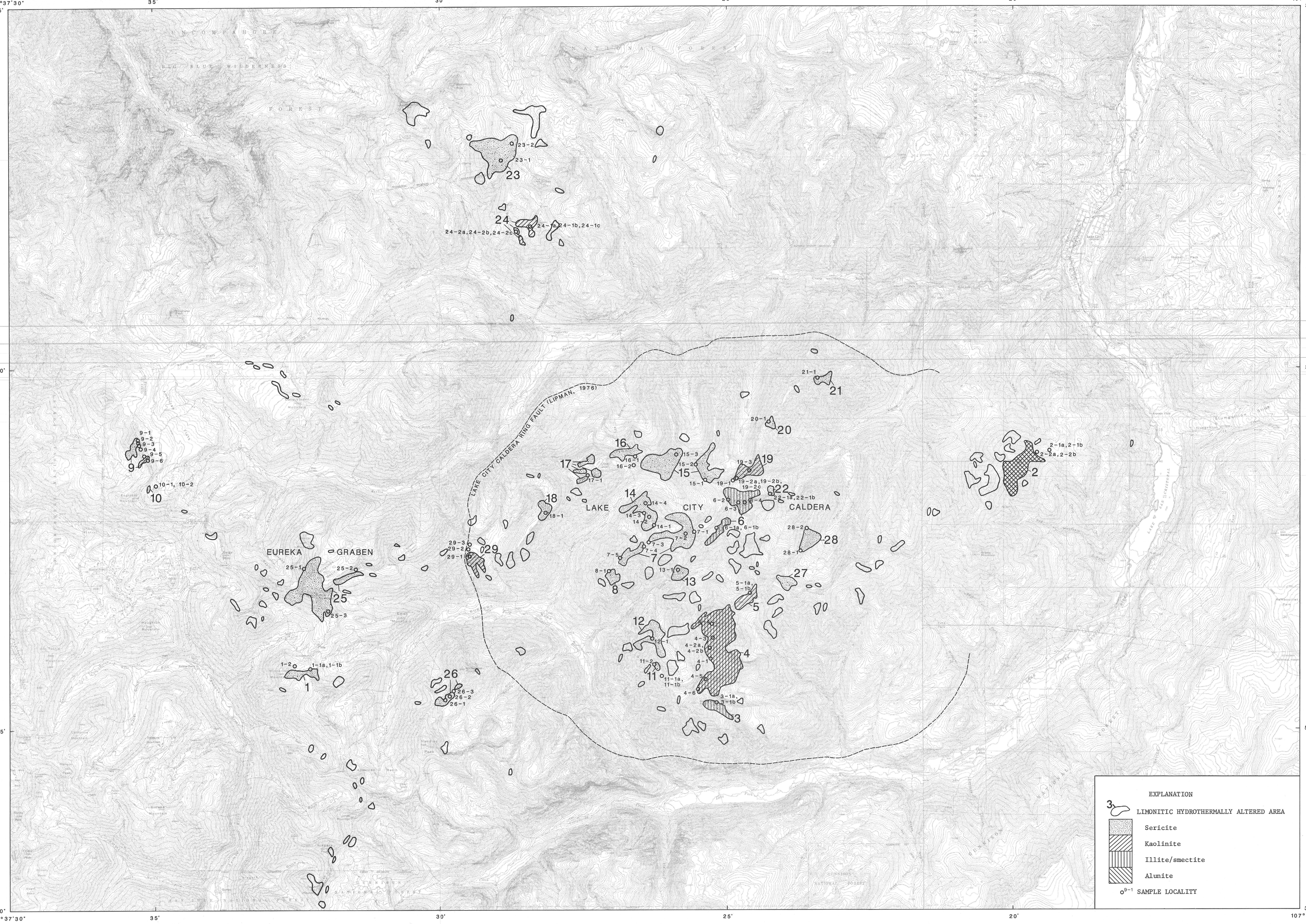
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

MISCELLANEOUS FIELD STUDIES
MAP MF-1868



Base from U.S. Geological Survey, 1:24,000
Handies Peak, 1955; Lake City, Uncompahgre
Peak, Wetterhorn Peak, 1963; Lake San
Cristobal, Redcloud Peak, 1964

SCALE 1:48 000

1 ½ 0 1 2 3 MILES

1 .5 0 1 2 3 KILOMETERS

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Table 1.--Alteration mineralogy and geochemistry of limonitic hydrothermal alteration areas

[A, alunite; G, goethite; H, hematite; I, illite/smectite; J, jarosite; K, kaolinite; Q, quartz; P, pyrite; S, sericite; -, not recognized; --, not anomalous]

Map no.	Area	Alteration mineralogy									Geochemical anomalies				
		Q	S	P	K	A	I	H	G	J	As	Sb	Ag	Mo	Other
1	Cinnamon Pass	Q	S	P	-	-	-	-	-	-	As	Sb	Ag	--	--
2	Red Mountain	Q	-	P	K	A	-	-	-	-	--	Sb	--	--	Ba
3	Sunshine Peak	Q	S	P	-	-	I	-	-	-	As	Sb	--	--	--
4	Redcloud Peak	Q	-	P	K	-	I	H	G	-	As	Sb	Ag	Mo	Bi, Cd, Hg, Zn, Pb
5	Redcloud Peak NE	-	-	-	K	-	-	-	-	-	--	Sb	--	--	--
6	Radio repeater	Q	S	-	-	-	I	-	-	-	--	Sb	--	--	--
7	Silver-Cooper Divide	Q	S	P	-	-	-	H	-	-	As	Sb	--	--	--
8	Silver-Cooper Divide W	-	S	P	-	-	-	H	-	-	--	--	--	--	--
9	Engineer Pass N	Q	S	P	K	-	-	-	-	-	As	Sb	Ag	--	Bi, Hg, Pb
10	Hough mine	Q	S	P	-	-	-	-	-	-	As	Sb	--	--	Cu
11	Sunshine Peak NW	Q	S	P	-	-	-	H	-	-	As	Sb	--	--	--
12	Sunshine Peak NW	Q	S	P	-	-	-	H	-	-	As	--	Ag	--	Pb
13	Silver-Cooper Divide S	Q	S	P	-	-	-	H	-	-	--	--	Ag	--	--
14	Silver-Cooper Divide N	Q	S	P	-	-	-	-	-	-	--	--	--	Mo	--
15	Cooper Lake E	Q	S	P	-	-	-	-	-	-	As	--	Ag	Mo	--
16	Cooper Lake NE	Q	S	P	-	-	-	-	-	-	--	Sb	Ag	Mo	--
17	Cooper Lake	Q	S	P	-	-	-	-	-	-	--	--	Ag	--	--
18	Cooper Lake SW	Q	S	P	-	-	-	-	-	-	As	--	Ag	Mo	--
19	Bitch Ridge	Q	S	P	K?	-	-	-	G	-	--	--	--	--	--
20	Owl-Alpine Divide	Q	S	P	-	-	-	-	-	-	--	--	--	Mo	--
21	Owl-Alpine Divide NE	Q	S	P	-	-	-	-	-	-	--	--	--	--	--
22	Bitch Ridge S	Q	S	P	-	-	-	H	-	J	As	--	Ag	Mo	--
23	Iron Beds N	Q	S	P	-	-	-	-	-	J	--	--	--	--	--
24	Iron Beds S	Q	-	P	K	-	-	H	G	-	As	Sb	--	--	Bi, Ba, Hg, Cu
25	Wood Mountain	Q	S	P	-	-	-	-	-	-	As	Sb	Ag	--	--
26	Whitecross Mountain	Q	S	P	-	-	-	-	-	-	As	Sb	Ag	Mo	--
27	Alpine Gulch	-	S	-	-	-	-	-	-	-	--	--	--	--	--
28	Alpine Gulch	Q	S	P	-	-	-	H	-	-	--	Sb	--	Mo	--
29	9 o'clock ring fault	Q	S	P	K	-	-	-	-	-	As	Sb	Ag	Mo	Cd, Zn, Ba

Table 2.--Alteration minerals as determined by spectral reflectance and X-ray diffraction (XRD)

[A, alunite; G, goethite; H, hematite; I, illite/smectite; J, jarosite; K, kaolinite; n, not determined; Q, quartz; P, pyrite; S, sericite; ---, no analysis]

Sample no.	Spectral reflectance	XRD	Sample no.	Spectral reflectance	XRD
1-1a	S	---	11-1a(2)	S	---
1-1b	n	---	11-2	S	---
2-1b	n	---	14-2	n	---
2-2b	K,A	---	14-4	S	S
3-1b(1)	n	---	16-1	S	S
3-1b(2)	I?	I?	19-1	n	---
4-2a(1)	H,K	H?,K	19-2b(1)	G,S	---
4-2a(2)	G	I?	19-2b(2)	G,K?	---
4-2a(3)	G,K	K	19-2c	n	---
4-2a(4)	K	---	22-1a	J	J,Q
5-1b	K	---	23-2	J	J,Q
6-1a	I?	I?	24-1c(1)	G	---
6-1b	I?	---	24-1c(2)	H,K	---
7-5	S	---	24-2c	K	K
9-2	S	---	26-3	S	---
9-5	K	---	28-2	H	---
11-1a(1)	H	---	29-1	S	---

Table 3.--Anomalous trace-element geochemistry

[ppm, parts per million; C, concentration in ppm; AC, anomaly contrast (concentration in ppm divided by threshold concentration in ppm); --, not anomalous (below threshold concentration); *, insufficient sample. Detection limit is the lowest concentration at which element could be measured. Threshold concentration is the concentration above which an element is considered anomalous.]

			Atomic absorption														Emission spectrometry									
			As		Bi		Cd		Hg		Sb		Zn		Au		Ag		Cu		Mo		Pb		Ba	
Detection limit (ppm)			5		2		0.1		0.02		2		2		0.1		0.5		1		5		10		30	
Threshold concentration (ppm)			30		5		1		0.1		5		100		0.1		0.5		100		10		70		2000	
Area or rock unit		Sample no.	C	AC	C	AC	C	AC	C	AC	C	AC	C	AC	C	AC	C	AC	C	AC	C	AC	C	AC	C	AC
Lake City Caldera	Unit 3[1]	3-1a	34	1.1	--	--	--	--	--	--	8	1.6	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Unit 2[1]	4-2b	488	16	52	10	1.7	1.7	0.86	8.6	57	11	128	1.3	--	--	1	2.0	--	--	10	1.0	700	10	--	--
		4-4	81	2.7	--	--	--	--	--	--	13	2.6	--	--	--	--	--	--	--	--	--	--	--	--	--	--
		11-1b	39	1.3	--	--	--	--	--	--	7	1.4	--	--	--	--	--	--	--	--	--	--	--	--	--	--
		12-1	33	1.1	--	--	--	--	--	--	--	--	--	--	--	--	1	2.0	--	--	--	--	150	2.1	--	--
		17-1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1	2.0	--	--	--	--	--	--	--	--
		18-1	56	1.9	--	--	--	--	--	--	--	--	--	--	--	--	0.5	1.0	--	--	10	1.0	--	--	--	--
		29-2	40	1.3	--	--	2.1	2.1	--	--	8	1.6	277	2.8	*	--	3	6.0	--	--	15	1.5	--	--	3000	1.5
		29-3	75	2.5	--	--	--	--	--	--	--	--	--	--	--	--	1.5	3.0	--	--	30	3.0	--	--	--	--
	Unit 1[1]	5-1a	--	--	--	--	--	--	--	--	9	1.8	--	--	--	--	--	--	--	--	--	--	--	--	--	--
		6-3	--	--	--	--	--	--	--	--	8	1.6	--	--	--	--	--	--	--	--	--	--	--	--	2000	1.0
		7-4	34	1.1	--	--	--	--	--	--	7	1.4	--	--	--	--	--	--	--	--	--	--	--	--	--	--
		13-1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7	14	--	--	--	--	--	--	--	--
		14-3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	15	1.5	--	--	--	--
		15-1	35	1.2	--	--	--	--	--	--	--	--	--	--	--	--	1	2.0	--	--	30	3.0	--	--	--	--
		16-2	--	--	--	--	--	--	--	--	5	1.0	--	--	--	--	1.5	3.0	--	--	15	1.5	--	--	--	--
		20-1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	15	1.5	--	--	--	--
		22-1b	61	2.0	--	--	--	--	--	--	--	--	--	--	--	--	0.7	1.4	--	--	15	1.5	--	--	--	--
		28-1	--	--	--	--	--	--	--	--	6	1.2	--	--	--	--	--	--	--	--	15	1.5	--	--	--	--
Whitecross area		26-1	3480	116	--	--	--	--	--	--	140	28	--	--	--	--	15	30	--	--	70	7.0				
Eureka graben area		1-2	257	8.6	--	--	--	--	--	--	76	15	--	--	*	--	7	14	--	--	--	--	--	--	--	--
		9-1	54	1.8	20	4.0	--	--	1.1	11	19	3.8	--	--	--	--	7	14	--	--	--	--	200	2.8	--	--
		10-2	85	2.8	--	--	--	--	--	--	32	6.4	--	--	--	--	--	--	100	1.0	--	--	--	--	--	--
		25-3	219	7.3	--	--	--	--	--	--	5	1.0	--	--	--	--	1.5	3.0	--	--	--	--	--	--	--	--
Iron Beds area		24-1a	--	--	--	--	--	--	0.15	1.5	5	1.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
		24-1b	384	13	12	2.4	--	--	1.2	12	46	9.2	--	--	--	--	--	--	100	1.0	--	--	--	--	5000	2.5
		24-2a	1650	55	--	--	--	--	0.2	2.0	11	2.2	--	--	--	--	--	--	--	--	--	--	70	1.0	--	--
Red Mountain area		2-1a	--	--	--	--	--	--	--	--	37	7.4	--	--	--	--	--	--	--	--	--	--	--	--	3000	1.5
		2-2a	--	--	--	--	--	--	--	--	15	3.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--

[1] Subdivision of the Sunshine Peak Tuff by K. Hon (written commun., 1984).

INTRODUCTION

The objective of the map is to show areas of limonitic hydrothermal alteration in the Lake City caldera area (fig. 1). Data from this study aided in the assessment of the mineral resource potential of three wilderness study areas: Red Cloud Peak, Handies Peak, and American Flats.

This map is derived primarily from interactive digital image analysis of Landsat multispectral scanner data that were interpreted for limonite associated with hydrothermal alteration. The remote sensing interpretation was supported by limited field checking, spectral reflectance measurements, X-ray diffraction measurements, and trace-element geochemical analyses.

"Limonite" is used in this report as defined by Blanchard (1968) "to denote the undifferentiated ferric oxide precipitates as a group. By common consent the word has become accepted as a collective term designating all of the reddish, yellowish, brownish, and blackish-brown supergene ferric oxide or ferric oxide hydrate precipitates"***which have not been more specifically identified."

The term "limonitic hydrothermal alteration" is used for that hydrothermal alteration that is limonitic. All hydrothermal alteration would be of interest for mineral appraisal studies, but current remote sensing capability allows us to map only that hydrothermal alteration that has limonite developed at the ground surface.

About 53 percent of the surface in the map area is obscured by vegetation (fig. 2) to the extent that no evaluation of the occurrence of limonitic hydrothermal alteration could be made. The mapped limonitic hydrothermally altered areas constitute about 1.5 percent of the area or about 3.2 percent of the exposed rock. Almost all of the limonitic areas shown on the map are above timberline.

A geologic map of this area is available (Lipman, 1976) at the same scale as this map (1:48,000).

REMOTE SENSING

Landsat satellites provide imagery data that can be processed to yield information on the surface occurrences of limonite. Limonite is very common in the Lake City caldera area, however,and specialized, interactive processing (Lee, 1985) was needed to separate limonite associated with hydrothermal alteration from much more abundant limonite not associated with hydrothermal alteration.

Where pyritization accompanied hydrothermal alteration, as it often did in this area, the pyrite weathers at the surface to limonite. A gossan may form or, more commonly, limonite staining occurs. This limonite is capable of being remotely sensed, even in quite small quantities. Limonite absorbs strongly in the wavelength region sensed by Landsat scanners, and the multispectral data can be analyzed to identify limonite and processed to produce a map of limonite exposed at the surface.

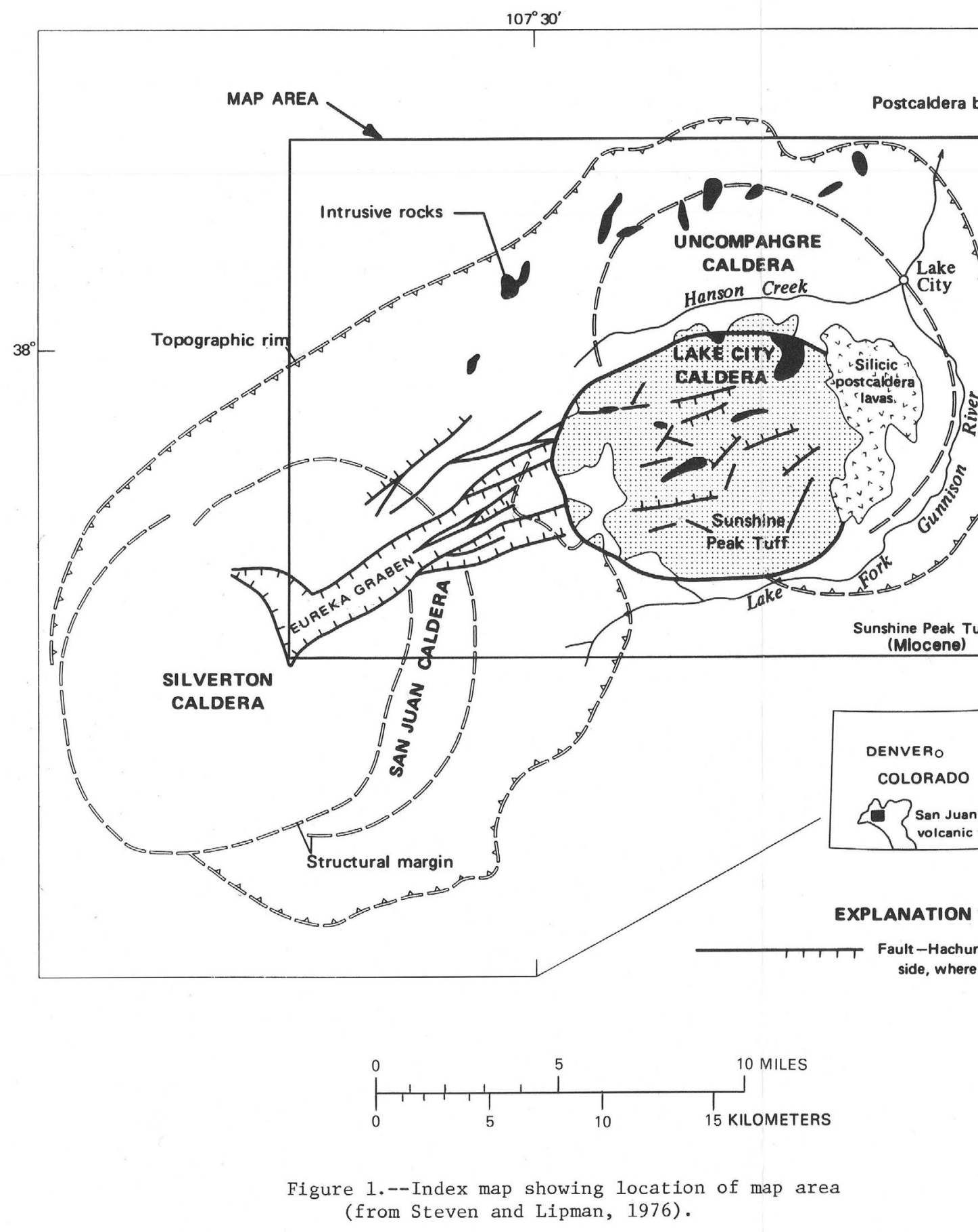


Figure 1.--Index map showing location of map area (from Steven and Lipman, 1976).

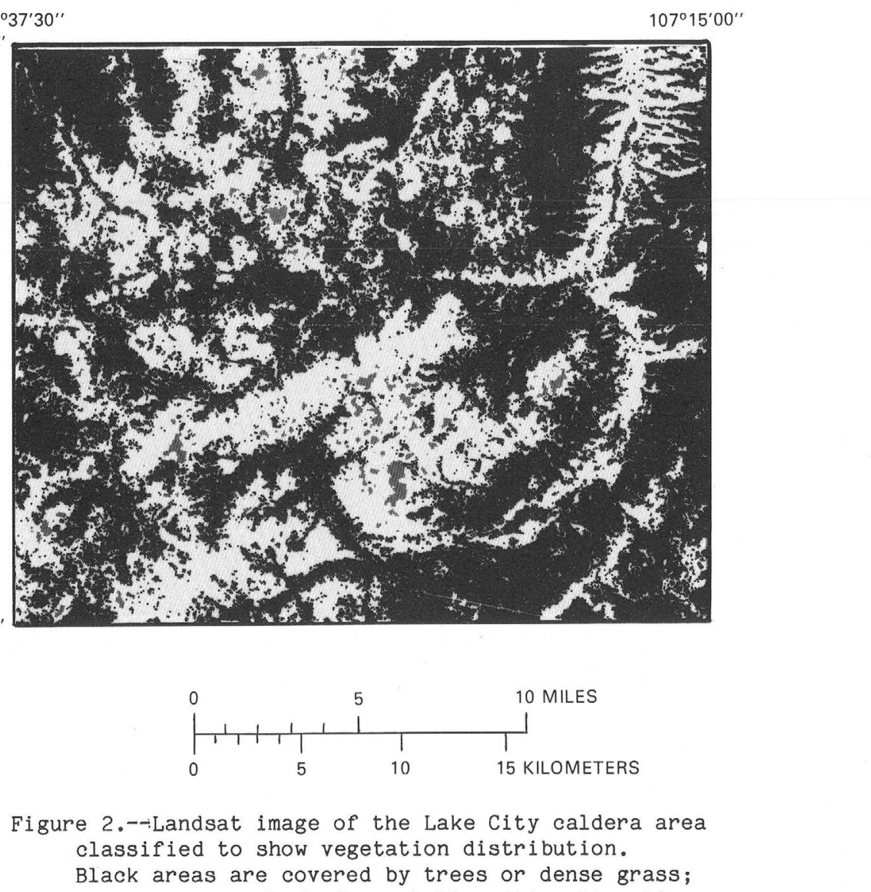


Figure 2.--Landsat image of the Lake City caldera area classified to show vegetation distribution. Black areas are covered by trees or dense grass; gray areas are hydrothermal limonitic alteration (generalized); white areas are nonvegetated rock and soil surfaces without hydrothermal limonite.

A Landsat computer-compatible tape of scene 11127-16541, acquired 24 August 1975, was "preprocessed" to reformat the image, to destripe it (equalize the six detectors), and to geometrically correct it for skew effect of the earth's rotation (Raines and others, 1978). Individual bands were ratioed to maximize spectral variations, minimize illumination differences (very commonly from slope effect), and produce a color-ratio-composite (CRC) image. The CRC image processed for the Lake City caldera area used the B4/B5 ratio coded red, B6/B7 coded green, and B4/B6 coded blue. Limonitic surfaces thus appear green (Rowan and others, 1974; Raines and others, 1978).

The CRC image of the Lake City caldera area, however, showed abundant limonite, much of it not associated with hdyrothermal alteration. In order to discriminate "hydrothermal" limonite from "nonhydrothermal" limonite, the Landsat data from three exposures of hydrothermally altered rocks (mapped by Lipman, 1976; these areas are at areas 2, 4, and 23 on the map) were analyzed to determine the spectral characteristics of "hydrothermal" limonite. Interactive digital image analysis techniques (Lee, 1985) then sought spectrally similar "hydrothermal" limonitic areas and screened out "nonhydrothermal" limonitic areas.

In order to seek systematic differences in the green pixels that may relate to different types of limonite and to quantitatively analyze these differences, the CRC colors were transformed to Munsell color coordinates--hue, value, and chroma (Raines, 1977). Interactive digital image analysis of the scene viewed on a color monitor defined the range of hues associated with the known "hydrothermal" limonite and the hues of "nonhydrothermal" limonite. By defining a processing algorithm to separate the hues of interest, some of the "nonhydrothermal" limonitic areas were eliminated from further study. Similar analysis in the value domain of the CRC further reduced the number of limonitic pixels by about 40 percent, still retaining the known "hydrothermal" limonite pixels. Analysis of chroma was also effective in further eliminating "nonhydrothermal" limonitic surficial deposits (alluvium, colluvium, landslides, and mudflows).

The map was used as a basis for field work in 1984 when most of the "hydrothermal" limonite areas were field checked and rock samples were collected for spectral reflectance, X-ray diffraction, and trace-element geochemical analyses. All of the areas interpreted as "hydrothermal" limonite by remote sensing were found to be limonitic when sampled in the field, and in every case the limonite was associated with hydrothermal alteration. No field mapping was done; the boundaries of the areas of limonitic hydrothermal alteration shown on the map were derived from the final Landsat image product.

In areas like the Lake City caldera, where vegetation is both dense and extensive, it is imperative to know whether a lack of detected limonite is attributable to nonlimonitic bedrock or to dense vegetation that obscures the surface. To this end, vegetation training areas were used to derive the Munsell color coordinates of aspen, conifers, and grasses. A thematic classification image was prepared that shows distribution of limonitic bedrock, nonlimonitic bedrock, and vegetation (fig. 2). From the Landsat data, it was determined that 53 percent of the area is covered by vegetation: 10 percent aspen, 14 percent conifers, and 29 percent tundra vegetation and alpine meadows.

LIMONITIC HYDROTHERMAL ALTERATION

A clear relationship exists between limonitic hydrothermal alteration and faults; alteration often occurs along and across faults, which mostly have a northeast trend. A strike frequency analysis of Lipman's (1976) mapped faults shows a statistically significant trend of faults bearing N 37°-76°E.

Alteration is discontinuous, and intense alteration may occur for a few meters or tens of meters, usually along quartz veins, with only weakly altered rocks surrounding the quartz veins. The alteration does not appear to be related to lithology, except that, locally, there is correlation (from limited observations) between alteration and breccia units.

Lipman (1976, p. 15) states that "*** the most intensely altered rock within the resurgent dome occurs around margins of the granite porphyry," although Lipman and others (1976) state that "*** many of the distension fractures cutting the Sunshine Peak Tuff in the resurgent dome localized hydrothermal alteration." Observations in this study agree with the latter statement in that much of the alteration appears to be more closely related to faults rather than to the intrusion(s). Although there is a proximal relationship between the Silver Creek-Cooper Creek altered area and the intrusion, large outcrops of the intrusion to the northeast (Alpine and Owl Gulches and the intervening divide) have only limited, weak alteration. Where the intrusion is exposed in the divide between Silver and Cooper Creeks, the intrusion-wall-rock contact strikes northwest, whereas the outcrop of limonitic alteration (area 6) trends northeast, parallel to faults on that ridge. It may be that the intrusion(s) drove the convective circulation, but it seems the faults controlled the flow of the hydrothermal solutions.

Hydrothermal alteration does not appear to be concentrated along the caldera ring fault, but because most of the trace of the ring fault is below timberline, limonite would not have been detected, even if present. The trace of the ring fault is above timberline at four areas in the southwestern part of the caldera; one of these four areas has limonitic hydrothermal alteration (area 29).

Alteration in the Red Mountain area (area 2) appears to be caused by a separate hydrothermal system from that in the resurgent dome. The limonitic areas mapped from Landsat data are within (or head within) the central quartz-alunite zone of this separate system as mapped by D. J. Bove (written commun., 1984).

Alteration in the Eureka graben area is clearly related to the faults mapped by Lipman (1976). The Wood Mountain area (area 25), for example, is extensively faulted. Two altered areas are not related to faulting: the alteration at area 9 (westernmost edge of mapped area) is related to a breccia pipe, and the cluster at Dolly Varden Mountain (not visited) appears to be restricted to the ash-flow member of the Oligocene Crystal Lake Tuff (Lipman, 1976).

Alteration in the Iron Beds area may be related to nearby rhyolite intrusions. Numerous similar rhyolite intrusions to the northeast and southwest, however, lack observable alteration.

All of the limonite is presumed to be of supergene origin. No crystallinity was observed at any outcrop, and the X-ray diffraction patterns indicate very poor and(or) very fine crystallinity. Hematite is the dominant limonite alteration mineral. Of the 12 areas from which a limonite mineral was determined, hematite is the only limonite mineral identified in seven of the areas, and hematite is present in three other areas, two in combination with goethite and one with jarosite (table 1). Hematite occurs throughout the region, whereas jarosite was found at only two sample localities (22-1 and 23-2), and goethite was identified from only three sample locations (4-2, 19-2, and 24-1). No correlation is apparent between limonite alteration minerals and lithology. A correlation does exist between limonite minerals and other alteration minerals: goethite occurs only where kaolinite is present.

Of the alteration minerals other than limonite, sericite is the most common. It is present in 25 of the 29 areas, and it is the only non-limonite alteration mineral in 20 of the areas (table 1). Kaolinite is the next most common alteration mineral, occurring in seven areas. Sericite is also the most widespread alteration mineral, found throughout the region except for the Iron Beds and Red Mountain areas. Alunite occurs only at Red Mountain.

IDENTIFICATION OF ALTERATION MINERALS

Classification of hydrothermal alteration is based primarily on clay minerals, some of which are difficult to identify. Hunt (1979) and Hunt and Ashley (1979) have shown that many alteration minerals and rocks can be identified by their spectral reflectance in the wavelength region from 0.4 to 2.5 micrometers. Thirty-four samples from 19 sample localities were measured in this wavelength region by Fred Kruse. The minerals identified (table 2) were kaolinite, sericite, alunite, illite/smectite, hematite, goethite, and jarosite.

Conventional powder X-ray diffraction (XRD) analysis of nine samples from eight different sample localities was conducted at the Colorado School of Mines. Table 2 lists the minerals that were identified. Limonite minerals were more easily identified by spectral reflectance measurements than by XRD, because the lack of good crystallinity gives an extremely weak X-ray pattern.

TRACE-ELEMENT GEOCHEMISTRY

Rock samples from many limonitic areas were analyzed for trace elements. Field criteria for sampling included greatest degree of apparent alteration and greatest development of limonite, thus the analyses tend to highgrade an outcrop rather than representatively sample it. Selected samples were analyzed by atomic absorption for As, Au, Bi, Cd, Hg, Sb, and Zn. Semiquantitative emission spectrographic analyses were performed for 31 elements including Ag, Cu, Mo, Pb, and Ba.

Analytical results are summarized in table 3, which shows only those elements considered to occur in anomalous concentrations. The definition of "anomalous" is somewhat arbitrary but is based on considerations of median concentrations for felsic igneous rocks, surface mobility, and detection limits. The threshold concentrations used are from 1.7 (Zn) to 500 (Bi) times greater than the average concentrations for felsic rocks (as given by Vinogradov, 1962) and range from 1.1 to 16 times the upper range of average concentrations for felsic rocks (as given by Wedepohl, 1969-1978).

The Lake City caldera area as a whole is characterized by anomalous concentrations of Sb, As, Ag, and Mo. Few clear spatial patterns emerge, although Mo is more common within the caldera than without, and no Mo anomalies were observed in the Eureka graben area. Anomalous concentrations of Hg were found particularly in the Iron Beds area, but sampling there was very limited.

Within the Lake City caldera, anomalous concentrations of Sb, As, Ag, and Mo are common. Mo occurs more commonly in the northern part of the caldera, whereas the other elements show no clustering. Although the data are limited, the percentage of samples having anomalous concentrations of As and Ag appears to increase upward in the section, whereas Mo shows a concomitant decrease.

No anomalous concentrations of Au or Cu were observed within the caldera. Anomalous concentrations of Bi, Cd, Hg, Zn, and Pb were found near Red Cloud Peak (sample locality 4-2b) and at the westernmost part of the ring fault (sample locality 29-2). These two sample localities are anomalous among the intracaldera rocks because they have high concentrations of many other elements as well.

Sample locality 4-2b, near Red Cloud Peak, contains anomalous concentrations of Hg, As, Sb, Bi, Pb, Ag, Cd, Zn, and Mo. It contains the only anomalous concentrations of Hg, Bi, and Pb in the caldera and, along with the ring fault samples, the only anomalous concentrations of Cd and Zn. The ring fault sample locality (29-2) has anomalous concentrations of many elements, including the only significant concentration of Ba in the caldera. Concentrations of Mn at this sample locality also are much higher (5000 ppm) than at any other intracaldera sample locality (300 ppm) or extracaldera sample locality (700 ppm).

Samples from the Eureka graben area are similar to the caldera samples and are characterized by anomalous concentrations of Sb, As, and Ag. A notable difference between the Eureka graben area and the caldera is that Mo was not found in anomalous concentrations in any of the sample localities in the Eureka graben area.

The single sample from the White Cross Mountain area has high concentrations of As, Sb, Ag and Mo, the same elements that occur in anomalous concentrations within the caldera. The concentrations of these elements, however, are greater at White Cross Mountain than within the caldera.

Samples from the Iron Beds area have high concentrations of Hg, As, and Sb. They differ from the intracaldera rocks in that they have higher Hg concentrations, and they do not have anomalous concentrations of Ag.

Two samples from the Red Mountain area have anomalous concentrations of Sb, and one of them contains an anomalous concentration of Ba.

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MAP SHOWING AREAS OF LIMONITIC HYDROTHERMAL ALTERATION IN THE LAKE CITY CALDERA AREA, WESTERN SAN JUAN MOUNTAINS, COLORADO

By

Keenan Lee

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