quicksilver per ton (Bailey and Phoenix, 1944, p. 184). Cinnabar, native mercury, and calomel occur in fractures and as disseminations in argillized and alunitized rocks of the Alta Formation and in small pods and veins along a north-trending fault dipping 55° E.

Although prospectors undoubtedly have examined much of the remaining parts of the Virginia City quadrangle, only the area in the vicinity of the Washington Hill prospect, about 6½ km (4 mi) north of the Castle Peak mine, appears to have attracted much interest. Cinnabar was found in the Washington Hill prospect, but only a few flasks of quicksilver were produced (Bailey and Phoenix, 1944, p. 187). The cinnabar occurs as minute disseminated crystals and in small irregular veinlets in rocks of the Kate Peak Formation that are altered to opalite and to alunite and quartz. Mercury assays of samples from the open pit, adit, and shallow trenches on the property have been published by Benson (1956, p. 17), but they were completed before the recent improvements in measurement techniques. The widespread distribution of mercury in the bleached rocks of the Washington Hill area was demonstrated by values of greater than 6 parts per million mercury found in 34 widely spaced sample localities (Whitebread and Hoover, 1968, p. 18).

Farther east in the Virginia Range, a small production of gold and silver is recorded in the Talapoosa and Ramsey mining districts. The ore in both districts occurs in altered rocks of the Kate Peak Formation (Rose, 1969, p. 25).

ROCKS

The Alta and Kate Peak Formations were regarded as the most favorable host rocks for ore deposits, and therefore most of the fieldwork was conducted in areas underlain by these two units. The descriptions below are limited to them. A more complete description of other formations is given in reports by Gianella (1936), Calkins (1944), Thompson (1956), and Thompson and White (1964).

ALTA FORMATION

The Alta Formation is most extensively exposed west and north of Virginia City, where it extends for about 16 km (10 mi) in the footwall block of the Comstock fault (fig. 2). In the hanging wall blocks of the Comstock and Silver City faults, it is exposed in a broad band that extends from about 1½ km (1 mi) north of Virginia City to about 5 km (3 mi) south of Silver City, and it is also exposed in an area of several square kilometres in the Flowery district. The Alta overlies the Hartford Hill Rhyolite Tuff and is in turn overlain by the Kate Peak Formation. In some places it probably interfingers with the Kate Peak, but at other places the two formations are separated by an unconformity (Thompson, 1956, p. 52). Flows and flow breccias make up the main part of the Alta, but in the Comstock Lode district it contains the sedimentary Sutro Member. Calkins (1944, p. 12) described four members of the Alta that have an aggregate thickness of about 825 m (2,700 ft); Gianella (1959) gave a thickness of 1,050 m (3,600 ft) for the Alta. Outside the Comstock Lode district the Alta is thinner, and members are not readily recognized. Rose (1969, p. 12) reported that the Alta is about 245 m (800 ft) thick in the Ramsey district, about 27 km (17 mi) northeast of Virginia City. Because the thickness and diversity of units decrease rapidly away from the Comstock Lode district, it seems likely that one of the volcanic centers from which the Alta was erupted was in the district, as proposed by Thompson (1956, p. 52).

The Alta generally has been classified as andesite, but chemically it ranges from andesite to rhyodacite; Thompson (1956, p. 51) found some soda trachyte on the west flank of the Virginia Range. Analyzed samples of the Alta given in table 2 are chemically dacite, rhyodacite, and trachyandesite, as determined by the classification systems of Rittmann (1952), Nockolds (1954), and O'Connor (1965); petrographically they are hornblende-pyroxene andesite and pyroxene andesite. Normative feldspar ratios of these samples and those of the Kate Peak Formation are compared in figure 6. Molecular normative quartz exceeds 10 percent in all samples, but no quartz phenocrysts are developed; thus the high silica content results from a silicic groundmass.

The Alta Formation in the Comstock Lode district has been described in detail by Gianella (1936) and Calkins (1944). The hornblende-pyroxene andesite and pyroxene andesite in the footwall of the Comstock fault north of Virginia City ranges from dark gray to shades of bluish gray or green, depending on the degree of alteration. Phenocrysts of plagioclase (calcic andesine to labradorite), hornblende, augite, and hypersthene are contained in a devitrified groundmass. Phenocrysts of plagioclase 1–3 mm long are conspicuous in all but freshly broken surfaces of the freshest rocks. The hornblende phenocrysts, mostly 3–5 mm long, typically have a dull appearance and have a reaction rim of magnetite. The small pyroxene phenocrysts are commonly altered and are almost indistinguishable from the groundmass. Apatite, magnetite, and ilmenite are accessory minerals.

South of the Castle Peak mine the uppermost Alta is composed of flow breccias and flows that weather to shades of gray, purple, and green. Because of the highly variable size and abundance of the plagioclase and hornblende phenocrysts, as well as the variable degree of alteration, these rocks are extremely difficult to distinguish from the basal Kate Peak, and the location of the contact is tenuous at some localities.

The Alta has been widely propylitized and generally is more altered than the overlying Kate Peak Formation. Because of the wide range in the intensity of propylitic alteration in the Alta, the question commonly arises whether certain fresh or very weakly altered outcrops are parts of later dikes or merely represent rocks that have escaped alteration.

The Alta was considered to be of Miocene age by Calkins (1944, p. 15) on the basis of the fossil flora, but more complete collections were dated later as Oligocene by Axelrod (1949; 1958, p. 96). A Miocene age for the Alta is now well established because the enclosing formations—the Hartford Hill Rhyolite Tuff and the Kate Peak Formation—have both been dated radiometrically as Miocene. An early or middle Miocene age for the Alta is indicated by potassium-argon dates of 14.4 m.y. (table 1) and 16.5 m.y (Silberman and McKee, 1972, p. 12). Although the single age of 14.4±0.4 m.y. shown in table 1 for the Alta must be considered somewhat tentative, its close agreement with the oldest ages obtained for the Kate Peak indicates that very little time elapsed between the deposition of the Alta and the Kate Peak.

KATE PEAK FORMATION

The Kate Peak Formation, of Miocene age, consists principally of flows, flow breccias, tuff-breccias, and intrusive rocks. Mineralogically, most of the Kate Peak is andesite, but its color, texture, and composition are

TABLE 2.—*Analyses and norms of the Alta and Kate Peak Formations*

[Sample localities are shown in fig. 2. Chemical analyses by P. L. D. Elmore, S. D. Botts, Gillison Chloe, James Kelsey, Hezekiah Smith, Lowell Artis, and J. L. Glenn: ND, not determined. Semiquantitative spectrographic analyses by Chris Heropoulos and R. E. Mays; the following elements were not detected or were below the limit of detection shown—Ag(1), As(200), Au(15), Bi(7), Cd(50), La(30), Pd(1), Pt(10), Sb(100), Sn(7), Te(1,000), U(500), W(30), Zn(100), Ce(70), Ge(7), Hf(50), In(2), Li(200), Re(15), Ta(50), Th(150), Tl(50)]

	Alta Formation				Volcanic rocks, Kate Peak Formation						Intrusive Rocks, Kate Peak Formation			
Sample No	2	11	12	13	4	5	8	14	15	16	3	7	17	18
Field No	6–144	6–154	6–156A	112–1	5–267B	5–61A	99–157	97–98	99–10	99–153	6–75	96–159	112–84	5–262
Chemical analyses (weight percent)														
SiO_2	56.7	59.2	55.3	57.0	61.9	59.7	59.0	60.7	61.0	60.7	61.8	62.4	60.5	61.7
Al_2O_3	17.5	17.0	16.1	17.5	17.0	17.2	17.0	16.6	17.0	16.7	16.5	16.6	17.0	16.4
Fe_2O_3	7.0	2.9	2.8	3.5	3.7	3.9	4.5	3.0	4.4	3.3	.82	4.2	2.7	3.5
FeO	.28	2.7	3.2	3.2	1.2	1.8	1.6	2.4	1.4	2.2	3.8	.92	2.6	1.4
MgO	3.7	3.1	3.6	3.2	2.4	3.0	3.0	2.7	2.0	3.0	2.3	2.1	3.0	2.9
CaO	6.6	4.3	8.8	6.8	4.8	5.7	5.6	5.4	5.0	5.5	4.3	4.8	6.0	5.0
Na_2O	3.4	4.3	2.8	3.3	3.6	3.5	3.3	3.2	3.5	3.6	3.4	3.9	3.7	3.4
K_2O	1.8	2.5	1.7	1.2	2.6	1.3	2.4	2.9	2.5	2.5	2.5	2.2	2.1	2.3
H_2O^+	1.0	1.9	1.3	1.6	1.3	1.8	1.4	1.4	.90	1.2	1.8	.74	1.1	1.6
H_2O^-	.46	.60	.36	.99	.72	1.1	.89	.35	1.1	.14	1.8	.66	.28	.67
TiO_2	.78	.68	.68	.71	.54	.66	.84	.74	.72	.72	.51	.70	.68	.54
P_2O_5	.20	.23	.18	.21	.17	.18	.25	.19	.22	.21	.16	.26	.20	.19
MnO	.14	.14	.09	.16	.11	.10	.07	.15	.10	.12	.09	.08	.12	.11
CO_2	.51	.22	2.7	.42	<.05	<.05	.05	<.05	.05	.05	<.05	<.05	<.05	.32
Total (rounded)	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Bulk density	ND	ND	2.69	2.68	ND	ND	2.46	2.62	2.60	ND	ND	2.40	2.63	ND
Powder density	2.68	2.64	2.76	2.70	2.58	2.58	2.68	2.68	2.68	2.60	2.56	2.68	2.68	2.60
CIPW norms														
Q	12.6	11.4	15.1	14.9	17.8	18.4	15.4	16.3	18.4	15.3	18.1	19.0	14.5	19.6
C	----	.5	.3	----	----	.1	----	----	.1	----	.8	----	----	.4
Or	10.7	14.9	10.1	7.2	15.5	7.8	14.3	17.2	15.0	14.8	15.1	13.1	12.4	13.7
Ab	28.9	36.7	23.9	28.3	30.7	30.0	28.2	27.2	30.0	30.5	29.4	33.4	31.4	29.0
An	27.3	18.6	25.6	29.8	22.7	27.4	24.7	22.5	23.3	22.1	20.7	21.5	23.6	21.7
Wo	----	----	----	.1	.1	----	.6	1.3	----	1.5	----	.3	2.0	----
En	9.3	7.8	9.0	8.1	6.0	7.6	7.5	6.8	5.0	7.5	5.8	5.3	7.5	7.3
Fs	----	1.7	2.6	2.1	----	----	----	1.0	----	.3	5.7	----	1.6	----
Mt	----	4.2	4.1	5.1	2.7	4.3	3.0	4.4	2.8	4.8	1.2	1.2	3.9	3.3
Hm	7.0	----	----	----	1.9	1.0	2.5	----	2.5	----	----	3.4	----	1.2
Il	.9	1.3	1.3	1.4	1.0	1.3	1.6	1.4	1.4	1.4	1.0	1.3	1.3	1.0
Tn	.7													
Ru	.01	----	----	----	----	----	----	----	----	----	----	----	----	----
Ap	.5	.5	.4	.5	.4	.4	.6	.5	.5	.5	.4	.6	.5	.5
Cc	1.2	.5	6.2	1.0	----	----	.1	----	.1	.1	----	----	----	.7
Total (rounded)	99	98	99	99	99	98	99	99	99	99	98	99	99	98
Semiquantitative spectrographic analyses (parts per million)														
B	<7	<7	<7	<7	30	<7	30	30	15	30	<7	10	20	<7
Ba	700	700	1,000	1,000	1,000	700	1,000	1,000	700	700	700	1,000	1,000	700
Be	<1	<1	<1	<1	<1	<1	<1	<1	2	<1	<1	<1	1	<1
Co	30	20	20	30	15	15	20	20	30	20	15	20	30	15
Cr	30	20	30	15	30	7	70	50	10	20	10	50	100	30
Cu	50	70	70	100	30	30	30	50	50	30	30	50	50	30
Mo	<2	<2	3	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Nb	<7	<7	7	7	<7	<7	7	7	<7	<7	<7	7	<7	<7
Ni	30	30	70	20	20	7	30	20	15	15	7	70	50	20
Pb	20	20	20	20	20	20	20	20	10	20	20	15	15	20
Sc	20	10	30	15	10	15	20	20	15	15	10	15	15	10
Sr	500	700	100	1,000	700	700	1,000	1,000	1,000	700	500	1,000	1,000	700
V	200	150	150	150	100	150	200	200	150	150	100	150	150	100
Y	20	20	20	20	15	15	50	20	30	20	15	15	15	15
Zr	100	100	100	100	100	100	150	150	150	100	100	100	100	100
Ga	20	20	15	20	20	20	20	20	15	20	20	15	15	20
Yb	3	3	2	2	2	2	7	2	3	3	2	1.5	1.5	2

quite varied. Samples collected by Thompson and White (1964, p. 6–7) throughout a large area in the Virginia City and Mount Rose quadrangles have chemical compositions that range from andesite to rhyodacite, except for a rhyolite vitrophyre unit that is of relatively small extent. Samples of the Kate Peak analyzed during the current project (tables 2, 4) are chemically dacite and rhyodacite. Figure 6 shows the normative feldspar ratios of these samples plotted in the fields defined by O'Connor (1965). Modal analyses of typical samples of the Kate Peak from the four drill holes are shown in table 3.

North of Virginia City, extensive exposures of the Kate Peak Formation east of the Comstock fault are porous to dense, gray to pale-red dacite and rhyodacite with conspicuous phenocrysts of plagioclase. Hornblende occurs in all specimens and is more abundant than either biotite or pyroxene. All three minerals are found in many samples.

In hand specimens, the prominent plagioclase phenocrysts commonly are 5 mm long or more, but in thin sections a complete range in size down to microlites is commonly seen, imparting a seriate texture to the rock. The phenocrysts show well-developed zoning and

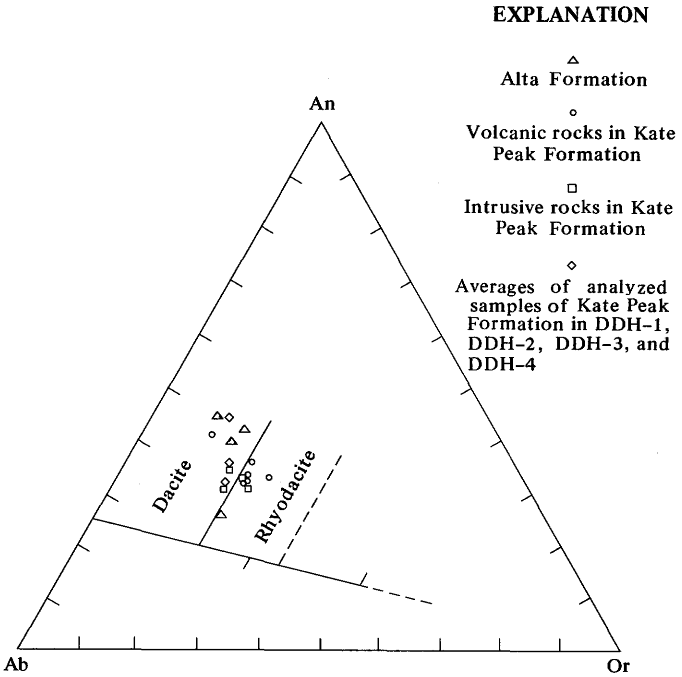


FIGURE 6.—Molecular normative feldspar ratios from samples of the Alta and Kate Peak Formations. Field boundaries are based on classification of O'Connor (1965).

range from andesine to labradorite. Within any particular sample some plagioclase phenocrysts may show selective alteration of one or more zones to clay, and a few may be completely altered. Much of the hornblende, which is commonly oxyhornblende, has a resorption rim of magnetite, and in some specimens it is almost completely replaced by magnetite, plagioclase, pyroxene, and material too fine grained to identify. Small brown and green prisms of augite and hypersthene are more widespread and generally more abundant than biotite. The hypersthene is commonly completely altered to antigorite, and the augite is partly altered. Biotite, where present, occurs as prominent hexagonal crystals or as small grains. Very sparse, deeply embayed phenocrysts of quartz are found in a few specimens. The chief accessory minerals are magnetite, ilmenite, and apatite. The magnetite and ilmenite occur as accessory grains and as fine disseminations through the groundmass. The apatite occurs both as small colorless crystals and larger brownish crystals. The groundmass is microcrystalline to granular. Much of the silica of the rock is contained in the groundmass, probably as quartz, cristobalite, or amorphous silica. The groundmass is especially susceptible to alteration, and a splotchy pattern seen in thin section indicates partial alteration to allophane or montmorillonite.

The dense dark-gray dacites and rhyodacites in the vicinity of the Washington Hill prospect are younger than the rocks described above. They are composed of zoned plagioclase (calcic andesine to labradorite), augite, hypersthene, and minor basaltic hornblende in a dark-brown glassy groundmass. The pyroxene phenocrysts make up about 10 percent of the rock, whereas hornblende makes up only about 1–2 percent. Scattered small biotite crystals are found in some flows.

The intrusive bodies of the Kate Peak are very similar petrographically and chemically to the flows and are locally indistinguishable from them. They are best identified by their contact relations, but large plagioclase phenocrysts and well-developed biotite commonly suggest their presence. Columnar jointing is characteristic of some of the intrusive bodies in the Comstock Lode district (Coats, 1936, p. 71), and it readily distinguishes the intrusive rocks from the surrounding Alta Formation 5 km (3 mi) west of Virginia City (fig. 2).

The Kate Peak Formation and rocks of similar age and composition were erupted from many vents over a large area of western Nevada and eastern California (Thompson and White, 1964; Bonham, 1969). Many of the intrusive bodies in the Kate Peak probably were feeders, and several dikes containing breccia similar to the extrusive breccias also were interpreted as probable feeders by Thompson (1956, p. 55).

A middle Miocene age for the Kate Peak is shown by potassium-argon ages that range from 14.9 m.y. to 12.3 m.y. (table 1).

TABLE 3.—*Modal analyses (volume percent) of unaltered rock of the Kate Peak Formation from DDH-1 to DDH-4*

[Sample numbers indicate drill hole and depth in feet]

Sample No.	1–96	1–256	1–411	1–463	2–129	2–209	2–293	3–339	4–84	4–679
Groundmass	61.1	54.9	68.4	64.5	54.8	53.2	50.8	53.0	53.5	59.9
Plagioclase	28.8	31.3	22.5	23.4	31.8	32.2	33.6	34.0	32.4	25.7
Hornblende	3.3	6.2	3.2	5.1	7.8	8.3	6.9	3.7	.8	1.7
Pyroxene	4.2	4.3	3.8	3.8	3.7	4.2	6.1	6.3	11.2	9.5
Magnetite or ilmenite	2.5	3.0	2.1	2.9	1.7	1.7	2.5	2.8	2.1	3.1
Apatite	.1	.3	----	.1	.2	.4	.1	.2	----	.1
Quartz	----	----	----	.2	----	----	----	----	----	----
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

HYDROTHERMAL ALTERATION

The altered rocks in the Virginia City quadrangle previously were divided into two main types: propylitized and bleached. The bleached rocks are generally confined to the oxidized zone; they form by supergene alteration of pyrite-bearing altered rocks. In surface exposures, therefore, propylitized or other hydrothermally altered rocks that contain disseminated pyrite are converted to bleached rocks. Distinguishing features of earlier hydrothermal alteration are largely obscured in the bleached rocks, but drill cores show that altered rocks below the oxidized zone are propylitized, argillized, and alunitized. The composition and geochemistry of these hydrothermally altered rocks is described before further consideration of the bleached rocks.

Subdivision of the hydrothermally altered rocks is based upon the various assemblages of alteration minerals developed. Characteristic minerals resulting from decomposition of silicates during hydrothermal alteration are chlorite, calcite, and montmorillonite in the propylitic zone; montmorillonite, mixed-layer illite-montmorillonite, and kaolinite in the argillic zone; and alunite and jarosite in the alunitic zone. Quartz and pyrite are components of nearly all the assemblages.

The lithology and alteration pattern in DDH–1 and DDH–2 are shown in the columnar section in figure 7. The alteration pattern is simple and represents a weak argillic alteration characterized by montmorillonite and cristobalite, commonly accompanied by pyrite and zeolites. In DDH–3 and DDH–4, however, a variety of alteration minerals formed, and the alteration pattern generally reveals a zonal arrangement with an inner alunitic zone, an intermediate argillic zone, and an outer propylitic zone (fig. 8). Detailed sections showing the distribution of mineral assemblages within the individual zones are included on plate 1. The propylitic zone is subdivided into a weakly altered chlorite-montmorillonite-calcite-quartz assemblage and the more thoroughly altered montmorillonite-chlorite-calcite-quartz-pyrite and montmorillonite-calcite-quartz-pyrite assemblages; the argillic zone contains the illite-montmorillonite (mixed layer)-quartz-pyrite and kaolinite-quartz-pyrite assemblages; and the alunitic zone contains the alunite-quartz-pyrite and alunite-jarosite-quartz assemblages. The boundaries of the various assemblages are gradational in many places and are commonly defined arbitrarily.

The zonal arrangement from the most intensely altered rock in the alunitic zone outward to slightly altered rock in the propylitic zone represents the simultaneous reactions of the wallrock to changes of temperature and composition of the hydrothermal fluids outward from faults or fractures that were the main channelways. Similar zonal patterns have been described in numerous mining districts, including Goldfield, Nev. (Harvey and Vitaliano, 1964), Summitville, Colo. (Steven and Ratté, 1960, Cochiti, N. Mex. (Bundy, 1958), and Cerro de Pasco, Peru (Graton and Bowditch, 1936).

More complete descriptions of the mineral assemblages in the propylitic, argillic, and alunitic zones are given in the following sections. It should be recognized that the assemblages described apply only to the rocks in the immediate vicinity of the drill holes; some other assemblages characterized by epidote and albite, zeolites, or pyrophyllite are developed elsewhere.

PROPYLITIC ZONE

Becker (1882, p. 81–90) first recognized that volcanic rocks in the Comstock Lode district previously called propylites were merely altered andesites. (Coats (1940) studied the rocks originally described as propylites, and on this basis he defined propylitization as the alteration of andesite characterized by epidote and albite replacing plagioclase, and chlorite, calcite, and epidote replacing ferromagnesian minerals. Wilshire (1957, p. 244) described propylitization as the alteration of any rock by a process, unattended by strong deformation, that produces in andesites some combination of epidote, albite, chlorite, and calcite. In this report, a similar but less restrictive definition was followed in order to accommodate the weakly propylitized rocks. Meyer and Hemley (1967, p. 175) listed sericite, pyrite, iron oxides, zeolites, and montmorillonite in addition to the above minerals as part of the assemblage of minerals that may be found in propylitized rocks.

Gianella (1936), Coats (1940), and Calkins (1944) described the highly propylitized rocks of the Alta Formation in the vicinity of the Comstock and Silver City lodes. These dull-green or greenish-gray rocks typically contain chlorite, calcite, epidote, and albite. Less intensely propylitized rocks of the Alta and Kate Peak Formations north of Virginia City are partly altered to chlorite, montmorillonite, calcite, quartz, minor epidote and albite, and local zeolites. Thompson and White (1964, p. A28) found abundant zeolites in propylitized rocks of the Alta Formation from a drill hole near the top of the Geiger Grade. The Kate Peak Formation generally is less propylitized than the Alta Formation.

The propylitized rocks penetrated in DDH–3 and DDH–4 are subdivided into a chlorite-montmorillonite-calcite-quartz assemblage, a montmorillonite-chlorite-calcite-quartz-pyrite assemblage, and a montmorillonite-calcite-quartz-pyrite assemblage (pl. 1). These assemblages are generally lacking in epidote

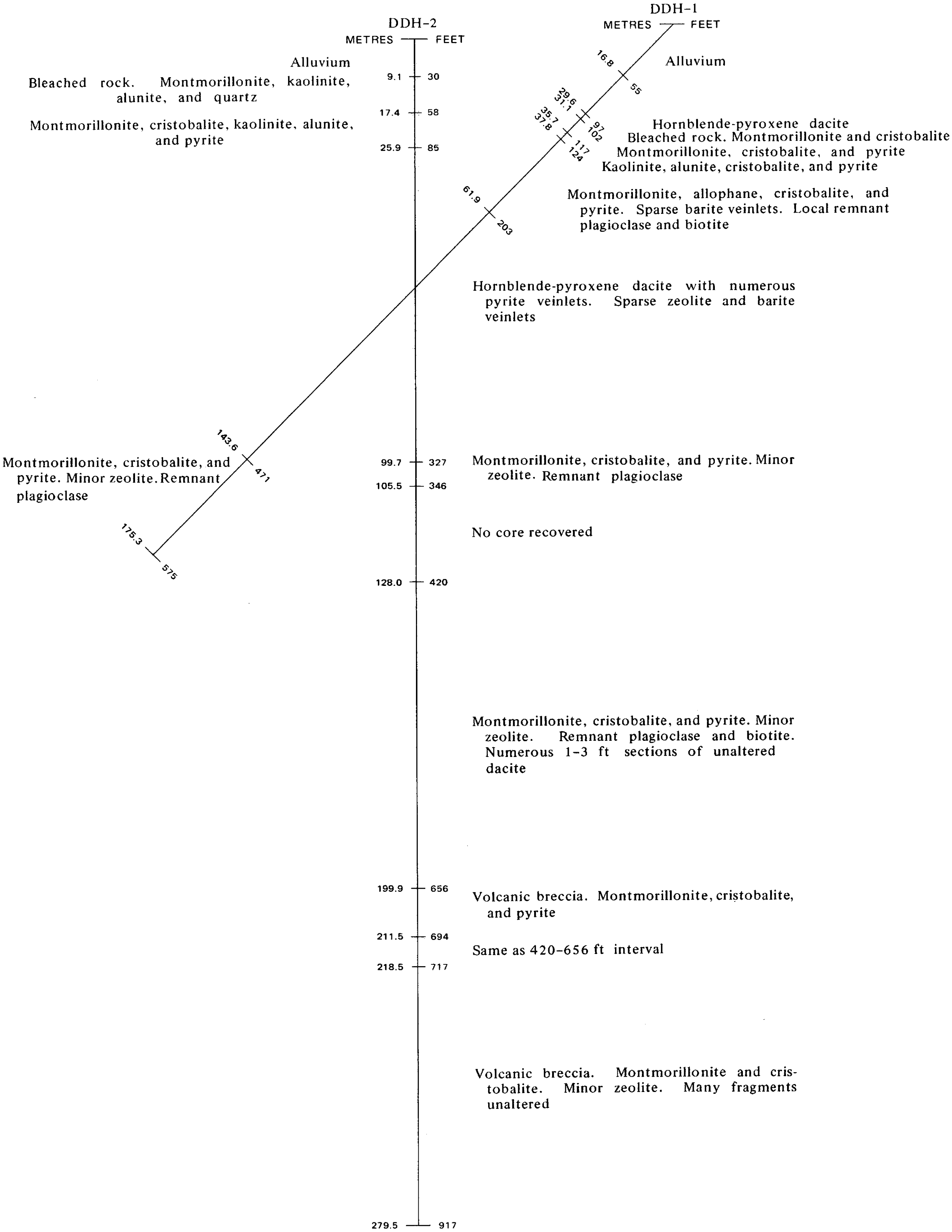


FIGURE 7.—Section through DDH-1 and DDH-2 showing alteration mineral assemblages in the Kate Peak Formation.

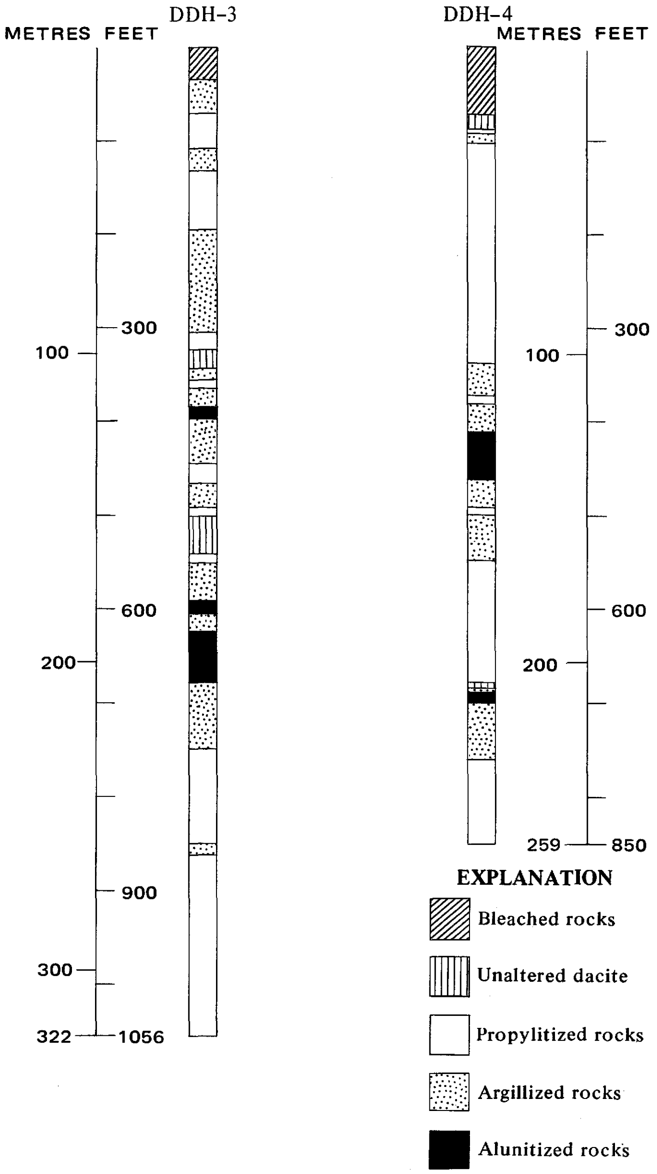


FIGURE 8.—Columnar sections of DDH–3 and DDH–4 showing zonal patterns of propylitic, argillic, and alunitic alteration.

and albite, which characterize many propylitized rocks, but X-ray diffraction patterns of a variety of propylitized rocks indicate that montmorillonite is more common than previously indicated. The propylitized rocks grade into argillized rocks, and where they are indistinguishable because of the extensive development of montmorillonite, the presence of calcite was used to distinguish the propylitic zones from argillic zones.

CHLORITE-MONTMORILLONITE-CALCITE-QUARTZ ASSEMBLAGE

The weakly propylitized rocks of the chlorite-montmorillonite-calcite-quartz assemblage are gradational into virtually unaltered Kate Peak dacite and into more altered rocks of the montmorillonite-chlorite-calcite-quartz-pyrite assemblage. They more closely resemble the unaltered rocks, for they are characterized by a medium-dark-gray to greenish-gray groundmass, plagioclase phenocrysts that are only little altered, and little or no disseminated pyrite. The groundmass is microcrystalline and is partly altered to calcite, chlorite, quartz, and montmorillonite. Some plagioclase, especially the microlites and smaller phenocrysts, is partly altered to calcite or montmorillonite and locally to epidote or albite. Relict hornblende can be found in some of the less altered rocks, and outlines of the phenocrysts are rimmed by magnetite. The hornblende is altered to chlorite, calcite, montmorillonite, quartz, and disseminated opaque material. Magnetite and ilmenite remain as accessory grains and as minute disseminations in the groundmass.

MONTMORILLONITE-CHLORITE-CALCITE-QUARTZ-PYRITE ASSEMBLAGE

About 40 percent of the rocks in DDH–4 and 10 percent of those in DDH–3 are altered to the montmorillonite-chlorite-calcite-quartz-pyrite assemblage. Although this assemblage differs from the chlorite-montmorillonite-calcite-quartz assemblage by the presence of pyrite, it is distinguished chiefly by the larger amount of montmorillonite. Boundaries are not precise in many places because of gradational contacts. Because of extensive alteration to montmorillonite, the rocks of the montmorillonite-chlorite-calcite-quartz-pyrite assemblage are generally softer, and they have a greenish-gray, yellowish-gray, or very light gray groundmass that resembles the mixed-layer clay rocks of the argillic zone. With increasing alteration, the original pilotaxitic or seriate texture is obliterated, as the microlites and small phenocrysts of plagioclase become indistinguishable from the groundmass. As in the chlorite-montmorillonite-calcite-quartz assemblage, the small plagioclase phenocrysts are altered to montmorillonite, whereas the larger phenocrysts may contain calcite, montmorillonite, and local small amounts of albite, epidote, or chlorite. Altered phenocrysts of hornblende are accentuated by a rim of pyrite that has replaced the earlier magnetite. Pyrite also replaces the minute disseminated grains of magnetite in the groundmass. The altered pyroxene phenocrysts are rarely distinguishable from the groundmass. Biotite is more resistant to alteration, but it is commonly altered to reddish-brown to colorless mica. Leucoxene locally replaces ilmenite and persists in the argillic and alunitic groups. Apatite is unaltered and is a common accessory mineral.

MONTMORILLONITE-CALCITE-QUARTZ-PYRITE ASSEMBLAGE

The montmorillonite-calcite-quartz-pyrite assemblage most commonly occurs between the montmorillonite-chlorite-calcite-quartz-pyrite assemblage and the illite-montmorillonite (mixed layer)- quartz-pyrite assemblage of the argillic group and is gradational into both. The assemblage is well developed only in DDH–3, where it occurs in zones as much as 18 m (60 ft) thick. In DDH–4 a narrow zone extending from 114 to 116 m (373–381 ft) that contains the iron carbonate siderite has been included in this assemblage. The soft clay-rich rocks are very similar in appearance to parts of the mixed-layer illite-montmorillonite rocks in the argillic zone, and they were differentiated during initial logging of the core by the presence of calcite in the altered plagioclase phenocrysts. X-ray diffraction patterns later indicated the difference in content of clay minerals. The X-ray studies show that the position of the (001) montmorillonite peak ranges from about 14.5 to 15 A; it expands to 17 A after treatment with ethylene glycol.

The porphyritic texture of the rock is preserved, although the phenocrystic minerals are entirely altered except for some plagioclase. White spots composed of montmorillonite and calcite represent original plagioclase, and hornblende is seen locally as prisms of yellowish-gray montmorillonite with scattered pyrite and leucoxene. In most places, however, the ferromagnesian minerals cannot be distinguished readily from the groundmass. Sparse small flakes of biotite are altered to quartz and montmorillonite. The pyrite is present as finely disseminated grains.

An argument might be advanced that the montmorillonite-chlorite-calcite-quartz-pyrite and, especially, the montmorillonite-calcite-quartz-pyrite assemblages should be included in the argillic group because of their pervasive alteration to montmorillonite. Certainly the appearance of these soft, crumbly rocks would weigh heavily towards their classification as argillic. Chlorite and calcite are widely associated with propylitized rocks, although chlorite is stable in some argillic assemblages (Creasey, 1966, p. 60), and calcite may be a minor constituent where albite is developed. Argillic alteration, however, is distinguished by the absence of carbonate minerals. In final analysis, the two assemblages are gradational between the propylitic and argillic zones, but they were included in the propylitic group because they contain calcite.

ARGILLIC ZONE

The argillic zone includes the montmorillonite-cristobalite-pyrite assemblage of DDH–1 and DDH–2 and the illite-montmorillonite (mixed layer)-quartz-pyrite and kaolinite-quartz-pyrite assemblages of DDH–3 and DDH–4.

MONTMORILLONITE-CRISTOBALITE-PYRITE ASSEMBLAGE

The most common assemblage of alteration minerals in DDH–1 and DDH–2 is montmorillonite-cristobalite-pyrite; zeolites also are present in many places. Pyrite, which is finely disseminated through most of the altered rock, is not present in the lower part of DDH–2. The rocks within the montmorillonite-cristobalite-pyrite zones show varying degrees of alteration and hardness. Numerous 0.3- to 1-m (1- to 3-ft) sections of nearly unaltered dacite occur between 128 and 200 m (420 and 656 ft) in DDH–2 (fig. 7), but elsewhere much of the core relatively rich in montmorillonite was plastic when removed from the core barrel, and it became soft and crumbly after drying. The soft plastic rock presents problems during drilling, as the walls tend to swell shut. Drilling was stopped at 175 m (575 ft) in DDH–1 because of the swelling clay, and no core was recovered in similar material from 105 to 128 m (346–420 ft) in DDH–2.

The montmorillonite gives a basal X-ray spacing of 14.7–15.4 A, which indicates the calcium- or magnesium-rich variety (Weaver, 1958, p. 268). It expands to 17 A when treated with ethylene glycol vapor and collapses to about 9.8 A when heated to 400°C.

Plagioclase and biotite are the only phenocrystic minerals that have survived the pervasive montmorillonite alteration, but the porphyritic texture is preserved in even the most altered rocks of DDH–1 and DDH–2. Some large plagioclase phenocrysts are unaffected by alteration, but most others are completely altered. Some sparse biotite grains are virtually unaltered, but others are converted to white mica. Hornblende is altered to montmorillonite or allophane with scattered pyrite and leucoxene, and the prismatic outlines of the altered phenocrysts commonly are well defined by pyrite that replaced the iron-rich reaction rims. The small phenocrysts of pyroxene also are altered to clay and commonly are indistinguishable from the groundmass. Heulandite or clinoptilolite is locally developed in the groundmass and along small fractures. Pyrite and minor leucoxene are disseminated through the groundmass and also replace larger accessory grains of magnetite-ilmenite.

A slightly weaker alteration without the accompanying pyrite is confined to the volcanic breccia unit in DDH–2 that extends from 219 m (717 ft) to the bottom of the hole at 279 m (917 ft). The breccia unit contains angular to subangular fragments of Kate Peak dacite in a light-olive-gray matrix. In some fragments the degree of alteration equals that of the matrix, but other fragments are fresh. Commonly only the groundmass of the matrix has been altered, and so fresh hornblende and pyroxene remain in both the matrix and fragments. The groundmass is composed of montmorillonite and cristobalite and possibly has some amorphous clays and silica. The montmorillonite in this zone gives the same X-ray diffraction patterns as that in the montmorillonite-cristobalite-pyrite zone.

Allophane is developed in the upper part of the montmorillonite-cristobalite-pyrite assemblage extending from 38 to 62 m (124 to 203 ft) in DDH–1. Inconclusive X-ray diffraction patterns of samples from the upper part of the interval suggest that small amounts of undetermined clays may be present. The rock grades from light gray in the soft upper part of the interval to medium dark gray below, but casual inspection of the rock does not reveal the extent of the alteration. Thin sections observed in plain light show much detailed structure preserved in the groundmass, but as viewed with crossed nicols, the groundmass is composed of intergrown isotropic clay, finely crystalline clay, cristobalite, and possibly some amorphous silica.

The altered rocks in DDH–1 and DDH–2 are similar megascopically to rocks in parts of the propylitic and argillic zones in DDH–3 and DDH–4, and they are also similar mineralogically except that they contain cristobalite instead of quartz. As quartz is an alteration product in all the altered rocks in DDH–3 and DDH–4, in bleached rocks, and in many outcrops of propylitized rocks and is the stable form of silica in these rocks, the section penetrated by DDH–1 and DDH–2 is atypical and apparently represents an unstable phase of only local extent. The relation of the cristobalite to the argillic alteration is not certain. Hemley and Jones (1964, p. 550) and Hemley, Meyer, and Richter (1961, p. D339) noted that cristobalite forms more readily than quartz in lower temperature reactions involving the alteration of feldspars to montmorillonite. D. E. White (written commun., 1974), however, suggested that the cristobalite in this assemblage may have crystallized from early relatively high temperature devitrification of the high-silica groundmass.

ILLITE-MONTMORILLONITE (MIXED LAYER)-QUARTZ-PYRITE ASSEMBLAGE

The rocks containing the illite-montmorillonite (mixed layer)-quartz-pyrite assemblage occur in intervals from about 0.3 to 15 m (1–50 ft) thick in DDH–3 and DDH–4. The description of nearly all these rocks is based on megascopic examination and X-ray diffraction patterns because the rocks are so soft and rich in clay that they are not suitable for thin sections; much of the drill core is plastic when first brought to the surface, and after drying, it tends to crumble. The altered rock is very light gray with numerous white spots of clay that represent original plagioclase phenocrysts. The ferromagnesian minerals are mostly obliterated; some can be recognized, however, as patches of yellowish-gray clay and leucoxene, and others are outlined by rims of pyrite. The pyrite is mostly finely disseminated through the rock; it formed by sulfidization of the iron from magnetite and ilmenite and the iron freed by alteration of other minerals. Heavy-mineral separates show that rutile and anatase are accessory minerals.

Mixed-layer illite-montmorillonite is the most common clay developed, but montmorillonite, illite, kaolinite, mixed-layer montmorillonite- chlorite, and chlorite also occur with the illite-montmorillonite, especially in the gradational boundaries with other alteration zones. In most places, the illite and montmorillonite are combined in regular mixed layers that give a (001) peak at 24–30 A. The diffraction patterns obtained are very similar to those described by Heystek (1954). Comparison of the X-ray diffraction patterns with data from Weaver (1956), MacEwan, Amil, and Brown (1961), and Hower and Mowatt (1966, p. 830) showing migration of peak positions for interstratified clays indicates that the mixed-layer clay is composed of about 70 percent illite and 30 percent montmorillonite. The clay in the altered plagioclase has the same mixed-layer character as that in the remainder of the rock, and altered hornblende also contains mixed-layer illite-montmorillonite of about the same ratio as that in the whole rock.

KAOLINITE-QUARTZ-PYRITE ASSEMBLAGE

The kaolinite-quartz-pyrite assemblage in DDH–3 and DDH–4 generally forms an envelope around alunitized rocks. The kaolinitic envelopes range in thickness from about 1.5 to 6 m (5–20 ft). No inner alunitic zones were penetrated in the intervals from 36 to 38 m (117–125 ft) and 61 to 91 m (199–300 ft) in DDH–3, but they may be adjacent to the drill hole at those depths.

No systematic attempt was made to distinguish individual members of the kaolinite group of clay minerals, and throughout this report the term kaolinite is used as a group name. X-ray diffractograms indicate, however, that kaolinite is present at depths less than 38 m (125 ft) in DDH–3 and that dickite occurs at greater depths in DDH–3 and from 141 to 143 m (461–470 ft) in DDH–4.

The light-gray to very light gray rocks of the kaolinite-quartz-pyrite assemblage are generally slightly harder than the adjacent rocks containing mixed-layer clays. The groundmass and phenocrysts of the rock are completely altered to kaolinite and quartz. The original porphyritic texture is vaguely discernible because of the concentration of light-colored kaolinite replacing the plagioclase phenocrysts. The ferromagnesian minerals are altered to clay with dispersed leucoxene. Pyrite is finely disseminated throughout the rock and replaces the earlier magnetite; in some places it is concentrated as a border around the altered hornblende phenocrysts, and locally it occurs in minute irregular veinlets. Leucoxene or rutile has replaced ilmenite, and anatase is a minor accessory mineral.

ALUNITIC ZONE

The alunitic zone, which contains the alunite-quartz-pyrite and alunite-jarosite-quartz assemblages, is the most intensely altered zone in the drill holes. The alunite-quartz-pyrite assemblage is well developed in DDH–3 in several intervals ranging from 4 to 16 m (12–54 ft) thick and in a single thin interval in the lower part of DDH–4. The alunite-jarosite-quartz assemblage was found only in DDH–4. It is best developed in an interval extending from a depth of 125 to 141 m (411–461 ft), but it also was recognized in the oxidized zone. Alunite also occurs with montmorillonite, kaolinite, cristobalite, and pyrite at shallow depths in DDH–1 and DDH–2. The alunitic zones are bordered by rocks having the kaolinite-quartz-pyrite assemblage except in the thin alunitic zone at about 210 m (690 ft) in DDH–4. The alunitized rocks are generally harder than the enclosing argillized rocks, and in surface exposures they form resistant ledges.

ALUNITE-QUARTZ-PYRITE ASSEMBLAGE

The alunite-quartz-pyrite rocks are light gray to very light gray. The porphyritic texture of the original rock is obvious where the altered plagioclase phenocrysts are discernible, but it is obliterated where the rock is porous or highly siliceous. As seen in thin section, the plagioclase is replaced by alunite which commonly is coarser grained than the alunite in the matrix. The original ferromagnesian minerals cannot be distinguished except where altered phenocrysts are marked by a concentration of leucoxene and pyrite. The matrix is a microcrystalline mosaic of quartz with widely variable amounts of alunite. Most of the quartz grains range in size from 0.005 to 0.02 mm, but patches composed of coarser grains as much as 0.05 mm are common; the minute laths of alunite are mostly less than 0.02 mm long. Former grains of accessory magnetite-ilmenite are replaced by leucoxene or rutile, and the liberated iron commonly occurs in an outer rim of pyrite. Pyrite is most abundant, however, as finely disseminated grains, many of which replace magnetite in the groundmass. In a few places the rock is cut by narrow irregular veinlets or alunite or quartz.

A narrow interval of vaguely banded porous rock at a depth of 209 m (684–686 ft) in DDH–4 superficially resembles the highly silicified parts of the ledges seen on the surface. It is composed of microcrystalline quartz with finely disseminated pyrite. Plagioclase phenocrysts have been replaced by a mosaic of quartz grains distinctly smaller than those in the remaining parts of the rock.

Alunite with compositions approaching both the potassium- and sodium-bearing end members of the alunite-natroalunite isomorphous series is present in the alunite-quartz pyrite assemblage. The composition of the alunite was estimated by comparison of the X-ray diffraction patterns with data from Parker (1962, p. 131). Nearly all the X-ray diffraction patterns indicate the coexistence of members with an approximate K_{65-70} to Na_{30-35} ratio and members with an approximate K_{20-30} to Na_{70-80} ratio. Parker (1962, p. 136) reported similar mixtures of alunite and natroalunite in two samples from Marysvale, Utah.

A hypogene origin for the alunite is supported by sulfur isotope analyses of alunite of similar occurrence in the Goldfield district. There the alunite that replaces the plagioclase phenocrysts and that is scattered through the groundmass of altered volcanic rocks is primary (Jensen and others, 1971, p. 619).

ALUNITE-JAROSITE-QUARTZ ASSEMBLAGE

The grayish-yellow alunite-jarosite-quartz rock typically is finely granular and appears to be more siliceous than alunite-quartz-pyrite rock. In the interval from 125 to 141 m (411–461 ft) in DDH–4, the rock is locally quite porous and contains numerous small vugs suggestive of thorough leaching. The original porphyritic texture has been destroyed, but in thin section some traces of phenocrysts can be detected. Jarosite and lesser alunite are concentrated in altered phenocrysts of the ferromagnesian minerals, and vague outlines within which alunite is more abundant represent altered plagioclase. The matrix is a very fine grained mosaic of quartz with varying amounts of alunite and jarosite. The colorless alunite occurs as laths 0.05 mm or less in length. A composition nearer alunite than natroalunite is indicated by X-ray patterns from which a K_{65-75} to Na_{25-35} ratio is computed. The yellow to greenish-yellow jarosite occurs in fine-grained aggregates and subhedral grains 0.01–0.02 mm long. The alunite and jarosite are intimately intergrown and show no apparent tendency to form a solid solution series as described by Brophy, Scott, and Snellgrove (1962). Leucoxene replaces ilmenite or titaniferous magnetite, and anatase and diaspore are visible under high magnification.

Unlike the alunite-quartz-pyrite assemblage, the jarosite-bearing rocks do not contain pyrite. The jarosite is believed to be hypogene, although it has been described more commonly as a supergene mineral that develops from the alteration of pyrite. Jarosite forms in an acid environment with moderately oxidizing Eh (oxidation-reduction potential) values greater than the Eh values for pyrite (Brown, 1971, p. 250). Hypogene jarosite occurring with alunite also has been found in the Goldfield district, Nevada (Ashley and Keith, 1973).

CHEMICAL CHANGES DURING HYDROTHERMAL ALTERATION

Analyses of samples representative of the different zones of alteration show a progressive change in composition from the outer unaltered or weakly propylitized zones to the inner alunitic zone. The most pronounced chemical changes are the loss of calcium, magnesium, and sodium and the addition of water, or hydrogen ions, and sulfur. Analyses of samples typical of the various alteration assemblages and their approximate unaltered equivalents are listed in table 4. The assemblages are arranged in the approximate order of the intensity of alteration. Most of the assemblages are represented by two or more analyses; however, only single analyses were available for three of the assemblages, and, therefore, chemical changes determined for those assemblages are least reliable. Gains and losses of the various components in each assemblage, shown graphically in figure 9, and the average percentage of gain or loss, given in table 5, are based on a comparison of analyses of the various assemblages with average values determined from unaltered rocks from the same drill hole. The samples in each hole were collected through a considerable vertical range, and thus they are not necessarily from correlative units. Therefore, the computations are not intended to show precise changes, because some apparent gains or losses may be due to differences in the original composition of the samples.

Weak propylitization, in which varying amounts of chlorite, montmorillonite, calcite, and quartz developed mainly from alteration of the ferromagnesian minerals and the groundmass, caused only slight changes in composition. More intense alteration causing extensive alteration of the groundmass and plagioclase phenocrysts and involving introduction of sulfur to form pyrite resulted in a marked decrease of calcium and sodium, moderate decreases of silica, aluminum, iron, magnesium, potassium, titanium, and phosphorus, and a gain of sulfur, carbon dioxide, and water. The losses of silica and titanium in the montmorillonite-chlorite-calcite-quartz-pyrite assemblage, although not of major proportions, are significant because no further large losses of these elements took place during argillic or alunitic alteration (table 5), and aluminum was further depleted only in the alunite-jarosite-quartz assemblage. Carbon dioxide is present only in the propylitic zone, where it is a component of calcite.

Calcium and sodium are greatly depleted in the argillic zone, but sodium is less depleted in the alunitic zone, where it is a component in alunite or natroalunite. Changes in the amount of potassium are somewhat erratic. The potassium in the kaolinite-quartz-pyrite assemblage is almost totally depleted, but a sharp reversal takes place in the alunite-quartz-pyrite assemblage, where potassium was added to form alunite (table 5). The potassium was introduced in the alunitic zone by hydrothermal solutions or was derived from the adjacent wallrocks. With the exception of the montmorillonite-cristobalite-pyrite assemblage in DDH–1 and DDH–2, magnesium is progressively leached during alteration, and it is almost totally absent in the kaolinite- and alunite-bearing assemblages. Ferrous iron is depleted in the argillic and alunitic zones, but the bar graph of total iron shown in figure 9 indicates that after an initial loss of iron in the propylitic zone, most remaining ferrous and ferric iron freed during alteration combined with sulfur to form pyrite. Finely disseminated pyrite in the propylitized rock reflects the introduction of sulfur, and pyrite increases progressively with increased intensity of alteration as sulfur combines with iron lost from other minerals (fig. 9). All the reported sulfur was assumed to occur as pyrite in the propylitized and argillized rocks. In the rocks containing both pyrite and alunite, the relative amounts of FeS_2 and SO_3 reported in table 4 are approximate because the amount of sulfur present as SO_3 was computed on the basis of the amount of sodium and potassium available to form natroalunite, and the remaining sulfur was reported as pyrite.

The gain in H_2O during alteration is readily apparent in figure 9. The role of water and the hydrogen ion in wallrock alteration was emphasized by Hemley and Jones (1964), who pointed out that the hydrolytic decomposition of silicates is quantitatively the most significant process involved in hydrothermal alteration. Calcium, magnesium, sodium, and potassium ions are removed and are replaced by an equivalent amount of hydrogen ions. Table 6 shows the loss of Ca^{++}, Mg^{++}, Na^{+}, and K^{+} ions and the corresponding gain of H^{+} ions expressed in gram equivalent values for the various alteration assemblages. The gain of hydrogen ions exceeds the loss of the cations in all the assemblages shown in the table except in the very weekly propylitized rocks and in the mixed-layer clay and alunite-jarosite assemblages. The discrepancies in the latter two probably are related to abnormal values in the single analysis upon which each is based.

The semiquantitative spectrographic analyses in table 4 show that changes in the abundance of minor elements are most pronounced in the alunite-jarosite-quartz assemblage. Here copper is decreased, cobalt and nickel are entirely removed, and lead, strontium, and gallium are slightly enriched. More comprehensive data on the minor-element content were obtained from analyses of chip samples of core collected within every 1.5-m (5-ft) interval in each drill hole. The distribution of Hg, As, Sb, Cu, Pb, Mo, Co, Ni, Ba, Sr, and Mn in DDH–3 and DDH–4 is plotted on plate 1; distribution of Zn in DDH–3 and of Au, Ag, and Bi in DDH–4 also is shown. Minor-element distribution in DDH–1 and DDH–2 is not shown because alteration to the montmorillonite-cristobalite-pyrite assemblage that predominates in these holes did not produce appreciable changes. As noted later, however, Ag and Au occur in DDH–2 in anomalous amounts. The distribution patterns for several of the elements further emphasize additions or depletions related to the hydrothermal alteration. Anomalously high or low values that occur singly in the section, however, are not considered to be significant unless they are related to veins. Nearly all the anomalous values are in the assemblages containing alunite or kaolinite, but with the possible exception of mercury, the values reflect only a very minor addition of metals.

As shown on plate 1, anomalous mercury in DDH–3 occurs mainly in the kaolinite-quartz-pyrite and alunite-quartz-pyrite assemblages; Pb, Sb, and Mo occur in the alunite-quartz-pyrite assemblage from 190 to 207 m (624–678 ft); and zinc occurs chiefly in the kaolinite-quartz-pyrite assemblages. Zinc was plotted only for DDH–3 because only a few scattered samples from the other drill holes contained detectable amounts. Strontium also is most abundant in the kaolinitic and alunitic assemblages, although the highest values, which are in the lower part of DDH–3, are from samples of propylitized rocks that contain veinlets of celestite. In DDH–4, changes are most pronounced in the alunite-jarosite-quartz assemblage, where anomalous amounts of mercury, gold, silver, antimony, bismuth, and lead have been introduced. Nowhere, however, are these elements concentrated in sufficient abundance for their mode of occurrence to be identified. In all the drill holes, manganese is especially sensitive to the degree of alteration, and its relative abundance as shown in the distribution patterns coincides quite closely with that of calcium and magnesium.

None of the samples from DDH–3 contained detectable gold, and, as shown on plate 1, groups of two or more adjacent samples from DDH–4 containing anomalous gold, silver, or bismuth occur only in the alunite-jarosite-quartz assemblage from 125 to 141 m (411–461 ft) and in the oxidized zone in the alunite-jarosite-quartz assemblage and the overlying silicified ledge. In DDH–2, gold, in amounts ranging from 0.02 to 0.7 ppm, was found in 30 samples of drill core, nearly all of which were from unaltered Kate Peak dacite cut by narrow pyrite veinlets in the interval from 26 to 100 m (85–327 ft) (fig. 7). Gold, ranging from 0.04 to 0.5 ppm, was detected in eight samples of similar occurrence from DDH–1. Silver did not exceed 0.5 ppm, the minimum detectable amount, in DDH–2 or DDH–3, and none was reported from DDH–1. Only DDH–4 contained bismuth.

In table 7, approximate background values of 14 elements in the various alteration assemblages indicate enrichment of Hg and Sr in the kaolinite-quartz-pyrite assemblages; enrichment of Hg, Sr, Sb, and Pb and depletion of Ni in both assemblages of the alunitic zone; and enrichment of Au, Ag, Bi, and Mo and depletion of As and Co in the alunite-jarosite-quartz assemblage. Nb and Zr, which are not included in the table, also have some higher values in the alunite-jarosite-quartz assemblage. The background values, which represent the average concentration, were determined from the cumulative frequency distribution of the elements plotted on log-normal probability paper (Lepeltier, 1969). The degree of reliability of these values is related to the number of samples in each assemblage, and, therefore, the background values given for the assemblages containing kaolinite and alunite are the least reliable. The range of values of the elements for each assemblage generally reflects the changes noted from the background values. For certain elements the concentration seems to remain uniform or the distribution of values varies without apparent relation to mineral assemblages. The range in values for these elements (in parts per million), most of which are not included in table 7, is as follows: B, <10–50; Be, <1–5; Cr, <5–200; La, <20–70; Nb, <10–50; Sc, <5–30; V, 50–500; Y, <10–100; Zr, 50–1,000. The values for Cd, Sn, and W are below the limits of detection in all samples.

Because a detailed classification by alteration assemblages ordinarily would not be feasible in most sampling programs in similar rocks, the analyses also were arranged into a simpler twofold division corresponding to varieties that would form unbleached and bleached rocks in surface exposures. Unaltered and nonpyritic propylitized rocks were combined, and the pyrite-bearing assemblage of the propylitic, argillic, and alunitic zones constitute the second group. The background and range of values for 14 elements for both groups are given in table 8. The effects of hydrothermal alteration can be noted in the background levels only by an increase in Hg and by a slight increase in Pb and decrease in Cu, Ni, and Sr in the altered rocks. Data on the average concentration of Au, Ag, Bi, Mo, and Zn, however, are inadequate because most of the values for these elements were below the minimum amount de-

TABLE 4.—*Analyses of unaltered and altered rocks*

[Chemical analyses by P. L. D. Elmore, Gillison Chloe, Hezekiah Smith, S. D. Botts, Lowell Artis, James Kelsey, and J. L. Glenn:--, not detected; ND, not determined. Semiquantitative Sn(7), Te(1,000), U(500), W(30), Ce(70), Ge(7), Hf(50), In(2), Li(200), Re(15), Ta(50), Th(150), Tl(50). Field numbers indicate drill hole and depth in feet. Abbreviations used in table: mont-crist-py, montmorillonite-cristobalite-pyrite; M–l ill-mont-qtz-py, mixed layer illite-montmorillonite-quartz-pyrite; kaol-qtz-py, kaolinite-quartz-pyrite; alun-qtz-py, alunite-

	Propylitic zone										
	Unaltered rock						Chl-mont-cal-qtz assemblage			Mont-chl-cal-qtz-py assemblage	
Sample No.	1	2	3	4	5	6	7	8	9	10	11
Field No.	1–96	1–463	2–209	3–339	3–514	4–84	3–148	4–396	4–493	4–126	4–522
											Chemical analyses
SiO_2	60.0	60.4	62.1	59.5	59.7	59.8	56.9	63.1	59.5	57.6	56.3
Al_2O_3	19.2	18.2	18.0	17.2	17.0	17.0	17.2	16.5	16.5	16.8	15.2
Fe_2O_3	3.1	3.7	3.4	2.5	3.2	2.7	3.1	2.7	2.5	1.7	.64
FeO	1.0	1.6	1.7	3.1	2.9	3.1	3.0	3.1	5.0	2.2	3.0
MgO	1.5	.95	1.0	3.0	2.8	2.9	3.0	2.1	2.4	2.2	2.9
CaO	4.5	5.2	4.7	6.9	6.7	6.5	6.3	2.7	3.1	3.1	4.3
Na_2O	3.7	4.1	3.8	3.0	3.2	3.6	2.9	2.6	2.5	1.9	1.8
K_2O	2.1	2.2	2.2	1.1	1.7	2.0	1.6	2.5	2.2	1.0	2.1
H_2O+	1.4	.60	.90	.90	1.4	.66	1.2	1.5	1.5	4.3	4.0
H_2O-	2.2	1.3	1.2	1.1	1.2	.84	2.1	1.1	1.2	5.4	3.9
TiO_2	.80	.87	.76	.76	.70	.80	.87	.64	.72	.65	.62
P_2O_5	.32	.35	.26	.29	.19	.28	.26	.27	.21	.43	.19
MnO	.06	.05	.05	.15	.15	.12	.18	.15	.25	.15	.19
CO_2	.05	<.05	<.05	<.05	.22	<.05	1.1	.55	1.6	.75	2.3
FeS_2[1]	----	----	----	.41	----	----	----	.09	----	1.6	2.8
SO_3[2]	----	----	----	----	----	----	----	----	----	----	----
Total (rounded)	100	100	100	100	101	100	100	100	99	100	100
Bulk density	2.46	2.44	2.36	2.64	2.69	2.68	2.56	2.58	2.65	2.06	2.47
Powder density	2.62	2.66	2.66	ND	ND	ND	ND	ND	ND	ND	ND
											Analyses converted to
SiO_2	1,476.0	1,473.8	1,465.6	1,570.8	1,605.9	1,602.6	1,456.6	1,628.0	1,576.8	1,186.6	1,390.6
Al_2O_3	472.3	444.1	424.8	454.1	457.3	455.6	440.3	425.7	437.2	346.1	375.4
Fe_2O_3	76.3	90.3	80.2	66.0	86.1	72.4	79.4	69.7	66.2	35.0	15.8
FeO	24.6	39.0	40.1	73.9	78.0	83.1	76.8	80.0	132.5	45.3	74.1
MgO	36.9	23.2	23.6	79.2	75.3	77.7	76.8	54.2	63.6	45.3	71.6
CaO	110.7	126.9	110.9	182.2	180.2	174.2	161.3	69.7	82.2	63.9	106.2
Na_2O	91.0	100.0	89.7	79.2	86.1	96.5	74.2	67.1	66.2	39.1	44.5
K_2O	51.7	53.7	51.9	29.0	45.7	53.6	41.0	64.5	58.3	20.6	51.9
H_2O+	34.4	14.6	21.2	23.8	37.7	17.7	30.7	38.7	39.8	88.6	98.8
H_2O-	54.1	31.7	28.3	29.0	32.3	22.5	53.8	28.4	31.8	111.2	96.3
TiO_2	19.7	21.2	17.9	20.1	18.8	21.4	22.3	16.5	19.1	13.4	15.3
P_2O_5	7.9	8.5	6.1	7.6	5.1	7.5	6.6	7.0	5.6	8.8	4.7
MnO	1.5	1.2	1.2	4.0	4.0	3.2	4.6	3.9	6.6	3.1	4.7
CO_2	1.2	----	----	----	5.9	----	28.2	14.2	42.4	15.4	56.8
FeS_2	----	----	----	10.9	----	----	----	2.3	----	33.0	69.2
SO_3	----	----	----	----	----	----	----	----	----	----	----
											Semiquantitative spectrographic
B	15	15	<7	<7	<7	<7	<7	<7	<7	<7	<7
Ba	1,000	700	1,000	1,500	1,500	1,500	1,500	1,500	1,000	1,500	1,500
Be	1.5	1.5	<7	<1	<1	<1	<1	1.5	<1	<1	<1
Bi	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7
Co	15	15	15	20	20	20	15	15	20	7	15
Cr	15	15	15	20	50	20	20	20	50	20	50
Cu	70	70	50	70	50	30	50	30	50	10	50
Ga	20	20	20	15	15	15	15	15	15	15	15
La	30	<30	<30	<30	<30	<30	<30	<30	<30	30	<30
Mn	500	500	500	1,000	1,000	1,000	1,000	1,000	1,500	1,000	700
Mo	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Nb	7	7	7	<7	<7	<7	<7	<7	<7	<7	<7
Ni	15	20	15	20	20	15	20	15	20	10	15
Pb	20	10	15	10	10	10	7	15	7	15	7
Sc	20	20	20	20	20	20	15	15	15	15	15
Sr	1,000	1,000	1,000	1,500	1,000	1,500	1,000	1,000	700	500	500
V	150	200	200	150	150	150	100	100	150	70	100
Y	50	20	30	15	10	15	15	20	20	15	20
Yb	5	2	3	1.5	1.5	2	1.5	2	2	1.5	1.5
Zn	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
Zr	150	100	100	100	100	100	70	100	100	100	100

[1] Total sulfur determined by B. P. Fabbi by X-ray fluorescence, except as noted in footnote 2. Sulfur reported as FeS_2 and iron corrected.
[2] Total sulfur determined by wet-chemical method by Sarah T. Neil.

of the Kate Peak Formation from drill holes

spectrographic analyses by Chris Heropoulos: the following elements were not detected or were below the limit of detection shown—Ag(1), As(200), Au(15), Cd(50), Pd(1), Pt(10), Sb(100), chl-mont-cal-qtz, chlorite-montmorillonite-calcite-quartz; mont-chl-cal-qtz-py, montmorillonite-chlorite-calcite-quartz-pyrite; mont-cal-qtz-py, montmorillonite-calcite-quartz-pyrite; quartz-pyrite; alun-jaros-qtz, alunite-jarosite-quartz]

Argillic zone										Alunitic zone	
Mont-cal-qtz-py assemblage	Mont-crist-py assemblage			M-1 ill-mont-qtz-py assemblage			Koal-qtz-py assemblage			Alun-qtz-py assemblage	Alun-jaros-qtz assemblage
12 3–94	13 1–156	14 1–509	15 2–334	16 3–566	17 3–718	18 4–389	19 3–266	20 3–618	21 4–468	22 3–643	23 4–416
(weight percent)											
55.3	58.8	51.7	55.2	61.1	63.7	62.6	62.4	64.4	69.7	51.3	62.4
16.3	18.4	15.9	16.5	17.2	14.8	17.5	18.4	19.4	15.7	15.2	11.5
2.4	----	3.4	2.1	1.0	1.2	2.8	1.5	1.1	----	----	4.2
.12	.86	.24	1.1	.72	.40	.12	.20	.12	.24	.16	.08
2.0	.74	2.5	1.7	2.5	.70	1.4	----	.10	.10	----	.10
6.2	2.7	1.9	2.3	.80	.70	.80	.10	.60	.20	.30	.40
1.5	2.8	.31	1.6	----	.10	.10	----	.10	----	1.2	.80
.80	1.9	1.1	1.8	1.3	2.1	3.4	----	----	.20	2.0	2.1
4.4	2.7	4.1	3.9	5.6	3.6	4.0	8.0	7.9	6.4	8.5	4.6
5.6	3.6	13.1	8.6	5.2	3.5	2.8	.71	.21	.28	.36	.12
.69	.71	.70	.67	.69	.65	.60	.74	.72	.65	.51	.72
.18	.09	2.1	.18	.08	.08	.07	.29	.05	.29	.23	.21
.18	.02	.03	.06	.06	.03	.06	----	.06	.09	.03	----
2.8	<.05	.11	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05
4.2	6.6	3.9	5.0	4.1	8.3	4.6	8.6	6.6	6.7	8.4	----
----	----	----	----	----	----	----	----	----	----	13.5	13.4
103	100	101	101	100	100	101	101	101	101	102	101
2.21	2.18	1.92	2.04	2.13	2.08	1.96	2.34	2.06	2.34	2.55	1.80
ND	2.66	2.28	ND	ND	ND	ND	ND	ND	ND	ND	ND
milligrams per cubic centimetre											
1,222.1	1,281.8	1,178.8	1,126.1	1,301.4	1,325.0	1,227.0	1,460.2	1,326.6	1,631.0	1,308.2	1,123.2
360.2	401.1	362.5	336.6	366.4	307.8	343.0	430.6	399.6	367.4	387.6	207.0
53.0	----	77.5	42.8	21.3	25.0	54.9	35.1	22.7	----	30.6	75.6
2.6	18.7	5.5	22.4	15.3	8.3	2.4	4.7	2.5	5.6	4.1	1.4
44.2	16.1	57.0	34.7	53.2	14.6	27.4	----	2.1	2.3	----	1.8
137.0	58.9	43.3	46.9	17.0	14.6	15.7	2.3	12.4	4.7	7.6	7.2
33.2	61.0	7.1	32.6	----	2.1	2.0	----	2.1	----	30.6	14.4
17.7	41.4	25.1	36.7	27.7	43.7	66.6	----	----	4.7	51.0	37.8
97.2	58.9	93.5	79.6	119.3	74.9	78.4	187.2	162.7	149.8	216.8	82.8
123.8	78.5	298.7	175.4	110.8	72.8	54.9	16.6	4.3	6.6	9.2	2.2
15.2	15.7	16.0	13.7	14.7	13.5	11.8	17.3	14.8	15.2	13.0	13.0
4.0	2.0	47.9	3.7	1.7	1.7	1.4	6.8	1.0	6.8	5.9	3.8
4.0	.4	.7	1.2	1.3	.6	1.2	----	1.2	2.1	.8	----
61.9	----	2.5	----	----	----	----	----	----	----	----	----
92.8	143.9	88.9	102.0	87.3	172.6	90.2	201.2	136.0	156.8	165.8	----
----	----	----	----	----	----	----	----	----	----	242.2	158.4
analyses (parts per million)											
<7	7	<7	<7	<7	<7	<7	7	<7	<7	<7	<7
1,500	700	300	700	700	2,000	500	700	1,000	150	1,000	2,000
<1	1.5	1.5	1.5	3	<1	<1	<1	<1	<1	<1	<1
<7	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7
20	30	20	15	15	15	10	15	15	15	10	<2
20	15	10	10	20	20	15	15	20	50	20	30
100	70	70	70	70	100	30	100	100	150	50	3
15	20	15	15	15	15	20	10	15	15	15	50
<30	<30	<30	<30	<30	<30	<30	<30	<30	30	<30	30
1,500	200	300	200	200	1,000	150	10	15	10	2	5
<2	<2	<2	<2	<2	<2	<2	<2	<2	5	<2	<2
<7	7	7	<7	<7	<7	<7	<7	<7	<7	<7	<7
20	20	20	20	10	10	7	20	10	15	7	<1
10	15	10	10	10	20	10	15	15	10	10	70
20	15	20	20	15	30	10	15	20	10	10	10
500	700	200	500	70	500	100	500	100	1,000	1,000	1,500
100	150	150	100	100	150	70	100	150	150	100	70
20	50	20	20	15	15	15	20	15	15	<7	7
1.5	5	1.5	2	1.5	2	1.5	2	2	1	1	1
<100	<100	<100	<100	300	<100	<100	300	<100	<100	<100	<100
70	100	70	70	100	70	100	70	100	100	50	150

tectable, but their abundance in the individual mineral assemblages has been discussed previously.

ENVIRONMENT OF THE HYDROTHERMAL ALTERATION

The alteration mineral assemblages that formed in the wallrock at a given temperature and pressure are determined largely by the composition of the hydrothermal solution; the most important compositional parameter is the base cation/H^+ activity ratio in the solution (Hemley and Jones, 1964). The mineral as-

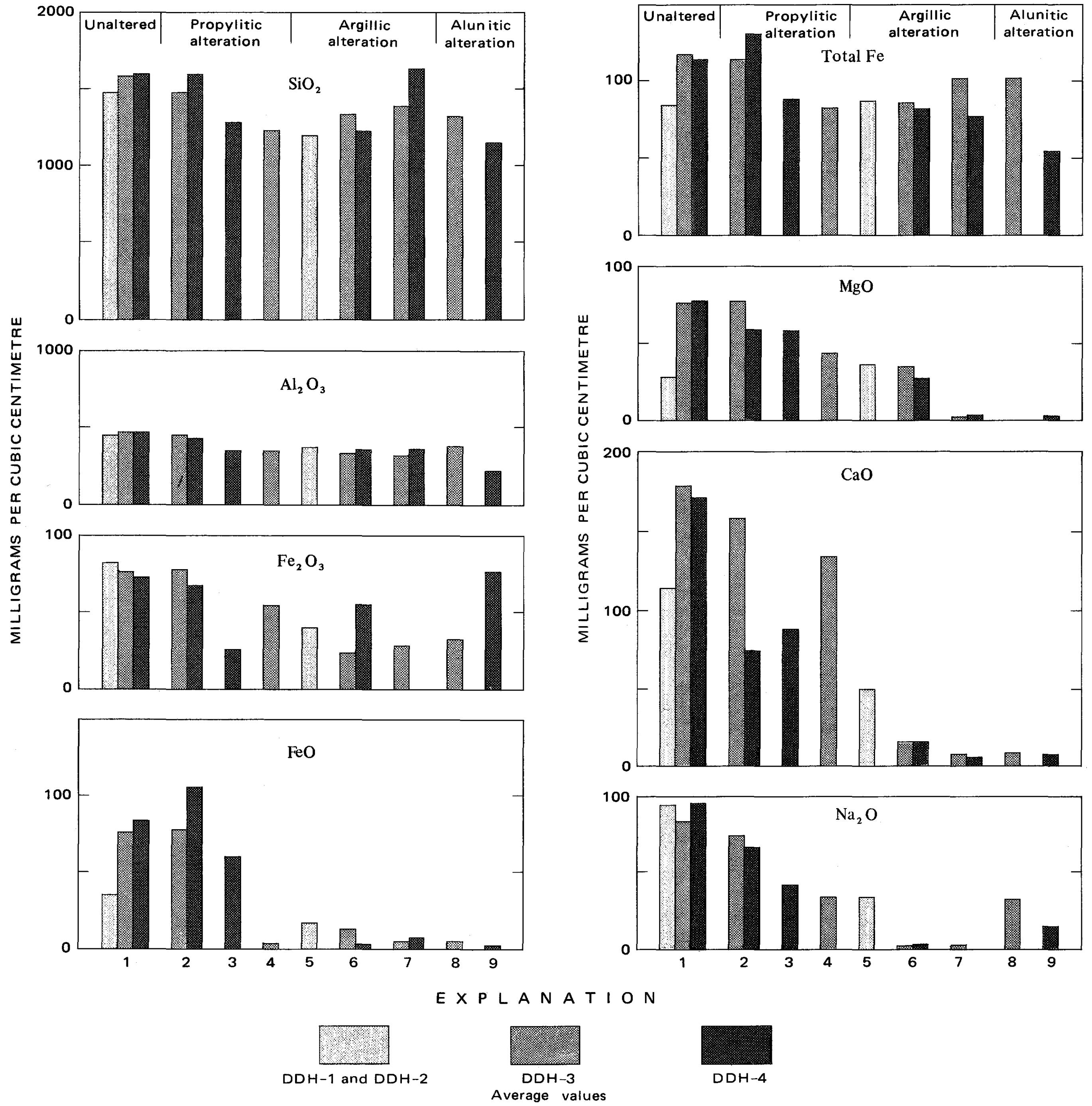


FIGURE 9.—Gains and losses of principal rock-forming constituents during hydrothermal alteration. Values shown are averages from analyses in table 4. 1, unaltered dacite; 2, chlorite-montmorillonite-calcite-quartz assemblage; 3, montmorillonite-chlorite-calcite-quartz-pyrite assemblage; 4, montmorillonite-calcite-quartz-pyrite assemblage; 5, montmorillonite-cristobalite-pyrite assemblage; 6, illite-montmorillonite (mixed layer)-quartz-pyrite assemblage; 7, kaolinite-quartz-pyrite assemblage; 8, alunite-quartz-pyrite assemblage; 9, alunite-jarosite-quartz assemblage.

semblages reflect the depletion of calcium, sodium, and other cations and their replacement by hydrogen ions. The propylitic zone has undergone relatively little depletion of these cations and only slight enrichment in hydrogen ions, whereas the argillic and alunitic zones have undergone appreciable hydrogen metasomatism and cation depletion.

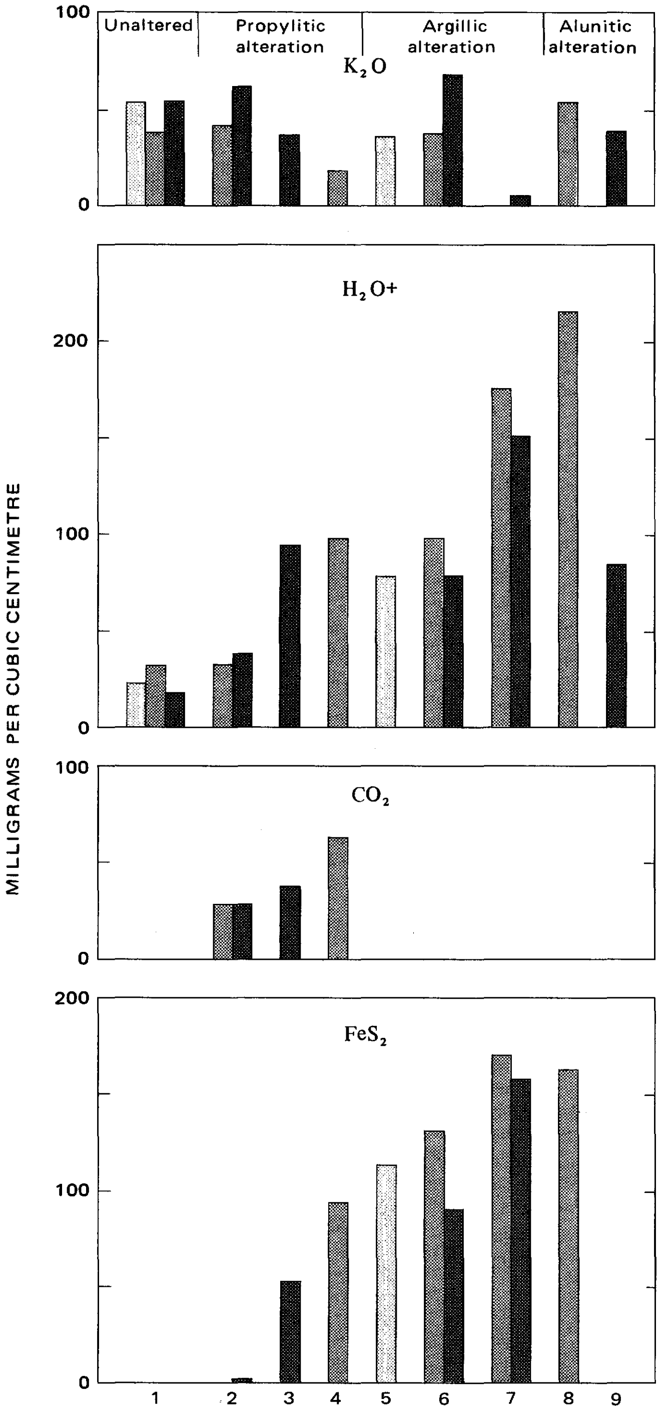


FIGURE 9.—Continued.

The results of experimental studies on the stability relations of some of the clay minerals and alunite are applicable to the alteration assemblages found in the drill holes. The reaction curves by Hemley and Jones (1964) and Hemley, Montoya, Nigrini, and Vincent (1971) define the stability fields of montmorillonite, kaolinite, and other minerals formed by alteration of plagioclase. Hemley, Montoya, Nigrini, and, Vincent (1971) investigated the following reactions that occur at low temperatures and decreasing cation/H^+ ratios of the hydrothermal fluid:

$$\underset{\text{Anorthite}}{1.17\,CaAl_2Si_2O_8} + 1.32SiO_2 + 2H^+ = \underset{\text{Montmorillonite}}{Ca_{0.17}Al_{2.34}Si_{3.66}O_{10}(OH)_2} + Ca$$

$$\underset{\text{Montmorillonite}}{Ca_{0.17}Al_{2.34}Si_{3.66}O_{10}(OH)_2} + 0.34H^+ + 1.17H_2O = \underset{\text{Kaolinite}}{1.17Al_2Si_2O_5(OH)_4} + 0.17Ca^{+2}$$

TABLE 5.—*Average percentage gain (+) or loss (−) of constituents in alteration assemblages during hydrothermal alteration*

[Alteration assemblages are listed in same order as in table 4. All figures are based on comparison with unaltered rock. Numbers in parentheses indicate averages determined fromgreatly differing values. Abbreviations used are chl-mont, chlorite-montmorillonite; mont-chl, montmorillonite-chlorite; mont-cal, montmorillonite-calcite; mont-crist, montmorillonite-cristobalite; m-1 ill-mont, mixed-layer illite-montmorillonite; kaol, kaolinite; alun, alunite; alun-jaros, alunite-jarosite]

	Propylitic zone			Argillic zone			Alunitic zone	
	Chl-mont	Mont-chl	Mont-cal	Mont-crist	M-l ill-mont	Kaol	Alun	Alun-jaros
SiO_2	(−4)	−20	−23	−19	−20	(−5)	−18	−30
Al_2O_3	−4	−21	−21	−18	−25	−14	−15	−55
Fe_2O_3	(−1)	−65	−30	−51	−47	(−1)	−60	+4
FeO	(+15)	−28	−97	−55	−91	−94	−95	−98
MgO	(−12)	−25	−43	+29	−60	−98	−100	−98
CaO	(−33)	−50	−24	−57	−91	−97	−96	−96
Na_2O	−21	−57	−60	−64	−98	−99	−63	−85
K_2O	+13	−32	−53	−34	(+12)	−95	+36	−29
H_2O^+	(+45)	+430	+217	+230	+263	+571	+606	+368
H_2O^-	+58	+361	+304	+384	+176	−68	−70	−93
TiO_2	0	−33	−22	−23	−37	−23	−33	−39
P_2O_5	(−11)	−10	−38	−62	−78	−23	−8	−49
MnO	+37	+21	−1	−40	−71	−62	−81	−100

TABLE 6.—*Average total loss (−) of* Mg^{++}, Ca^{++}, Na^+, *and* K^+ *ions and gains (+) of* H^+ *ions in the various mineral assemblages*

[Values are expressed in gram equivalents. Abbreviations used are chl-mont, chlorite-montmorillonite; mont-chl, montmorillonite-chlorite; mont-cal, montmorillonite-calcite; mont-crist, montmorillonite-cristobalite; m-l ill-mont, mixed-layer illite-montmorillonite; kaol, kaolinite; alun, alunite; alun-jaros, alunite-jarosite]

	Propylitic zone			Argillic zone			Alunitic zone	
	Chl-mont	Mont-chl	Mont-cal	Mont-crist	M-l ill-mont	Kaol	Alun	Alun-jaros
Mg^{++}	−0.5	−1.0	−1.6	+0.4	−2.3	−3.8	−3.8	−3.8
Ca^{++}	−2.1	−3.1	−1.6	−2.4	−5.8	−6.1	−6.2	−6.0
Na^+	−.6	−1.8	−1.6	−1.9	−2.8	−2.9	−1.7	−2.7
K^+	+.1	−.4	−.4	−.4	+.1	−.9	+.3	−.3
Total	−3.1	−6.3	−5.2	−4.3	−10.8	−13.7	−11.4	−12.2
H^+	+1.2	+8.5	+7.4	+6.0	+7.1	+15.5	+20.8	+7.2

TABLE 7.—*Background levels and range of values of minor elements in unaltered and altered rocks in DDH–1 to DDH–4*

[Values in parts per million. Numbers in parentheses indicate number of analyses from which the value was determined. Abbreviations used in table: chl-mont, chlorite-montmorillonite; mont-chl, montmorillonite-chlorite; mont-cal, montmorillonite-calcite; mont-crist, montmorillonite-cristobalite; m-l ill-mont, mixed-layer illite-montmorillonite; kaol, kaolinite; alun, alunite; alun-jaros, alunite-jarosite]

Element		Propylitic zone			Argillic zone			Alunitic zone	
	(121) Unaltered	(65) Chl-mont	(85) Mont-chl	(36) Mont-cal	(135) Mont-crist	(63) M-l ill-mont	(33) Kaol	(15) Alun	(9) Alun-jaros
Background values									
Au	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.02
Hg	.1	.2	.2	.5	.2	.3	.2	1.5	2
As	15	10	10	20	15	15	30	70	10
Sb	1.5	1.5	1.5	2	1.5	1.5	2	3	7
Ag	<.5	<.5	<.5	<.5	<.5	<.5	<.5	<.5	1
Ba	1,000	1,000	1,000	700	700	1,000	1,000	700	1,000
Bi	<10	<10	<10	<10	<10	<10	<10	<10	15
Co	30	20	15	15	20	20	20	15	10
Cu	70	50	30	50	30	50	50	30	30
Mo	<5	<5	<5	<5	<5	<5	<5	<5	5
Ni	30	20	15	15	20	15	20	10	7
Pb	15	20	20	15	15	20	20	30	100
Sr	700	500	300	200	500	300	1,000	1,000	1,000
Zn	<200	<200	<200	<200	<200	<200	<200	<200	<200
Range of values									
Au	<0.02–0.7	<0.02–0.1	<0.02	<0.02	<0.02–0.2	<0.02	<0.02	<0.02	<0.02–0.2
Hg	<.02–1	<.02–3	<.02–1.5	.03–2	.05–1.5	<.02–5	.3–>10	1–5	.2–>10
As	<10–200	<10–100	<10–100	<10–70	<10–70	<10–100	<10–70	<10–150	<10–10
Sb	<1–5	<1–3	<1–3	<1–3	<1–7	<1–5	<1–7	2–7	1–15
Ag	<.5–.5	<.5–.5	<.5–.5	<.5	<.5–.5	<.5–.05	.5–2	<.5–.5	<.5–2
Ba	500–>5,000	300–3,000	200–3,000	<200–2,000	200–5,000	<200–3,000	<200–1,500	500–2,000	500–2,000
Bi	<10	<10	<10	<10	<10	<10	<10	<10	10–100
Co	5–70	7–50	<5–30	7–20	7–50	7–50	5–50	7–20	<5–10
Cu	20–200	10–150	5–70	15–100	10–150	10–150	10–100	15–70	<10–100
Mo	<5–5	<5–10	<5–100	<5–10	<5–10	<5–10	<5–5	<5–50	<5–10
Ni	5–70	5–50	<5–30	5–50	5–70	5–70	5–50	7–30	<5–15
Pb	<10–50	<10–50	<10–70	<10–30	<10–30	<10–100	<10–50	15–100	50–150
Sr	150–1,000	200–1,500	<100–>5,000	<100–>5,000	100–1,000	<100–3,000	150–1,500	500–1,500	500–1,500
Zn	<200–200	<200–200	<200–500	<200–500	<200–200	<200–700	<200–7,000	<200–300	<200

TABLE 8.—*Background and range of values for elements in unaltered or nonpyritic propylitized rocks and pyritic alteration assemblages*

[Values in parts per million. All samples are from DDH–1 to DDH–4]

Element	Background		Range	
	1	2	1	2
Au	<0.02	<0.02	<0.02–0.7	<0.02–0.2
Hg	.15	.3	<.02–3	<.02–>10
As	15	15	<10–200	<10–150
Sb	1.5	1.5	<1–5	<1–15
Ag	<.5	<.5	<.5–.5	<.5–2
Ba	1,000	1,000	300–>5,000	<200–5,000
Bi	<10	<10	<10	<10–100
Co	20	20	5–70	<5–50
Cu	50	30	10–200	5–150
Mo	<5	<5	<5–10	<5–100
Ni	30	15	5–70	<5–70
Pb	15	20	<10–50	<10–150
Sr	700	500	150–1,500	<100–>5,000
Zn	<200	<200	<200–200	<200–7,000

1. 186 samples of unaltered and nonpyritic propylitized rocks.
2. 376 samples of pyritic rocks of the propylitic zone and the assemblages of the argillic and alunitic zones.

At higher temperatures montmorillonite is converted to a mixed-layer phase that was interpreted as regular 1:1 montmorillonite-pyrophyllite. Experimental studies on the equilibrium relations of alunite by Hemley, Hostetler, Gude, and Mountjoy (1969) show that kaolinite may alter to alunite as follows:

$$\underset{\text{Kaolinite}}{3Al_2Si_2O_5(OH)_4} + 2K^+ + 6H^+ + 4SO_4^{-2} = \underset{\text{Alunite}}{2KAl_3(SO_4)^2(OH)_6} + 6SiO_2 + 3H_2O$$

The equations for the alteration of andesine, involving both calcium and sodium, or for the formation of alunite containing both potassium and sodium would be more complex.

Harvey and Vitaliano (1964, p. 575) have shown that the reaction of illite with sulfuric acid to form alunite was an important step in the alteration at Goldfield, Nev. The reaction may be represented as follows:

$$\underset{\text{Illite}}{KAl_3Si_3O_{10}(OH)_2} + 4H^+ + 2SO_4^{--} = \underset{\text{Alunite}}{KAl_3(SO_4)_2(OH)_6} + 3SiO_2$$

The alunitic zone surrounded by illite-bearing rocks near the bottom of DDH–4 may be due to a similar reaction.

The zonal sequence of alteration minerals indicates a decrease in acidity of the solutions outward from the alunitic zone to the propylitic zone. Experimental studies on alunite by Hemley, Hostetler, Gude, and

Mountjoy (1969, p. 608) show that a low cation/H^+ ratio is required in the alunite-quartz system under hydrothermal conditions, and Hemley, Meyer, and Richter (1961, p. D340) determined that kaolinite forms instead of montmorillonite during the alteration of plagioclase at moderately low cation/H^+ ratios. Montmorillonite can form under a variety of conditions. With the progressive neutralization of acidic hydrothermal solutions outward from the alunitic zone, a slightly acidic environment seems probable to form mixed-layer illite-montmorillonite, but neutral or slightly basic solutions are indicated in the propylitic zone.

The widespread propylitization of the Kate Peak and Alta Formations cannot readily be explained as part of a geometric arrangement. Penetration of the altering agents responsible for the concentric zoning was quite limited, and an extensive propylitized zone due entirely to introduction of these fluids could not be expected in the country rock. Regional propylitization in the Virginia Range and in numerous other mineralized districts is not related to veins or other obvious channelways. Coats (1940, p. 6–7) proposed that deeper parts of the Davidson Granodiorite might be the source of altering agents of the propylitized rocks in the Comstock Lode district, and Calkins (1944, p. 21) recognized that the intensity of alteration decreases outward from this intrusive body. Burbank and Luedke (1969, p. 27) observed that "the generally low grade of alteration in some propylites is such that rocks so classified may very well have been formed under a variety of conditions wherever hot waters and associated gases permeated the rocks."

Two varieties of propylitized rocks thus may be present: one that was part of the widespread propylitization and a second more localized variety constituting the outer part of a zonal pattern. The widespread variety might be represented in the drill cores by the chlorite-montmorillonite-calcite-quartz assemblage, although local more intensely propylitized parts might contain considerable epidote and albite, and the localized variety might be represented by the assemblages rich in montmorillonite. They may have formed during the same episode of hydrothermal activity, or the localized alteration may be a later argillic overprint on the propylitized rocks. The introduced sulfur that combined to form pyrite in the propylitic and argillic zones and that formed alunite, jarosite, and pyrite in the alunitic zone is indicative of the solfataric environment described by Burbank (1950, 1960) and others.

The alteration assemblages in DDH–1 and DDH–2 differ from the montmorillonite-bearing assemblages in the propylitic zone of DDH–3 and DDH–4 chiefly by the absence of calcite and quartz and by the common occurrence of zeolites. The lack of carbonate in DDH–1 and DDH–2 indicates that the hydrothermal fluids locally were poor in CO_2. This inference is supported by the studies of Zen (1961, p. 408), who concluded that zeolites are stable where the chemical potential of CO_2 is low in relation to that of H_2O.

The relation between the mineralizing solutions of the lode deposits and those of the alunitic zones is not clear. Taylor (1974, p. 870) cited data from oxygen-isotope analyses as evidence that the gold and silver deposits in the Comstock Lode, Goldfield, and several other districts in western Nevada were formed from meteoric-hydrothermal fluids containing low concentrations of heavy metals derived from intrusive bodies and volcanic country rocks. Becker (1882, p. 225) previously had proposed a similar source of the gold and silver in the Comstock lode. Propylitic alteration, which is intense in the vicinity of the Comstock lode, resulted from solutions that probably were of nearly neutral or slightly alkaline composition, whereas an acidic environment is required to form assemblages in the alunitic zone and some assemblages in the argillic zone. The gold ores in the alunite-quartz ledges at Goldfield were deposited both during and slightly after the hydrothermal alteration of the wallrock (Ransome, 1909; Ashley and Albers, 1973, p. 22), and therefore the ore-bearing solutions must have been acidic. However, Burbank (1950) and Steven and Ratté (1960) proposed that deposition of sulfide ores in alunitic zones in the San Juan region of Colorado was dependent upon a change from acid to alkaline conditions. No ore has been reported in the alunite-quartz ledges in the hanging wall block of the Comstock fault near Virginia City, but anomalous amounts of mercury, lead, and other metals are disseminated in alunitic zones elsewhere in the quadrangle and probably formed contemporaneously with the alteration minerals.

Temperatures during alteration can be estimated from studies of fluid inclusions in samples of the alunite-quartz-pyrite assemblage in DDH–3 and the alunite-jarosite-quartz assemblage in DDH–4. Thin sections of these samples were examined by J. T. Nash (written commun., March 19, 1973), who stated

> Small fluid inclusions occur in hydrothermal quartz associated with alunite and jarosite. The vapor bubble of the liquid plus vapor inclusions amounts to only a few percent, perceptibly smaller than in similar inclusions in comparable alteration zones at Goldfield. Considering the low vapor fraction of the inclusions and reasonable correction for pressure, the quartz appears to have formed at less than 200°C.

Because pyrophyllite forms instead of kaolinite at higher temperatures in the presence of quartz (Hemley and Jones, 1964, p. 548), the absence of pyrophyllite in the drill cores is supporting evidence of low to moderate temperatures. The limit of high-temperature stability of kaolinite in a quartz-saturated system at 1,000 bars H_2O is about 310°C (Reed and Hemley, 1966). Pyrophyllite was found in some bleached rocks in the Geiger Grade area, however, indicating that temperatures were higher locally.

Water with temperatures as high as 77°C in the lower levels of the Comstock mines was charged with carbon dioxide and hydrogen sulfide (Becker, 1882, p. 386). The process of hydrothermal alteration thus may be active locally at the present time. Because of the great length of time since the ore mineralization in the Comstock lode, however, the source of the thermal energy for the present-day hot waters is probably more closely related to that of the Steamboat Springs system, a few kilometres west of the Virginia Range, than to a system active in Miocene time.

Alteration at shallow depths is indicated by bodies of opaline material closely associated with argillized and alunitized rocks near the Washington Hill mercury prospect (fig. 5). At Steamboat Springs, opal is not found at depths more than about 30 m (100 ft), where temperatures are as high as 125°C (White, 1955, p. 112). Yates and Roberts (1941) concluded that the depth of deposition of opalite occurring in many mercury deposits was controlled by the ground-water level, and Yates (1942, p. 338) suggested that opalite in the Opalite quicksilver district was formed where rising hydrothermal solutions were cooled and diluted by ground water. There is a strong possibility, therefore, that at some places the hydrothermal solutions reached the surface as hot springs.

SUPERGENE ALTERATION

Supergene alteration has produced conspicuous patches of bleached rocks mainly in the Alta and Kate Peak Formations and locally in other rocks. The supergene alteration takes place in areas underlain by pyrite-bearing rocks; the bleaching is caused by the action of sulfuric acid produced by oxidation of the pyrite. The highly acid environment was demonstrated by Thompson and White (1964, p. A27), who measured pH as low as 3.5 in the soils of the bleached zones. Supergene alteration generally is most intense within a few metres of the surface, but the bleached zone extends to depths ranging from 10 to 28 m (34–92 ft) in the drill holes, and bleached rocks locally were found at greater depths along the Sutro Tunnel east of Virginia City. On the surface many contacts between bleached rocks and unaltered or propylitized rocks appear to be sharp. In drill holes the contact with the underlying unbleached rocks is marked by an abrupt change in color from yellowish gray or grayish orange to light gray and by the disseminated pyrite in the unoxidized rock.

The degree to which supergene alteration has modified the hydrothermally altered rocks is difficult to determine, and it varies from place to place. The mineral assemblage in a bleached rock may be due almost entirely to hypogene alteration, to a combination of hypogene and supergene alteration, or to mainly supergene alteration. Grim (1968, p. 491) pointed out the problems of distinguishing between minerals of hypogene and supergene origin, especially when the same mineral may be formed by hydrothermal alteration and again by supergene alteration superimposed on the earlier alteration products. Kaolinite forms under acid conditions from supergene processes, which accounts for its widespread occurrence in the bleached rocks, but it also developed in the argillic zone during hypogene alteration. Montmorillonite is not as characteristic of supergene alteration as is kaolinite (Meyer and Hemley, 1967, p. 174). The alunite that formed during hydrothermal alteration commonly remains unchanged in the oxidized zone; the alunite occurring in veins and coating fractures, however, is probably supergene.

BLEACHED ROCKS

The pyrite-bearing rocks that have undergone bleaching include those from propylitic, argillic, and alunitic zones of alteration, and thus they range from weakly altered rocks containing small amounts of chlorite and calcite to thoroughly altered rocks containing mainly quartz and clay or alunite. The bleached rocks, in turn, range from dense rocks with unaltered feldspar phenocrysts to thoroughly altered and leached varieties composed almost entirely of fine-grained quartz. Bleaching merely denotes the light color imparted to the rocks; the term does not imply the presence of a particular assemblage of minerals, but the bleaching does define areas underlain by rocks that contained disseminated pyrite. Various types of bleached rocks are especially well displayed near Virginia City, in roadcuts along the Geiger Grade, and in the Washington Hill area (fig. 2).

The typical white to grayish-yellow bleached rocks are irregularly stained by brown, red, and yellow iron oxide, and locally they are cut by fractures coated with dark iron oxide. The porphyritic character of the original rocks is preserved in most of the bleached rocks by white spots that represent original plagioclase phenocrysts and in some specimens by outlines of altered hornblende or biotite. The most common varieties of bleached rocks are fairly nonresistant rocks composed mainly of clays and quartz. Kaolinite is probably the most widespread clay mineral, but montmorillonite, illite, and mixed-layer clays are also common. Anatase, diaspore, rutile, and leucoxene are present in small amounts, and gypsum is found locally along fractures. Pyrophyllite was found in numerous samples from the Geiger Grade area, but elsewhere it has been found in only a few places; no pyrophyllite was found in the drill cores. It occurs with quartz, diaspore, leucoxene, and local alunite or kaolinite. The similar appearance of the above varieties of clay-rich bleached rocks prevents any practical subdivision of these rocks in the field, but they can be distinguished from rocks containing alunite and quartz which form prominent topographic features.

Alunitic zones within the bleached rocks are of particular interest because of their similarity to alunitic zones closely associated with gold deposits in the Goldfield district, Nevada (Ransome, 1909), and in the Red Mountain and Summitville districts in Colorado (Burbank, 1941, 1950; Steven and Ratté, 1960). Ransome used the term ledge to avoid the terms vein and lode in the descriptions of the irregularly shaped masses in which the Goldfield ore bodies were found. The ledges are especially widespread in the Washington Hill and Geiger Grade areas, but they are also found elsewhere in less abundance and are developed in both the Alta and the Kate Peak Formations. Several ledges were noted in the bleached rocks near the main mine workings in the Comstock lode, but, unlike those at Goldfield, apparently none of them was significant to the localization of the ore minerals. In other parts of the quadrangle, some of the silicified ledges contain anomalous amounts of mercury, silver, bismuth, and other metals. The ledges that contain these metals, however, are identical in appearance to the many others that are barren.

Most of the ledges have linear outlines that suggest their development along faults or fractures, although no conclusive evidence of these features is preserved. In the vicinity of the Washington Hill prospect (fig. 5), most of the ledges trend north or northeast; however, their trends characteristically are widely variable, and a ledge of one trend may join with one of a divergent trend. The outcrop pattern of some is roughly equidimensional, but this may be caused by coalescence of two or more ledges. Five kilometres (3 mi) west of Virginia City, however, several silicified ledges clearly follow faults in propylitized andesite of the Alta Formation.

Numerous randomly oriented fractures cut the ledges, and breccias that are developed locally may indicate structural discontinuities. Some breccia fragments, however, were interpreted to be features of the original flows and not related to later fracturing.

The map pattern of some alunite-quartz ledges suggests that they dip steeply, whereas others seem to be nearly flat lying. Nearly everywhere, however, the contacts between the resistent ledges and the adjacent softer bleached rock are poorly exposed, and little information about their attitude and vertical extent can be obtained from surface exposures. Their development at depth is confirmed in the drill holes, where alunitic zones were penetrated to a depth of 213 m (697 ft). In the Goldfield district, some ledges extended only to shallow depths; others were followed in mine workings to depths of more than 300 m (1,000 ft), and their dip commonly changes considerably from one level to another (Ransome, 1909, p. 150–155; Searls, 1948). Alunite veins have a depositional range of more than 600 m (2,000 ft) at Cerro de Pasco (Graton and Bowditch, 1936, p. 665) and in the Marysvale district, Utah (Callaghan, 1938, p. 117), and probably about 1,500 m (5,000 ft) in the Red Mountain district, Colorado (Burbank, 1950, p. 310).

Outcrops of the alunite-quartz ledges differ from equivalent unoxidized parts at depth chiefly by their color and lack of pyrite. The light-gray unoxidized rock becomes pinkish gray or yellowish gray in outcrops, and it may be stained by iron oxides of various colors. The most resistant parts are composed entirely of compact microcrystalline quartz or of strongly leached porous quartzose rock with numerous cavities, many of which probably represent original phenocrysts. More commonly, the ledges contain both quartz and alunite, and kaolinite is a common constituent near their borders. Where alunite is too sparse or too fine grained to identify with a hand lens, its presence often is indicated by the sparkle of minute crystal faces in bright sunlight. Where alunite is abundant, crystals larger than 1 mm are commonly developed in the small cavities. Alunite pseudomorphs after plagioclase are inconspicuous because of the overall light color of the rock. As seen in thin section, leucoxene is dispersed in and around patches formerly occupied by ferromagnesian minerals and is ubiquitous as a replacement of magnetite-ilmenite. Small crystals of rutile are visible locally; anatase and diaspore are the other minor accessories. The scattered iron oxides give no conclusive evidence of the earlier presence of disseminated pyrite, but disseminated pyrite is preserved in rare small pods of dark-gray dense quartzose rock. Barite was found along fractures and in vugs in several ledges in the Washington Hill area.

The ledge penetrated in the upper part of DDH–4 is composed mainly of microcrystalline quartz that is stained pinkish gray to grayish orange. Locally, iron oxides coat cavities and irregular fractures; jarosite or alunite that coats other fractures also formed during supergene alteration. Much of the rock is porous, owing largely to the small cavities formed by the leaching of earlier minerals. The lower part of the ledge is composed of alunite, jarosite, and quartz and appears to be relatively unaffected by supergene processes.

In the vicinity of the Washington Hill prospect and locally elsewhere, some resistant outcrops are composed largely of opaline material that ranges from white to shades of brown or purple. X-ray diffraction patterns show that much of the opal has been converted to cristobalite. In a few places the opalite apparently has replaced unaltered rock, as indicated by detailed preservation of the original texture, but in other places the opalite appears to grade into a silicified ledge of quartz or alunite and quartz in which the texture has been obliterated. Yates and Roberts (1941) first recognized that the opalite in many mercury deposits is not siliceous sinter deposited by hot springs but is formed by silicification of permeable ash, tuff, sediments, and, more rarely, other rocks. Most opal forms as near-surface deposits at temperatures below 140°C (White and others, 1956, p. 54).

CHEMICAL CHANGES DURING SUPERGENE ALTERATION

Comparison of analyses of samples of bleached rocks and adjacent unaltered or weakly propylitized rocks will not necessarily characterize changes related to supergene alteration because many of the elements depleted from the bleached rocks were at least partly removed during earlier hydrothermal alteration. Background values for selected elements in bleached rocks and in their unoxidized equivalents (table 9) indicate that cobalt and nickel were removed additionally during bleaching. Despite the high mobility of copper in an acidic environment such as that in the bleached zone, the average concentration was only slightly lowered. The background values of mercury and lead are slightly higher in the bleached rocks, but this probably results from a larger proportion of silicified ledge samples included in the group of bleached rocks.

Figure 10 shows the relations observed in a roadcut in the Alta Formation at the top of Geiger Grade where weakly propylitized rock containing finely disseminated pyrite grades into bleached rocks. Blocks of light-yellowish-gray bleached rock adjacent to the propylitized rock commonly have medium-light-gray pyrite-bearing cores. Although the darker colored cores superficially resemble the fresher rocks, they are more altered and are depleted in ferrous iron, magnesium, calcium, and manganese, as shown in table 10. Thin sections show that the light-colored rims are only slightly more altered than the cores, but the pyrite has been leached, with a resulting decrease in ferric iron

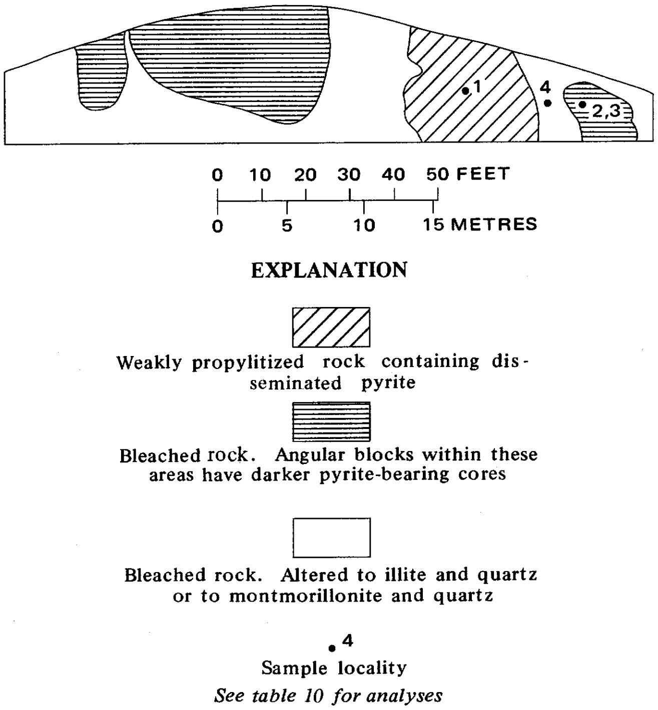


FIGURE 10.—Roadcut at top of Geiger Grade showing relations of weakly propylitized and bleached rocks in the Alta Formation.

TABLE 9.—*Background levels and range of values for selected elements in bleached rocks and in their unoxidized equivalents*

[Values in parts per million]

Element	Background			Range		
	1	2	3	1	2	3
Au	<0.02	<0.02	<0.02	<0.02–0.7	<0.02–0.2	<0.02–2
Hg	.15	.3	.5	<.02–3	<.02–>10	<.01–>10
As	15	15	15	<10–200	<10–150	<10–700
Sb	<100	1.5	<100	<1–5	<1–15	<100
Ag	<.5	<.5	<.5	<.5–1.5	<.5–2	<.5–15
Ba	1,000	1,000	700	300–>5,000	<200–5,000	<200–>5,000
Bi	<10	<10	<10	<10	<10–100	<10–200
Co	20	20	<5	5–150	<5–50	<5–100
Cu	50	30	20	<5–200	5–150	<5–500
Mo	<5	<5	<5	<5–10	<5–100	<2–200
Ni	30	15	<5	<5–100	<5–70	<5–100
Pb	15	20	30	<10–70	<10–150	<10–2,000
Sr	700	500	500	150–3,000	<100–>5,000	<100–>5,000
Zn	<200	<200	<200	<200–200	<200–7,000	<200–300

1. 247 samples of unaltered and nonpyritic propylitized rocks from outcrops and diamond-drill holes.
2. 376 samples of pyritic rocks of the propylitic zone and the assemblages of argillic and alunitic zones from drill holes.
3. 453 samples of bleached rocks from outcrops.

and sulfur. Cobalt, copper, and nickel are depleted in these rocks and also in the other bleached rocks. Softer typical bleached rocks surrounding this incompletely bleached rock are altered to quartz and montmorillonite or illite. These bleached rocks are almost entirely depleted in calcium and sodium, as shown by sample 4.

A zonal pattern of hydrothermal mineral assemblages is obscured in most surface exposures of bleached rocks, but in some roadcuts minerals formed during hydrothermal alteration remain with little modification during the bleaching process except for the removal of pyrite. One such roadcut along the lower part of the Geiger Grade (fig. 11) exposes a resistant ledge bordered by clay-rich bleached rocks. The ledge at the top of the roadcut is capped by a highly silicified outcrop composed of porous chalcedonic quartz with minor kaolinite, but lower in the roadcut it is composed of an inner zone of alunite and quartz and a slightly less resistant outer zone of kaolinite and quartz that together make up a zone about 12 m (40 ft) wide. Softer bleached rocks adjacent to the ledge are mostly altered to mixed-layer illite-montmorillinite, montmorillonite, and quartz, but locally they contain some remnant plagioclase.

TABLE 10.—*Analyses of propylitized and bleached rocks in the Alta Formation from a roadcut at the top of Geiger Grade*

[Sample localities are shown in fig. 10. Chemical analyses by P. L. D. Elmore, Gillison Chloe, Hezekiah Smith, S. D. Botts, Lowell Artis, James Kelsey, and J. L. Glenn; --, not detected. Semiquantitative spectrographic analyses by Chris Heropoulos]

Sample locality	1	2	3	4
Field No.	81–2C	81–2D	81–2D	81–2E
Chemical analyses (weight percent)				
SiO_2	62.4	63.8	66.2	67.8
Al_2O_3	17.2	17.6	18.8	18.9
Fe_2O_3	1.9	--	.67	.63
FeO	1.5	.12	.04	.08
MgO	2.1	.15	.22	1.0
CaO	3.7	2.1	2.1	.16
Na_2O	3.0	2.6	2.6	.13
K_2O	2.0	2.3	2.2	3.6
H_2O+	2.0	3.4	3.8	3.5
H_2O-	1.3	1.7	2.0	2.6
TiO_2	.61	.66	.66	.62
P_2O_5	.20	.13	.10	.06
MnO	.09	.00	.00	.00
CO_2	.08	<.05	<.05	<.05
FeS_2[1]	1.7	6.4	--	--
Total (rounded)	100	101	99	99
Bulk density	2.51	2.45	2.34	1.91
Powder density	2.66	2.66	2.52	2.62
Analyses converted to milligrams per cubic centimetre				
SiO_2	1,566.2	1,563.1	1,549.1	1,295.0
Al_2O_3	431.7	431.2	439.9	361.0
Fe_2O_3	75.3	112.7	15.7	12.0
FeO	37.6	2.9	.9	1.5
MgO	52.7	3.7	5.2	19.1
CaO	92.9	51.4	49.1	3.1
Na_2O	75.3	63.7	60.8	2.5
K_2O	50.2	56.4	51.5	68.8
H_2O^+	50.2	83.3	88.9	66.8
H_2O^-	32.6	41.6	46.8	49.7
TiO_2	15.3	16.2	15.4	11.8
P_2O_5	5.0	3.2	2.3	.1
MnO	2.3	.0	.0	.0
CO_2	2.0	.0	1.2	.0
FeS_2	42.7	156.8	--	--
Semiquantitative spectrographic analyses (parts per million)				
B	<10	<10	10	150
Ba	1,000	1,000	1,000	500
Be	2	<1	1.5	<1
Co	20	15	<5	<5
Cr	10	10	10	20
Cu	50	150	20	15
Ga	20	15	20	15
Mn	700	50	50	70
Ni	15	7	<5	<5
Pb	10	20	20	15
Sc	15	20	15	15
Sr	700	500	500	150
V	150	70	50	150
Y	100	15	10	7
Yb	10	1.5	1.5	1.5
Zr	100	100	100	70

1. Weakly propylitized Alta Formation containing finely disseminated pyrite.
2. Pyrite-bearing dark-colored inner core of block with outer envelope of bleached rock.
3. Outer bleached part of block that grades inward to unbleached core.
4. Bleached rock altered to illite and quartz.

[1] Total sulfur determined by H. N. Elsheimer by X-ray fluorescence.

Spectrographic and chemical analyses of the various alteration assemblages in table 11 show that the rocks are similar in composition to equivalent unoxidized rocks except for the decrease in sulfur. The highly silicified part of the ledge at the top of the roadcut, however, has undergone near-surface leaching of aluminum and enrichment of silica.

RESULTS OF GEOCHEMICAL SAMPLING

Samples of rock, soils, fracture fillings, and vein material were collected and analyzed to determine the distribution of metals in parts of the Virginia City quadrangle and to outline areas where anomalous values might be concentrated. Because the more intensely altered areas were believed to be more promising for exploration, a large number of the samples were taken from the extensive bleached areas near Virginia City,

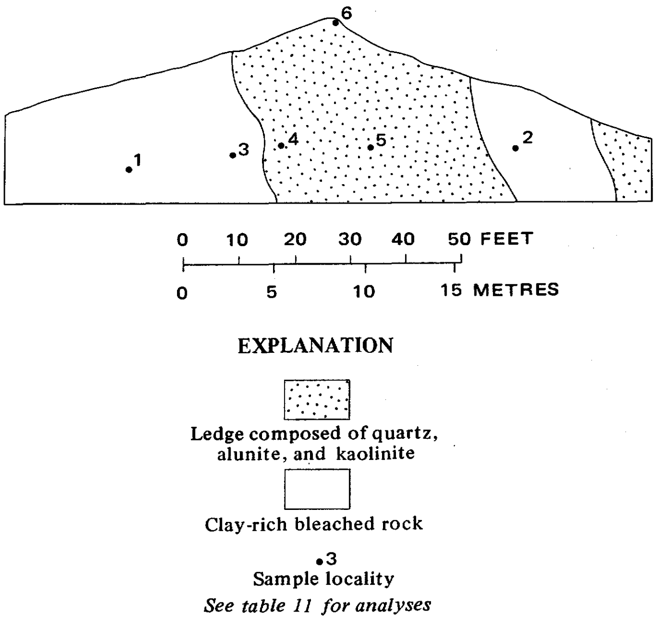


FIGURE 11.—Section across resistant ledge in bleached rock exposed in a roadcut along lower part of Geiger Grade.

TABLE 11.—*Analyses of bleached rocks exposed in a roadcut along the lower part of Geiger Grade*

[Sample localities are shown in fig. 11. Chemical analyses by P. L. D. Elmore, Gillison Chloe, Hezekiah Smith, S. D. Botts, Lowell Artis, James Kelsey, and J. L. Glenn: --, not detected; ND, not determined. Semiquantitative spectrographic analyses by E. L. Mosler; the following elements were not detected or were below the limit of detection shown—Ag(1), Au(.02), Be(1), Bi(7), Cd(50), Co(5), Mo(2), Nb(7), Sn(7), W(30), and Zn(100)]

Sample locality	1	2	3	4	5	6
Field No	81–1C	81–1K	81–1E	81–1G	81–1H	81–1A
Chemical analyses (weight percent)						
SiO_2	54.6	74.5	73.3	ND	60.1	91.6
Al_2O_3	24.2	14.8	15.0	ND	15.3	2.6
Fe_2O_3	.55	.59	.91	ND	.12	2.7
FeO	.08	.04	.08	ND	.04	.04
MgO	.57	.64	.24	ND	.05	.00
CaO	.08	.26	.09	ND	.14	.03
Na_2O	.16	.21	.22	ND	1.1	.01
K_2O	1.7	1.8	1.0	ND	2.6	.07
H_2O^+	8.7	3.3	2.9	ND	6.1	1.2
H_2O^-	8.8	3.4	4.1	ND	.00	.08
TiO_2	.62	.43	.87	ND	.46	.78
P_2O_5	.05	.06	.27	ND	.24	.12
MnO	.00	.00	.00	ND	.00	.00
CO_2	.05	<.05	.05	ND	<.05	.10
SO_3[1]	ND	ND	ND	ND	16.6	ND
Total (rounded)	100	100	100	ND	103	99
Bulk density	1.47	1.81	1.80	ND	2.24	1.98
Powder density	2.66	2.62	2.40	ND	2.80	2.70
Analyses converted to milligrams per cubic centimetre						
SiO_2	802.6	1,348.4	1,319.4	ND	1,346.2	1,813.7
Al_2O_3	355.7	267.9	270.0	ND	342.7	51.5
Fe_2O_3	8.1	10.7	16.4	ND	2.7	53.5
FeO	1.2	.72	1.4	ND	.90	.79
MgO	8.4	11.6	4.3	ND	1.1	.00
CaO	1.2	4.7	1.6	ND	3.1	.59
Na_2O	2.4	3.8	4.0	ND	24.6	.20
K_2O	25.0	32.6	18.0	ND	58.2	1.4
H_2O^+	127.9	59.7	52.2	ND	136.6	23.8
H_2O^-	129.4	61.5	73.8	ND	.00	1.6
TiO_2	9.1	7.8	15.7	ND	10.3	15.4
P_2O_5	.74	1.1	4.9	ND	5.4	2.4
MnO	.00	.00	.00	ND	.00	.00
CO_2	.74	.00	.90	ND	.00	2.0
Semiquantitative spectrographic and other analyses (parts per million)						
As[2]	10	30	30	40	40	50
B	10	50	50	15	20	20
Ba	700	1,000	500	1,000	1,000	300
Be	1	<1	<1	<1	<1	<1
Cr	20	5	20	20	10	<1
Cu	10	5	<5	30	<5	7
Hg[3]	.10	.22	.16	.45	.18	.26
La	<20	20	<20	20	20	<20
Mn	50	20	10	<10	10	15
Ni	10	5	<5	5	5	5
Pb	10	10	15	50	30	<10
Sb[4]	1	3	2	4	1	3
Sc	10	10	15	20	15	7
Sr	150	200	1,000	1,500	1,000	500
V	100	100	150	150	150	50
Y	<10	15	10	10	<10	<10
Zr	50	100	70	70	70	70

1. Illite, poorly crystallized clays, quartz, and minor remnant plagioclase.
2. Mixed-layer illite-montmorillonite, montmorillonite, and quartz.
3. Mixed-layer illite-montmorillonite, minor kaolinite, and quartz.
4. Kaolinite and quartz.
5. Alunite and quartz.
6. Chalcedonic quartz with minor kaolinite.

[1] Total sulfur determined by H. N. Elsheimer by X-ray fluorescence.

[2] Analyses by H. King by wet-chemical and colorimetric methods.

[3] Analyses by J. V. Desmond by instrumental atomic absorption.

[4] Analyses by S. L. Noble by wet-chemical and colorimetric methods.

within the Flowery district, northeast of Jumbo, in the Geiger Grade area, in the vicinity of the Castle Peak mine and the Washington Hill prospect, and near the Comstock fault north of Virginia City (fig. 2). Dumps of most small mines and prospect pits were sampled, but in the vicinity of the main Comstock lode samples were collected mainly from outcrops. Outside the known mineralized areas no well-developed quartz veins were found, and even minor quartz veinlets are rare. Cornwall, Lakin, Nakagawa, and Stager (1967, p. B11) previously reported anomalous amounts of mercury in the bleached rocks and pointed out several areas that they considered promising for gold-silver mineralization. Bonham (1969, p. 107) also considered the large areas of alteration to be attractive exploration targets.

The distribution of anomalous values of gold, silver, lead, and mercury in nearly 1,100 samples of rock and soil is shown on the geochemical maps in figures 12–15. Where several samples were collected from a single locality, the highest value reported is shown, and one symbol may represent several localities where samples are closely spaced. The threshold level, the value above which the concentration of an element is considered to be anomalous, was determined from cumulative frequency curves plotted on log-normal probability paper (Lepeltier, 1969, p. 544). The threshold level is the value above which 2.5 percent of the sample population falls, assuming the distribution is log-normal. The threshold levels used are those determined for unaltered and nonpyritic weakly propylitized rocks in surface exposures and drill holes. Because most of the values for gold and silver were below the minimum amount detectable, the threshold levels for these elements were arbitrarily defined as these minimum values (0.02 ppm gold and 0.5 ppm silver).

Anomalous gold and silver are scattered widely through most of the areas sampled, but all samples containing 5 ppm or more of gold or more than 15 ppm silver are from veins in the Comstock Lode, Flowery, or Jumbo districts. Most occurrences of lead in quantities of 500 ppm or more are also in these districts. Anomalous values of these metals in the footwall block of the Comstock fault west of Virginia City are mostly from small veins related to the Davidson Granodiorite. Although this area has been heavily prospected, no significant ore deposits have been developed. Only a few samples in the northern two-thirds of the quadrangle contained 1 ppm or more of gold or silver. Of the four samples in the Geiger Grade area that contain 1–5 ppm gold (fig. 12), two are from alunite-quartz ledges, the third is from typical clay-rich bleached rock, and the fourth is from a fracture filling in similar rock. Of the two samples along the northern part of the Comstock fault that contain 15 ppm silver (fig. 13), one is from an alunite-quartz ledge, and the other is from fractured propylitized rock that contains abundant zeolites. The scattered samples containing 1–10 ppm silver in this area and in the Geiger Grade and Washington Hill areas are from several varieties of bleached rocks.

The average concentration of lead is slightly higher in bleached rocks than in their unoxidized equivalents or in relatively unaltered rocks (table 9), but anomalous values (>50 ppm) are only sparsely scattered in the areas sampled (fig. 14). Anomalous lead values in bleached rocks are mainly from samples of alunite-quartz ledges, although some of the values in the vicinity of the Washington Hill prospect are from opalite. Geochemical maps for copper and zinc were not included in the report because of the small number of anomalous localities. Anomalous copper (>150 ppm) was found at only 16 localities, and most of these are in the southern one-third of the quadrangle.

The relatively few sample localities where anomalous quantities of silver, gold, copper, or lead were found do not provide adequate data for a statistical determination of correlation coefficients. Simple tabulations of the frequency of mutual occurrence of these metals indicate a correlation between silver and gold in the vicinity of Virginia City, but no correlations between these metals or with copper or lead are indicated elsewhere.

As shown in table 9, the average concentration of mercury in the hydrothermally altered rocks and bleached rocks is higher than in the relatively unaltered rocks. The higher background levels result mainly from anomalous values (>1.5 ppm) in samples from the alunitic zones. The excess of high values results in a non-log-normal distribution of mercury, as shown for surface samples in figure 16 by a break in the slope of the cumulative frequency distribution line. Anomalous mercury is concentrated in bleached rocks near the Castle Peak mine, along the northern extension of the Comstock fault, north of Jumbo, and near the Washington Hill prospect (fig. 15). Anomalous mercury was reported in samples of clay-rich bleached rocks, alunite-quartz ledges, and minor opalite near DDH–3, and it is closely associated with alunite-quartz-pyrite and kaolinite-quartz-pyrite assemblages to a depth of 214 m (700 ft) in the drill hole. The bleached areas in the vicinity of Virginia City, the Flowery district, and the Geiger Grade yielded only a few samples containing anomalous mercury, although alunite-quartz ledges are very common in the Geiger Grade area.

The mercury anomalies north of Jumbo mainly occur in and adjacent to resistant alunite-quartz ledges. Some of the ledges developed along small northeast- and east-trending faults in propylitized Alta Formation (fig. 17). Silicified ledges in nearby bleached rocks have similar trends and also probably are along faults or

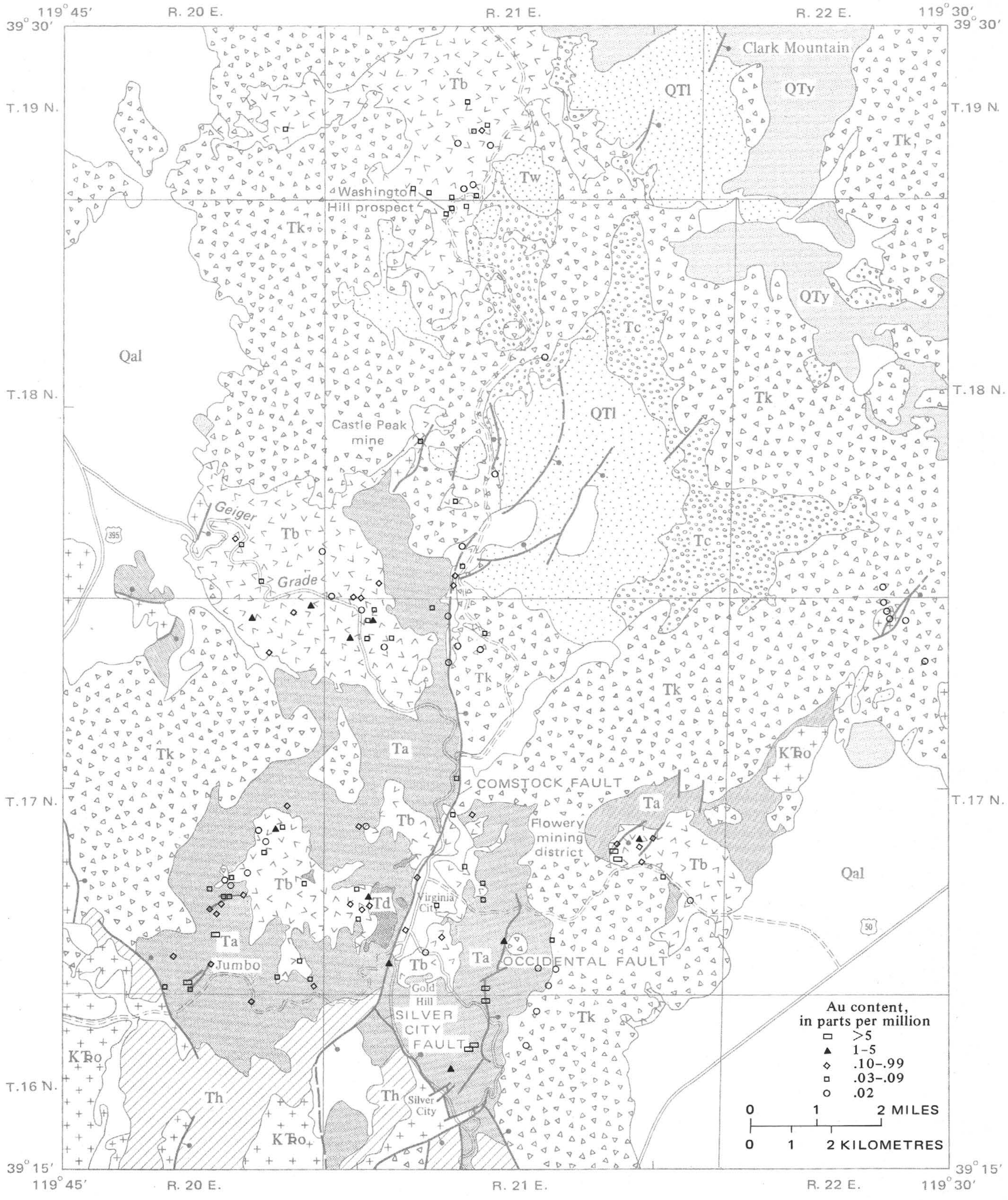


FIGURE 12.—Geochemical map showing distribution of anomalous gold in Virginia City quadrangle. See figure 2 for explanation of geology.

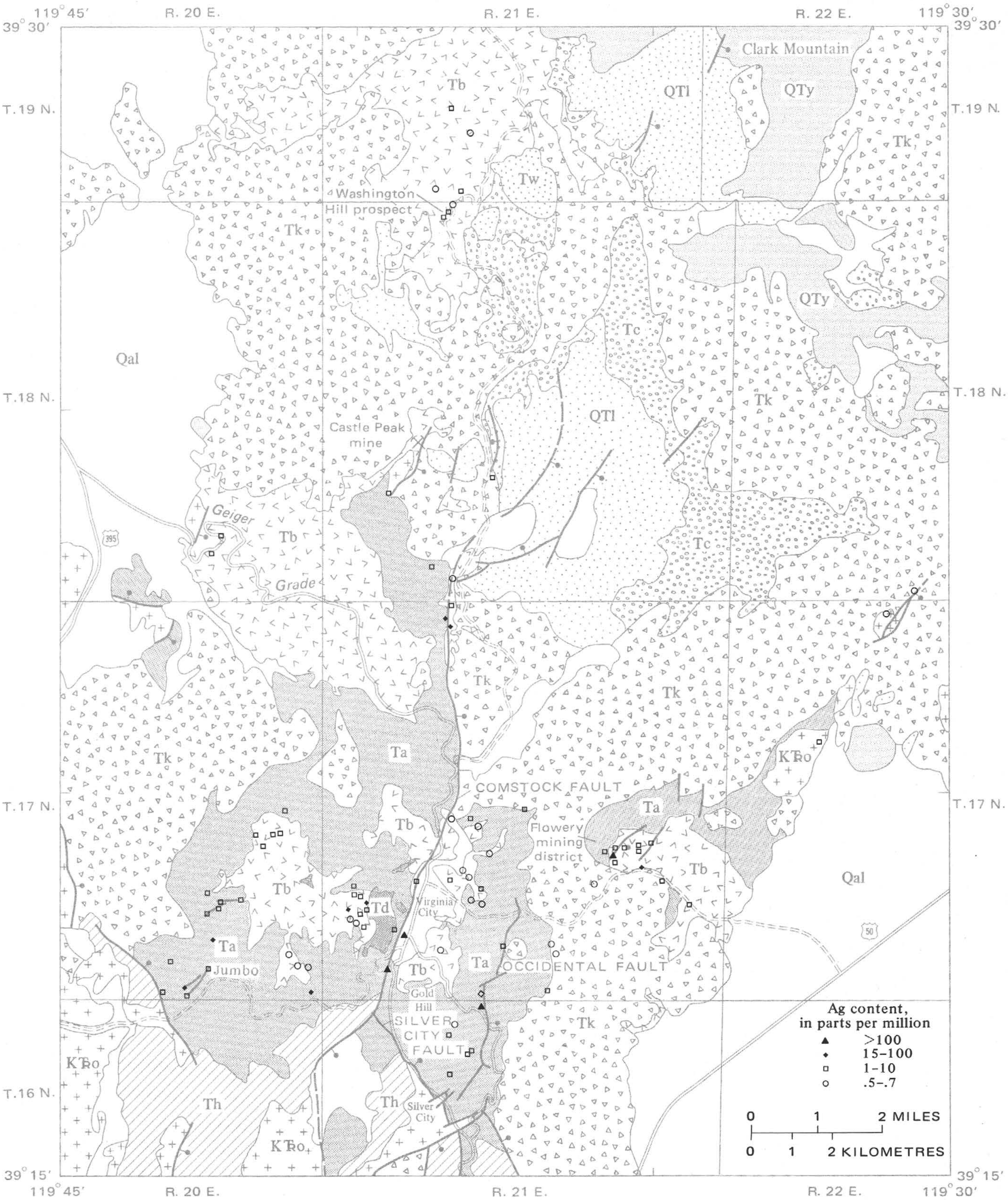


FIGURE 13.—Geochemical map showing distribution of anomalous silver in Virginia City quadrangle. See figure 2 for explanation of geology.

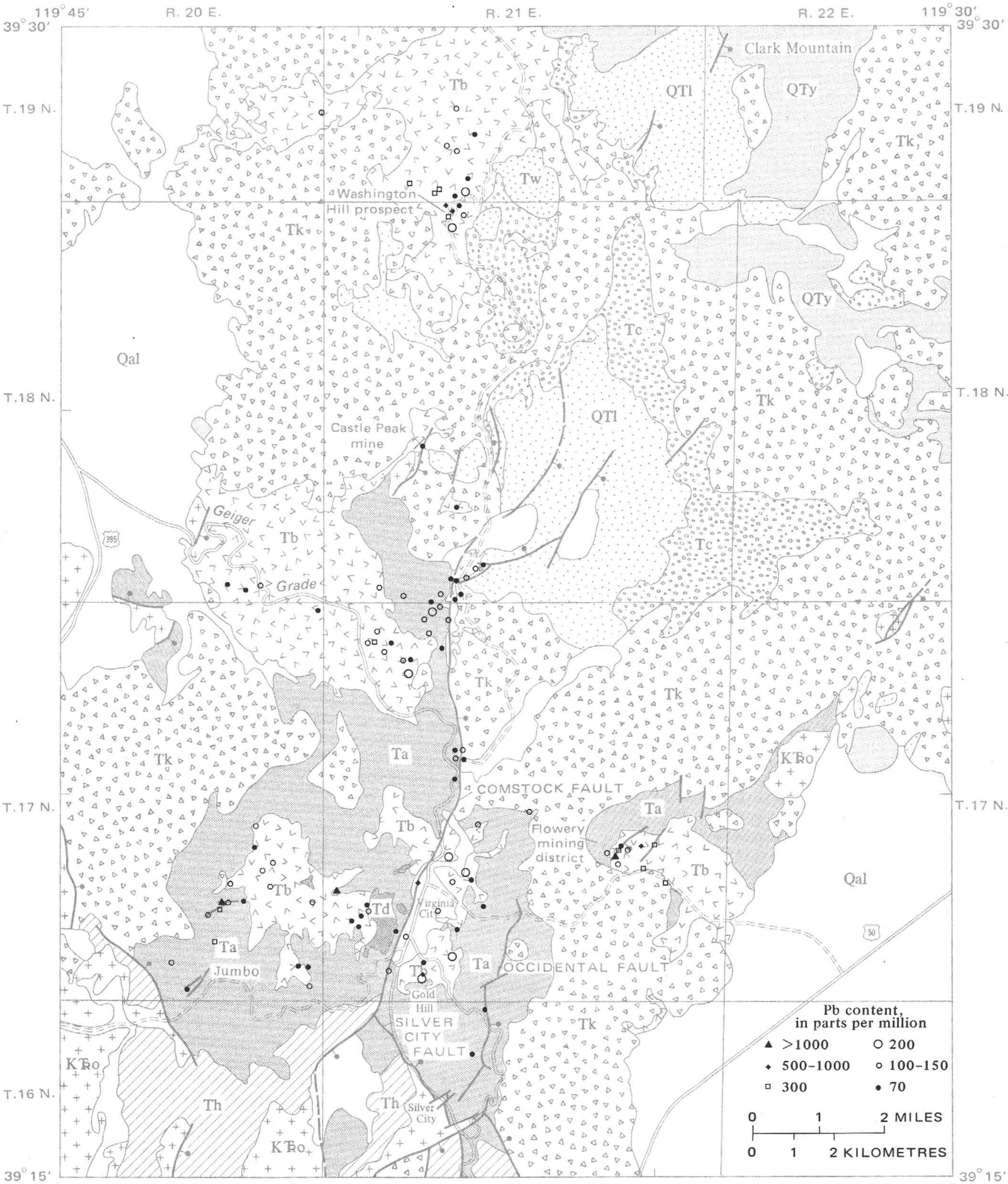


FIGURE 14.—Geochemical map showing distribution of anomalous lead in Virginia City quadrangle. See figure 2 for explanation of geology.

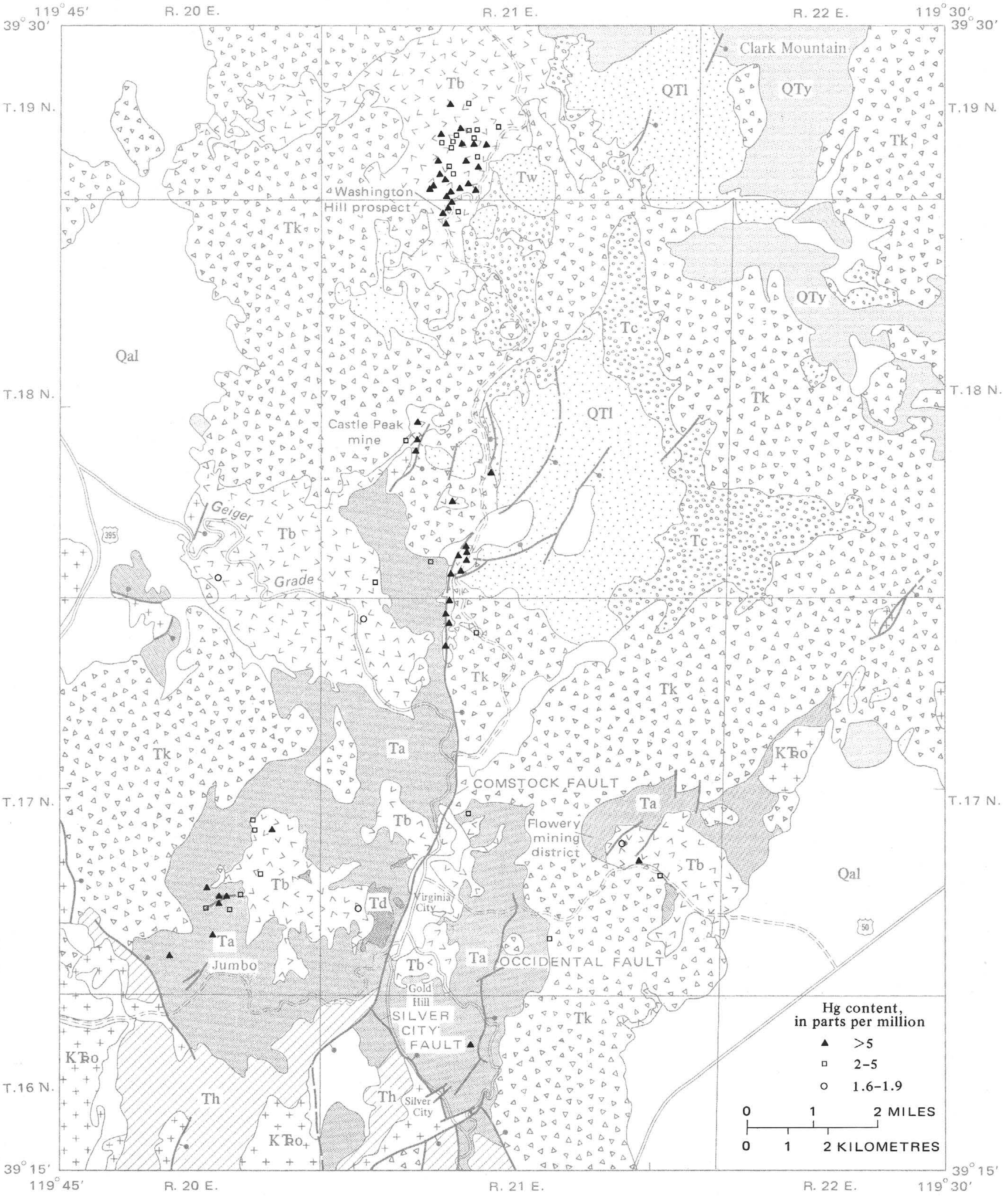


FIGURE 15.—Geochemical map showing distribution of anomalous mercury in Virginia City quadrangle. See figure 2 for explanation of geology.

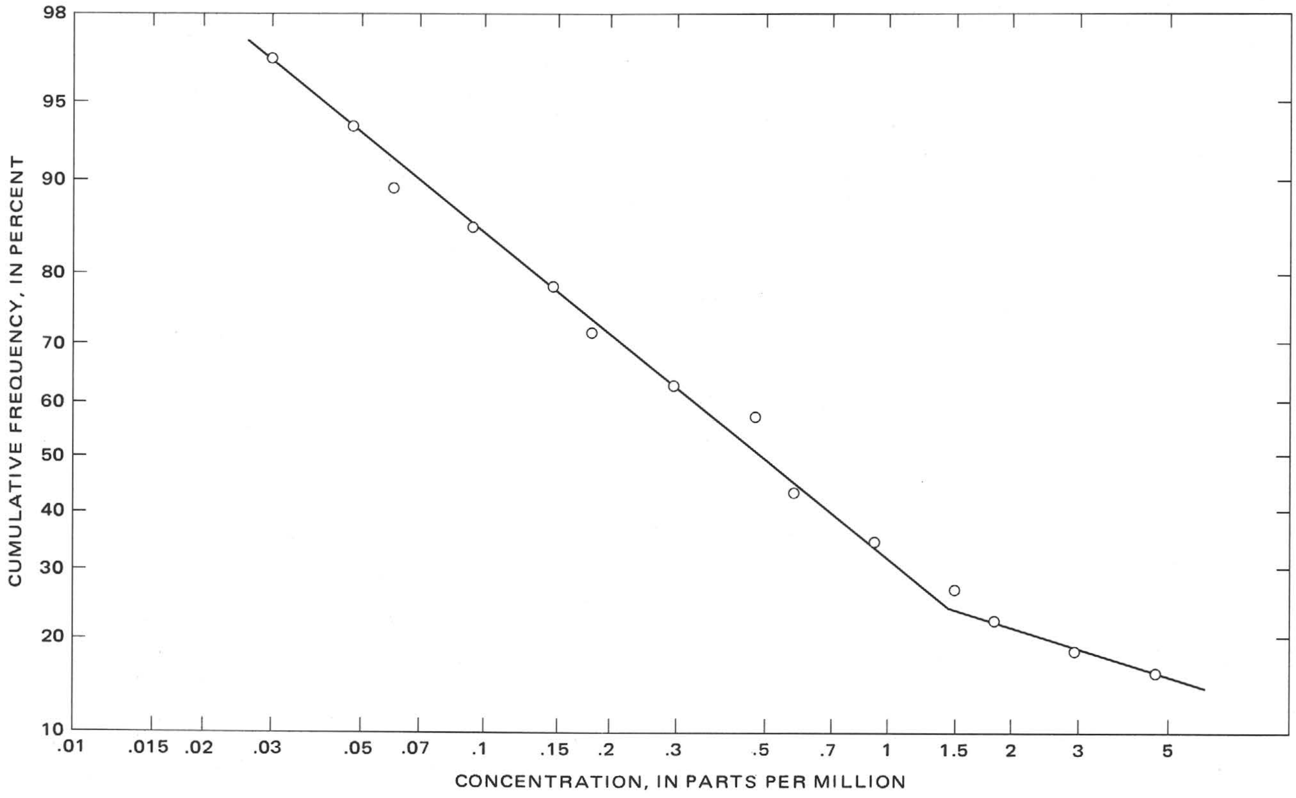


FIGURE 16.—Cumulative frequency distribution of mercury in 606 samples of bleached rocks and soils.

fractures. The ledges in the propylitized rock are commonly 1.5–3 m (5–10 ft) wide and have a narrow border zone composed of quartz and kaolinite, montmorillonite, or mixed-layer illite-montmorillonite. Several samples from the ledges or the adjacent argillized envelopes also contain anomalous antimony (200–500 ppm), silver (1–3 ppm), gold (0.04–6 ppm), arsenic (500–1,000 ppm), or lead (200–300 ppm).

Red iron-oxide stains in the bleached rock in the vicinity of the Washington Hill prospect apparently attracted prospectors searching for cinnabar (Thompson, 1956, p. 72); however, only a few flasks of mercury were produced from the Washington Hill prospect, and no other workable ore has been found. The widespread anomalous mercury in the area has been noted by Cornwall, Lakin, Nakagawa, and Stager (1967, p. B11–B13) and by Whitebread and Hoover (1968, p. 18). The highest concentrations of mercury are in opalite and in alunite-bearing ledges, most of which trend north or northeast. Analyses of several samples from the resistant ledges, opalite, and iron-stained fracture fillings are given in table 12. The anomalous mercury in DDH–4 about one-half km northeast of the Washington

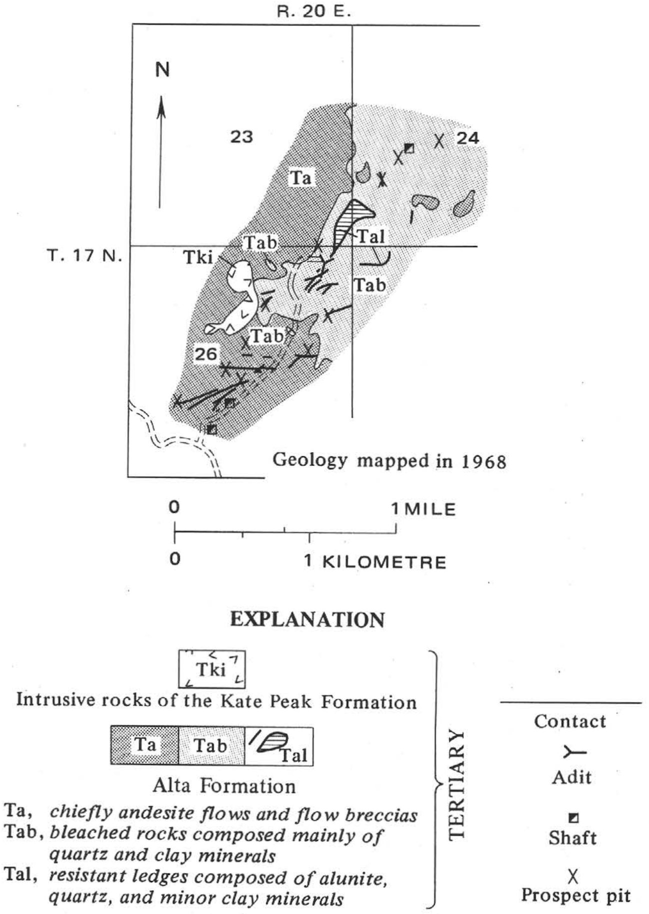


FIGURE 17.—Geologic map of area northeast of Jumbo showing distribution of alunite-quartz ledges in both bleached and propylitized rocks of the Alta Formation.

Table 12.—*Analyses of samples containing anomalous mercury and other metals from alunite- and jarosite-bearing resistant ledges, opalite, and fracture fillings in the vicinity of the Washington Hill prospect*

[Sample localities are shown in fig. 5. All values are in parts per million. Semiquantitative spectrographic analyses for all elements except gold and mercury by D. J. Grimes and E. L. Mosier. The following elements were not detected or were below the limit of detection shown in all samples: Be(1), Cd(20), Co(5), Sn(10), W(50), Zn(200). Analyses of Au by W. L. Campbell, M. S. Rickard, T. A. Roemer, and R. F. Hansen by atomic absorption spectrophotometry. Analyses of Hg by K. Murphy and J. V. Desmond by instrumental atomic absorption]

	Alunite-quartz ledges						Alunite-jarosite-quartz ledges				Opalite				Fracture fillings	
Sample No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	[1]15	[2]16
Field No	4–46B	99–70B	99–99H	99–88	99–96A	4–21H	4–21E	4–36A	99–94B	99–95B	4–49E	99–100A	99–110G	99–112	4–27	4–30F
Ag	<0.5	<0.5	0.5	<0.5	2	2	0.5	<0.5	0.5	1	<0.5	<0.5	0.7	0.7	<0.5	0.5
As	<200	<200	<200	<200	<200	4	<200	<200	<200	<200	<200	<200	300	200	100	200
Au	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	.04
B	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	10	10	15	20	20
Ba	700	700	3,000	700	300	1,000	1,000	200	1,000	700	200	700	5,000	3,000	2,000	2,000
Bi	<10	<10	<10	<10	10	150	70	<10	50	300	<10	<10	70	70	100	200
Cr	10	5	30	10	5	10	10	5	15	7	20	70	70	30	5	10
Cu	20	30	30	30	20	15	15	5	20	30	100	20	70	150	500	100
Hg	6.5	>6	>6	>6	>6	.36	7.5	4.9	>6	5	3.6	>6	>6	>6	.21	.36
La	<20	50	100	<20	<20	<20	<20	<20	20	30	<20	70	70	50	<20	<20
Mn	50	15	<10	10	10	10	<10	50	<10	10	10	20	15	30	20	20
Mo	10	<2	<2	<2	<2	5	5	<2	<2	5	<2	<2	7	<5	20	20
Nb	10	<7	<7	<7	<7	<10	<7	10	<7	<10	10	10	10	15	10	10
Ni	5	<2	<2	2	3	<5	<2	5	<2	2	<2	<2	3	10	5	5
Pb	20	20	70	<10	20	300	300	100	150	50	10	10	200	200	100	30
Sb	<100	<100	<100	<100	<100	500	100	<100	<100	<100	<100	<100	<100	100	150	500
Sc	15	7	7	5	7	5	5	5	7	7	15	20	7	7	15	<5
Sr	200	1,000	3,000	300	300	500	500	700	1,500	700	300	700	700	700	500	<100
V	200	100	150	50	30	200	100	100	70	100	150	200	100	150	50	150
Y	10	10	<10	10	<10	<10	<10	<10	10	10	<10	30	<10	<10	50	<10
Zr	150	70	150	150	100	100	50	100	70	150	200	300	300	300	500	200

[1]Sample collected 790 m (2,600 ft) N. 35° W. from sample 2.
[2]Sample collected 700 m (2,300 ft) N. 50° W. from sample 2.

Hill prospect is associated with alunite-quartz-pyrite and alunite-jarosite-quartz assemblages to depths as much as 214 m (700 ft).

Several of the samples in table 12 also contain anomalous bismuth, lead, and silver. Bismuth in amounts greater than 10 ppm was found at only 16 localities in the Virginia City quadrangle; it is present in amounts of 50 ppm or more at seven of the localities, all of which are in alunite-quartz or opaline rocks or fracture fillings in the vicinity of the Washington Hill prospect. Analyses of the seven samples (table 12) show some correlation between bismuth and anomalous amounts of silver, antimony, and several other elements, and a similar relation was noted at depth in DDH–4.

Arsenic and antimony in nearly all samples are below the minimum values detectable by spectrographic methods, and because many samples were not analyzed for these elements by the more sensitive colorimetric methods, the data on distribution of anomalous values is not complete. Arsenic in amounts of 200 ppm or more was found at 29 localities, and antimony in amounts of 100 ppm or more was found at 14 localities, most of which were siliceous ledges in the vicinity of the Washington Hill prospect or north of Jumbo. Several of the higher values for arsenic are from samples of fracture fillings in the bleached rocks. About half the samples that contain anomalous antimony also contain anomalous arsenic and mercury, and a few contain anomalous lead or copper.

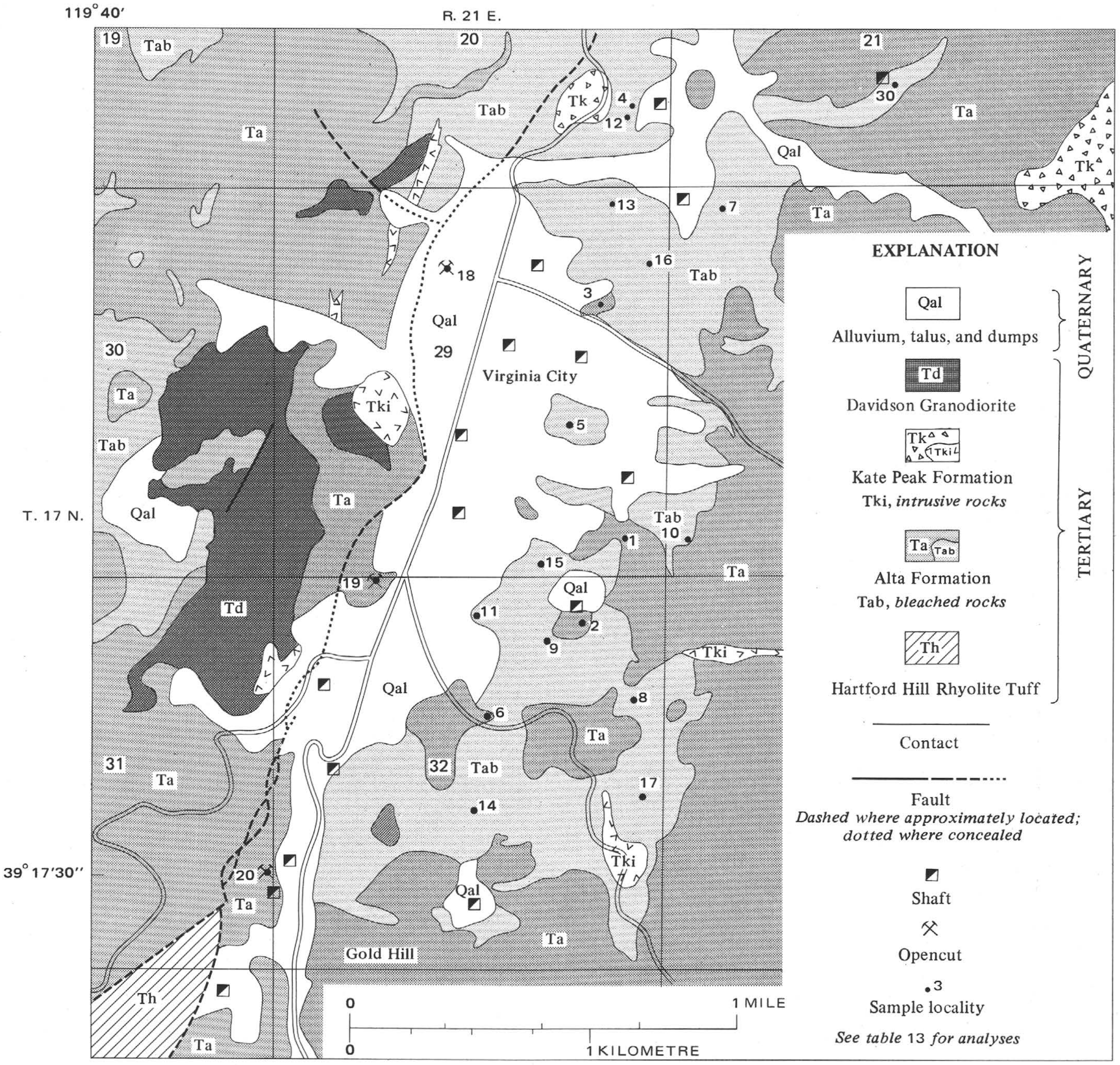
Bleached rocks are extensive in the hanging-wall block of the Comstock fault in the vicinity of Virginia City (fig. 18), and their presence is accentuated by the large amount of bleaching that has occurred in pyrite-rich rocks on the mine dumps. The ore contained gold, argentite, sphalerite, galena, chalcopyrite, pyrite, and minor polybasite and stephanite (Bastin, 1923). Gold, silver, and lead are relatively immobile in the supergene environment and thus would be the best indicator elements of the major ores, whereas zinc and copper are readily leached. Some analyses of typical samples of altered country rock, veins, and fracture fillings in the area are given in table 13. Sampling near the outcrop of the Comstock fault was largely prevented by the mine dumps and colluvium downslope from the fault. The quartz vein material was collected from three large open cuts where low-grade ore was mined along the Comstock fault.

Although a few samples contain anomalous amounts of lead, bismuth, or arsenic, results of the geochemical sampling in the vicinity of Virginia City indicate little dispersal of ore-related metals into the country rock, and thus sampling for gold-silver lode deposits like those in the Comstock Lode, Flowery, and Jumbo dis-

TABLE 13.—*Analyses of rocks, fracture fillings, and quartz vein material*

[Sample localities are shown in fig. 18. All values are reported in parts per million. ND, not determined. Analyses of Ag, Bi, Ci, Pb, and Zn by E. L. Mosier, J. M. Motooka, D. J. F. Hansen, and J. G. Viets by atomic absorption spectrophotometry. Analyses of As by W. L. Campbell and H. King by wet chemical and

	Propylitized rock, Alta Formation			Montmorillonite-illite-quartz				Kaolinite-quartz				Alunite-quartz		
Locality No	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Field No	6–154	6–28A	6–38A	6–126	6–146A	6–156B	6–51B	6–21	6–31	6–40	6–33	6–127B	6–59A	6–150B
Ag	<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
Au	ND	<.1	<.1	<.02	<.02	<.02	<.1	<.1	<.1	<.1	<.1	<.02	<.1	<.02
As	ND	5	0	ND	ND	<10	10	40	5	0	10	40	30	ND
Bi	<10	<10	<10	<10	<10	<10	<10	30	<10	<10	<10	<10	<10	10
Cu	70	50	100	10	2	15	10	10	10	7	10	50	70	100
Hg	ND	.12	.10	.03	.03	.20	.12	.40	.10	.11	.11	.70	.03	.04
Pb	20	20	15	70	50	10	300	200	50	70	50	50	<10	1,000
Zn	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200



Geology modified from Calkins and Thayer (1945)

FIGURE 18.—Geologic map of Virginia City area showing distribution of bleached rocks in the Alta Formation.

in the hanging-wall block of the Comstock fault near Virginia City

Grimes, and K. C. Watts by semiquantitative spectrographic methods. Analyses of Au by T. G. Ging, G. H. Van Sickle, W. L. Campbell, M. S. Richard, T. A. Roemer, R. B. Tripp, R. colorimetric methods. Analyses of Hg by W. L. Campbell, K. Murphy, W. W. Janes, and J. V. Desmond by instrumental atomic absorption]

Quartz ledge		Fracture fillings									Quartz vein material		
15 6–35	16 6–49	2 6–28F	3 6–38E	8 6–21F	9 6–31F	11 6–33F	13 6–59F	15 6–35F	16 6–49F	17 6–22F	18 6–89C	19 6–90B	20 6–93K
<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.7	0.5	<0.5	3	30	30
<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	—	<.02	<.02	.7
20	10	5	10	240	160	40	40	10	30	30	10	5	ND
<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
5	50	30	100	30	100	100	70	30	70	300	1,000	50	20
.08	.08	.10	.06	.19	.74	.19	.28	1.3	.13	.80	.12	.45	.26
<10	100	30	20	15	20	30	30	15	70	30	1,000	100	100
<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	1,000	<200	<200

tricts should be limited to veins, associated fractures, and alluvial or colluvial debris from the veins.

A feature common to all the known gold and silver deposits in the quadrangle is their close relation to faults; the main ore control for the quicksilver deposits at the Castle Peak mine also is a fault. The gold and silver at the Ramsey–Comstock mine a few kilometres farther east in the Flowery Range is in an alunitic zone along a northeast-tending fault (Rose, 1969, p. 25). Anomalous amounts of metals are disseminated in some alunite-quartz ledges, but with the possible exception of the Washington Hill prospect, they have not been found in economic concentrations.

Most fracture zones along which alunite-quartz ledges formed apparently did not provide access to ore-bearing fluids. The alunite-quartz ledges may be analogous to those in the Goldfield district, where they are nearly barren of ore except for those near the Columbia Mountain fault (Searls, 1948, p. 20). Further geochemical exploration in areas of bleached rocks should concentrate on those ledges developed along or near faults or breccia zones or along the projection of such structures into the bleached areas. It seems doubtful that extensive geochemical sampling in areas of bleached rocks lacking such structures is warranted by the occurrences of anomalous but generally minor concentrations of metals.

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