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DETECTION AND MAPPING OF HYDROTHERMALLY ALTERED ROCKS IN THE VICINITY OF THE COMSTOCK LODE, VIRGINIA RANGE, NEVADA, USING ENHANCED LANDSAT IMAGES

By R. P. Ashley, A. F. H. Goetz,
L. C. Rowan, and M. J. Abrams

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By R. P. Ashley,[1] A. F. H. Goetz,[2]
L. C. Rowan,[3] and M. J. Abrams[2]

ABSTRACT

The Virginia Range, immediately southeast of Reno, Nev., consists mainly of flows, breccias, and tuffs of Miocene age. Most of these volcanic rocks are of intermediate composition; rhyodacite is the most common rock type. Basalt, rhyolite and rhyolite tuff, and tuffaceous sedimentary rocks of Miocene and Pliocene age also cover substantial areas in the range. Pre-Tertiary metasedimentary, metavolcanic, and granitic rocks are exposed in scattered inliers, mostly along the southern and eastern margins of the range. Several large areas and many small areas within the volcanic pile were subjected to hydrothermal alteration during and after the period of intermediate volcanic activity. Economic precious metal mineralization is spatially and temporally associated with the hydrothermal alteration in several areas. The most important deposit is the Comstock Lode, which produced 192 million troy ounces of silver and 8.3 million troy ounces of gold from epithermal veins (Bonham, 1969).

The hydrothermally altered rocks include silicified, advanced argillic, montmorillonite-bearing argillic, and propylitic types. The first three types typically contain pyrite, and some propylitic rocks contain pyrite as well. Supergene oxidation of these pyritic rocks produces limonitic bleached rocks. The term "limonite," as used here, refers to any combination of the minerals hematite, goethite, and jarosite. Where vegetation cover is sparse to moderate, these limonitic rocks are readily identified on Landsat images enhanced by the color-ratio composite technique developed by Rowan and others (1974), so the altered areas can be mapped. About 30 percent tree cover (here mainly pinyon pine) is sufficient to change the spectral signature of individual picture elements (pixels) enough so that limonitic materials can no longer be uniquely identified. As in all other areas where this technique has been applied, limonitic unaltered rocks with intermediate to high albedos have the same appearance on the color-ratio composite as limonitic altered rocks. This problem represents the most important limitation to the use of enhanced Landsat images for detection and mapping of hydrothermally altered rocks. Reflectance spectra of altered and unaltered rocks taken in the field in the Virginia Range show that most altered rocks have a conspicuous absorption band near 2.2 μm produced by clay minerals or alunite, whereas unaltered rocks have no features in this spectral region. Thus spectral information for selected bands in the 1.1-2.5 μm region may allow discrimination between limonitic

[1]U.S. Geological Survey, Menlo Park, California 94025
[2]Jet Propulsion Laboratory, Pasadena, California 91103
[3]U.S. Geological Survey, Reston, Virginia 22092

altered and limonitic unaltered rocks (Rowan and others, 1977; Abrams and others, 1977; Rowan and Abrams, 1978).

Another potential limitation is loss of spectral information on slopes with low effective sun angle. Although a minor problem in the Virginia Range, loss of information sufficient to preclude identification of limonitic altered rocks occurs with effective sun angle lower than 20-25 degrees. Thus, even at moderate latitudes substantial parts of areas with high topographic relief may be lost to observation.

INTRODUCTION

Many studies have shown that limonitic rocks can be discriminated from other rocks in Landsat Multispectral Scanner (MSS) images (Vincent, 1973, 1975; Rowan and others, 1974; Schmidt, 1976; Offield, 1976; Raines, 1977). Rowan and others (1974) have shown that limonitic hydrothermally altered rocks can be recognized in enhanced Landsat Multispectral Scanner (MSS) images for a test area in south-central Nevada.

Rowan and others (1974) made gray-tone film positives for MSS band ratios 4/5, 5/6, and 6/7, and used these positives to screen blue, yellow, and magenta diazo foils, respectively[1]. The three diazo films, in which degree of saturation is inversely proportional to ratio value, are overlaid to produce a color subtractive color-ratio composite (CRC image). In this composite image, limonitic hydrothermally altered rocks generally appear green, because for such rocks reflectance rises rapidly with increasing wavelength in the visible region (0.4-0.7 μm), giving low 4/5 (intense blue) and low to moderate 5/6 (intense yellow), then drops from 0.75 to about 0.9 μm and rises again to 1.1 μm, giving a relatively high 6/7 (weak magenta). The minimum at 0.9 and the relatively steep slope of the spectral reflectance curve from 0.4 to 0.75 μm are produced by electronic transitions in the ferric ion present in limonite minerals (Hunt and others, 1971).

The purpose of this study is to test the usefulness of this band-ratioing enhancement method in another area with similar altered rocks but different vegetation and slope conditions. In south-central Nevada Rowan and others (1974) readily separated bleached and limonitic silicified, advanced argillic, phyllic, and argillic rocks of the Goldfield, Cactus Springs, Antelope Springs, Gold Crater, and Gold Reed mining districts from surrounding unaltered rocks and most nearby alluvium. Relief in the altered areas is low to moderate and vegetation is sparse. The Virginia Range was chosen as a second test area for the following reasons: (1) vegetation cover is heavier than in south-central Nevada, but variable enough over the altered areas to get an idea of maximum acceptable vegetation cover (2) proportions of various rock types and proportions of heavily forested areas relative to sparsely vegetated areas are different in the vicinity of the Virginia Range than in south-central Nevada (3) topographic relief is greater (4) good geologic maps are available (Thompson, 1956; Rose, 1969) which show hydrothermally altered rocks, and (5) access is generally good. Time did not permit detailed examination of the entire Virginia Range, so we devoted most of our effort to the Virginia City quadrangle, which includes the most prominent altered areas (fig. 1). The discussion, however, includes some comments on less detailed observations made elsewhere in the range.

With regard to vegetation cover, the purpose here is to determine semiquantitatively the amount of cover that results in enough loss of spectral information from rock and soil so that hydrothermally altered rocks can no longer be discriminated from other materials. Furthermore, the proportion of vegetation in a particular Landsat scene affects the contrast stretch (mathematical transformation) used to match the range of values for each

[1]MSS band 4 covers the spectral range 0.5-0.6 μm, band 5 covers 0.6-0.7 μm, band 6 covers 0.7-0.8 μm, and band 7 covers 0.8-1.1 μm.

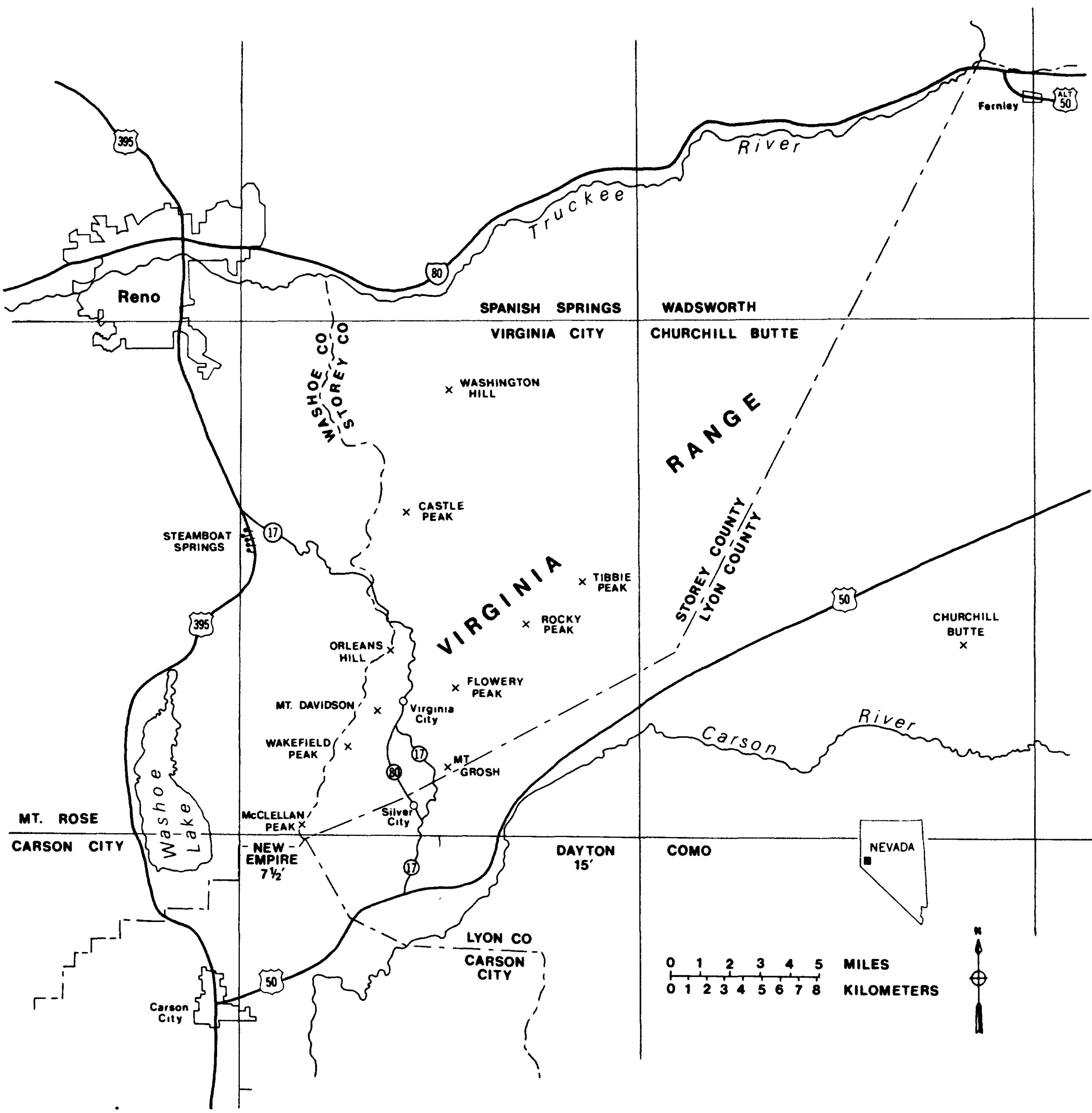
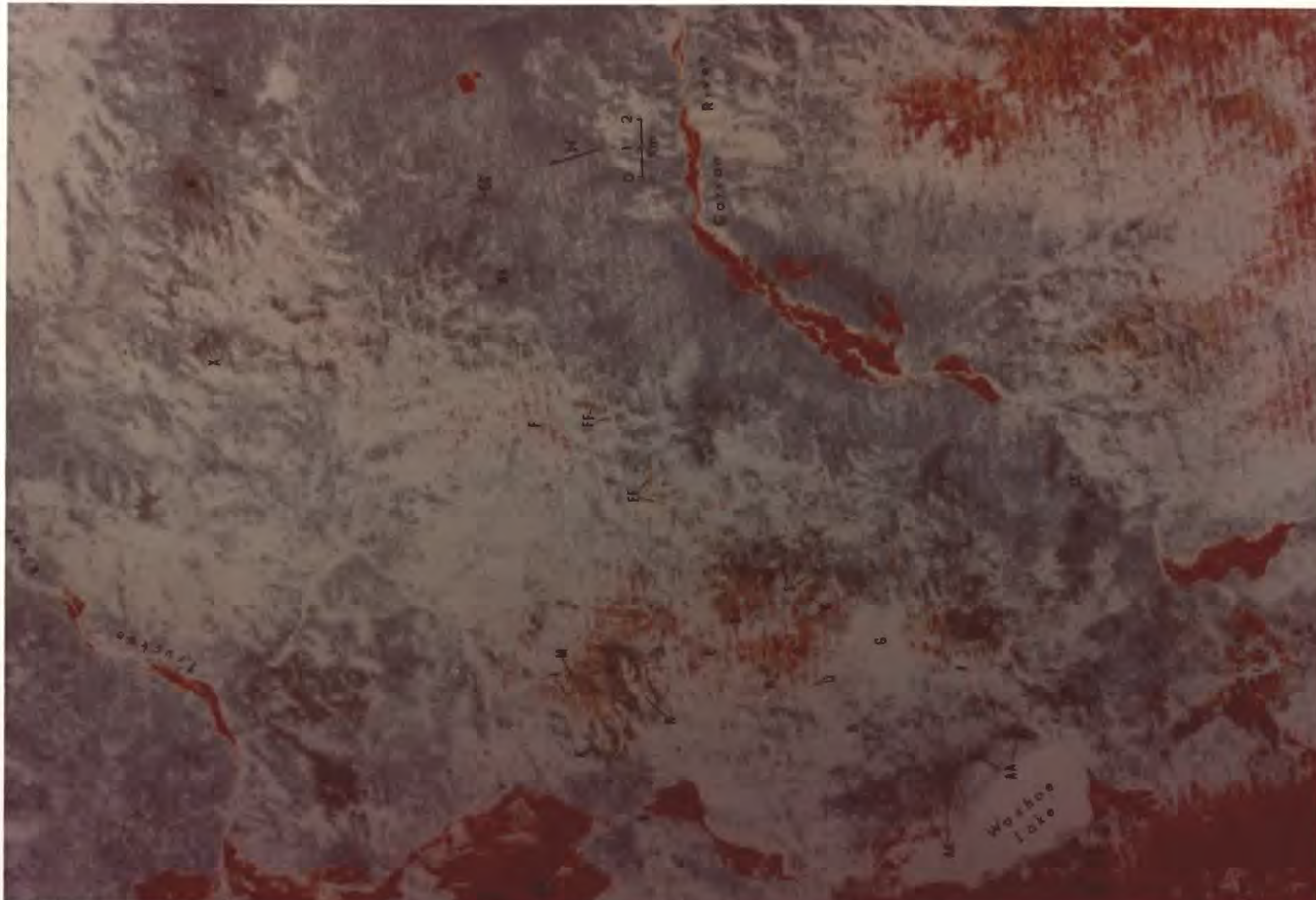


Figure 1. Location map for the Virginia Range and vicinity, Nevada.

Ashley and others Fig 4



spectral band or band ratio to the dynamic range of the film recording medium (see Rowan and others, 1974; Soha and others, 1976; and Goetz and others, 1975, for further explanation). A different proportion of vegetation in the scene (and to a lesser extent a different mix of rock types) therefore allows us to test whether the technique is highly sensitive to the type of stretch used, and if so, what variations in the technique may be required for optimum results in different areas. Although ratioing tends to remove first-order slope angle affects which are related mainly to variations in sun angle, steep topography may produce residual slope affects. Topographic relief in the altered areas studied in the south-central Nevada scene was not large enough to see whether such affects could produce significant variations in the appearance of altered areas in enhanced images. In the Virginia Range altered areas relief is relatively high, but generally not high enough to produce significant shadow areas, giving us a better opportunity to examine this potential source of variation.

ACKNOWLEDGMENTS

This study was carried out as part of NASA Landsat follow-on experiment number 389. We would like to thank personnel of the Nevada Bureau of Mines and Geology, especially E. C. Bingler and H. F. Bonham, for valuable discussions of the geology of the Virgina Range. Susan T. Miller of the U.S. Geological Survey assisted in making field spectral measurements and in laboratory work on samples. Helen Paley of the Jet Propulsion Laboratory assisted with reduction of the field spectral data and also assisted with field spectral measurements. Others who assisted in various ways for brief periods include Dennis Krohn, Gary Raines, Pamela Wetlaufer, and Carolyn Pugh of the U.S. Geological Survey, and James Soha of the Jet Propulsion Laboratory.

METHODS

General

To evaluate the usefulness of the Landsat Multispectral Scanner (MSS) band-ratioing technique for delineating hydrothermally altered areas in terrain like that of the Virginia Range, we produced various color ratio composite images and intermediate image products and compared them with Thompson's (1956) geologic and alteration map. The altered areas were then examined in the field, with particular attention paid to localities where boundaries of altered areas determined by field mapping differed from those inferred from the CRC images. In an attempt to fully determine differences between altered and unaltered rocks and sources of variation within altered areas, we obtained in situ field spectral reflectance measurements, and determined the sources of spectral features by semiquantitative determinations of mineral composition. Thus to cover the full range of activities involved in this project, image processing methods, field measurement of reflectance spectra, field sampling methods, and laboratory petrographic methods must all be described. Abrams, Rowan, and Goetz were primarily responsible for image processing, Ashley and Rowan for image interpretation and field examination, Goetz and Abrams for field spectral reflectance measurements and data reduction, and Ashley for field sampling and petrography.

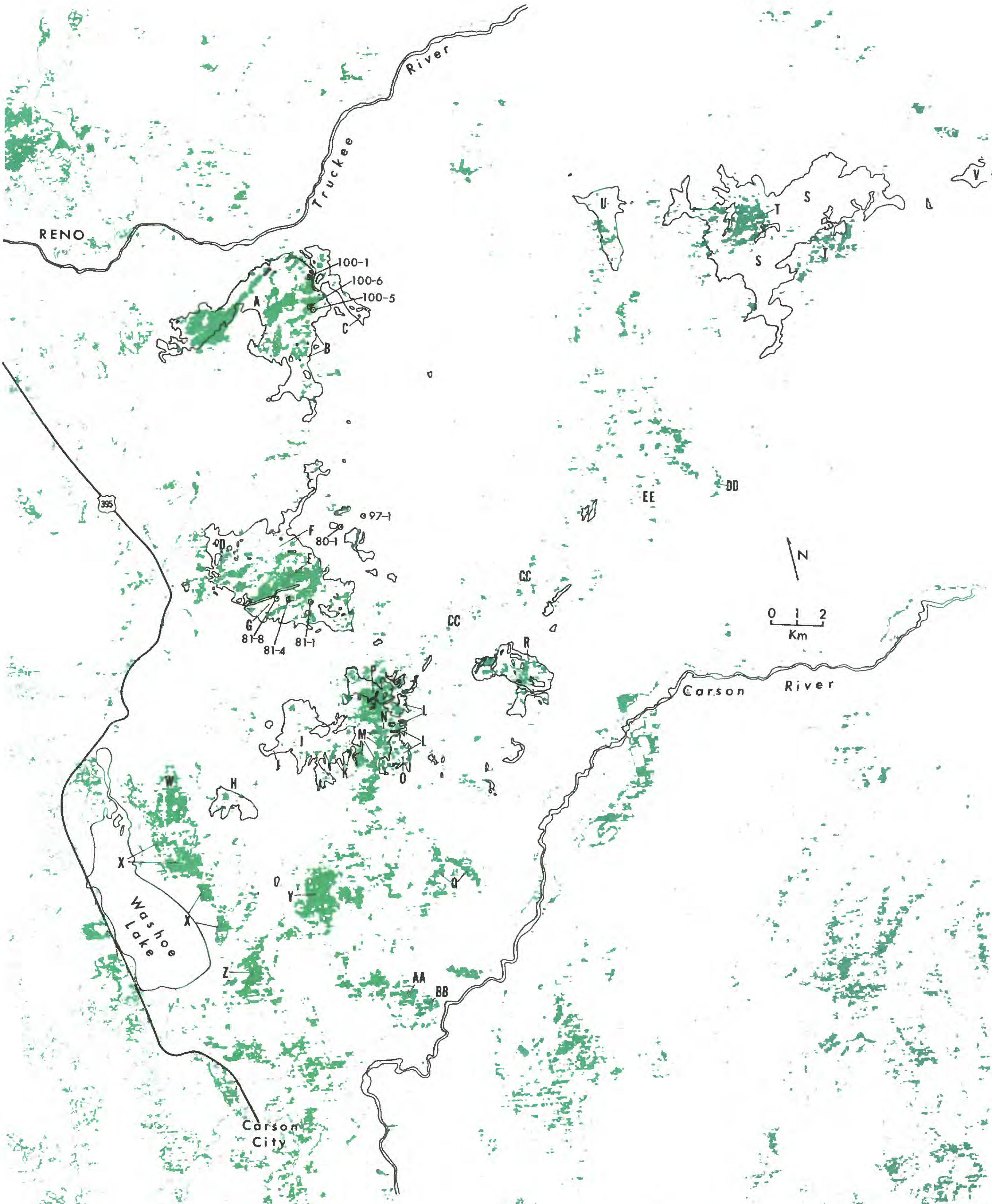

Truckee River
RENO
100-1
100-6
100-5
A
B
C
U
T
S
S
T
V
395
DD
EE
97-1
F
80-1
D
E
G
81-8
81-4
81-1
CC
CC
N
0 1 2
Km
R
Carson River
P
L
N
M
L
I
J
K
O
H
W
X
X
Washoe Lake
O
Y
Q
Z
AA
BB
Carson City

Image Processing

The Landsat image used for this study is E1380-18111, acquired August 7, 1973, with a sun elevation of 56°. Only the northeast quarter of this frame was subjected to the full range of image processing techniques employed. The following band ratios were produced from the digital number (DN) values, pixel by pixel: 4/5, 4/6, 4/7, 5/6, 5/7, 6/7. The values for each ratio were mathematically transformed using a cumulative density function (CDF stretch). Here the ratio values are transformed so that an equal number of values are assigned to each class interval of the distribution (here there are 256 class intervals each containing one number, labeled 0 through 255). When an image is produced from DN values or ratio values, the CDF stretch tends to increase contrast at the upper and lower ends of the DN range, but how it affects contrast in the middle of the range depends upon the shape of the original histogram. Geometrically corrected positive black-and-white film transparencies were made for each ratio using a large-format playback device, the Geospace 34/10 plotter; high ratios correspond to lighter tones in these transparencies. This playback device has a precision of about ±0.25 pixel at the original recording scale, about 1:158,000 for approximately one-fourth of an MSS scene. CRC's produced for earlier studies often had internal misregistrations of as much as several pixels, causing some pixels to be miscoded, and producing difficulties in using extreme enlargements. Use of this device eliminates these problems. Blue, yellow, and magenta diazo transparencies were then exposed using the positive film transparencies as screens. On the basis of experience gained previously by Rowan and others (1974), the diazo work was restricted to combinations of various exposures of 4/5 with blue film, 4/6 or 5/6 or both with yellow film, and 6/7 with magenta film. A composite consisting of blue film for 4/5, yellow film for 4/6, and magenta film for 6/7 produced the best results with respect to detecting hydrothermally altered rocks. Although 5/6 was more effective than 4/6 for the same purpose in southern Nevada, here the 5/6 image was noisy and had low contrast, giving rise to difficulties in providing the color ratio composite image with a suitably saturated yellow component. Reasons for this difference in most effective ratios are further explored in a later section. For additional details of this image processing method, see Rowan and others (1974), Goetz and others (1975), and Soha and others (1976).

The basic products selected for evaluation included three color ratio composite images that are the same except for differing degrees of exposure of the yellow diazo foil (4/6). Of these three, the CRC with the least saturation with respect to yellow was selected for discussion here. Other products obtained to help evaluate the image processing method include histograms of unstretched ratios 4/5, 4/6, 5/6, and 6/7, a density slice of the 5/6 ratio done in ten ten-percent increments and a scan of the CRC performed with the Dupont Line-O-Scan Model 204, adjusted to objectively classify green pixels in the image.

Tree cover estimates were made on 1:32,000 scale black-and-white aerial photographs using a stereo viewer at magnifications of both 4x and 8x. In each area selected for a tree cover estimate, 2 to 12 blocks of ground yielded individual estimates that provided a mean value and an idea of the range of variation in cover. These blocks ranged in size from about 6,000 m^2 (nearly the size of a Landsat pixel) to about 60,000 m^2. These estimates provide an idea of tree cover only, because no other vegetation is visible in these photos. Shadows produced by the trees, on the other hand, are included with the trees in the estimates. Even with the tree shadows included, the estimates are probably minimal relative to total vegetation cover.

Characterization of Spectral and Mineralogical Properties of Altered Rocks

Field Spectral Measurements

The JPL portable field radiance spectrometer (PFRS) was used for all field measurements. At each field locality we usually obtained at least 10 spectra, each covering an area of about 200 cm^2 on the ground, selected to include all typical materials present within an area of about 100 m^2. We made no attempt, either in the field or later in processing the data, to sample randomly or to weight individual spectra proportionally to the percentage of area represented at the site. Details of use of the instrument are given by Goetz and others (1975).

For this study we have attempted to characterize the spectral reflectance characteristics of some typical field localities by averaging the results for all PFRS sites at that locality and presenting an average curve with a $\pm 1\sigma$ envelope.

Field Sampling and Laboratory Procedures

In the Virginia Range substantial areas of outcrop are found mostly in parts of the range that are underlain by unaltered andesites, for example, along the range front east of Virginia City (figs. 1 and 2). Few large outcrop areas occur where hydrothermally altered rocks are abundant. The most common surficial material in altered areas consists of rock fragments from nearby or subjacent outcrops, with minor amounts of soil. Consequently, most of our samples consist of rock fragments with minor soil. Talus covers significant areas in the steeper parts of the range, such as on the east side of Mount Davidson above Virginia City, locally in the canyons northeast of Jumbo, and on the sides of the major canyon that occupies most of the Geiger Grade altered area.

At sites consisting of fragmental material with soil, we visually estimated the percentage of soil on the undisturbed surface, then collected the upper 2-3 cm of material using a shovel. In the laboratory the material was sized using U.S. Standard 200, 80, and in some cases, 32 mesh screens, and the size fractions weighed and X-rayed using cell packs in order to provide qualitative or crude semiquantitative estimates of the mineralogical composition of the soil. Although the sampling method used often biased the sample toward finer grain sizes, the 80 mesh screen size is about at the visual threshold where fragments are discernable; thus, an approximate correction for this bias was possible using the visual estimates of soil percentage on the undisturbed surface.

One or two rock chips (generally about 0.5 kg) were collected from PFRS sites on outcrops. A portion of each sample was ground to pass 200 mesh and X-rayed, again using a cell pack. In most cases, a standard thin section was prepared and in some cases a section stained for K-feldspar was also prepared. For the coarse fragmental portion of most of the soil-bearing samples, and for samples consisting of soil-free talus fragments, a representative-looking fragment was selected and treated in the same way as an outcrop sample.

Many rocks and soil fractions from hydrothermally altered areas in the Virginia Range and elsewhere contain expandable clays, especially montmorillonite and mixed-layer clays containing montmorillonite interlayers. Wherever we suspected the presence of such clays, we prepared an oriented mount by drying a clay-water suspension on a glass slide, treated the mount with ethylene glycol, and heated the preparation incrementally to 400° and 600°C, X-raying after each step.

Although the altered rocks dealt with here are generally very fine grained, a crude semiquantitative estimate of mineral proportions is usually possible to achieve by point-counting thin sections. For the purposes of this study, 300-400 points per section were considered adequate. Within groups of samples from single field localities, which were generally X-rayed and petrographically examined together, the point counts allowed us to make rough abundance versus peak height comparisons with the X-ray diffractograms.

Partial analyses for some altered rocks of relatively simple mineralogy provided a check on some of the semiquantitative estimates of mineral abundances made by the above methods.

GEOLOGY

General

The Virginia Range is dominated by intermediate volcanic rocks of Miocene age. The pre-Tertiary metasedimentary, metavolcanic, and plutonic rocks on which these volcanic rocks lie are exposed in only a few places, mainly along the southern and southwestern edges of the range. The Miocene flows and breccias are extensively hydrothermally altered at many localities. Post-alteration sedimentary rocks and capping flows of basalt, basaltic andesite, and andesite appear mainly in the northern half of the Virginia City quadrangle, and just south of the quadrangle (figs. 1 and 2). Quaternary sedimentary deposits include pre-Lake Lahontan gravels, Lake Lahontan sands and silts, stream and alluvial fan deposits, and some talus deposits. Siliceous sinter deposits at Steamboat Springs, at the west edge of the Virginia City quadrangle, are also of Quaternary age.

Rock Units

The oldest rocks in the Virginia Range are metasedimentary and metavolcanic rocks probably of Triassic age, with parts of the sequence possibly as old as Paleozoic and as young as Jurassic (Thompson, 1956; Thompson and White, 1964; Rose, 1969; see fig. 2). Sedimentary rock types include argillite, slate, phyllite, sandstone and conglomerate derived from volcanic rocks, and minor limestone. Volcanic rock types include basalt and andesite. These pre-Tertiary rocks have been metamorphosed everywhere to at least greenschist facies, best shown by development of albite, epidote, chlorite, and amphibole in the volcanic rocks. Near plutonic contacts more intense metamorphism produced amphibolite facies hornfels, schist, marble, and skarn. Both metasedimentary and metavolcanic rocks generally have low albedos

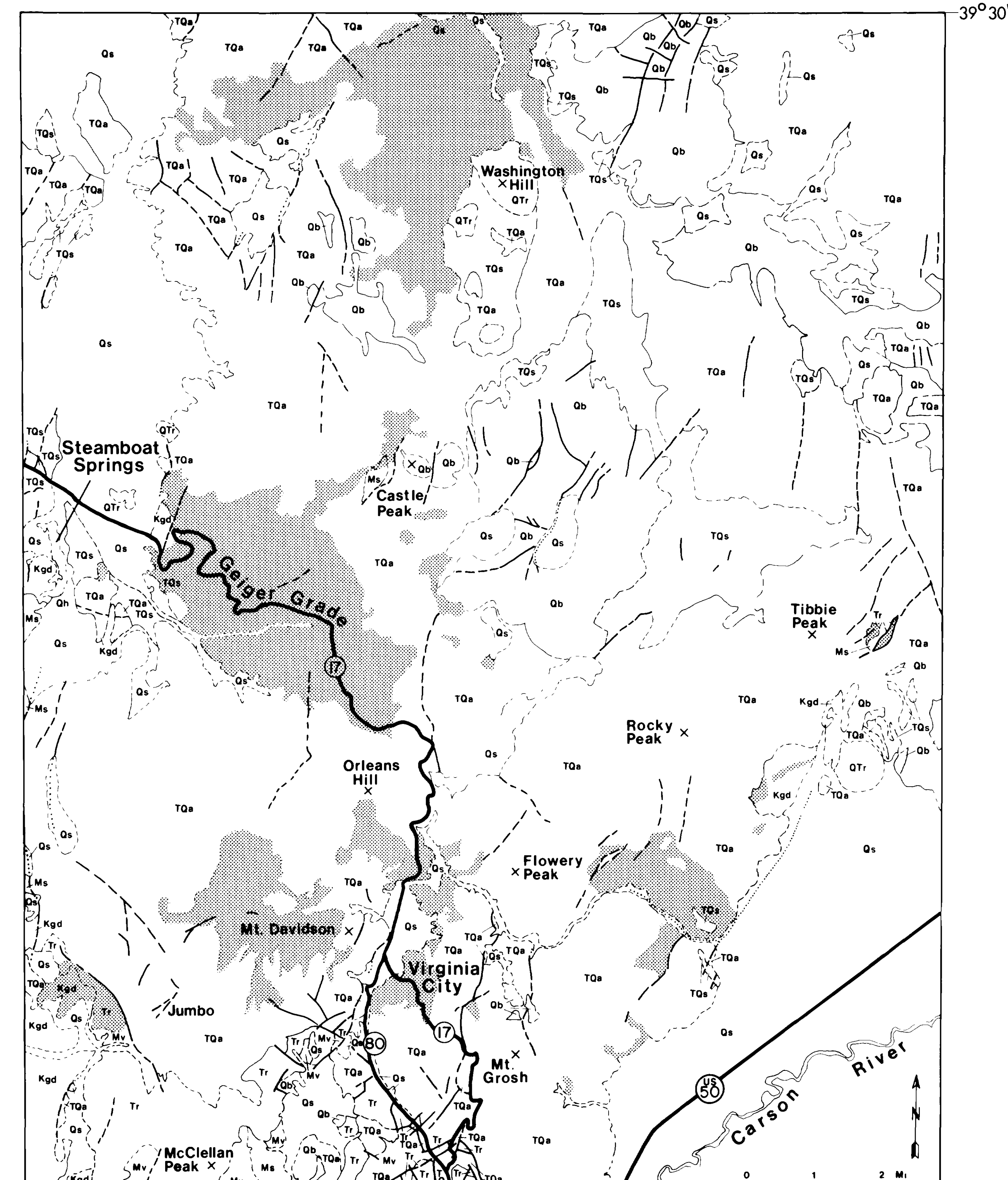


Figure 2. Generalized geologic map of the Virginia City quadrangle, Nevada, modified from Thompson (1956). Mapped hydrothermally altered areas are patterned.

Figure 2 Explanation

Qs	Gravel, sand, and silt. Includes lacustrine deposits of Lake Lahonton and isolated higher small lakes, stream deposits, minor aeolian deposits, and talus, landslide and mine dumps in the Comstock Lode district
Qh	Hotspring deposits
Qb	Basaltic andesite and basalt flows. Includes Lousetown Formation of Upper Pliocene or Quaternary age, McClellan Peak Olivine Basalt of Quaternary age, and Knickerbocker Andesite of Pliocene or Quaternary age
QTr	Rhyolite domes, including Washington Hill Rhyolite of Middle or Upper Miocene age, and Steamboat Hills Rhyolite of probable Quaternary age
TQs	Sedimentary rocks, mainly Middle Miocene Truckee Formation of Thompson (1956), including volcanic sandstone and conglomerate, shale, and diatomite. Also includes pre-Lake Lahonton alluvial gravels of probable Quaternary age
TQa	Intermediate volcanic and intrusive rocks. Includes Alta and Kate Peak Formations of Middle Miocene age (mainly rhyodacite flows and breccias), and Mustang Andesite of Upper Miocene age (Morton and others, 1977). Also includes the Sutro Member of the Alta Formation (shale and conglomerate), American Ravine Andesite Porphyry, and Davidson Granodiorite recognized only in the Comstock Lode district
Tr	Rhyolite ash-flow tuffs (Hartford Hill Rhyolite of Thompson, 1956; see also Bingler, 1977,1978)
Kgd	Granodiorite, locally foliated, with minor pegmatite and aplite. Includes small quartz monzonite porphyry intrusions near the Comstock Lode
Mv	Metavolcanic rocks. Includes basalt and andesite regionally metamorphosed to greenschist facies and locally contact metamorphosed to higher grades
Ms	Metasedimentary rocks. Mainly dark-colored argillite, slate, and hornfels with minor limestone, locally contact metamorphosed to schist and marble

and little limonite. Limonite is moderately abundant locally near plutonic contacts.

Plutonic rocks form scattered small bodies in the metavolcanics in the vicinity of Steamboat Springs and south of the Comstock Lode (fig. 2), and form a moderately large body east of Washoe Lake extending into the southwest corner of the Virginia City quadrangle and south into the Carson City and New Empire quadrangles. Another small body intrudes metasedimentary and metavolcanic rocks in the eastern part of the range just south of Ramsey. Several small inliers surrounded by Tertiary and Quaternary rocks also appear near the east edge of the Virginia City quadrangle and in the adjacent part of the Churchill Butte quadrangle. Most bodies are mainly granodiorite, but the small intrusions in the Comstock Lode area are quartz monzonite porphyry (Thompson, 1956; Thompson and White, 1964; Calkins, 1944). Unweathered plutonic rocks contain no limonite, and sulfide minerals, if present, must be very scarce. Minor but pervasive limonite stain, however, is common in weathered material, which is seldom exposed but visible locally in road cuts. Much of the regolith in areas underlain by plutonic rocks is grus; the constituent quartz and feldspar grains have very thin partial coatings of limonite, giving the grus a pale brown color. Because it has a high albedo, the grus is locally recorded as limonitic material on the color-ratio composite image, even though the actual amount of limonite present in probably less than one percent.

The oldest Tertiary rocks in the Virginia Range are rhyolite ash-flow tuffs originally mapped as Hartford Hill Rhyolite (Gianella, 1936), exposed mainly in the southwest corner of the Virginia City quadrangle, and also east of the Virginia City quadrangle in the Ramsey district. Recent work by E. C. Bingler (1977, 1978) in the New Empire quadrangle indicates that the Hartford Hill consists of several ash-flow units of late Oligocene to early Miocene age, some of which were recently recognized and named in the Singatse Range (Proffett and Proffett, 1976) and Gabbs Valley Range (Ekren and others, 1979), 30 to 120 km to the southeast of the Virginia Range. Some ash-flow units contain disseminated deuteric hematite, which is easily detected on the CRC.

Extensive eruptions of intermediate volcanic rocks followed deposition of the ash flows of the Hartford Hill. This volcanism was the first and most voluminous from sources within the Virginia Range. The resulting volcanic pile has been divided into two major formations, the Alta and the Kate Peak (Gianella, 1936; Thompson, 1956; Thompson and White, 1964). The two formations include flows, tuffs, tuff breccias, and intrusions. Volcanic conglomerates and sandstones, and, in the Alta Formation, shales are interbedded with the flows and pyroclastic rocks. Rock compositions include andesite, trachyandesite, dacite, rhyodacite, and rhyolite in the Kate Peak Formation, and andesite and soda trachyte in the Alta Formation (Thompson and White, 1964; Whitebread, 1976). Petrographically, all but the most silicic varieties in the Kate Peak have only plagioclase phenocrysts and some combination of pyroxene, hornblende, and less commonly biotite phenocrysts, so that in the field these rocks have generally been called andesites. Rose (1969) included olivine-bearing trachybasalt exposed in the Truckee Canyon in the Wadsworth quadrangle with the Alta Formation. The most common rock type in the Virginia Range is probably rhyodacite, and the most common textural variety is tuff breccia (Thompson and White, 1964).

The Alta and Kate Peak were originally distinguished in the vicinity of the Comstock Lode on the basis of unconformable relations and more pervasive alteration of the Alta. Thompson and White (1964, p. A12), however, state, "* * *structural discordance, though marked locally, is slight or nonexistent on a regional basis; and the degree of alteration, relied on by previous workers, varies more from area to area than from one formation to the other. Evidence that the two formations may intertongue was found in the Virginia City quadrangle (Thompson, 1956, p. 52)." Potassium-argon ages reported by Whitebread (1976) and Silberman and McKee (1972) for the Alta and Kate Peak range from about 12 to 16 m.y. and overlap in the vicinity of 14 m.y., and are thus consistent with the idea that the two formations represent a somewhat arbitrary subdivision of the products of a single episode of intermediate volcanism. Zircons from the Davidson Granodiorite, which cuts the Alta, yield ages of about 17 m.y. (Ashley, unpub. data). Thus the episode of intermediate volcanism lasted at least 5 million years.

In the south half of the Wadsworth quadrangle, at the northeast corner of the Virginia Range, Rose (1969) described a 1,900-m-thick section of interbedded rhyolite tuffs, tuffaceous sandstones and shales, diatomite, and flows having the full range of compositions seen in the Alta and Kate Peak. He assigned these rocks to three formations which, from oldest to youngest, are the Old Gregory, mainly rhyolite tuff, the Chloropagus, mainly basalt and andesite flows, and the Desert Peak, mainly basalt, andesite, dacite, and rhyodacite flows, and tuffaceous and diatomaceous sedimentary rocks. This section lies between the Alta and Kate Peak Formations. It seems to represent interfingering of intermediate-composition flows with affinities to the Alta and Kate Peak with tuffs and sediments deposited in a basin located to the east and northeast of the Virginia Range. An age of 14.5 ± 1.5 m.y. reported by Bonham (1969) for the Chloropagus Formation is in accord with stratigraphic placement of this section between the Alta and Kate Peak.

Two other units have been mapped separately near the Comstock Lode: the American Ravine Andesite Porphyry and the Davidson Granodiorite (Gianella, 1936). The age of the American Ravine Andesite Porphyry is somewhat uncertain, but it is probably between the Alta and the Kate Peak as they are distinguished south of the Comstock Lode (Calkins, 1944; Thompson, 1956), and thus is part of the major episode of intermediate volcanism that produced the Alta and the Kate Peak Formations.

The Davidson Granodiorite is a Tertiary stock that cuts the Alta Formation on and near Mount Davidson, immediately west of the Comstock Lode. It is medium grained with hypidiomorphic-granular texture. Thompson (1956) gives evidence indicating that the Davidson Granodiorite is contemporaneous with the Kate Peak Formation, but recent potassium-argon and fission-track dating of the Davidson (M. L. Silberman and R. P. Ashley, unpub. data) suggests that it is older, having been emplaced about 17 m.y. ago. The Davidson is important as the only known intrusion in the Virginia Range having a texture suggesting relatively deep (but still probably hypabyssal) emplacement. Its composition is similar to that of dacitic rocks found commonly in the Kate Peak Formation.

The Alta Formation, Kate Peak Formation, American Ravine Andesite Porphyry, and Davidson Granodiorite are probably all cogenetic products of Miocene intermediate volcanism of regional extent, and thus are designated as a single unit on figure 2. All show effects of hydrothermal alteration at many localities. Mineralization in the Comstock Lode probably took place during emplacement of the Kate Peak Formation, according to potassium-argon ages from the Alta, Davidson, Kate Peak, and vein minerals from the mineral deposits (Bonham, 1969; Silberman and McKee, 1972; Whitebread, 1976; Ashley and Silberman, unpub. data). The dominantly intermediate calc-alkalic volcanic pile of the Virginia Range is similar to other volcanic piles in western Nevada that host large epithermal precious metal deposits (Silberman and others, 1976). These rocks are particularly important to this study because of the extensive hydrothermal alteration and mineralization found within them. Where unaltered, these rocks generally contain little limonite, but locally they contain enough limonite coatings on fractures, disseminated deuteric hematite, or both, to be identifiable as limonitic material on the CRC image.

The Kate Peak Formation is overlain by fluvial and lacustrine sedimentary rocks designated Truckee Formation. The Truckee is composed predominantly of andesitic-rhyodacitic conglomerate and sandstone derived mainly from the Kate Peak Formation (Thompson, 1956; Thompson and White, 1964). Lacustrine deposits that accumulated in several local basins include shale and diatomite. Rose (1969) found an area of similar lacustrine deposits and associated fluvial deposits north of U.S. Highway 50 and south of the Ramsey district, and included it with the Coal Valley Formation. Tuffs and tuff breccias similar to those of the Kate Peak are interbedded with the Truckee sedimentary rocks, showing that some volcanism continued during deposition of the Truckee. The Kate Peak Formation interfingers with the Truckee, and locally contains volcanic conglomerates of earlier Kate Peak debris formed between flows. These relations indicate that the transition from the Kate Peak to the Truckee represents a waning of intermediate volcanism, with eruptions occurring at increasingly long intervals, so that erosion and sedimentation in local basins became dominant over accumulation of new lavas, tuffs, and breccias. Sometime during Truckee deposition, intermediate volcanism finally ceased. The Truckee is widely distributed in the vicinity of Reno, but in the Virginia City quadrangle the only large exposure areas are located south and southeast of Washington Hill, in the east-central and north-central parts of the quadrangle. The Truckee ranges in age from Late Miocene to early Pliocene. A pumice block from a rhyolite tuff breccia in the Truckee in the Virginia City quadrangle yielded a potassium-argon age of 12.3 ± 0.5 m.y. (Silberman and McKee, 1972). The Truckee is generally limonite poor.

Late Miocene, Pliocene, and Pleistocene basalt, basaltic andesite, and andesite flows, and rhyolite domes are scattered throughout the Virginia Range. The oldest of this group of generally unaltered Late Tertiary units is the Washington Hill Rhyolite, which forms a dome near the northern edge of the Virginia City quadrangle. Pumice produced during an early explosive phase of Washington Hill activity is incorporated in beds of the Truckee Formation. The rhyolite dome itself, mostly devitrified, cuts the Kate Peak Formation and the Truckee, and later beds of the Truckee contain fragments of devitrified rhyolite from the dome (Thompson, 1956, p. 56). The Washington Hill Rhyolite is thus contemporaneous with the upper part of the Truckee Formation. Silberman (unpub. data, 1976) obtained a potassium-argon age of approximately 10 m.y. on the Washington Hill dome.

Distinctly later rhyolite domes of Pleistocene age are fresh, glassy and pumiceous, and locally perlitic. These domes, named Steamboat Hills Rhyolite by Thompson (1956, p. 58) for a dome in the Steamboat Hills, 4 km west of the west-central edge of the Virginia City quadrangle, occur also at the west edge of the range just northwest of Geiger Grade, and near the east edge of the quadrangle at the southeast edge of the range near the Flowery district (figs. 2 and 3). Potassium-argon ages of 1.2 to 1.5 m.y. (Silberman, unpub. data, 1976) were obtained from alkali feldspars in these domes.

Post-Truckee Formation andesite, basaltic andesite, and basalt flows are much more voluminous and widespread than the Washington Hill Rhyolite or Steamboat Springs Rhyolite. The major formations recognized include the Lousetown Formation (basaltic andesite and basalt), Mustang Andesite, and McClellan Peak Olivine Basalt. Of these, the Lousetown flows are most extensive, covering about 40 km^2 in the Virginia City quadrangle (fig. 2), a similar but slightly smaller area in the adjacent Mount Rose quadrangle, and about half that area at the east end of the range, in the Wadsworth and Churchill Butte quadrangles. Dalrymple and others (1967) report a potassium-argon age of 6.9 ± 0.2 m.y. for the lower part of the Lousetown. The Mustang Andesite is found mainly in a patch spanning the northern border of the Virginia City quadrangle, partly surrounding a vent just outside the quadrangle boundary at the north end of Clark Mountain. Morton and others (1977) give potassium-argon ages of about 9 m.y. for two samples of Mustang Andesite. The McClellan Peak olivine basalt is named for flow remnants found south and southeast of McClellan Peak, in the New Empire quadrangle (Thompson, 1956, p. 59; Bingler, 1977). The series of outcrops of McClellan Peak basalt extending from Cinder Mountain and an adjacent cinder cone in the northwest part of the Churchill Butte quadrangle to the Truckee River north of the Virginia City quadrangle constitute an intracanyon flow that went down Long Valley Creek into the Truckee River Canyon (Thompson, 1956, p. 59; Rose, 1969). Doell and others (1966) report a potassium-argon age of 1.14 ± 0.04 m.y. for a small remnant of McClellan Peak basalt near Silver City. The post-Truckee units are all limonite poor except for some small low-albedo areas of hematitic red cinder associated with the McClellan Peak basalt.

Quaternary sedimentary deposits are mainly gravel and sand forming stream alluvium, terrace gravels, fans, and pediment surfaces. Limonitic rock debris is abundant enough to be detectable on the CRC image in only a few places. These deposits range in age from Late Pliocene or early Pleistocene (pre-Lake Lahontan) to recent (Thompson, 1956, p. 60-62). Lake deposits composed of sand and silt occupy the major valleys on both sides of the Virginia Range and some small dry lakes in closed basins within the range. Lacustrine materials along the Carson and Truckee Rivers were clearly deposited from Lake Lahontan. Patches of windblown sand derived from both fluvial and lacustrine deposits are widespread and are common in the vicinity of the Carson River.

Talus accumulations are common on steep slopes in the Virginia and Flowery Ranges and in the deeper canyons, but most cover relatively small areas. Many surfaces underlain by Kate Peak Formation are characterized by a lag of subangular and subrounded andesite or rhyodacite blocks weathered out of the relatively soft matrix of underlying volcanic breccias typical of the formation.

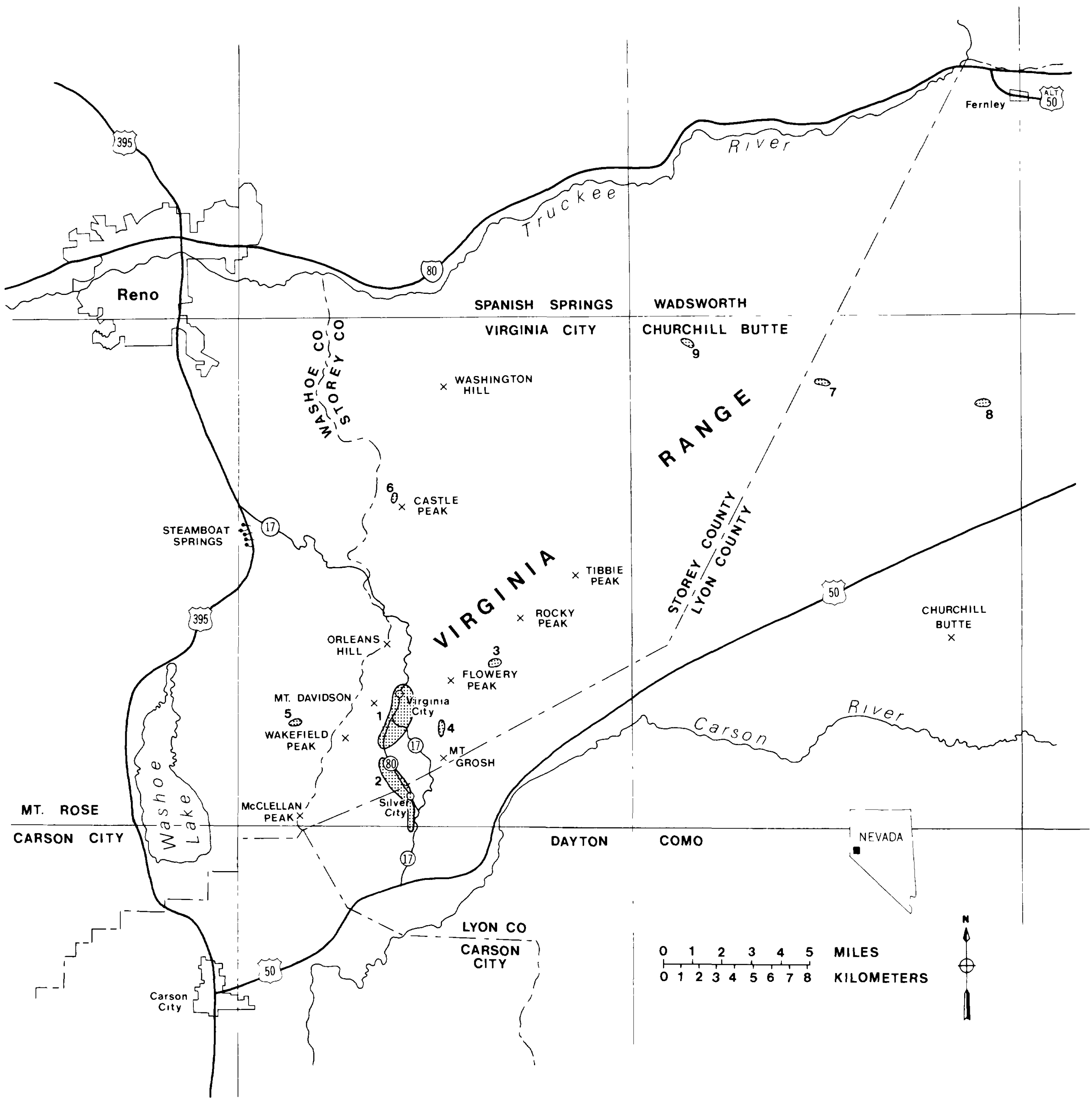


Figure 3. Map of the Virginia Range and vicinity, Nevada, showing orebearing areas: (1) Comstock Lode district, (2) Silver City district, (3) Flowery district, (4) Occidental Lode district, (5) Jumbo district, (6) Castle Peak mine, (7) Ramsey-Comstock mine, (8) Talapoosa district, (9) Gooseberry mine.

Structure

Faults in the western part of the Virginia Range are mostly northerly trending and steeply to moderately steeply dipping to the east (Thompson, 1956; Thompson and White, 1964; Bonham, 1969). Displacements are probably mainly dip-slip. Bedding generally dips at low to moderate angles to the west. Relatively low easterly dips of some faults are probably the result of concurrent rotation of the fault planes from originally steep easterly dips. In the eastern part of the Virginia Range normal and high-angle reverse faults with east-west trends are common (Rose, 1969). The longest single fault zone in the Virginia City quadrangle is the Comstock Fault, which is at least 11 km long. The precious metal production of the Comstock Lode is mainly from this fault zone, and where it is productive the fault zone lies in hydrothermally altered rocks. Other major altered areas, however, such as those at Geiger Grade and Washington Hill, are not obviously related to other major faults (fig. 2). The faults range in age from Miocene to Quaternary; some cut only Alta and Kate Peak rocks whereas others cut younger units including pre-Lake Lahontan gravels.

Altered Rocks

Mineralization in the Virginia Range is of three ages: pre-Tertiary, Miocene, and Holocene. The pre-Tertiary mineralization consists of mineralized fault zones, veins, and local skarns near the contacts of Mesozoic granitic rocks (Bonham, 1969; Moore, 1969). These deposits have yielded minor amounts of tungsten, lead, zinc, copper, and precious metals, and include an iron deposit.

The Miocene deposits are mainly epithermal veins containing bonanza ore bodies, including the major veins on and near the Comstock Fault and lesser veins on the Silver City fault, Occidental fault, and on faults in the Flowery district and at Jumbo (see Thompson, 1956, and fig. 3). The Castle Peak mine, immediately northwest of Castle Peak, produced a modest amount of mercury. In the eastern part of the Virginia Range, modest amounts of gold and silver were produced from silicified fracture zones at Ramsey and Talapoosa, and silver is currently being produced from a single vein at the Gooseberry mine. This episode of mineralization has been directly dated at about 12-14 m.y. by means of three potassium-argon determinations on adularia from the Comstock and Occidental veins (Whitebread, 1976; Bonham, 1969). Seven potassium-argon age determinations on the Kate Peak range from 12 to 15 m.y. (Whitebread, 1976; Silberman and McKee, 1972; Bonham, 1969). Potassium-argon age determinations on adularia from Talapoosa and the Gooseberry mine give 10-11 m.y., distinctly younger than presently available Kate Peak ages (Garside and Silberman, 1973; Silberman, 1977). The particular Kate Peak flows that host these deposits, however, have not been dated. The widespread hydrothermal alteration typically affects rocks as young as Kate Peak Formation, but not younger units. An exception is local bleaching of the Truckee Formation near Washington Hill (Thompson, 1956, p. 63), but a potassium-argon age determination of 12.3 ± 0.5 m.y. for the Truckee (Silberman and McKee, 1972) overlaps ages determined for the Kate Peak. In the Comstock Lode, wallrock alteration was approximately contemporaneous with introduction of vein material (Becker, 1882; Gianella, 1936). Alteration at other deposits in the range is probably also essentially the same age as mineralization or slightly older. Thus the age of hydrothermal alteration in the Virginia Range, although somewhat variable from place to place, is probably 10-14 m.y.

Steamboat Springs is an active hydrothermal system presently depositing siliceous sinter from hot spring waters. Hydrothermal alteration produced by this system probably began more than 2 million years ago (M. L. Silberman and others, in press), and continues in the subsurface beneath the sinter deposits (White, 1964; Schoen and others, 1974). Some sinter and mud in hot pools contains minor but anomalous amounts of mercury, antimony, gold, and silver (White, 1967). Hot water was abundant below a depth of about 300 m in the mine workings of the Comstock Lode (Becker, 1882).

The only other mineral deposits of Holocene age are gold placers located at the south end of the Virginia Range. The most productive placer ground was in Gold Canyon, mainly in the lower part of the drainage southeast of Silver City within the Dayton quadrangle, and on the north side of the Carson River Valley in the vicinity of Dayton (Moore, 1969).

This report is concerned mainly with the extensive surface manifestations of the hydrothermal alteration of Miocene age. The largest altered areas in the Virginia City quadrangle are those just west of Washington Hill, at Geiger Grade, 2 km northeast of Jumbo, at Virginia City, and at the Flowery district. Mineralogical and zonal variations within these altered areas have been described by Becker (1882), Gianella (1936), Coats (1940), Calkins (1944), Thompson (1956), Thompson and White (1964), and Whitebread (1976). A summary of their descriptions and additional data generated in the course of this study follows.

Propylitized rocks form a zone of weak alteration transitional to unaltered rocks. The most characteristic mineral assemblage is albite-epidote chlorite-calcite (Coats, 1940), but montmorillonite and pyrite are also common, and zeolites are abundant locally. Epidote, furthermore, is not always present. Whitebread (1976) described in detail the following assemblages: chlorite-montmorillonite-calcite-quartz, montmorillonite-chlorite-calcite-quartz-pyrite, and montmorillonite-calcite-quartz-pyrite. The second assemblage differs from the first not only in presence of pyrite, but in containing more montmorillonite as well.

The propylitized rocks also grade into argillized rocks, which are more intensely altered. The assemblage montmorillonite-calcite-quartz-pyrite is most commonly found in the transition zone between montmorillonite-chlorite-calcite-quartz-pyrite propylitized rocks and argillic rocks containing mixed-layer illite-montmorillonite.

Argillic zone mineral assemblages described in detail by Whitebread include montmorillonite-cristobalite-pyrite, illite-montmorillonite (mixed layer)-quartz-pyrite, and kaolinite-quartz-pyrite. The montmorillonite-cristobalite-pyrite assemblage was common in two of the four drill holes (three located 3 km south of Lousetown, and one located 1.5 km west of Washington Hill) that provided unoxidized materials for Whitebread's study. Zeolites were locally but commonly developed. The two drill holes with abundant cristobalite are no more than about 60 m apart so this mineral assemblage may not be typical of the altered rocks throughout the Virginia City quadrangle.

Rocks having the illite-montmorillonite (mixed layer)-quartz-pyrite assemblage are probably common. The illite and montmorillonite layers in the mixed layer clay are usually regularly interstratified. These rocks may also contain montmorillonite and illite (not mixed layer), kaolinite, mixed layer montmorillonite-chlorite, and chlorite.

Kaolinite-quartz-pyrite rocks surround alunitized rocks and separate them from rocks with montmorillonitic argillic assemblages. The greatest thickness of kaolinitic argillic rock encountered in any of Whitebread's drill holes was 6 meters, whereas montmorillonitic argillic rocks reached thicknesses as great as 20 m, indicating that montmorillonite-free rocks form a relatively small part of the argillic zone.

Silicified rocks typically having the mineral asemblage alunite-quartz-pyrite also occur in Whitebread's drill holes. The alunite preferentially replaces former feldspar phenocrysts. One silicified rock interval was pyrite free, with the assemblage alunite-jarosite-quartz. Silicified zones form along fractures; they represent the most intensely altered rocks in the hydrothermally altered areas. Owing to the abundance of quartz, which forms an interlocking microcrystalline mosaic, these rocks form craggy outcrops where they are exposed at the surface. Pyrophyllite and diaspore found in some surface exposures are probably also hypogene minerals. The outer parts of some resistant silicified zones exposed at the surface are slightly less resistant than the cores of the zones, and have the assemblage quartz-kaolinite, similar to the inner part of the argillic zone except for greater abundance of quartz.

Oxidation of pyrite near the surface produces sulfuric acid, which reacts with relict minerals and to a lesser extent with hypogene minerals to further modify the mineralogy of the altered rocks. The most conspicuous change is conversion of pyrite to limonite, which includes the minerals jarosite, goethite, and hematite. Jarosite is relatively uncommon, although probably more common than is generally recognized, because it is unstable with respect to goethite and hematite (Brown, 1971). The iron freed during oxidation of pyrite may remain at the sites of the pyrite grains as limonite pseudomorphs, or may be transported distances of millimeters to tens of meters and deposited in small pores in the rock, leaving a limonite stain, or as limonite coatings in fractures (Blanchard, 1968). All these modes of occurrence of limonite are seen commonly in the Virginia Range and in other pyritic hydrothermally altered areas. Unoxidized altered rocks are typically pale to medium gray in color, but after supergene oxidation they are bleached white where pyrite was removed and stained yellow, brown, orange, or red where limonite was deposited. Other changes include increases in the amount of clay minerals present, particularly kaolinite, bleaching of biotite to colorless hydromica, and formation of alunite, gypsum, or halloysite veinlets. Bleached rocks and their interpretation with respect to their parent unoxidized hydrothermally altered rocks are particularly important to this study, as these rocks are visible in enhanced Landsat imagery (see following section of this report).

In general, mineralogical changes associated with supergene alteration are minimal in rocks previously subjected to the most intense hypogene alteration even though almost all such rocks are pyrite bearing. Rocks with progressively weaker hypogene alteration show progressively greater supergene changes, although in most cases the exact proportions of minerals of hypogene versus supergene origin are ambiguous. Oxidized silicified rocks, aside from being limonitic, show no conspicuous changes relative to equivalent unoxidized rocks, although at the weathered surface there may be some enrichment of silica owing to more rapid removal of alunite and kaolinite relative to quartz. Some redistribution of silica may occur during supergene alteration, furthermore, resulting in deposition of additional quartz in the silicified zones. Part of the kaolinite in both silicified and montmorillonite-free argillized rocks may be supergene, but since much of the kaolinite is intergrown with quartz and relict textures are often well preserved, it seems likely that most of it is hypogene. Montmorillonitic argillized rocks often contain several clay minerals, including kaolinite, illite, and mixed-layer clays in addition to montmorillonite. Partly altered phenocrysts, particularly plagioclase, may have clays of different mineralogical and textural character than the groundmass. Also, gypsum veinlets are particularly common in montmorillonitic rocks. These features suggest that supergene alteration, although variable in intensity, has a significant effect on the mineralogy of these rocks. Pyritic propylitized rocks are most strongly affected by supergene alteration. Supergene acid attacks relict plagioclase and albite that is a propylitic product, converting them to clays. It also attacks relict mafic minerals, bleaching biotite to hydromica or illite and converting other mafics to clays. Chlorite is oxidized to oxychlorite or altered to mixed-layer clays, and calcite is depleted or removed. Whitebread studied a road cut at the top of Geiger Grade where an unoxidized relict of weakly propylitized rock containing pyrite is exposed. His examination revealed that pyritic propylitized rocks here were converted to bleached rocks with the assemblage quartz-montmorillonite-illite. This observation indicates that propylitized rocks with sufficient pyrite can be converted into rocks indistinguishable from oxidized argillized rocks.

All samples collected at field spectra sites are oxidized. In the Geiger Grade altered area, argillized rocks sampled (16 rocks and soils) contain montmorillonite and mixed-layer illite-montmorillonite in varying proportions, quartz, and relict plagioclase. Leucoxene is a minor constituent and kaolinite or K-mica or both occur in some samples. A few samples contain some opal. Geothite occurs in all samples but jarosite or hematite or both are present in many. In the Washington Hill altered area, the five samples examined all contain quartz, montmorillonite and mixed-layer illite-montmorillonite, possibly opal, goethite, jarosite, and relict plagioclase.

Advanced argillic rocks at Geiger Grade (4 samples) contain abundant alunite, generally lesser amounts of quartz, minor amounts of leucoxene, and minor amounts of kaolinite. One sample contains a trace of pyrophyllite. Goethite is present in all samples and is accompanied by hematite in most. Three samples from Washington Hill included in this alteration zone are also mainly alunite and quartz, and all have goethite and minor leucoxene. Two samples, however, also contain opal and jarosite; one contains minor pyrophyllite and the other a trace of diaspore. No phyllic rocks or montmorillonite-free argillic rocks were encountered in our sampling in the Virginia Range.

Silicified rocks in the Geiger Grade area (23 samples) all contain quartz and greatly varying amounts and proportions of alunite and kaolinite, with the exception of one highly leached rock that is almost entirely quartz with minor rutile and goethite. Most samples contain goethite and hematite; a few have goethite only or hematite only, and a few have jarosite in addition to hematite and goethite. Leucoxene is present in minor amounts in every sample except for the sample noted above, which has rutile, and two other rutile-bearing samples. Several samples have minor pyrophyllite.

Silicified rocks in the Washington Hill area (4 samples) all contain quartz, goethite, and jarosite. Three samples have moderately abundant alunite; only one of these has kaolinite and the other two have minor opal. One sample has neither alunite nor kaolinite but instead has pyrophyllite and K-mica. Again, all samples contain minor leucoxene.

Mineralogically, the altered rocks sampled fall into two major groups; one group in which montmorillonite and mixed-layer illite-montmorillonite are the most important alteration minerals and relict feldspar is often present, and one in which quartz, alunite, and kaolinite are the most important minerals. The montmorillonitic rocks are typically soft, easily eroded, and are an important contributor to soils in the altered areas. The quartz-alunite-kaolinite rocks are relatively well exposed, forming outcrops that disintegrate and shed talus fragments over adjacent argillized rocks. Overall, alunite is more abundant than kaolinite in these rocks. It is uncertain whether montmorillonite-free kaolinitic argillized rocks are truly scarce in these areas or whether our sampling by chance missed them. The unoxidized altered rocks encountered by Whitebread (1976) in drill holes include such rocks, as described earlier in this section.

INTERPRETATION OF COLOR RATIO COMPOSITE

Construction of Color Ratio Composite Image

The color-ratio composite image (fig. 4) was produced by making positive transparencies for MSS band ratios 4/5, 4/6, and 6/7. The 4/5 transparency was used to screen a blue diazo transparency, 4/6 a yellow transparency, and 6/7 a magenta transparency. As decribed earlier, with this system, depth of color produced is inversely proportional to ratio value. The diazo transparencies were registered together to produce a color-subtractive color-ratio composite (CRC) image. This enhancement procedure is similar to that used in the southern Nevada test area by Rowan and others (1974) except that here 4/6 along with 4/5 and 6/7 was more successful in detecting altered rocks than 5/6. The reasons for this are discussed below. Regardless of this difference, altered areas appear green on this CRC, just as is the case for the 4/5, 5/6, 6/7 composite for the southern Nevada test site.

Effect of Vegetation

Healthy green vegetation is scarlet, red, or magenta on the CRC image, owing to high reflectance at 0.8-1.1 μm, and in consequence, has a very low 6/7 ratio and a low to moderate 4/6 ratio. Most obvious are tree-covered slopes of the Carson Range (A, fig. 4), meadow and tree-covered areas in Truckee Meadows (northwest corner of Virginia City quadrangle, B, fig. 4), Steamboat Valley (west center edge of Virginia City quadrangle, C, fig. 4), and along the Carson River (D, fig. 4). Trees in the latter three areas are mainly cottonwoods. Locally vegetation is dense enough at high elevations in the Virginia Range, especially on north-facing slopes, to produce magenta in

Figure 4. Landsat color ratio composite (CRC) image of the Virginia Range and vicinity, Nevada. See text for explanation of locations designated by letters.

the CRC. A strip extending from Mount Davidson north to the ridge north of Geiger grade is particularly prominent (E, fig. 4). The patchy appearance of magenta within this strip results from variations in vegetation density. Vegetation density varies markedly with sun exposure, and varies to a lesser extent within areas of similar sun exposure, presumably as a result of subtle differences in soil conditions or other factors that affect availability of water. Some variations on uniformly oriented slopes are visible here, apparently because vegetation is just dense enough to have a marginal affect on the CRC image in many pixels. A smaller magenta strip follows the crest of the Flowery Range (F, fig. 4). The white area extending from Jumbo eastward to the ridge crest south of Mt. Davidson (G, fig. 4) is the site of a range fire that occurred in July 1973, only about one month before the Landsat frame used here was acquired. The charcoal that must have dominated the surface at this time apparently has very low spectral reflectance throughout the visible-near infrared (VNIR) range.

All vegetation areas have some associated yellow pixels. The yellow usually results from moderate green vegetation density. This results from the large rise in reflectance of green vegetation at about 0.7 μm. Because the spectral reflectance curve continues to rise to about 0.85 μm and remains high to 1.1 μm, heavy green vegetation cover has relatively low 6/7 as well as 4/6, and thus is orange, red, or magenta. Since the decrease in 4/6, however, is more pronounced than the decrease in 6/7 (see Siegal and Goetz, 1977), addition of green vegetation is noticed first in 4/6, with a resulting shift of the CRC image to yellow. Heavy sage cover can produce the same effect on the CRC image as moderate green vegetation cover, because sage shows a sharp increase in reflectance at 0.7 μm but a relatively minor increase in reflectance beyond 0.7 μm, so that the only ratio sage affects notably is 4/6 (see Rowan and Abrams, 1978). Green vegetation, however, is likely the dominant cause of yellow in the CRC. Yellow areas west of Virginia City and at Geiger Grade (H and I, fig. 4) apparently result from partial vegetation cover over altered rocks. This will be discussed further in a later section. The 4/5 ratio (blue) is little affected by any type of vegetation.

Discrimination of Unaltered Rocks

The unaltered intermediate volcanic rocks that dominate the Virginia Range are mostly pale blue to white on the CRC image. Average spectral reflectance curves with one-standard-deviation envelopes for three sites (fig. 5) normalized by ratioing to a Fiberfrax standard, are shown in figures 6 and 7 for representative rocks from this group. Reflectance is low to moderate throughout the visible-near infrared (VNIR) range, and except for some dropoff toward 0.4 μm, the curves are relatively flat. White in the image indicates areas with very flat spectral reflectance curves; all three ratios (4/5, 4/6, 6/7) are relatively high (see Table 1), so there are no color contributions from any of the three diazo transparencies used to make the composite. Where these rocks appear blue in the CRC, the 4/5 ratio is low enough to add blue to the image, as one might predict from some of the spectral reflectance curves. The white to blue areas include most of the outcrops of pre-Tertiary rocks, unaltered parts of the Kate Peak Formation, the Truckee Formation, Washington Hill Rhyolite, Lousetown Formation, Steamboat Hills Rhyolite, Mustang Andesite, and McClellan Peak Basalt (fig. 2). North and northwest of McClellan Peak, small areas of Hartford Hill rhyolite are also white to blue (J, fig. 4). The spectral reflectance curves

Figure 5. Hydrothermally altered areas of the Virginia Range (from Thompson and White, 1964, and rose, 1969), compared with green pixels from CRC image (fig. 4), shown in green. Classification and compilation of green pixels performed with Dupont Line-O-Scan Model 204. Numbered localities provided field spectra shown in figures 6 and 7. See text for explanation of localities designated by letters.

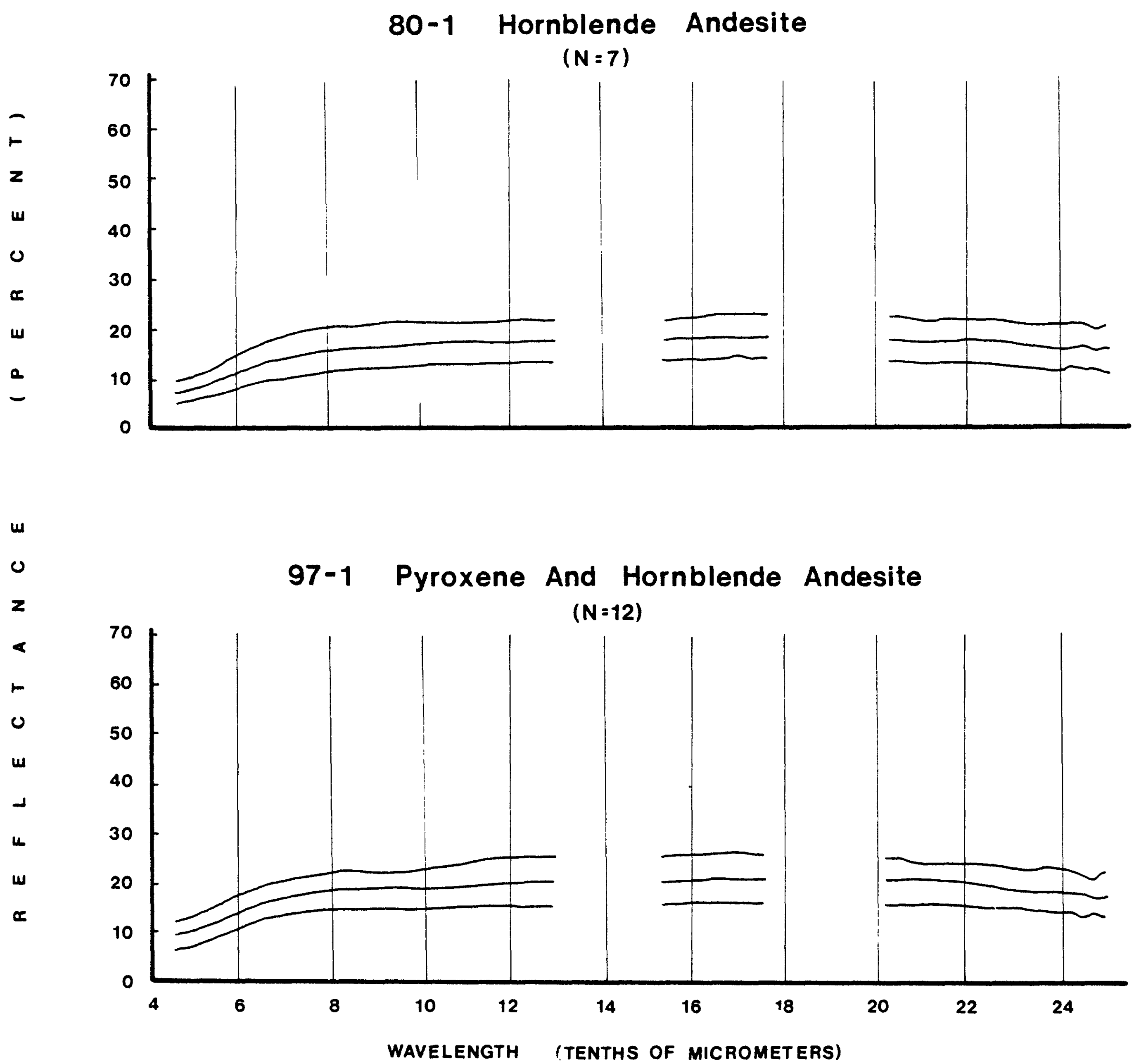


Figure 6. Average spectral curves for 5 sites at Geiger Grade. The middle curve of each diagram is the average curve; the curves above and below the average curve are $+1\sigma$ and -1σ curves, respectively. Sites 80-1 and 97-1 are in unaltered rocks; 81-1, 81-4, and 81-8 are in altered rocks.

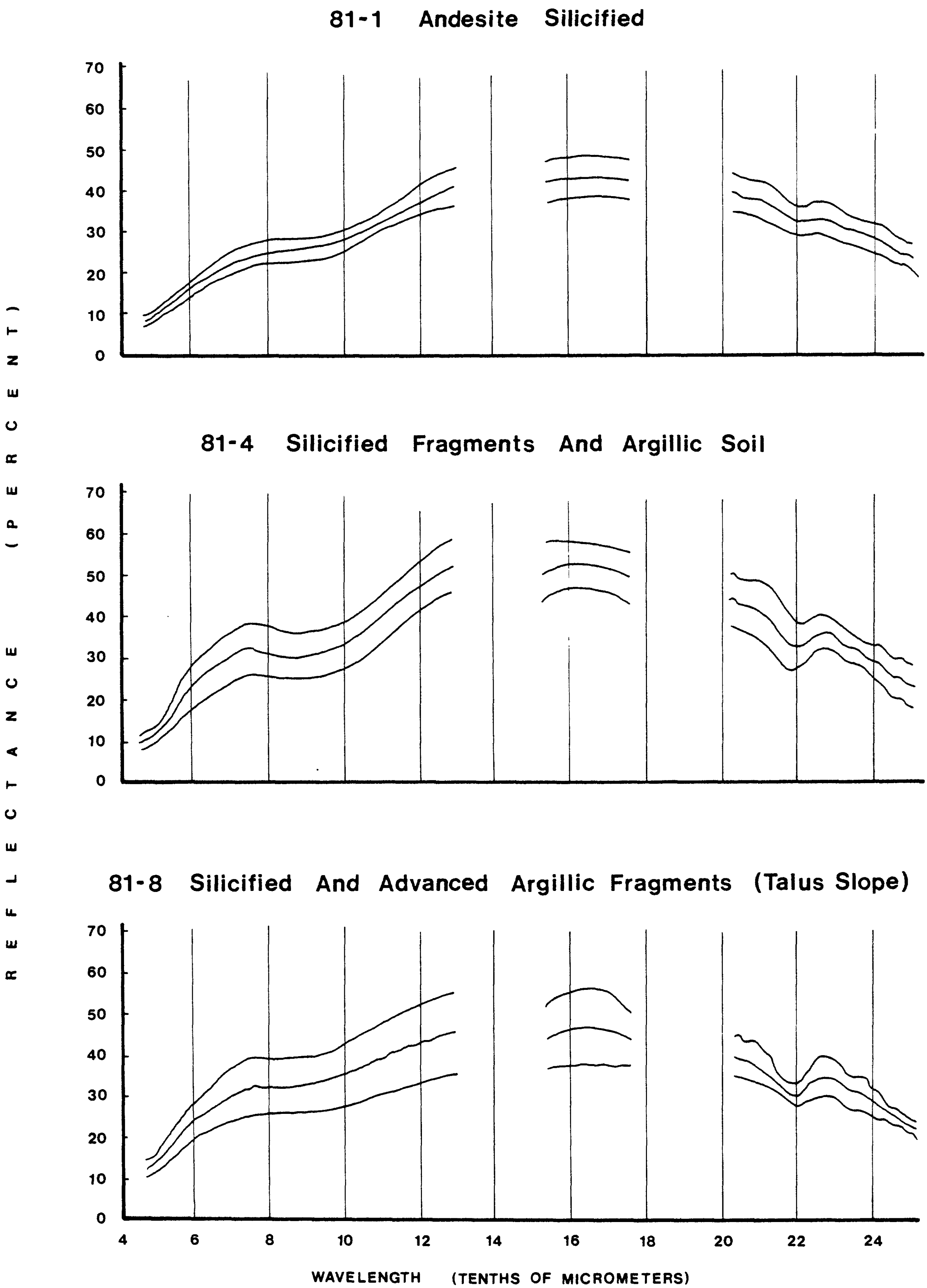

81-1 Andesite Silicified
81-4 Silicified Fragments And Argillic Soil
81-8 Silicified And Advanced Argillic Fragments (Talus Slope)
REFLECTANCE (PERCENT)
0
10
20
30
40
50
60
70
4
6
8
10
12
14
16
18
20
22
24
WAVELENGTH (TENTHS OF MICROMETERS)

Figure 7. Average spectral curves for 3 sites at Washington Hill. The middle curve of each diagram is the average curve; the curves above and below the average curve are +1σ and -1σ curves, respectively. Site 100-6 is in unaltered rock; sites 100-5 and 100-1 are in altered rocks.

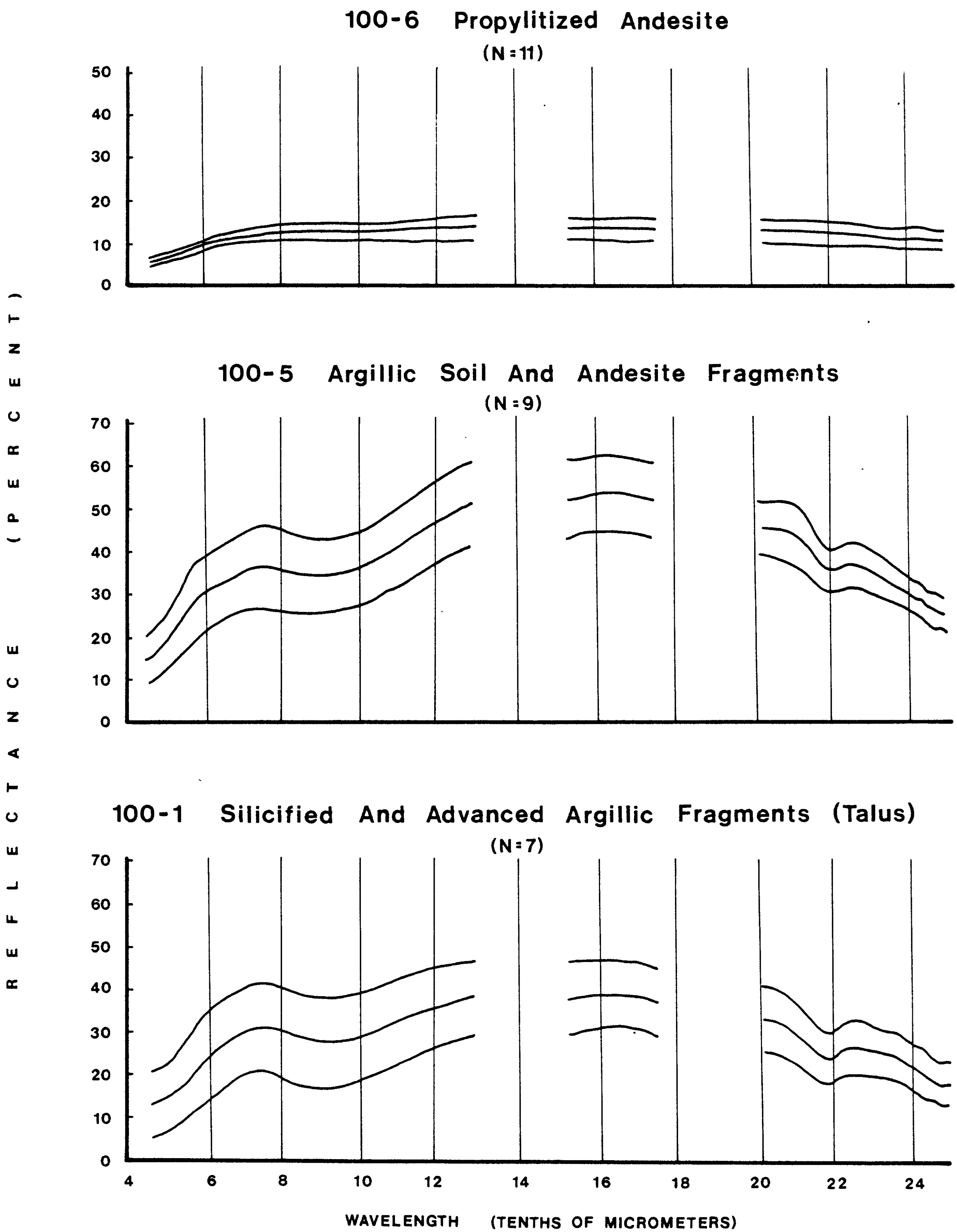


Table 1.--MSS band ratios for sites at Geiger Grade and Washington Hill, Virginia Range, derived from field spectra obtained with JPL portable field reflectance spectrometer (ratio values differ from actual MSS ratio values but are adequate for comparison purposes; see Rowan and others, 1977).

Locality	Description	4/5	4/6	6/7
Geiger Grade				
80-1	Unaltered andesite	0.727	0.633	0.920
97-1	Unaltered andesite	.759	.680	.959
81-4	Silicified fragments, argillic soil	.626	.534	1.013
81-8	Silicified and advanced argillic fragments	.679	.593	.956
81-1	Silicified andesite	.651	.540	.925
Washington Hill				
100-6	Propylitized andesite	.729	.652	.968
100-1	Silicified and advanced argillic fragments	.655	.589	1.088
100-5	Argillic soil and unaltered andesite fragments	.704	.631	1.029

for all these rocks are relatively flat regardless of albedo, which is low for the Lousetown, low to intermediate for the andesitic units, and moderately high for the rhyolitic units and the Truckee Formation. Consequently, because ratioing largely eliminates albedo variations, all these rock types look the same on the CRC. Blue instead of white seems to result from very minor amounts of limonite. Most of the alluvium within and on alluvial fans around the Virginia Range is blue; this alluvium typically includes as much as 10 percent rock fragments with yellow-brown surface coatings of goethite. Blue within bedrock areas of the range presumably also results from at least minor limonite, again mostly as surface coatings.

Discrimination of Altered Rocks

Thompson (1956) mapped several large areas and numerous small areas of bleached rocks in the Virginia Range (figs. 2 and 5). The two largest areas are those at Geiger Grade and Washington Hill. We collected field spectra at 19 sites in the Geiger Grade area and six sites near Washington Hill. Figures 6 and 7 show the results of these measurements at 5 sites (fig. 5) presented as average spectral curves with one-standard-deviation envelopes. All spectra representing altered materials show a relatively rapid rise in reflectance from 0.5 to 0.6 μm, then a less pronounced rise to 0.75 μm, and a broad absorption band centered at about 0.87-0.90 μm. Above 0.9 μm reflectance increases again relatively rapidly. Ferric iron produces the absorption features at about 0.9 μm and below 0.55 μm that account for the typical spectral shape seen at all these sites. The most abundant ferric iron-bearing (limonite) mineral is goethite, with more or less subordinate hematite. Jarosite is also important at several localities, particularly in the Washington Hill area. The depths of these absorption bands are approximately proportional to the abundance of limonite minerals, if the surface is not obscured and darkened by black limonite coatings or desert varnish. The spectra for altered rocks show two other characteristic features: an absorption band at about 2.2 μm, and high reflectance at 1.6-1.7 μm. These features, although of great importance for mapping hydrothermally altered rocks, are beyond the 1.1 μm upper limit of the Landsat MSS. Mineralogical details related to the ferric iron spectral absorptions are discussed elsewhere (Hunt and others, 1971; Hunt and Ashley, in prep.).

The spectral curves for altered rocks and the MSS band ratios derived, therefore, serve to demonstrate the color effects expected in the CRC. These rocks should produce notably lower 4/5 and 4/6 ratios than do unaltered rocks, but, because band 7 averages intensities for wavelengths across nearly the entire 0.9 absorption band, 6/7 should not change much. Table 1 shows that 4/5 and 4/6 are lower in altered rocks than in unaltered rocks, but 6/7 values overlap between the two groups of rocks. In the CRC image the result should be increased amounts of blue and yellow, but not magenta, producing green.

Comparison between Thompson's map of bleached rocks in the Virginia City quadrangle (fig. 2) and areas of green pixels on the CRC (fig. 4) show considerable correspondence in the major altered areas (see fig. 5). Careful examination of Thompson's map, aerial photographs, and distribution of rock units and surficial materials in the field, shows that discrepancies between areas of mapped alteration and green pixels can be categorized as follows: (1) unaltered rock talus or alluvium covering altered rocks, (2) limonitic weakly altered rocks mapped as unaltered rocks, (3) enough vegetation so that its spectral radiance is dominant over rock and soil, (4) unaltered rocks containing enough limonite and bright enough to have the same effect on the CRC image as altered rocks, and (5) altered rocks containing so little limonite that they appear the same on the CRC image as unaltered rocks.

In the Washington Hill area almost all green pixels are within the area of mapped hydrothermal alteration, but substantial parts of the area show white or blue instead of green pixels. Along the north edge of the area, unaltered rock colluvium from adjacent rhyodacite breccias of the Kate Peak Formation partly covers the altered rocks. In addition, many patches of unaltered andesite and rhyodacite occur within the altered area. Although these unaltered patches are small, they shed debris over adjacent altered rocks, which are argillized (montmorillonite bearing) and consequently soft and poorly exposed. At A, figure 5, gray to white limonite-free silicified rocks dominate exposures; the resulting pixels in the CRC image are mainly white. The east side of the area, immediately west and southwest of Washington Hill, is obscured by unaltered rock colluvium (stabilized talus with soil developed) from the adjacent Washington Hill Rhyolite and Truckee Formation (B, fig. 5). Altered rocks in Long Valley in secs. 34 and 35 are also obscured by talus (C, fig. 5). Southwest of A, figure 5, altered rock debris dominates alluvium in sec. 36, T. 19 N., R. 20 E., producing green pixels located outside the mapped altered area. The Washington Hill altered area is relatively unvegetated, supporting 10 to 20 percent juniper cover, and thus vegetation has no discernible affect on the green color anomaly produced in the CRC image by altered rocks.

In general, the Geiger Grade area is well delineated on the CRC image. As is the case with the Washington Hill area, however, in detail the CRC image response is quite varied. Here most of the major drainages are completely within the altered area, but in the northwest corner of the area scattered relicts of unaltered Alta and Kate Peak flows and small outliers of postalteration Lousetown Formation flows partly cover the altered rocks (K, fig. 4; D, fig. 5). The northern edge of the area is mainly white and blue instead of green, because unaltered Kate Peak Formation forms the ridge crest to the north, and it forms talus which completely covers altered Alta Formation (northeast of K, fig. 4; D, fig. 5). Large, well-exposed south-facing slopes of altered rocks, especially the one on the north side of the old Geiger Grade Toll Road, are green on the CRC image (L, fig. 4; E, fig. 5), but nearby north-facing slopes have many yellow pixels. The north-facing slopes have considerably more vegetation than the south-facing slopes, mainly increased numbers of pinyon pines and sage brush with some junipers, and locally vegetation is dense enough to produce magenta pixels on the CRC image (M, fig. 4; F, fig. 5). The vegetation may be responsible for the shift from green to yellow on the CRC image, and perhaps important is the fact that north-facing slopes also have more soil than south-facing slopes, which have more loose talus. We saw no consistent differences, however, between field spectra for altered rocks and soils derived from the same rocks, probably because the weathering process in this environment is dominated by mechanical disintegration. Siegal and Goetz (1977) showed that increasing amounts of green vegetation over limonitic argillized rocks decrease MSS 4/6 strongly relative to 4/5 and 6/7, which show only minor changes. Thus argillized rocks and vegetation combined could be responsible for the yellow in the Geiger Grade area and other vegetated altered areas. The CRC image pixels seem to shift to yellow when tree cover reaches about 30 percent, and to magenta when it reaches about 45-50 percent. Unexplained, however, are blue and white pixels on the north-facing slope south of the Old Geiger Grade Toll Road (N, fig. 4; G, fig. 5). This steep slope is composed entirely of altered rock talus with scattered outcrops, and has moderately heavy to heavy pinyon pine cover (35-75 percent) with patches occupied solely by scattered ponderosa pine (Billings, 1950; cover about 15 percent). Apparently the effective sun angle on this slope at the time of overflight was low enough (about 20-25 degrees) that the characteristic spectral signatures of altered rocks and vegetation are lost. In order to avoid destroying spatial information needed for locating features on the CRC image, no path radiance correction was made. When the angle between the perpendicular to a slope and the sun becomes large, sky illumination becomes a significant part of the energy received by the spacecraft unless this correction is made. Where this angle is large the correction is difficult because it depends in detail on variations in slope orientation (Rowan and others, 1977). As path radiance becomes larger, spectral reflectance of the surface becomes relatively smaller, and the error consequently introduced in a band ratio rapidly becomes larger. This situation is similar to the increase in ratio error with decrease in average spectral reflectance at constant path radiance calculated for 4/5 by Rowan and others (1977, fig. 6).

A small altered area mapped by Thompson 1 to 2.5 km west of Jumbo has small associated green areas on the CRC image (O, fig. 4; H, fig. 5). The alteration here affects ash-flow tuff of the Hartford Hill Rhyolite, and granodiorite. Unaltered alluvium in the drainage that cuts through this altered area is blue-white on the CRC image. The southeastern part of this altered area is obscured by the western end of the burned-over area described earlier.

The large patch of bleached rocks centered 3 km northeast of Jumbo is represented by yellow pixels with small spots of green broken up by east-west bands of orange, red, and magenta pixels (P, fig. 4; I, fig. 5). The latter areas are north-facing slopes in the canyons of westward-flowing intermittent streams that drain the northerly trending crest of the Virginia Range. Tree cover here reaches 60 percent, and low-growing vegetation is denser than anywhere else in the range. The most abundant species are mountain mahogany and willow, but many other species thrive here as well. These sheltered slopes at altitudes of 2,000-2,280 m must retain snow cover, providing wet enough conditions to partially exclude the pinyon-juniper-sage community. The south-facing slopes, however, have only slightly higher density of tree cover than the south-facing slopes at Geiger Grade, which are 300-500 m lower (average cover at Jumbo is about 15-20 percent versus average cover at Geiger Grade of about 10-12 percent). Thus the dominance of yellow pixels is not explained by differences in tree cover alone. Possibly additional sage and grass cover at Jumbo is responsible for the shift to yellow in the CRC image. The narrow belt of altered rocks extending westward 2 km north of Jumbo has moderate tree cover, and adjacent unaltered Alta flows and Kate Peak plugs shed debris over these altered rocks, so the CRC image shows white and some magenta pixels (Q, fig. 4; J, fig. 5). The only part of this area that appears notably green is the L-shaped patch that extends along the crest of the range southwestward toward Wakefield Peak and southeastward to Mount Bullion (R, fig. 4; K, fig. 5). Along the crest vegetation is generally sparse, consisting of stunted sage (maximum 20 percent cover) with occasional stands of fir.

Immediately east of the above described area is the large altered area surrounding the main productive part of the Comstock Lode (fig. 2; L, fig. 5). Much of the bedrock here is covered by alluvium. The CRC image shows a narrow strip of green pixels that trend north-northeast along the west (uphill) side of the townsite (S, fig. 4; M, fig. 5). Altered rocks exposed in extensive open cuts coincide with the east side of this strip, but green pixels on the west side of the strip are apparently produced by moderately limonitic oxidized propylitized andesites. Some exposures of these rocks appear highly limonitic, but close examination shows that much of the limonite is on fractures, and is really only moderately abundant. The amount of pyrite present in these rocks before oxidation is unknown; presumably it was sufficient to produce limonite but not sufficient to produce bleaching. Because these rocks disintegrate by breakage along the limonite-coated fracture planes, much limonite is exposed in soils and talus where these limonitic propylitized rocks occur. Limonitic quartz debris eroded from quartz veins and fragments of limonitic bleached rocks which form halos around these veins are also present.

Some green areas appear in the patch of alluvium upon which most of Virginia City is built (N, fig. 5). These green areas probably represent extensive mine dumps and material washed downslope from them, but because precise geographic location on the CRC image is difficult, it is not possible to identify specifically which dumps notably affect the CRC image. Oxidation of pyrite at the surface of dumps results in bleaching, and produces a variety of hydrated iron sulfate minerals, the most conspicuous one being yellow copiapite.

The irregular area of green pixels extending south-southwest from Virginia City includes the southern extension of the Comstock fault and extends eastward to include the northern end of the Silver City fault. The rocks here are altered and contain abundant goethite stain and fracture coatings. They are mostly medium brown in color with patches of both gray unaltered rocks and pale-brown bleached rocks; they probably were not mapped as bleached by Thompson because of their relatively dark color. Owing to extensive natural and man-made exposures including pits, dumps, and roads, they nevertheless produce green pixels in the CRC. Colluvial soil on the steeper slopes in the western part of this area contains abundant fragments of limonitic more or less strongly bleached andesite and limonitic quartz vein material.

The southeastern part of the Virginia City bleached area mapped by Thompson is partly blue white on the CRC image, owing to patches of unaltered Alta Formation (O, fig. 5).

The extension of the Virginia City bleached area northwestward onto Cedar Hill is well represented on the CRC image (P, fig. 5). The western part is obscured by abundant sage brush and other bushes (70-80 percent vegetation cover) in the same way that parts of the altered area north of Jumbo are obscured (T, fig. 4). The green area on the CRC image (U, fig. 4; P, fig. 5) is larger than that mapped by Thompson: it extends southward into Ophir Ravine and northward into the lower part of Cedar Hill Canyon. Limonitic propylitized rocks locally bleached along fractures, similar to those on the west side of Virginia City, described above, are the cause.

Although Thompson mapped no bleached rocks in the vicinity of Silver City, the CRC image shows a green area shaped like an inverted "V" extending southwest and southeast of Silver City (V, fig. 4; Q, fig. 5). Alteration here is generally weak, manifested by conversion of feldspar and biotite to clay, limonite staining, and limonite coatings on fractures in Hartford Hill Rhyolite (here an ash flow that is part of the Santiago Canyon Tuff; Bingler, 1977). The Kate Peak, Alta, and pre-Tertiary metavolcanic rocks are not bleached but limonite stains and coatings on fractures are common. The metavolcanics generally have low albedo, whereas the tuff has high albedo, so most of the green area on the CRC image corresponds to outcrops of the tuff. The limonitic character of these rocks, which host several productive veins, is probably the result of weak but nearly pervasive hypogene pyritization. Thus, although Thompson must have considered this area too weakly altered to warrant mapping it as bleached rock, the green color anomaly on the CRC image is a valid indication of mineralization.

The bleached area mapped by Thompson (1956) which includes the Flowery district, located at the eastern front of the Virginia Range, matches well with another large but patchy green area on the CRC image (R, fig. 5). This area is similar to the Washington Hill area in that vegetation is sparse and therefore not a problem, but the CRC image includes significant areas of blue and white pixels within the area mapped as bleached. Patches of pre-Lake Lahontan gravels, composed mostly of unaltered Kate Peak Formation rhyodacite clasts, conceal the altered rocks over larger areas than are shown on Thompson's map because they cap ridges and shed debris over altered rocks on adjacent slopes. The Flowery altered area also contains many patches of propylitized rocks including green limonite-free, dark brown weakly limonitic, and medium brown moderately limonitic, and weakly bleached varieties. These dark rocks with little or no limonite are probably as important as the pre-Lake Lahontan gravels in producing the patchy response of the CRC image. The stream drainages contain unaltered rock debris derived both from Kate Peak Formation to the north and from the pre-Lake Lahontan gravels on adjacent ridges. This debris obscures small parts of the mapped altered area.

The only other large altered area in the Virginia Range is located at Ramsey (fig. 3), near the north edge of the Churchill Butte quadrangle. Green areas on the CRC only partly coincide with outlines of the altered area as mapped by Rose (1969; S, fig. 5). Rose's alteration boundary seems to be a line drawn around all occurrences of bleached or propylitized rocks in the Kate peak Formation in the vicinity of Ramsey. It thus includes substantial areas of more or less limonitic but unbleached propylitized rocks (S, fig. 5) which grade into bleached rocks that were probably originally propylitic and relatively pyrite rich (P. Wetlaufer, unpub. data). It also includes some patches of unaltered rhyodacite of the Kate Peak Formation. In addition to the propylitized rocks there are two east-northeast-trending belts of limonitic argillized and alunite-bearing silicified rocks, one about 2 km long extending from the Ramsey-Comstock mine to San Juan Hill, and one possibly as much as 3 km long centered about 2 km southeast of the Ramsey-Comstock mine. The two largest and most coherent green patches on the CRC in the vicinity of Ramsey coincide with these belts of argillized and silicified rocks (W, fig. 4; T, fig. 5). The southeastern belt is not shown on Rose's map because the alteration affects units other than Kate Peak, which is the only stratigraphic unit for which alteration is shown. The smaller green patches within Rose's alteration boundary are scattered spots of propylitized rocks that are bright enough and contain enough limonite to notably affect the CRC image. Rose inferred that alteration comes to about the same stratigraphic level on the west and north sides of the mapped altered area, and his alteration boundary reflects this, but here talus cover from adjacent unaltered Kate Peak flows is extensive. Thus the discrepancies between the mapped altered area and the CRC image are due partly to unaltered rock debris also.

The Gooseberry mine, currently active, is located near the northwest corner of the Churchill Butte quadrangle, about 7 km west-northwest of the Ramsey-Comstock mine. The CRC image shows a green area immediately south of the mine (X, fig. 4), whereas Rose's (1969) map shows an altered area that includes the Gooseberry mine and much of the east-west-trending fault zone that contains the Gooseberry vein, and extends southward from the mine for about 3 km (U, fig. 5). Field examination shows that the rocks in the immediate vicinity of the fault and vein are only locally weakly altered. Beginning 0.5 km south of the vein, however, and extending southward for 1 km, is a belt of bleached rocks, representing mainly oxidized pyritic propylitized Kate Peak flows. The green areas on the CRC image coincide with these bleached rocks. The western boundary of this green area against adjacent blue and white on the CRC image is very irregular, owing possibly to local hematitic areas in adjacent unaltered rhyodacite flows of the Kate Peak Formation.

The Talapoosa mine, located 9.5 km east-southeast of the Ramsey-Comstock mine, also is surrounded by altered rocks of the Kate Peak Formation according to Rose (1969; V, fig. 5). The corresponding green area on the CRC image, however, is much smaller than the altered area shown on Rose's map. The part of the Talapoosa altered area shown on figure 5 is almost completely surrounded by hills capped with unaltered basalts mapped as Lousetown Formation by Rose. Debris from these flows and from unaltered rhyodacite, adjacent to the altered area, cover most of the altered rocks. The few exposures within the altered area are mostly nonlimonitic or dark brown, weakly to moderately limonitic propylitized rocks. Only a small spot of argillic and limonitic propylitized rocks east of the Talapoosa mine is well enough exposed to produce green pixels on the CRC image.

The siliceous sinter deposits of Steamboat Springs are white to pale blue on the CRC image (Y, fig. 4). At the surface these deposits consist of white limonite-free porous opaline sinter. Although this material has very high albedo, its spectral reflectance curve must be nearly flat.

Other CRC Image Anomalies

The CRC image also includes many green areas that do not coincide with mapped altered areas, but some of these are related to other mineralization.

The green area about 2 km in diameter located about 2 km east of the north end of Washoe Lake (Z, fig. 4; W, fig. 5) contains local tungsten mineralization in skarn associated with the contact zone between Mesozoic metasedimentary rocks and Cretaceous granodiorite (Bonham, 1969; Tabor and Ellen, 1975). Although the skarn deposits form only a very small part of this anomalous green area, the metasedimentary host rocks typically have goethite coatings on fractures. Limonitic metasedimentary rock outcrops occupy the northernmost quarter of the anomalous green area, but debris from these rocks spreads widely downslope over adjacent granodiorite, which weathers to grus. The quartz and feldspar grains of the grus also have thin partial goethite coatings. The limonitic debris scattered over the high-albedo grus surface and the limonite in the grus apparently accounts for the remainder of this green area.

Patchy green areas on the east side of Washoe Lake, just south of the metasedimentary-rock area described above, are mostly in alluvial materials, including transported sand derived from the nearby granodiorite grus, and stream alluvium forming the fan at the mouth of Jumbo Creek and other fans immediately south of Jumbo Creek (AA, fig. 4; X, fig. 5). The source of the CRC image anomaly in the sand is again goethite coatings on the grains, giving the sand a pale brown color. The Jumbo Creek fan contains both grus-derived sand and altered-rock debris derived from the hydrothermally altered area on the ridge crest east and northeast of Jumbo, and possibly from other completely eroded altered areas in the vicinity of Jumbo.

A large green area appears at McClellan Peak (BB, fig. 4; Y, fig. 5), on the southern border of the Virginia City quadrangle. It extends from the top of the peak down the east side. No alteration is associated with this anomaly; it is caused by abundant hematite of deuteric origin in devitrified ash-flow tuffs of the Hartford Hill Rhyolite (mapped mainly as Mickey Pass Tuff and Lenihan Canyon Tuff by Bingler, 1977).

An irregular green area immediately southeast of Washoe Lake is mainly grus derived from underlying granodiorite (CC, fig. 4; Z, fig. 5), but the surface is littered with abundant angular chips of hematitic and limonitic tuff derived from an ash flow (Nine Hill Tuff, Bingler, 1977) that covers part of the west flank of McClellan Peak and caps the higher hills. Minor goethite in the grus and hematitic debris from a cinder deposit at the west edge of the McClellan Peak basalt may also contribute to this color anomaly. The white area between this anomaly and the top of McClellan Peak is McClellan Peak basalt.

The patchy green area forming an east-west belt north of the Carson River about 8 km northeast of Carson City (DD, fig. 4; AA, fig. 5) is again tuff originally mapped as Hartford Hill Rhyolite and now including Mickey Pass Tuff, Nine Hill Tuff, and Santiago Canyon tuff (Bingler, 1977). Tuff in this green patch and in a smaller green area about 2 km farther northeast is mainly unaltered but contains deuteric hematite. Along the railroad grade from Mound House south to the Carson River, however, the tuffs may be zeolitized and have abundant goethite and locally hematite stain and coatings on fractures (EE, fig. 4; BB, fig. 5). The CRC image anomaly results from limonitic fragments and soil produced by weathering of the tuffs.

Many small green spots with some associated yellow occur along the crest of the Flowery Range in the vicinity of Rocky Peak and Tibbie Peak (FF, fig. 4; CC, fig. 5). No alteration is mapped here, and field examination confirms that the porphyritic rhyodacite flows and flow breccias that dominate this part of the area are indeed unaltered. Deuteric hematite occurs locally in some fragments in the breccias but does not seem abundant enough to account for these CRC image anomalies. Goethite occurs locally on fractures. Some of these goethitic areas appear to affect the CRC image while others do not.

Amount of goethite, albedo of the rocks, and possibly vegetation cover (here pinyon cover is about 10-15 percent) apparently interact to affect the spectral signature in a complex manner within each pixel, making it difficult to relate field observations to CRC image response in a consistent manner.

The CRC image shows a green area at the site of the Dayton iron deposit, about 6 km west-northwest of the conspicuous cultivated field on U.S. Highway 50, along the east front of the Virginia Range about halfway between the Flowery and Ramsey districts (GG, fig. 4; DD, fig. 5). The color anomaly centers on a low hill occupied by a partly oxidized contact (skarn) magnetite deposit (Roylance, 1966). The surface here consists of abundant pebble- and cobble-size fragments of hematite and magnetite in dark yellowish-brown soil. The soil probably contains goethite derived from pyrite by oxidation; unoxidized iron ore beneath the hill averages about 7 percent pyrite. The hematite and goethite produce the CRC image anomaly. Magnetite is opaque throughout the visible near-infrared spectral region, and thus could not itself directly affect the CRC image except by reducing albedo somewhat (Hunt and others, 1971).

About 3 km west of the Dayton iron deposit, and a similar distance north-northwest of U.S. Highway 50, is an area about 1 km in diameter having patchy green color on the CRC image (HH, fig. 4; EE, fig. 5). This area is underlain by small patches of propylitized granodiorite that intrude Triassic-Jurassic metasedimentary rocks. The granodiorite, which has moderately abundant limonite coatings on fractures and weathers to small blocky fragments or grus, and limonitic contact metamorphosed wall rock, probably account for this CRC image color anomaly. A stronger anomaly northwest of the Dayton iron deposit is in diorite which intrudes Mesozoic metasedimentary rocks and is probably of similar origin. The CRC image anomalies located 1.5 to 3 km northwest of Talapoosa (V, fig. 5) are caused by prominent outcrops of silicified volcanic breccia within the Desert Peak Formation (Rose, 1969). These outcrops have abundant red-brown and yellow-brown limonite coatings on fractures and shed limonitic debris over large surrounding areas of poorly exposed argillic rocks.

OPTIMUM BAND RATIOS

The most effective MSS band ratios for detecting limonite in the Virginia Range are 4/5, 4/6, and 6/7, whereas in southern Nevada 4/5, 5/6, and 6/7 proved to be the best ratios for this purpose (Rowan and others, 1976). The reasons for this difference are discussed in this section.

Figure 8 shows cumulative frequency (probability) plots for MSS ratio 5/6 for Goldfield (northeast quarter of Landsat frame 1054-18001) and the Virginia Range (northeast quarter of Landsat frame 1380-18111). The cumulative frequency distribution for Goldfield can be approximated between the 0.03 and 95 percentiles by two straight lines intersecting at about the 5 percentile. Because a straight line on a probability plot represents a Gaussian distribution, the Goldfield data (excluding 5 percent at the upper tail and 0.03 percent at the lower tail) form two overlapping Gaussian distributions. Density slicing of the 5/6 ratio image at 10 percentile intervals reveals that the lower Gaussian distribution (0.3-5 percentiles) must be dominated by vegetation. In the upper distribution, vegetation affects a significant number of pixels up to about the 20 percentile (5/6=1.02), but pixels

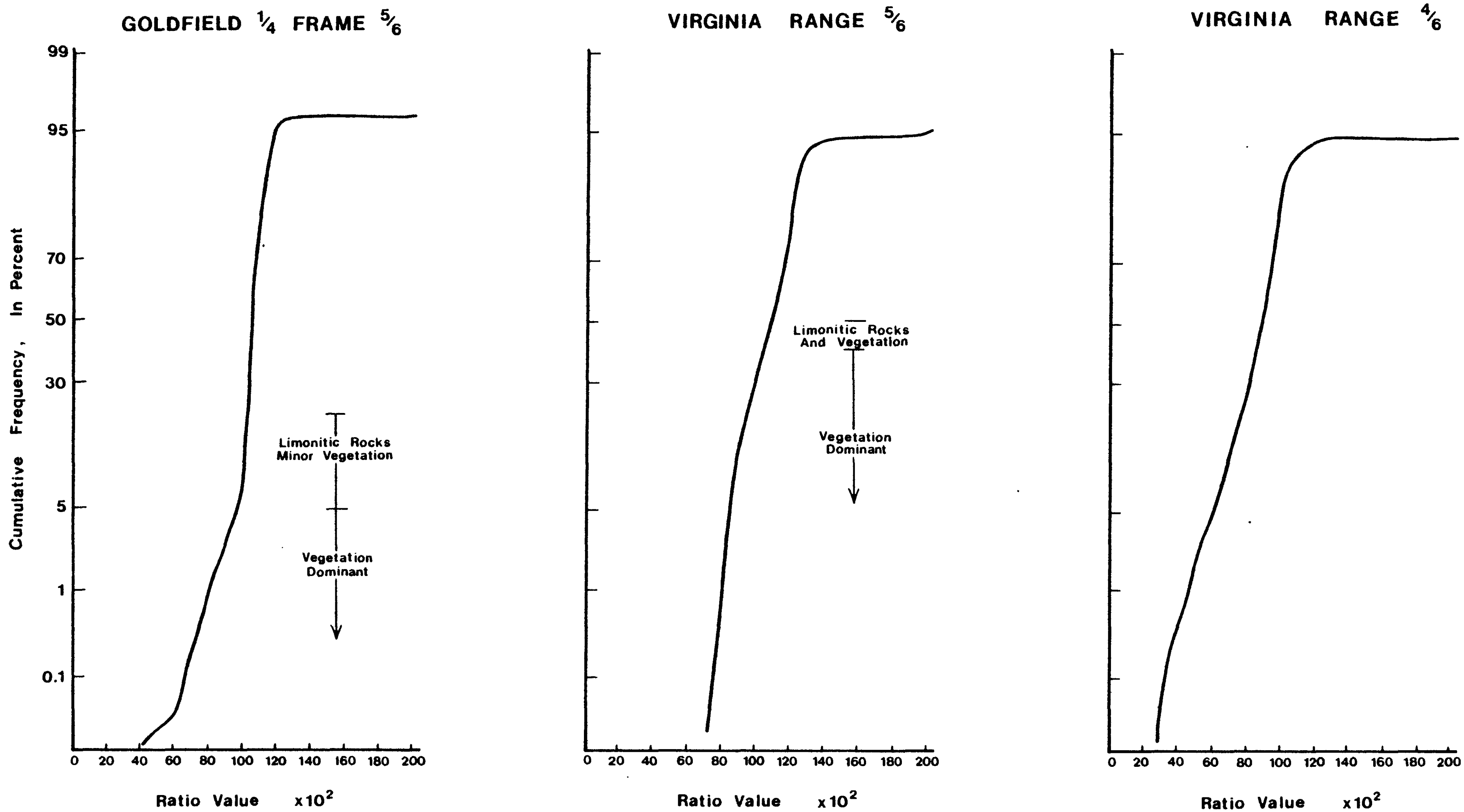


Figure 8. Cumulative frequency plots for Goldfield 5/6, Virginia Range 5/6, and Virginia Range 4/6.

dominated by limonitic rocks become increasingly important with increasing 5/6. Limonite-dominated pixels are also important in the 20-30 percentile range. The stretch used to produce a film transparency for diazo compositing was a linear stretch with approximately the lowermost 3.5 percent and uppermost 3.5 percent of the ratio values saturated (Rowan and others, 1974). Because limonitic areas have 5/6 ratios that fall in the lower part of the frequency distribution, any typical automatic linear stretch, in which 2-10 percent of the highest and lowest values is saturated, will result in high film densities for limonitic rocks. The high film densities in turn produce intense yellow on the diazo film used for 5/6, providing a satisfactory enhancement of limonitic areas, even though overall contrast in the 5/6 film positive is low (see Rowan and others, 1974).

The probability plot for the Virginia Range area, which includes considerably more vegetation than the Goldfield area, departs significantly from a Gaussian distribution below the 94 percentile, but contains no sharp breaks, making subdivision of the data set by fitting it to two or three overlapping Gaussian distributions ambiguous. Density slicing at 10 percentile intervals here shows that most pixels below the 40 percentile level owe their relatively low 5/6 to vegetation. Limonitic areas are conspicuous only in the 40-50 percentile range. In this case, limonitic areas would be near the middle of the gray scale with any linear stretch that might commonly be applied, and no enhancement would result. Enhancement can be produced only by a severe stretch, in which a very large part (20 percent or more) of the data at the tails of the distribution are saturated. Rowan and Abrams (1978) tried this approach at Tintic, Utah, but found that such a severe stretch produced a very noisy image, owing to overemphasis of small radiance variations represented in the remaining data.

The third cumulative frequency curve shown in figure 8 is of MSS 4/6 for the Virginia Range area. The lower part of the distribution is also dominated by vegetation, but the bulk of the 4/6 data cover a DN range 50 percent larger than the bulk of the 5/6 data. Thus the severe stretch required to enhance limonite pixels is possible here because the contrast available in the remaining data is large enough so that the image does not become too noisy.

For this particular study, a cumulative density function (CDF) stretch was actually applied to the entire distribution instead of a linear stretch. The result in this case, however, is similar to a 10 percent automatic linear stretch.

CONCLUSIONS

This study confirms results of earlier work in the vicinity of Goldfield, Nevada, showing that alteration products typical of acid-sulfate hydrothermal activity in volcanic rocks, including silicified, advanced argillic, and argillic types are easily detectable in Landsat multispectral images by using enhancement techniques designed to take advantage of the spectral characteristics of limonite minerals.

The Virginia Range test area differs from the Goldfield test area in having more abundant vegetation. In the color-subtractive diazo color-ratio composites used to enhance limonitic materials, altered rocks shift from green to yellow when tree cover reaches about 20-30 percent, the variation possibly being due to amount of sage and other low-growing species, and to orange or magenta when tree cover reaches about 45-50 percent. Sage alone is dense enough in some places in the valleys to appear yellow on the CRC but usually not dense enough in the altered areas to obscure altered rocks in the absence of other larger species. Vegetation cover found at higher elevations on north-facing slopes is dense enough to obscure altered rocks. More important, relatively abundant vegetation in a scene forces modification of enhancement methods. Whereas MSS band ratio 5/6 is most effective for the yellow component of the CRC in the Goldfield area and in other sparsely vegetated areas, here vegetation dominates the lower 5/6 ratios. Because the range of 5/6 ratio values is relatively small, and the 5/6 ratio positive lacks contrast, the severe stretch necessary to enhance the pixels dominated by limonitic altered rocks produces a noisy ratio image. This problem can be largely overcome by using 4/6 instead of 5/6. Here vegetation also dominates low-ratio values, but the range of ratio values is large enough and ratio-image contrast high enough so that the necessary severe stretch can be performed without rendering the resulting ratio image too noisy.

Where vegetation is not a significant problem, areas of altered rocks inferred from mapping of limonitic materials using the CRC agree well in general with altered areas mapped by conventional methods, but agree only moderately well in detail. The most important source of differences is partial to complete cover of altered rocks by unaltered rock talus or alluvium. Since alteration boundaries beneath such materials are largely inferred, this is a limitation only in that the low spatial resolution of Landsat imagery makes such inferences much less precise than is possible with field observation aided by low-level aerial photographs. The most serious discrepancy in this image with respect to mapping hydrothermally altered rocks is enhancement of limonitic unaltered rocks on the CRC. Attempts to reduce this source of false color anomalies by varying the stretch or degree of diazo exposure invariably results in loss of information within altered areas as well, because the spectral characteristics of relatively high albedo limonitic unaltered rocks (here silicic ash-flow tuffs and intermediate flows and breccias) and altered rocks are similar from 0.4 to 1.1 μm, and consequently ranges of MSS ratios commonly overlap considerably (Rowan and others, 1977).

One other problem encountered in this area, although of minor importance here, is loss of information on a poorly iluminated slope dipping away from the sun. Significant information loss occurred here with an effective sun angle of 20-25 degrees, indicating that in some areas having high relief, much larger areas than those actually in shadow might be lost.

These results show that Landsat images enhanced by the method of Rowan and others (1974) can be used for reconnaissance alteration mapping in moderately heavily vegetated semiarid terrain as well as in the sparsely vegetated arid to semiarid terrain where the technique was originally developed. Significant vegetation cover in a scene, however, requires use of MSS ratios 4/5, 4/6, and 6/7 rather than 4/5, 5/6, and 6/7, and requires careful interpretation of the results. Supplementary information suitable for vegetation identification and cover estimates, such as standard Landsat false-color composites and low-altitude aerial photographs of selected areas, is desirable.

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