UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Geologic interpretation of aeromagnetic survey of Glacier Peak Wilderness, Northern Cascades, Washington

by

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Introduction

Under the provisions of the Wilderness Act (Public Law 88-577, September 3, 1964) and related acts, the U.S. Geological Survey and the U.S. Bureau of Mines have been conducting mineral surveys of certain areas on Federal lands to determine their mineral potential. The act directs that results of such surveys are to be made available to the Public and be submitted to the President and the Congress. This report presents results of the compilation of existing aeromagnetic data and related data acquired specifically the Glacier Peak Wilderness (GPW) study (pl. 1). In addition a second plate has been prepared which presents a qualitative interpretation to illustrate how the many magnetic anomalies or patterns can be related to specific geologic features (pl. 2). The interpretative map is overlain on a preliminary simplified geologic base map.

Geologic and economic background for this interpretation is provided by Grant (1982, 1969) and Stotelmeyer and others (1982). A comprehensive list of publications bearing on the geology, geochemistry and geophysics of the Northern Cascades has been prepared by Ford (1982).

The Glacier Peak Wilderness and recommended Wilderness additions lie within the geologic province of the Northern Cascades discussed in detail by Misch (1966) and Grant (1982) (fig. 2). The 2000 km^2 study area transects the North Cascades crystalline core of various metamorphic and plutonic terranes. In late Cretaceous to early Tertiary pre-existing plutonic and supercrustal rocks were subjected to regional metamorphism. This event triggered a long period of igneous activity lasting until Recent times as evidenced by plutons of widespread Tertiary age and as young as 18 m.y. (R. J. Fleck unpub. data) and by eruption of Quaternary lavas of Glacier Peak and present thermal-spring activity. Grant (1982) suggests that palingenesis of pre-existing crystalline terranes contributed to the complex composite magmatic history of the Cascade intrusions. Magnetic susceptibility measurements, as will be discussed later, suggest wide variability in content of magnetic minerals within the crystalline rocks.

The predominant structural trends in the study area are north-northwest. Transverse structural lineaments, long recognized as an important factor in the search for economic mineralization trend approximately N60-90^{o}E. Two such transverse structural trends that have been recognized in the GPW study area are: the Buckindy belt and the Glacier Peak belt (Grant, 1969).

There are several other mineralization features in the GPW Cu-porphyry deposits, in addition to the transverse structural belts mentioned above, that might show some expression in the magnetic data. Pyrrhotite along with pyrite and other sulphide minerals occur in certain porphyry deposits. Pyrrhotite has a very high magnetic susceptibility (1.25×10^{-1} cgs). However, the comparatively small porphyry deposits might have been missed by the 0.5 and 1.0 mile flight line spacing used in this aeromagnetic survey. Secondly, hydrothermal fluids have played an important part in the deposition of mineralization and alteration of minerals in the GPW porphyry deposits. Magnetite may either be enriched or depleted during the emplacement of porphyry systems depending upon the intensity and degree of alteration of the host rocks, thus normally polarized magnetic highs and lows may be indicative of such an system. Whether or not these systems might have been detected in

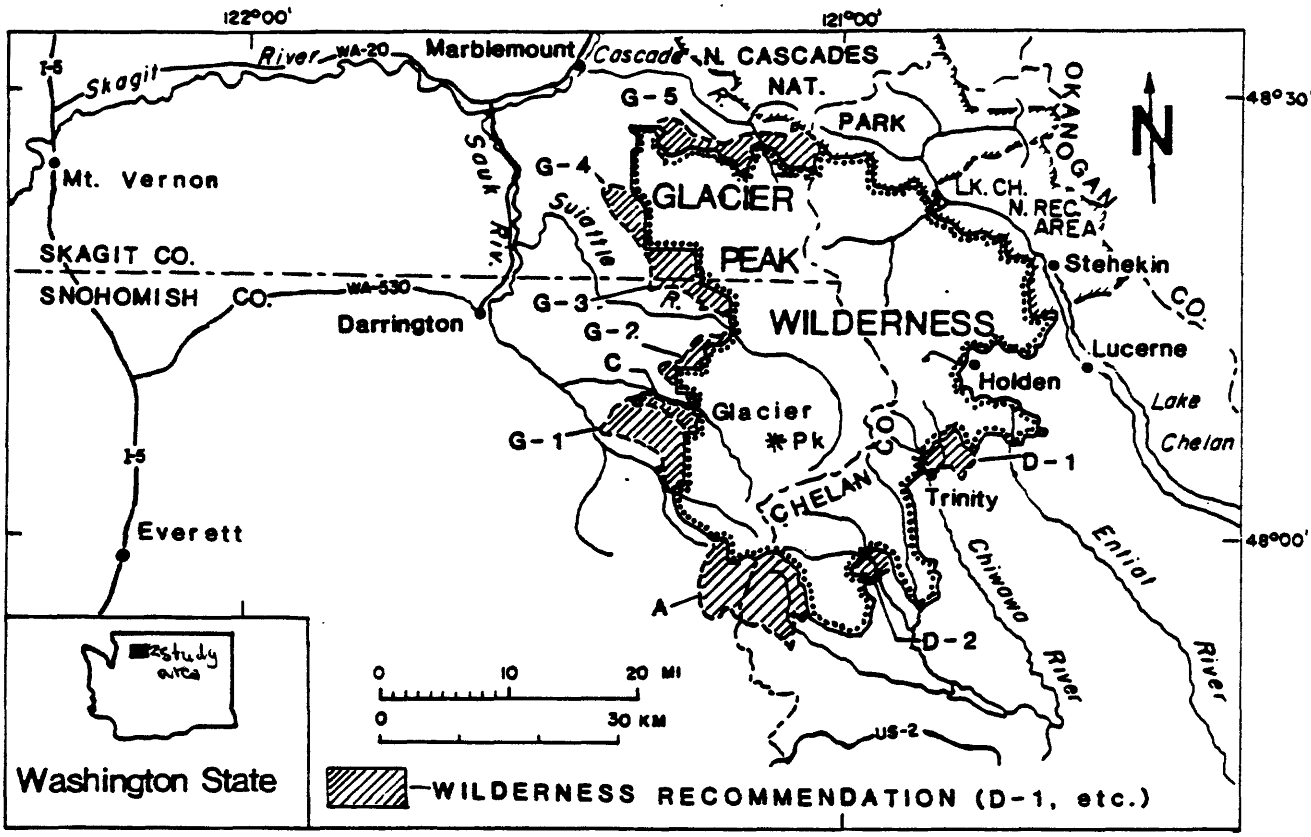

Figure 1. Index map of part of Washington State showing location of the Glacier Peak Wilderness.

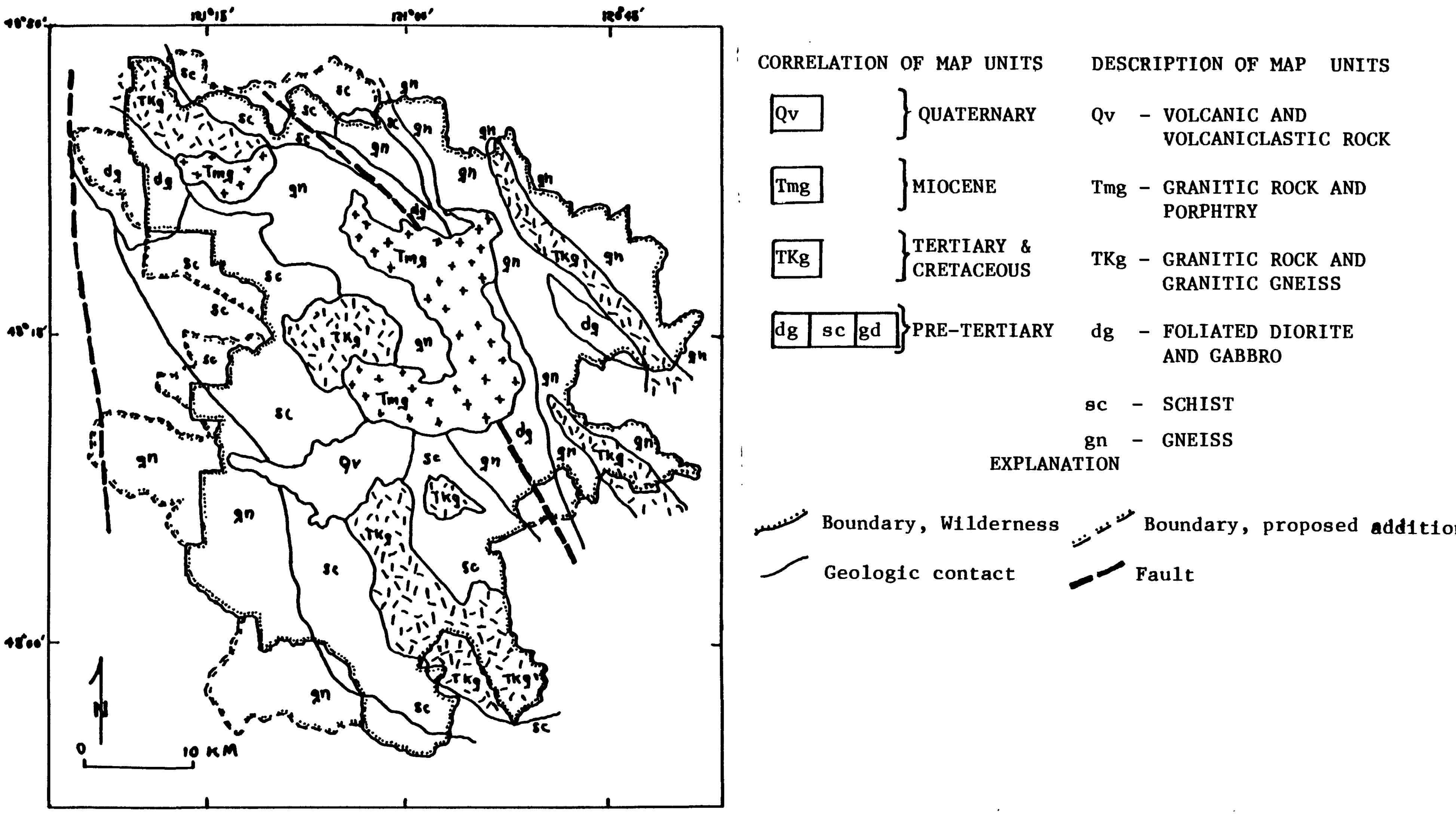

Figure 2. Geologic sketch map of Glacier Peak Wilderness and adjacent proposed additions.

our regional magnetic survey would depend largely on the size of the deposit, as well as the content of magnetite in the unaltered rock which contribute to the contrasting magnetic imprint of the mineralized zone.

Aeromagnetic Survey

The aeromagnetic map (pl. 1) is a composite of three individual surveys made in the period from 1977 to 1982 (fig. 3). All of the surveys were flown at roughly the same survey specifications except as noted below. Flight direction was northeast-southwest, flight altitude was nominally 1000 feet above the terrain. The International Geomagnetic Reference Field (IGRF) of 1975 updated to survey month was removed from the observed data. In addition, a different arbitrary base value was removed from the observed total field, to facilitate data compilation. Area 1 (fig. 3) was flown at a 1.0 mi (1.6 km) flight spacing (USGS, 1979). Area 2 (fig. 3) was flown at 0.5 mi (0.8 km) line spacing (USGS, 1982), as was the survey made for Washington Public Power Supply System (WPPSS) shown as area 3. Inasmuch as area 3 was not available in digital form, an analog compilation was made which required a certain degree of artistic license along survey boundaries. There was, however, sufficient overlap in the data sets to insure a reasonably accurate compilation at the overlapping areas of the surveys. Acknowledgment and thanks are given to WPPSS for use of this unpublished data in the Glacier Peak Wilderness study.

There are errors inherent in aeromagnetic data induced where constant terrain clearance cannot be strictly maintained. Thus, in a magnetic terrane where the distance between the ground and the magnetic sensor changes, as when the aircraft passes over a topographic ridge, an apparent magnetic high is sensed. The reverse is true when the aircraft passes over a deep valley in which a constant terrain clearance cannot be followed. Griscom (1975) discusses in more detail problems inherent in drape-flown aeromagnetic surveys. A comparison of the magnetic map to the topographic map of the study area indicates that some of the short wavelength anomalies lie over mountain peaks or ridges. In many cases, these magnetic highs are only a part of a larger long wavelength anomaly suggesting that although the short wavelength anomalies may be terrain induced, the long wavelength magnetic anomaly is real. Specific examples of terrain induced anomalies will be mentioned later during the discussion of the interpretative map.

Aeromagnetic map features and bedrock geology

To facilitate discussion, major features of the aeromagnetic map (Plate 1) are shown on Plate 2 superimposed on a simplified bedrock geologic map of the Wilderness and vicinity. Areas of positive anomaly are labelled as M_1-M_{18}; and those of negative anomaly, delineated by hachured dashed lines, as L_1-L_4. Areas of moderate to high magnetic susceptibility, identified by contrasting magnetic response or pattern, and magnetic lineaments indicated by alinement of steep magnetic gradients are also shown. The geologic base is greatly simplified from a 1:100,000-scale geologic map of the Wilderness prepared by A. B. Ford, W. H. Nelson, R. A. Sonnevil, and others (unpublished map, 1982) that in many areas incorporates more detailed mapping from numerous sources (given in Ford, 1983).

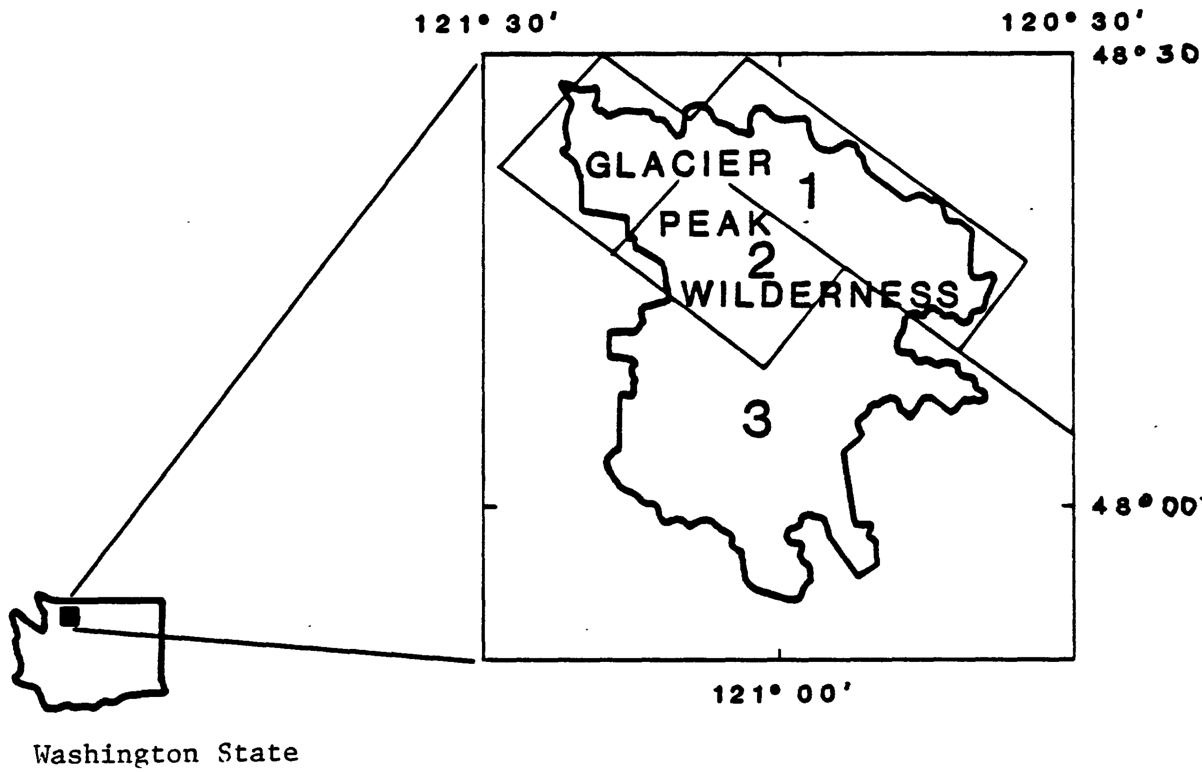

Figure 3. Index map of the Glacier Peak Wilderness showing location of aeromagnetic surveys used in the compilation of Plate 1.

The bedrock geology of nearly the entire map area is characterized by strong north-northwest trends of structures, including metamorphic foliation and principal faults, and distribution of lithologic units. The trends are strongly reflected in the pattern of aeromagnetic anomalies in the northeast third of the map, but are much less distinct or absent elsewhere, even where units of greatly differing lithologies occur. For example, the boundary of the large bodies of foliated tonalite of the Tenpeak and Sulphur Mountain plutons with micaschist units to the west shows no imprint in the aeromagnetic map (anomalies L_3-L_4, pl. 2). Approximately 30 plutons of probable Triassic or older to Miocene age occur in the area. Most are tonalitic to granodioritic in composition, except chiefly for the hornblende dioritic and quartz dioritic MT. Chaval pluton and the layered hornblende gabbroic Riddle Peaks pluton. Some plutons having broadly comparable lithologies show great differences reflected in the aeromagnetic map. For example, the Sloan Creek pluton is marked by conspicuous positive anomalies but the Tenpeak pluton shows no magnetic imprint, even though both consist of hornblende-bearing to locally hornblende-rich, folitaed tonalite. Similar comparison exists between the two most mafic large igneous bodies in the area, the Riddle Peaks and Chaval plutons. The two principal high-angle faults are (1) the northwest-trending Entiat fault and its probable pre-Miocene northward extension, the Le Conte fault, in the east and north part of the area; and (2) the north-trending Straight Creek fault near the west border of the area. Whereas, the Entiat and Le Conte fault system is seen to be strongly reflected in the aeromagnetic map, little aeromagnetic imprint of the Straight Creek fault is seen.

Geologic features in the vicinity of numbered aeromagnetic anomalies (Plate 2) are as follows:

Anomaly M_1--The anomaly is one of a number of northwest-trending elliptical or subcircular anomalies aligned along the east side of the Entiat and Le Conte fault system. It occurs over a hornblende-quartz diorite gneiss unit of the Seven-fingered Jack and Entiat plutons (Cater and Wright, 1967, unit "jdg"). To the north where the anomaly dies out, the gneiss is cut by the Tertiary Rampart Mountain pluton. The gneiss continues southeastward (Tabor and others, 1980) for a great distance beyond the anomaly termination; thus, the anomaly reflects local mineralogic variation and possibly in part the small rhyodacite dikes and several minor faults in this vicinity (Cater and Wright, 1967).

Anomaly M_2--The northern part of the anomaly, in the Lucerne 1:62,500 quadrangle, occurs over a sheared and mylonitic contact phase of the Seven-Fingered Jack and Entiat plutons (Cater and Wright, 1967, unit "jc"). On geologic strike southeastward in the Chelan 1:100,000 quadrangle, the strongest part of the anomaly is centered over a unit of the Entiat pluton (Tabor and others, 1980, map unit "Kcbg") consisting of banded hornblende and biotite gneiss. The eastern edge of the anomaly approximately marks the contact with the Tertiary Duncan Hill pluton; and the western edge and southern termination of the anomaly approximately marks the contact with a different unit of the Entiat pluton, consisting of (Tabor and others, 1980, map unit "Kce"). The anomaly therefore appears to be rather closely related to only one of the major phases of the pluton (see anomaly L_2 discussion). The anomaly relations further suggest correlation between the contact phase of Cater and Wright (1967, unit "jc") and the banded gneiss of Tabor and others

(1980, unit Kcbg) the hornblende-biotite quartz diorite unit of the Seven-Fingered Jack and Entiat plutons of Cater and Wright (1967, unit "jbq") and the tonalite of the Entiat pluton of Tabor and others (1980, unit "Kce"). Parts of anomaly M_2 are believed to reflect terrain-induced errors, especially where anomaly maxima peaks lie over topographic highs such as Kelly Mountain and Klone Peak.

Anomaly M_3--The anomaly lies almost wholly over the northwest-trending Cardinal Peak pluton of pre-Tertiary age (Cater and Wright, 1967). The northeast edge of the anomaly approximately coincides with the contact of the Bearcat Ridge pluton (Cater and Wright, 1967), and the southwest edge is coincident with the contact of the Duncan Hill and other Tertiary granitic bodies and a belt of schist and gneiss. The anomaly is clearly related to the Cardinal Peak pluton. However, the pluton extends nearly 15 km northwestward beyond the termination of the anomaly as a discrete feature on the magnetic map and may in part be due to the influence of the much greater anomaly in the vicinity of Riddle Peaks.

Anomaly M_4--The anomaly is among the largest in amplitude in the Wilderness and lies distinctly east of the belt of anomalies along the Entiat and Le Conte fault system. It is centered over the Riddle Peaks pluton consisting of massive to well-layered hornblende gabbro and associated hornblende schist, amphibolite, and hornblendite. Petrographic studies indicate the presence of traces to several modal percent of Fe-Ti oxide minerals, in part magnetite, and sulfide minerals, including pyrrhotite, in many rocks. The steep magnetic gradient on the northeast edge of the anomaly lies over the contact with the Tertiary granodioritic Railroad Creek pluton, but the western part of the anomaly overlaps part of the Cardinal Peaks pluton and the belt of schist and gneiss of Martin Ridge indicating little magnetic contrast between Riddle Peaks and Cardinal Peaks plutons at least at the contact or perhaps suggesting that the magnetic Riddle Peak pluton may extend southwestward beneath the less magnetic Cardinal Peaks pluton and schist and gneiss.

Anomaly M_5--The anomaly is part of the northwest-trending belt of anomalies lying along the east side of the Entiat and Le Conte fault system. It occurs over a narrow belt of hornblende-bearing metaplutonic rock of the Marblemount Meta-quartz diorite (Misch, 1966, Tabor, 1961). Most rocks are sheared and highly altered, in thin section, abundant retrograde metamorphic development of chlorite, epidote, and opaque minerals, in part probably magnetite are indicated. Steep magnetic gradients defining the southwest edge of the anomaly coincides with the fault contact adjoining schist and gneiss, and the northeast edge lies over a contact with alaskitic gneiss of Magic Mountain (Misch, 1966, Tabor, 1961).

Anomaly M_6--The anomaly is a broad one with an unusual northeast trend. It lies over biotite-hornblende tonalite of the Buckindy pluton, the youngest major granitic body in the Wilderness and yielding a Miocene K-Ar radiometric age of about 18 m.y. (R. J. Fleck, written commun., 1982). The body shows local hydrothermal alteration and contains occurrences of porphyry copper that have been prospected and drilled by Bear Creek Mining Company (Grant, 1982). The pluton and its anomaly lie on a northeast structural lineament (Grant, 1969). To the northwest and southeast, gradients defining edges of the anomaly coincide with contacts, of the Cyclone Lake pluton and biotite gneiss of the Bench Lake area respectively. The southwest part of the anomaly overlaps the eastern part of the Chaval pluton.

Anomaly M_7--This small but conspicuous anomaly lies over part of the Miocene Cascade Pass pluton (Tabor, 1961). Part of the anomaly probably reflects terrain-induced errors, where it lies over Johannesburg Mountain, an area of unusually great relief.

Anomaly M_8--This broad area consists of a complex of anomalies of smaller wavelength (Plate 1) that overall define the extent of Quaternary andesite and dacite of Glacier Peak volcano (Ford, 1959, Crowder and others, 1966). The magnetic expression of the volcanic pile is characterized by interwoven magnetic highs of 400-500 gammas and lows of less than 100 gammas. The volcano, of 10,543 ft elevation, is the highest peak in the Wilderness and it is likely that some terrain effect is present. Tabor and Crowder (1969) concluded from polarity measurements of oriented specimens from five volcanic flows capping Gamma Ridge on Glacier Peak that the flows were normally polarized, thus, the complex magnetic pattern is most probably related to terrain effects or variability of magnetite content within the flow or perhaps to both.

Anomaly M_9--This arcuate anomaly northeast of Glacier Peak is composed of numerous moderate to short wavelength (< 5 km) interwoven magnetic highs of 100-500-gamma amplitude. Where centered over such major topographic highs as Fortress Mountain, Saddle Bow Mountain, or Dome Peak, magnetic highs may be partly terrain induced. The overall anomaly defines the areal extent of biotite-hornblende tonalite, granodiorite, and related porphyry of the Miocene Cloudy Pass pluton (Ford, 1959, Crowder, 1967, and Grant, 1966). However, magnetic highs near Dumbell Mountain and Bonanza Peak in the southeast part of the anomaly overlap with and probably in part reflect effects of the Dumbell Mountain plutons (Cater and Crowder, 1967). The Dumbell Mountain bodies lie immediately east of the northward projection of the Entiat fault (here cut by the Cloudy Pass pluton) and are correlative with the Marblemount Meta-Quartz Diorite to the north (Misch, 1966) (see anomaly M_5 discussion). The Cloudy Pass pluton near the Suiattle River extends southwestward beyond the limit of the anomaly. In this area, the pluton is mostly overlain by Glacier Peak volcanic rocks that complicate the magnetic pattern. At the northern end of the pluton, near Spire Point, the anomaly shows a marked linear crossing westward of the pluton's contact, where it closely follows a large dikelike body of ultramafic rock (Grant, 1966).

Of particular interest in the magnetic pattern of the Cloudy Pass anomaly is an east-west low that transects the pluton (shown on Plate 2 by an intermittant bar line). The linear magnetic low extends eastward beyond the pluton in the vicinity of Railroad Creek, where it interrupts and displaces northwest magnetic lineaments, such as, that associated with the Entiat fault system. The magnetic low lies along a transverse structural belt (Grant, 1969) and is more fully discussed later in interpretation of magnetic features related to mineralization.

Anomaly M_{10}--This conspicuous, but, small subcircular anomaly of about 2 km diameter and 100-gamma amplitude lies in the eastern part of a large area of mostly biotite schist south of the anomaly (M_6) associated with the Buckindy pluton and in an area of otherwise uniform magnetic character. The anomaly is centered over a small podiform body of ultramafic rock in hornblende schist (Ford, 1980, unpublished map). The body is of insufficient size to show on our 1:100,000-scale geologic map. The rock is seen in thin section to be a partly serpentinized peridotite containing minor secondary magnetite. The size of the anomaly suggests that other unsampled parts of the body probably contain significant amounts of magnetite.

Anomalies M_{11} and M_{12}--These subcircular anomalies lie over and near units of biotite- and hornblende-bearing foliated tonalite of the Sloan Creek plutons (Crowder and others, 1966). The larger, northern anomaly (M_{11}) lies partly over altered Tertiary volcanics of Round Lake, which probably account for part of its magnetic character. Gradients defining the west margin of anomaly M_{11} coincide with the Straight Creek fault which cuts the Sloan Creek rocks in this area near Pugh Mountain. The anomalies poorly define the areal extent of the Sloan Creek bodies that continue southeastward far beyond the south limit of anomaly M_{12}. The mineralogic or other reason for localization of the two anomalies is presently unknown. The anomalies are separated by a northeast-trending magnetic low that projects past Glacier Peak and continues several tens of kilometers farther northeastward.

Anomaly M_{13}--This small circular anomaly lies over the terminus of the White Chuck Glacier and about mid way between two small nearby granitic plutons, the Foam Creek and Sitkum stocks (Crowder and others, 1966). The anomaly probably reflects the magnetic character of both bodies, but its position suggests greater influence of the Sitkum stock of pyroxene-biotite-hornblende tonalite than of the Foam Creek of biotite granodiorite.

Anomaly M_{14}--This pear-shaped anomaly consists of two maxima of 100 and 150 gamma amplitude that lie over Tertiary intrusive complexes, including numerous dikes, of biotite- and hornblende-bearing hypersthene dacite (Tabor and others, 1982, units Tcd and Tci). The dacite intrudes a widespread unit of heterogeneously layered mica schist, amphibolite, and granitic gneiss. Of interest, other dacite bodies of similar type in the vicinity exhibit no anomalies, including that containing the highly altered, sheared, and sulfide-bearing Goff prospect (labeled no. 33, Plate 2) where alteration extends over several square miles (Stotelmeyer and others, 1982).

Anomaly M_{15}--This broad wavelength anomaly of moderate, 100 to 150 gamma amplitude on eastern Wenatchee Ridge occurs over a large area of light-colored tonalitic and granodioritic gneiss containing numerous small bodies of serpentinized peridotite and meta-peridotite, many altered to talc-tremolite rocks (Tabor and others, 1980, unit "Kbwgu"). The area of the anomaly rather closely defines the area of gneiss containing the ultramafic rock bodies.

Anomaly M_{16}--Like anomaly M_{15}, this broad arcuate anomaly is obviously related to presence of ultramafic rock bodies. The anomaly consists of two low- to moderate-amplitude highs at either end of the arc. The lower-amplitude high, at the west end, occurs over a large mass of ultramafic rock in foliated tonalite of the Tenpeak pluton; and the higher-amplitude one, at the east end, occurs over an area of Chiwaukum Schist containing several small mapped bodies of the ultramafic rock (Tabor and others, 1980). It is of interest that the higher-amplitude magnetic maximum is associated with the smaller outcrop-area of ultramafic rock. The trend of the anomaly approximately parallels bedrock structural trends.

Anomaly M_{17}--This small circular anomaly is centered over an outcrop of about the same size of dacite porphyry on the south side of Basalt Peak (Tabor and others, 1980, unit "Tbd").

Anomaly M_{18}--Elongation of this anomaly on Chiwawa Ridge closely parallels structural trend of schist and gneiss units over which it lies. It lies over hornblende schist and gneiss mixed with thin layers of quartzitic rock and marble (Cater and Crowder, 1967). Similar lithologies extend northwestward and southeastward far beyond limits of the anomaly, except for a unit "nag" (Cater and Crowder, 1967) of mica-quartz augen gneiss which is confined within the anomaly and thus, is the only apparent rock unit to which the anomaly might be related.

Anomaly M_{19}--This large area in the southwest corner of the map extends westward into the mining districts of Monte Cristo and Eagle Rocks where the magnetic character displays a highly complex pattern. The overall anomaly, M_{19}, occurs over a highly heterogeneous terrane of granitic and volcanic rock of mostly Tertiary age, (Tabor and others, 1982). Magnetic gradients defining the east edge of the anomaly approximately coincide with the trace of the Straight Creek fault, to the east of which an extensive area of schist and gneiss shows little magnetic character.

Anomaly L_1--This northwest-trending magnetic low closely overlies the Tertiary quartz dioritic and granodioritic Duncan Hill pluton (Cater and Wright, 1967).

Anomaly L_2--This northwest-trending magnetic low approximately follows a massive to foliated, tonalite to quartz diorite member of the Entiat pluton of probable Cretaceous age, (Tabor and others, 1980, unit "Kce"). An adjoining member of the pluton shows a conspicuous positive anomaly (see anomaly M_2 discussion).

Anomaly L_3 and L_4--These two subcircular areas of magnetic character, separated by the high-amplitude anomalies of Glacier Peak volcano (M_8) and the Cloudy Pass pluton (M_9) are prominent features on the aeromagnetic map. A third but much smaller broad, subcircular low occurs just north of the positive anomaly (M_6) associated with the Buckindy pluton. Together, the three form a broad central magnetic "valley", paralleling general trends of bedrock units and structures, except for being interrupted by the two above-mentioned transverse belts of positive anomalies. The rocks underlying the anomalies are highly varied and include large bodies of massive to foliated granitic rock (Tenpeak and Sulphur Mountain plutons); numerous small bodies of granitic rock (Downey Creek and High Pass plutons, among others); wide belts of nearly uniform pelitic schist (Chiwaukum Schist and schist of the Green Mountain area); belt of heterogeneously mixed biotite schist, hornblende schist, and amphibolite; and, in the western third of anomaly L_3, a wide belt of mixed schist, gneiss, and migmatite. The area of magnetic low north of the Buckindy pluton overlies geologic units as varied as the Cyclone Lake pluton, which consists of alaskite with only a few percent biotite, and the highly mafic Chaval pluton consisting of diorite and quartz diorite containing up to about 50 percent hornblende and, in places, hornblende schist and hornblendite. The western part of anomaly L_3 overlaps the trace of the Straight Creek fault and extends westward beyond the fault to overlie greenschist and blueschist of the Shuksan Greenschist (Misch, 1966). The Straight Creek fault shows little or no magnetic expression north of anomaly M_{11}.

Magnetic provinces

The characteristics of magnetic patterns shown by Plates 1 and 2 suggest subdivision of the area into three distinctive magnetic provinces (fig. 4): (1) a northeast province characterized by northwest-trending strongly lenticular or linear highs and lows and steep magnetic gradients; (2) a broad central province characterized by generally subdued magnetic relief broken by subcircular to elliptical positive anomalies and, conspicuously, by two transverse magnetic belts, one from Mount Buckindy to Sonny Boy Creek, and the other from Glacier Peak to near Bonanza Peak; and (3) a southwest province characterized by a highly complex group of subcircular to elliptical highs and lows showing little general orientation. The northeast province includes anomalies M_1-M_5 and L_1-L_2. All other numbered anomalies lie in the central province, except for grouped anomaly M_{19} comprising the southwest province.

Discussion of aeromagnetic map features

As discussed above, nearly all of the positive anomalies or clusters of anomalies outlined on Plate 2 can be rather closely related, at least geographically, to distinctive geologic features that may be magnetic sources. However, many other aeromagnetic map features are more difficult to interpret in terms of known geology and petrography. Questionable features include (1) the great difference in magnetic character of large units of rock having general lithologic similarity, such as seen in comparisons between the Sloan Creek pluton (M_{11}-M_{12}) and Tenpeak and Sulphur Mountain plutons (L_3-L_4) that are all composed of massive to gneissose tonalite, and between the Riddle Peaks (M_4) and Chaval plutons that are the two most mafic large bodies in the Wilderness; and (2) the similarity in magnetic character of major units having greatly different lithology, such as seen in comparisons between the Sulphur Mountain pluton and the adjoining schist belt to the west, and between the alaskitic Cyclone Lake pluton and the more mafic-mineral-rich Jordan Lake and Chaval plutons. Physical properties of a limited number of samples from some of the rock units were determined (table 1) to investigate those and other questions. Many more determinations are obviously needed for more complete understanding of the aeromagnetic map. Magnetic variations may in places reflect variation of reversal in remanent-magnetization directions that have not been determined for any rocks in our preliminary study.

Of the three magnetic provinces, the northeast province shows closest general correspondence between pattern of magnetic highs and lows to known bedrock geology. The linear highs and lows correspond rather closely with individual geologic map units striking parallel with the overall pattern of anomalies. The western edge of the province in most places closely follows the Entiat and Le Conte fault system, the trace of which lies near the west margins of anomalies L_2, M_1, and M_5 and elsewhere is marked by steep gradients, or magnetic lineaments. In the central sector of this line, the magnetic characteristics appear to be influenced and complicated by effects of the Cloudy Pass pluton.

Major bedrock units and structures of the central province also show

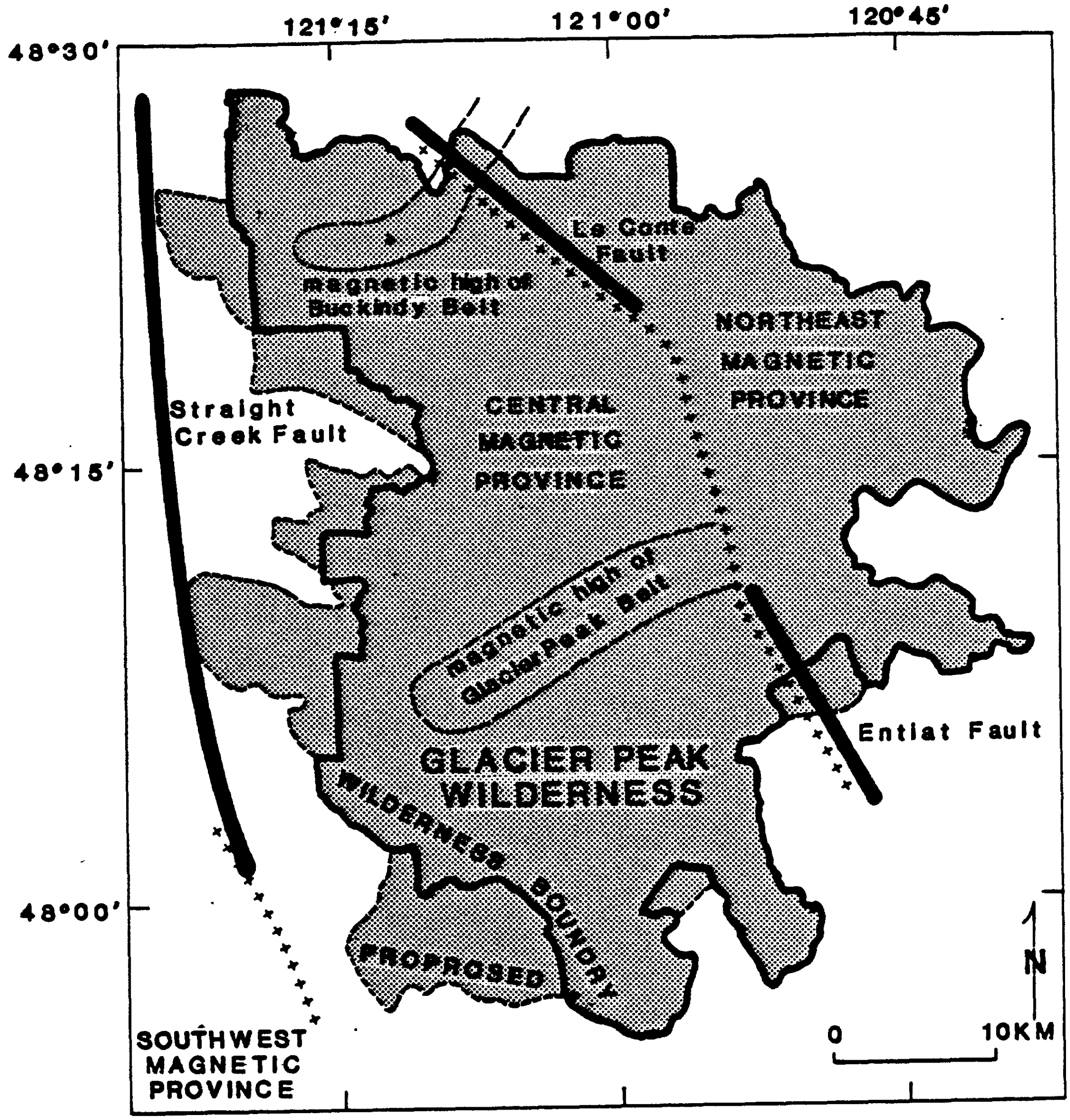

Figure 4. Magnetic provinces of Glacier Peak Wilderness and vicinity.

strong northwest trends, paralleling those of the northeast province but, except for the minor anomaly M_{18}, they are little reflected in the aeromagnetic map. Instead, broad fields with little magnetic gradient extend widely across major belts of rock of greatly diverse lithology, including schist, gneiss, and massive granitic rock (Tenpeak and Sulphur Mountain plutons). Two transverse magnetic features cross the province in a northeastward direction and closely follow transverse structural belts (Grant, 1969), the northern called the Buckindy belt and the southern the Glacier Peak belt. The Buckindy belt is marked by anomaly M_6 and the Glacier Peak belt by anomaly M_8 and southern part of M_9.

Selected geologic features and their imprint on the aeromagnetic map of the Wilderness are discussed below:

Faults---The Entiat and Le Conte fault system and the Straight Creek fault are by far the largest of many high-angle faults mapped in the area, and both extend far beyond the Wilderness boundary. The aeromagnetic map shows the faults probably only where rocks of appreciable magnetic contrast are juxtaposed, which presumably is the case along most of the magnetically well marked Entiat and Le Conte fault system. Magnetic susceptibilities have not been determined for rock units along the fault, but the meta-quartz diorites along most of its east side are seen in thin section to contain appreciable amounts of secondary magnetite that may account for the positive anomalies. The Straight Creek fault is well marked only in the southwest part of the map, where magnetically well displayed (anomaly M_{19}) Tertiary igneous rocks abut a terrane of presumably less magnetic pre-Tertiary schist and gneiss. Farther north, except locally for the Sloan Creek tonalite bodies (anomalies M_{11} and M_{12}), rocks on either side of this major fault show no magnetic expression, even where rocks as diverse as quartz diorite and diorite (Chaval pluton) and mica schist and gneiss are faulted against metavolcanic rock and phyllite on the west, as along the entire length of the fault north of anomaly M_{11} to and beyond Bettys Pass.

Ultramafic rocks--Small bodies of fresh to highly serpentinized peridotite and meta-peridotite are widespread in schist and gneiss through the central magnetic province, where a few underlie and are apparent sources for some of the short wave-length anomalies. Most bodies are small, less than a few tens of meters across, but even such small ones can show conspicuous anomalies (for example, anomaly M_{10}). However, no magnetic expression is shown by other much larger bodies, such as several mapped near the mouth of Sulphur Creek. The largest bodies known include one of nearly 5 km length near Spire Point (Grant, 1966) and another, about 2.5 km long (Tabor and others, 1980), at the mouth of Napeequa River. Both are expressed by anomalies (northwest corner of Cloudy Pass general anomaly M_9, and west end of anomaly M_{16}) but that in comparison with other ultramafic-related anomalies, are not of a magnitude comparable to their size. This great variability in magnetic response is believed to reflect variable degree of serpentinization or other alteration. In their study, Coleman and Keith (1971) report that though fresh ultramafic rock is free of magnetite, it is ubiquitous in serpentinized alterations. (See also our discussion of anomaly M_{10}.)

Granitic plutons--Plutons of massive to foliated granitic rock show considerable variety in their magnetic expression. Those with marked positive anomalies are the two youngest, of Miocene age--the Buckindy (anomaly M_6) and

Cloudy Pass (M_9) plutons. Both overall anomalies consist of grouped magnetic highs and interspersed moderate lows. Among granitic rock units of table 1, they have the highest, though moderate, magnetic susceptibilities averaging 0.0024 cgs units (Buckindy) and 0.00092 cgs units (Cloudy Pass). The bodies consist of nonfoliated biotite-hornblende tonalite, ranging to granodiorite and locally (Cloudy Pass) granite, with common porphyry and dike complexes. Areas of hydrothermally altered rock containing sulfide minerals are locally present and particularly extensive in the Cloudy Pass pluton in the area from Miners Ridge to near Bonanza Peak (southern part of anomaly M_9). Magnetic highs in some of those areas may in part reflect concentrations of secondary magnetite and sulfides, if pyrrhotite, but mineralogy of the rocks has not been determined.

The aeromagnetic map suggests that most other major granitoid bodies are much less magnetic, except for the Sloan Creek plutons (anomalies M_{11} and M_{12}). The only two bodies for which magnetic susceptibility data are available (table 1) are the foliated, pyroxene-biotite tonalitic Sulphur Mountain pluton, with susceptibilities averaging a very low 0.000060 cgs units; and the foliated biotite tonalitic Jordan Lakes pluton, with susceptibilities averaging an even lower 0.000045 cgs units. The steep magnetic gradients around the contact between the Cloudy Pass and Sulphur Mountain plutons obviously reflect their great difference in determined susceptibilities. Anomaly M_3, over the Cardinal Peak pluton, indicates that this body of altered and commonly heterogeneous granitic rock is more magnetic than many other granitic plutons in the study area.

Mafic plutons--Two of the largest plutons of mafic to intermediate rock, the Riddle Peaks and Chaval plutons, show considerable difference in aeromagnetic expression (compare the Riddle Peaks anomaly, M_4, with the area of low magnetic relief of the Chaval pluton just west of the Buckindy pluton anomaly, M_6). The susceptibility average of 0.00525 cgs units (range, 0.00025 to 0.0127 cgs) for Riddle Peaks samples is the highest of any determined Glacier Peak Wilderness body. Lithology of the body is described in the discussion of anomaly M_4. The Chaval pluton, consisting of hornblende diorite, quartz diorite, and in places hornblendite, has far lower average susceptibility, 0.000081 cgs units, than the Riddle Peaks body, which accounts for differences in their aeromagnetic map expression.

Although susceptibilities have not been determined, the aeromagnetic map indicates that other highly magnetic mafic to intermediate bodies include the Marblemount Meta-Quartz Diorite, the Dumbell Mountain plutons, and members of the Seven-Fingered Jack and Entiat plutons (see discussions of anomalies M_1, M_2, and M_5).

Units of generally homogeneous gneiss--The three major units of gneiss for which susceptibility data are available (table 1) include the Swakane Biotite Gneiss, the Skagit Gneiss, and a large unit of mostly biotite tonalitic gneiss of the Bench Lake area east of Mount Buckindy. All show uniformly very low magnetizations, on the order of 0.00005 cgs units that are similar to those of the Jordan Lakes and Sulphur Mountain plutons. As inferred from the aeromagnetic map, the major gneiss and schist units west of the Sulphur Mountain pluton probably have magnetizations of about the same magnitude as the above gneiss units.

Table 1. Rock properties measurements

Rock Unit	No. Samples	Density (gm/cm^3)				Susceptibility (cgs units)			
		Range			Standard	Range			Standard
		From	To	Mean	Deviation	From	To	Mean	Deviation
Bench Lake gneiss	7	2.61	2.73	2.67	0.04	0.00001	0.00007	0.00004	0.00002
Buckindy Pluton	4	2.63	2.69	2.66	0.02	0.0022	0.0026	0.0024	0.0002
Cascade Pass Pluton	2	2.66	2.70	2.68	0.03	0.00007	0.0015	0.0008	0.001
Cloudy Pass Pluton	23	2.61	2.77	2.72	0.04	0.0001	0.0024	0.0009	0.00068
Jordon Lakes Pluton	6	2.61	2.68	2.64	0.03	0.00001	0.00007	0.00005	0.00002
Mt. Chaval Pluton	14	2.68	2.99	2.83	0.057	0.00002	0.0001	0.00008	0.00003
Riddle Peaks Pluton	13	2.72	3.04	2.89	0.08	0.00025	0.0127	0.0053	0.0044
Skagit Gneiss	10	2.61	2.71	2.66	0.03	0.00003	0.00008	0.00006	0.00002
Sulphur Mtn. Pluton	11	2.62	2.69	2.64	0.02	0.00002	0.00001	0.00006	0.00002
Swakane gneiss	4	2.63	2.66	2.65	0.01	0.00004	0.00007	0.00005	0.00001
Marblemount Metaquartz diorite	15	2.72	3.02	2.80	0.17	0.00004	0.0017	0.00054	0.0007
Dumbell Mountain pluton	14	2.64	2.83	2.75	0.07	0.00003	0.0035	0.0011	0.0013
Magic Mountain gneiss	4	2.64	2.73	2.67	0.04	0.00013	0.0035	0.0015	0.0014

Aeromagnetic anomalies and mineralization

The northern Cascade Range is considered to be predominantly a porphyry copper province, with sulfide deposition in many places controlled by northeast to east-west trending structures oriented approximately normal to the regional northwest pattern of bedrock structures (Grant, 1969, 1982). The two best defined of Grant's (1969, fig. 12) transverse structural belts--The Glacier Peak belt and the Buckindy belt--cross the area of the Wilderness where they are well marked by transverse magnetic features in the central magnetic province (fig. 4).

Many of the known mineral deposits, occurrences, and prospects described by Grant (1982) and Stotelmeyer and others (1982) show a spatial relation to distinctive magnetic features that may, accordingly, provide useful exploration guides and criteria for evaluating the area's mineral-resource potential. Apparent relations are, for convenience, presented in table 2. The location of mineralized areas named in the table are shown by number on the aeromagnetic interpretation map (plate 2) and are predominantly from Grant (1982).

Three classes of relationship between mineralized areas and the magnetic data are apparent: (1) those related to northwest lineaments; (2) those related to northeast and east-west trending lineaments; and (3) those related to magnetic highs or flanks of magnetic highs elsewhere. It should be noted, however, that some, including the possibly significant Royal Development Mine near Trinity, show little apparent relation to magnetic features. Mineralized areas related to northeast lineaments include those of the Buckindy belt (areas 2, 4, and possibly 31 and 32) and the Glacier Peak belt (areas 1, 3, 6, 15, 22, 34 and others). Those related to northwest lineaments include 10, 11, 12, 19, and to flanks of highs are numbers 16, 17, 18 and others.

Grant (1982) suggests that preparation of host rock by fracturing or faulting prior to mineralization was a principal factor controlling subsequent mineral deposition and that intersections of northwest and northeast-trending fracture systems provide an optimum environment for deposition. Examples include deposits such as Glacier Peak (1) and the Holden Mine (34). The projection southwestward of the magnetic low between anomalies M_{11} and M_{12} and the magnetic low lineaments northeast of Glacier Peak extend into the Monte Cristo mining district, where northeast structures were important mineralization controls (Grant, 1969). Intersection of major magnetic lineaments at the Holden Mine (plate 2) possibly reflects an intersection of bedrock structures that may have controlled Holden mineralization. Intersections of major linear magnetic features elsewhere may also indicate sites of intersection of bedrock structures, such as, at the east end of the Buckindy anomaly (M_6) and at the east end of the northeast-trending linear magnetic low north of Miners Ridge. A zone of apparently minor mineralization (Milt Creek prospect, area 4) occurs near the Buckindy intersection, and the Carmen and Copper King prospects (Stotelmeyer and others, 1982) lie near the intersection north of Miners Ridge. The Pioneer (32) and Epoch (31) prospects lie near the intersection between a northeast extension (anomaly M_7) of the Buckindy anomaly and a northwest-trending magnetic lineament. Major mineral properties that show no relation with intersecting magnetic lineaments include the Glacier Peak and Royal Development Mines.

Table 2. Relationship of mineral deposits to magnetic data in the Glacier Peak Wilderness area

Map Number	Name	Type	Location	Elements	Alteration	Nature of associated magnetic anomaly
1	Glacier Peak	porphyry	Sec. 10, 11, T31N, R15E	Cu, Mo, Pb W, Ag, Bi, As	Controlled by brecciation	Lies along east-west magnetic low- (Glacier Peak transverse structural lineament of Grant, 1969
2	Buckindy	porphyry	Sec. 10-14, T33N, R12E	Cu, Mo, W, Ag	Most intense along NE fractures	Along SE flank of northeast trending magnetic high (Buckindy transverse structural belt of Grant, 1969)
3	Fortress Mountain	porphyry	Sec. 24, T31N, R15E	Cu	Present	Adjacent to east-west magnetic low (transverse structural lineament)
4	Milt Creek	porphyry?	Sec. 29, 30 T34N, R13E	Cu	Fracture controlled NE-ENE	Along SE flank of northeast trending magnetic high (Buckindy transverse structural alinement)
5	Red Mountain	porphyry?	Sec. 29, 33, T31N, R16E	Cu, Mo, As	Fracture controlled limonitic	Flank of magnetic high associated with Cloudy Pass batholith
6	Crown Point	Hydrothermal vein?	Sec. 7, T31N, R16E	Cu, Mo, As, Ag	unknown	Adjacent to east-west magnetic low (Glacier Peak transverse structural lineament)
7	Canyon Creek	Hydrothermal vein?	Sec. 3, T31N, R14E	Cu	weak	Adjacent to northeast trending magnetic lineament.
8	Sitting Bull	unknown	Sec. 26, T32N, R15E	Cu, Mo	none to weak	Lies along northeast magnetic low, possible Glacier Peak transverse structure?
9	Bannock Mountain	porphyry?	Sec. 14, 15 T32N, R14E	Cu, Mo	weakly	Along western flank of Cloudy Pass magnetic high
10	Pass Creek	porphyry?	Sec. 29, 33 T33N, R16E	Cu, Mo	present	Adjacent to northwest magnetic lineament

Map Number	Name	Type	Location	Elements	Alteration	Nature of associated magnetic anomaly
11	Company Creek	unknown	Sec. 15, 16, 21, 22, T32N, R16E	Pb, Zn, As	unknown	Adjacent to northwest magnetic lineament
12	South Cascade Glacier	stock work veins porphyry?	Sec. 21, T34N, R13E	Cu, Mo	present	Along northwest trending lineament
13	Suiattle River	contact metamorphic?	Sec. 4, 9, T31N, R14E	Minor Cu, Mo	present	Lies along projection of east-west magnetic lineament (GP transverse structural lineament)
14	West Red Mountain	porphyry?	Sec. 22, T30N, R12E	Cu, Mo	limonitic present	Lies adjacent to magnetic low trending northeast
15	Deer Fly	porphyry	Sec. 11, T31N, R14E	Cu, Pb, Zn	present	Lies along east-west magnetic low-(GP transverse structural lineament)
16	Martin Peak	contact metamorphic?	Sec. 26, 35 T32N, R16E	Fe (py)	limonitic present	Lies along flank of magnetic high associated with Riddle Peaks pluton
17	Riddle Peak	contact metamorphic?	Sec. 33, T32N, R17E	Fe (py)	limonitic present	Lies along flank of magnetic high associated with Riddle Peaks pluton
18	Nine Mile Creek	contact metamorphic	Sec. 4, T31N, R17E	Cu, Au	unknown	Lies along flank of magnetic high associated with Riddle Peaks pluton
19	Red Cap	contact metamorphic? or structure?	Sec. 35, T32N, R16E	Fe (py) minor Au	limonitic present	Lies along projections (NW and SE) of northwest trending magnetic lineament
20	Ebbutt's Breccia	structure?	Sec. 2, T31N, R16E	unknown	limonitic present	Lies along projections (NW and SE) of northwest trending magnetic lineament
21	Buckskin Mountain	porphyry	Sec. 20, T31N, R16E	Cu, Zn	limonitic present	Lies along northest trending magnetic lineament
22	Northside Dumbell Mountain	contact metamorphic?	Sec. 3, 10, T31N, R16E	unknown	limonitic present	Lies along east-west magnetic lineament (GP transverse structural lineament)

Table 2. (Continued)

Map Number	Name	Type	Location	Elements	Alteration	Nature of associated magnetic anomaly
23	West side Bonanza Peak	contact metamorphic?	Sec. 32, 33 T32N, R16E	Fe (py)	limonitic present	Lies along east-west magnetic lineament (GP transverse structural lineament)
24	Red Mountain Chiwawa	contact metamorphic	Sec. 20, 21, 28, 29, T31N, R16E	Fe (py), minor Cu	limonitic present	Lies along southern flank of magnetic high associated with Cloudy Pass batholith
25	North Star	vein	Sec. 6, T31N, R16E	Pb, A	none present	In magentic high associated with Cloudy Pass batholith
26	Blankenship	unknown	Sec. 10, T33N, R16E	Cu?	unknown	Possible minor magnetic high
27	Bryan	Breccia Pipe?	Sec. 9, T30N, R16E	Cu, Au, Ag	unknown	Flank of magnetic low
28	lake Shyall	unknown	Sec. 16, T34N, R15E	Cu, Au, Ag	unknown	Flank of magnetic low
29	Silver Trail	vein	Sec. 8, T31N, R15E	Cu, Ag, Pb, Zn, Au	unknown	Lies along east-west magnetic low, (GP transverse structural lineament)
30	Cascade	vein	Sec. 7, T34N, R13E	Pb, Ag	unknown	Flank of magnetic high
31	Epoch	vein	Sec. 10, T34N, R13E	Pb, Ag	unknown	Near northwest trending magnetic lineament
32	Pioneer	vein	Sec. 2, 11, T34N, R13E	Pb, Zn	unknown	Near northwest trending magnetic lineament
33	Goff	vein in Tertiary volcanics	Sec. 19, 20, 29, 30, T29N, R14E	Au, Ag, Cu	limonitic present	Flank of magnetic high
34	Holden	vein?		Au, Ag, Cu		East-west magnetic lineament (CP) transverse structural lineament)

Except for chiefly the Buckindy, Glacier Peak, and Royal Development properties that are all associated with Miocene porphyry bodies, nearly all known areas of significant mineralization (Stotelmeyer and others, 1982; Grant, 1982) are concentrated in the northeast magnetic province. The Buckindy and Glacier Peak properties occur in transverse magnetic belts in the central magnetic province.

Conclusions

The aeromagnetic map of the Glacier Peak Wilderness and vicinity can be broadly subdivided into three large magnetic provinces (fig. 4) showing different overall patterns of anomalies. Individual anomalies or groups of anomalies identify many major and some minor geologic features. The northeast magnetic province, lying northeast of northwest magnetic lineaments is composed of belts of steep magnetic gradient or magnetic highs and lows. Magnetic highs are particularly well marked over pre-Tertiary bodies of mafic to intermediate composition, including the layered gabbroic Riddle Peaks pluton and a north-west-trending belt containing the Marblemount Meta-Quartz Diorite and members of the Dumbell Mountain, Seven-Fingered Jack, and Entiat plutons. Linear magnetic lows occur over the Tertiary Duncan Hill and Railroad Creek plutons and approximately over the pre-Tertiary Cardinal Peaks pluton. The central magnetic province is a broad area of generally low magnetic relief but crossed by two transverse belts of positive anomalies associated with the Miocene Buckindy and Cloudy Pass plutons and the Quaternary volcanic rocks of Glacier Peak. The southwest magnetic province is marked by complex anomaly patterns associated with Tertiary plutons and volcanic rocks west of the Straight Creek fault.

The aeromagnetic map also shows features that are related to areas of known mineralization and therefore may be useful guides for future exploration activity or to mineral appraisal. Many mineral properties are spatially related to northeast and east-west-trending magnetic belts and lineaments or to intersections of lineaments, the most notable of the latter being the highly productive Holden Mine. Some of the smaller magnetic anomalies may reflect small bodies, in places, perhaps not exposed. Several subcircular anomalies are clearly associated with ultramafic bodies, the magnetic expressions of which probably vary with content of secondary magnetite produced by serpentinization. Among other features are the flanks of magnetic highs, where some prospects are located and where mineralization of contact type might be expected to occur. It is equally important to point out that some areas of significant known mineralization, such as the Trinity Royal Development Mine, occur in areas of nondistinctive magnetic expression on the aeromagnetic map.

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