

Tectonic setting of the southern Cascade Range as interpreted from its magnetic and gravity fields

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ABSTRACT

We have compiled and analyzed aeromagnetic data from the southern Cascade Range and compared them with residual gravity data from the same region in order to investigate regional aspects of these young volcanic rocks and of basement structures beneath them. Various constant-level aeromagnetic surveys were mathematically continued upward to 4,571 m and numerically mosaicked into a single compilation extending from lat. 40°10'N to lat. 44°20'N. These data were reduced to the pole, upward continued an additional 10 km, and compared with a magnetic topographic model and with residual gravity data upward continued to the same level. Several intriguing regional features are suggested by these data. (1) The Trinity ophiolite complex that is exposed west of Mount Shasta probably dips at a shallow angle to the east and continues in the subsurface at least 10 km east of Mount Shasta. (2) Mount Shasta, Lassen Peak, and Medicine Lake volcanoes are located in a widespread magnetic low possibly caused by an upwarp of the Curie-temperature isotherm. (3) Crater Lake caldera is located at the intersection of various linear anomalies interpreted to be related to structure in basement rocks below the Cascade Range. (4) Three Sisters volcanoes and Newberry Crater are connected to each other by an arcuate magnetic source. (5) The High Cascades, from lat. 40°10'N to at least lat. 44°30'N, are marked by a residual gravity low which includes the Three Sisters volcanoes, Mount Shasta, Medicine Lake volcano, Mount McLoughlin, and Crater Lake. (We believe this gravity feature represents a major structural depression beneath the High Cascades.) (6) Except for Newberry Crater,

every major volcano of the study area is located on the perimeter of a local gravitational low. We suggest that the gravity lows reflect subsidence of low-density volcanic material relative to denser country rock and that the major volcanoes have developed over structures at the perimeters of their respective depressions.

COMPILATION AND ANALYSIS OF THE DATA

During the past six years, Oregon State University has systematically collected aeromagnetic data of exceptional quality over the entire southern part of the Cascade Range, from lat. 40°10'N to lat. 44°20'N (Connard, 1979; Connard and others, 1983; McLain, 1981; Hupponen and others, 1982). These data consist of various surveys, each flown at constant elevation. East-west flightlines were spaced 1.6 km apart or less, north-south flightlines were spaced 8 km apart, and there was synchronous operation of a ground magnetometer for diurnal corrections. Aircraft locations were determined by a ground-based transponder navigation system. Consequently, crossing errors rarely exceeded 10 nT, and most were <5 nT, exceptionally small errors for aeromagnetic surveys over volcanic terrane.

Our objective was to combine these individual surveys into a single constant-elevation survey of the northern California and southern Oregon Cascade Range (Fig. 1). First, we calculated x, y coordinates for each datum using a transverse mercator projection, and transformed each survey to a consistent rectangular grid with 1-km spacing in both the x and y directions using standard interpolation techniques (Webring, 1981). Second, we upward continued each survey grid to an altitude of 4,571 m,

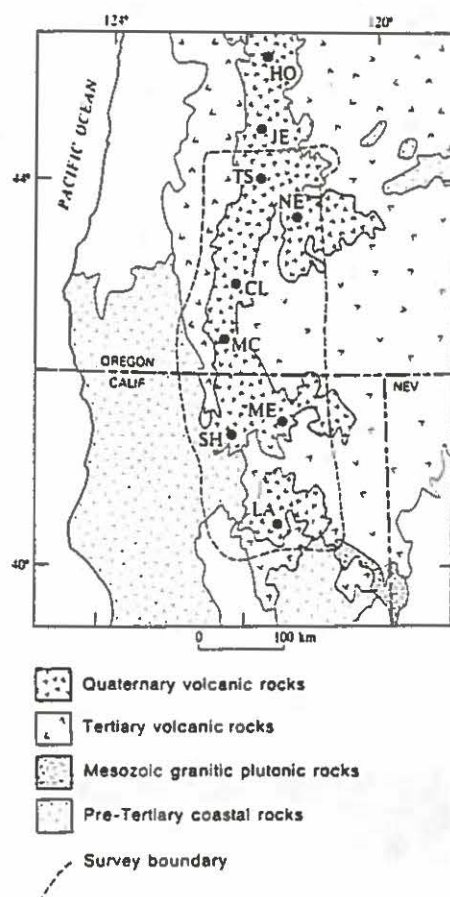


Figure 1. Generalized geology of southwest Oregon, northern California, and northwestern Nevada, modified after King (1969). Dashed line shows the boundary of aeromagnetic compilation. Solid dots show location of major volcanoes: LA = Lassen Peak, SH = Mount Shasta, ME = Medicine Lake, MC = Mount McLoughlin, CL = Crater Lake, NE = Newberry Crater, TS = Three Sisters, JE = Mount Jefferson, and HO = Mount Hood.

the level of the highest survey, which is located directly over Mount Shasta (elevation 4,316 m). Third, individual survey grids were numerically mosaicked into a single regional grid. The boundary of each survey overlapped its neighboring surveys by several kilometres but, in every case, the discrepancies in the overlap regions after upward continuation were minimal (<10 nT), which greatly facilitated the mosaicking procedure. The resulting compilation (Fig. 2) represents a continuous, constant-elevation aeromagnetic data set of the southern Cascade province, which includes a number of major volcanic features: Lassen Peak, Mount Shasta, Medicine Lake volcano, Crater Lake caldera, Mount McLoughlin, Newberry volcano, and Three Sisters volcanoes.

Young volcanic rocks often have high magnetic susceptibilities and significant natural remanent magnetizations, and so aeromagnetic maps of relatively undeformed volcanic topography often contain a complex pattern of high-amplitude, short-wavelength magnetic anomalies. Although these are of importance to localized studies (for example, see Blakely and Christiansen, 1978; Flanagan and Williams, 1982), they tend to encumber regional interpretations. To reduce topographic effects, the aeromagnetic compilation was continued upward to various higher elevations. Figure 3, for example, shows the data upward continued to 14,571 m, which is 10 km above the altitude of the original compilation. The data in Figure 3 also have been reduced to the pole in order to remove the dependence of the shape of the anomalies on the direction of magnetization and on the direction of the ambient field. In so doing, we have assumed that the average direction of magnetization is parallel or antiparallel to the field of a geocentric dipole (inclination = 61° , declination = 0°), the average directions of the normal and reversed Earth's field during the formation of most of the Cascades.

Figure 3 shows many anomalies with wavelengths of 10 km and greater. To investigate the possibility that some of these anomalies may be caused by long-wavelength topographic features, a topographic model was constructed (Blakely and Grauch, 1983) using terrain digitized at ~ 400 -m intervals. The model assumes that the top of the magnetic layer corresponds to the digital terrain, the bottom is a horizontal plane, and the magnetization is uniform. The amplitude of anomalies calculated from the topographic model is proportional to the intensity of magnetization chosen for the calculation. We selected 10 A m^{-1} , by trial and error, as the intensity which best matches amplitudes of cal-

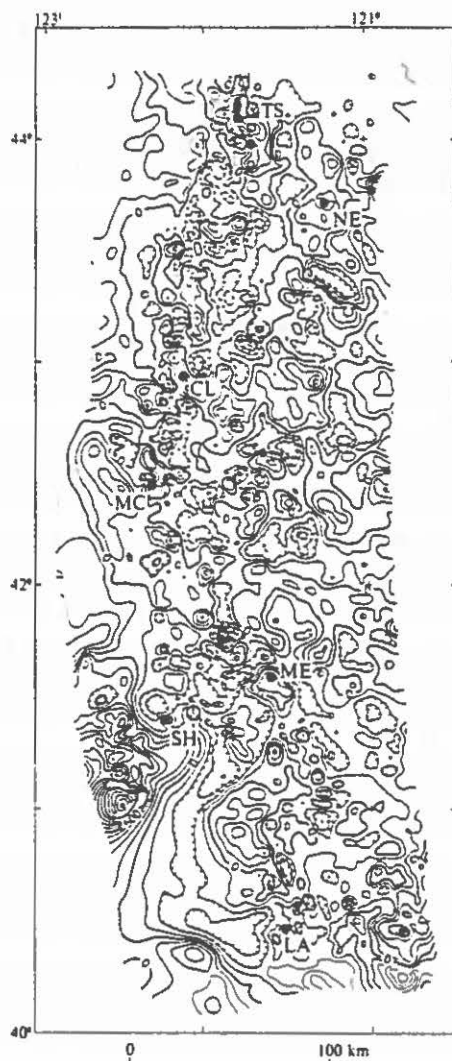


Figure 2. Low-level compilation of aeromagnetic data. Various constant-level surveys were gridded, upward continued to 4,571 m, and numerically mosaicked together. See text for sources of data. Contour interval = 100 nT. See Figure 1 for description of symbols.

culated anomalies with amplitudes of observed anomalies. Figure 4 shows the anomalies calculated from this topographic model. These calculated anomalies are also reduced to the pole and upward continued to 14,571 m so that they are comparable to the data shown in Figure 3. Observed anomalies that have counterparts in Figure 4 are probably produced by topographic sources, whereas observed anomalies that do not have corresponding model anomalies may be caused by magnetic features below the topographic surface. Interpretations of our aeromag-

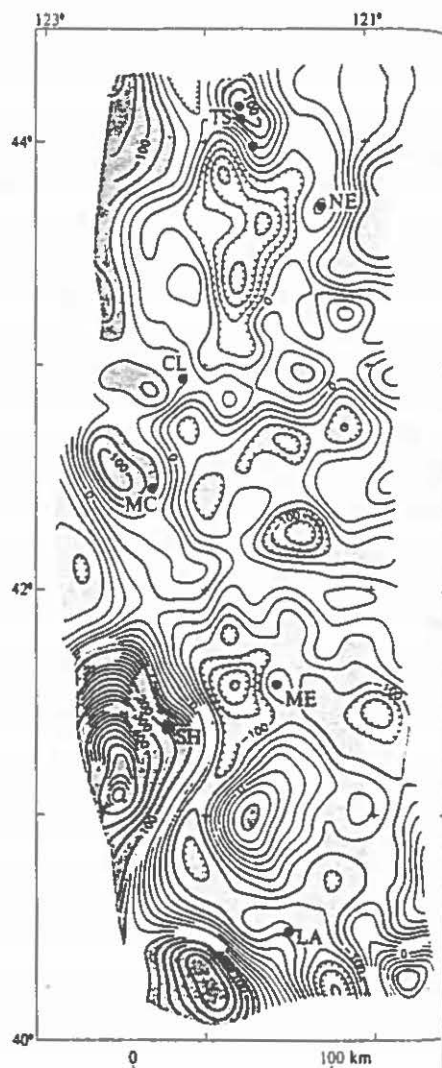


Figure 3. Upward-continued aeromagnetic data. The compilation of Figure 2 was reduced to the pole and continued upward 10 km to 14,571 m. Contour interval = 20 nT. Hachures indicate direction of decreasing magnetic intensity; stipple patterns indicate anomaly values >60 nT and <-60 nT. See Figure 1 for description of symbols.

netic data should include comparisons with Figure 4.

The following discussion will refer occasionally to the gravity map shown in Figure 5. The map was produced from a recent compilation of gridded Bouguer values for the conterminous United States (Godson and Scheibe, 1982) by calculating and subtracting a regional gravity field according to an isostatic model (Simpson and others, 1983) and upward continuing the residual 10 km to conform with the aeromagnetic map of Figure 3. Topography was assumed

have a density of 2.67 g/cm^3 for these computations.

INTERPRETATIONS

Trinity Ultramafic Sheet of Irwin (1977)

The most striking anomaly of Figure 3 is centered southwest of Mount Shasta (SH), over part of the Klamath Mountains that includes the Trinity ophiolite complex. The Trinity ophiolite complex contains the largest exposed ultramafic body in North America (Irwin, 1966) and is the source of this high-amplitude anomaly (Griscom, 1977). The planned boundary of the ultramafic body with the younger volcanic rocks of the Cascade Range is located ~20 km southwest of Mount Shasta (Fig. 6). The magnetic anomaly associated mainly with the ultramafic body, however, extends ~30 km east and northeast from this geologic boundary. Whether this indicates continuation of the ultramafic body below the volcanic terrane depends on the cross-sectional shape of the ultramafic body. If the ultramafic sheet dips and thins to the east, as shown by detailed modeling experiments using aeromagnetic data (A. Griscom, 1983, personal commun.), the leading edge of the sheet is located near the outer limits of its anomaly. We have confirmed this interpretation by comparing three-dimensional magnetic models of the ultramafic sheet to the upward-continued magnetic data. Moreover, Fuis and others (1985) have concluded from seismic refraction and velocity data that rocks similar to the Trinity ultramafic sheet underlie Mount Shasta at a depth of ~5 km below sea level. Our interpretation of the magnetic data (Fig. 7, feature A) shows the lateral extent of these rocks beneath Mount Shasta and the surrounding volcanic terrane.

The magnetic data also indicate that the Trinity ophiolite complex continues north of its mapped extent at shallow depth below less magnetic rocks of the eastern Klamath belt, as shown earlier by LaFehr (1966) based on Bouguer gravity data and by Griscom (1977) based on magnetic data. The magnetic anomaly ends abruptly at about lat. $41^{\circ}44'N$, coincident with the south-dipping thrust fault, which is basal to the Trinity ophiolite complex (Irwin, 1966). Although the magnetic data indicate that the ultramafic sheet ends at this thrust contact, the very high over the northern part of the Trinity ultramafic sheet appears to continue ~25 km to the north (Fig. 5) (Griscom, 1980). The continuation of the gravity anomaly across the magnetic boundary reflects the juxtaposition of high-density units: the Trinity ophiolite

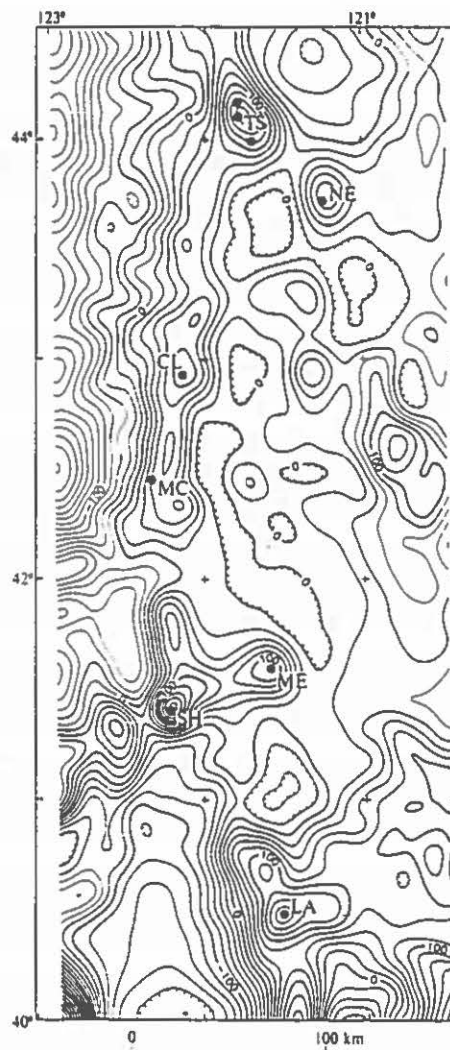


Figure 4. Calculated magnetic anomalies due to uniformly magnetized upper crust. The magnetic source is approximated with a top surface equal to topography digitized at 400-m intervals, with a horizontal flat bottom, and with uniform magnetization of 10 A m^{-1} . Anomalies are calculated on a level plane at 14,571 m and with vertical magnetization in order to conform with upward continued data of Figure 3. Contour interval = 20 nT; hachures indicate direction of decreasing magnetic intensity. See Figure 1 for description of symbols.

complex to the south (Griscom, 1980) and a unit that includes high-grade metamorphic rocks (Irwin, 1981; Coleman and others, 1983) of the western Paleozoic and Triassic belt to the north (Jachens and Elder, 1983). The low-level magnetic data (Fig. 2; Fig. 7, feature B) also suggest that a northeast-trending discontinuity exists in

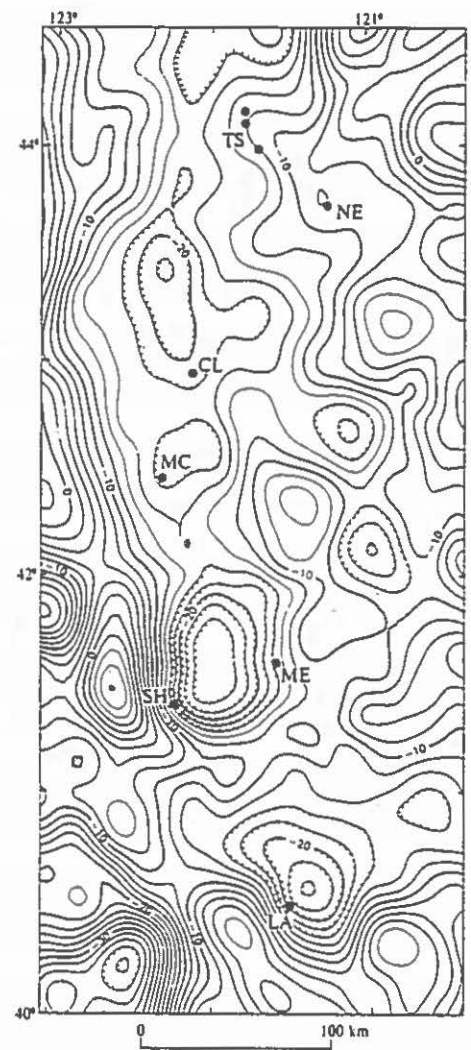
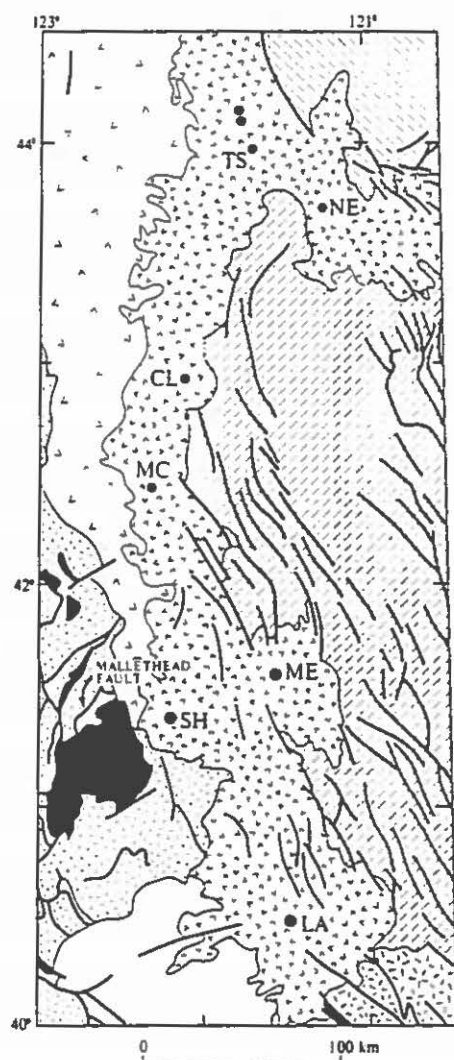


Figure 5. Upward-continued gravity data. A regional field, calculated by assuming isostatically compensated topography (Simpson and others, 1983), was subtracted from the Bouguer gravity compilation of Godson and Scheibe (1982), and residual anomalies were upward continued 10 km to conform with Figure 3. Contour interval = 2 mgal; hachures indicate direction of decreasing gravity. See Figure 1 for description of symbols.

the ultramafic sheet roughly coincident with the Mallethead thrust fault. This feature may manifest the suture proposed by Hamilton (1978) within the Trinity ophiolite complex.

The southeastern boundary of the Trinity anomaly is formed by a broad gradient and indicates that the Trinity ophiolite complex continues laterally at least 25 km beneath less magnetic Paleozoic rocks of the eastern Klamath



EXPLANATION

- Volcanic rocks of the High Cascades (Quaternary)
- Volcanic rocks of the western Cascades (Tertiary)
- Volcanic rocks of the Columbia Plateau (Tertiary)
- Volcanic rocks of the Great Basin (Tertiary)
- Crustal rocks of the Klamath Mountains (pre-Tertiary)
- Great Valley sequence (Tertiary, Cretaceous, and Jurassic)
- Granitic plutonic rocks of the Sierra Nevada batholith (Mesozoic)
- Ultramafic rocks (age uncertain)
- Fault trace

Figure 6. Geologic map of the southern Oregon and northern California Cascade Range (simplified from King and Beikman, 1974). Dashed lines indicate strike-slip fault zones discussed by Lawrence (1976). See Figure 1 for description of other symbols.

belt. Griscom (1973) suggested that the Trinity ophiolite complex may extend even farther southeast to approximately lat. $40^{\circ}20'N$ and long. $122^{\circ}00'W$ on the basis of a low-level aeromagnetic survey and on Bouguer gravity data.

Regional Minimum over Medicine Lake Volcano and Lassen Peak

The upward-continued magnetic data (Fig. 3) show that the Medicine Lake (ME) and Lassen Peak (LA) volcanoes produce minor positive anomalies within a widespread magnetic depression (Fig. 7, feature C). The depression is bounded on the west by the Trinity anomaly and along the north by an east-west magnetic ridge (Fig. 7, feature G discussed below). The depression is interrupted at the southwest by the hypothesized extension (Fig. 7, feature D) of the Trinity ophiolite complex (Griscom, 1973) and at the southeast by a positive anomaly (Fig. 7, feature E) located over a mapped sequence of Paleozoic metavolcanic rocks (Lydon and others, 1960) which possibly is underlain by an ultramafic body (A. Griscom, 1983, personal commun.).

An oval-shaped, positive anomaly (Fig. 7, feature F) occurs within the magnetic depression. We believe that this anomaly is caused by an isolated fragment of mafic or ultramafic rock buried at shallow depth below the younger rocks of the Cascade Range. The upward continued gravity data (Fig. 5) show a linear, positive anomaly trending $N70^{\circ}E$ which passes 20 km northwest of the center of this magnetic anomaly and may be related to the same buried feature. Chapman and Bishop (1968) and Griscom (1980) have proposed that near-surface basement rocks are the cause of the gravitational high. Moreover, near long. $121^{\circ}W$, the gravity anomaly coincides with a basement high inferred from seismic refraction data—a high that is composed of material with a seismic P-wave velocity similar to that of the Trinity ultramafic sheet to the west (Fuis and others, 1985).

Comparison of Figure 3 to Figure 4 clearly indicates that the magnetic depression is not caused by topography. The topographic model (Fig. 4) shows high-amplitude, positive anomalies over Mount Shasta, Medicine Lake, and Mount Lassen and a negative anomaly centered between these volcanoes, whereas the observed magnetic data (Fig. 3) show the opposite relationship. Huppunen and others (1982) applied a spectral-analysis technique to these data and showed an unusually shallow depth-extent of magnetic sources at four locations within the magnetic depression. Moreover, the upward-continued gravity data (Fig. 5) show two prom-

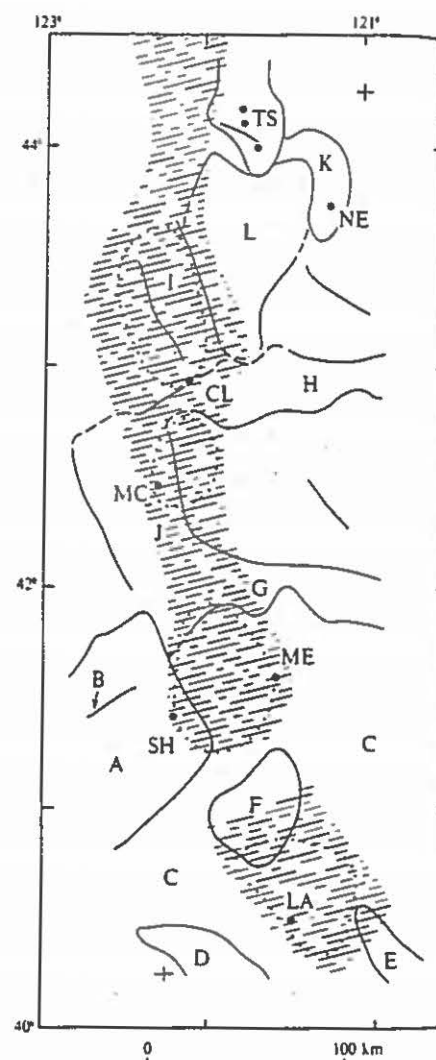


Figure 7. Map showing anomaly interpretations. Solid lines (dashed where uncertain) indicate approximate boundaries of magnetic and gravity sources interpreted from Figures 2, 3, and 4. Stippled pattern and dotted ovals indicate north-south graben and local subsidence structures, respectively, as interpreted from the gravity data of Figure 5. Double-letter symbols are described in Figure 1. Single-letter symbols are keyed to discussion in text.

inent lows northeast of Mount Shasta and of Lassen Peak. LaFehr (1965) showed that these anomalies are caused by near-surface sources perhaps partly by graben subsidence of volcanic material into higher density basement rock and partly by thermal expansion of intrusive rocks below Mount Shasta and Lassen Peak. We suggest that the entire magnetic depression represents an upwarp of the Curie-temperature isotherm.

East-West Magnetic Ridges

Two east-trending magnetic anomalies are present in the upward-continued magnetic data (Figs. 3 and 7) at latitudes $42^{\circ}00'N$ (Fig. 7, feature G) and $43^{\circ}00'N$ (Fig. 7, feature H). The topographic model (Fig. 4) demonstrates that they are not the consequence of topographic anomalies, nor are they related to exposed geologic features. These anomalies probably reflect either two narrow, east-west zones of volcanic rocks with higher concentrations of magnetite or two east-west structural features in the basement rocks below the Cascade volcanic rocks. They remain problematical because they are not parallel to the generally north-northeast- and northwest-trending structure of the Basin and Range province, which likely forms the basement of the Cascade Range in this area (Fig. 6), nor are they reflected in the upward-continued gravity data (Fig. 5).

Crater Lake (CL), the caldera remains of Mount Mazama, is located near the western end of the east-west anomaly at lat. $43^{\circ}00'N$ (Fig. 3). Using older data, Blank (1968) noted a pattern of northwest-trending magnetic anomalies in the vicinity of Crater Lake and suggested that they reflect deeply buried magnetic sources. Specifically, he identified a northwest-trending anomaly with a right-lateral offset at Crater Lake and ascribed the offset to a northeast-trending fault in the magnetic basement below Crater Lake. These short-wavelength magnetic features (discussed by Blank) are also present in our low-level compilation (Fig. 2) but do not remain when the data are upward-continued (Fig. 3), which argues against a deep-seated, regional source. The upward-continued data do show, however, that Crater Lake is situated at the intersection of the east-west anomaly at lat. $43^{\circ}00'N$ (Fig. 7, feature H) and a 60-km long, north-northeast-trending anomaly (Fig. 7, feature I). These anomalies may reflect major structural features related to the evolution of Crater Lake. A third linear anomaly (Fig. 7, feature J) in the vicinity of Crater Lake and coincident with Mount McLoughlin (MC) trends north-west and extends for nearly 100 km. It is approximately coincident with mapped massive basaltic andesite and andesite flows and breccias of the Western Cascades (Wells and Peck, 1961), but there is no particular reason to believe that these units are exceptionally magnetic. This linear anomaly also may reflect buried structures.

Anomalies over Three Sisters Volcanoes and Newberry Crater

The upward continued anomalies (Fig. 3) over the Three Sisters volcanoes (TS) and New-

berry Crater (NE) also appear with similar shapes in the topographic model (Fig. 4), which probably indicates that these regional anomalies are largely a consequence of the topographic relief of this part of the High Cascades. The upward continued data, however, include an arcuate positive anomaly (Fig. 7, feature K) not related to the topography which connects the Three Sisters and Newberry Crater anomalies. A similar connection appears in the upward-continued gravity data (Fig. 5). Couch and others (1982) postulated from more detailed gravity data that the Three Sisters and Newberry volcanoes are structurally connected at depth by fractures or lithologic discontinuities. Apparently, this structural connection is also represented in the magnetic data.

A pronounced negative magnetic anomaly occurs directly south of the Three Sisters volcanoes (Fig. 3; Fig. 7, feature L). It is caused partly by the topographic relief of the area (Fig. 4), but it is too widespread and too intense to be produced entirely by the topography. Connard and others (1983) concluded from low-pass filtered aeromagnetic data that this negative anomaly is caused by a basin structure several kilometres deep.

GRAVITY DEPRESSION

Thayer (1936) proposed that an eastward-facing, north-trending fault scarp, which he termed the "Cascade fault," forms the structural boundary between the Western and High Cascades in Oregon. Movement along the Cascade fault raised the older Western Cascades at least 600 m relative to the eastern block and was followed by initiation of High Cascade volcanism to the east which largely buried the surface expression of the fault. Allen (1965) proposed a second north-trending fault, down-dropped to the west, parallel to and ~30 km east of the Cascade fault. The resulting graben includes Mount Hood, Mount Jefferson, the Three Sisters, and Crater Lake. South of Crater Lake, the trend of the graben swings southeast to exclude Mount McLoughlin (Allen, 1965).

A structure of this size should be detectable by geophysical techniques. Couch and others (1981, 1982) examined residual gravity data from the Cascades. Finding a narrow, north-trending gravitational minimum that extends from the Columbia River to nearly the Oregon-California border, they proposed that this minimum delineates a major fracture or brecciated zone. The gravitational minimum is approximately coincident with the graben of Allen (1965), but it lies west of Mount Jefferson and the Three Sisters.

The upward-continued gravity data should

help to describe the regional characteristics of this major geologic feature and how it continues south of the Oregon-California border. Figure 5 shows that the major volcanoes of our study (Three Sisters volcanoes, Crater Lake caldera, Mount McLoughlin, Mount Shasta, and Medicine Lake volcano) are located along the edge of a long (370 km), north-trending, gravitational depression. The position of the gravitational depression in Oregon agrees with the location of the buried graben proposed by Allen (1965), except that the depression includes Mount McLoughlin. Lassen Peak is also located in a regional gravitational depression that is separated from the main depression by the east-trending high at about lat. $41^{\circ}10'N$, discussed above. All of these volcanoes are located at the edge of local gravity minima.

It might be argued that both the inferred graben and the local depressions are artifacts of the data reduction. Originally, topographic features were assumed to have a density of 2.67 g/cm^3 in order to calculate the gravity map of Figure 5, but because this density might possibly have been too high for typical Cascade volcanic rocks, we recomputed the upward-continued, isostatic residual map using densities of 2.43 and 2.28 g/cm^3 and, without exception, the gravity features described earlier were preserved. Consequently, the gravity minima are not a result of our selection of an improper density for the Cascade Range.

We propose that each of these minima reflects subsidence of major volumes of low-density volcanic material and that the volcanoes have formed along the related perimeter faults where magma can more easily progress to the surface. Except for Medicine Lake volcano, each of these volcanoes is near the southern end of their respective depressions. In at least two cases, the structural features causing the gravity depressions are also reflected in the magnetic data. A magnetic minimum (Fig. 3) exists between Mount Shasta and Medicine Lake volcano in approximately the same position as the gravity depression here, which suggests that the subsided, low-density volcanic material causing the gravity depression is also relatively nonmagnetic or else it is composed predominantly of reversely magnetized material. The opposite relationship seems to exist north of Crater Lake, where positive magnetic feature I (Figs. 3 and 7) corresponds with the gravity minimum extending north from Crater Lake caldera.

CONCLUSIONS

We had anticipated at the outset of this study to find certain consistencies in the regional characteristics of the major volcanoes of the southern

Cascade Range. Although some consistencies do exist, we are left with an obvious conclusion: all volcanoes are not alike. As expected, all of the volcanoes produce short-wavelength anomalies in the low-level aeromagnetic compilation (Fig. 2) related to their topographic edifices, but the regional magnetic anomalies that remain after upward continuation (Fig. 3) vary from volcano to volcano. The southern volcanoes (Mount Shasta, Medicine Lake, and Lassen Peak) are associated with a widespread regional magnetic depression, whereas the northern volcanoes (Crater Lake, Mount McLoughlin, Three Sisters, and Newberry Crater) are associated with smaller positive magnetic anomalies. The regional gravity characteristics of Newberry Crater are markedly different from those of the other volcanoes of the study area. For example, Newberry Crater is not associated with a gravity minimum; its evolution may have been influenced by its location to the east and to the outside of the graben structure which contains the other volcanoes.

Highly magnetic rocks and high topographic relief in volcanic terranes often hinder the application of aeromagnetic data to the solution of regional geologic and tectonic problems. However, the combined interpretation of aeromagnetic, gravity, and topographic information using the computational tools of upward continuation and forward modeling has proven useful toward this goal in the southern Cascade Range.

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REFERENCES CITED

- Allen, J. E., 1965, The Cascade Range volcano-tectonic depression of Oregon: Lunar Geological Field Conference, Bend, Oregon, Transactions, p. 21-23.
- Blakely, R. J., and Christiansen, R. L., 1978, The magnetization of Mount Shasta and implications for virtual geomagnetic poles determined from seamounts: *Journal of Geophysical Research*, v. 83, p. 5971-5978.
- Blakely, R. J., and Grauch, V. J. S., 1983, Magnetic models of crystalline terranes: Accounting for the effect of topography: *Geophysics*, v. 48, p. 1551-1557.
- Blank, H. R., 1968, Aeromagnetic and gravity surveys of the Crater Lake region, Oregon, in Dole, H. M., ed., *Andean Conference, Guidebook: Oregon Department of Geology and Mineral Industries Bulletin 63*, p. 42-52.
- Chapman, R. H., and Bishop, C. C., 1968, Bouguer gravity map of California. Alturas sheet: California Division of Mines and Geology, 3 p., scale 1:250,000.
- Coleman, R. G., Helper, M. D., and Donato, M. M., 1983, Geologic map of the Condrey Mountain roadless area, Siskiyou County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1540A, scale 1:50,000.
- Connard, G. G., 1979, Analysis of aeromagnetic measurements from the central Oregon Cascades (M.S. thesis): Corvallis, Oregon, Oregon State University, 101 p.
- Connard, G. G., Couch, R., and Gemperle, M., 1983, Analysis of aeromagnetic measurements from the Cascade Range in central Oregon: *Geophysics*, v. 48, p. 376-390.
- Couch, R. W., Gemperle, Michael, Connard, Gerald, and Pitts, G. S., 1981, Structural and thermal implications of gravity and aeromagnetic measurements made in the Cascade volcanic arc (abs.): *Society of Exploration Geophysicists Annual International Meeting*, Los Angeles, California, p. 14.
- Couch, R. W., Pitts, G. S., Gemperle, Michael, Brame, D. E., and Veen, C. A., 1982, Gravity anomalies in the Cascade Range in Oregon: Structural and thermal implications: Oregon Department of Geology and Mineral Industries Open-File Report 0-82-9, 66 p.
- Flanagan, Guy, and Williams, D. L., 1982, A magnetic investigation of Mount Hood, Oregon: *Journal of Geophysical Research*, v. 87, p. 2804-2814.
- Fu, G. S., Zucca, J. J., Mooney, W. D., and Miller, B., 1985, A geologic interpretation of seismic refraction results in northeastern California: *Geological Society of America Bulletin*, v. 96 (in press).
- Godson, R. H., and Scheibe, D. M., 1982, Description of magnetic tape containing continuous U.S. gravity data in a gridded format: U.S. Department of Commerce, National Technical Information Service publication PB82-254798.
- Griscom, Andrew, 1973, Bouguer gravity map of California, Redding sheet: California Division of Mines and Geology, 13 p., scale 1:250,000.
- , 1977, Aeromagnetic and gravity interpretation of the Trinity ophiolite complex, northern California: *Geological Society of America Abstracts with Programs*, v. 9, no. 4, p. 426-427.
- , 1980, Klamath Mountains province, in Oliver, H. W., ed., *Interpretation of the gravity map of California and its continental margin*: California Division of Mines and Geology Bulletin 205, p. 34-36.
- Hamilton, Warren, 1978, Mesozoic tectonics of the western United States, in Howell, D. G., and McDougall, K. A., eds., *Mesozoic paleogeography of the western United States*: Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 33-70.
- Huopinen, J. L., Couch, R. W., Connard, G. G., and Gemperle, Michael, 1982, Geothermal and structural implications of magnetic anomalies observed over north-central California (abs.): *EOS (American Geophysical Union Transactions)*, v. 63, p. 1091.
- Irwin, W. P., 1966, Geology of the Klamath Mountains province, in Bailey, E. H., ed., *Geology of northern California*: California Division of Mines and Geology Bulletin 190, p. 19-38.
- , 1977, Review of Paleozoic rocks of the Klamath Mountains, in Bailey, J. H., Stevens, C. H., and Fritsche, A. E., eds., *Paleozoic paleogeography of the western United States*: Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 441-454.
- , 1981, Tectonic accretion of the Klamath Mountains, in Ernst, W. G., ed., *The geotectonic development of California*: Eaglewood Cliffs, New Jersey, Prentice-Hall, p. 29-49.
- Jachens, R. C., and Elder, W. P., 1983, Aeromagnetic map and interpretation of geophysical data from the Condrey Mountain roadless area, Siskiyou County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1540B, scale 1:50,000.
- King, P. B., 1969, Tectonic map of North America: U.S. Geological Survey, scale 1:5,000,000.
- King, P. B., and Beikman, H. M., 1974, Geologic map of the United States: U.S. Geological Survey, scale 1:2,500,000.
- LaFehr, T. R., 1965, Gravity, isostasy, and crustal structure in the southern Cascade Range: *Journal of Geophysical Research*, v. 70, p. 5177-5190.
- , 1966, Gravity in the Klamath Mountains, California: *Geological Society of America Bulletin*, v. 77, no. 11, p. 1177-1190.
- Lawrence, R. D., 1976, Strike-slip faulting terminates the Basin and Range province in Oregon: *Geological Society of America Bulletin*, v. 87, p. 846-850.
- Lydon, P. A., Gay, T. E., and Jennings, C. W., 1960, Geologic map of California, Westwood sheet: California Division of Mines and Geology, scale 1:250,000.
- McLain, W. H., 1981, Geothermal and structural implications of magnetic anomalies observed over the southern Oregon Cascade Mountains and adjoining Basin and Range province (M.S. thesis): Corvallis, Oregon, Oregon State University, 151 p.
- Simpson, R. W., Jachens, R. C., and Blakely, R. J., 1983, AIRYROOT: A FORTRAN program for calculating the gravitational attraction of a Airy isostatic root out to 166.7 km: U.S. Geological Survey Open-File Report 83-883, 66 p.
- Thayer, T. P., 1936, Structure of the north Santiam River section of the Cascade Mountains in Oregon: *Journal of Geology*, v. 44, p. 70.
- Wehring, Michael, 1981, MINC: A gridding program based on minimum curvature: U.S. Geological Survey Open-File Report 81-1224, 41 p.
- Wells, F. G., and Peck, D. L., 1961, Geologic map of Oregon west of the 121st meridian: U.S. Geological Survey Miscellaneous Geologic Investigations Map 1-325, scale 1:500,000.

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