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AEROMAGNETIC AND GRAVITY SURVEYS OF THE CRATER LAKE REGION, OREGON*

By H. Richard Blank, Jr.**

Introduction

Since 1962 the U.S. Geological Survey has been engaged in a continuing program of geophysical studies in southwestern Oregon, primarily concerned with delineating and interpreting the regional Bouguer gravity field (Blank, 1966). In the course of this study the gross features of the gravity field in the vicinity of Crater Lake were delineated. It was early apparent that the Crater Lake complex does not produce a large negative gravity anomaly such as is commonly associated with calderas of the Krakatoan type (Yokoyama, 1963). This result was not unexpected in view of the evident lack of an appreciable thickness of low-density fill within the caldera. However, it was felt that a more complete definition of the geophysical environment of the caldera might shed some light on its regional structural position and on the question of whether related intrusive bodies are present at depth. To this end additional gravity work was performed, including the establishment of a number of stations within the caldera on the perimeter of the lake and on Wizard Island, and an aeromagnetic survey was made of the caldera and its immediate surroundings. The cooperation and assistance of the National Park Service greatly facilitated work within the Park and are gratefully acknowledged.

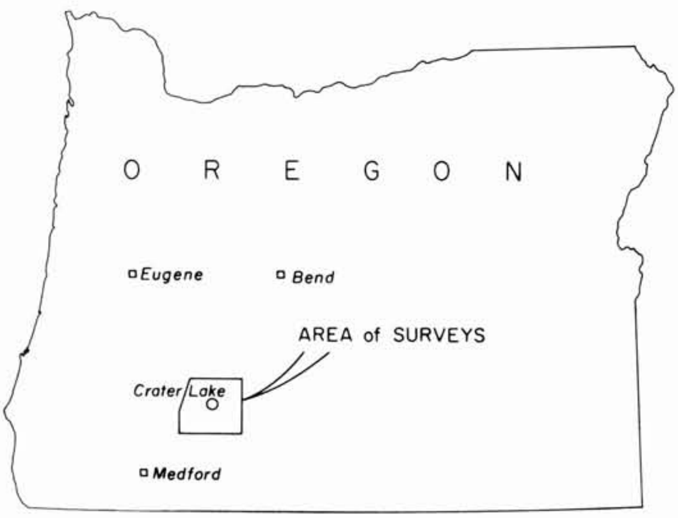

Figure 1. Index map of Oregon.

Physiographic Setting

The region considered in this paper includes all of Crater Lake National Park and extends across the entire width of the High Cascades physiographic province, from several miles east of U.S. Highway 97 to the western slopes of the upper Rogue River Valley. It is bounded on the north by approximately the latitude of Diamond Lake and on the south by the latitude of Fort Klamath. Figure 1 locates the region with respect to Eugene, Bend, and Medford.

Figure 2 is a simplified topographic map of the region with contours at 1000-foot intervals. The High Cascades are roughly delineated by the belt of topography above 5000 feet in elevation east of the Rogue River. Mounts Bailey and Thielsen, west and east of Diamond Lake, respectively, and Mount Mazama, the volcanic complex whose partial engulfment resulted in the formation of Crater Lake caldera, comprise large areas above 7000 feet in elevation. Southwest of Crater Lake is Union Peak, a lesser

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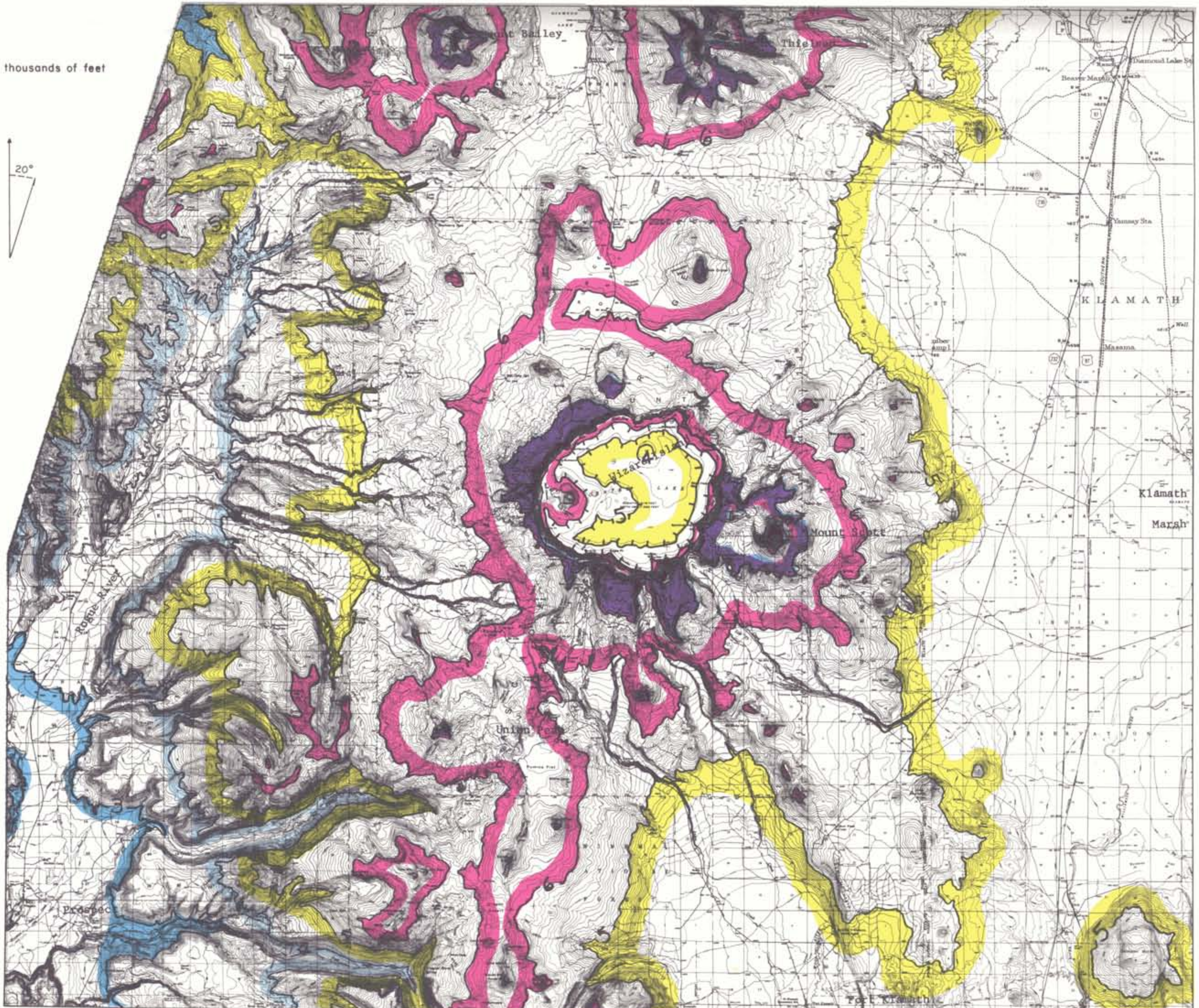
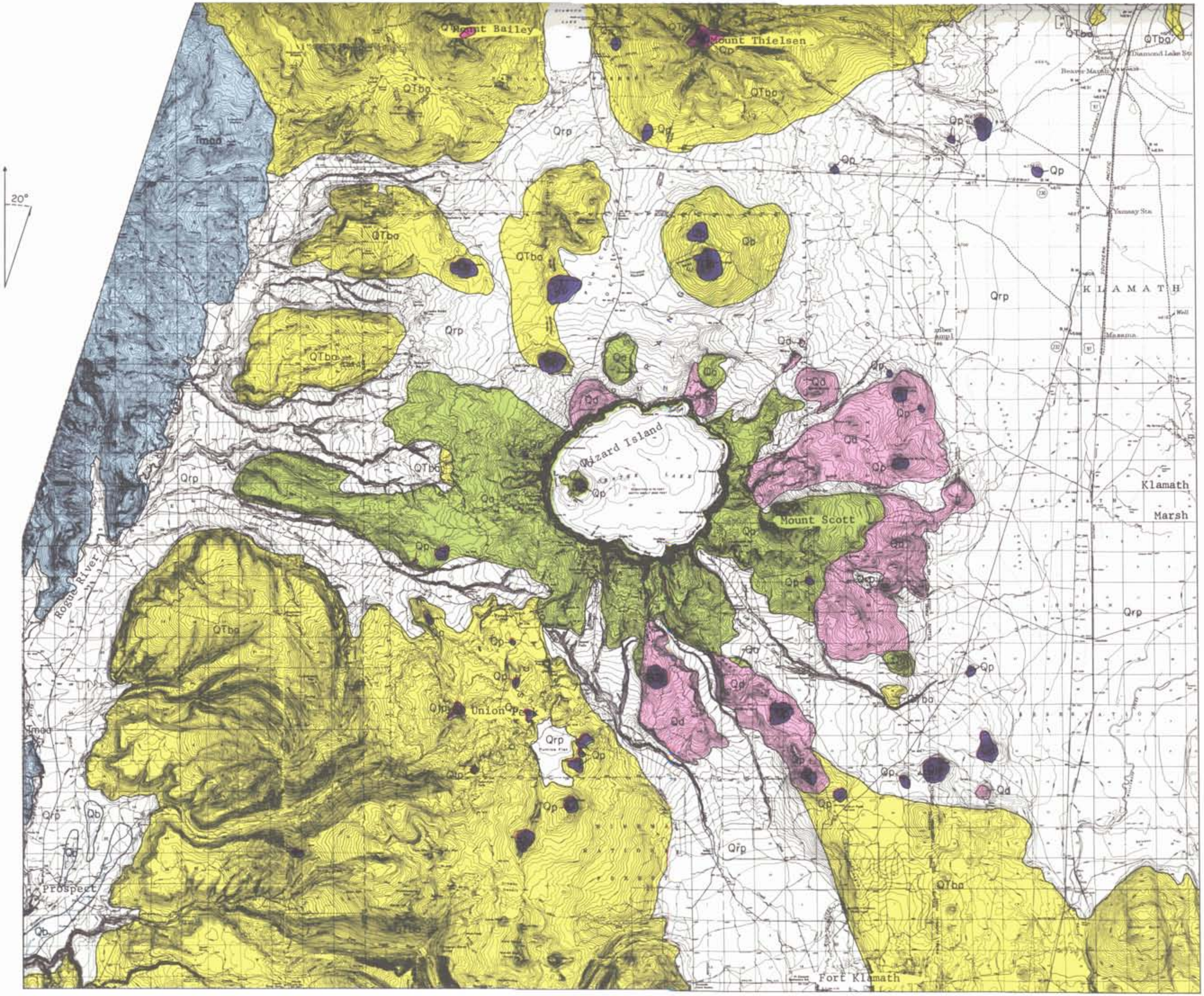
Elevations given in thousands of feet



KEY TO MAP UNITS

QUATERNARY	Recent	Qrp	Dacite pyroclastic rocks erupted from Mount Mazama: Pumice, ash-flow, and ash-fall deposits; includes alluvium
QUATERNARY	Pleistocene and Recent (Age relationship not implied by position)	Qb	Basaltic and andesitic lava flows, domes, and intracanyon flows
		Qp	Basaltic and andesitic pyroclastic rocks of parasitic cones
		Qa	Mount Mazama andesites: Lava flows, domes and explosion breccia, with some interbedded glacial deposits; includes andesites of Mount Scott
		Qd	Dacite lava flows and domes
QUATERNARY – TERTIARY	Plioc. and Pleistocene (Age relationship not implied by position)	Qtp	Basaltic and andesitic pyroclastic rocks: Tuff, tuff breccia, and agglomerate; includes mafic intrusive rocks associated with vents
		Qtba	Basalt and andesite of High Cascades sequence: Lava flows with subordinate breccia, forming lava domes, cones, and intracanyon flows
TERTIARY	Oligocene and Miocene	Tmoa	Andesite and basaltic andesite of Western Cascades sequence: dominantly lava flows of middle(?) and upper Miocene age, with some older pyroclastic rocks


20°
Mount Bailey
Mount Thielsen
Diamond Lake Sta.
Beaver Marsh
Yamsay Sta.
KLAMATH
Klamath
Marsh
Wizard Island
Mount Scott
Union Peak
Rogue River
Prospect
Fort Klamath
QTba
Tmad
Qrp
Qp
Qb
Qd
Qa

prominence. By extending the contours beyond the map area it can be seen that the High Cascades change their trend from nearly north-south, south of Crater Lake, to more nearly northeast, north of Crater Lake; the change in trend coincides with a change in width of the range. Three areas of high topography -- Mount Bailey, an area west of Union Peak, and the "arm" above 5000 feet extending southeast from Crater Lake -- are offset from the main range axis. Finally, a sharp offset of the eastern range front occurs near the southern margin of the map due west of Fort Klamath. These features are reflected in the geophysical maps and their possible significance will be discussed later.

The High Cascades are bordered on the east by Klamath Marsh and the upper Klamath basin, which are physiographically included in the Basin-Range province, and on the west by the Western Cascades.

Figure 2 also serves as a simplified terrain clearance map that can be used in conjunction with interpretation of the aeromagnetic map discussed in a subsequent section.

Geologic Framework

The geology of Crater Lake National Park has been described in a classic paper by Williams (1942); only a brief synopsis is in order here. The geologic map of figure 3 is adapted from Williams' National Park map and from reconnaissance maps by Williams (1957) and Wells and Peck (1961).

The oldest rocks exposed in the region are Oligocene to Miocene pyroclastics and lavas, composed chiefly of hypersthene andesite, and belonging to the so-called Western Cascades sequence. These rocks have an aggregate thickness probably in excess of 20,000 feet west of the map area; they dip generally eastward and doubtless are present at depth beneath the High Cascades.

Rocks of the so-called High Cascades sequence are Pliocene to Pleistocene in age. According to Williams (1942), they may be locally in fault contact with rocks of the Western Cascades sequence. In places they fill deep canyons carved in the older rocks. The lower part of the High Cascades sequence consists almost entirely of olivine-bearing basalt to basaltic andesite lava flows that form shield volcanoes of low relief; the upper part is more andesitic in composition, and consists of alternating lava flows and pyroclastics erupted from strato-volcanoes that were erected on a platform of coalescing shields. Mounts Bailey, Thielsen, Scott (east of Crater Lake) and Mazama and Union Peak are the largest of these strato-volcanoes in the region studied. Mafic intrusive rocks are associated with the vents of Bailey, Thielsen, and Union Peak.

Rocks of Mount Mazama affinity are distinguished separately on the geologic map. According to Williams, the development of the main volcanic edifice was characterized by relatively quiet outpourings of andesitic lava, with explosive eruptions playing a subordinate role. The waning stages of activity were marked by eruption of diverse magma types--dacite in the form of viscous flows, pumice, and domes; and basalt or basaltic andesite as parasitic cinder cones or scoria cones. Williams points out that this sequence is characteristic of many andesitic volcanoes throughout the world.

Vast quantities of dacitic pumice and ash were ejected during the climactic eruptions of Mount Mazama. The bulk of the deposits consists of pumice-flow material whose age has been established as about 6600 years (Rubin and Alexander, 1960). The air-fall deposits are thickest to the northeast and east of Crater Lake because of the influence of prevailing winds. Rapid extravasation of the dacite and consequent withdrawal of support led to collapse of the summit area and formation of the caldera. The caldera is eccentric with respect to the former summit, which apparently lay well to the south of the center of what is now Crater Lake (Williams, op. cit.).

The discovery of abundant accidental fragments of granitoid rocks, chiefly partially fused granodiorite, in the products of the culminating eruptions has recently been reported by Taylor (1967). He suggests that partial fusion of granodioritic crustal material may have produced the reservoir of dacite magma.

Crater Lake is situated astride a broad upwarp of crystalline rocks that is presumed to extend northeast from the Klamath Mountains to the Ochoco-Blue Mountains uplift of northeast Oregon (Peck and others, 1964). The possible detection of structures in the crystalline rocks through their influence on regional gravity trends has been noted previously (Blank, op. cit.). A second major set of regional structural elements is represented by vents of the Western and High Cascades, which in a broad sense lie in north-south trending belts that are probably related to deep fracture zones that channeled ascending magma (Peck and others, op. cit.). A third set of regional structural elements consists of northwest-trending shear zones in areas east of Crater Lake. One of the best documented of these structures is the Brothers fault zone, mapped by Walker and others (1967) in the east half of the Crescent 1:250,000 quadrangle. Northwest trends predominate in the geophysical data, as will be seen shortly.

Aeromagnetic Survey

The aeromagnetic survey of the Crater Lake region was carried out by the Geological Survey during the summer of 1965 under the direction of J. L. Meuschke. The equipment used consisted of a fluxgate magnetometer model AN/ASQ-10 mounted in the tail of a Convair CV-240; the basic system and procedures were similar to those described by Balsley (1952). Continuous analogue tape recordings of the total magnetic field intensity at an elevation of 9000 feet above sea level were made along east-west lines spaced at intervals of about 1 mile, with north-south control lines at wider intervals for accurate reduction to a common datum. Instantaneous position of the aircraft was ascertained by referring fiducial marks on the readout chart to corresponding marks on continuous strip photographs. However, difficulty was experienced with registration of the fiducial marks due to camera malfunction, leading to some uncertainties in horizontal position; individual profiles may be translated somewhat from their true position along a flight line. Since this survey was made, the aircraft has been equipped with a completely automated digital recording system and Doppler navigation (Evernden and others, 1967).

A total intensity magnetic contour map with a contour interval of 10 gammas (1 gamma = 10^{-5} oersted) and datum arbitrary is presented in figure 4. Flight paths are indicated by dashed lines. The color pattern has been chosen to emphasize gross levels of intensity.

The gradient produced by the earth's main field has not been removed; in the Crater Lake region, this amounts to an increase of about 8 gammas per mile northeasterly (roughly N. 33° E.), so that the map may be considered as tilted up in that direction.

Comparison of the aeromagnetic map with the simplified topographic map of figure 2 reveals at best an erratic correlation. The magnetic response due to minor topographic features is strongly dependent upon their location relative to traverse lines; the effect of some topography is "filtered out" as a result of the 1-mile traverse spacing. Other features produce a negligible response even when directly overflown. This can be attributed to weak polarization of the near-surface rocks, or, in the case of mafic cinder cones, to low density and lack of coherent effect of the permanent polarization.

One of the most significant characteristics of the map is the northwest and, to a lesser extent, northeast grain of positive anomalies with long spatial wavelength. The trends are probably real, but they are locally distorted by artificial "chevron" effects related to the horizontal position uncertainty and are further obscured by the contributions of local or particularly intense souces; hence they must be interpreted with caution. Long wavelength anomalies are generally associated with deeply buried magnetic sources. It appears that the distribution of magnetic material at depth is primarily controlled not by north-south structures associated with High Cascades lineaments, but by structures oriented more nearly parallel to the Brothers fault zone, and by other structures more or less parallel to the axis of the Klamath Mountains crystalline belt.

A northwest-aligned magnetic high corresponding roughly to a topographic high extends across the center of the map to the northwest wall of the Crater Lake caldera, where it terminates in a sharp magnetic discontinuity. This seems to imply that a block of magnetic "basement" has been truncated by a fault near the caldera margin. The fault would trend northeast and would intersect the "northern arc of vents" described by Williams (op. cit.). Similar magnetic features are characteristic of calderas surveyed in Japan (Blank and others, 1966); it has been speculated that they represent deep-seated tensional fractures which promoted the rapid egress of magma.

The magnetic pattern associated with Crater Lake is to some extent modified by the effect of the caldera topography. This effect should be strongest over the south rim for a perfectly symmetrical, uniformly magnetized caldera, but here it is exaggerated because the north rim is lower. Mount Scott and the Wizard Island lava field also produce distinct anomalies.

Several large positive anomalies with more or less circular symmetry command attention. The three of greatest amplitude -- 1000 to 1500 gammas above datum -- are associated with the High Cascades volcanoes Mount Bailey, Mount Thielsen, and Union Peak. These anomalies are too broad with respect to the terrain clearance to be the result only of topography; moreover, the crest of the anomaly is about 1 mile south of the summit of the volcano in each case. It is possible that they are produced by a hypabyssal mafic

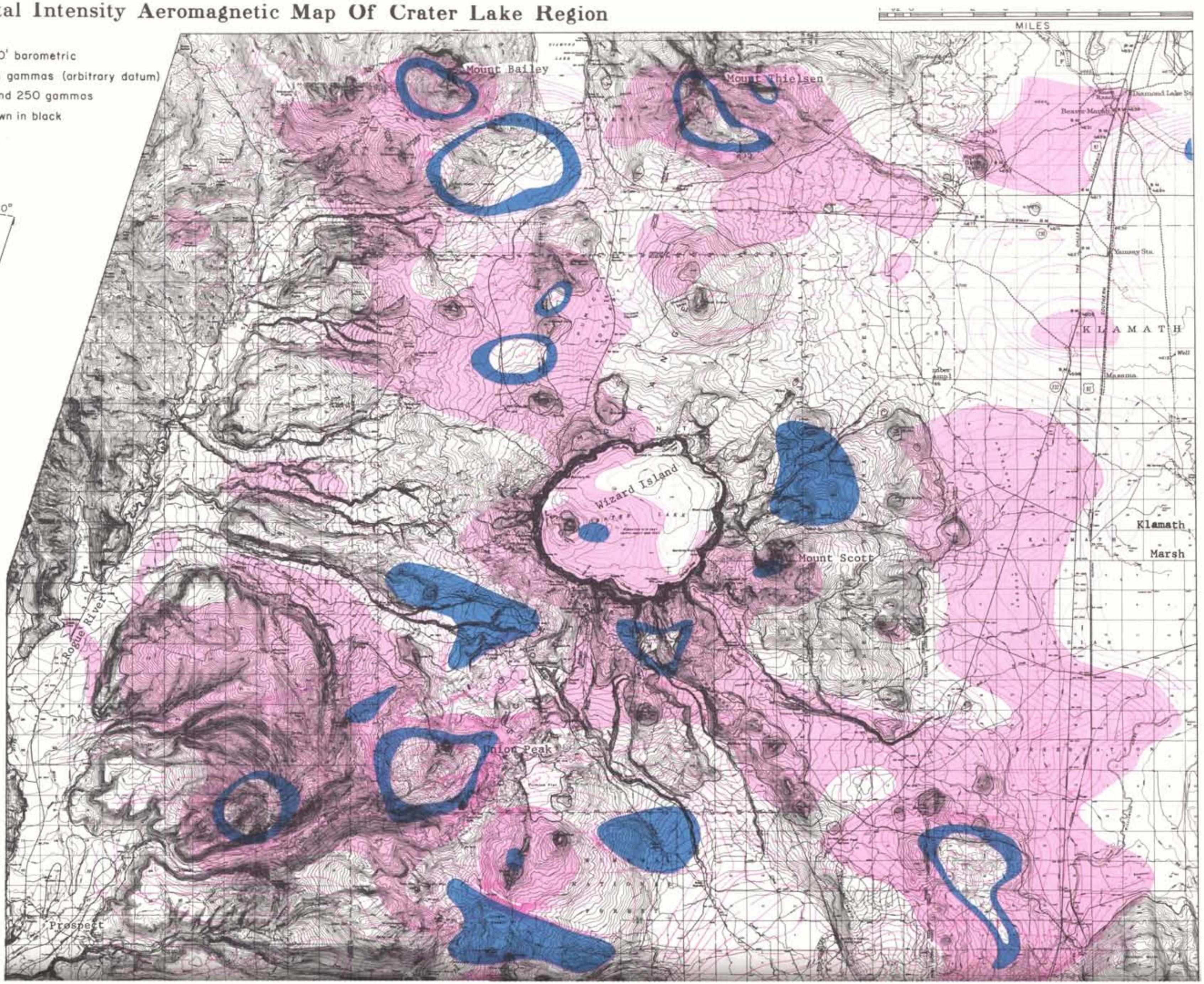
Fig. 4 Total Intensity Aeromagnetic Map Of Crater Lake Region

Flight elevation 9,000' barometric

Isoanomalic values in gammas (arbitrary datum)

Contour interval 50 and 250 gammas

Geologic contacts shown in black



intrusive complex centered beneath the volcanoes, the depth to the main sources accounting for the large southerly displacement of the anomalies, and that the topographic contribution is subordinate. The known presence of mafic intrusive rock in the vents of these volcanoes lends a measure of support to this interpretation. A fourth large positive anomaly with almost perfect symmetry is located 6 miles west of Union Peak and is not related to a well-defined volcanic edifice. This may be associated with a shield volcano of the older High Cascades sequence, or with an eruptive center that is completely concealed.

The magnetic lows indicated by closed hachured contours on the total intensity map are in some cases simply polarization lows located on the north side of positive anomalies because of the northerly magnetic inclination. However, two large negative anomalies located respectively northeast of Crater Lake and southwest of Diamond Lake probably cannot be explained wholly on this basis. They appear to represent structural depressions, or alternatively, masses of inversely polarized rock. No inversely polarized rocks have yet been reported from the Crater Lake area, although they are known to be present in the lower part of the High Cascades sequence farther north (A. R. McBirney, oral communication).

A sharp northwest-oriented magnetic low near the southern border of the map is also difficult to explain by normal polarization alone. Whatever its source, the low is rather well aligned with an offset of the High Cascades range front. These features may be controlled by a northwest-trending fault zone.

Gravity Survey

Altogether some 300 gravity observations were made in the Crater Lake region, as defined here, during the summers of 1962, 1963, and 1965. Observed gravity for most stations was referred to three primary base stations located at Prospect, Diamond Lake, and Fort Klamath, as well as to a network of auxiliary base stations, including a station conveniently located on the concrete porch of the Crater Lake National Park headquarters building. The base net is ultimately tied to an assumed value of 980,236.5 mgals for observed gravity at the Woollard (1958) airport station at Medford. All data have been reduced with the aid of an electronic computer to Bouguer anomaly values based on the International ellipsoid. A standard density of 2.67 and an alternative density of 2.45 gm/cm^3 were used in the reduction.

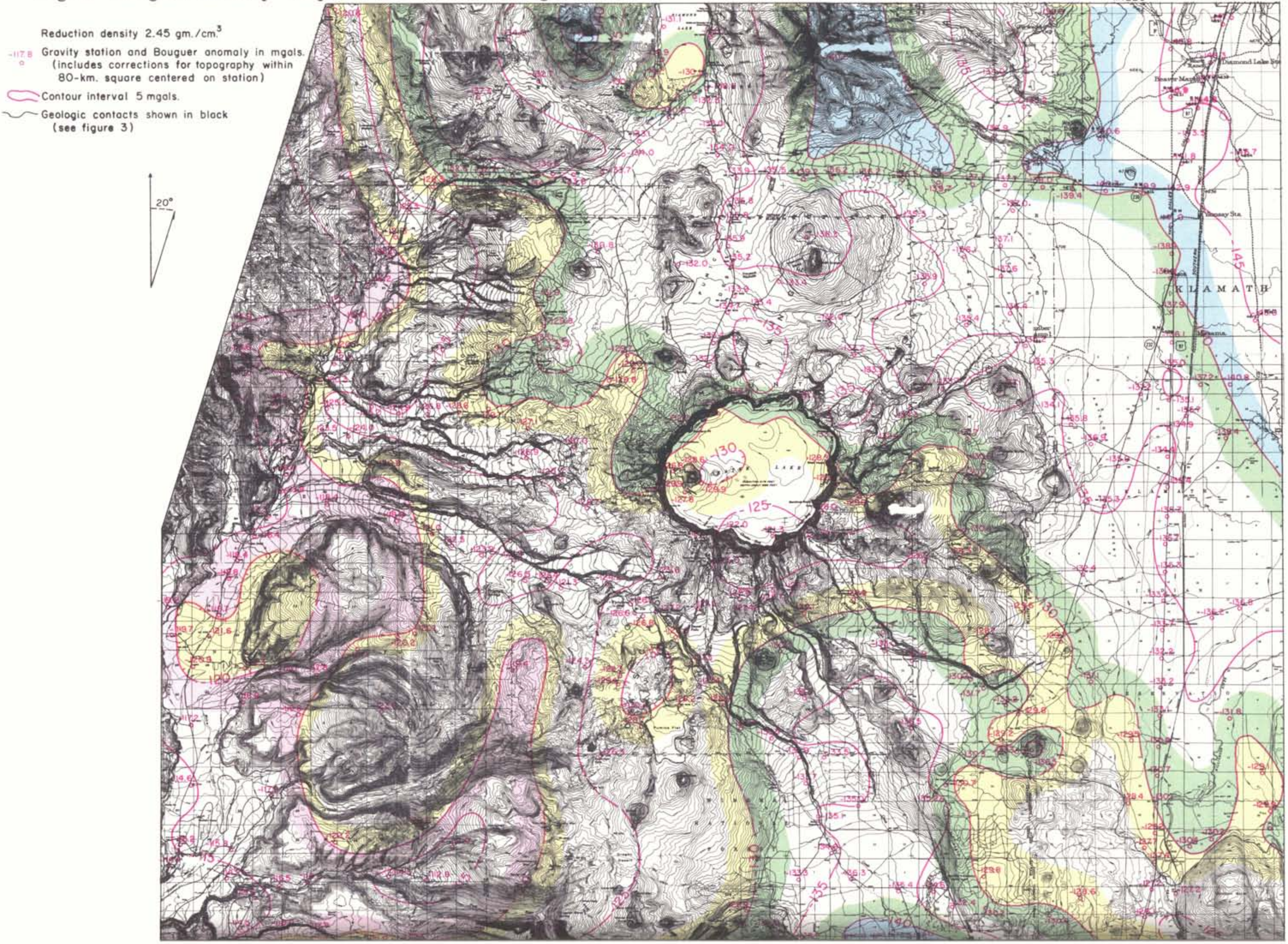
Terrain corrections for 1962 and 1963 stations were made using the computer method of Kane (1962) with 2-km instead of 1-km unit squares. In this method the effect of topography in the interval between two squares of sides 80 x 80 km, and 4 x 4 km, centered about each station, is computed by machine, and the effect of topography within the inner square is computed by hand. The inner square was assumed equivalent to Hayford-Bowie zones A-F; this approximation introduces very small (generally less than 0.1 mgal) errors into the total correction. Terrain corrections for 1965 stations (about 20) were done by hand for Hayford-Bowie zones A through L plus $\frac{1}{2}$ M, so that they are only approximately equivalent to those done by Kane's method. Where terrain effects are large the uncertainty of the calculation is likewise large. The maximum uncertainty in the terrain corrections applies to stations on the caldera rim or lake shore, and amounts to about 2 mgals, with the exception of the correction for Mount Thielsen ($\pm$ 5-10 mgals). For inner zone corrections involving water compartments in Crater Lake the detailed bathymetric chart published by Byrne (1962) was employed.

The complete Bouguer anomaly map of figure 5 is based on a reduction density of 2.45 gm/cm^3. Ninety-five percent of the complete Bouguer anomaly values are believed accurate within $\frac{1}{2}$ contour interval ($2\frac{1}{2}$ mgals). As in the case of the magnetic map, color is used to enhance broad gravity contrasts.

Maximum gravity relief shown by the map is about 35 mgals. Much of this relief is expressed as a negative gradient directed easterly to northeasterly across the region, which tends to mask the weaker local features.

Gravity contours in the High Cascades south of Crater Lake trend more or less north-south parallel to the eastern margin of the range (probably a fault-line scarp), the Bouguer values falling off to a low over the alluvial fill of Klamath basin. North of Crater Lake the pattern abruptly changes: contours generally transect the range, and northwesterly trends prevail. A northwest-trending positive anomaly is associated with the divide between the Klamath basin and Klamath Marsh. Its axis is slightly north of the axis of the corresponding positive magnetic anomaly. This feature extends as far northwest as the vicinity of Crater Lake, where it merges with a distinct high associated with the main mass of Mount Mazama, south to southeast of the center of the caldera. The northwest rim of the caldera lies within a northeast-trending gravity embayment roughly coincident with the magnetic discontinuity. Thus the gravity data are consistent

Fig. 5 Bouguer Gravity Map Of Crater Lake Region



with the concept of a northwest-trending "basement" structure truncated by a northeast-trending structure at the caldera. The nature of this structure remains a matter of speculation. It may consist of no more than upwarped or up-faulted rocks of the older High Cascades sequence.

Because of the very large topographic relief involved, the detailed configuration of the anomaly associated with the Crater Lake caldera can be altered somewhat by selection of a different reduction density. The use of a lower reduction density will increase the elevation factor and hence decrease the consistent discrepancy between Bouguer anomalies on the lakeshore and proximal points on the rim. Nevertheless the anomaly associated with Mount Mazama remains positive with respect to the regional background. This anomaly may be due to the presence of unusually large quantities of intrusive rock, probably dacite, at shallow levels within the complex. A weak negative anomaly is superimposed on the main gravity field near the center of the caldera, and other minima occur to the north and northeast. These features probably reflect local accumulations of low density pyroclastics.

Mounts Bailey and Thielsen, in contrast to Mount Mazama, appear to be associated with negative gravity anomalies, of amplitude as much as 10 mgals. This indicates a low bulk density relative to the reduction density of 2.45 gm/cm^3 and suggests that intrusive material in these volcanoes is subordinate. In the case of Union Peak no gravity effect was detected, but here the volcanic edifice is much smaller.

The broad negative gravity anomaly west of Union Peak is almost exactly coincident with the circular magnetic anomaly discussed earlier. The fact that this is both a gravity and magnetic feature makes it an inviting target for future investigation.

Conclusions

Regional gravity and aeromagnetic surveys have shown that Crater Lake lies in an area strongly influenced by northwest-trending, and to a lesser extent, by northeast-trending lineaments; north-south trending lineaments associated with the High Cascades have little or no geophysical expression. The northwest set may be part of a shear zone related to the Brothers fault zone, or it could represent a western extension of Basin-Range normal faulting; the northeast set may reflect either deeply buried structures in the Klamath Mountains belt or tensional structures associated with shearing. A prominent northwest-trending gravity and magnetic lineament entering Crater Lake from the southeast is apparently truncated near the northwest wall of the caldera by a major northeast-trending structure. The location of Mount Mazama at such a structural intersection may have facilitated the rapid rise of magma which led to its ultimate engulfment.

Several High Cascades volcanoes are compared with respect to their gravity and magnetic signatures. Mount Thielsen and Mount Bailey have a strong magnetic effect, attributable at least in part to mafic intrusive rock beneath the volcanic edifice; and each is also associated with a gravity low because of its relatively low bulk density. Union Peak does not perturb the gravity field, possibly because it is in a more advanced stage of dissection and lacks a thick mantle of low density pyroclastics, but its magnetic expression is close to that of the others. Mount Mazama has a weaker magnetic expression but produces a gravity high; this may be accounted for by the presence of weakly magnetic dacite intrusives at shallow depths within the edifice, although it is possibly due to the andesite pile alone.

A positive magnetic and negative gravity anomaly with circular symmetry in the High Cascades west of Union Peak may be associated with an as yet unknown older volcanic center.

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