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GRAVITY ANOMALIES IN THE CASCADE RANGE IN OREGON: STRUCTURAL AND THERMAL IMPLICATIONS

by

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Introduction

The High Cascade Mountains, a consequence of the subduction of the Juan de Fuca Plate beneath the continental margins of northern California, Oregon, Washington, and British Columbia, extend, as a volcanic arc, from northern California to British Columbia. Lavas and pyroclastics of Miocene through Recent age, variable in both time and space, have intruded into, passed through, and covered older rocks of unknown age, structure, and composition; consequently the evolution and constitution of the Cascade Range is very complex.

Because of marked differences in the densities and depths of the different geologic units that form the Cascade Range, measurements of the earth's gravity field can outline many of the structural units and provide limits on estimations of the densities, depths and petrology of the subsurface units particularly when used in conjuction with other geophysical, geological, and geochemical data. This report summarizes gravimetric measurements made by many investigators in the Cascades and surrounding regions since approximately 1965; provides free-air, Bouguer, regional, and residual gravity maps of the Cascade Range in Oregon between 121° W. lon. and 122°30' W. lon.; and discusses some of the structural and geothermal implications of the observed anomalies.

Gravity Measurements

Measurements of the earth's gravitational acceleration, reported by Blank (1965), Blank (1968), Leutsher (1968), Thiruvathukal (1968), Griscom (1974), Griscom (1975), Hassemer and Peterson (1977), Van Deusen (1978), Blakely (1979), Couch and Gemperle (1979), Pitts (1979), Finn (1980), Braman (1981), and Veen (1981), provide the principal facts for approximately 5210 gravity stations located (Figure 1) in the Cascade Range.

All of the gravity stations are referenced to the International Gravity Base Station located at the Carnegie Institute, Washington, D.C., through a series of primary and secondary base stations established in Washington, Oregon, and California (e.g. Woollard and Rose, 1963; Berg and Thiruvathukal, 1965; Blank, 1968; Barnes, 1968; Pitts, 1979; Braman, 1981; and Veen, 1981).

The circles in Couch and others (1982)* show the location of the gravity stations in the Cascade Mountains region. The average station density for the approximately 46,000 km^2 area is one station per 9 square kilometers; however, station densities within large sectors of the survey area vary significantly. Closely spaced stations occur near Timberline Lodge on Mount Hood, along the Bonneville Power Administration transmission line between Mount Hood and Mount Jefferson, across Green Ridge east of Mount Jefferson, around Paulina and East Lakes in Newberry Caldera and along many of the roads and highways in the region. Sparsely surveyed areas include the area between Mount Hood and the Columbia River, the Western Cascades west and southwest of Mount Hood,

*Residual gravity anomaly maps from this study have been released by the Oregon Department of Geology and Mineral Industries as Geologic Map Series GMS-26 (printed on topographic base, scale 1:250,000).

the Mount Jefferson Wilderness area, the Three Sisters Wilderness area and the Klamath Graben north of Klamath Lake. The station density is more than sufficient to outline most of the major structures of the Cascade Range; however, the observed anomalies undoubtedly do not reflect many of the smaller faults, cones, hypabyssal intrusions, and other geological structures present in the region.

The high-relief of the terrain in the Cascade Range makes good position control both difficult and imperative for successful gravity measurements. U.S. Geological Survey, U.S. Coast and Geodetic Survey, Oregon State Highway, U.S. Forest Service, and Bonneville Power Administration benchmarks, spot elevations shown on U.S. Geological Survey 7.5- and 15-minute topographic maps, and measurements with aneroid altimeters provided station elevations. Geodetic leveling on Mt. Hood and stero aerophotos of Crater Lake provided the elevations of a few selected stations. Benchmark locations and U.S. Geological Survey 7.5- and 15-minute maps provided horizontal position information.

Descriptions of the position and base station control, drift and tide corrections, meter and reduction parameters and field procedures used by the investigators are contained in their respective reports. The principal facts of the measurements compiled for and described in this report are currently archived in the Geophysics Group, Oregon State University, the Defense Mapping Agency, St. Louis, Missouri, and in the National Geophysical Solar-Terrestial Data Center, Boulder, Colorado.

Calculation of the Free-air and Bouguer Gravity Anomalies

The principal facts of the gravity measurements described above were reduced to free-air anomalies using the formula:

$$\underline{FAA} = \underline{OG} + \underline{FAC} - \underline{THG}$$

where OG is the observed gravitational attraction at the station, FAC is the free-air correction for the elevation of the station with respect to sea level, and THG is the theoretical gravitational attraction on the earth spheroid as given by the 1930 International Gravity Formula. The free-air correction, as formulated by Scheibe and Howard (1964), is

$$\underline{FAC} = (.09411549 - 0.000137789 \sin^2\underline{\phi})\underline{h} - 0.067 * 10^{-8}\underline{h}^2$$

where $\underline{h}$ = elevation of the station in feet and $\underline{\phi}$ is the latitude of the station. The 1930 International Gravity formula (Swick, 1942; Heiskanen and Vening Meinesz, 1958) is

$$\underline{THG} = 978049.0(1 + 0.0052884 \sin^2\underline{\phi} - 0.0000059 \sin^2 2\underline{\phi})$$

The complete Bouguer anomaly (CBA) which takes into account the elevation of the station (FAC) and the effects of the mass of the earth between the station and the spheroid is given by the relation:

$$\underline{CBA} = \underline{FAA} - \underline{SBC} - \underline{CC} - \underline{TC}$$

where SBC is the simple Bouguer correction, CC is the curvature correction, and TC is the terrain correction.

The simple Bouguer correction (Bullard, 1936) is the attraction of an infinite slab of thickness $\underline{h}$ and density $\underline{\rho}$ given by the relation

$$\underline{SBC} = 2 \underline{G} \underline{h} = 0.012774 \underline{h}$$

where $\underline{G}$ is the universal gravitational constant and $\underline{h}$ is in feet. A standard reduction density of 2.67 gm/cm^3 was used in the computation of the simple Bouguer correction and the complete Bouguer anomalies.

The curvature correction reduces the effect of the infinite slab to that of a spherical cap of radius 166.7 km and thickness $\underline{h}$ (Swick, 1942). The correction is:

$$\underline{CC} = \underline{h} * (1.671 * 10^{-4} + \underline{h} * (-1.229 * 10^{-8} + \underline{h} * (4.67 * 10^{-16}))).$$

The terrain correction ($\underline{TC}$), which compensates for the effects of local topography on gravity measurements was made by hand from field notes on the topography out to a radial distance of 68 m (Hayford and Bowie, 1912; zones A and B) from the station using the methods of Robbins and Oliver (1970). Terrain corrections for radial distances of 68 m to 166.7 km from the station (Hayford and Bowie, 1912; zones C through O) were made by computer with a program developed by Plouff (1977). Digital topographic information, obtained from the National Cartographic Information Center (NCIC) and reduced to areal blocks of one-half minute, one minute, and three minutes, provided the data base to compute the terrain correction for each station. Digital topography was not available for all zones around several stations. Terrain corrections for those zones were calculated by hand using techniques described by Oliver and others (1969). Terrain corrections for stations from Blank (1965) and Thiruvathukal (1968) were recomputed for zones C through O (Hayford and Bowie, 1912).

Pitts (1979), Braman (1981), and Veen (1981) estimated root-mean-square uncertainties of less than 1 mgal for free-air anomalies and less than 1.5 mgal for complete Bouguer anomalies in the Cascade Mountains region. Thiruvathukal (1968) estimated uncertainties of 1 to 2 mgal for the Bouguer anomalies included in his compilation of data for the gravity map of Oregon.

Free-Air Gravity Anomalies

Pitts and Couch (1978) and Pitts (1979) prepared a free-air gravity anomaly map of the central Cascade Mountains at a scale of 1:125,000, and Couch and others (1981a) and Couch and others (1981b) have prepared free-air gravity anomaly maps of the northern and southern Cascade Mountains at a scale of 1:250,000. Figures 3, 4, and 9 show their free-air gravity anomaly maps of the north, central, and south sectors, respectively, reduced to a scale of approximately 1:1,000,000. Anomaly contours occur at 10-mgal intervals, and heavy contours occur at 50-mgal intervals. The free-air gravity anomalies range from less than -90 mgal along the Columbia River gorge to over +150 mgal on Mount Hood and the Three Sisters.

The free-air gravity anomaly reflects the total gravitational acceleration at a point and includes the total mass of the earth in the measurement. Hence the free-air gravity anomalies depend in part on station elevation and yield a free-air anomaly map which resembles the topography, especially at short wavelengths. Figures 3 and 6, however, show that the average free-air anomaly in the Willamette Valley is approximately the same as in the Deschutes Valley, although the valley east of the Cascade Mountains is more than 3,000 feet higher in elevation than the valley west of the Cascade Mountains. The free-air anomalies indicate that the extra mass of the plateau east of the mountains is compensated either by less dense crustal materials or a thicker crust east of the mountains. Calculations reported by Dehlinger and others (1968), Thiruvathukal and others (1970), and Dehlinger and others (1970) based on gravity measurements indicate the crust is 20 to 25 km thick west of the Cascade Mountains and 35 to 45 km thick east of the mountains.

Recent seismic refraction measurements in the Cascade Mountains reported by Wegener and others (1980) and Hill and others (1981) indicate the crust is 40 to 45 km thick along the axis of the Cascade Mountains in northern Oregon.

Bouguer Gravity Anomalies

Figures 4, 7, and 10 show the Bouguer gravity anomalies of the Cascade Range in northern, central, and southern Oregon respectively. The anomalies range from greater than -50 mgal near the Columbia River in the northwestern portion of the Cascade Range to less than -170 mgal in the Basin and Range Province of southeastern Oregon. The mapped Bouguer gravity anomalies exhibit a marked gravity gradient with values decreasing irregularly from northwest to southeast. The constancy of the free-air anomalies and the change in Bouguer anomalies is interpreted as compensation of the elevated terrain in eastern Oregon by an increase in the thickness of the crust. Along the western portions of the mapped anomalies in Figures 4, 7, and 10, the high gravity gradient suggests not only a relatively rapid change in crustal thickness in a short distance in the vicinity of the Western Cascades but also a change in the near-surface structures from west to east.

The Bouguer anomalies about the Three Sisters and Newberry Crater areas are less pronounced than on the free-air gravity anomaly map, whereas the anomalies about Powell Butte are very prominent. This indicates that Bouguer correction and hence the reduction density of 2.67 gm/cm^3 is nearly correct for Newberry Crater and for portions of the Sisters volcanic complex. The Three Sisters, which have only a limited number of measurements about them, appear to be overcorrected in Figure 7; hence, their average density is less than the reduction density of 2.67 gm/cm^3. The large anomaly in the vicinity of Powell Butte is due to a large subsurface body whose density is greater than the surrounding country rock.

Large mass deficiencies are indicated in the area south of the Three Sisters and west of Newberry Crater and in the area northwest of Klamath Lake. These closed negative anomalies indicate large filled or partially filled sedimentary basins.

The observed anomalies are discussed further below after discussion of spectral separation of the anomalies into their regional and residual components.

The Separation of Regional and Residual Gravity Anomalies

Bouguer gravity anomalies arise from differences in densities between the topographic features of interest and the reduction density used to compute their anomalies and to density inhomogeneities at depth. Because the observed gravitational attraction is proportional to the inverse of the distance to the source body squared, structures at greater depth produce gravity anomalies of lower amplitude and longer wavelength than similar sources at shallower depths. Hence the separation of the longer wavelength anomalies or residual anomalies assists in the interpretation of the gravity measurements with respect to the shallower structures.

Spectral separation techniques applied to the complete Bouguer gravity anomalies described above yielded the regional gravity anomalies in Figure 11 and the residual gravity anomalies in Figures 14, 15 and 16. To achieve anomaly separation, initially the data, separated into three regions as originally mapped (Figures 4, 7 and 10), were prefiltered to detrend the data (Rayner, 1971). The detrended data were then gridded using the minimum curvature technique of Briggs (1974) as described by Boler (1979) and Boler and others (1978). A grid spacing of 6 km was used to create a data matrix that included regional data outside the survey area. Periodicity of the data, necessary for the application of the fast Fourier transformation, was forced by repeating the data matrix. The gridded, periodic data were transformed using a routine of Brenner (1968) after Cooley and Tukey (1965).

Application of a "boxcar" filter described by Rayner (1971) and

Nettleton (1976) with a cosine squared taper to the transformed data yielded spectral separation. Subsequently the inverse transformation and retrending resulted in a regional gravity map for the complete matrix. These techniques were described in detail by Boler and others (1978), Pitts (1979), Braman (1981) and Veen (1981).

The residual anomaly value at each station was calculated with the relation

$$\underline{RA}(\underline{\rho}) = \underline{CBA}(\underline{\rho}) - \underline{REG}(\underline{\rho})$$

where $\underline{RA}(\underline{\rho})$ is the residual anomaly at a reduction density of $(\underline{\rho})$, $\underline{CBA}(\underline{\rho})$ is the complete Bouguer anomaly at a reduction density of $(\underline{\rho})$ and $\underline{REG}(\underline{\rho})$ is the regional anomaly at a reduction density of $(\underline{\rho})$.

A reduction density of 2.43 gm/cm^3 was selected to minimize the effects of terrain in the area of the Cascade Range outlined in Figure 1. This density is a reasonable average for the area; however, a comparison of the free-air, Bouguer and residual gravity anomalies suggests a density of 2.6 to 2.7 gm/cm^3 would yield better results for Newberry Caldera and the Yamsay Mountains, whereas a density of 2.3 gm/cm^3 would yield better results for Mt. Hood and the Three Sisters. Indeed, Couch and Gemperle (1979) show a best reduction density for Mt. Hood of 2.27 gm/cm^3. As a consequence of the large variation in actual densities of the structures of the region, care is advised in interpreting singular anomalies.

The spectral separation of the anomalies occurred at a wavelength of approximately 90 km. This wavelength of separation yields residual anomalies with wavelengths shorter than 90 km that are due to sources at depths of less than approximately 20 km. A depth of 20 km is approximately one half the thickness of the earth's crust beneath and east of the Cascade Range. Figures 14, 15 and 16 show the residual gravity anomalies of the Cascade Range in Oregon calculated as outlined above.

Figure 11 shows a map of the regional gravity anomalies with wavelengths longer than 90 km. However, conversely, the source depths of the regional anomalies, although primarily due to deeper sources, are not limited to sources below a depth of 20 km. Near-surface geologic units of large areal extent also can produce long-wavelength anomalies that may be included in the regional gravity map.

Regional Gravity Anomalies

Figure 11 shows a map of gravity anomalies in the Cascade Range in Oregon with wavelengths longer than 90 km. The regional gravity anomalies decrease in general from the Coast Range to eastern Oregon and from the Columbia River to the Basin and Range Province of southeastern Oregon. Changes in the long wavelength components of the gravity field reflect changes in the thickness of the crust. Computations by Thiruvathukal and others (1970) and Dehlinger and others (1970) based on gravity measurements indicate that the earth's crust in the vicinity of the Coast Range and Willamette Valley is approximately 20 to 25 km thick and east of the Cascades it is 35 to 45 km thick. Hill and others (1981) interpret reflected seismic waves observed along a refraction profile in the north-central Cascade Range to indicate a crustal thickness of approximately 40 km. Their results are in good agreement with those based on gravity measurements. The crustal cross section in Figure 20 illustrates the change in crustal thickness from west to east across the Cascade Range and shows that the change in thickness occurs most rapidly beneath the Western Cascades.

The regional gravity anomalies also suggest that the earth's crust is about 30 km thick near the Columbia River north of Mt. Hood and as much as 45 km thick between the Three Sisters and Crater Lake. Southeast of Crater Lake the gravity data suggest the crust may be more than 45 km thick; however, an intermediate or transition layer may be present between the lower crust and upper mantle in the Basin and Range Province (e.g. see Cook, 1962; Pakiser, 1963). We postulate that the lower crust and upper mantle in southeastern Oregon includes the northward extension of the intermediate layer observed by Pakiser and Hill (1963) and Eaton (1963) in the Basin and Range Province in Nevada. The crustal cross section in Figure 21 shows the intermediate layer and suggests the crust above the intermediate layer may be less than 30 km thick in southeastern Oregon.

The northward excursion of the -80-mgal regional contour about Mt. Hood and the northward excursion of the -40-mgal contour about the Three Sisters may indicate changes in the crustal thickness or structure of the lower crust beneath the volcanic centers, or alternatively the anomalies may reflect compensating masses in the upper crust complimentary to the masses that cause the positive anomalies observed about the volcanic centers mapped in Figures 3, 6, 14, and 15.

Figure 12 shows topographic and gravimetric profiles along the axis of the High Cascades between the Columbia River and the California border. The elevations along the profile increase from just above sea level at the Columbia River to almost 6000 feet between Mt. Washington and Mt. Mcloughlin except for the LaPine valley and the area about Wickiup Reservoir. The short-wavelength positive free-air gravity anomalies reflect both the topography and many local mass concentrations in the upper crust, particularly beneath the stratovolcanoes. The average free-air anomaly is positive due both to uncompensated near-surface flows and intrusions and to an "edge effect" caused by the change in crustal thickness beneath the Western Cascades. The complete Bouguer gravity anomaly decreases as the topographic elevation increases, thereby indicating the higher elevations of the Cascade Range are compensated at depth.

Figure 13 shows topographic and gravity profiles, oriented west-to-east, across six of the High Cascades volcanoes. Mt. Hood, Mt. Jefferson, South Sister, and Mt. McLoughlin exhibit similar topographic and free-air gravity anomalies. The free-air anomalies start near zero and increase in amplitude to a value approximately proportional to the volume of the respective mountain. If the central peak anomaly of South Sister is omitted, the free-air anomaly signature of South Sister, Newberry Crater, and Crater Lake are similar. The anomalies suggest a mass concentration at shallow depths beneath the summits. The Bouguer gravity anomalies show a general decrease in amplitude from north to south as in Figure 12. This long-wavelength change in the Bouguer anomaly is due to the change in crustal thickness along the axis of the Cascades. A comparison of the free-air Bouguer and residual gravity anomalies suggests that the average reduction density of 2.43 gm/cm^3 is approximately correct for Crater Lake (or Mt. Mazama), slightly too light for Mt. McLoughlin and Newberry Caldera, and too dense for Mt. Hood, South Sister, and probably Mt. Jefferson. The average density of Mt. McLoughlin is probably between 2.43 and 2.50 gm/cm^3, whereas that of Mt. Hood, South Sister, and probably Mt. Jefferson is near 2.3 gm/cm^3. The shape of the Bouguer and the residual gravity anomaly profiles suggests that each of the volcanoes has a high density core or more dense mass beneath the summit. This may take the form of a dense central conduit in Mt. Hood (Couch and Gemperle, 1979), Mt. Jefferson, South Sister, and Mt. McLoughlin; a large intrusive within the volcano or near the base of the volcano (Williams and Finn, 1981); or a series of relatively dense flows that form the base of the volcano in Newberry Caldera, Crater Lake, and South Sister.

Residual Gravity Anomalies of the Cascade Range in Oregon

The maps in GMS-26 (Couch and others, 1982) show the residual gravity anomalies of the northern, central, and southern sectors respectively of the Cascade Range in Oregon at a scale of 1:250,000, and Figures 14, 15 and 16 show the residual gravity anomalies at a scale of approximately 1:1,000,000. The gravity anomalies, whose sources are located in the upper 20 km of the earth's crust, range from less than -26 mgal north of Klamath Lake to more than 30 mgal near Terrebonne north of Redmond.

The High Cascades exhibit positive residual gravity anomalies along the volcanic arc that are more extensive than the prominent peaks. In the vicinity of Mt. Hood the anomalies are small, and although no single outstanding anomaly is coincident with the topographic peak, the region about the peak is in general a residual gravity high. This suggests that though the density of the surface features is low, more dense rock occurs at a shallow depth beneath the surficial features. The positive anonalies are in part associated with the Columbia River basalts and may outline the extent of the basalts beneath the post-Miocene rocks about and northeast of Mt. Hood. The anomalies also may indicate more dense basement rocks beneath the basalts in the vicinity of Mt. Hood. Similarly, Hill and others (1981) interpreted their seismic measurements to indicate a regional thinning of the low-velocity near-surface rocks or a doming of the "basement" within 10 km of Mt. Hood.

A prominent positive anomaly encircles and connects Newberry Caldera and the Three Sisters. The anomaly also extends northeastward from the north flank of Newberry to the area about Powell Butte, north-northwestward from the north flank of Newberry to the area about the Three Sisters, and then north-northwestward from the Three Sisters toward Three Fingered Jack. The residual gravity anomaly pattern suggests that the Three Sisters, Newberry Caldera, and Powell Butte volcanic centers are connected at depth and further that their placement is structurally controlled by fractures or lithologic discontinuities oriented northwest-southeast and northeast-southwest.

A narrow band of contiguous gravity lows extends from southwest of Mt. Hood near 45°10' N. lat., 121°50' W. lon. to the area south of Oakridge near 43°15' N. lat., 122°20' W. lon., then southeastward through Klamath Lake to Klamath Falls, and then southward into northern California. This band of gravity lows varies in width from less than 10 km south of Oakridge and west of Mt. Jefferson to more than 20 km southwest of the Three Sisters and is interrupted only by the Mt. Hood and Mt. Mazama volcanic complexes. North of Crater Lake the lows are located along and extend across the zone of contact between the Western Cascades and the High Cascades. They cross the axis of the High Cascades at Crater Lake and extend into the Basin and Range Province of southern Oregon and into the Modoc Plateau of northern California. We interpret these gravity anomalies to indicate a large fracture system and an associated broad breccia zone that extends along the Cascade Range from the Columbia River to northern California. The gravity anomaly minima suggest that vertical displacements of 2 to 3 km occur along the west side of the fracture zone. This zone has been covered, in part, by younger volcanic deposits and lava flows of High Cascade origin and obscured by contemporary intrusions. For example, gravity anomaly highs southeast of Oakridge, west of the Three Sisters, west of Mt. Washington and west of Mt. Jefferson outline flows or intrusions that cover or extend into the eastern side of the brecciated zone.

Steep gravity gradients east of Mt. McLoughlin outline a fault-bounded graben that extends from the southeastern flank of Mt. Mazama to the south end of Klamath Lake. Computations based on the gravity minimum of -26 mgal and a density contrast between sediments in the graben and basement rock of 0.5 gm/cm^3 suggest the sediment thickness in the graben is 1 to 1.3 km in the vicinity of Fort Klamath.

The gravity low south of the Three Sisters outlines a sediment-filled basin, herein termed the Shukash Basin, in the vicinity of Wickiup Reservoir and Lookout Mountain. An arm of the basin, herein termed the Paulina Basin, extends southeastward along the base of the western flank of Paulina Shield. Computations based on gravity data suggest that the sediment thickness is about 1 km in the basin and about 0.5 km along the southwest base of Paulina Shield. Neither of these basins is apparent on geologic maps of the area (e.g. see Peterson and others (1976) and Walker (1977). The surface geology in the area includes Holocene cinder cones and glacial debris. The circularity of the anomaly and the presence of young cinder cones in and particularly along the northern rim of the Shukash Basin suggest subsidence of an older volcanic center. The postulated sediments of the Paulina Basin may lie beneath the younger flows and tuffs of the Paulina shield.

A broad gravity low outlines the Deschutes Basin east of Three Fingered Jack and Mt. Jefferson and west of the Deschutes River. Computations based on the gravity data suggest that more than 0.5 km of sediments fill the eastern part of the basin. A relative gravity high between the two lows in the central part of the basin coincides with

Green Ridge, a tilted fault block that extends across the basin from north to south. The Deschutes Basin gravity low also extends into the area between and west and south of Redmond and Bend.

A gravity low, elongated in the east-west direction, extends eastward from the southeast flank of Mt. Hood to the White River - Tygh Valley area. The negative gravity anomaly, where it is widest, coincides generally with the Tygh Valley Formation in the Tygh Basin described by Farooqui and others (1981). The gravity data suggest the sediment thickness south of Tygh Ridge is more than 0.5 km and that the basin shoals toward the south.

Prominent positive residual gravity anomalies include the Yamsay Mt. and Newberry Mt. complexes, a marked northeast-trending high between Redmond and Madras and an easterly trending high north of Warm Springs. The configuration and areal extent of the Yamsay Mt. and Newberry Mt. anomalies suggest the structure of the complexes consists of uncompensated high-density flows that increase in number and/or thickness toward the center of the complexes. In addition or alternatively, as Williams and Finn (1981) have suggested, the mountains may include large intrusive bodies at shallow depths beneath their summits. Walker Rim, prominent on topographic and geologic maps, does not exhibit a marked residual gravity anomaly; consequently it is believed to be only a surface or near-surface structure.

The positive gravity anomaly between Redmond and Madras is on trend with the Blue Mountain anticline and is probably related to shoaling of the pre-Tertiary basement along the anticline. If this is correct, the basement uplift along the anticline ends abruptly and in effect forms the eastern edge of the Deschutes Basin. Similarly the gravity high north of Warm Springs outlines the easterly trending anticlinal uplift associated with the outcrops of the pre-Tertiary rocks of the Mutton Mountains.

Gravity Anomaly Lineations in the Cascade Range in Oregon

Density discontinuities that occur along lithologic boundaries, such as intrusions, flow fronts, and erosional or fault contacts, often are marked by steep gravity gradients. Linear anomaly contours in steep gravity gradient areas, particularly when they extend for large distances or are co-linear with other anomaly patterns, form gravity anomaly "lineations". Although the lineations, so indicated, may mark various kinds of lithologic changes, more generally they indicate vertical displacement of geological units across normal or high-angle reverse faults. However, because of the complexity and the heterogeneity of the geology in the Cascade Range, the sparsity of field data, and the fact that many of the contacts may be covered by younger strata, we retain the term "lineation" initially to describe some of the patterns of the residual gravity anomalies.

Figures 17, 18 and 19 show the residual gravity anomalies in the Cascade Range of northern, central and southern Oregon respectively. Superimposed on the maps are lineations suggested by the anomalies. Heavy lines demark prominent lineations, and narrow lines show less prominent lineations. Prominent lineations occur along steep gravity gradients where anomaly amplitudes are large and anomaly contours are straight or where a series of high gradients of several anomalies are aligned. Less prominent lineations occur where anomalies are lower in amplitude and in gradient and where contours are more sinuous or outline structures other than those which the lineation suggests. Many other lineations are visible on the residual gravity anomaly maps, particularly those which parallel the marked lineations, but are omitted to prevent obscuring the lineations shown.

The most prominent and striking of the lineation patterns is the system of subparallel lineations that strikes about N 10° E from approximately 43°40° N. lat., southeast of Oakridge to approximately 45°30' N. lat. near Mt. Hood. This system is about 210 km (130 mi) long and about 60 km (40 mi) wide. The western boundary, although exhibiting short wavelength serations, is surprisingly straight and is located along the west side of a prominent series of contiguous gravity anomaly minima. Contrastingly, the eastern boundary is not well defined. The anomalies which suggest the location of the eastern boundary include an offset in the Mutton Mts. anomaly, the zone of contact between the Deschutes Basin and the western end of the Blue Mt. uplift, and the saddle between the gravity minima of the Shukash Basin, south of the Three Sisters, and the Paulina Basin, west of the Paulina Shield.

The N 10° E pattern of lineations in this zone is interrupted northwest of Mt. Jefferson by lineations that are oriented approximately N 15° W and that extend from near the Columbia River east of Gresham to the headwaters of the Clackamas River between Mt. Hood and Mt. Jefferson.

South of Oakridge near 43°15' N. lat. the lineations change strike to about N 20° W and extend south-southeastward apparently through the Crater Lake area to Klamath Lake. At and south of Klamath Lake some of the lineations strike about N 37° W, but many other orientations are observable also. Along the gravity minima that extend from Crater Lake to Mt. Hood, lineations that bound the gravity lows strike approximately N 40° E to N 60° E and approximately N 40° W to N 50° W. Lineations with these orientations are more numerous west of the High Cascades than are indicated on the figures. However east of the Cascades these orientations are only suggested in the Deschutes Basin and maybe in the Shukash Basin and Mutton Mts. areas.

In the Mt. Hood area lineations are observed that are oriented approximately N 30° W, N 15° W, N 7° E and N 82° E. The Mt. Mazama area shows a similar complex lineation pattern that includes orientations of about N 80° W, N 60° W, N 0° E, N 10° E, and N 70° E.

East of the Cascade Mountains easterly lineations include the anomaly gradient east of Mt. Hood that strikes about N 82° E and includes Tygh Ridge south of The Dalles, the flanks of the Blue Mountains uplift north of Redmond, the Powell Butte anomaly, the northeast flank of Yamsay Mt., along the northeast flanks of the Newberry and the Three Sisters volcanic complexes, and a lineation that extends along the southern boundary of the Paulina Basin and the Fort Rock Basin and transects the Shukash Basin. The latter lineation is the only one that may extend west of the High Cascades.

The Northern Oregon Crustal Cross Section

Line A-A' in Figure 2 maps the location of the geophysical crustal cross section of northern Oregon. The Northern Oregon Section, Figure 20, oriented approximately normal to the Cascade Range, extends from a point in Cascadia Abyssal Plain west of Oregon to a point in central Idaho. The section intersects the Humble Wicks No. 1 well on the east side of the Willamette Valley, crosses the Cascade Range near the divide between the Clackamas and Warm Springs Rivers, crosses the Deschutes River south of Maupin, and intersects the Standard Kirkpatrick No. 1 well near Condon. Logs of the two deep wells and topographic, geologic, gravimetric, and seismic refraction observations constrain the geophysical model cross section.

Shor and others (1968) made seismic refraction measurements in Cascadia Abyssal Plain west of Oregon along lines parallel to the continental margin. Their measurements provide data on the depth and seismic velocities of the crustal layers and top of the mantle on the westernmost end of the cross section. Seismic refraction observations by Hill (1972) provide data on the crustal thickness in eastern Oregon near the east end of the cross section, and the results of a seismic refraction experiment in the Cascades reported by Wegener and others (1980) and Hill and others (1981) provide information on the velocitites and thicknesses of the crustal layers in the Cascade Range.

The gravity data described in this report provided control for the central portion of the section between 121° and 122°30' W. lon., and the regional data described by Thiruvathukal and others (1970) and Dehlinger and others (1970) provided control for the eastern and western portions of the section.

The crustal cross section assumes a two-dimensional structure, a standard mass column of 50 km (30 mi) and 6442 mgal corresponding to a zero free-air gravity anomaly (Barday, 1974) and no lateral variations in density below a depth of 50 km (30 mi) (Braman, 1981). Iterative adjustments of layer boundaries constrained by land elevations, geologic contacts, refracting horizons, and horizons determined from the well logs were made until the gravity, computed with the method of Talwani and others (1959) and Gemperle (1975), agreed with the observed free-air anomalies. This process yielded the northern Oregon geophysical cross section.

Figure 20 shows the northern Oregon geophysical cross section. The section, approximately 400 km (250 mi) long, is oriented N 84° E approximately normal to the Willamette Valley and Cascade Range and intersects the High Cascades between Mt. Hood and Mt. Jefferson about 20 km north of Breitenbush Hot Springs. The continental crust is approximately 20 km thick in the vicinity of the Coast Range and increases in thickness to about 25 km on the east side of the Willamette Valley. The crust increases in thickness eastward in the vicinity of the Western Cascades and is about 35 km thick beneath the High Cascades. In eastern Oregon the crust is about 30 km thick.

Little structural control is available for the Deschutes-Umatilla Plateau in eastern Oregon; hence the cross section shows a lower crustal unit of 2.85 gm/cm^3 overlain by a layer of 2.63 gm/cm^3. The 2.85 gm/cm^3 layer beneath the plateau is observed at 6700 feet in the Standard Kirkpatrick No. 1 well as pre-Tertiary marine rocks similar in age and origin to rocks that crop out in the John Day Mountains south of the Deschutes-Umatilla Plateau.

The cross section shows layers of 2.43 and 2.55 gm/cm^3 in the vicinity of the Humble Wicks No. 1 well which correspond to the volcanics of the Western Cascades. These layers thin westward and are covered by or interfinger with the lighter (2.25 gm/cm^3) sedimentary rocks in the Willamette Valley. These sedimentary rocks, as observed in the Humble Wicks No.1 well, are composed of Oligo-Miocene tuffs and sands with interbedded volcanic fragments (Newton, 1969). The model section indicates that two large east-dipping normal faults displace rocks of the Western Cascades approximately 10 and 20 km east of the Humble Wicks No. 1 well. The model suggests that these unmapped faults extend to at least 5 km. Miocene volcanics of the Western Cascades form the surface layer of 2.43 gm/cm^3 density. The 2.55 gm/cm^3 layer beneath the Miocene volcanics is identified in the Humble Wicks No. 1 well as rock of the Fisher and Calapooya Formations of late Eocene age (Newton, 1969). The layer of density 2.70 gm/cm^3 may correlate with the Siletz River Volcanics of the Coast Range. Newton (1969) inferred that the Siletz River Volcanics shoal eastward beneath the Humble Wicks well at a depth of approximately 3 km.

The large intrusion of density 2.80 gm/cm^3 beneath the Clackamas River correlates with the massive Detroit or Hall Ridge Pluton located north of Detroit that has been described by Hammond and others (1982). Immediately east of the pluton a seismic refraction line, shot approximately normal to the section along the High Cascades (Wegener and others, 1980; Hill and others, 1981), constrains the thickness of the crustal layers. Baldwin (1959), Peck and others (1964), and Hammond and others (1982) map the surface of the uppermost layer in this region as andesites and basalts of Pliocene to Recent age. This layer of High

Cascade rocks is low in density (2.27 gm/cm^3) and less than 1.5 km thick over most of width of the region except near the intrusion where the layer thickens to over 3 km.

The low-density material of High Cascades origin overlies material with a density 2.60 gm/cm^3. This material, indicated by the gravity and seismic refraction measurements, very likely corresponds to the early High Cascades basalt platform and/or the "Plio-Cascades" described by Taylor (1980) that extend from the Western Cascades beneath the High Cascades to the Deschutes Basin.

In the cross section the units with densities of 2.60 and 2.80 gm/cm^3 shoal along the east flank of the Cascade Range. The elevation of the high-density rocks, indicated by a positive free-air gravity anomaly, occurs in the vicinity of Beaver Butte and may be associated with the early and pre-Tertiary rocks of the Mutton Mountains anticlinorium. Pre-Tertiary marine rocks were encountered at 6700 feet in the Standard Kirkpatrick No. 1 well near Condon, Oregon, approximately 100 km east of Beaver Butte. These rocks, indicated on the section as having an average density of 2.85 gm/cm^3, may be continuous with those of 2.80 gm/cm^3 beneath the Cascades.

Geophysical Cross Section of the Cascade Range in Southern Oregon

Line C-C' in Figure 8 shows the trace of the geophysical cross section across southern Oregon, and Figure 21 shows the cross section. The Southern Oregon Section, oriented east-west approximately normal to the Cascade Range, extends from the Gorda Basin offshore of southern Oregon to a point in southern Idaho. The section passes immediately south of Mt. McLoughlin, obliquely through the northern end of Klamath Lake and intersects the Humble Thomas Creek No. 1 well east of the area mapped in Figure 8.

The gravity data described in this report provided control for the central portion of the section between 121° and 122°30' W. lon., and the data described by Thiruvathukal and others (1970) in Oregon provided regional control.

The geologic maps of Wells and Peck (1961), Peterson and McIntyre (1970), and Walker (1977) provided information on near-surface geologic units, and interface locations and seismic logs from the Humble Thomas Creek No. 1 well provided estimates of the densities of the near-surface units via empirical relations between seismic velocity and density reported by Ludwig and others (1970). Aeromagnetic measurements reported by McLain (1981), modeled using the techniques described by Lu and Keeling (1974), helped constrain the structures between 121° and 122°30' W. lon. (Veen, 1981). The model crustal cross section assumes a two-dimensional structure, a standard mass column of 50 km and 6442 mgal corresponding to a zero free-air gravity anomaly (Barday, 1974), and no lateral variations in density below a depth of 50 km (30 mi) (Veen, 1981). Iterative adjustments of layer boundaries, constrained by land elevations, geologic contacts, and horizons determined from the well logs of the Humble Thomas Creek No. 1 well, made until the gravity of the model computed with the method of Talwani and others (1959) and Gemperle (1975) agreed with the observed free-air anomalies, yielded the Southern Oregon Geophysical Cross Section.

Thiruvathukal and others (1970) computed a crustal thickness of 40 to 50 km for south-central and southeastern Oregon using gravity measurements and a model that consisted of a constant-density crust over a constant-density mantle. Studies by Hill and Pakiser (1967), Cook (1966), Scholz and others (1971) and Priestly and Brune (1978) indicate that the structure of the Basin and Range province is more complex and is characterized by a relatively thin crust and an anomalously low-velocity low-density upper mantle. In Figure 21 we extend this concept into the northern extent of the Basin and Range Province in southeastern Oregon and indicate a computed crustal thickness of approximately 30 km in the vicinity of the cross section. This crustal thickness agrees well with the recent seismic refraction measurements of Priestly and others (1982) in northern Nevada and southeastern Oregon. Figure 21 shows a relatively low-density (3.27 gm/cm^3) layer approximately 10 km thick overlying a mantle with a density 3.32 gm/cm^3. We would expect the low-density uppermost mantle to have a compressional-wave velocity of 7.7 to 7.9 km/sec and the mantle beneath to exhibit a compressional wave velocity of 8.0 to 8.2 km/sec.

Figure 21 shows a block of material of 2.70 gm/cm^3 density near the west end of the section that corresponds to Paleozoic and Mesozoic metamorphic sediments and volcanics of the Klamath Mountains. Rock of density 3.0 gm/cm^3 within the block corresponds to a band of ultramafic intrusive rocks mapped by Wells and Peck (1961). A large intrusive body of 2.85 gm/cm^3 density rises asymmetrically to the surface along the east flank of the Klamath block and, as mapped by Wells and Peck (1961), consists of granitoid, gabbroid, and ultramafic rocks. The easterly dip and high density of this unit are consistent with the suggestion of Irwin (1966) that the large intrusive body may be the eroded lip of a mafic or ultramafic sheet whose roots lie buried beneath rocks of the eastern Klamath Mountains.

Along the surface the units with densities of 2.10 and 2.2 gm/cm^3 are indicative of sediment-filled basins and are consistent with the units mapped by Peterson and McIntyre (1970) and Walker (1977). The basins are bounded by faults on the eastern and/or western sides and are associated with pluvial deposits in Pleistocene lakes.

The western end of the 2.50 gm/cm^3 unit and the 2.70 gm/cm^3 unit west of 122°30' W. lon. correspond to the volcanics of the Western Cascade Mountains. The model section suggests these rocks may extend a considerable distance eastward beneath the Pliocene and Pleistocene sediments and volcanics of the Basin and Range Province which are at least 4 km thick at the Humble Thomas Creek No. 1 well.

The two units of 2.65 gm/cm^3 density west of Upper Klamath Lake are basaltic andesites of the High Cascades. These units overlie a layer of 2.50 gm/cm^3 density that represents andesites of Mt. McLoughlin. A density of 2.50 gm/cm^3 for Mt. McLoughlin is similar to the density of 2.54 gm/cm^3 determined for Mt. Shasta by LaFehr (1965).

The model section indicates that the sedimentary layer with a density of 2.20 gm/cm^3 extends eastward to Abert Rim and may cover a series of step-like faults that form the western side of a graben. The model also suggests that this fault system extends to a depth of at least 3 km and displaces rocks with a density of 2.65 gm/cm^3.

The large irregularly shaped body with a density of 2.65 gm/cm^3 east of Klamath lake coincides with a large residual gravity anomaly (see Figure 16) located immediately south of the Sprague River Valley. The density and model configuration suggests a large buried intrusive body that might be the heat source for the thermal springs in the valley.

Between the irregular block with a density of 2.65 gm/cm^3 and the Humble Thomas Creek No. 1 well, a five-km-thick layer of 2.50 density coincides with the southern extent of a large negative residual gravity anomaly which extends northward to Yamsay Mountain. This unit may reflect, in part, low-density material in a synclinal basin. Peterson and McIntyre (1970) proposed a synclinal basin in the area of Yamsay Mountain, Sycan Marsh and the Sprague River valley. The data along the section are insufficient to delineate or determine the depth of such a basin.

The geologic maps of Wells and Peck (1961) and Peterson and McIntyre (1970) and the cross section in Figure 21 indicate that a series of step-like faults form the graben that contains Upper Klamath Lake. The model suggests that the sediments that fill the graben may be 1.2 km thick and that the graben floor may be downdropped a total of 1.6 km. These estimates depend on the densities assumed for the sediments and surrounding rocks. On the residual gravity anomaly map (Figure 16) the negative anomaly associated with the graben increases in width and amplitude northwest of Upper Klamath Lake and decreases toward the south. Hence the displacements on the bounding faults and the thickness of sediment also increase toward the north and decrease toward the south.

Structural and Geothermal Implications of the Cascade Gravity Anomalies

The residual gravity anomalies in Figures 14, 15, and 16, and the consequent prominent lineations in Figure 17, 18, and 19 outline a major fault zone, herein called the Cascade fracture zone, that extends along and across the transition between the Western Cascades and High Cascades north of Crater Lake. South of 43°10' N. latitude the Cascades fracture zone passes through Mt. Mazama and includes the Fort Klamath Basin and Klamath Graben. South of Klamath Lake the fracture zone appears to extend south and/or southeasterly into northern California. An arm of the fracture zone may strike southwesterly from the northwest flank of Crater Lake.

The gravity anomaly minima and the consequent lineations that outline the 400-km (250-mi)-long fracture zone are interpreted as indicating normal faulting with the east side down. Recent geologic mapping in the area of Cougar Reservoir northeast of Oakridge (Priest and Woller, 1982) and in the North Santiam River area southwest of Mt. Jefferson (Hammond and others, 1982) confirms a large fault zone with vertical displacement. The down faulting and down-faulted blocks probably extend farther eastward than the gravity data suggest. The expected gravity low east of the observed low is quite likely obscured by the high-density material that overlies the down-faulted blocks and forms the basal units of the younger High Cascades. The gravity lows along the fracture zone reflect the brecciated material and low-density intrusions in the fracture zone and the low-density material of High Cascade origin that overlies and fills the graben formed by the down-faulted blocks. The sequence of parallel lineations, oriented N 10° E, on the west side of the Cascades are interpreted as delineating the western side of a Cascades graben. The lineations, and hence the graben boundary, between 42°15' and 44°45' are remarkable for their linearity. Less prominent lineations east of the High Cascades suggest an eastern side of the graben that may actually lie east of Green Ridge, near the western ends of the Mutton Mts. and Blue Mts. anticlines, and between the Shukash and Paulina Basins. This eastermost boundary, if it exists, exists at depth and may actually be a monoclinal flexure in some areas rather than a fault. The lineations suggest the fault system or graben is approximately 60 km (40 mi) or more wide north of 43°30' N. latitude between Crater Lake and Mt. Hood. Many faults both east and west of the High Cascades occur within the graben and parallel the sides.

In addition to the north-trending faults which define the Cascades fracture zone and graben, many lineations, some very prominent, transect the graben structure in northeast-southwest and southwest-northeast directions. The residual gravity anomalies indicate that vertical displacement has occurred on these faults also, particularly on the west side of the High Cascades. Structural blocks defined by these complimentary faults and the N 10° E-trending faults have dropped to form small, generally filled grabens and basins.

Interestingly, most of the hot springs in the Western Cascades (indicated by the triangles in Figures 17, 18, and 19) seem to occur on or near northeasterly oriented faults or near the junction of the northeasterly striking faults and northerly or northwesterly striking faults.

In Figure 20, the material of density 2.27 gm/cm^3 represents High Cascades flows and pyroclastics that are porous and permeable. Water that penetrates these rocks would flow downward and westward where it would contact hot rock at relatively shallow depths beneath the High Cascades or percolate down graben faults which extend 4 km or more deep to deeper heat sources beneath the Western Cascades. After becoming heated and flowing generally westward, the water would rise to the surface along the faults that form and transect the western side of the Cascade Graben. If such geothermal systems prevail in the Cascade Range, exploration targets would include the larger transecting faults along the western side of the Cascade Graben that are still active or open. Further, if such systems have been active for long periods of time, extensive mineralization zones should exist along some of the faults or fault zones.

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Figure Captions

Figure 1. Regional geology of the Pacific Northwest. Rectangles outline the areas of gravity surveys in the Cascade Range of northern, central, and southern Oregon.

Figure 2. Topography of the Cascade Range in northern Oregon. Elevation contours occur at 1000-foot intervals. A-A' shows the location of the seismic refraction line reported by Wegener and others, 1980, and Hill and others, 1981. B-B' shows the trace of the northern Cascade Range geophysical cross section shown in Figure 20.

Figure 3. Free-air gravity anomalies of the Cascade Range of northern Oregon. Heavy contours occur at 50-mgal intervals.

Figure 4. Complete Bouguer gravity anomalies of the Cascade Range of northern Oregon. Heavy contours occur at 10-mgal intervals.

Figure 5. Topographic map of the Cascade Range in central Oregon.

Figure 6. Free-air gravity anomaly map of the Cascade Range in central Oregon. Heavy contours occur at 50-mgal intervals.

Figure 7. Complete Bouguer gravity anomalies of the Cascade Range in central Oregon. Heavy contours occur at 10-mgal intervals.

Figure 8. Topography of the Cascade Range in southern Oregon. Elevation contours occur at 1000-foot intervals. C-C' shows the trace of the geophysical cross section shown in Figure 21.

Figure 9. Free-air gravity anomalies of the Cascade Range in southern Oregon. Heavy contours occur at 50-mgal intervals.

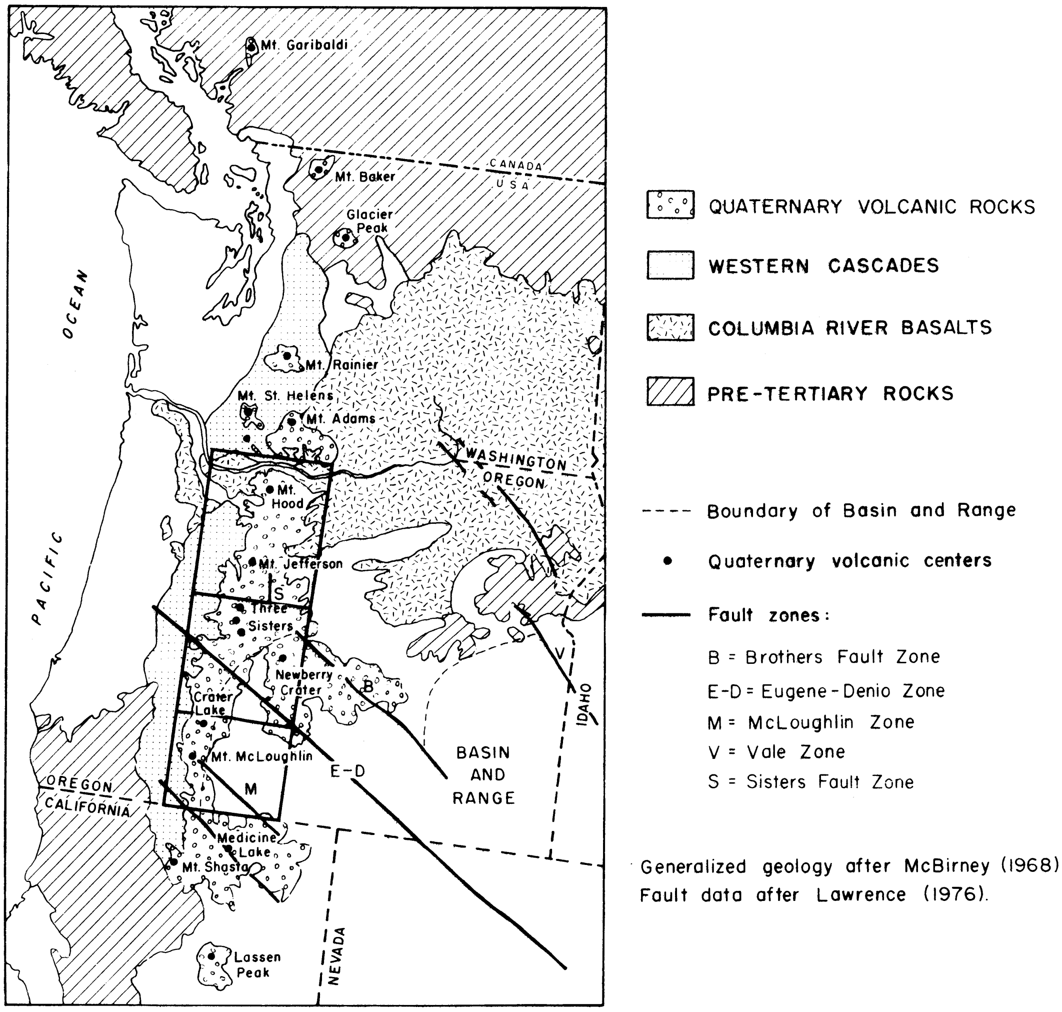
Figure 10. Complete Bouguer gravity anomalies of the Cascade Range in southern Oregon. Heavy contours occur at 10 mgal intervals.

Figure 11. Regional gravity anomalies of the Cascade Range in Oregon. Reduction density is 2.43 gm/cm^3. Map shows anomalies with wavelengths greater than 90 km. Dotted lines outline gravity survey areas.

Figure 12. Topographic and gravity anomaly profiles along the axis of the Cascade Range in Oregon.

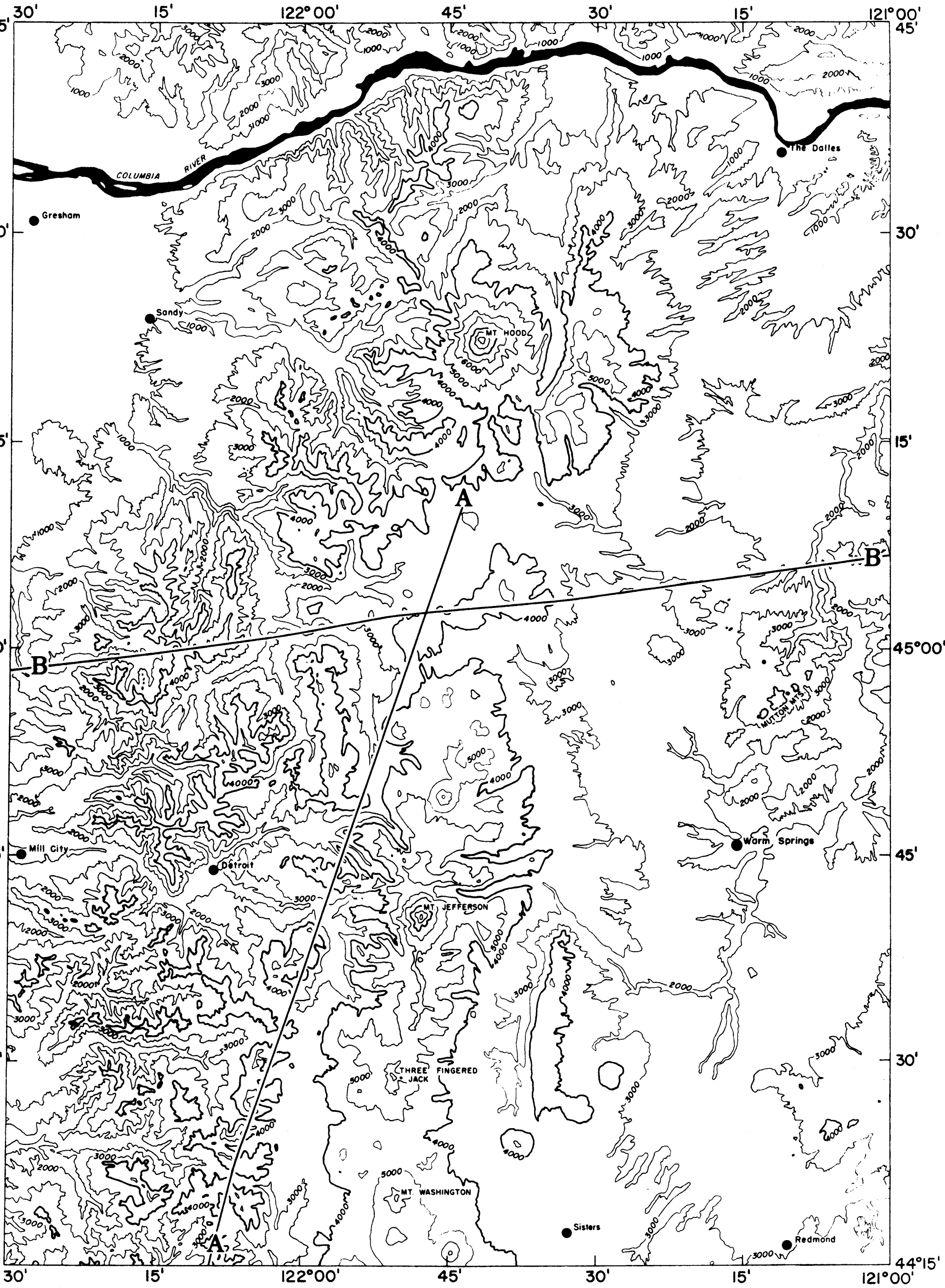
Figure 13. West-to-east topographic and gravity profiles of High Cascade Volcanoes.

Figure 14. Residual gravity anomaly map of the Cascade Range in northern Oregon. Heavy contours occur at 10-mgal intervals.



Mt. Garibaldi
CANADA
USA
Mt. Baker
Glacier Peak
PACIFIC
OCEAN
Mt. Rainier
Mt. St. Helens
Mt. Adams
WASHINGTON
OREGON
Mt. Hood
Mt. Jefferson
S
Three Sisters
Newberry Crater
B
Crater Lake
Mt. McLoughlin
E-D
M
BASIN AND RANGE
IDAHO
V
OREGON
CALIFORNIA
Medicine Lake
Mt. Shasta
NEVADA
Lassen Peak
QUATERNARY VOLCANIC ROCKS
WESTERN CASCADES
COLUMBIA RIVER BASALTS
PRE-TERTIARY ROCKS
Boundary of Basin and Range
Quaternary volcanic centers
Fault zones:
B = Brothers Fault Zone
E-D = Eugene-Denio Zone
M = McLoughlin Zone
V = Vale Zone
S = Sisters Fault Zone
Generalized geology after McBirney (1968).
Fault data after Lawrence (1976).

Figure 1.



TOPOGRAPHIC MAP

CASCADE MOUNTAIN RANGE, NORTHERN OREGON

MAP LOCATION

DATA FROM USGS 1:250,000 QUADRANGLE MAPS
BEND NL 10-12
SALEM NL 10-11
VANCOUVER NL 10-8
THE DALLES NL 10-9

KILOMETERS
0 5 10 15 20
0 5 10
MILES

TRANSVERSE MERCATOR PROJECTION
CONTOUR INTERVAL 1000 FEET

Figure 2.

OREGON STATE UNIVERSITY
DECEMBER, 1980

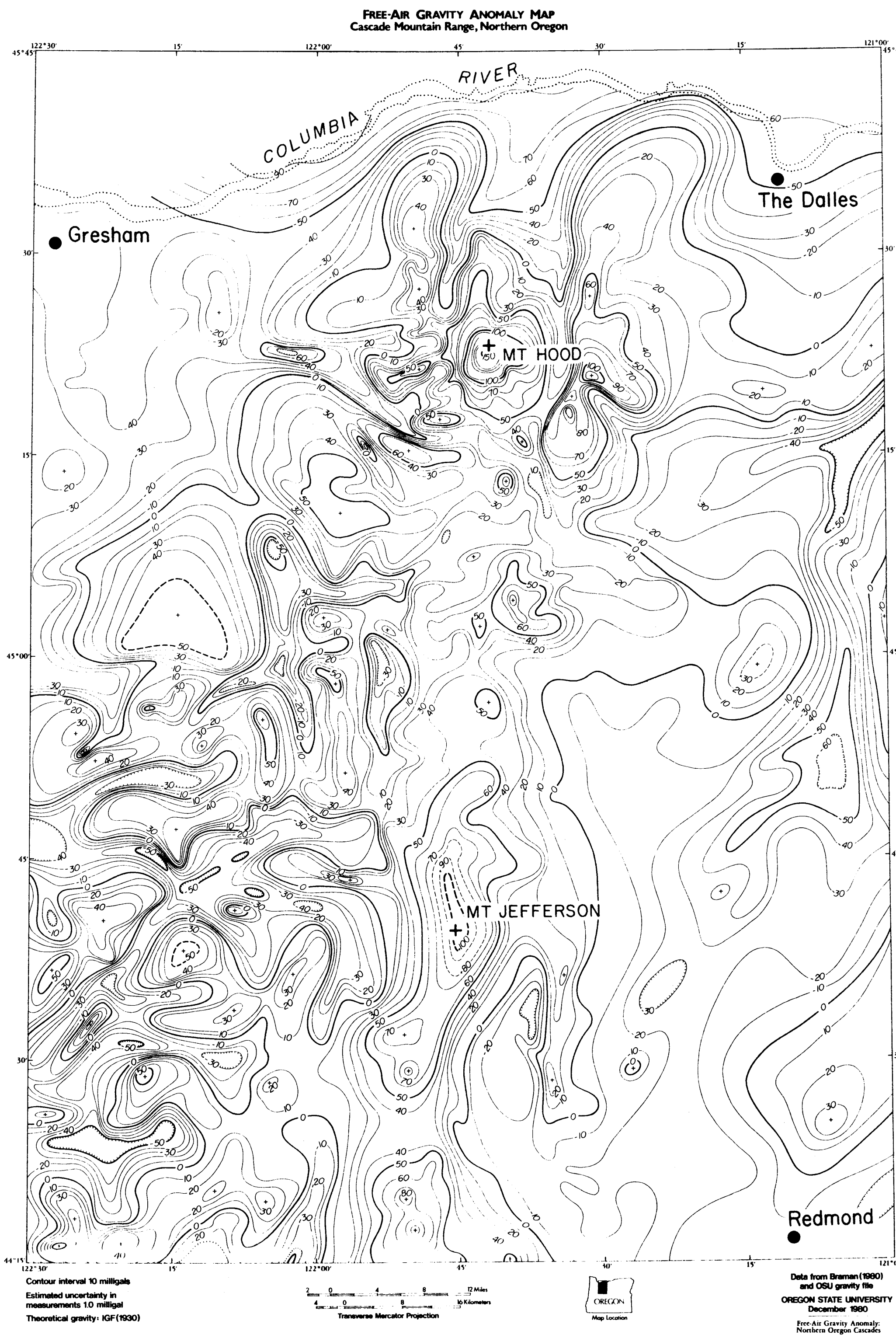

FREE-AIR GRAVITY ANOMALY MAP
Cascade Mountain Range, Northern Oregon
COLUMBIA
RIVER
Gresham
The Dalles
MT HOOD
MT JEFFERSON
Redmond
Contour interval 10 milligals
Estimated uncertainty in measurements 1.0 milligal
Theoretical gravity: IGF(1930)
12 Miles
16 Kilometers
Transverse Mercator Projection
OREGON
Map Location
Data from Braman (1980) and OSU gravity file
OREGON STATE UNIVERSITY
December 1980
Free-Air Gravity Anomaly: Northern Oregon Cascades

Figure 3.

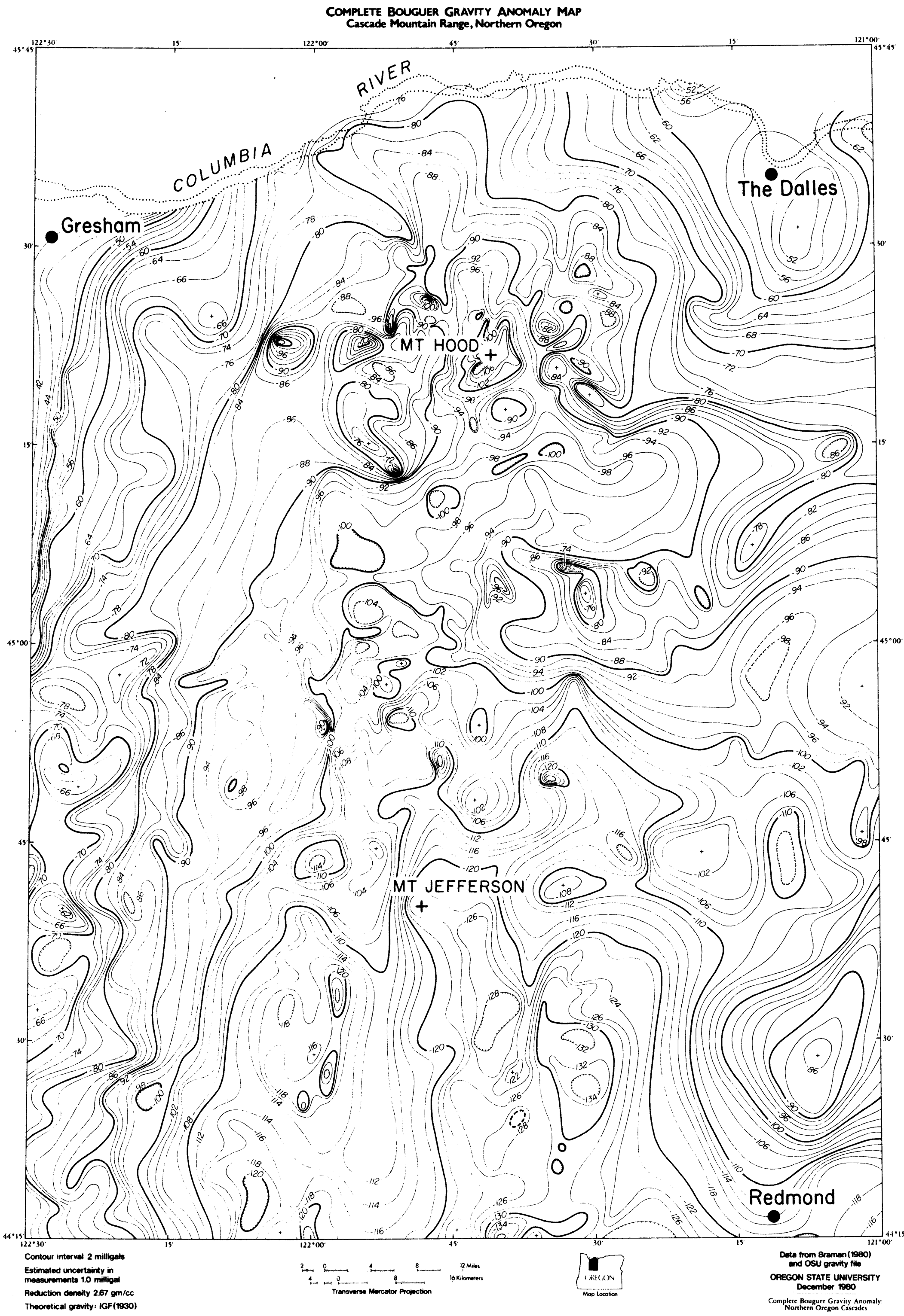

COMPLETE BOUGUER GRAVITY ANOMALY MAP
Cascade Mountain Range, Northern Oregon
COLUMBIA RIVER
Gresham
The Dalles
MT HOOD
MT JEFFERSON
Redmond
Contour interval 2 milligals
Estimated uncertainty in measurements 1.0 milligal
Reduction density 2.67 gm/cc
Theoretical gravity: IGF(1930)
Transverse Mercator Projection
OREGON
Map Location
Data from Braman (1980) and OSU gravity file
OREGON STATE UNIVERSITY
December 1980
Complete Bouguer Gravity Anomaly: Northern Oregon Cascades

Figure 4.

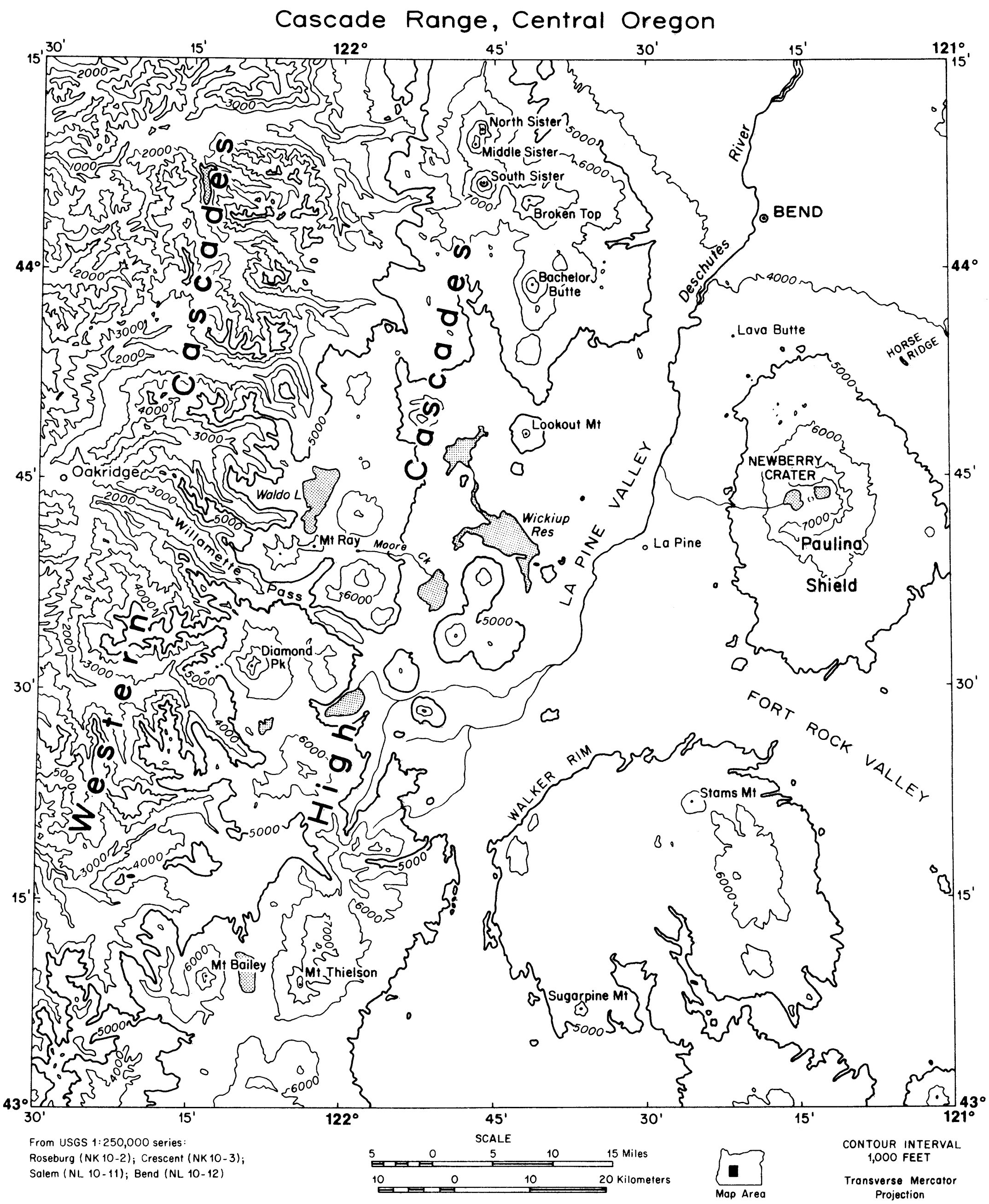

Cascade Range, Central Oregon
North Sister
Middle Sister
South Sister
Broken Top
BEND
Deschutes River
Bachelor Butte
Lava Butte
HORSE RIDGE
Lookout Mt
NEWBERRY CRATER
Paulina Shield
Oakridge
Waldo L
Wickiup Res
LA PINE VALLEY
La Pine
Mt Ray
Moore Ck
Willamette Pass
Diamond Pk
Western Cascades
High Cascades
FORT ROCK VALLEY
WALKER RIM
Stams Mt
Mt Bailey
Mt Thielson
Sugarpine Mt
From USGS 1:250,000 series: Roseburg (NK 10-2); Crescent (NK 10-3); Salem (NL 10-11); Bend (NL 10-12)
SCALE
15 Miles
20 Kilometers
Map Area
CONTOUR INTERVAL 1,000 FEET
Transverse Mercator Projection

Figure 5.

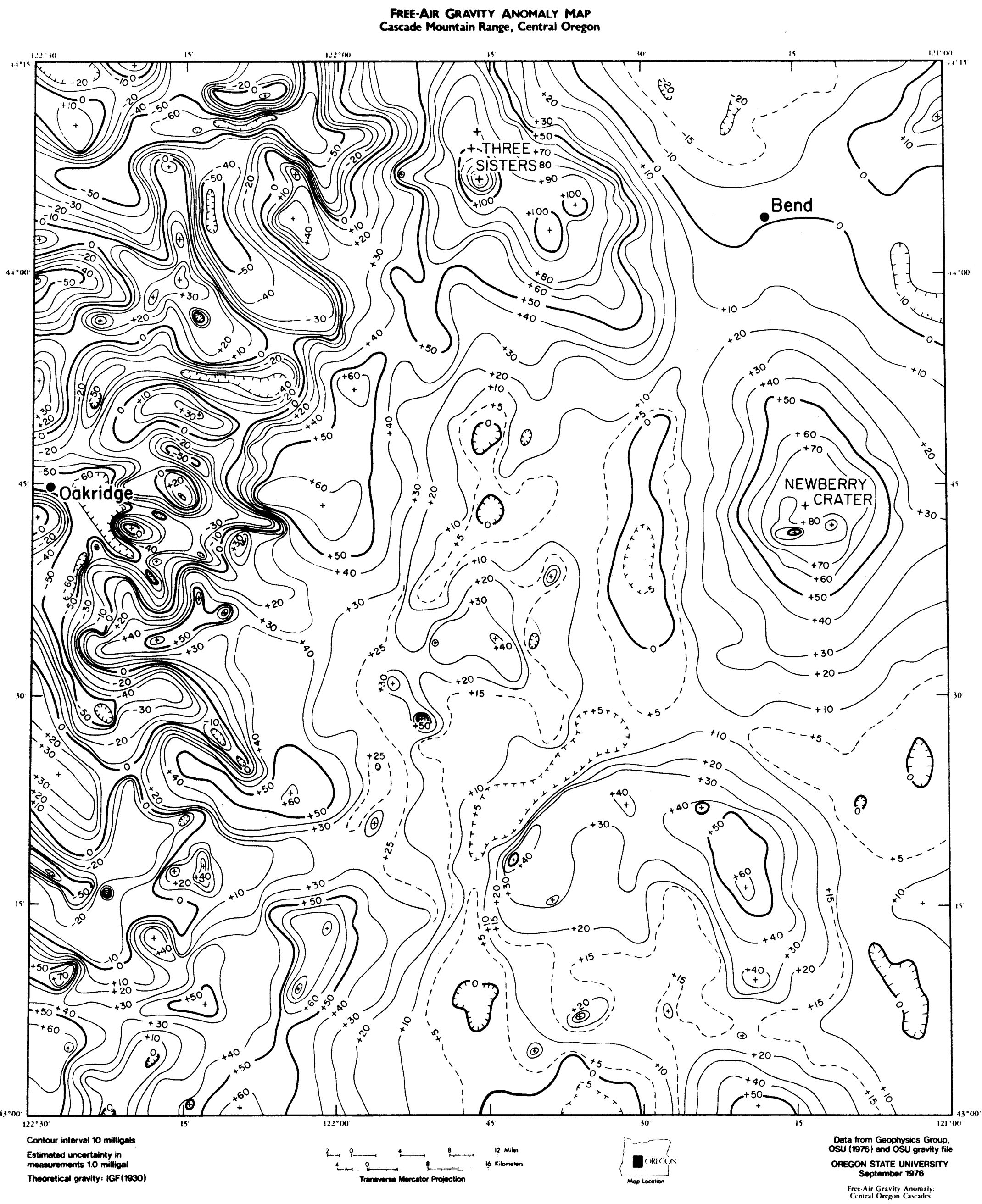

FREE-AIR GRAVITY ANOMALY MAP
Cascade Mountain Range, Central Oregon
THREE SISTERS
Bend
Oakridge
NEWBERRY CRATER
122°30′
15′
122°00′
45′
30′
121°00′
43°00′
Contour interval 10 milligals
Estimated uncertainty in measurements 1.0 milligal
Theoretical gravity: IGF(1930)
12 Miles
16 Kilometers
Transverse Mercator Projection
OREGON
Map Location
Data from Geophysics Group, OSU (1976) and OSU gravity file
OREGON STATE UNIVERSITY
September 1976
Free-Air Gravity Anomaly: Central Oregon Cascades

Figure 6.

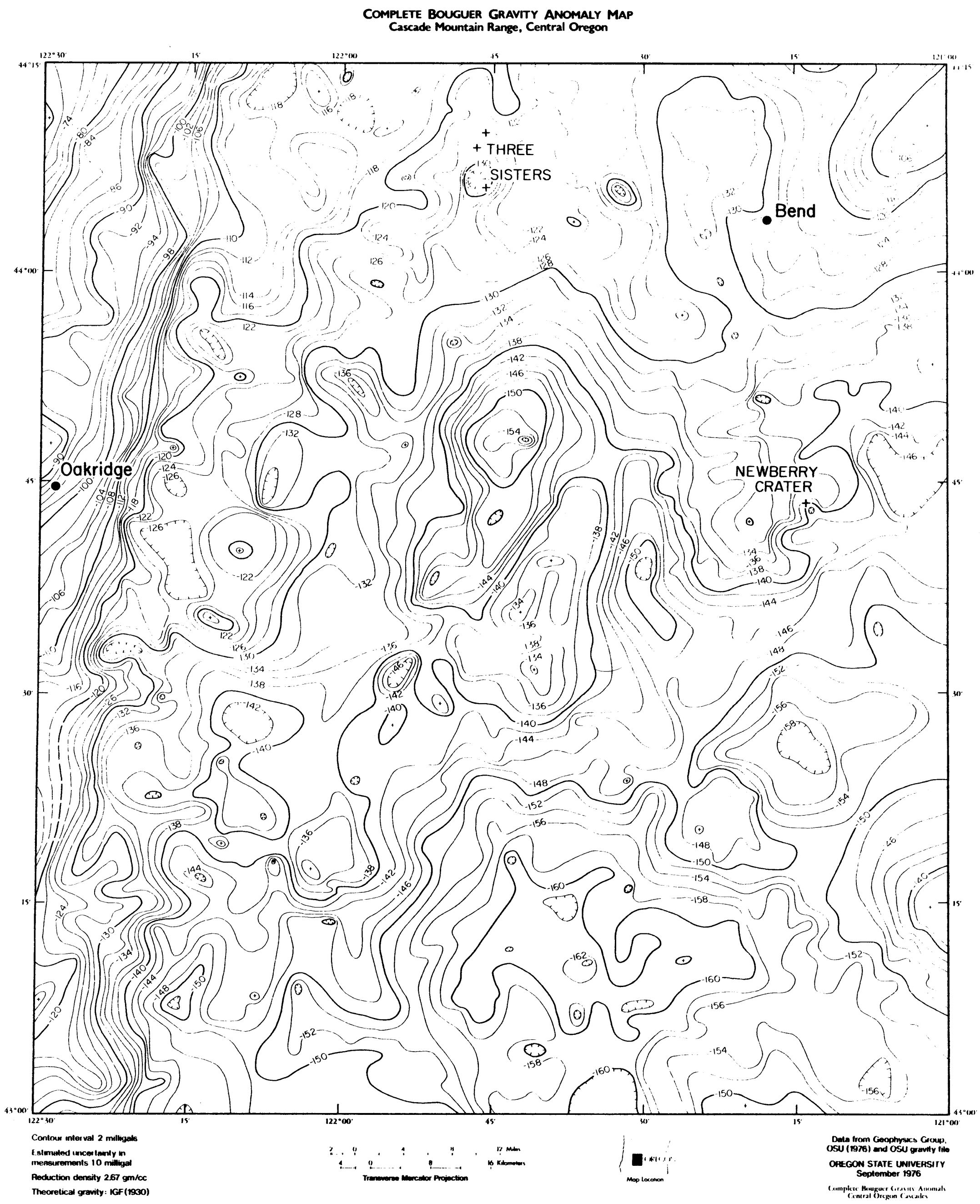
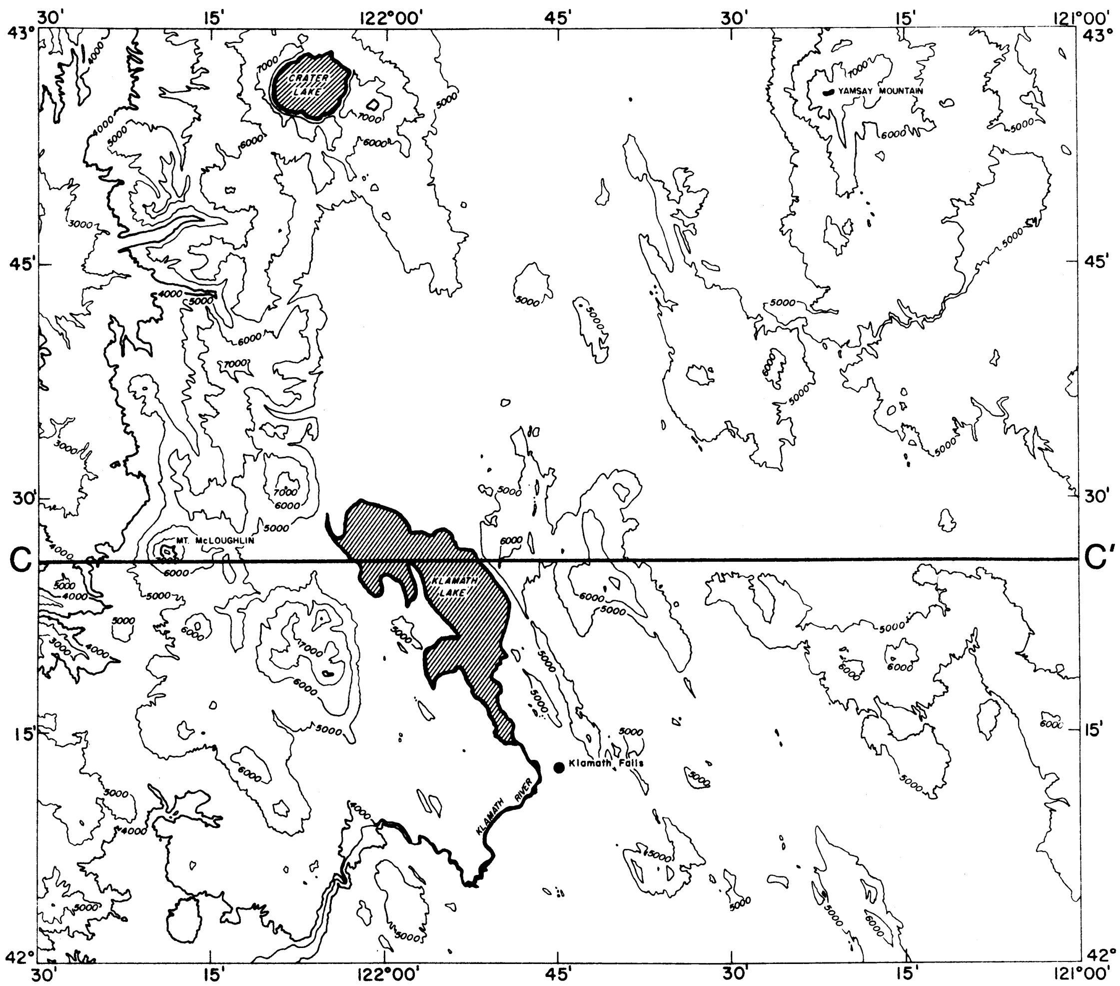

COMPLETE BOUGUER GRAVITY ANOMALY MAP
Cascade Mountain Range, Central Oregon
THREE
SISTERS
Bend
Oakridge
NEWBERRY
CRATER
Contour interval 2 milligals
Estimated uncertainty in measurements 1.0 milligal
Reduction density 2.67 gm/cc
Theoretical gravity: IGF(1930)
Transverse Mercator Projection
Map Location
Data from Geophysics Group, OSU (1976) and OSU gravity file
OREGON STATE UNIVERSITY
September 1976

Figure 7.



TOPOGRAPHIC MAP
CASCADE MOUNTAIN RANGE, SOUTHERN OREGON

MAP LOCATION

DATA FROM USGS 1:250,000 QUADRANGLE MAPS
KLAMATH FALLS NK 10-6
MEDFORD NK 10-5

KILOMETERS
0 5 10 15 20
0 5 10
MILES

TRANSVERSE MERCATOR PROJECTION
CONTOUR INTERVAL 1000 FEET

OREGON STATE UNIVERSITY
DECEMBER, 1980

Figure 8.

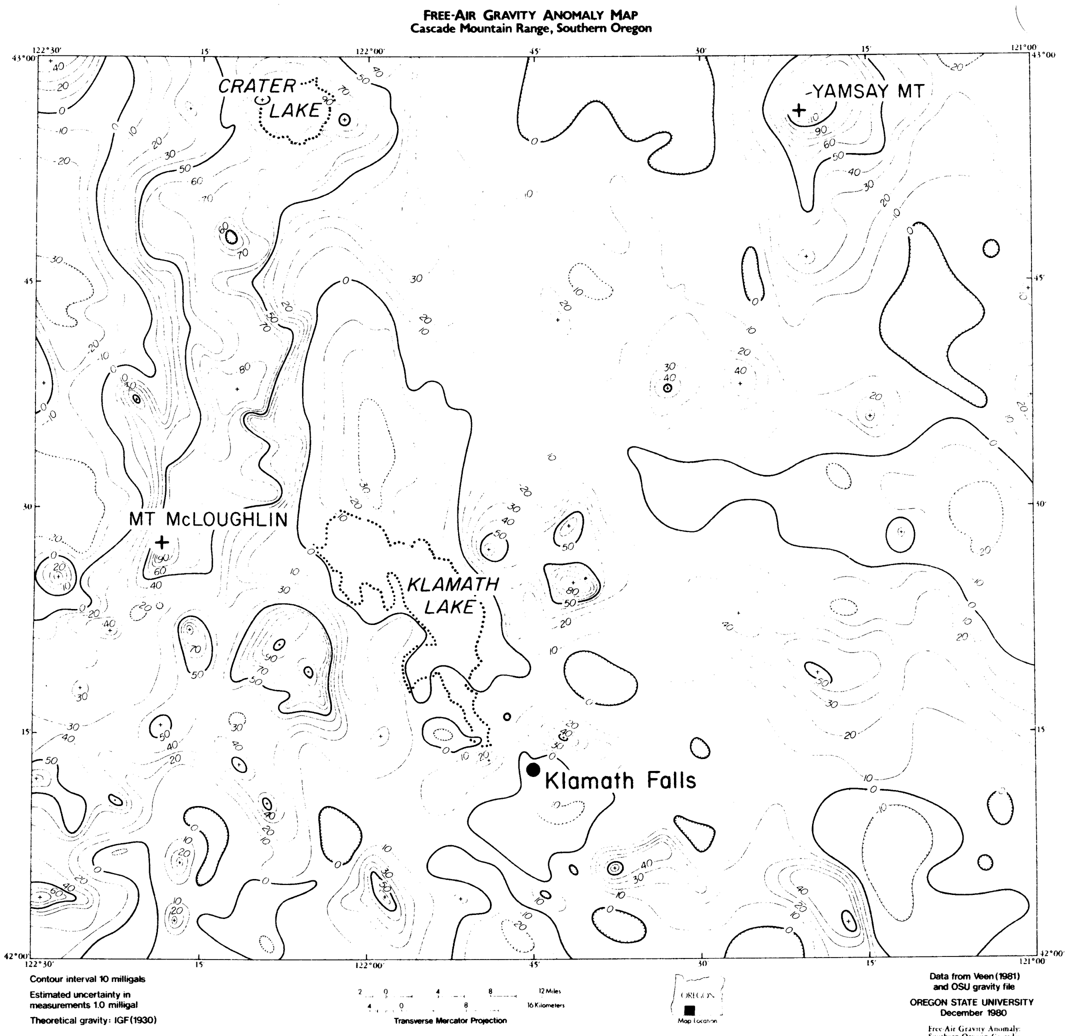

FREE-AIR GRAVITY ANOMALY MAP
Cascade Mountain Range, Southern Oregon
CRATER LAKE
YAMSAY MT
MT McLOUGHLIN
KLAMATH LAKE
Klamath Falls
Contour interval 10 milligals
Estimated uncertainty in measurements 1.0 milligal
Theoretical gravity: IGF(1930)
12 Miles
16 Kilometers
Transverse Mercator Projection
OREGON
Map Location
Data from Veen (1981) and OSU gravity file
OREGON STATE UNIVERSITY
December 1980
Free-Air Gravity Anomaly: Southern Oregon Cascades

Figure 9.

Complete Bouguer Gravity Anomaly Map
Cascade Mountain Range, Southern Oregon

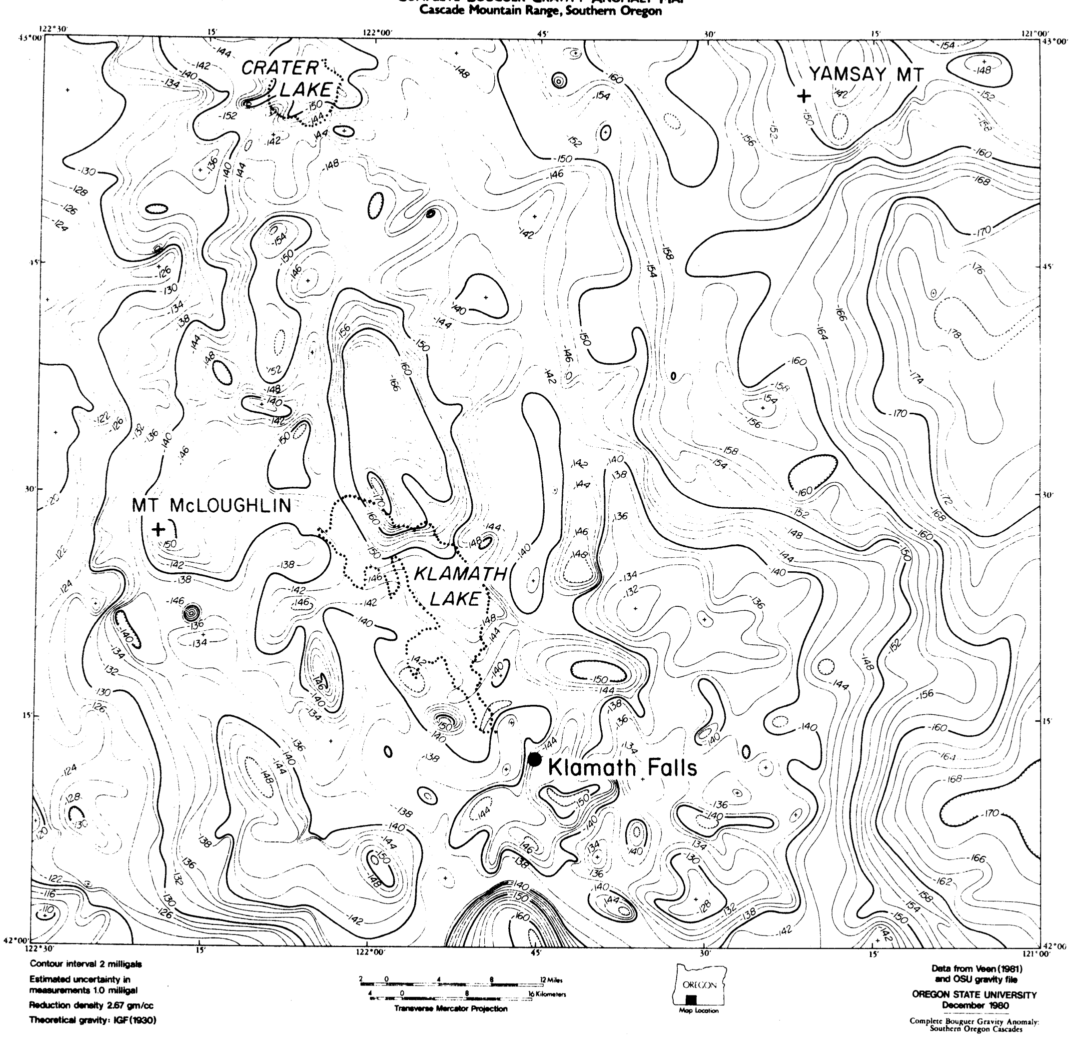
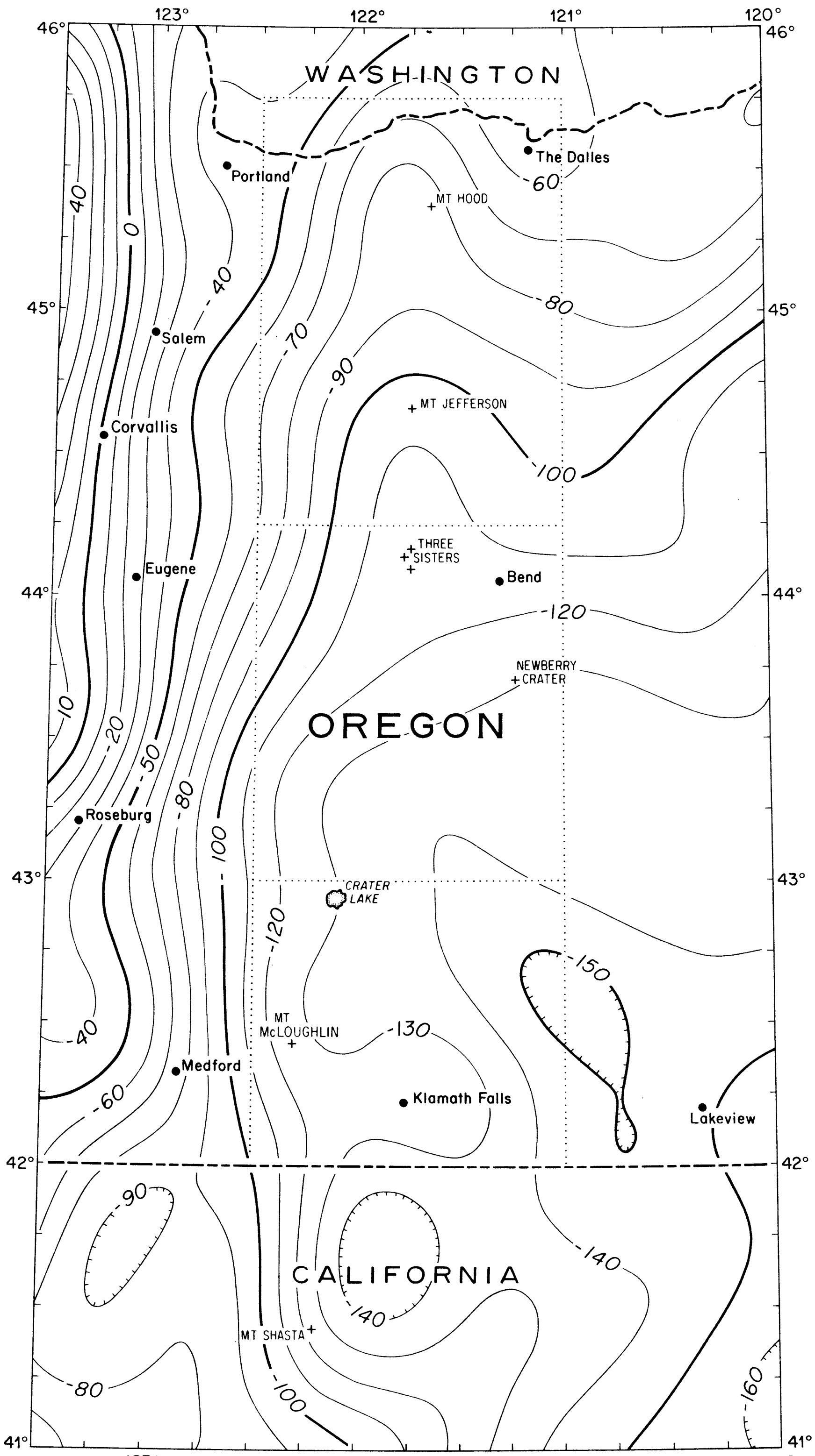
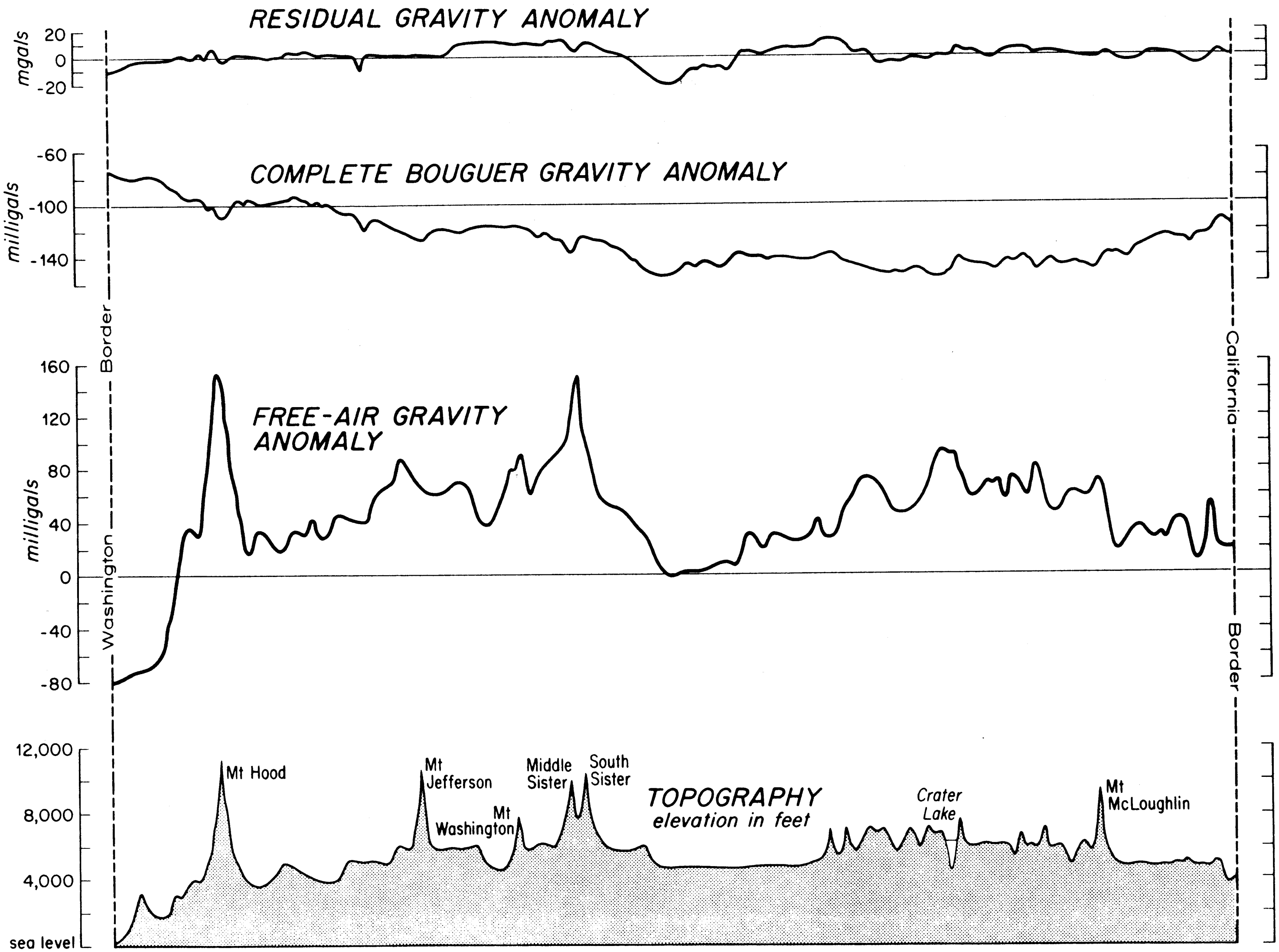


Figure 10.



WASHINGTON
OREGON
CALIFORNIA
Portland
The Dalles
MT HOOD
Salem
Corvallis
MT JEFFERSON
THREE SISTERS
Bend
Eugene
NEWBERRY CRATER
Roseburg
CRATER LAKE
MT McLOUGHLIN
Medford
Klamath Falls
Lakeview
MT SHASTA
123°
122°
121°
120°
46°
45°
44°
43°
42°
41°
0
10
20
40
50
60
70
80
90
100
120
130
140
150
160

Figure 11.



RESIDUAL GRAVITY ANOMALY
mgals
20
0
-20
COMPLETE BOUGUER GRAVITY ANOMALY
milligals
-60
-100
-140
FREE-AIR GRAVITY ANOMALY
milligals
160
120
80
40
0
-40
-80
Washington Border
California Border
TOPOGRAPHY
elevation in feet
12,000
8,000
4,000
sea level
Mt Hood
Mt Jefferson
Mt Washington
Middle Sister
South Sister
Crater Lake
Mt McLoughlin

Figure 12.

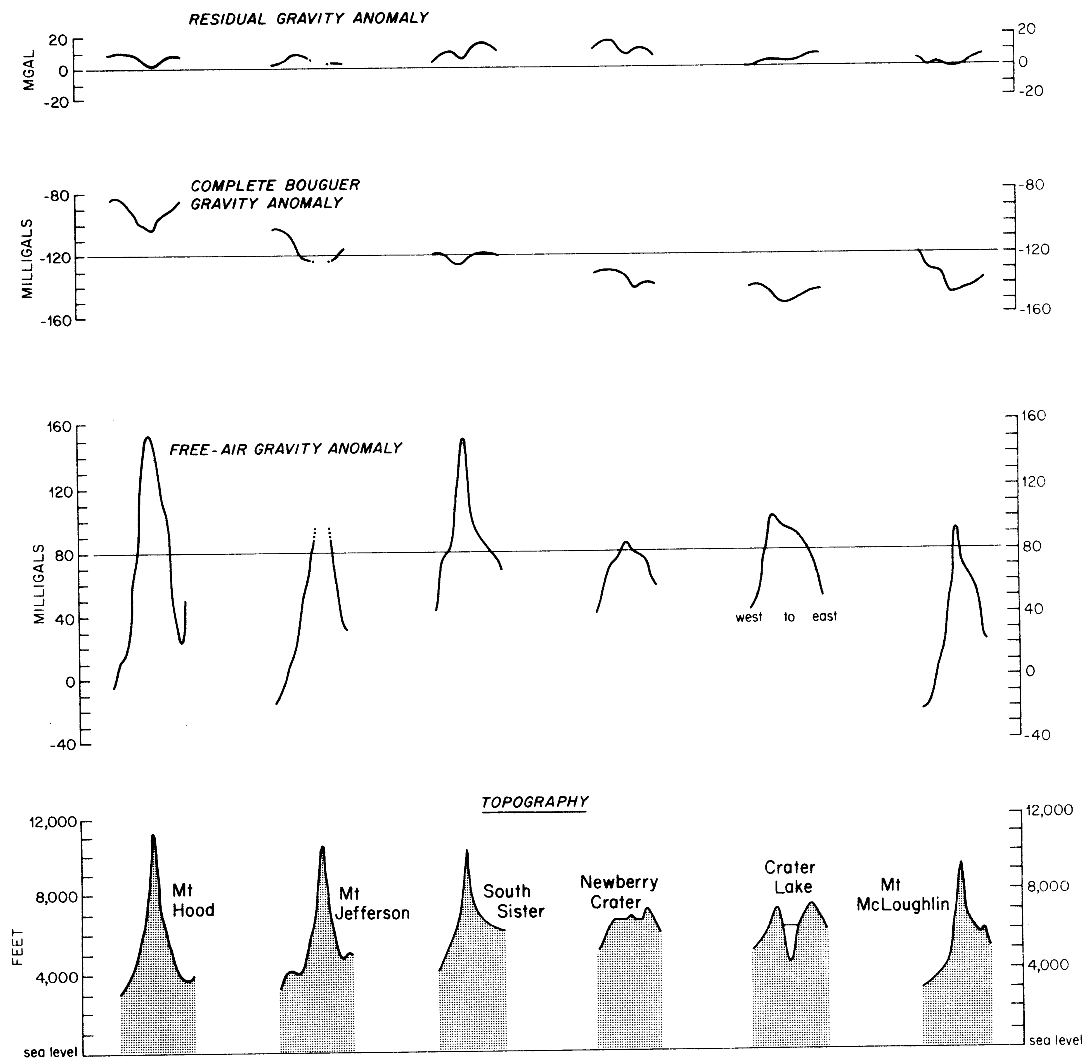
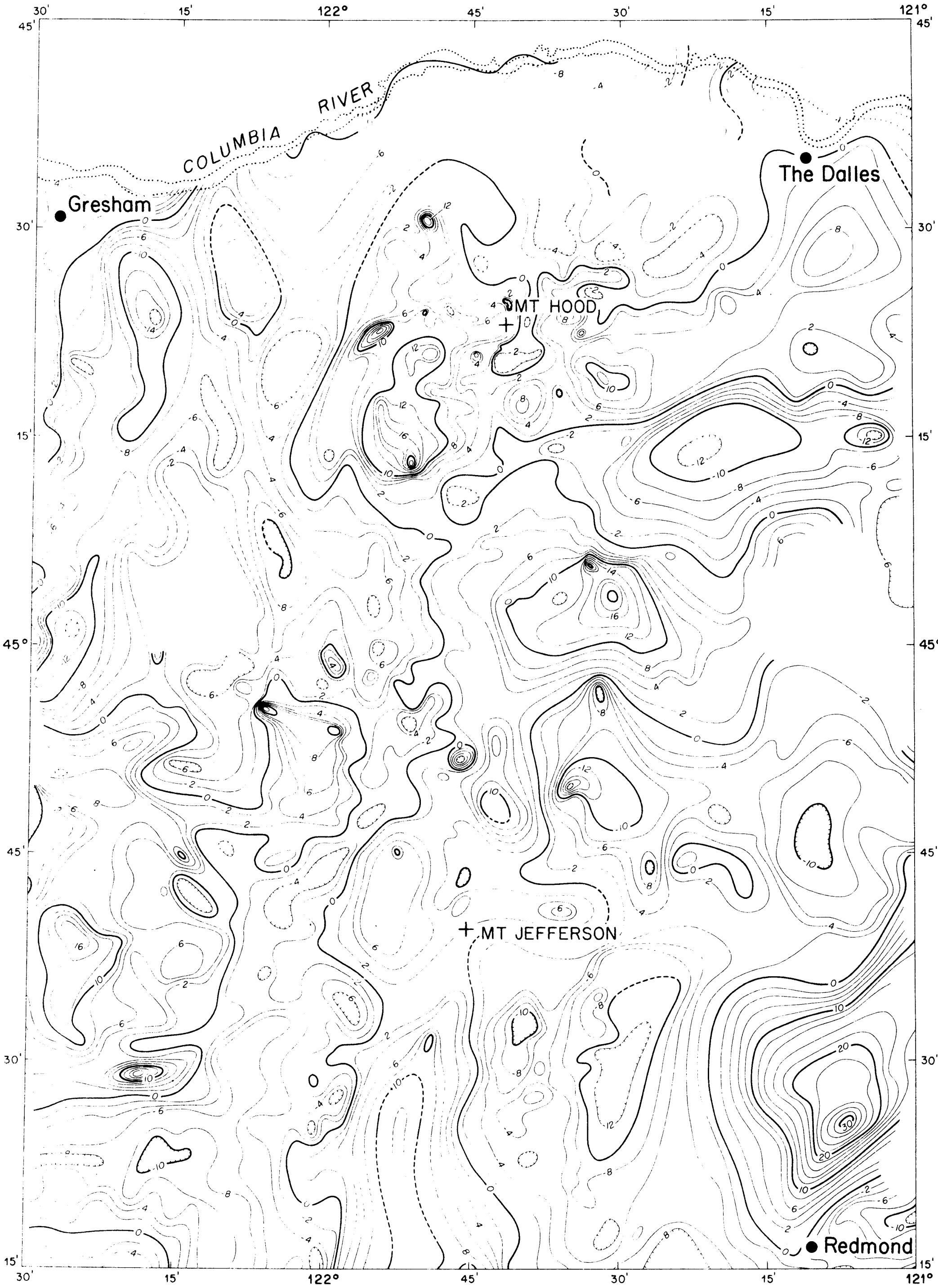

RESIDUAL GRAVITY ANOMALY
MGAL
20
0
-20
COMPLETE BOUGUER GRAVITY ANOMALY
MILLIGALS
-80
-120
-160
FREE-AIR GRAVITY ANOMALY
MILLIGALS
160
120
80
40
0
-40
west to east
TOPOGRAPHY
FEET
12,000
8,000
4,000
sea level
Mt Hood
Mt Jefferson
South Sister
Newberry Crater
Crater Lake
Mt McLoughlin

Figure 13.

RESIDUAL GRAVITY ANOMALY MAP
Cascade Mountain Range, Northern Oregon



Estimated uncertainty in measurements 1.0 milligal

Theoretical gravity: IGF (1930)

Reduction density 2.43 g/cc

Regional components greater than 90 km are removed

SCALE
5 0 5 10 mi
5 0 5 10 15 km
CONTOUR INTERVAL 2 MILLIGALS
Transverse Mercator Projection

OREGON
Map Location

Prepared by R.W. Couch, G.S. Pitts, M. Gemperle, and D. Braman

GEOPHYSICS GROUP
OREGON STATE UNIVERSITY

November 1981

Figure 14.

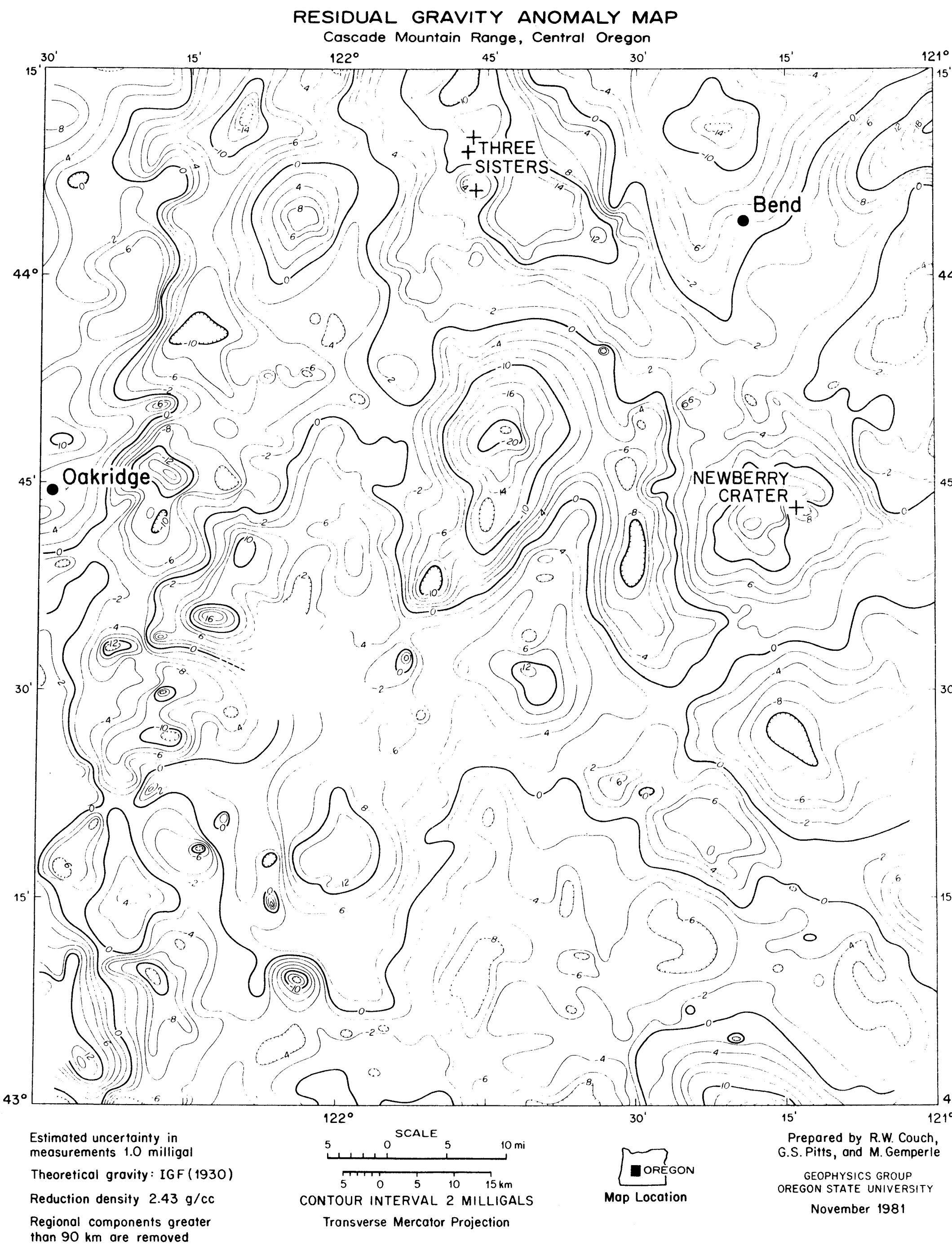

RESIDUAL GRAVITY ANOMALY MAP
Cascade Mountain Range, Central Oregon
30'
15'
122°
45'
30'
15'
121°
44°
45'
30'
43°
THREE SISTERS
Bend
Oakridge
NEWBERRY CRATER
Estimated uncertainty in measurements 1.0 milligal
Theoretical gravity: IGF (1930)
Reduction density 2.43 g/cc
Regional components greater than 90 km are removed
SCALE
5 0 5 10 mi
5 0 5 10 15 km
CONTOUR INTERVAL 2 MILLIGALS
Transverse Mercator Projection
OREGON
Map Location
Prepared by R.W. Couch, G.S. Pitts, and M. Gemperle
GEOPHYSICS GROUP
OREGON STATE UNIVERSITY
November 1981

Figure 15.

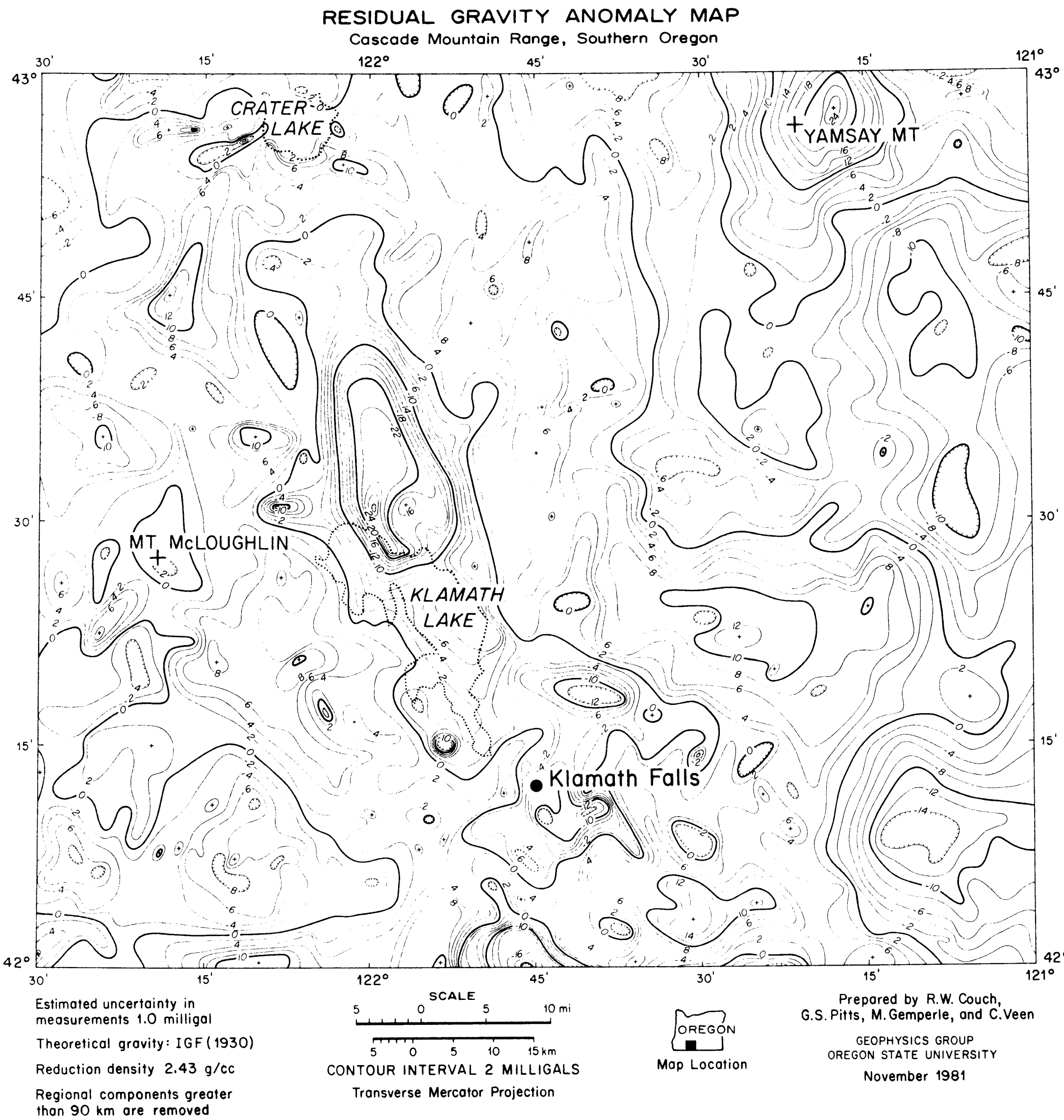

RESIDUAL GRAVITY ANOMALY MAP
Cascade Mountain Range, Southern Oregon
CRATER LAKE
YAMSAY MT
MT McLOUGHLIN
KLAMATH LAKE
Klamath Falls
43°
42°
122°
121°
Estimated uncertainty in measurements 1.0 milligal
Theoretical gravity: IGF (1930)
Reduction density 2.43 g/cc
Regional components greater than 90 km are removed
SCALE
5 0 5 10 mi
5 0 5 10 15 km
CONTOUR INTERVAL 2 MILLIGALS
Transverse Mercator Projection
OREGON
Map Location
Prepared by R.W. Couch, G.S. Pitts, M. Gemperle, and C. Veen
GEOPHYSICS GROUP
OREGON STATE UNIVERSITY
November 1981

Figure 16.

RESIDUAL GRAVITY ANOMALY MAP

Cascade Mountain Range, Northern Oregon

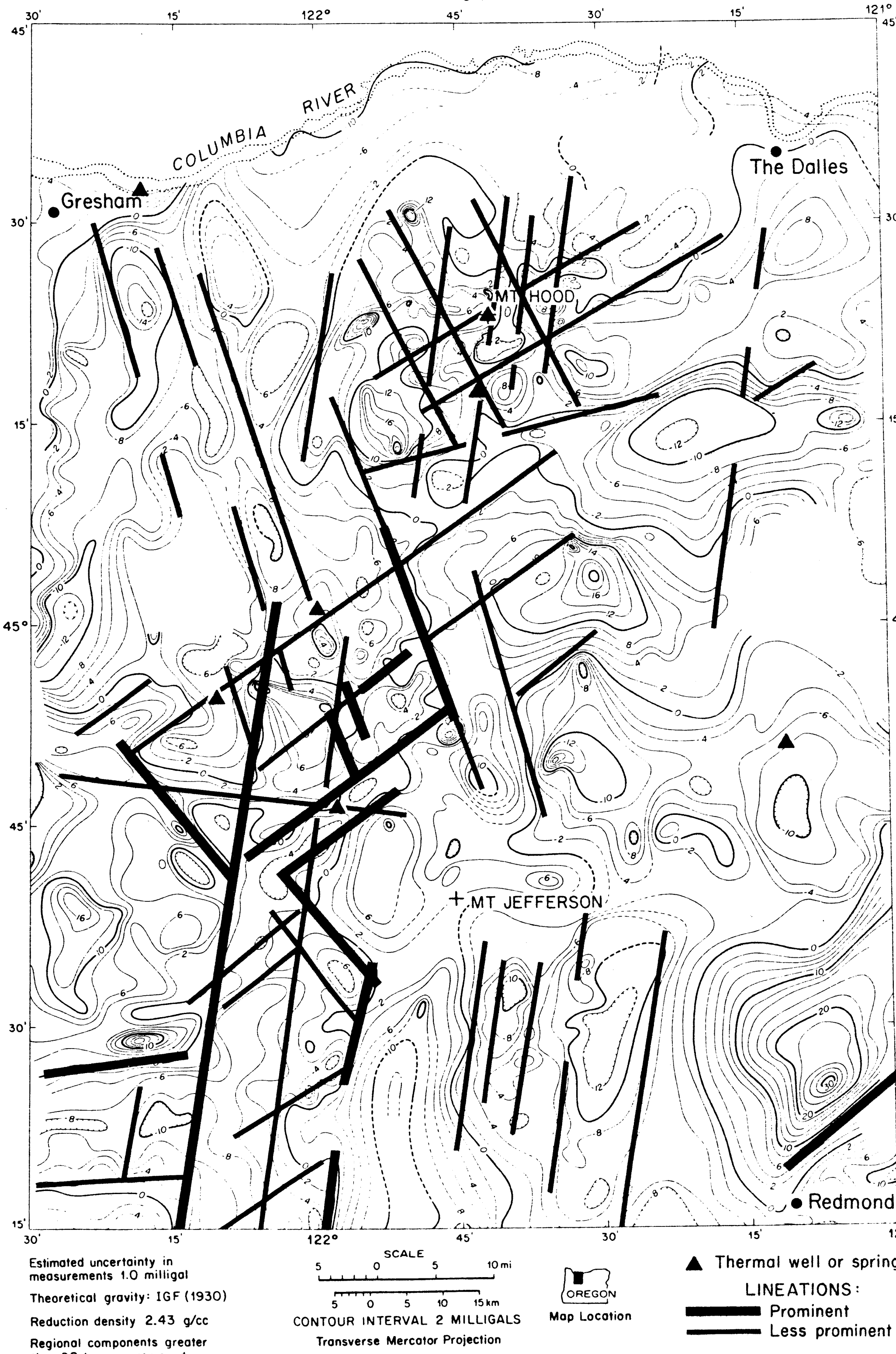
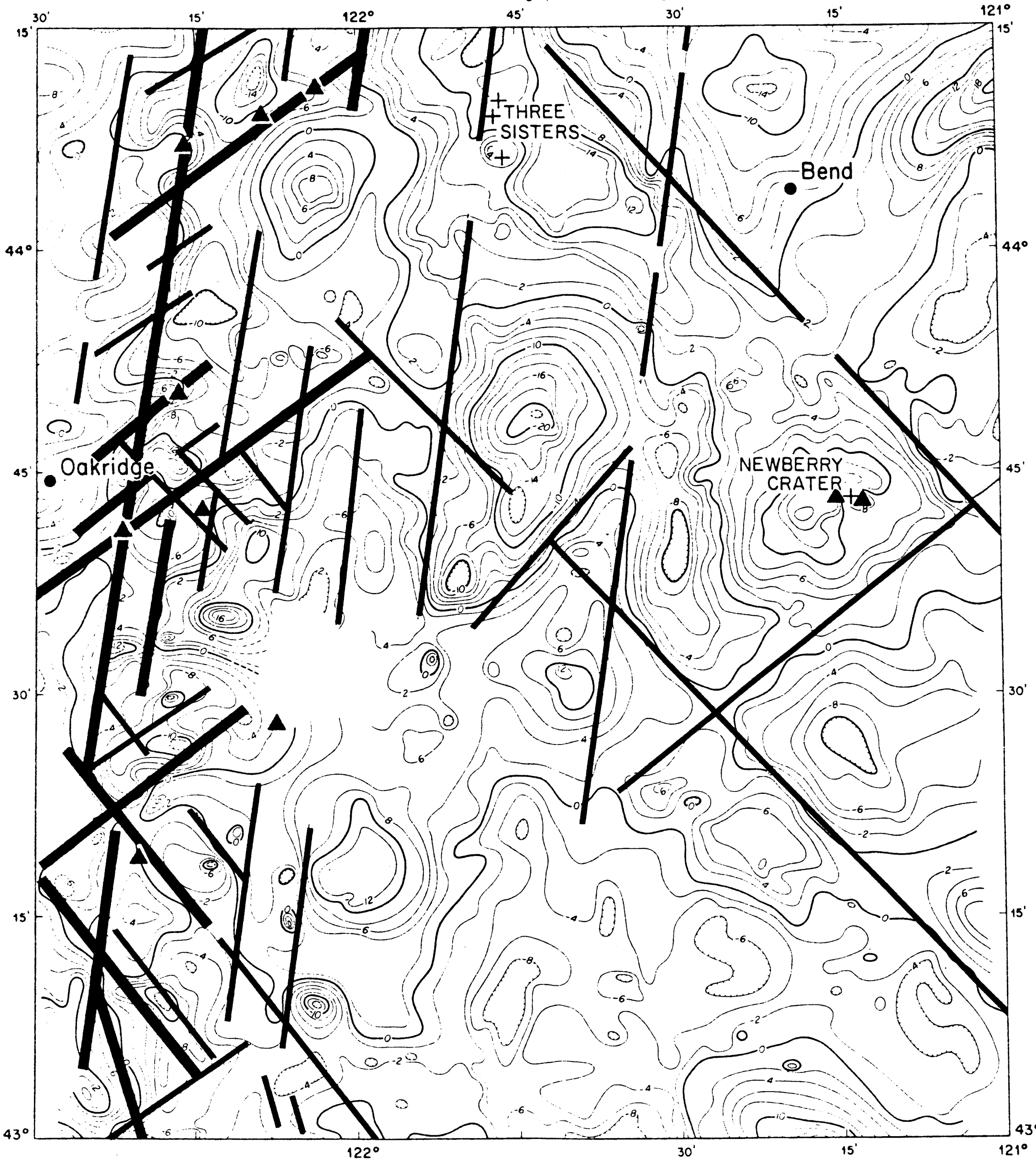


Figure 17.

RESIDUAL GRAVITY ANOMALY MAP

Cascade Mountain Range, Central Oregon



Estimated uncertainty in measurements 1.0 milligal

Theoretical gravity: IGF (1930)

Reduction density 2.43 g/cc

Regional components greater than 90 km are removed

SCALE

5 0 5 10 mi

5 0 5 10 15 km

CONTOUR INTERVAL 2 MILLIGALS

Transverse Mercator Projection

OREGON

Map Location

▲ Thermal well or spring

LINEATIONS:

Prominent

Less prominent

Figure 18.

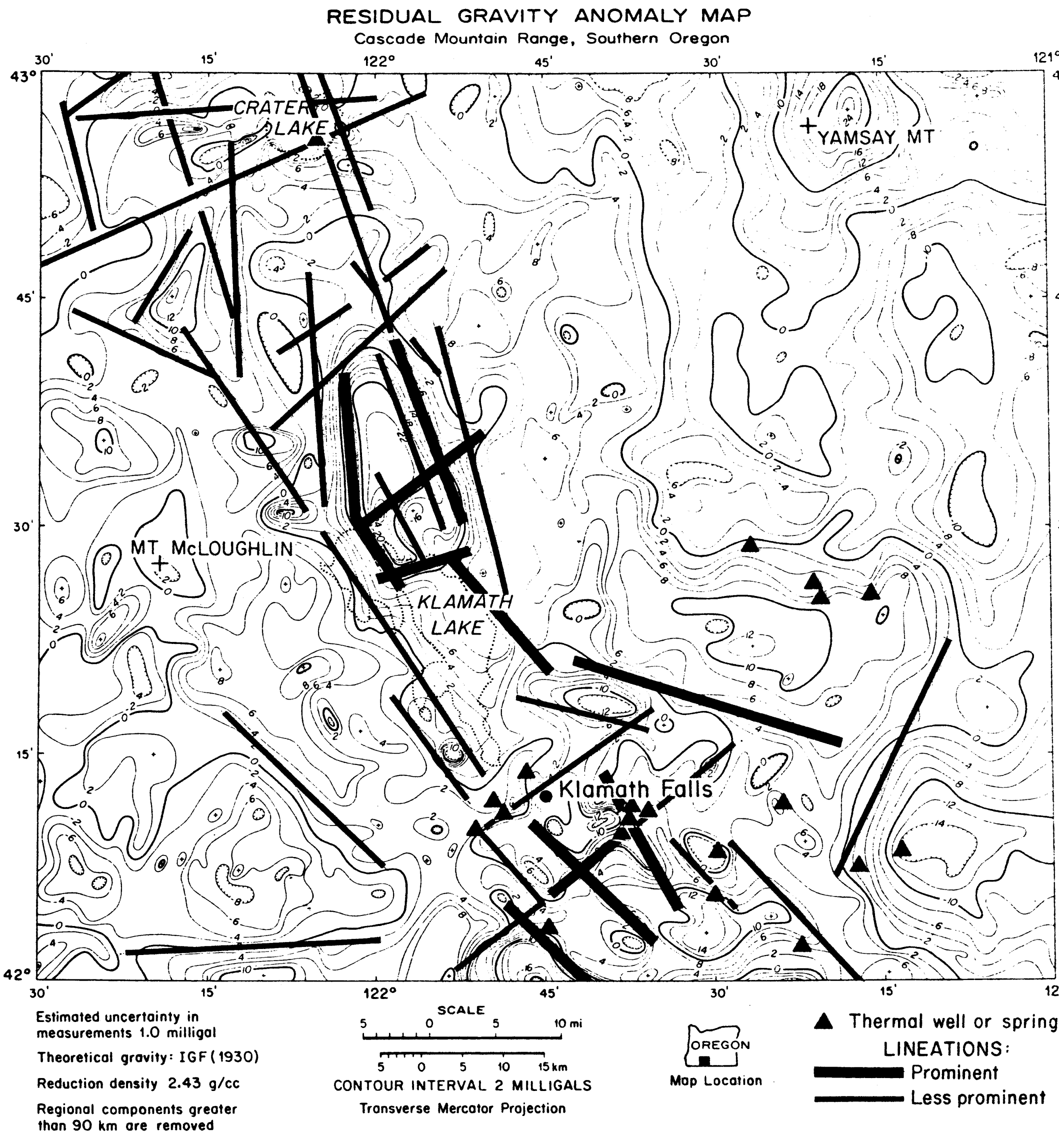
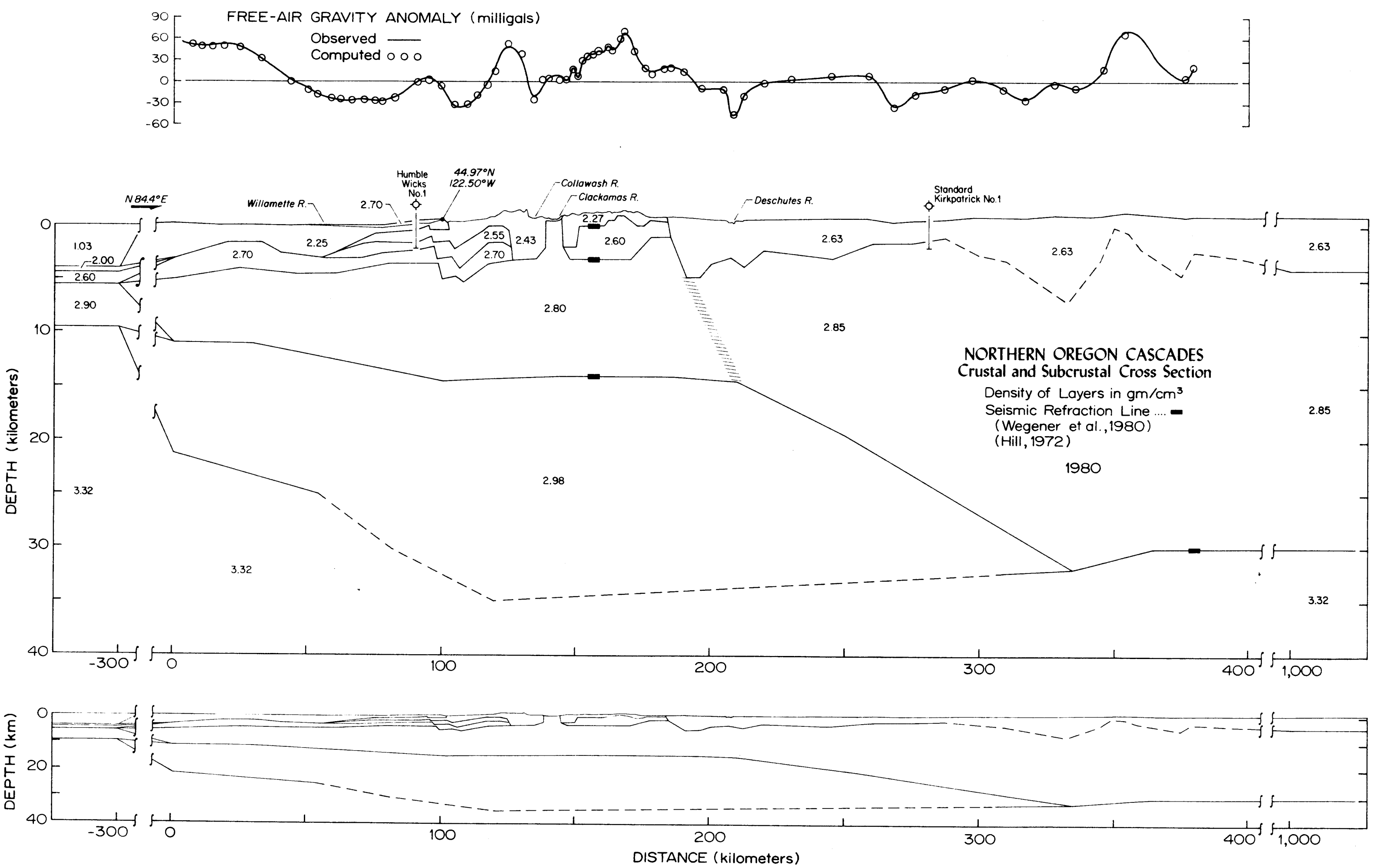
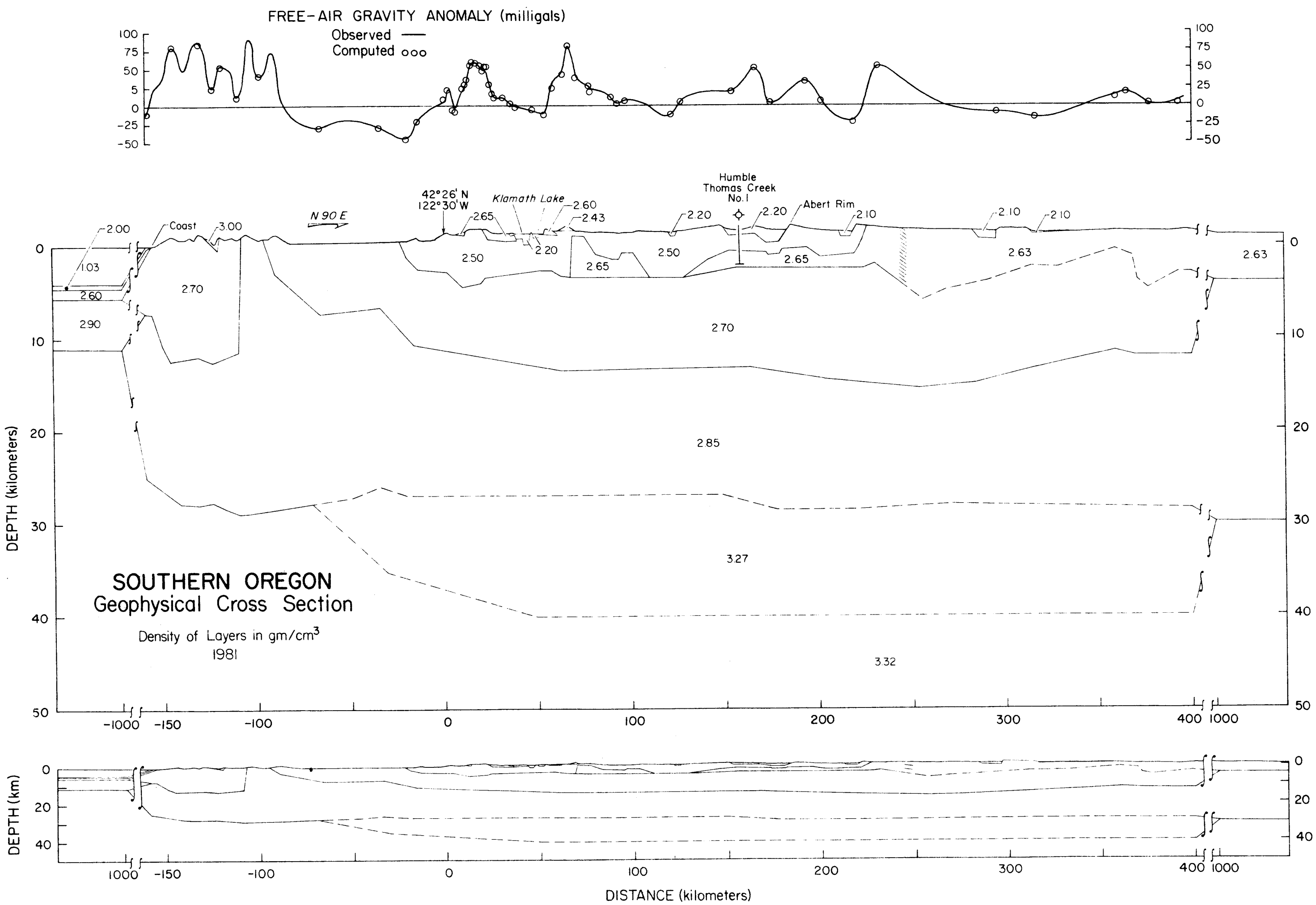

RESIDUAL GRAVITY ANOMALY MAP
Cascade Mountain Range, Southern Oregon
CRATER LAKE
YAMSAY MT
MT McLOUGHLIN
KLAMATH LAKE
Klamath Falls
43°
42°
122°
121°
Estimated uncertainty in measurements 1.0 milligal
Theoretical gravity: IGF (1930)
Reduction density 2.43 g/cc
Regional components greater than 90 km are removed
SCALE
5 0 5 10 mi
5 0 5 10 15 km
CONTOUR INTERVAL 2 MILLIGALS
Transverse Mercator Projection
OREGON
Map Location
Thermal well or spring
LINEATIONS:
Prominent
Less prominent

Figure 19.



FREE-AIR GRAVITY ANOMALY (milligals)
Observed
Computed o o o
90
60
30
0
-30
-60
N 84.4°E
Willamette R.
2.70
Humble Wicks No.1
44.97°N
122.50°W
Collawash R.
Clackamas R.
Deschutes R.
Standard Kirkpatrick No.1
1.03
2.00
2.60
2.90
2.70
2.25
2.55
2.70
2.43
2.27
2.60
2.63
2.63
2.63
2.80
2.85
2.85
2.98
3.32
3.32
3.32
NORTHERN OREGON CASCADES
Crustal and Subcrustal Cross Section
Density of Layers in gm/cm³
Seismic Refraction Line ....
(Wegener et al., 1980)
(Hill, 1972)
1980
DEPTH (kilometers)
0
10
20
30
40
-300
0
100
200
300
400
1,000
DEPTH (km)
0
20
40
-300
0
100
200
300
400
1,000
DISTANCE (kilometers)

Figure 20.



FREE-AIR GRAVITY ANOMALY (milligals)
Observed
Computed ooo
42°26' N
122°30' W
Klamath Lake
Humble
Thomas Creek
No. 1
Abert Rim
Coast
N 90 E
2.00
3.00
2.65
2.60
2.43
2.20
2.10
1.03
2.60
2.70
2.90
2.50
2.65
2.63
2.85
3.27
3.32
SOUTHERN OREGON
Geophysical Cross Section
Density of Layers in gm/cm³
1981
DEPTH (kilometers)
DEPTH (km)
DISTANCE (kilometers)

Figure 21.