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MAP OF THE WALKER LAKE 1° BY 2° QUADRANGLE, CALIFORNIA AND NEVADA, SHOWING THE REGIONAL DISTRIBUTION OF HYDROTHERMALLY ALTERED ROCKS

By

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INTRODUCTION

The main objective of the remote sensing studies conducted in the Walker Lake 1° by 2° quadrangle, California and Nevada, was to contribute to the mineral appraisal of the quadrangle by compiling a map showing the regional distribution of hydrothermally altered rocks and to evaluate the relationship between their distribution and the distributions of faults and fractures and other rock units.

The map of hydrothermally altered rocks (accompanying map) was produced through field evaluation of a limonite map that was compiled from digitally processed images derived from the Landsat Satellite Multispectral Scanner (MSS) (Rowan and others, 1980). We also examined the distribution of mines and prospects because altered rocks were not detected in some known mineralized areas. The distribution of hydrothermally altered rocks and mineralized areas was then compared to the distribution of faults (Stewart and others, 1982) and Landsat derived lineaments (Rowan and Purdy, 1984). Concentrations of altered rocks were also compared to aeromagnetic and gravity anomalies.

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HYDROTHERMALLY ALTERED ROCKS

Image Processing

The approach used for mapping hydrothermally altered rocks is based on the unique spectral reflectance of iron-oxide and hydrous iron-oxide minerals, collectively referred to as limonite, in the MSS response range of 0.5-1.1 μm and on the presence of limonite in altered rocks where pyrite has been oxidized (Rowan and others, 1974; 1977; Rowan and Abrams, 1978; Vincent, 1977; Blodget and others, 1978; Raines and others, 1978). In order to display the diagnostic spectral reflectance of limonite, ratio images were generated to minimize brightness variations due to topographic slope and albedo differences. Ratios were calculated for each of the spatially registered picture elements (pixels), and a linear transformation was applied to optimize image contrast so that these values could be transferred to film via a digital-to-analog film recorder utilizing the total contrast available on the film. In the black-and-white ratio images generated by the film recorder, low ratios were assigned high film density values and high ratios were represented by low film density. The images were geometrically rectified prior to recording the digital data onto film. No corrections were made for atmospheric scattering or scan-line striping. In order to cover the entire 1° by 2° quadrangle, two MSS scenes were processed (E1380-18111 and E2951-17300).

Color images were made from black-and-white ratio images using diazo film to produce a color subtractive composite image. Two color-ratio composite (CRC) images of each of the two Landsat scenes were prepared for initial evaluation. In one CRC image, MSS 4/5, 5/6, and 6/7 were displayed as blue, yellow, and magenta diazo films; in the other CRC image, MSS 4/6 was substituted for 5/6. The latter CRC image was selected for mapping limonitic areas because of its higher image quality due mainly to lower electronic noise in the MSS 4/6 ratio.

Compilation of the Limonitic Bedrock Map

Pixels representing limonitic areas appear green in the CRC image used in this study. Locations of the green pixels were projected optically from the CRC image onto 1:250,000-scale prints of Return Beam Vidicon (RBV) images of the eastern two-thirds of the quadrangle and 1:62,500-scale topographic maps of the western one-third where cloud-free RBV images were not available. The RBV images were used because their spatial resolution of approximately 25 m, compared with the 79 m resolution of the MSS images, permitted better identification of roads, streams and other topographic features that were useful for location during field evaluation. Therefore, compiling the locations of the limonitic areas onto the 1:62,500-scale topographic maps was not necessary for the eastern two-thirds of the quadrangle. Occurrences of limonitic bedrock were also compiled on the 1:250,000-scale topographic map for the quadrangle (Rowan and others, 1980). Alluviated areas were deleted from this and subsequent compilations using published geologic maps, and both Skylab color photographs and Landsat images where the mapping was still incomplete.

Field Evaluation

Extensive field evaluation of the limonitic bedrock areas was necessary for determining which of the limonitic areas are altered, because limonite resulting from oxidation of pyrite associated with hydrothermally altered deposits formed by sulfur-rich solutions is not distinguishable on the CRC from limonitic staining associated with weathering of ferromagnesian and opaque minerals not related to hydrothermal alteration. Most of the limonitic areas were examined by the authors, but information about some areas was obtained from other geologists. Each area examined was categorized as being either altered or unaltered. This determination was usually straightforward in areas consisting of volcanic and intrusive rocks, owing to the presence of pyrite or limonite pseudomorphs after pyrite, replacement of feldspar by alunite, sericite, and clay minerals, oxidation and conversion of ferromagnesian minerals to chlorite and clay minerals, and, locally, introduction of large amounts of silica. However, in a few areas of limonitic sedimentary and metasedimentary rocks the origin of the limonite was not clear, and the decision was based on a comparison of the normal mineral content and texture of the lithologic unit with that of the limonitic exposure. The altered rocks were also categorized, on the basis of limited field examination, according to the dominant type of altered rock present (see legend of accompanying map) where adequate information was obtained. The unaltered limonitic rocks were also categorized with respect to the type of rock present at each locality (Rowan and Purdy, 1980).

Hydrothermally altered rocks that are not limonitic, such as bleached silicified and argillized rocks, were not consistently distinguished in the CRC images (Rowan and others, 1977). These rocks were mapped during the field evaluation, especially in areas with dense vegetation cover.

Distribution

The Walker Lake quadrangle encompasses parts of two physiographic provinces. The eastern three-fourths of the quadrangle lies within the Great Basin province and the western one-fourth within the Sierra Nevada province. Hydrothermally altered rocks are widespread in the Great Basin part of the quadrangle but sparse in the Sierra Nevada portion. Approximately 30 percent of the limonitic areas (Rowan and others, 1980) proved to be altered, including skarn deposits. Argillized rocks, including sericitized rocks, are the most widespread type, accounting for approximately 32 percent of the total area consisting of altered rocks. Complexly related argillized and silicified rocks, which are not differentiated on the alteration map (accompanying map), occupy about 42 percent of the total altered area. Silicified rocks underlie about 12 percent of the area. Miscellaneous altered rocks, including hematite alteration and assemblages of chlorite-epidote-quartz and andalusite-cordierite-quartz, and skarn deposits are estimated to account for 3 and 1 percent, respectively. Approximately 10 percent of the altered areas are not categorized as to dominant alteration type.

Walker Lane Alteration Belt—In the Great Basin part of the quadrangle, most of the altered areas are located within several large clusters, some of which form roughly linear belts. The most well-defined linear belt is coincident with the Walker Lane, a northwest-trending, right-lateral, strike-slip fault zone (Gianella and Callaghan, 1934; Nielsen, 1965; Albers, 1967). This belt, which is approximately 20 km wide and at least 65 km long, covers most of the Gabbs Valley Range in the northeastern part of the quadrangle (fig. 1). These altered rocks are closely associated with the mainly 29 to 18 million year (m.y.) old, rhyolite ash-flow tuffs and flows and associated intrusive rocks that underlie most of this range (Stewart and others, 1977). For convenience of discussion, we refer to this major linear concentration of altered rocks as the Walker Lane alteration belt (fig. 2). Altered rocks are much less extensive in the Mesozoic metasedimentary and metavolcanic rocks that dominate exposures to the southwest in the Gillis Range (fig. 1). Northeast of the Gabbs Valley Range, where northeast-rather than northwest-trending faults dominate, altered rocks are sparse in the Cenozoic volcanic and sedimentary rocks of similar age and in Mesozoic granodioritic rocks.

Markleeville Alteration Belt—A cluster of altered areas is also present in the northwestern part of the quadrangle. The cluster appears to consist of two areas that are separated by a roughly 6 km-wide, generally northwest-trending area. The larger altered area located to the southwest of this separation lies almost entirely within 18-11 m.y. old rocks which are mainly andesitic (Stewart and others, 1977; 1982). As will be discussed later, numerous faults and lineaments are also present in this area. The smaller area to the northeast is situated within mainly Jurassic metasedimentary and metavolcanic rocks, but altered Mesozoic granodioritic rocks also are present. The rocks exposed in the area separating the two clusters of altered rocks are generally equivalent in age and lithology to the rocks that are extensively altered in the larger southwestern cluster. The larger area trends generally north-northeast. The orientation of the smaller altered area is roughly north; however, a substantial cover of Tertiary gravel deposits northwest of this area may obscure altered rocks whose presence would change the overall trend of the alteration zone. Together, these two altered areas constitute a broad northeast-oriented zone, which we refer to as the Markleeville alteration belt (fig. 2).

The areal distribution of altered rocks is more complex in the southern half of the quadrangle. However, we envision two broadly defined, but major belts: the Sweetwater Mountains-Garfield Flat and Aurora-Bodie Hills alteration belts (fig. 2).

Sweetwater Mountains-Garfield Flat Alteration Belt—If the areas of altered rocks in the Aurora-Bodie Hills districts and the southeastern corner of the quadrangle are excluded, a west-northwest-oriented belt is apparent that extends westward from the eastern

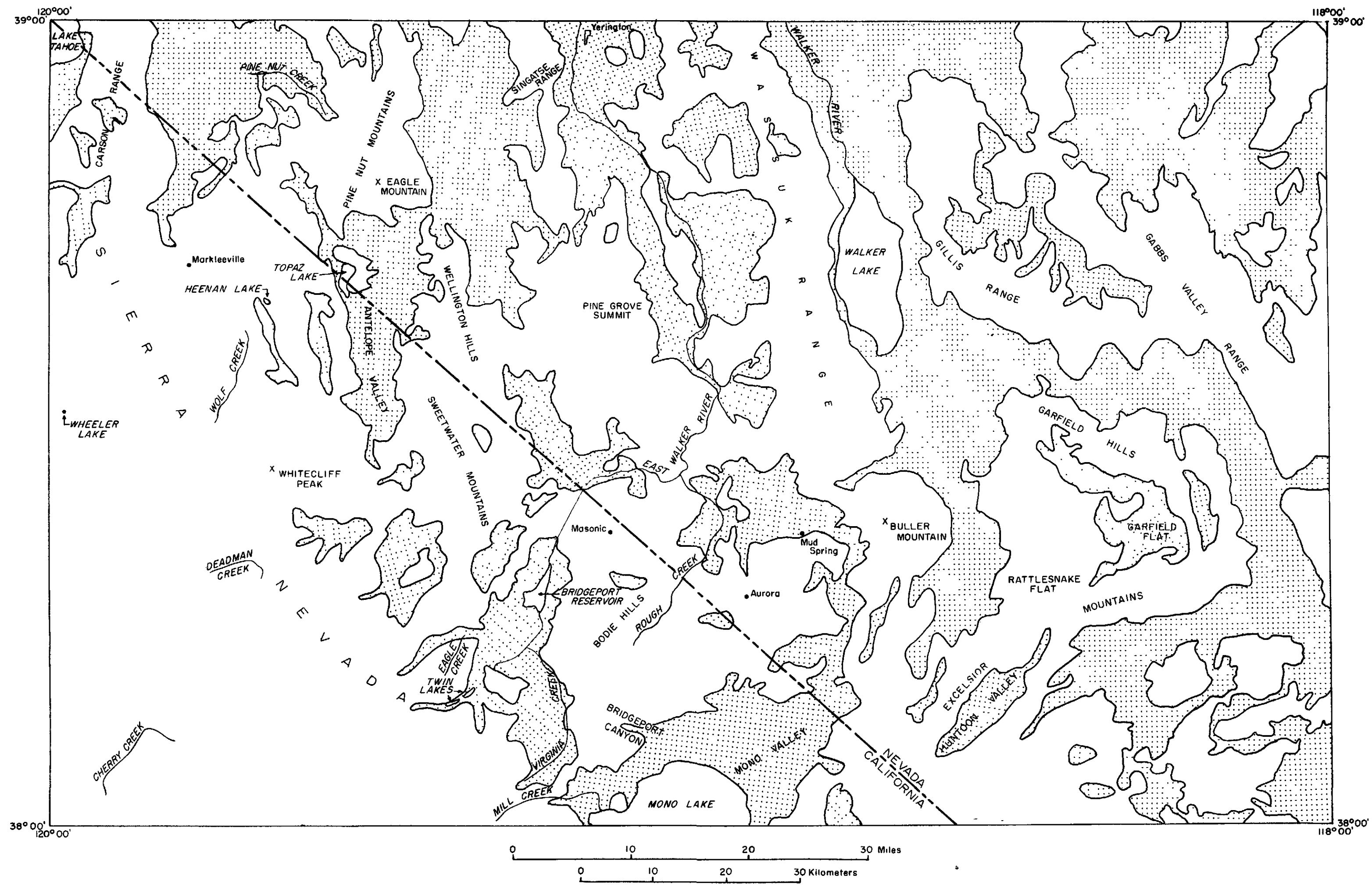


Figure 1.--Generalized distribution of alluvial deposits (stipple pattern). Cultural and topographic features referred to in the text are shown.

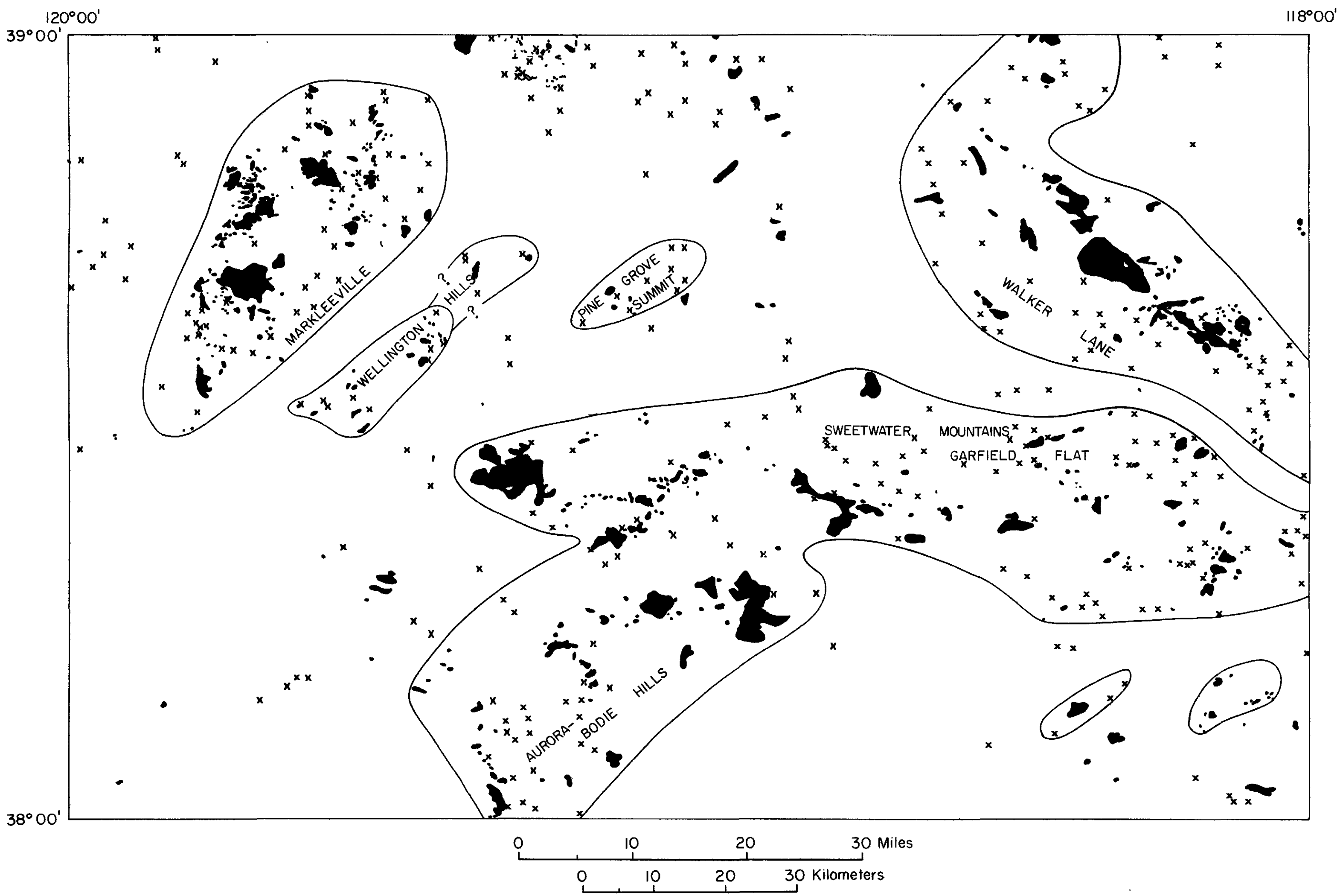


Figure 2.--Distribution of hydrothermally altered rocks, mines, and prospects where altered rocks were not mapped. Mines and prospects are indicated by X's on the map. Heavy lines define approximate boundaries of interpreted alteration belts named on the map.

border of the quadrangle to the Sweetwater Mountains. Within this belt, northeast as well as west-northwest trends are evident in the areal distribution of altered rocks, especially in the Masonic district - East Walker River area, near Mud Spring, and in the Garfield Hills area. Throughout this zone, which we named the Sweetwater Mountains-Garfield Flats alteration belt, the altered areas occur dominantly within 18-11 m.y. old andesite flows and Cretaceous granodioritic rocks.

Aurora-Bodie Hills Alteration Belt—In the area south of the Sweetwater Mountains-Garfield Flat alteration belt and north of Mono Lake, definition of a pattern of the distribution of the altered areas is difficult. Although the broad cluster of altered areas is generally northeast oriented, it can be divided into three subclusters. Two of these subclusters are northwest-trending and the third is east-trending. The alteration in the southwestern most area is associated with northeast-trending fractures in Mesozoic metasedimentary and metavolcanic rocks (William Kieth, USGS, Menlo Park, Calif., personal commun., 1980). In addition, northeast-trending fractures are prominent in the Aurora district (Ross, 1961) where the dominant rocks are 11-8 m.y. old rhyolitic flows, andesites that are 18 m.y. old or younger and Cretaceous granodiorites. We tentatively suggest that the altered rocks in this part of the quadrangle are concentrated along this northeast-trending belt, referred to as the Aurora-Bodie Hills alteration belt, but that northwest oriented fractures were also important in the localization of alteration.

As previously mentioned, a large number of mines and prospects either do not have sufficiently large areas of altered rocks to permit detection in the MSS images or detection is difficult because of the type of alteration present. In order to gain a more complete picture of the regional distribution of mineralized areas, we prepared a map which combines the locations of precious and base metal deposits that were not already marked by altered rocks shown on the alteration map (see accompanying map). The location of the mines and prospects were obtained from the U.S. Bureau of Mines' Mineral Availability System and from a compilation prepared by Don Huber (USGS, Menlo Park, Calif, written commun., 1981). Although primary uranium deposits are included in figure 2, clearly secondary deposits were excluded (Durham and Felmlee, 1980).

The resulting map confirms the pattern of the Markleeville alteration belt with a slight broadening to the northeast, and the Aurora-Bodie Hills alteration belt is strengthened considerably by the presence of numerous mines within the alteration belt (fig. 2). The Walker Lane belt is extended to the southeast and broadened southwestward, although hydrothermal activity still appears to have been most intense along the central part of this belt. Another apparent change in alteration pattern between the alteration map (accompanying map) and figure 2 is the suggestion of a northeast-oriented belt at the northwestern terminus of the Walker Lane alteration belt. Northeast-trending faults are dominant in this area (Stewart and others, 1982). However, the shape of this apparent belt may be a function of the distribution of alluvium (fig. 1), and studies northeastward of this quadrangle will be needed for evaluating this feature.

The Sweetwater Mountains-Garfield Flat alteration belt is also broadened in the eastern part (fig. 2). This area is especially complex, probably because it is situated where this belt and the Pancake Range lineament intersect. The Pancake Range lineament (Rowan and Wetlaufer, 1973; 1975; 1979; 1981; Ekren and others, 1976) is an east-trending feature defined by the termination and disruption of several mountain ranges. It extends from the Pancake Range, 160 km east of the Walker Lake quadrangle, to Mono Valley (fig. 1). In addition, this area of intersection is highly faulted, and northwest-trending faults, probably related to the Walker Lane, are locally abundant (Stewart and others, 1982).

The addition of mines and prospects to the alteration map also points out several other smaller concentrations, most of which are elongate in the northeast direction. The largest areas are located in the vicinity of the Wellington Hills and Pine Grove Summit (fig. 1).

Wellington Hills Alteration Belt—The Wellington Hills alteration belt consists of three areas of altered rocks and mines which are separated from the adjacent areas by several kilometers. The southwestern area is separated from the middle area by Antelope Valley. The rocks separating the northeastern and middle areas are mainly 18-11 m.y. old andesite, sedimentary rocks less than 8 m.y. old, and Tertiary gravel deposits. Whether the mineralization in these two areas is older than these deposits and hence obscured by them is not known. Tentatively, we regard this alinement of altered rocks and mines as a minor alteration belt and refer to it as the Wellington Hills alteration belt (fig. 2).

Pine Grove Summit Alteration Belt—The Pine Grove Summit area is a slightly smaller area, but the distribution of the mines and altered areas forms a distinctly northeast-elongate pattern, which we named the Pine Grove Summit alteration belt (fig. 2). In addition, northeast-trending linear features are abundant within this pattern (Rowan and Purdy, 1983).

Two smaller, northeast-oriented areas of altered rocks and known deposits are located in the southeastern corner of the quadrangle (fig. 2). Some important areas, including the Yerington district and the northern part of the Wassuk Range, do not appear to fit into these or other belts.

In summary, hydrothermally altered rocks, including skarn deposits, and mines and prospects located where altered rocks were not mapped are mainly distributed within four major belts: (1) the northwest-trending Walker Lane alteration belt, (2) the west northwest-trending Sweetwater Mountains-Garfield Flat alteration belt, and the northeast-trending (3) Markleeville and (4) Aurora Bodie Hills alteration belts. Within the Sweetwater Mountains Garfield Flat alteration belt, northeast trends are evident, whereas northwest trends are prominent in the Aurora-Bodie Hills belt. Four smaller areas of altered rock, all considered minor, are also present. The two larger of these belts are located in the Wellington Hills and Pine Grove Summit areas.

Discussion

An analysis of linear features mapped on Landsat MSS images by Rowan and Purdy (1984) to extend and supplement mapped faults resulted in the identification of eleven lineaments described in table 1 and shown in figure 3. Where the location of a

Table 1.-- *Characteristics of lineamants in the Walker Lake 1^{o} x 2^{o} quadrangle*

Lineament	Trend	Defining Azimuth Range	Associated mapped faults	Aeromagnetic expression	Gravity expression	Associated Alteration	Miscellaneous
Walker Lane	NW	N30°-45°W	high density of northwest-trending faults, some of which are coincident with linear features	lies just north of strong northwest-trending high	similar alignment of anomalies	coincident with, though narrower than, Walker Lane alteration belt	
Pine Nut Creek	NE	N14°-19°W, N27°-28°W	some of the linear features are coincidnet with mapped faults	northwest trending anomalies terminate abruptly at lineament	associated with northern part of Markleeville alteration belt	coincident with the northwestern part of the Markleeville alteration belt	transects boundary between Great Basin and Sierra Nevada provinces
Markleeville	NE	N53°-82°E	a few northwest-trending faults	none	none	generally coincident with the Markleeville alteration belt	transects boundary between Great Basin and Sierra Nevada provinces
Wolf Creek	NNE	N8°-12°E, N16°-31°E	north-northeast-trending faults dominate this area and some are coincident with linear features	weak	weak	coincident with Markleeville alteration belt, except in southwestern part of lineament	
Cherry Creek	NNE	N8°-12°E, N16°-31°E	none	similar alignment of anomalies	none	only alteration mapped in this area lies along this lineament	close spatial relationship with Whitecliff Peak lineament
Whitecliff Peak	NNE	N14°-19°W, N27°-28°W	north-northwest-trending faults are abundant in northeastern part of lineament	none	none	northeastern part of lineament is coincident with Wellington Hills alteration belt	transects boundary between Great Basin and Sierra Nevada provinces
Deadman Creek	ENE	N66°-75°E	northwestern end of lineament is dominated by northeast-trending faults	similar alignment of anomalies	none	intersects Sweetwater Mountains-Garfield Flat and Eagle Creek lineaments in viscinity Sweetwater Mountains, one of the largest altered areas	transects boundary between Great Basin and Sierra Nevada provinces
Sweetwater Mountains-Garfield Flat	WNW	N74°-76°W, N81°-88°W	various directions of faulting are present	similar alignments of anomalies	parallels northeastern border of large low	eastern two-thirds is generally coincident with Sweetwater Mountains-Garfield Flat alteration	transects boundary between the Great Basin and Sierra Nevada provinces
Aurora-Bodie Hills	NNE	N39°-50°E	scattered northeast- and northwest-trending faults	none	parallels eastern margin of northeast-trending low	coincident with central portion of Aurora-Bodie Hills alteration belt	
Eagle Creek	NNE	N39°-50°E	scattered northeast- and northwest-trending faults	none	parallels northwest side of northeast-trending low	intersects Sweetwater mountains-Garfield Flat and Deadman Creek lineaments in viscinity of Sweetwater Mountains, one of the largest altered areas	
Wheeler Lake	NW	N30°-45°W	none	parallels northeast side of high	none	several very small patches of alteration associated with this lineament	

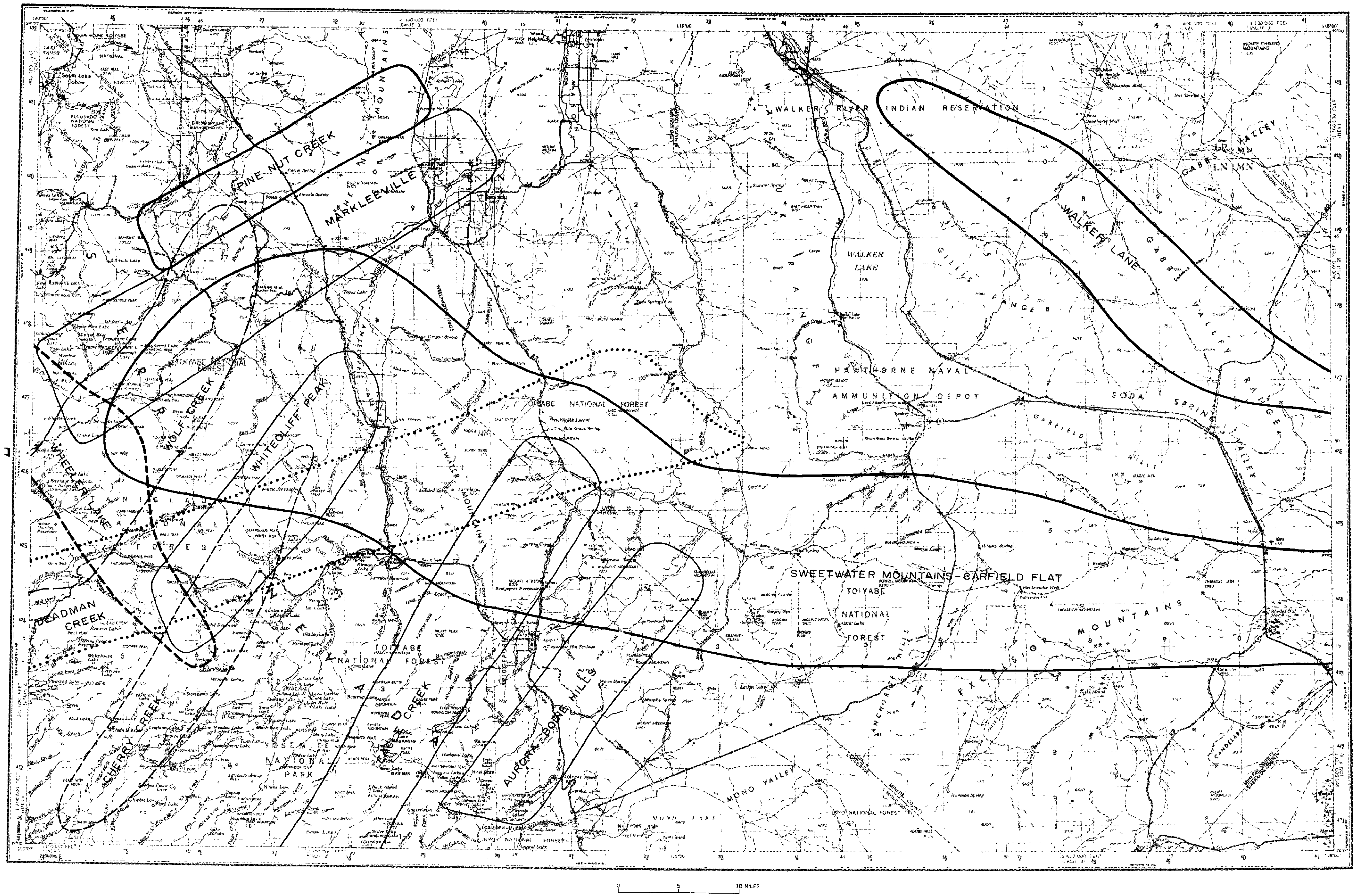


Figure 3.—Distribution of lineaments.

lineament coincides with an alteration belt we have given both features the same name. Most of the altered areas occur along these lineaments, but in many cases, the patterns of individual altered areas with respect to the lineaments is complex. In the simplest case, the Walker Lane, the trend of the altered rocks is in concert with the orientation of the northwest-trending lineament representing the right-lateral, strike-slip faults (figs. 2 and 3). However, there is a suggestion of east-northeast trends in the southeastern part of the alteration belt.

In the Markleeville alteration belt, most individual altered areas are north-northwest- to northwest-trending. Faults mapped in this area are also predominently north-northwest- to northwest-trending, and the Pine Nut Creek lineament (fig. 3) appears to consist of northwest-trending linear features that mark many of these fault traces. These spatial relationships indicate localization of the hydrothermal activity along northwest-oriented faults. In addition, the presence of northeast-oriented altered areas and aeromagnetic anomalies (fig. 4) suggests that the northeast-oriented Wolf Creek and Markleeville lineaments (fig. 3) may represent structural features that also served as conduits for migrating hydrothermal fluids. These structural features may be fracture and microfault zones, such as those described by Lockwood and Moore (1979), rather that substantial faults. Displacement along such fractures may have been greater in the Great Basin than in the Sierra Nevada owing to the greater extension of the Great Basin (Lockwood and Moore, 1979), but the general paucity of mapped northeast-trending faults along these lineaments implies that the displacement is still minor.

The relationship between lineaments and altered rocks is especially complex within the Sweetwater Mountains-Garfield Flat alteration belt (fig. 2). In the central part of this belt, two orientations are evident in the distribution pattern of altered areas. The dominant pattern is west-northwest, apparently reflecting the orientation of the Sweetwater Mountains-Garfield Flat lineament (fig. 3). The other pattern is northeasterly, suggesting the influence of the northeast-oriented Aurora-Bodie Hills and Eagle Creek lineaments and other similarly oriented features. Trends of altered areas east of the large altered area in the Sweetwater Mountains suggests some influence by the Deadman Creek lineament (figs. 2 and 3). Note that the large area of alteration in the Sweetwater Mountains occurs at the intersection of the Sweetwater Mountains-Garfield Flat, Deadman Creek, and Eagle Creek lineaments.

Although west- to west-northwest-trending faults have been mapped along the Sweetwater Mountain-Garfield Flat lineament, they are abundant in only one area east of the Sweetwater Mountains (Stewart and others, 1982). However, the orientation of the altered areas and the presence of a series of prominent aeromagnetic anomalies along the entire extent of the alteration belt (figs. 2 and 4) strongly suggest that the hydrothermal activity was at least partially controlled by a major crustal feature with this west- to west-northwest-orientation. We believe that the Sweetwater Mountains-Garfield Flat lineament is the surface expression of this crustal feature.

The eastern part of the Sweetwater Mountains-Garfield Flat alteration belt is complicated by faults and linear features with trends other than west-northwest. The most common trends are northwest, which are probably related to the Walker Lane, and east-northeast, which we attribute to the Pancake Range lineament. Studies by Albers (1981) suggest that the Pancake Range lineament extends into the Sierra Nevada region and influenced the distribution of tungsten deposits. In the western part of the Sweetwater Mountains-Garfield Flat lineament, alteration is sparse, except within the Markleeville and Wellington Hills belts where northeast- and northwest-trending fractures appear to have been the main controlling structures.

The Aurora-Bodie Hills and Eagle Creek lineaments (fig. 3) also appear to be structural zones that localized hydrothermal activity. Mapped northeast-oriented faults are abundant in the northern parts of both lineaments, and we suggest extending these fractured zones southwestward along the prominent northeast-oriented low gravity anomaly present in this area (Plouff, 1983). Also, altered rocks are more common in the northern parts of these lineaments where numerous faults have been mapped. However, northwest-trending structures were also involved in the localization of hydrothermal activity within these lineaments.

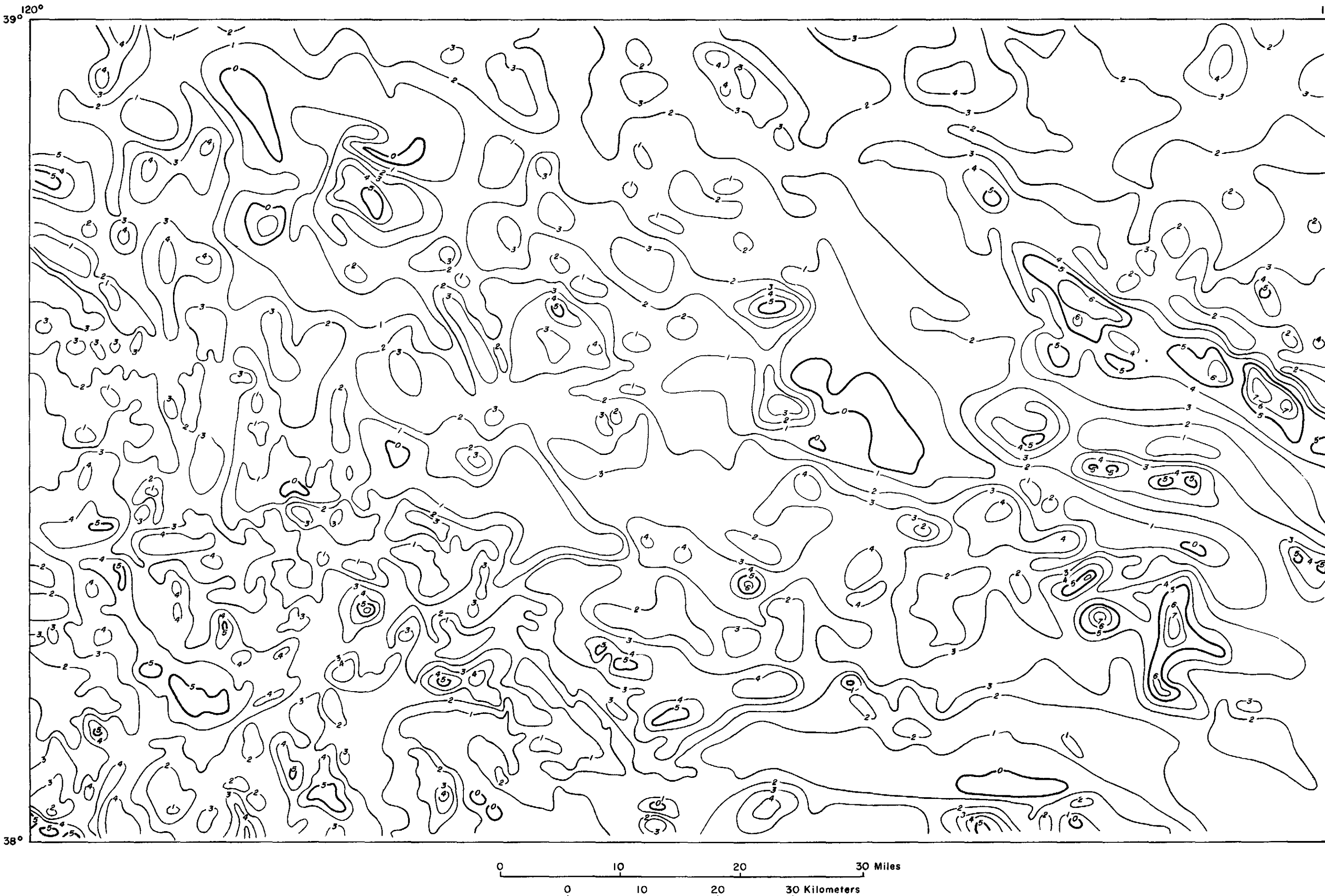
There is also a close spatial association between altered rocks and northeast-trending linear features within the minor Pine Grove Summit alteration belt. A few of these linear features represent fault traces (Stewart and others, 1982).

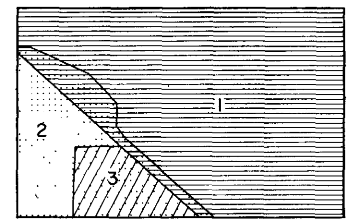
There are several very small areas of altered rocks located along the northwest-trending Wheeler Lake lineament (figs. 2 and 3), which lies entirely within the Sierra Nevada where alteration is sparse. This lineament may also be related to the microfaulting described by Lockwood and Moore (1979).

The lack of altered rocks along portions of some lineaments, and at some intersections of lineaments, clearly indicates the importance of other factors, such as the composition and age of host rocks. In the Walker Lane alteration belt, 29-18 m.y. old rhyolitic rocks are the most commonly altered rocks. Southwest of the Walker Lane, 18-11 m.y. old volcanic rocks, which are mainly andesitic (Stewart and others, 1977; 1982), form a crude northwest-oriented zone. Altered rocks are particularly widespread in this zone along the Markleeville and Sweetwater Mountain-Garfield Flat alteration belts, but rocks of similar age and composition in the Sierra Nevada south of the Markleeville belt are only rarely altered, even where lineaments and mapped faults are present. In a similar manner, Mesozoic intrusive rocks are commonly altered in the Great Basin, but alteration is sparse in correlative rocks in the Sierra Nevada. Evidently, the Sierra Nevada batholith either acted as a barrier to the developement of hydrothermal systems or the faults needed as conduits for hydrothermal fluids were not sufficiently well developed.

Summary

Six alteration zones were delineated during the course of this study (fig. 2), four of them major and two minor. The alteration zones were delineated from a limonite map derived from processed Landsat images, which was then field checked, and a map showing the distribution of mines and prospects in the quadrangle. The locations of the alteration zones were compared with those of the lineaments defined by Rowan and Purdy (1983) (fig. 3). A strong, but not





The index map indicates sources of data used to compile the aeromagnetic map: 1.) U.S. Geological Survey, 1971, Aeromagnetic map of parts of the Walker Lake, Reno, Chico, and Sacramento 1° by 2° quadrangle, Nevada-California: U.S. Geological Survey Geophysical Investigations Map, GP-751; 2.) U.S. Geological Survey, Aeromagnetic map of parts of the Walker Lake and Mariposa 1° by 2° quadrangles, Nevada-California, unpublished data; 3.) U.S. Geological Survey, 1979, Aeromagnetic map of the Hoover-Walker Lake area, California: U.S. Geological Survey Open-File Report 79-1194.

Figure 4.—Total intensity aeromagnetic map. Magnetic contours show total intensity magnetic field of the earth in gammas relative to an arbitrary datum. Contour interval 100 gammas.

absolute, correlation between alteration zones and lineaments was observed in the Great Basin portion of the quadrangle. Due to the paucity of alteration in the Sierra Nevada part of the quadrangle there is a generally poor correlation between lineaments and alteration zones. The correlation between the alteration and the lineament zones suggests that the lineaments define structural zones of faulting and fracturing which acted as conduits for hydrothermal fluids.

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