

AN ABSTRACT OF THE THESIS OF

CYNTHIA ANN VEEN for the degree of MASTER OF SCIENCE

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Title: GRAVITY ANOMALIES AND THEIR STRUCTURAL IMPLICATIONS FOR THE

SOUTHERN OREGON CASCADE MOUNTAINS AND ADJOINING BASIN AND

RANGE PROVINCE

*Redacted for Privacy*

Abstract approved: \_\_\_\_\_ Richard W. Couch

Gravity measurements made during 1979 and 1980, combined with existing gravity measurements, provide data for the interpretation of upper crustal structures relevant to the assessment of the geothermal potential of south-central Oregon.

West of Upper Klamath Lake, free-air gravity anomalies trend north-south and average near 35 mgals. East of Upper Klamath Lake, free-air gravity anomalies trend west to northwest, and average near ten mgals.

The complete Bouguer anomaly field exhibits a regional gradient of nearly .4 mgals/km, which is attributed to the existence of a low-density upper mantle layer beneath the Basin and Range province. The large northwest-trending negative anomaly associated with the Klamath graben suggests a depth of low-density fill of up to 2300 m (7500 feet).

The regional gravity field exhibits a broad regional high over the area surrounding Klamath Falls which may be caused by a shallow mantle or a large intrusive body at depth, or may simply be due to intense silicification of the area by thermal waters.

The residual anomaly field exhibits broad bands of positive anomalies which enclose the negative anomaly associated with the Klamath graben. The easternmost of these broad, positive trends may correspond to the eastern flank of an anticline which may have existed prior to graben faulting. Positive anomalies west of the graben coincide with the Mount McLoughlin lineament. A large positive anomaly located south of Sprague River is interpreted to be a volcanic center and the heat source for thermal waters found in the Sprague River Valley.

A two-dimensional cross section near  $42^{\circ}26'$  N. latitude suggests that step-like faults form the west side of the Klamath graben. The model indicates the presence of a high density body south of Sprague River that is interpreted to be a buried volcanic source for local extrusive volcanic rocks.

Northwest-trending gravity anomalies west of Upper Klamath Lake indicate that structural trends of the Basin and Range province extend into the Cascade Mountains, and suggest that a heat source for thermal waters may exist beneath the High Cascades, rather than beneath the areas which exhibit geothermal activity.

Gravity Anomalies and Their Structural Implications  
for the Southern Oregon Cascade Mountains and  
Adjoining Basin and Range Province

by

Cynthia A. Veen

A THESIS

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Date Thesis is presented 2 July 1981

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GRAVITY ANOMALIES AND THEIR STRUCTURAL IMPLICATIONS  
FOR THE SOUTHERN OREGON CASCADE MOUNTAINS AND  
ADJOINING BASIN AND RANGE PROVINCE

INTRODUCTION

South-central Oregon provides a unique setting in which to study two provinces designated as potential geothermal resources, the High Cascades portion of the Cascade Mountain Range, and the Basin and Range province. The High Cascade Mountains have been designated by Godwin and others (1971) as an area of potential geothermal resource, while Grose and Keller (1979) suggest that high heat flow, thin crust, and extensive faulting characterize the Basin and Range province as a region of potential geothermal resource. Blackwell and others (1978) infer heat-flow values of  $100 \text{ mW/m}^2$  or greater for much of south-central Oregon.

Numerous thermal springs and wells exist south and east of Upper Klamath Lake in the Basin and Range province of south-central Oregon (Bowen and Peterson, 1970). No thermal manifestations are reported in the Cascade Mountains of southern Oregon, but the simultaneous occurrence of Basin and Range faulting and High Cascade volcanism during Pleistocene time, and the existence of structural trends in the High Cascades similar to those observed in the Basin and Range province, indicate that the thermal phenomena observed south and east of Upper Klamath Lake may be a result of the juxtaposition of the two provinces. The extensive faulting that occurs south of Upper Klamath Lake may provide conduits for meteoric waters from the High Cascades which

have become heated by hot rocks at depth. A heat source for these thermal waters may either exist directly beneath the thermal activity or beneath the High Cascades.

The objective of this study was to interpret gravity anomalies due to upper crustal structures in order to facilitate the understanding of the Cascade Mountain and Basin and Range geologic provinces, and the geothermal systems which lie in south-central Oregon. Gravity data were collected and analyzed for the area, shown in Figure 1, between 42°00' and 43°00' N. latitude, and 121°00' and 122°30' W. longitude. Standard reduction techniques were used to compute free-air and complete Bouguer anomalies. Residual anomalies, which facilitate the delineation of upper crustal structures, were calculated by computing the complete Bouguer anomaly at a reduction density of 2.43 gm/cm<sup>3</sup>, and then removing long-wavelength components from the data set.

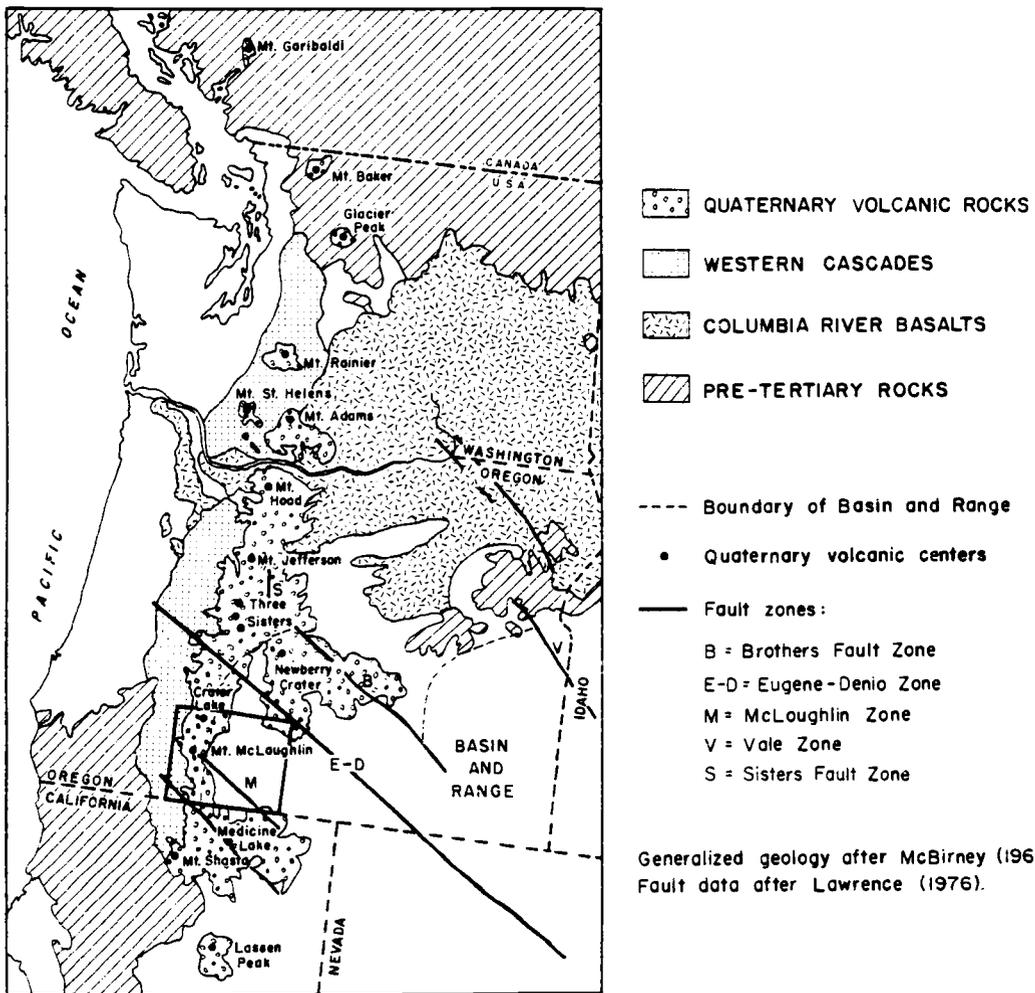


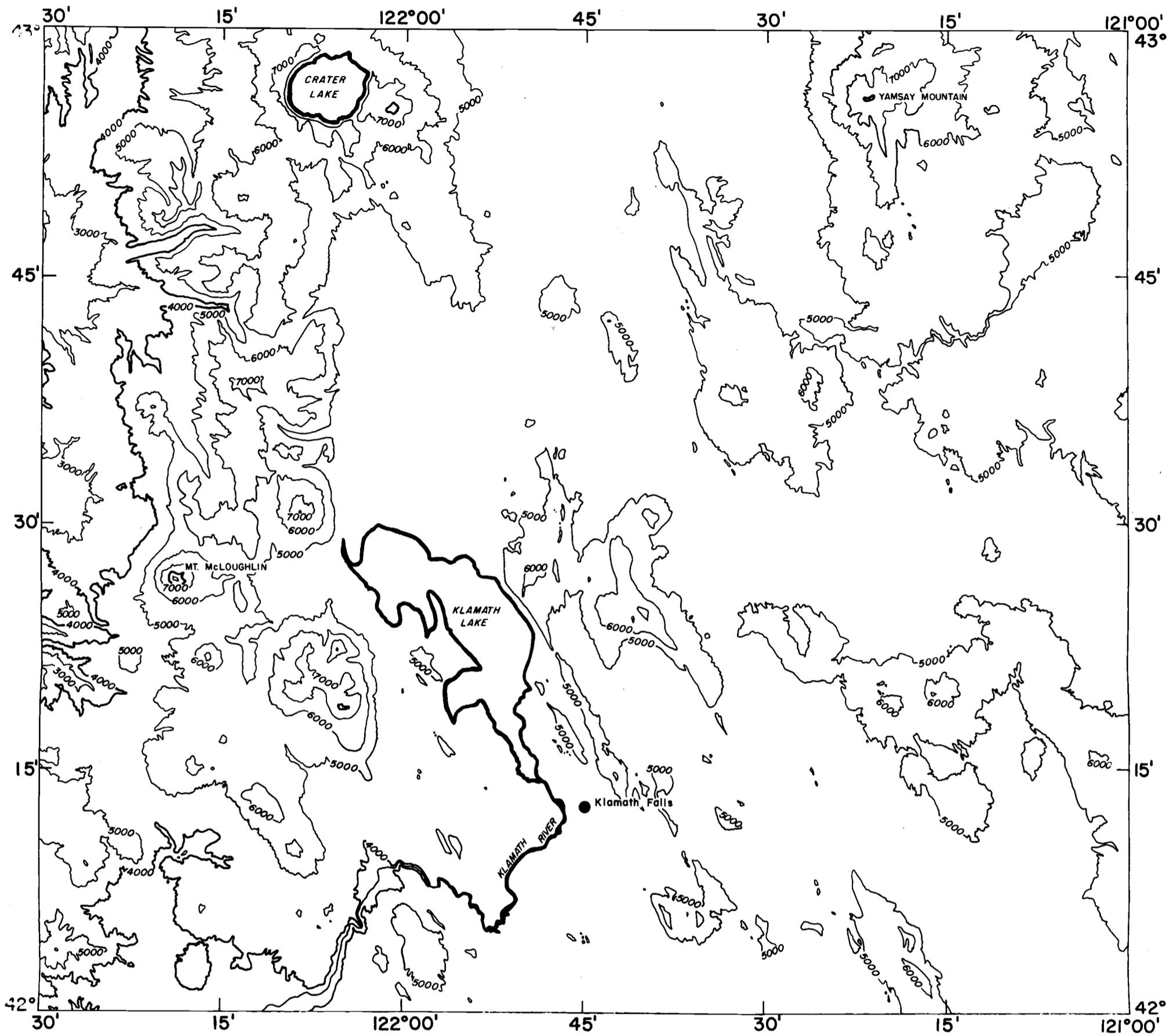
Figure 1. Study area outlined on map of physiographic provinces of Pacific Northwest.

## GEOLOGIC SETTING

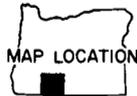
The study area includes portions of two major physiographic provinces: the Cascade Mountain Range, west of approximately 122°00' W. longitude, and the Basin and Range province, which occupies the eastern two-thirds of the study area (Figure 1). Peck and others (1964) divide the Cascade Mountain Range into the deeply dissected Western Cascade Mountains, which generally lie west of 122°15' W. longitude and have elevations of less than 1500 m (5000 feet), and the High Cascade Mountains, which form a belt of high, relatively undissected volcanic peaks, east of the Western Cascades (Figure 2). The Basin and Range province, east of 122°00' W. longitude is an area of lesser relief, with elevations generally ranging from 1200 to 2100 m (4000 to 7000 feet), which consists of north to northwest trending fault blocks and basins with internal drainage. The Klamath graben, a northwest-trending sediment-filled structural depression located north of Klamath Falls, is presumably related to Basin and Range tectonism. Table 1 gives the approximate location of physiographic features referred to in the text. Figure 3 is a geologic map of the study area.

Rocks of the Western Cascade Mountains range in age from Eocene to late Miocene. Volcanic rocks of similar age are found in eastern Oregon, and Maynard (1974) indicates that deposition of both groups may have occurred in the same large tectonic basin. Wells (1956) divided the section into three units: the Colestin Formation, the Little Butte Series, and the Heppsie Andesite.

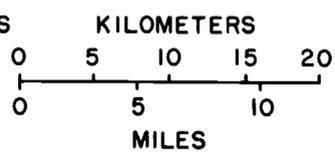
Wells (1956) described the Western Cascade stratigraphy for the



TOPOGRAPHIC MAP  
 CASCADE MOUNTAIN RANGE, SOUTHERN OREGON



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



TRANSVERSE MERCATOR PROJECTION  
 CONTOUR INTERVAL 1000 FEET  
 SCALE 1:500,000

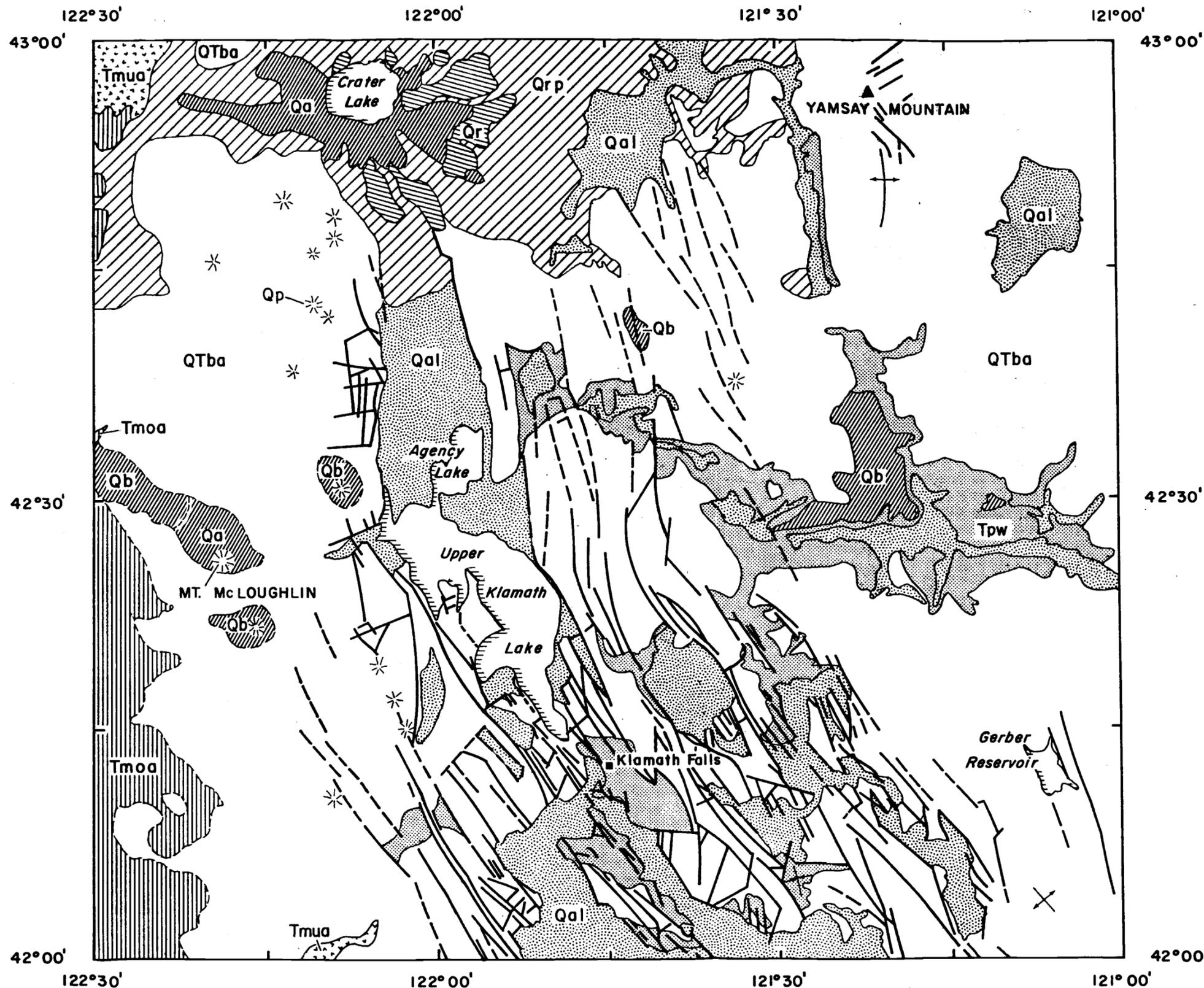
OREGON STATE UNIVERSITY  
 DECEMBER, 1980

Figure 2

Table 1. Locations of physiographic features.

	Latitude	Longitude
Agency Lake	42°32'	121°57'
Aspen Butte	42°18.9'	122° 4.1'
Crater Lake	42°56'	122° 6'
Fort Klamath	42°42.2'	121°59.8'
Greylock Mountain	42°21.9'	122° 8.2'
Humble Thomas Creek Number One Well	42° 6.0'	120°20.0'
Kingsley Field Air Force Base	42° 9.5'	121°45.0'
Klamath Falls	42°12'	121°45'
Klamath Hills	42° 4'	121°46.2'
Klamath Marsh	42°54'	121°45'
Lower Klamath Lake	42° 2'	121°49'
Mt. McLoughlin	42°26.7'	122°18.8'
Olene Gap	42°10.4'	121°36.8'
Parker Mountain	42° 6.3'	122°16.6'
Pelican Butte	42°30.8'	122° 7.6'
Poe Valley	42° 9'	121°30'
Sprague River (City)	42°27.4'	121°30.2'
Sprague River Valley	42°27.7'	121°30'- 121°00'
Swan Lake Valley	42°18'	121°38'
Upper Klamath Lake	42°14'- 42°30'	121°48'- 122° 2'
Yamsay Mountain	42°55.8'	121°21.5'

# GEOLOGY OF SOUTH CENTRAL OREGON



- |                          |        |   |
|--------------------------|--------|---|
| RECENT                   | Qal    | ALLUVIUM<br>Unconsolidated silt, clay, and pumice   |
|                          | Qrp    | PUMICE and ASH; Pumice blocks, dacite ash fall and ash flow, from either Mt. Mazama or Newberry Crater.   |
| PLEISTOCENE and RECENT   | Qa, Qb | Qa: ANDESITE; Pyroxene and olivine-bearing, composite cones & intracanyon flows.<br>Qb: BASALT; Olivine-bearing forming lava domes and intracanyon flows. |
|                          | Qr, Qp | Qr: RHYOLITE and DACITE; Porphyritic flows and domes.<br>Qp: PYROCLASTICS; Basaltic and andesitic pyroclastic rocks forming cinder cones.                 |
| PLIOCENE and PLEISTOCENE | QTba   | BASALT and ANDESITE; Open-textured olivine basalt and olivine andesite underlying and overlying the Yonna formation.                                      |
| PLIOCENE                 | Tpw    | WATERLAID VOLCANIC ROCKS; YONNA FORMATION: Diatomite, volcanic sandstone, siltstone, tuff, and thin interbedded basalts.                                  |
| MIOCENE                  | Tmua   | ANDESITE<br>Pyroxene andesite and basaltic andesite, dominantly flows.  |
| OLIGOCENE and MIOCENE    | Tmoa   | ANDESITE<br>Massive basaltic andesite with with interbedded pyroclastics.   |
- 
- |         |  |
|---------|--|
| ---     | Fault Trace (dashed where approximate) |
| - - - - | Contact (dashed where approximate)     |
| ↑       | Anticline                              |
| ∩       | Syncline                               |

From Wells & Peck, 1961

Scale 1: 500,000

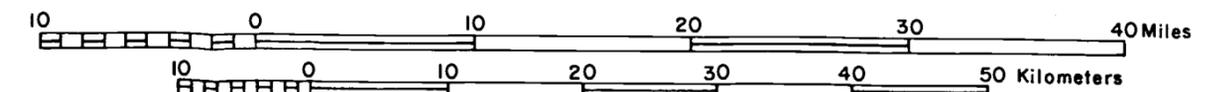


Figure 3

Medford Quadrangle, west of the study area. The following description is a summary of Wells' text. The lower Eocene Umpqua Formation, consisting of submarine lavas and shales, underlies rocks of the Western Cascades. Overlying the Umpqua Formation unconformably is the Colestin Formation, of late Eocene age. The formation is composed of volcanoclastic material with a few interbedded andesite flows. Maximum thickness is estimated to be approximately 600 m (2000 feet). The Roxy Formation, of Oligocene age, and the lower member of the Little Butte Series, unconformably overlies the Colestin Formation and consists of approximately 600 m (2000 feet) of andesite flows and flow breccias. The upper unit of the Little Butte Series, the Wasson Formation, is early Miocene in age, and comprises approximately 300 m (1000 feet) of siliceous tuff. Massive andesite flows of the Heppsie Andesite overlie the Wasson Formation. The Heppsie Andesite dips gently eastward and may exceed 450 m (1500 feet) in thickness. Estimates of the total thickness of the Western Cascade sequence range from 1000 to 1500 m (3000 to 5000 feet) in the Medford quadrangle (Wells, 1956) to at least 4500 m (15,000 feet) in the study area (Naslund, 1977). Following Western Cascade volcanism, the rocks were uplifted, gently folded and deeply eroded (Maynard, 1974). Normal faults which cut the Western Cascade Mountains south of Crater Lake are probably associated with the folding (Naslund, 1977).

The following outline of High Cascade stratigraphy summarizes a description given by Maynard (1974). A pronounced unconformity separates the Western Cascade sequence from the generally undeformed lavas

of the High Cascade Mountains. The High Cascade lavas include several series of flows, Pliocene to Pleistocene in age, each of which was deeply eroded before emplacement of the next group of flows. The two lower units are predominantly basalt. The flows of the upper unit are basalt and andesite, and form the high peaks and the shield volcanoes along the crest of the Cascades. In places some of the younger flows of the High Cascades have poured onto the Western Cascades or down the valleys as intracanyon flows (Baldwin, 1980). The volcanoes are normally polarized, and thus appear to be less than 670,000 years in age (McBirney, 1978). The highest peak in the area, Mt. McLoughlin, is an andesitic composite cone (Williams, 1962; Maynard, 1974) as is the ancient Mt. Mazama (Williams, 1962). A string of seven cinder cones, aligned parallel to the western fault of the Klamath graben, suggests that the numerous cinder cones which cover the area may be fault related (Maynard, 1974). Numerous normal faults cut the High Cascade rocks and are probably associated with Basin and Range faulting (Naslund, 1977).

The Basin and Range province in south-central Oregon consists of greater than 3000 m (10,000 feet) of mid-to-late Tertiary and Quaternary volcanic flows and sediments (Peterson and McIntyre, 1970). Imposed upon these sediments and flows are numerous north to northwest trending fault blocks and basins. The Klamath graben, north of Klamath Falls, is a sediment-filled basin bounded by northwest-trending faults. Hamilton and Myers (1967) and Smith (1977) suggested that regional extension produced the block faulting that resulted in either

horst-and-graben structures or tilted fault blocks. Stewart (1971) suggested that the horst-and-graben model may be more applicable to the Basin and Range province.

Scholz and others (1971) and Smith (1977) suggested that the compressive stress regime which existed during the subduction of the Falleron plate under the North American plate was released with subduction of the East Pacific Rise approximately 19 m.y.b.p. After 15 m.y.b.p. basaltic and rhyolitic volcanism and concurrent east-west extension predominated and migrated outward toward Basin and Range boundaries (Scholz and others, 1971). In the study area, normal faulting (Figure 3) was initiated during the Pliocene (Peterson and McIntyre, 1970). The formation of the present day basin and range topography began in early Pleistocene, contemporaneous with volcanism in the High Cascades. Peterson and McIntyre (1970) suggest that the Klamath graben structure was superimposed upon a pre-existing broad anticline, while the Yamsay Mountain - Sycan Marsh - Sprague River area is a broad, synclinal basin.

Peterson and McIntyre (1970) described the stratigraphy of the Basin and Range province in south-central Oregon. The following description is a summary of their text. The oldest rocks exposed in the Basin and Range province of the study area are volcanic rocks referred to as Tpw in Figure 3. These rocks are the mid-to-late Pliocene Yonna Formation, named by Newcomb (1958), and consist of an upper and lower basaltic lava sequence with a medial zone of waterlaid volcanoclastics, shales, and diatomites. These rocks reach thicknesses of 250 m (800

feet) near the town of Sprague River, and 450 m (1500 feet) southeast of Klamath Falls. Underlying the Yonna Formation are Pliocene basalt flows which are exposed east of the study area and reach thicknesses of up to 200 m (600 feet). Underlying these basalts are Miocene to Pliocene rhyolitic and dacitic tuffs and thin basalt and andesite flows which are at least 3500 m (11,000 feet) thick east of the study area at the Humble Thomas Creek number one well (Peterson and McIntyre, 1970). Thin basalt and andesite flows overlie the Yonna Formation over most of the area east of Upper Klamath Lake, and increase in thickness southeast of Klamath Falls. Numerous volcanic centers occur in the area, and range in composition from rhyolite to basalt. Yamsay Mountain is a predominantly andesitic eruptive center.

Most of the above rocks appear to be older than the faulting which produced the present topography. Younger rocks include Mazama and Newberry Crater pumice and ash which reach thicknesses of 20 m (65 feet) in the study area. Alluvium covers many of the low lying areas, and basin fill in the Klamath graben may reach thicknesses of up to 1800 m (6000 feet) (Sammel and Peterson, 1976).

## PREVIOUS GEOPHYSICAL INVESTIGATIONS

This study incorporates a total of 1236 previously established gravity stations. The southwest Oregon gravity survey of Blank (1965) established 481 stations within the study area. One hundred eighty-eight stations from Thiruvathukal (1968) used to construct the Oregon State gravity maps were located within the region. Van Deusen (1978) lists 455 stations for the Klamath Falls area. Sixty-one stations from Blakely (1979) lie in the western third of the study area, and 51 stations from Finn (1980) for the Crater Lake area also lie within the bounds of and are included in this study.

A hydrologic reconnaissance of the Klamath Falls geothermal area (Sammel and Peterson, 1976) includes a preliminary interpretation of data from 232 gravity stations and U.S. Geological Survey aeromagnetic measurements over the Klamath Falls area. Modelling of the gravity data indicates approximately 2000 m of fill in the Lower Klamath Lake area just north of the California-Oregon border, and 1000 m of fill for an area just east of Kingsley Field Air Force Base.

Berg and Baker (1963), and Couch and Lowell (1971) show epicenters from a total of nine earthquakes that occurred within the study area since 1841. Four of the epicenters are located near Klamath Falls and are most likely associated with block faulting. Three of the epicenters are located near Fort Klamath, southeast of Crater Lake.

A refraction study of the Summer Lake area (Donath, 1958, 1962; Donath and Kuo, 1962) indicates two major fault trends, one oriented N20°E to N30°E and the second oriented N30°W to N40°W. Donath (1962),

suggests that these faults originally developed as conjugate strike-slip shears along which the present system of fractures developed. Block faulting then took place along the previously developed fracture systems. Lawrence (1976) has identified these trends throughout the Basin and Range province in Oregon using LANDSAT images, but concluded that the two sets of faults resulted from the extension of blocks between shear zones, and right-lateral strike-slip motion along the shear boundaries.

Heat flow data for the state of Oregon (Blackwell and others, 1978) and the Klamath Falls area (Sass and Sammel, 1976) indicate heat flow values of greater than  $100 \text{ mW/m}^2$  for nearly the whole of the study area. A steep east-to-west gradient marks the western edge of the region and coincides with the boundary between the Western Cascades and the High Cascades. Within the Klamath Falls area, heat flow measurements are extremely variable, ranging from 12.6 to  $716.0 \text{ mW/m}^2$ . This large variation over small distances appears to be due to hydrologic effects and is characteristic of the heat flow in the Basin and Range province (Blackwell and others, 1978). A change from uniform heat flow in northeast Oregon to large variations in heat flow over small distances in southeast Oregon appears to coincide with the Brothers Fault Zone, which Lawrence (1976) believes to be the northern terminus of the Basin and Range province in Oregon.

Telluric current measurements in the Klamath Falls area (Bodvarsson and others, 1974) indicate a correlation between measured resistivity values and geothermal activity, but suggest that a NS-EW

anisotropy in resistivity values appears to correlate with the N-NW structural pattern in the area.

In conjunction with this study, an aeromagnetic survey was flown over the study area during the summer of 1981. Results are presented by McLain (1981). In addition, aeromagnetic studies by Scintrex (1972), Geometrics (1973), and Blank (1968) cover portions of the study area.

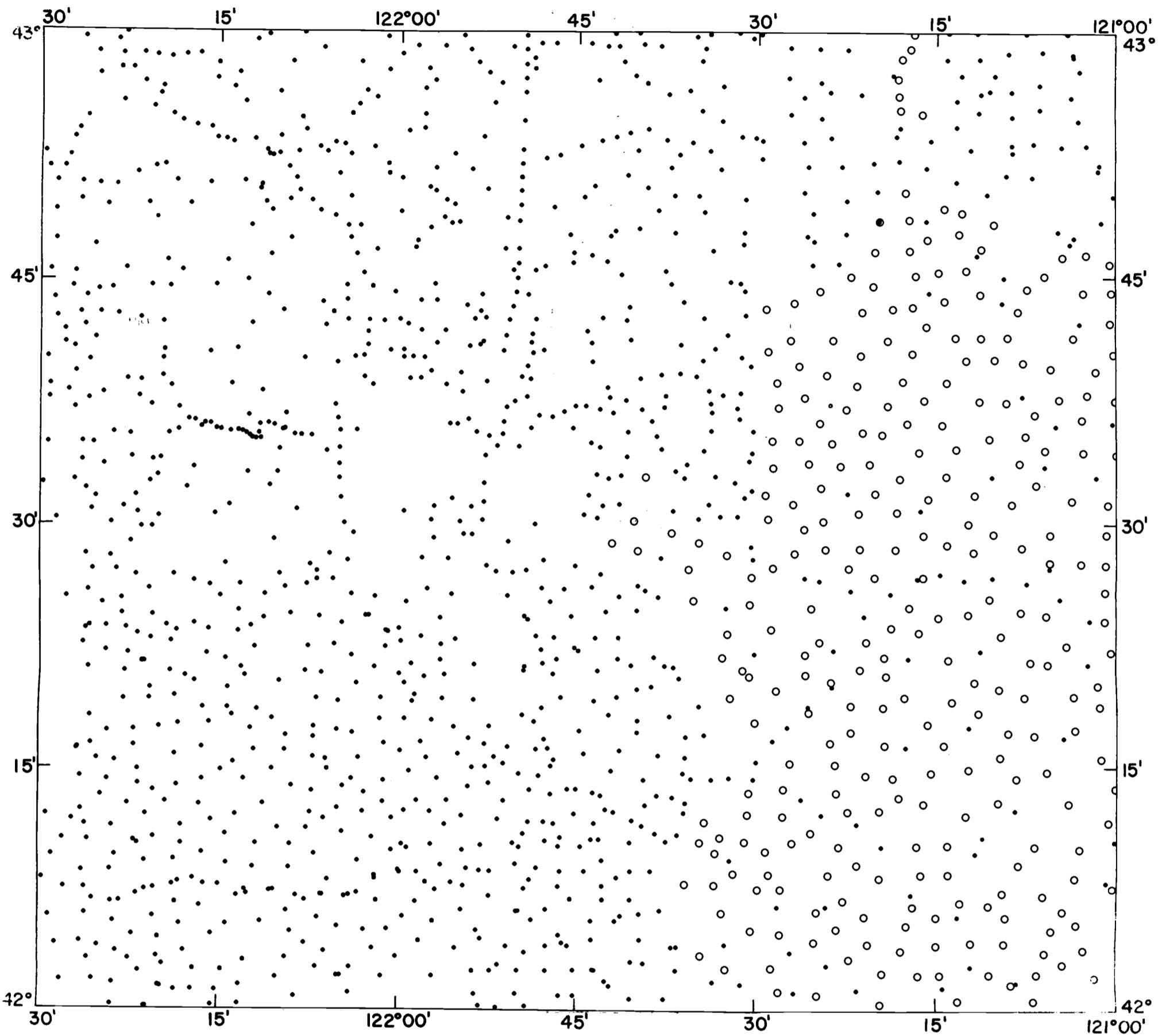
## GRAVITY SURVEY DATA

During the fall of 1979 and the summer of 1980, 362 gravity stations were established in the survey area. These data, combined with 1236 existing gravity stations from Blank (1965), Thiruvathukal (1968), Van Deusen (1974), Blakely (1979), and Finn (1980), yield a total of 1598 stations and an average spatial density of one station per 8.6 square km for the study area. Figure 4 shows locations of these stations.

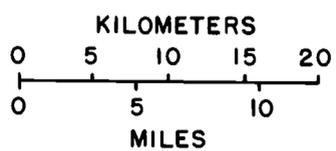
Primary and secondary base stations were established at Jackson Creek Guard Station, Thompson Reservoir, Bonanza, Sprague River, Fuego Mountain, Beatty, Ivory Pine Mill, Sycan Marsh, and Langell Valley. All base stations are tied indirectly to the Corvallis base station OSU-PC, established by Berg and Thiruvathukal (1965), which in turn is tied to the primary base station at the Carnegie Institution in Washington, D.C. (Berg and Thiruvathukal, 1965). Appendix C describes the base stations for this survey.

USGS and USC&GS benchmarks, and Oregon State Highway Department and U.S. Forest Service markers provided elevation control for the survey. Whenever possible, spot elevations from USGS 15 minute topographic maps were used. Aneroid barometers provided control when no known elevation was available. Terrain corrections for the stations were made out to a radial distance of 166.7 km (equivalent to Hayford-Bowie zone 0; Garland, 1977).

Free-air and complete Bouguer anomalies were calculated using values of theoretical gravity computed from the International Gravity



**GRAVITY STATIONS  
CASCADE MOUNTAIN RANGE, SOUTHERN OREGON**



TRANSVERSE MERCATOR PROJECTION  
SCALE 1:500,000

GRAVITY STATIONS  
O.S.U. GRAVITY FILE •  
VEEN 1981 ○

OREGON STATE UNIVERSITY

Figure 4

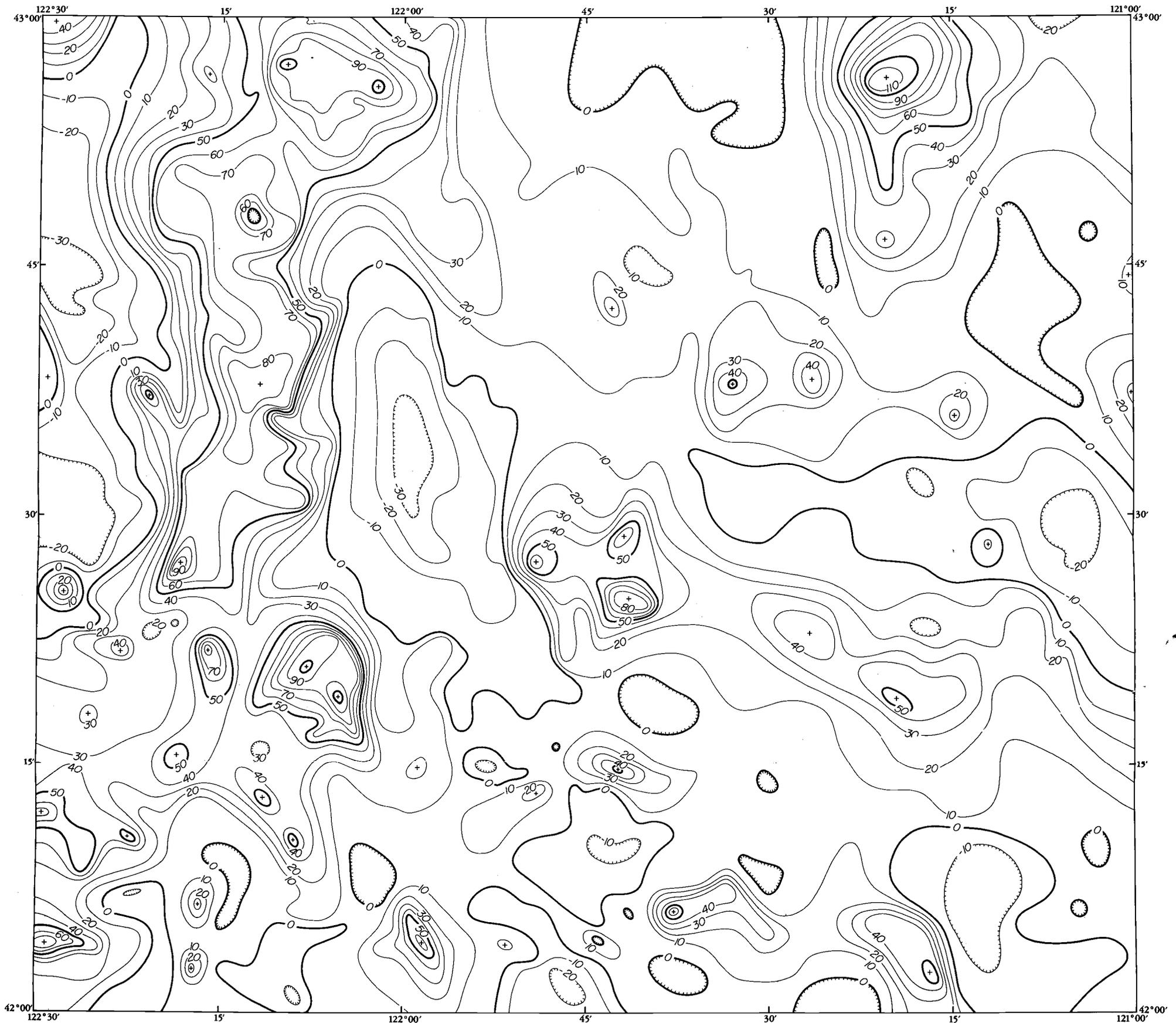
Formula, IGF-1930 (Swick, 1942). A reduction density of  $2.67 \text{ gm/cm}^3$  was used to calculate the complete Bouguer anomaly. Appendix A describes the data acquisition and reduction techniques.

## FREE-AIR GRAVITY ANOMALY MAP

Figure 5 shows the free-air gravity anomaly map of the south-central Oregon Cascade Mountain Range and adjoining Basin and Range province. The contour interval is ten mgals, and heavy contours occur at 50 mgal intervals. Amplitudes of the anomalies range from +110 mgals over Yamsay Mountain in the northeast corner of the map, to -30 mgals just west of Agency Lake and at the western edge of the map over a topographic low in which tributaries of the South Fork Rogue River flow. Appendix A discusses the calculation of the free-air anomalies.

The Cascade Mountain Range and Basin and Range physiographic provinces are evidenced west and east of  $122^{\circ}00'$  W. longitude, respectively. West of  $122^{\circ}00'$  W. longitude, free-air gravity anomalies trend north-south, and average approximately 35 mgals. East of  $122^{\circ}00'$  W. longitude, the anomalies trend west to northwest, are generally much broader and of lower amplitude than those in the western portion of the study area, and average near ten mgals. This difference reflects the character of the topography in each province. West of  $122^{\circ}00'$  W. longitude, the zero free-air anomaly contour generally coincides with the 4000 foot contour, while east of  $122^{\circ}00'$  W. longitude, the zero free-air anomaly corresponds to a level near 5000 feet. The above combination indicates that the crust may be either thicker or lighter in the eastern portion of the study area, or, as postulated later in the text, that there exists an anomalously low-density upper mantle layer beneath the Basin and Range province in Oregon. If a thicker or lighter crust accounts for the combination

**FREE-AIR GRAVITY ANOMALY MAP**  
**Cascade Mountain Range, Southern Oregon**



Contour interval 10 milligals  
 Estimated uncertainty in  
 measurements 1.0 milligal  
 Theoretical gravity: IGF (1930)

SCALE 1:500,000  
 2 0 4 8 12 Miles  
 4 0 8 16 Kilometers  
 Transverse Mercator Projection



Data from Veen (1981)  
 and OSU gravity file  
**OREGON STATE UNIVERSITY**  
 December 1980

Free-Air Gravity Anomaly:  
 Southern Oregon Cascades

Figure 5

of the zero free-air anomaly and elevation of 5000 feet described above, then the crust may be either  $.03 \text{ gm/cm}^3$  lighter in the Basin and Range portion of the study area than beneath the Cascade Mountains, assuming a crustal thickness of approximately 40 km, or it is approximately 2.5 km thicker in the eastern portion of the study area than in the west, assuming a density contrast of  $.4 \text{ gm/cm}^3$  between the crust and mantle.

Because the free-air anomaly is partially elevation dependent, areas of topographic low generally correspond to near zero or negative free-air anomalies, while positive free-air anomalies coincide with topographic highs. It is possible, however, to compare the relative amplitudes of anomalies associated with various features and give qualitative comparisons between these features. Mt. McLoughlin, for example, is the highest peak in the area, yet exhibits a lower free-air anomaly (+90 mgals) than do Greylock Mountain and Aspen Butte (+100 mgals), southwest of the gravity low associated with the Klamath graben, Crater Lake (+100 mgals), or Yamsay Mountain (+110 mgals). This comparison suggests that Mt. McLoughlin is composed of material of lighter average density than these other features, or that compensation occurs directly beneath the mountain. Yamsay Mountain, in particular, for reasons discussed above pertaining to the Basin and Range province, must be composed of material of higher average density than Mt. McLoughlin, and/or be associated with a high density body at depth.

The -30 mgal low centered north of Upper Klamath Lake is associated with the Klamath graben. At its northern end, this negative

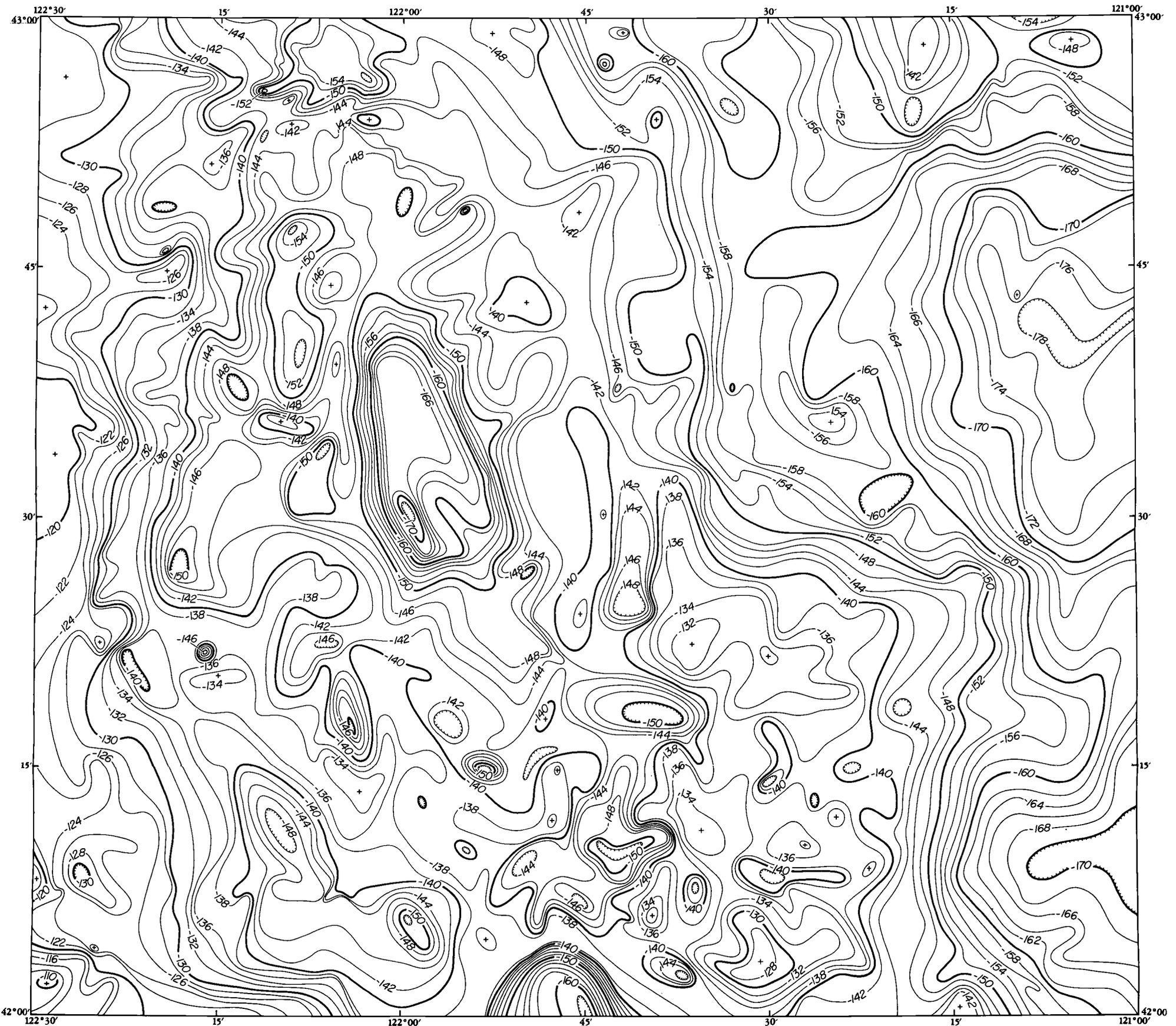
trend terminates against the positive anomaly associated with Crater Lake. The -20 mgal negative anomaly at the southern edge of the map corresponds to the northern portion of the Lower Klamath Lake graben, which, at its southern end, terminates at the positive anomaly associated with the Medicine Lake Highlands (Chapman and Bishop, 1968). South of the low associated with the Klamath graben, anomalies trend east-southeast, toward a ten mgal negative anomaly in the southeast corner of the map. A similar east-southeast trend is apparent on LANDSAT imagery, and Lawrence (personal communication) believes that these trends suggest that the Klamath graben trends near S60°E south of Upper Klamath Lake, and is not continuous with the Lower Klamath Lake graben complex to the south. The Klamath graben and Lower Klamath Lake graben complex are separated by a series of closed positive anomalies which trend northeast from 42°00' N. latitude and 122°00' W. longitude. A second theory proposed by Van Deusen (1978) suggests that this northeast positive trend may represent a barrier to crustal extension. Away from this barrier, a zone of right lateral shear offsets the Klamath graben and the Lower Klamath Lake graben complex. As a third alternative, the main Klamath graben may narrow as it intersects this positive trend and then widen southward to form the Lower Klamath Lake graben complex.

## COMPLETE BOUGUER GRAVITY ANOMALY MAP

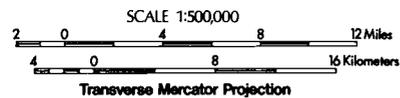
Figure 6 shows the complete Bouguer gravity anomaly map of south-central Oregon. The contour interval is two mgals and heavy contours occur at intervals of ten mgals. The contours trend north-south in the western portion of the map, and north-northwest in the eastern portion, parallel to structural trends of the Cascade Mountain Range and Basin and Range physiographic provinces. Amplitudes of the anomalies range from a high of -110 mgals at the southwest corner of the map to -178 mgals at the eastern edge of the map. A standard reduction density of  $2.67 \text{ gm/cm}^3$  (Nettleton, 1976, p. 257) was used to calculate the complete Bouguer anomalies. Appendix A discusses the calculation of the complete Bouguer anomalies for the gravity stations.

The west-to-east negative gradient apparent on the map is part of a regional gradient which becomes increasingly negative in a southeasterly direction. This regional gradient is portrayed by Thiruvathukal (1970) for Oregon between  $123^{\circ}00'$  and  $121^{\circ}00'$  W. longitude. Bouguer gravity anomaly values for the study area average approximately 40 mgals lower than those of Braman (1981) for the northern Oregon Cascade Mountains, and ten mgals lower than those of Pitts (1979) for central Oregon between  $122^{\circ}30'$  and  $121^{\circ}00'$  W. longitude. This gradient may, as suggested by Thiruvathukal (1970), reflect a thickening of the crust to the southeast. However, Hill and Pakiser (1967), Cook (1967), Scholz and others (1971), and Priestly and Brune (1973) suggested that the lower crust-upper mantle structure in the Basin and Range province may be more complex than the simple two-

**COMPLETE BOUGUER GRAVITY ANOMALY MAP**  
**Cascade Mountain Range, Southern Oregon**



Contour interval 2 milligals  
 Estimated uncertainty in  
 measurements 1.0 milligal  
 Reduction density 2.67 gm/cc  
 Theoretical gravity: IGF(1930)



Data from Veen (1981)  
 and OSU gravity file  
**OREGON STATE UNIVERSITY**  
 December 1980  
 Complete Bouguer Gravity Anomaly:  
 Southern Oregon Cascades

Figure 6

layer case (constant-density crust overlying constant-density mantle) used by Thiruvathukal (1970) in his work. However, none of the above studies extend into southern Oregon.

Once the regional gradient is recognized, the most striking feature on the map is the northwest-trending negative anomaly associated with the Klamath graben, and centered northwest of Upper Klamath Lake. The anomaly appears to either terminate at its southern end against a -138 mgal positive anomaly or to curve eastward south of approximately  $42^{\circ}25'$  N. latitude so that its trend is near  $S60^{\circ}E$ . The -138 mgal positive anomaly is coincident with the positive trend on the free-air gravity anomaly map which Van Deusen (1978) suggested may be a barrier to crustal extension. This closed high may be due to the barrier material, or to increased volcanism in a zone of weakness along a shear boundary associated with the barrier. An alternative interpretation of this closed high is that the Klamath graben may narrow at this point and then widen to form the Lower Klamath Lake graben complex. In this region, a decrease in the amount of graben fill and an increase in volcanism along this narrowing zone could account for the positive anomaly. Lawrence (personal communication) however, believes that the Klamath graben and the graben complex associated with Lower Klamath Lake are not structurally continuous, but that trends observed on LANDSAT imagery suggest a change in trend of the Klamath graben at Upper Klamath Lake to nearly  $S60^{\circ}E$ . The graben may be continuous with a structural basin which produces the negative anomaly in the southeast corner of the map. Lawrence (1976) has

suggested the presence of a Mount McLoughlin zone along which the north-south trend of the High Cascades is offset 15 to 20 km in a right lateral sense. Faults related to this S60°E trend of the Klamath graben would intersect this zone at oblique angles, which Lawrence (personal communication) suggests is common along shear zones.

The 20 mgal negative anomaly located over the Klamath graben suggests a depth of fill of from 450 m (1500 feet) to 2300 m (7500 feet) if the density contrast between the graben fill and the surrounding rock is  $1.0 \text{ gm/cm}^3$  and  $.2 \text{ gm/cm}^3$ , respectively. Van Deusen (1978) suggested that the density contrast may be near  $.3 \text{ gm/cm}^3$ . The depth of fill at this contrast would be approximately 1600 m (5300 feet), which is similar to a depth of fill of 1800 m (6000 feet) suggested by Sammel and Peterson (1976). The negative lobe on the eastern edge of the anomaly associated with the Klamath graben is probably associated with low-density fill in the Williamson River Valley.

The closed negative anomaly located at the northern edge of the map near 122°00' W. longitude is associated with Crater Lake but is centered north of the caldera. A ridge of positive anomalies extends from the southern rim of the caldera towards the southeast, where it separates the Klamath Marsh from the Klamath graben, and then southward along the eastern flank of the Klamath graben. Blank (1968) attributed this ridge to a northwest-trending 'basement' structure which merges with the main mass of Mt. Mazama south of the caldera. Peterson and McIntyre (1970) suggested that Basin and Range faulting

in south-central Oregon may have been superimposed on pre-existing broad, gentle folds. This 'basement' structure may be the eastern flank of an anticline which has since been obscured by faulting related to the formation of the Klamath graben. The negative anomaly associated with Crater Lake and other recent volcanic centers (e.g. Mt. McLoughlin) may reflect the inappropriateness of the  $2.67 \text{ gm/cm}^3$  reduction density.

The positive anomaly in the southwest corner of the map may represent the eastern extent of the Klamath Mountains along the Oregon-California border. On the geologic map of Wells and Peck (1961), the contact between the Klamath Mountains and the Western Cascades occurs near  $122^{\circ}35'$  W. longitude, but rocks of the Klamath Mountains may extend eastward beneath the Western Cascades in this region.

The positive anomaly at the western edge of the map coincides with a topographic low and a negative free-air anomaly discussed in the previous section. The anomaly trends north-northeast toward Crater Lake, against which it terminates. Wise (1963), and Naslund (1977), suggested that the similarity in age and structural trends between the Klamath Mountains and the Blue Mountains of northeast Oregon may indicate that these units are continuous beneath the Cascade Mountains. This northeast positive trend may be due to the presence of rocks of the Klamath Mountains beneath the Cascades in this area.

The broad negative anomaly located along the eastern portion of the map is due only in part to the regional gradient. The broad

nature of the anomaly suggests that it may be due to the presence of a large depression in which up to 1000 m (3300 feet) of sediments may have accumulated. Peterson and McIntyre (1970) indicated that regional dips in the area of Yamsay Mountain, Sycan Marsh, and Sprague River suggest the presence of a large synclinal basin which was formed prior to Basin and Range faulting. The positive anomaly associated with Yamsay Mountain may mask the effect of such a basin in this area, and suggests that there is a rather large mass associated with Yamsay Mountain.

The two positive anomalies in the southern half of the map near 121°30' W. longitude do not coincide with particular topographic features, or appear to be associated with any dense intrusive or extrusive bodies mapped by Wells and Peck (1961) or Peterson and McIntyre (1970). These anomalies suggest the presence of buried volcanic bodies or volcanic sources which may be in part responsible for the large volume of lava extruded in the area since Pliocene time.

## REGIONAL GRAVITY FIELD SEPARATION

The standard reduction density of  $2.67 \text{ gm/cm}^3$  used to calculate the complete Bouguer anomaly does not always represent the density of upper crustal rocks in a particular region. It is sometimes desirable to calculate a complete Bouguer anomaly using a more appropriate reduction density for an area that minimizes the correlation of the complete Bouguer anomaly with topography. Van Deusen (1978) determined a reduction density of  $2.43 \text{ gm/cm}^3$  for the Klamath Falls area by using the graphical method of Nettleton (1939) which involves finding the Bouguer gravity anomaly that least correlates with the topography along a profile. A  $2.43 \text{ gm/cm}^3$  reduction density has also been used by Pitts (1979) for central Oregon between  $122^\circ 30'$  and  $121^\circ 00'$  W. longitude, by Braman (1981) for the northern Oregon Cascade Mountains, and is chosen here to best represent the average density of the near-surface rocks in south-central Oregon. The complete Bouguer anomaly at a reduction density of  $2.43 \text{ gm/cm}^3$  is calculated by the equation

$$\text{CBA}(2.43) = (\text{CBA}(2.67) - \text{FAA}) * (2.43/2.67) + \text{FAA}$$

where CBA is the complete Bouguer anomaly and FAA is the free-air anomaly.

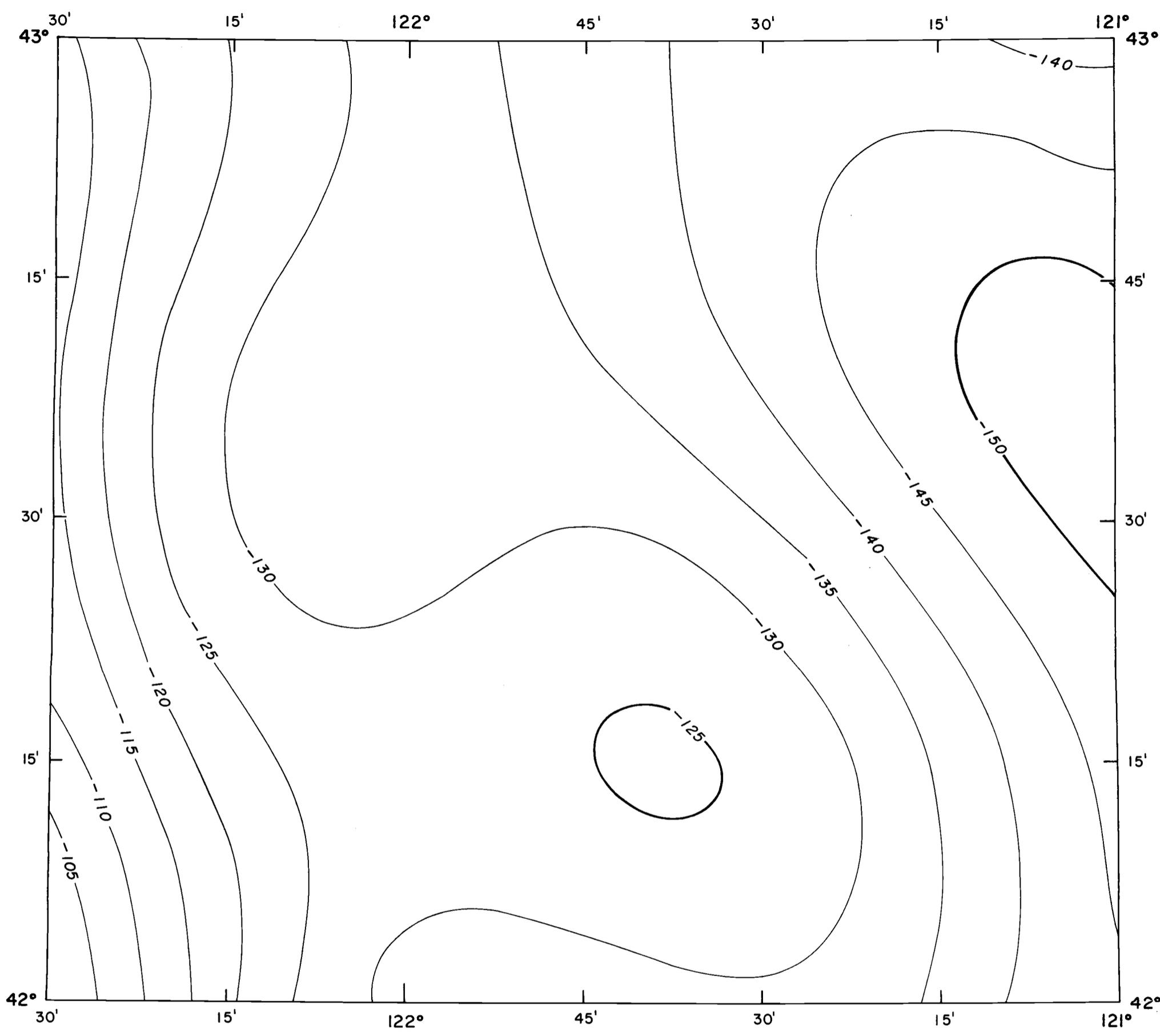
Separation of long-wavelength and short-wavelength components is also an important step in the interpretation of gravity data. Long-wavelength components are due either to shallow, broad features, or to deeper structures. Short-wavelength components are due to

relatively shallow features. Removal of long-wavelength components from a set of data facilitates the interpretation of those anomalies due to shallower features.

To compute the regional field for south-central Oregon, data for the study area were combined with data available for the remainder of Oregon and northern California (Blank, 1965; LaFehr, 1965a; Chapman, 1966; Chapman and Bishop, 1968; Thiruvathukal, 1968; Leutscher, 1968; Kim and Blank, 1973; Griscom, 1973, 1974, 1975; Larsen and Couch, 1975; Oliver and others, 1975; Alemi, 1978; Pitts, 1979; Braman, 1981; Finn, 1981). The combined data set was detrended and gridded into a 101 X 101 data matrix with a grid spacing of six km, using the method of Briggs (1974). This matrix occupies the center of a 128 X 128 matrix. Bouguer gravity anomaly values for the annulus of the larger matrix were obtained from a smoothing process using values from the outer rim of the inner data matrix. Appendix B describes the process of computing the regional gravity field.

A low-pass wavenumber filter, applied to the 128 X 128 matrix, eliminated wavelengths shorter than 90 km. Appendix B describes the process by which residual gravity anomalies for the study area were computed.

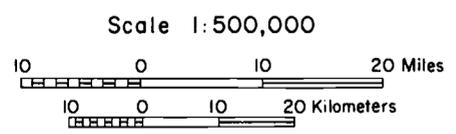
Figure 7 shows the regional gravity anomaly map for the study area. The contours trend subparallel to the Cascade Mountains in the western portion of the map, but appear to be affected by basin and range structures east of  $122^{\circ}15'$  W. longitude. A -125 mgal closed positive high is centered approximately ten km northeast of Klamath



Contour interval 5 milligals  
 Reduction density 2.43 gm/cc  
 Components less than 90 km are removed

### REGIONAL GRAVITY MAP SOUTH CENTRAL OREGON

Data from OSU gravity file  
 Oregon State University  
 April, 1981



Transverse Mercator Projection



Figure 7

Falls.

The -130 mgal contour crosses the Klamath graben at the northern end of Upper Klamath Lake and again just north of the Lower Klamath Lake graben complex. The regional gravity field in Figure 7 consists of wavelengths greater than 90 km. The field is caused by bodies whose lateral extent is greater than one-half wavelength, or 45 km, or point sources at depths of greater than one-eighth of 90 km, or 11 km (Thiruvathukal, 1970). The -125 mgal closed positive high north-east of Klamath Falls may be caused by a dense body located directly beneath the anomaly. A spherical body centered at a depth of 11 km below the -125 mgal closed high, with density contrasts of  $.2 \text{ gm/cm}^3$  and  $.3 \text{ gm/cm}^3$  between the sphere and the surrounding rock, and radii of 6 km and 5 km, respectively, would produce the anomaly. A horizontal slab with a lateral extent of at least 45 km and density contrasts of  $.2 \text{ gm/cm}^3$  and  $.4 \text{ gm/cm}^3$  between the slab and the surrounding rock, and thicknesses of 1.2 km and .6 km, respectively, would also produce an anomaly of the amplitude observed. A more probable explanation for the -125 mgal closed positive high is that the high is caused by a positive density contrast between the sediments and flows located between the graben structures and the basin fill in the Klamath graben and Lower Klamath Lake graben complex north and south of the closed high, respectively.

Wise (1963) and Naslund (1977) suggested that rocks of the Klamath Mountains may extend beneath the Cascade Mountains in a northeasterly direction and be structurally continuous with the Blue

Mountains of northeastern Oregon. Van Deusen (1978), however, has suggested that rocks of the Klamath Mountains may extend eastward beneath the Western and High Cascades into the area south of Upper Klamath Lake. If this were so, then the -105 to -125 mgal contours should also be deflected eastward in this vicinity. These contours appear to be more affected by the westward swing of the -130 mgal contour, which is probably related to the large vertical and lateral extent of the northern, deeper portion of the Klamath graben. The -130 mgal lobate anomaly located over the area surrounding Klamath Falls may correspond to, as postulated in previous section, a zone in which the Klamath graben complex is constricted, possibly accompanied by an increase in faulting and/or recent volcanism. Hydrothermal alteration of the sediments along fault zones, in the area where the Klamath graben is constricted, may increase the density of the graben fill. Sammel and Peterson (1976) suggested that the present areas of geothermal activity are the only remaining open conduits in which thermal waters may rise. They speculated that 'some thousands of cubic meters of rock' in the Klamath Falls area have been silicified. This region may also be, as suggested by Van Deusen (1978) a barrier to crustal extension along which right lateral shear and accompanying volcanism has taken place. Alternatively, the -130 mgal positive anomaly generally coincides with the change in trend of the graben structure suggested by Lawrence (personal communication), suggesting that an anomalous mass at depth may be associated with this structure. Any of the above theories may account for the -130 mgal regional

gravity high.

It is of interest to note that the positive anomaly discussed above includes the area in which most of the thermal springs located within the study area occur. It may be possible that a buried mass or a thin crust and shallow mantle is associated with these thermal manifestations. Thin crust and a low-velocity, low-density upper mantle are characteristic of the Basin and Range province (Scholz and others, 1971). A shallow mantle may extend beneath the Klamath graben and Lower Klamath Lake graben complex, but may be masked in the regional field by the large negative anomalies associated with these structures. It may also be possible that an increase in faulting in this area suggested on the geologic maps of Wells and Peck (1961), and Peterson and McIntyre (1970) and associated with the zone in which the graben structure is constricted, the shear zone, or the change in trend of the graben structure, provides a greater number of conduits in which thermal waters may rise. The combination of a shallow mantle and one of the above factors may be the cause of the thermal manifestations observed in the area.

The negative anomaly at the eastern end of the map may be due to a large, synclinal basin in the area suggested by Peterson and McIntyre (1970).

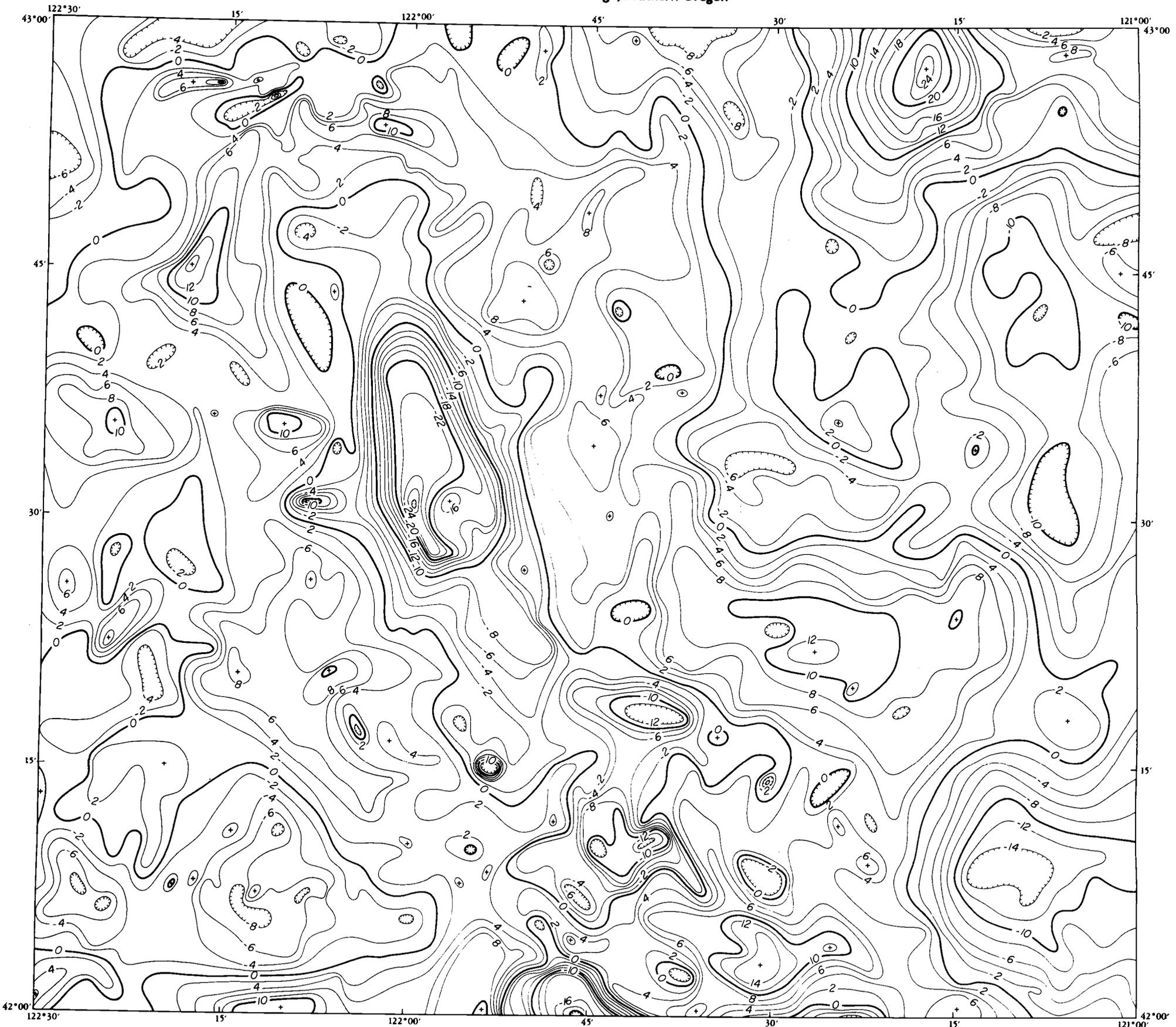
## RESIDUAL GRAVITY ANOMALY MAP

Figure 8 shows the residual gravity anomaly map for south-central Oregon. Residual gravity anomalies for the study area were calculated using a reduction density of  $2.43 \text{ gm/cm}^3$ , and by removing components of the gravity anomalies with wavelengths greater than 90 km, as discussed in Appendix B. The contour interval for the map is two mgals, and heavy contours occur at ten mgal intervals. Amplitudes of the residual anomalies range from a low of -28 mgals over the Klamath graben to +24 mgals over Yamsay Mountain.

The north-south trend associated with the Cascade Mountains is less evident on the residual gravity anomaly map than on the free-air and complete Bouguer anomaly maps. The anomalies in the western portion of the residual map trend north-northeast in the northern half of the map, but trend southeast south of Mt. McLoughlin. East of  $122^{\circ}00'$  W. longitude, trends of anomalies range from east-west near the Sprague River Valley to northwest near the Klamath graben and north-south in the northeastern quarter of the map. The discussion of particular trends and anomalies will refer to Figure 9, which is the residual gravity anomaly map with thermal springs marked as solid circles and other features marked with heavy lines and letters.

The closed positive anomalies located along the  $N25^{\circ}E$ -striking positive trend, shown as line A-A' on Figure 9, do not appear to correlate with particular topographic features. Indeed, the elongated +14 mgal closed anomaly strikes perpendicular to streams in the area, indicating that the body causing the anomaly does not influence local

**RESIDUAL GRAVITY ANOMALY MAP**  
**Cascade Mountain Range, Southern Oregon**



Contour interval 2 milligals  
 Estimated uncertainty in  
 measurements 1.0 milligal  
 Reduction density 2.43 gm/cc  
 Regional components greater  
 than 90 kilometers are removed  
 Theoretical gravity: IGF(1930)

SCALE 1:500000  
 2 0 4 8 12 Miles  
 4 0 8 16 Kilometers  
 Transverse Mercator Projection



Data from Geophysics Group,  
 OSU(1980) and OSU gravity file  
**OREGON STATE UNIVERSITY**  
 May 1981  
 Residual Gravity Anomaly:  
 Southern Oregon Cascades

Figure 3

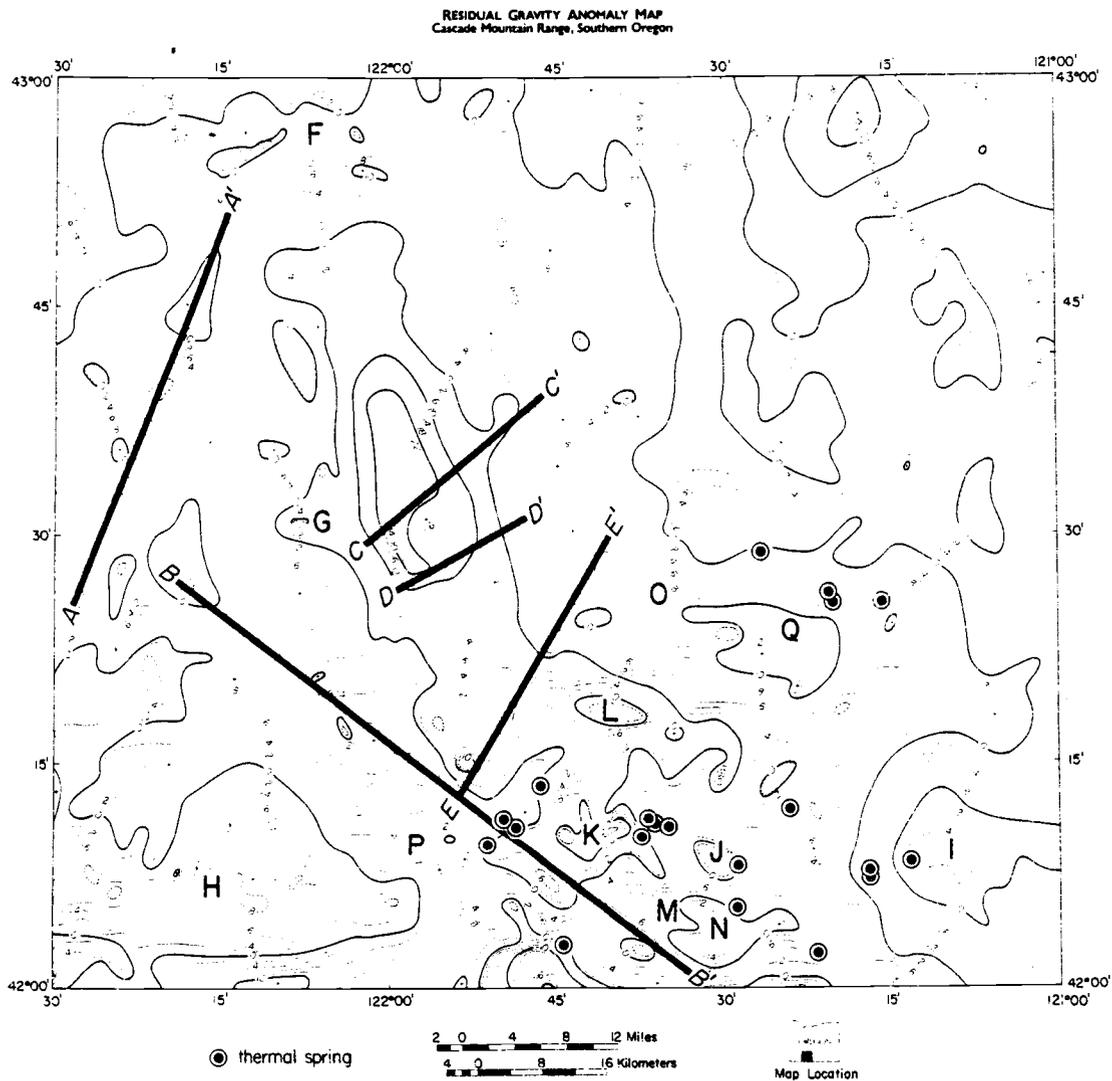


Figure 9. Thermal springs and anomaly trends plotted on residual gravity anomaly map.

drainage patterns. Wise (1963) and Naslund (1977), suggested that rocks of the Klamath Mountains may extend beneath the Cascade Mountains and be continuous with rocks of the Blue Mountains of northeastern Oregon. The northeast-trending high may be due to the presence of rocks of the Klamath Mountains beneath the Cascades, while the closed positive highs may be due to undulations in this surface. The gradient along the western edge of the +14 mgal closed anomaly is steep (five mgals/km) and rather linear in nature, however, and suggests the presence of a near-surface fault. There are no indications of faults in this area on the geologic map of Wells and Peck (1961), but the northeast alignment of cinder cones less than ten km east of the +14 mgal anomaly, and the suggestion by Maynard (1974) that cinder cones may be fault related, suggest that there may be northeast-trending faults beneath the upper units of the High Cascade lavas. This anomaly may also be due to a buried sill-like mass whose boundaries are fault controlled. If this feature is approximated by a slab with a density contrast between the slab and surrounding pyroclastics of the Western Cascades of  $.2 \text{ gm/cm}^3$ , a slab thickness of 1.2 km is required to produce this anomaly. The absence of a topographic expression of this feature suggests that if it is fault controlled, a structural depression may have been created by faulting and subsequently filled by either massive andesite flows, which are the upper unit of the Western Cascade sequence, or basaltic lavas of the lower High Cascade sequence.

Crater Lake (F) exhibits a small positive anomaly. The low

amplitude of this anomaly (less than two mgals) suggests that a reduction density of  $2.43 \text{ gm/cm}^3$  is appropriate for Mt. Mazama. Blank (1968) used a reduction density of  $2.45 \text{ gm/cm}^3$  in the Crater Lake area. West of Crater Lake, two elongate anomalies, one positive and one negative, extend outward. The positive anomaly is controlled by seven data points and the shape of the negative anomaly is controlled by 11 data points. The elongate nature of the negative anomaly suggests that it may be due to an anomalously thick section of pyroclastics which fill an ancient river canyon or glacial valley. If the pyroclastics are represented by a horizontal cylinder, then a cylinder with a radius of .2 km and a density contrast between the cylinder and andesite flows and pyroclastics of Mt. Mazama of  $.45 \text{ gm/cm}^3$  yields an anomaly similar to that observed. Similarly, the positive anomaly just north of this negative anomaly may be due to an intracanyon flow, or possibly a dike, and can be approximated by a similar cylinder with a positive density contrast between the cylinder and Mt. Mazama rocks of  $.4 \text{ gm/cm}^3$ . Both of these anomalies have a similar shape - a small high amplitude anomaly at the eastern end which broadens and becomes flatter away from Crater Lake. The shape of the anomalies suggests that both materials occur in ancient river canyons or glacial valleys, and may have 'ponded' at a sudden decrease in slope, then thinned out and widened away from the mountain as the valley or canyon widened. Southeast of Crater Lake, a positive anomaly has been suggested by Blank (1968) to be associated with the main mass of Mt. Mazama.

A broad positive anomaly with small, enclosed negative anomalies

strikes N120°E from Mt. McLoughlin, and is coincident with the Mount McLoughlin zone suggested by Lawrence (1976). Lawrence has proposed that the Mount McLoughlin zone offsets the High Cascades approximately 15 to 20 km in a right lateral sense, but is a less obvious and extensive feature than the Eugene-Denio zone and Brothers Fault zone located north of the study area. The right-lateral offset of Mt. McLoughlin from the north-south trend of the High Cascade volcanoes north of, and including Crater Lake is apparent on topographic maps, but on the residual anomaly map, right-lateral offset of a particular trend associated with the High Cascades is not obvious. The positive anomaly associated with this zone, however, could suggest a general increase in dense rocks associated with volcanic flows which may have occurred along this postulated shear zone.

The closed positive and negative anomalies along the Cascade Mountains are not generally as correlative with particular topographic features as anomalies on the free-air and complete Bouguer anomaly maps. This indicates that a reduction density of  $2.43 \text{ gm/cm}^3$  is appropriate for the area. There are two closed positive anomalies at the western edge of the map south of  $42^{\circ}30'$  N. latitude. Maynard (1974) has located several vents of the Heppsie Andesite near these anomalies. The positive anomalies may be due to the presence of source bodies for these vents.

The closed -12 mgal negative anomaly (G) just west of the main Klamath graben corresponds to Pelican Butte, and indicates that there is a substantial amount of low density material associated with the

mountain. On the Bouguer anomaly map (Figure 6), however, the anomaly is somewhat broader and of lower amplitude (approximately six mgals). The regional field in this area is affected by the large negative anomaly associated with the Klamath graben. On the regional gravity map (Figure 7), Pelican Butte is located just east of the -130 mgal contour, where the -130 mgal contour loops to the west. Consequently, the residual anomaly associated with Pelican Butte may be amplified by the removal of the regional field. Although it is difficult then, to determine a bulk density for the mountain, the negative residual anomaly associated with Pelican Butte suggests a composition of material of lower average density than the surrounding country rock.

The east-west trending low marked H on the map may be an area in which the lower High Cascade basalt flows are relatively thin. Parker Mountain, which lies just west of the eight mgal negative anomaly rests upon approximately 90 m (300 feet) of High Cascade lavas (Naslund, 1977). South of this negative trend is a ten mgal high which is closed upon addition of data from northern California (Van Deusen, 1978). The area includes a portion of the Klamath River canyon in which nearly 375 m (1200 feet) of flat-lying High Cascade flows are exposed. The Klamath River is antecedent in this area, and Naslund (1977) suggests that lavas may have ponded here, creating an unusually thick section of High Cascade basalts. If the High Cascade section which produces the ten mgal positive anomaly is only 285 m (900 feet) greater in thickness than the section near Parker Mountain, a density contrast of nearly  $1.0 \text{ gm/cm}^3$  is required to produce the observed

anomaly. A density contrast of  $1.0 \text{ gm/cm}^3$  suggests that rocks of the High Cascades have a density of nearly  $3.50 \text{ gm/cm}^3$ , which is an unreasonably high density for basalts. Because the steep gradients associated with this anomaly suggest near surface source bodies, the High Cascade section may be up to 1400 m (4500 feet) thick near  $42^\circ 00'$  N. latitude. Naslund (1977) has suggested that the existence of at least one peak in this area is fault controlled, so that faulting may be responsible for at least part of the steep gradient associated with the ten mgal positive anomaly. Sammel and Peterson (1976) also suggest a fracture zone exists along the Klamath River.

The -14 mgal anomaly in the southeastern corner of the map (I) occurs over a structural depression and a topographic low which is bounded by faults on the west near  $121^\circ 15'$  W. longitude, and on the east near  $121^\circ 00'$  W. longitude. The amplitude of this anomaly suggests that there is a substantial thickness of low density fill beneath a thin veneer of basalt flows overlying the area mapped by Peterson and McIntyre (1970). Lawrence (personal communication) suggests that the depression may be structurally continuous with the Klamath graben to the northwest. The circular nature of this anomaly suggests that the basin may be up to 500 m (1600 feet) deeper in the center. If the basin fill is approximated by a slab with a density contrast of  $.2 \text{ gm/cm}^3$  between the fill and the surrounding tuffs and basalt and andesite flows, approximately 1600 m (5250 feet) of fill are required to produce the observed anomaly. A thickness of 650 m (2100 feet) of sediments with a density contrast of  $.5 \text{ gm/cm}^3$  would

produce the same anomaly. Similarly, the ten mgal negative anomaly southeast of Yamsay Mountain suggests a thickness of 1200 m (4000 feet) of fill at a density contrast of  $.2 \text{ gm/cm}^3$  between the fill and the surrounding pyroclastics and basalts, or a thickness of 500 m (1650 feet) at a density contrast of  $.5 \text{ gm/cm}^3$ . This negative anomaly coincides with a synclinal basin suggested by Peterson and McIntyre (1970). The density contrasts of  $.2$  and  $.5 \text{ gm/cm}^3$  used in these simple models provide upper and lower bounds to the probable actual density contrasts between basin fill and surrounding rocks.

Three linear trends which strike approximately northeast, intersect the northwest-trending anomaly associated with the Klamath graben. The northernmost of these three trends, C-C', crosses the Klamath graben north of Upper Klamath Lake and trends approximately N50°E. The gradient associated with this trend suggests normal faulting with the down-thrown side to the north. The lobate anomaly which extends from the eastern side of the Klamath graben (C') coincides with the Williamson River, and suggests that its drainage may be fault-controlled. A similar magnetic trend crosses the Klamath graben north of Upper Klamath Lake (McLain, 1981). The second of these trends, D-D', trends near N70°E. The steep gradient and lack of lateral offset associated with this trend suggests normal faulting. A density contrast between basement rocks of the graben and low-density fill in the graben of  $.2 \text{ gm/cm}^3$  across the faults suggest vertical displacements of up to 1000 m (3300 feet). The southernmost of these trends, E-E', intersects the Klamath graben south of Upper Klamath Lake, where it

coincides with a ridge of positive anomalies. If the Klamath graben changes trend at Upper Klamath Lake, as suggested by Lawrence (personal communication), trend E-E' may represent a zone along which the Klamath graben has rotated. This northeast trend (E-E') also coincides with a N30°E to N40°E set of trends in the Basin and Range province identified by Lawrence (1976).

The complexity of the stratigraphy in the eastern portion of the study area hinders the correlation of particular geologic units with either positive or negative anomalies. Many of the closed negative anomalies in the southern quarter of the map between 121°15' and 122°00' W. longitude, however, correspond with small down-thrown blocks in which a substantial thickness of sediments may have accumulated. For example, the negative anomaly J occurs over the Poe Valley and is bounded on the east and west by inferred faults mapped by Peterson and McIntyre (1970). This anomaly suggests a thickness of fill of 720 m (2350 feet) assuming a negative density contrast of .2 gm/cm<sup>3</sup> between the fill and the surrounding basalts and pyroclastics, or a thickness of 270 m (900 feet) if the density contrast is .5 gm/cm<sup>3</sup>. Similarly, the -12 mgal negative anomaly (K) near Kingsley Field is probably associated with a thick section of basin fill. Sammel and Peterson (1976) indicate that 1000 m (3300 feet) of low-density fill at a contrast of .4 gm/cm<sup>3</sup> with the surrounding rock would produce the anomaly observed east of Kingsley Field. Faulting in this area is extensive and complex, and sediment-filled basins appear to be more localized, that is, smaller and shallower than the

Klamath graben and the Lower Klamath Lake graben complex.

The -12 mgal anomaly (L), elongated in the east-west direction, east of Upper Klamath Lake coincides with basin fill in Swan Valley. On the geologic map of Peterson and McIntyre (1970), most of the faults in the area trend approximately N30°W, but the nature of this anomaly suggests that faults trending near N60°W to N70°W bound the structure. This trend parallels the trend suggested by Lawrence (personal communication) for the Klamath graben south of Upper Klamath Lake.

Several positive anomalies in the eastern portion of the map (M,N,O,P) occur over areas mapped as QTb (basalt flows and pyroclastics) on the geologic map of Peterson and McIntyre (1970). This unit is not associated with any known vents, and the source and stratigraphic relationship of this unit is considered by Peterson and McIntyre (1970) to be an unsolved mapping problem. QTb is probably associated with sections of basalt of up to 100's of meters thick, rather than the thin basalt flows which cover many of the low-lying areas.

The positive anomaly associated with Yamsay Mountain is higher in amplitude on the residual anomaly map (+22 mgals) than on the complete Bouguer anomaly map (+16 mgals), which suggests that the actual density of Yamsay Mountain may be nearer to  $2.67 \text{ gm/cm}^3$  than  $2.43 \text{ gm/cm}^3$ . A density of  $2.80 \text{ gm/cm}^3$  is a realistic upper limit to the density of Yamsay Mountain, an andesitic eruptive center mapped by Peterson and McIntyre (1970). The anomaly is centered northeast of the peak, and is a broader feature on the complete Bouguer anomaly map than on the

residual anomaly map. A reduction density of  $2.80 \text{ gm/cm}^3$  would lower the amplitude of the anomaly by three to four mgals and possibly broaden the anomaly more. The anomaly can then be accounted for by a vertical cylinder with a height of 2.0 km, a radius of 3.0 km, and a density contrast of  $+0.2 \text{ gm/cm}^3$  between the cylinder and the surrounding basalts and pyroclastics, centered approximately six km northeast of the peak of the mountain. A similar cylinder with a height of 1.2 km, a radius of 3.0 km, and a density contrast of  $+0.3 \text{ gm/cm}^3$  between the cylinder and the surrounding rock would produce a similar anomaly.

The east-west elongate anomaly (Q) south of Sprague River is interpreted to be a large volcanic center which correlates with two extrusive or shallow intrusive light-colored bodies and a basaltic eruptive center mapped by Peterson and McIntyre (1970). This volcanic center is interpreted to be the heat source for four thermal springs and wells located in the Sprague River Valley. Curie-point analysis of the study area by McLain (1981) indicates that the Curie-point isotherm depth beneath the Sprague River Valley is as shallow as five to seven km below sea level. Peterson and McIntyre (1970) list the age for the basaltic eruptive center and shallow intrusive or extrusive bodies as Tertiary-Quaternary, but the presence of thermal waters whose temperatures range from  $14^\circ$  to  $21^\circ\text{C}$  ( $57^\circ$  to  $70^\circ\text{F}$ ) (Bowen and Peterson, 1970) suggests that the age of the volcanic center and possibly the eruptive center and shallow intrusives or extrusives thought to be associated with this center may be at least as young as Pleistocene. The relatively low temperatures of the thermal waters suggest

that a high temperature heat source for the waters is not necessary. The steep gradients associated with this anomaly suggest that the positions of portions of the body may be fault-controlled. Magnetic source-depth determinations by McLain (1981) suggest the presence of an east-west trending fault with a vertical displacement of 1.2 km, that coincides with the northern gravity gradient associated with this body. If such a fault exists, a density contrast of approximately  $+0.2 \text{ gm/cm}^3$  between the volcanic center and surrounding pyroclastics and lava flows across the fault would be required to produce the observed anomaly. A density contrast of  $0.2 \text{ gm/cm}^3$  is a reasonable contrast between a buried volcanic body and surrounding rocks composed of volcanoclastic sediments and thin lava flows.

All of the thermal springs and wells within the study area appear to be associated with steep linear gradients of one to eight mgals/km, that suggests that their occurrence is fault-related. The volcanic center south of the Sprague River is interpreted to be the heat source for four thermal springs and wells located in the Sprague River Valley, while the east-west trending fault suggested above may provide a conduit for the thermal waters. Northwest-trending faults near the Sprague River Valley mapped by Peterson and McIntyre (1970) may also provide conduits for thermal waters. Other thermal springs and wells occur in the Poe and Langell Valleys, and in Olene Gap, and coincide with faults mapped by Peterson and McIntyre (1970). A thermal well southwest of the Klamath Hills coincides with faulting related to the Lower Klamath Lake graben complex. Four thermal springs and wells are

located along or near the Klamath River west of Klamath Falls, and are associated with gradients of up to five mgals/km.

## GEOPHYSICAL CROSS SECTION

Line A-A' in Figure 10 shows the profile of a geophysical cross section constructed across the study area along 42°25.55' N. latitude. The cross section, shown in Figure 12, extends from approximately 124°30' to 117°00' W. longitude. Figure 13 shows an enlarged portion of the cross section through the study area.

The cross section was constructed using free-air gravity anomaly values for stations located along the profile, and values interpolated from the free-air anomaly map (Figure 5) for points between stations. The modelling process involves approximating areas of different density within the model by polygons, and computing the vertical attraction of the polygons at observation points on the surface using the line integral method described by Talwani (1959, modified by Gemperle, 1975). Boundaries and densities of the polygons are adjusted until the computed and observed anomalies are in agreement.

The model extends to a depth of 50 km below sea level, and uses standard sections reported by Barday (1974) and Braman (1981) on the western and eastern ends of the model such that 6442 mgals corresponds to a zero free-air anomaly. The model assumes that no lateral variations exist below a depth of 50 km. The standard oceanic mass column of Barday (1974) consists of 4.05 km of seawater with a density of 1.03 gm/cm<sup>3</sup>, a .46 km thick layer of sediments with a density of 2.00 gm/cm<sup>3</sup>, 1.10 km of rock with a density of 2.60 gm/cm<sup>3</sup>, a 4.00 km thick layer of rock with a density of 2.90 gm/cm<sup>3</sup>, and a 40.39 km thick layer of mantle with a density of 3.32 gm/cm<sup>3</sup>. The standard section

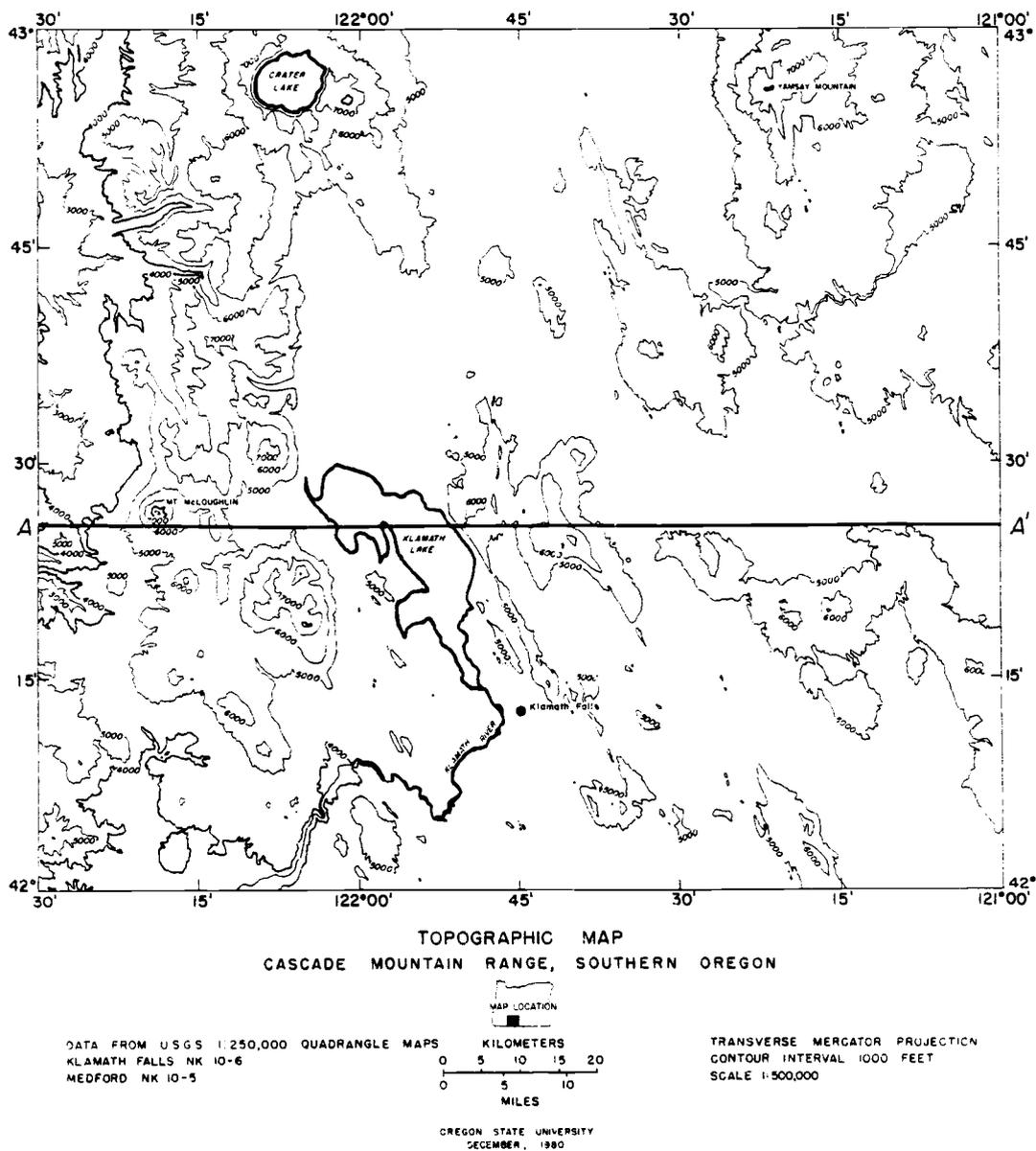


Figure 10. Topographic map of south-central Oregon. Line A-A' shows the traverse of the southern Oregon cross section depicted in Figures 12 and 13.

employed on the eastern end of the model (Braman, 1981) consists of 5.0 km of rock with a density of  $2.63 \text{ gm/cm}^3$ , a 26.0 km thick layer with a density of  $2.85 \text{ gm/cm}^3$ , and a 20.0 km thick layer of mantle rock with a density of  $3.32 \text{ gm/cm}^3$ .

Thiruvathukal (1970) computed a crustal thickness of 40 to 50 km for south-central and southeastern Oregon using a simple two layer (constant-density crust overlying constant-density mantle) model. Studies by Hill and Pakiser (1967), Cook (1967), Scholz and others (1971), and Priestley and Brune (1978) indicate that the structure of the Basin and Range province is more complex, and is characterized by thin crust and an anomalously low-velocity, low-density upper mantle. This anomalous mantle is interpreted to be the remnant of a mantle diapir thought to be responsible for the extension and outward migration of volcanism in the Great Basin portion of the Basin and Range province. Figure 11 shows the layer thicknesses and densities to a depth of 50 km computed by Priestley and Brune (1978), Hill and Pakiser (1967), and Cook (1967) for the Basin and Range province. Figure 11 also shows the standard oceanic mass column reported by Barday (1974), and the mass column computed for south-central Oregon at the Humble Thomas Creek number one well.

The mass column for south-central Oregon was computed using a two layer mantle model such that the vertical attraction of the column was 6472 mgals. This value corresponds to a free-air gravity anomaly of 30 mgals, the value interpolated from the free-air anomaly map at the Humble Thomas Creek number one well. Densities for three of the

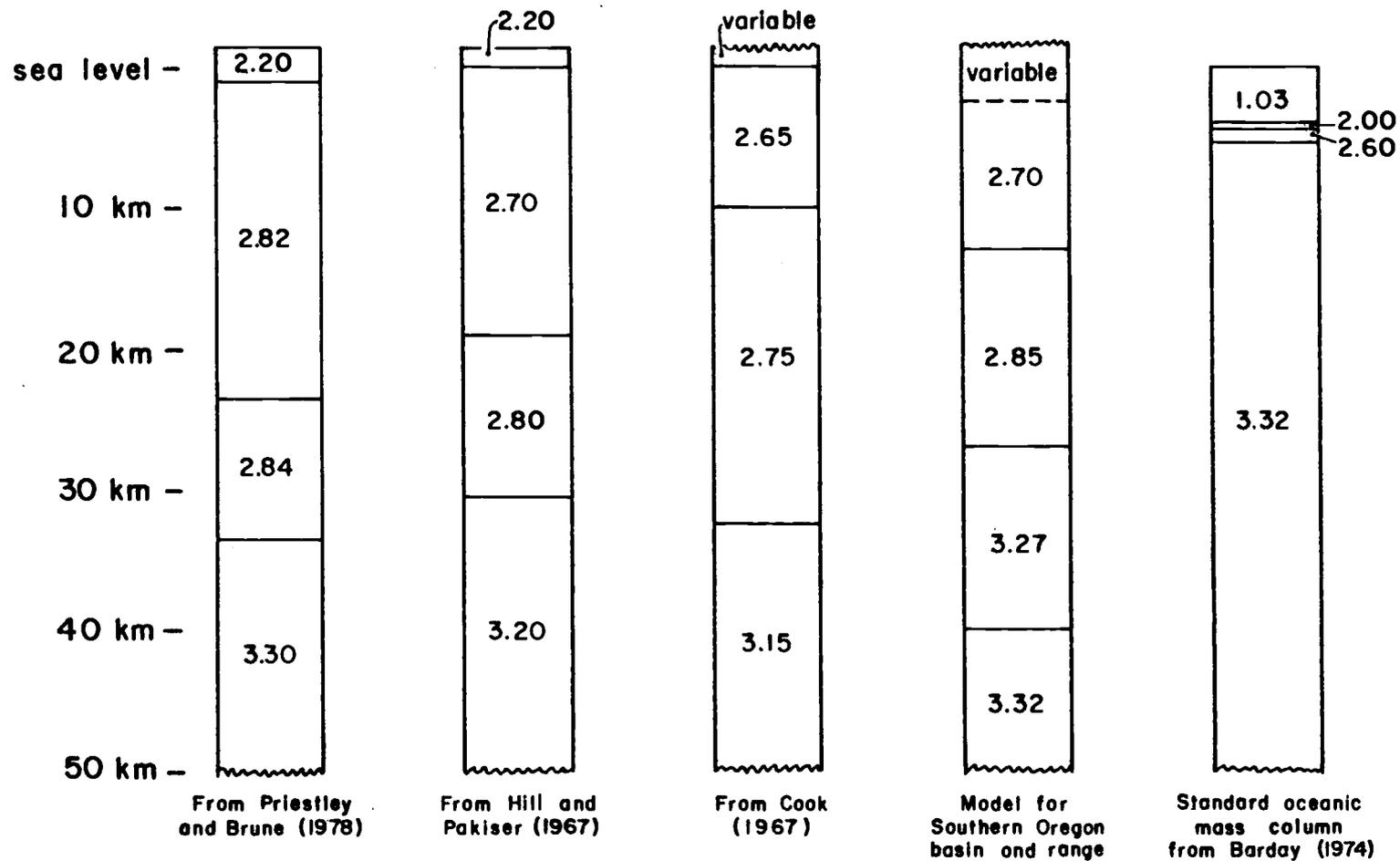


Figure 11. Standard mass column for southern Oregon Basin and Range province compared to standard sections of Priestley and Brune (1978), Hill and Pakiser (1967), Cook (1967), and Barday (1974).

layers were obtained from the seismic velocities given by Priestley and Brune (1978) using the seismic velocity-density relationships given by Ludwig and others (1970). Long range seismic studies similar to those of Hill and Pakiser (1967), Cook (1967), and Priestley and Brune (1978) have not been carried out in south-central Oregon, but the thin crust and low-density upper mantle structure is thought to be more appropriate than the simple two layer model presented by Thiruvathukal (1970). Calculations assuming a two layer model with a crustal density of  $2.8 \text{ gm/cm}^3$  and a mantle density of  $3.32 \text{ gm/cm}^3$ , yield depths to the mantle that are approximately two km greater than the depths calculated in the geophysical cross section of south-central Oregon.

Geologic maps of Wells and Peck (1961), Walker (1977), and Peterson and McIntyre (1970) provided information on near surface geologic units and interfaces. Densities for near surface layers near  $120^{\circ}30'$  W. longitude were obtained from seismic velocity logs from the Humble Thomas Creek number one well using the empirical relations between seismic velocity and density reported by Ludwig and others (1970). Aeromagnetic data reported by McLain (1981) were used to constrain the structure between  $122^{\circ}30'$  and  $121^{\circ}00'$  W. longitude using modelling techniques described by Lu and Keeling (1974).

The cross section in Figure 12 shows a block of  $2.70 \text{ gm/cm}^3$  density at its western end which corresponds to rocks of the Klamath Mountains. These rocks include late Paleozoic and Mesozoic metamorphosed sediments and volcanics. A density of  $2.70 \text{ gm/cm}^3$  is probably

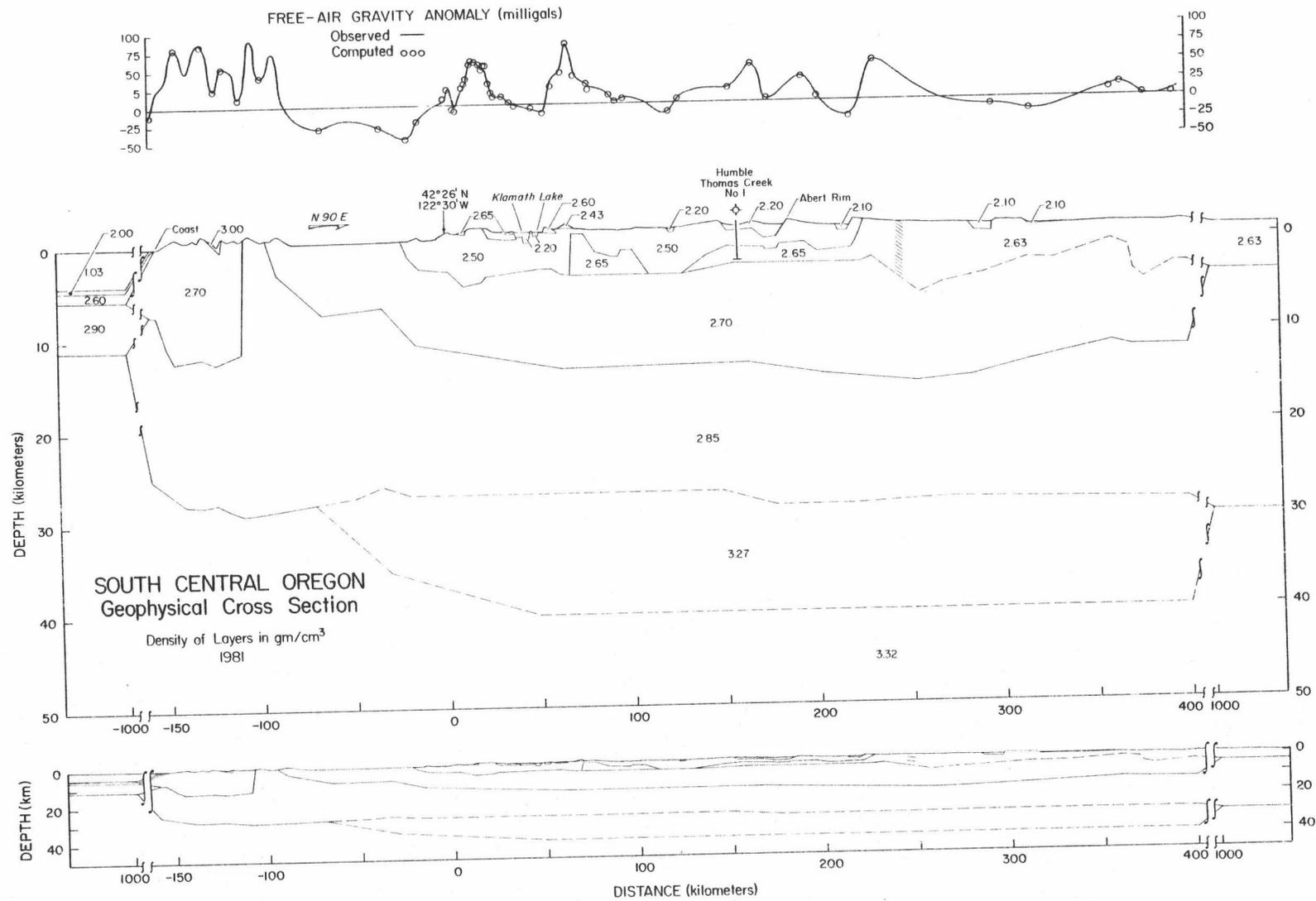


Figure 12. Geophysical cross section of southern Oregon near 42°26' N. latitude.

representative of most of these rocks. Within this block, a 'slice' of rock with a density of  $3.0 \text{ gm/cm}^3$  corresponds to a thin band of ultramafic intrusive rocks mapped by Wells and Peck (1961). Directly east of the  $2.70 \text{ gm/cm}^3$  unit, a large plug of  $2.85 \text{ gm/cm}^3$  density rises assymmetrically to the surface and correlates with a large intrusive body composed of granitoid, gabbroid, and ultramafic rocks mapped by Wells and Peck (1961). 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.

The nature of the transition between the two-layer uppermost mantle proposed for the Basin and Range province, and a single layer mantle which probably exists beneath the Klamath Mountains is uncertain. A depth to the mantle of approximately 30 km in the model agrees with a crustal thickness of 25 to 30 km calculated by Thiruvathukal (1970) for the Klamath Mountains.

The three units of  $2.10 \text{ gm/cm}^3$  density at the eastern end of the cross section are interpreted as basin fill sediments and are shown on the geologic map of Walker (1977). The basins are bounded by faults on the eastern and/or western sides, and occur in lake beds of large Pleistocene pluvial lakes. The steep dip in the  $2.63 \text{ gm/cm}^3$  layer near the eastern end of the section may be the subsurface expression of the system of northwest-trending faults, mapped by Walker (1977), which extend throughout the Basin and Range province in Oregon.

The western end of the  $2.50 \text{ gm/cm}^3$  unit west of  $122^\circ 30' \text{ W}$ .

longitude, corresponds to volcanics of the Western Cascade Mountains. These volcanics are thought to have been deposited at the western end of a large basin which may extend into southeastern Oregon. Beneath the Pliocene-Pleistocene sediments and volcanics of the Basin and Range province which are at least four km thick at the Humble Thomas Creek number one well, the Western Cascade rocks are represented by at least the upper portion of the  $2.70 \text{ gm/cm}^3$  layer.

The two units of  $2.65 \text{ gm/cm}^3$  density west of Upper Klamath Lake, shown in Figure 13, are lavas of the High Cascade Mountains, which, in southern Oregon, are primarily basaltic andesite. These units are intruded by a layer of  $2.50 \text{ gm/cm}^3$  density, which represents the andesitic Mt. McLoughlin. The density of  $2.50 \text{ gm/cm}^3$  for Mt. McLoughlin is similar to a density of  $2.53 \text{ gm/cm}^3$  determined for Mt. Shasta by LaFehr (1965). If Mt. McLoughlin is comprised of pyroclastics with a density of  $2.30 \text{ gm/cm}^3$ , which is similar to the density of  $2.27 \text{ gm/cm}^3$  determined by Couch and Gemperle (1979) for Mt. Hood, and andesite flows of density  $2.60 \text{ gm/cm}^3$ , the density determined by Christianson (1979) for massive andesites of Mt. Hood, then a density of  $2.50 \text{ gm/cm}^3$  represents a composition of approximately 65 percent andesite flows and 35 percent pyroclastics. The small unmagnetized block in the center of this body may be a cinder cone.

The fault zone suggested by Thayer (1936), Allen (1966), and Pitts (1979), to coincide with the Western Cascade - High Cascade Mountains boundary, does not appear to extend along the boundary of the Western Cascades and High Cascades south of Crater Lake. The

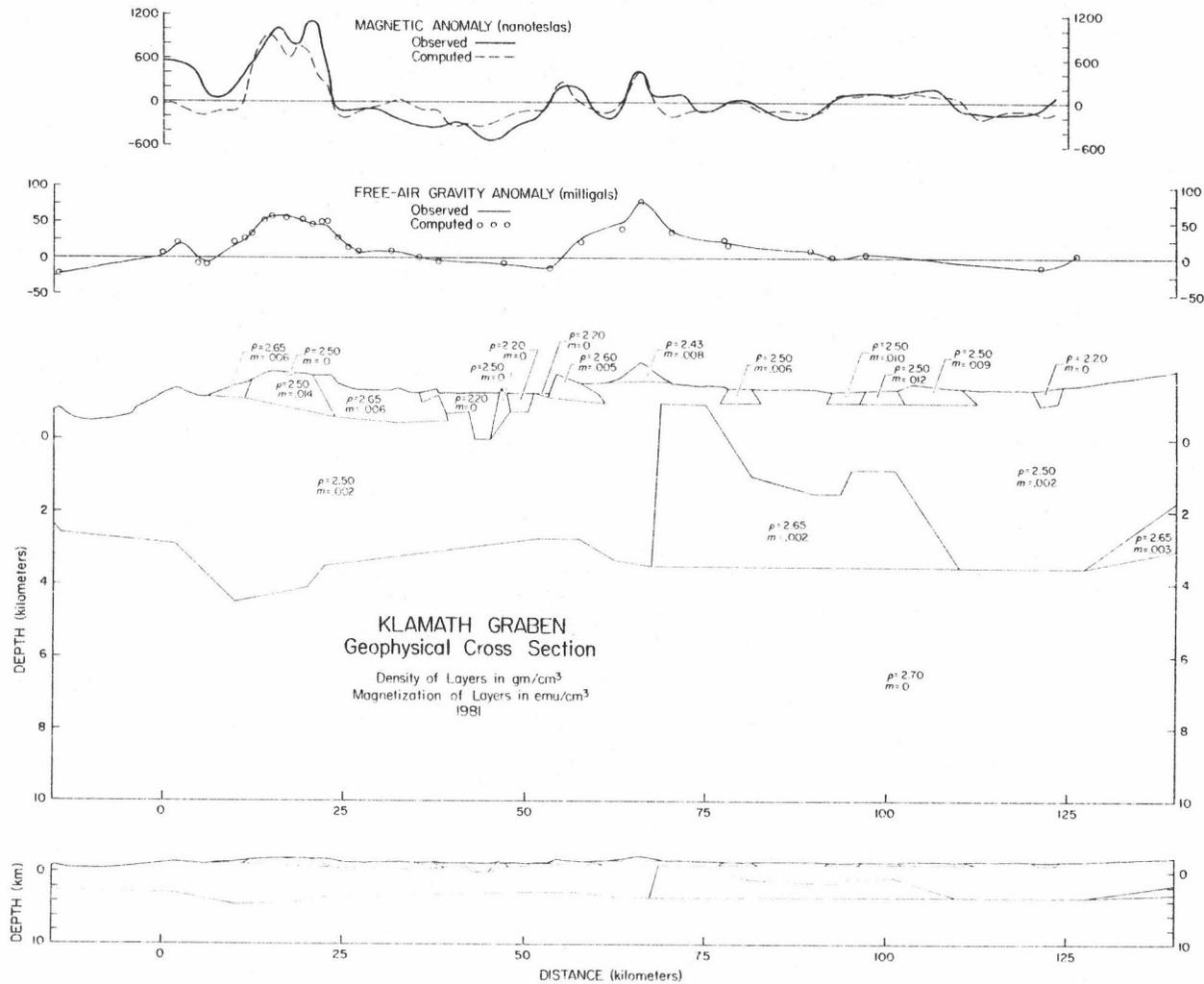


Figure 13. Detailed upper-crustal portion of southern Oregon cross section through study area.

fault zone may trend south-southeast south of Crater Lake and be continuous with the western faults of the Klamath graben. Furthermore, the thermal springs (Blackwell and others, 1978) associated with this proposed fault structure (Pitts, 1979), are not present along the boundary between the Western Cascade and the High Cascade Mountains south of Crater Lake.

The model indicates that the layer of  $2.20 \text{ gm/cm}^3$  density sediments exposed at the Humble well extends eastward to Abert Rim and may be a step-like system of faults, rather than a single symmetric graben block. The model suggests that this fault system extends to a depth of at least three km and displaces rocks of  $2.65 \text{ gm/cm}^3$ .

The large, irregularly-shaped block of  $2.65 \text{ gm/cm}^3$  density east of Klamath Lake coincides with a large positive residual gravity anomaly (Figure 8) located just south of the Sprague River Valley. The western face of this block coincides with a north-south trending linear anomaly with a gradient of approximately  $2.5 \text{ mgals/km}$ . This gradient suggests a source body in the upper five km of the crust. The structure is interpreted to be a buried volcanic source, and may be the source of the magnetized layers along the surface of the section directly above the body.

East of the block of  $2.65 \text{ gm/cm}^3$  density described above, a five km thick layer of  $2.50 \text{ gm/cm}^3$  density coincides with the southern extent of a large negative residual gravity anomaly which extends northward to Yamsay Mountain. This anomaly may be due to the presence of the large irregularly-shaped synclinal basin suggested by Peterson and

McIntyre (1970) in the area of Yamsay Mountain, Sycan Marsh, and the Sprague River.

As indicated in the cross section in Figure 13 and on the geologic maps of Peterson and McIntyre (1970) and Wells and Peck (1961), the graben structure that contains Upper Klamath Lake may be bounded by a series of step-like faults. The model indicates that the thickest section of sediments that fill the basin may be up to 1.2 km thick, and that the graben may be down-thrown a total of 1.6 km, assuming a density contrast between the sediments within the basin and the surrounding rocks of  $.3 \text{ gm/cm}^3$ . The density contrast between the basin fill and surrounding rock may be as great as  $1.0 \text{ gm/cm}^3$ . If the density contrast is  $1.0 \text{ gm/cm}^3$ , then the thickness of sediments would be .4 km, or approximately one-third as great as indicated in the model. The actual thickness of basin fill along the profile of the cross section is probably within these two extremes. The magnetic low located over the island within Upper Klamath Lake ( $2.50 \text{ gm/cm}^3$  density) may be due to hydrothermal alteration of the rock. The block beneath the island is unmagnetized in the model. The structure of the graben at this latitude is not representative of the graben structure north and south of the cross section. On the residual gravity anomaly map (Figure 8), the negative anomaly associated with the graben increases in width and amplitude northwest of Upper Klamath Lake, and appears to pinch out south of Upper Klamath Lake. Thus, the configuration of the graben in this model may represent the structure of only a small portion of the graben.

## SUMMARY AND CONCLUSIONS

The objective of this study was to interpret gravity anomalies due to upper crustal structures in south-central Oregon in order to better understand the Cascade Mountain and Basin and Range geologic provinces, and the geothermal systems which lie in south-central Oregon. Standard reduction techniques were used to calculate free-air and complete Bouguer anomalies. Residual anomalies, which facilitate the delineation of upper crustal structures, were computed by removing long-wavelength components, assumed to be associated with regional structures, from the data set. Computation of a two-dimensional cross section across the study area near  $42^{\circ}26'$  N. latitude also provided information on upper crustal structures.

The residual anomaly map exhibits broad bands of positive anomalies which enclose the large negative anomaly associated with the Klamath graben complex. East of the Klamath graben and north of Upper Klamath Lake, positive anomalies are located over a basement structure proposed by Blank (1968), that may be the eastern flank of an anticline, proposed to exist in the Upper Klamath Lake area by Peterson and McIntyre (1970) prior to basin and range faulting. On the western side of the Klamath graben, these positive anomalies may correspond to thick sections of High Cascade lavas, and are coincident with the Mount McLoughlin zone suggested by Lawrence (1976), southeast of Mt. McLoughlin. Numerous smaller closed positive and negative anomalies are associated with steep, linear gradients, that may delineate faults and hence suggest structural control for the

anomalous masses. The existence of northwest-trending linear anomalies west of the Klamath graben suggest that structural trends associated with the Basin and Range province extend into the High Cascades.

The amplitude of the negative anomaly associated with the Klamath graben and an assumed density contrast between the basin fill and the surrounding pyroclastics and basalt flows of  $.2 \text{ gm/cm}^3$  indicates that the thickness of fill may reach 2300 m (7500 feet). Three linear trends, oriented northeast-southwest, transect the Klamath graben. The two northernmost of these trends are interpreted to be normal faults. Assuming a density contrast across the faults of  $.2 \text{ gm/cm}^3$ , calculations suggest vertical displacements of 1000 m (3300 feet) along the faults. The southernmost of these trends, at the southern end of Upper Klamath Lake, may be due to a fracture zone, or may represent a zone along which the Klamath graben changes trend. The nature of the structure of the Klamath graben south of Upper Klamath Lake, and its relationship to the Lower Klamath Lake graben complex is uncertain. These two grabens may be structurally continuous, but shallower and narrower in the Klamath Falls area, or they may be, as suggested by Lawrence (personal communication), separate features.

The lower amplitude of the positive anomaly associated with Yamsay Mountain on the complete Bouguer gravity anomaly map than on the residual anomaly map suggests that the density of Yamsay Mountain is closer to  $2.67 \text{ gm/cm}^3$  than  $2.43 \text{ gm/cm}^3$ , and may be as much as  $2.80 \text{ gm/cm}^3$ . A mass excess at depth is still required to produce the

positive anomaly. Yamsay Mountain appears to lie in a large basin which may contain up to 1200 m (3900 feet) of low density sediments. Peterson and McIntyre (1970) suggested that folding of this area into a broad synclinal basin occurred prior to basin and range faulting.

A basaltic eruptive center and two light-colored intrusive or shallow extrusive bodies, mapped by Peterson and McIntyre (1970), suggest that the broad positive anomaly south of the Sprague River is due to a buried volcanic center. A composition near granodiorite would have a density contrast with the surrounding rocks that could produce the positive anomaly and be consistent with the vertical displacement suggested by McLain (1981) for an east-west trending fault coincident with the northern boundary of this body. The postulated volcanic center also is interpreted to be the heat source for the thermal waters found in the Sprague River Valley. The age of the volcanic center is unknown, but the presence of the local thermal waters suggests that the center is at least as young as Pleistocene.

The location of a heat source for the thermal waters, found south and east of Upper Klamath Lake, is as yet undetermined. Peterson and McIntyre (1970) indicate that the low content of dissolved solids in the thermal waters suggests that the fluid rising in geothermal zones may be steam, and that it may indicate the presence of a higher temperature geothermal source at depth. Sammel and Peterson (1976) believe however, that chemical analyses of local thermal waters suggest that the geothermal system in the Klamath Falls area represents a combination of convective transport of heat and fluids from depth

in a cyclic system, and a blocking of normal vertical heat flow by layers of rock having low thermal conductivities. A high temperature geothermal source is not necessary. Curie-point analysis of the study area by McLain (1981) indicates an elevated Curie-point isotherm beneath the Mt. McLoughlin - Upper Klamath Lake area, but which does not extend into the area east of Klamath Falls. This study suggests that the positive regional gravity field in the Klamath Falls area may be due to the presence of a large intrusive body at depth, or a shallow mantle. Other possibilities however, such as intense silicification of the area due to the presence of thermal waters suggested by Sammel and Peterson (1976) could also explain the regional gravity high. It is apparent however, that south-central Oregon offers a unique geologic situation for the occurrence of a geothermal system. The northwest structural trends associated with the Basin and Range province extend into the High Cascades portion of the Cascade Mountain Range, and meteoric waters from the High Cascades may percolate into these northwest-trending zones, become heated at depth, and rise to the surface in the conduits provided by the extensive faulting observed in the area surrounding Klamath Falls.

The relationship of the main Klamath graben to the Lower Klamath Lake graben complex is unclear. Three possibilities have been discussed. The Klamath graben may be constricted in the Klamath Falls area and then widen southward to form the Lower Klamath Lake graben complex. An increase in faulting and volcanism along this zone could account for the positive anomaly in the regional gravity field.

Van Deusen (1978) suggested the presence of a barrier to crustal extension along which right-lateral shear has taken place. Lawrence (personal communication) suggests that the Klamath graben changes trend at Upper Klamath Lake and is continuous with the structural basin in the southeast corner of the residual gravity anomaly map. The Lower Klamath Lake graben complex would then be a separate structure.

The existence of a northeast-trending zone of right-lateral shear south of Upper Klamath Lake, suggested by Van Deusen (1978), is unlikely. Van Deusen suggests that the barrier to crustal extension which forms this shear zone is related to rocks of the Klamath Mountains which extend eastward beneath the area between Upper Klamath Lake and Lower Klamath Lake. The regional gravity anomaly map (Figure 7) shows a gravity high located south of Upper Klamath Lake. If the gravity high is due to the presence of rocks of the Klamath Mountains, then the -105 to -125 mgal contours should also be deflected eastward. It is doubtful, then, that a barrier to crustal extension between Upper Klamath Lake and Lower Klamath Lake exists, along which right-lateral shear has taken place. The gravity data does suggest, however, that the Klamath graben either (1) is continuous with the Lower Klamath Lake graben complex, but is constricted south of Upper Klamath Lake, or (2) changes trend to S60°E south of Upper Klamath Lake, and is not continuous with the Lower Klamath Lake graben complex.

Several additional geophysical studies could help resolve some of the structural problems discussed above. Detailed local and long-

range seismic refraction studies would help in determining the relationship between the Klamath graben and the Lower Klamath Lake graben complex, and many of the smaller fault-controlled basins in the area. Refraction lines could be shot perpendicular to the three northeast trending linear anomalies which transect the graben. Detailed long-range refraction studies may help resolve the structure of the mantle beneath the Basin and Range province in Oregon, and determine the nature of the transition between High Cascades and Basin and Range structures. A detailed gravity study within and surrounding the Klamath graben could more specifically define its structure. Gravity measurements could be made in Upper Klamath Lake, Agency Lake, and the marshy area north of Upper Klamath Lake. Determination of the density of the graben fill would aid in the two- and three-dimensional gravity modelling of the graben structure. An interesting study for the area would be the calculation of complete Bouguer anomalies at several other reduction densities, and the removal of the regional field from the complete Bouguer anomaly field at other cutoff wavelengths, e.g. 70 km, 80 km, and 100 km.

## REFERENCES

- Alemi, M., 1978, A Gravity Survey of Coos Bay, Oregon: unpublished M.S. Thesis, University of Oregon, Eugene, Oregon.
- Allen, J.E., 1966, The Cascade Range Volcano - Tectonic Depression of Oregon, in Transactions of the Lunar Geological Field Conference Bend, Oregon, August 1965: Oregon Dept. of Geol. and Min. Indus., 98 p.
- Baldwin, E.M., 1980, Geology of Oregon: Kendall/Hunt Publishing Co., Dubuque, Iowa, 170 p.
- Barday, R.J., 1974, Structure of the Panama Basin from Gravity Data: unpublished M.S. Thesis, Oregon State University, Corvallis, Oregon, 99 p.
- Berg, J.W., Jr., and Baker, C.D., 1963, Oregon Earthquakes, 1941 through 1958: Bull. Seis. Soc. of Amer., v. 70, no. 1, pp. 95-108.
- Berg, J.W., Jr., and Thiruvathukal, J.V., 1965, Gravity Base Station Network, Oregon: Jour. Geophys. Res., v. 70, no. 14, pp. 3325-3330.
- Blackwell, D.D., Hull, D.A., Bowen, R.G., and Steele, J.L., 1978, Heat Flow of Oregon: Special Paper 4, Oregon Dept. of Geol. and Min. Indus., Portland, Oregon, 42 p.
- Blakely, R.J., 1979, Medford Gravity Survey, unpublished data, U.S. Geol. Survey, Menlo Park, CA.
- Blank, H.R., Jr., 1965, Southwest Oregon Gravity Data: U.S. Geol. Survey Open-File Report, 63 computer print-out sheets, 1 p., 1 map, scale 1:250000.
- Blank, H.R., Jr., 1968, Aeromagnetic and Gravity Surveys of the Crater Lake Region, Oregon: in Dole, J.M., ed., Andesite Conference Guidebook, Oregon Dept. of Geol. and Min. Indus., Bull. 62, pp. 42-52.
- Bodvarsson, G., Couch, R.W., MacFarlane, W.T., Tang, R.W., and Whitsett, R.M., 1974, Telluric Current Exploration for Geothermal Anomalies in Oregon: The Ore Bin, v. 36, no. 6, pp. 93-107.
- Bowen, R.G., and Peterson, N.V., 1970, Thermal Springs and Wells in Oregon: Oregon Dept. of Geol. and Min. Indus., Miscellaneous Paper Number 14, Portland, Oregon.

- Braman, D.E., 1981, Interpretation of Gravity Anomalies Observed in the Cascade Mountain Province of Northern Oregon: unpublished M.S. Thesis, Oregon State University, Corvallis, Oregon, 144 p.
- Brenner, N., 1968, FOR2D Subroutine Package for Multidimensional FFT: MIT Lincoln Laboratory, Boston, Massachusetts.
- Briggs, I.C., 1974, Machine Contouring Using Minimum Curvature: Geophysics, v. 39, no. 1, pp. 39-48.
- Bullard, E.C., 1936, Gravity Measurements in East Africa: Phil. Trans. of the Royal Society, v. 235, pp. 445-531.
- Chapman, R.H., 1966, Gravity Base Station Network: California Division of Mines and Geology Special Report 90, 49 p.
- Chapman, R.H., and Bishop, C.C., 1968, Bouguer Gravity Map of California - Alturas Sheet: California Division of Mines and Geology, San Francisco, California.
- Christianson, N., 1979, in: Gravity Measurements in the Area of Mt. Hood, Oregon, in: Geothermal Assessment of Mt. Hood, Oregon, Oregon Dept. of Geol. and Min. Indus., Open-File Report no. 0-79-8, pp. 137-189.
- Cook, K.L., 1967, Rift System in the Basin and Range Province, in: The World Rift System: Geological Survey of Canada, Paper 66-14, pp. 246-279.
- Cooley, J.W., and Tukey, J.W., 1965, An Algorithm for the Machine Calculation of Complex Fourier Series: Mathematics of Computation, v. 19, pp. 297-301.
- Couch, R.W., and Gemperle, M., 1979, Gravity Measurements in the Area of Mt. Hood, Oregon, in: Geothermal Assessment of Mt. Hood, Oregon, Oregon Dept. of Geol. and Min. Indus., Open-File Report no. 0-79-8, pp. 137-189.
- Couch, R.W., and Lowell, R.P., 1971, Earthquakes and Seismic Energy Release in Oregon: The Ore Bin, v. 33, no. 4, pp. 61-84.
- Donath, F.A., 1958, Basin and Range Structures of South-central Oregon: Ph.D. Thesis, Stanford University, Palo Alto, CA.
- Donath, F.A., 1962, Analysis of Basin-Range Structure, South-central Oregon: Geol. Soc. Am. Bull., v. 73, pp. 1-16.
- Donath, F.A., and Kuo, J.T., 1962, Seismic - Refraction Study of Block Faulting, South-central Oregon: Geol. Soc. Am. Bull., v. 73, pp. 429-434.

- Finn, C., 1980, Crater Lake Gravity Survey: unpublished data, U.S. Geol. Survey, Denver, CO.
- Finn, C., 1981, Principal Facts for Gravity Stations Near Medicine Lake Highlands and Mt. Shasta: U.S. Geol. Survey Open-File Report no. 81-427.
- Garland, G.D., 1977, The Earth's Shape and Gravity: New York, Pergamon Press, 185 p.
- Gemperle, M., 1975, Program GRAV2DS: Geophysics Program and Data Library, Oregon State University, Corvallis, Oregon, 9 p.
- Geometrics, Inc., 1973, Aeromagnetic Map of the Medford Sheet, Oregon: U.S. Geol. Survey Open-File Report, 1:250000.
- Godwin, L.H., Haigler, L.B., Rioux, R.L., White, D.E., Muffler, L.J.P., and Wayland, R.G., 1971, Classification of Public Lands Valuable for Geothermal Steam and Associated Geothermal Resources: U.S. Geol. Survey Circular No. 647, 18 p.
- Griscom, A., 1973, Bouguer Gravity Map of California - Redding Sheet: California Division of Mines and Geology, San Francisco, CA.
- Griscom, A., 1974, Wart Peak Gravity Survey: unpublished data, U.S. Geol. Survey, Menlo Park, CA.
- Griscom, A., 1975, Newberry Crater Gravity Survey: unpublished data, U.S. Geol. Survey, Menlo Park, CA.
- Grose, L.T., and Keller, G.V., 1979, Geothermal Energy in the Basin and Range Province, in: Newman, G.W., and Goode, H.D., eds., Basin and Range Symposium, Rocky Mountain Association of Geologists, pp. 361-369.
- Hamilton, W., and Myers, W.B., 1967, Cenozoic Tectonics of the Western United States, in: The World Rift System: Geological Survey of Canada, Paper 66-14, pp. 291-306.
- Hill, D.P., and Pakiser, L.C., 1967, Seismic Refraction Study of Crustal Structure Between the Nevada Test Site and Boise, Idaho: Geol. Soc. Am. Bull., v. 78, pp. 685-704.
- Irwin, W.P., 1966, Geology of the Klamath Mountains Province: California Division of Mines and Geology, Bull. 190, pp. 19-38.
- Kim, C.K., and Blank, H.R., Jr., 1973, Bouguer Gravity Map of California - Weed Sheet: California Division of Mines and Geology, San Francisco, CA.

- LaFehr, T.R., 1965a, Gravity Survey in the Southern Cascade Range, California: U.S. Geol. Survey Open-File Report, pp. 1-16.
- LaFehr, T.R., 1965, Gravity, Isostasy and Crustal Structure in the Southern Cascade Range: Jour. Geophys. Res., v. 70, no. 22, pp. 5581-5597.
- Larson, K.P., and Couch, R.W., 1975, Preliminary Gravity Maps of the Vale Area, Malheur County, Oregon: The Ore Bin, v. 37, no. 8, pp. 138-142.
- Lawrence, R.D., 1976, Strike-slip Faulting Terminates the Basin and Range Province in Oregon: Geol. Soc. Am. Bull., v. 87, pp. 846-850.
- Leutsher, J., 1968, Newberry Crater Gravity Survey: unpublished data, U.S. Geol. Survey, Menlo Park, CA.
- Longman, I.M., 1959, Formulas for Computing the Tidal Accelerations Due to the Moon and the Sun: Jour. Geophys. Res., v. 64, no. 12, pp. 2351-2355.
- Lu, R.S., and Keeling, K.M., 1974, A Simplified Program for the Rapid Calculation of Theoretical Marine Magnetic Anomalies: Science Reports of the National Taiwan University, no. 4, pp. 105-114.
- Ludwig, W.J., Nafe, K.E., and Drake, C.L., 1970, Seismic Refraction, in: Maxwell, H., ed., The Sea, New York, John Wiley, v. 4, pt. 1, pp. 53-84.
- Maynard, L.C., 1974, Geology of Mt. McLoughlin: unpublished M.S. Thesis, University of Oregon, Eugene, Oregon, 139 p.
- McBirney, A.R., 1968, Petrochemistry of Cascade Andesite Volcanoes, in: Andesite Conference Guidebook, Dole, H.M., ed., Oregon Dept. of Geol. and Min. Indus., Bull. 62, pp. 101-107.
- McBirney, A.R., 1978, Volcanic Evolution of the Cascade Range: Ann. Rev. Earth Planet. Sci., v. 6, pp. 437-456.
- McLain, W.H., 1981, Geothermal and Structural Implications of Magnetic Anomalies Observed Over the Southern Oregon Cascade Mountains and Adjoining Basin and Range Province: unpublished M.S. Thesis, Oregon State University, Corvallis, Oregon.
- Naslund, H.R., 1977, The Geology of the Hyatt Reservoir and Surveyor Mountain Quadrangles, Oregon: unpublished M.S. Thesis, University of Oregon, Eugene, Oregon, 127 p.

- Nettleton, L.L., 1939, Determination of Density for Reduction of Gravimeter Observations: Geophysics, v. 4, pp. 176-183.
- Nettleton, L.L., 1976, Gravity and Magnetism in Oil Prospecting, New York, McGraw-Hill Book Co., 464 p.
- Newcomb, R.C., 1958, Yonna Formation of the Klamath River Basin, Oregon: Northwest Science, v. 32, no. 2, pp. 41-48.
- Oliver, H.W., Griscom, A., Robbins, S.L., and Hanna, W.F., 1969, U.S.G.S. Gravity Data in California, part IV, U.S. Geol. Survey, Internal Report, Menlo Park, CA, 41 p.
- Oliver, H.W., Robbins, S.L., and Griscom, A., 1975, Preliminary Bouguer Gravity Map of the Susanville 1° X 2° Quadrangle, California: U.S. Geol. Survey Open-File Report 75-534, scale 1:250000.
- Peck, D.L., Griggs, A.B., Schlicker, H.G., Wells, F.G., and Dole, H.M., 1964, Geology for the Central and Northern Part of the Western Cascade Range in Oregon: U.S. Geol. Survey Prof. Paper 449, U.S. Govt. Printing Office, Washington, D.C.
- Peterson, N.V., and McIntyre, J.R., 1970, The Reconnaissance Geology and Mineral Resources of Eastern Klamath County and Western Lake County, Oregon: Oregon Dept. of Geol. and Min. Indus. Bull., v. 66, 70 p.
- Pitts, G.S., 1979, Interpretation of Gravity Measurements Made in the Cascade Mountains and Adjoining Basin and Range Province in Central Oregon: unpublished M.S. Thesis, Oregon State University, Corvallis, Oregon, 186 p.
- Pitts, G.S., 1980, Gravity Data Reduction Techniques: Geophysics Technical Report, Oregon State University, Corvallis, Oregon.
- Plouff, D., 1977, Preliminary Documentation for a FORTRAN Program to Compute Gravity Terrain Corrections Based on Topography Digitized on a Geographic Grid: U.S. Geol. Survey Open-File Report n. 77-535, U.S. Govt. Printing Office, Washington, D.C.
- Priestley, K., and Brune, J., 1978, Surface Waves and the Structure of the Great Basin of Nevada and Western Utah: Jour. Geophys. Res., v. 83, no. 35, pp. 2265-2272.
- Rayner, J.N., 1971, An Introduction to Spectral Analysis: London, England, Pion Limited, 174 p.

- Robbins, S.L., and Oliver, H.W., 1970, On Making Inner-Zone Terrain Corrections to Gravity Data: A contribution of the Regional Geophysical Branch, U.S. Geol. Survey, Menlo Park, CA, prepared on behalf of the U.S. Army Topographic Command, Washington, D.C.
- Sammel, E.A., and Peterson, D.L., 1976, Hydrologic Reconnaissance of the Geothermal Area Near Klamath Falls, Oregon: U.S. Geol. Survey, Water-Resources Investigation Open-File Report WRI76-127, 129 p.
- Sass, J.H., and Sammel, E.A., 1976, Heat Flow Data and Their Relation to Observed Geothermal Phenomena Near Klamath Falls, Oregon: Jour. Geophys. Res., v. 81, no. 26, pp. 4863-4868.
- Scholz, C.H., Barazongi, M., and Sbar, M.L., 1971 Late Cenozoic Evolution of the Great Basin, Western United States, as an Ensialic Interarc Basin: Geol. Soc. Am. Bull., v. 82, pp. 2979-2990.
- Schreibe, D.M., and Howard, H.W., 1964, Classical Methods for Reduction of Gravity Observations: U.S. Air Force, Aeronautical Chart and Information Center Ref., Publ. 12, 65 p.
- Scintrex Mineral Surveys, Inc., 1972, Aeromagnetic Map of the Klamath Falls and Crescent Sheets, Oregon: U.S. Geol. Survey Open-File Report, 1:250000.
- Smith, R.B., 1977, Intraplate Tectonics of the Western North American Plate: Tectonophysics, v. 37, pp. 323-336.
- Stewart, J.H., 1971, Basin and Range Structure: A System of Horsts and Grabens Produced by Deep-seated Extension: Geol. Soc. Am. Bull., v. 82, pp. 1019-1044.
- Swick, C.H., 1942, Pendulum Gravity Measurements and Isostatic Reductions: U.S.C. & G.S. Spec. Pub. no. 232, 82 p.
- Talwani, J., Worzel, J.L., and Landisman, J., 1959, Rapid Gravity Computations for Two-dimensional Bodies with Application to the Mendocino Fracture Zone: Jour. Geophys. Res., v. 64, pp. 49-59.
- Telford, W.M., Geldart, L.P., Sheriff, R.E., and Keys, D.A., 1978, Applied Geophysics: New York, Cambridge University Press, 860 p.
- Thayer, T.P., 1936, Structure of the North Santiam River Section of the Cascade Mountains in Oregon: Jour. Geol., v. 44, pp. 701-716.

- Thiruvathukal, J.V., 1968, Regional Gravity of Oregon: unpublished Ph.D. Dissertation, Oregon State University, Corvallis, Oregon, 92 p.
- Thiruvathukal, J.V., Berg, J.W., Jr., and Heinrichs, D.F., 1970, Regional Gravity of Oregon: Geol. Soc. Am. Bull., v. 81, pp. 725-738.
- Van Deusen, J.E., III, 1978, Mapping Geothermal Anomalies in the Klamath Falls, Oregon Region with Gravity and Aeromagnetic Data: unpublished M.S. Thesis, University of Oregon, Eugene, Oregon, 86 p.
- Walker, G.W., 1977, Geologic Map of Oregon East of the 121st Meridian: Oregon Dept. of Geol. and Min. Indus., Portland, Oregon.
- Wells, F.G., 1956, Geology of the Medford Quadrangle, Oregon - California: U.S. Geol. Survey Map GQ-89.
- Wells, F.G., and Peck, D.L., 1961, Geologic Map of Oregon West of the 121st Meridian: Oregon Dept. of Geol. and Min. Indus., Portland, Oregon.
- Williams, H., 1962, The Ancient Volcanoes of Oregon: Condon Lectures, Oregon State System of Higher Education, Eugene, Oregon, 68 p.
- Wise, D.U., 1963, An Outrageous Hypothesis for the Tectonic Pattern of the North American Cordillera: Geol. Soc. Am. Bull., v. 74, pp. 357-362.

APPENDICES

## APPENDIX A

## DATA ACQUISITION AND REDUCTION

During the months of October, 1979, and July and August, 1980, 362 gravity stations were established in the area between 42°00' and 43°00' N. latitude and 121°00' and 121°45' W. longitude. These data combined with recent gravity data from the U.S. Geological Survey for the Crater Lake area, (Finn, 1980) and the Medford Quadrangle (Blakely, 1979), and existing data from the Oregon State University gravity files (Blank, 1965; Thiruvathukal, 1968; Van Deusen, 1978) total 1598 stations for the area between 42°00' and 43°00' N. latitude and 121°00' and 122°30' W. longitude, and yield an average spatial density of one station per 8.6 square km.

Base Station Data

Gravity meter drift control was maintained by repeated occupation of primary and secondary base stations. Primary base stations were established at Jackson Creek Guard Station, Thompson Reservoir, and Bonanza, Oregon. The Jackson Creek Guard Station and Thompson Reservoir base stations were tied to PRB10 (Pitts, 1979) at Silver Lake, Oregon with one closed loop. The Bonanza base station was tied to the Klamath Falls OIT base station (Berg and Thiruvathukal, 1965) with six closed loops. PRB 10 is tied to the Diamond Lake Junction base station reported by Blank (1965), which is tied to the Corvallis base station OSU-OC reported by Berg and Thiruvathukal (1965) (Pitts, 1979). The OSU-OC base station and the Klamath Falls OIT base station are

tied to the OSU-PC secondary base station, which is tied to the national base station at the Carnegie Institution in Washington, D.C. (Berg and Thiruvathukal, 1965). Gravity stations reported by Van Deusen (1978), and Blank (1965) and used in this study are tied to the Klamath Falls OIT base station and the Diamond Lake Junction base station, respectively.

Secondary base stations were established at Sprague River, Feugo Mountain, Beatty, Ivory Pine Mill, Sycan Marsh, and in Langell Valley, Oregon. Secondary base stations were tied to the Bonanza base station. All base station ties were made with the Worden W-575 Gravimeter (OSU). Appendix C describes the base stations for this study.

#### Meter Information

The Worden Master gravimeter W-575 was used for this survey. Meter W-575 has an accuracy of  $\pm 0.02$  mgals and a 220 mgal dynamic range. The appropriate selection of the initial range, and the minimal topographic relief of the eastern half of the study area allowed the region to be surveyed with no meter reset. The Worden Master gravimeter is temperature compensated and temperature dependent calibration constants are provided with the meter. Internal meter temperature was monitored at each station.

#### Field Observations

During the fall of 1979 and summer of 1980, 362 gravity stations were established relative to the base stations described above. The gravity meter was tied to a primary or secondary base station as often

as possible (at approximately three hour intervals) and to a primary base station at the beginning and end of each day.

Elevation control was provided wherever possible by USGS and USC&GS benchmarks. Oregon State Highway Department, and U.S. Forest Service markers provided additional control. Spot elevations from USGS 15 minute topographic maps yielded uncertainties of ten feet. Elevations for approximately 215 stations were obtained with aneroid altimeters. To provide barometric control, the altimeters were read at a known elevation or a station within the loop that was reoccupied at least every two hours. The uncertainty of the elevation at the altimetrically controlled stations ranged from ten to 40 feet. The elevation for one station was interpolated from a 15 minute topographic map with an estimated uncertainty of one-half the contour interval or  $\pm 40$  feet.

Notes and sketches of the topography to a radial distance of 68 meters around the station (equivalent to Hayford-Bowie zones A and B; Garland, 1977) were made to enable estimation of near terrain gravity effects. Gravity effects were calculated for simple geometric models as described by Robbins and Oliver (1970).

#### Data Reduction

Elevations were calculated from altimeter readings using techniques outlined in the handbooks supplied with the American Paulin (AP) and Wallace and Terrin (WT) altimeters. The AP altimeters used are humidity compensated, and therefore required only a correction for ambient temperature variations. The WT data, however, required

corrections for relative humidity as well as temperature.

Gravity meter readings were converted to observed gravity (OG) by the following steps:

- 1) Conversion of meter readings to milligals using the conversion tables supplied with the meters
- 2) Correction of the data for earth tides using formulæ by Longman (1959)
- 3) Correction of the data for meter drift by interpolation along linear drift segments constructed from base station occupations
- 4) Calculation of OG relative to primary and secondary base stations.

The mean and standard deviation of the meter drift during the periods of observation were .0753 mgals/hr and .0272 mgals/hr, respectively.

Theoretical gravity (THG) was computed using the International Gravity Formula, IGF-1930 (Swick, 1942, p. 61):

$$\text{THG} = 978049. (1.0 + 0.0052884 \sin^2\theta - 0.0000059 \sin^2 2\theta)$$

where  $\theta$  is the latitude of the station.

The free-air correction (FAC) is applied to gravity measurements to correct for the elevation of the station above the surface of the spheroid. The free-air gravity anomaly (FAA) is given by:

$$\text{FAA} = \text{OG} - (\text{THG} - \text{FAC}).$$

The FAC is given by Schreibe and Howard (1964, p. 7) as:

$$\text{FAC} = (0.09411549 - 0.000137789 \sin^2\theta)h - 0.67 \cdot 10^{-8} h^2$$

where  $h$  is the elevation of the station in feet.

The complete Bouguer anomaly (CBA) takes into account the elevation of the station (FAC) and effects of the mass of the earth between the station and the spheroid. The CBA is calculated with the equation:

$$CBA = FAA - BSC - CC + TC$$

where BSC is the Bouguer slab correction, CC is the curvature correction, and TC is the terrain correction.

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

$$BSC = 2\pi G\rho h = 0.012774\rho h$$

where  $G$  is the universal gravitational constant and  $h$  is in feet. A standard reduction density of  $2.65 \text{ gm/cm}^3$  was used in this study.

The curvature correction reduces the effect of the infinite Bouguer slab to that of a spherical cap of radius 166.7 km and thickness  $h$  (Swick, 1942, p. 67). The correction is:

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

The terrain correction (TC) compensates for the effects of local topography on gravity measurements. A hand-terrain correction was made from field notes of topography out to a radial distance of 68 m (Hayford-Bowie zones A and B) from the station. Terrain corrections for a radial distance of 68 m to 166.7 km from the station (Hayford-

Bowie zones C-0) were made by computer with a computer program written by Plouff (1977) and modified to operate on the OSU-Geophysics computer system by Pitts (1980). 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 complete zones around several stations, and terrain corrections for those areas were calculated by hand using techniques described by Oliver and others (1969).

Terrain corrections for stations from Thiruvathukal (1968) and Blank (1965) were recomputed for Hayford-Bowie zones C-0 using the above method.

Calculations for the CBA at other reduction densities can be accomplished by multiplying the density dependent terms in the CBA calculation by the ratio of the new density to the old density, as follows:

$$CBA = (CBA(\rho_{old}) - FAA) * (\rho_{new} / \rho_{old}) + FAA.$$

#### Uncertainty of the Data

The calculated anomalies are subject to uncertainties of the gravimeter readings (SMR), of elevation (SEL), and of latitude (SLT). The uncertainty in measurements of the W-575 gravimeter is .02 mgals. The uncertainty of the meter reading at a station is the meter uncertainty divided by the square root of the number of readings at that station.

The uncertainty of the observed gravity at a station is given by:

$$\text{SOG} = (\text{SOG}_{b1}^2 + \text{SMR}_{b1}^2 + \text{SMR}_s^2 + \text{SMR}_{b2}^2 + \text{SOG}_{b2}^2)^{1/2}$$

where  $\text{SOG}_{b1}$  and  $\text{SOG}_{b2}$  are the uncertainties of the observed gravity at the first and last base stations of the loop which contains the station.

An uncertainty of one foot was assigned to elevations from benchmarks. The uncertainty of spot elevations from USGS topographic maps was assigned in the field and varied from five to fifteen feet depending on the topography near the marked elevation. The uncertainty of elevations determined from contour lines on USGS topographic maps is one-half the contour interval of the map. The uncertainty for altimetrically calculated elevations is:

$$\text{SEL}_A = \left( \sum_{i=1}^n D_i^2 \right)^{1/2} / \sqrt{n}$$

where  $n$  is the number of altimeters used and  $D_i$  is the difference between the elevation calculated from the  $i$ th altimeter and the average elevation.  $\text{SEL}_A$  was never assigned a value less than ten feet.

The latitudes and longitudes for this study were either measured from maps or taken from benchmark descriptions. The uncertainties assigned to the latitudes (SLT) are shown in Table A.1.

The uncertainty of the theoretical gravity is dependent upon the SLT and is calculated using

$$\text{STHG} = 1.504564 * \sin(2 * \text{LAT}) * \text{SLT}$$

where LAT is the latitude in minutes of the station. The uncertainty

of the free-air correction (SFAC) is

$$\text{SFAC} = 0.094115 * \text{SEL}$$

where SEL is the uncertainty in feet. The uncertainty of the Bouguer slab correction (SBSC) is also dependent on the uncertainty of the elevation and is given by:

$$\text{SBSC} = 0.012774 * \text{RO} * \text{SEL}$$

where RO is the reduction density. The uncertainty of the terrain correction (STC) was assumed to be 15 percent of the total terrain correction.

The uncertainty of the free-air and complete Bouguer anomalies (SFAA and SCBA) were calculated from the uncertainties discussed above using the equations:

$$\text{SFAA} = (\text{SOG}^2 + \text{SFAC}^2 + \text{STHG}^2)^{1/2}$$

$$\text{SCBA} = (\text{SFAA}^2 + \text{SBSC}^2 + \text{STC}^2)^{1/2}$$

The Root-Mean-Square uncertainty of the free-air gravity anomalies in this study was less than one mgal. The Root-Mean-Square uncertainty of the complete Bouguer anomalies was less than 1.5 mgals. Uncertainties for the free-air and complete Bouguer anomalies ranged from .25 mgals to approximately four mgals.

Table A.1. Uncertainties of latitudes for various sources

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<u>Source</u>	<u>SLT (decimal minutes)</u>
Benchmarks descriptions	0.01
7-1/2 minute USGS topographic map	0.02
7-1/2 minute aerial photograph	0.02
15 minute USGS topographic map	0.03
Fire District map	0.04
National Forest map	0.05

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## APPENDIX B

## CALCULATION OF THE RESIDUAL GRAVITY ANOMALY

A gravity measurement includes the sum total of the effects due to masses at deep, intermediate, and shallow depths. Gravity anomaly maps contain long wavelength components due to either broad, shallow sources, or more likely to deeper, regional features. Short wavelength components are due to relatively shallow features. Separation of these two components is a desirable and necessary step in the process of the interpretation of gravity data. Nettleton (1976) discusses a separation of the regional and residual anomalies by means of graphical methods, low-order polynomial fitting of the data, and spectral filtering. Residual anomalies for this study were calculated by the method of spectral filtering discussed below.

Detrending

Before transformation into the frequency domain, it is important to remove the mean and trend from the data matrix (Rayner, 1971). Detrending removes any power from the zero-frequency component of the spectrum. The trend is added back to the final data matrix so that comparisons can be made between filtered and unfiltered maps.

Gridding

The data is then gridded according to a method of Briggs (1974). Data from Oregon and northern California was gridded into a 101 X 101 data matrix which occupied the center of a 128 X 128 matrix.

The grid spacing was six km. Values for the data points in the annulus around the actual data matrix were obtained by finding a surface of minimum curvature through the point  $(i,j)$  using points  $(i\pm 1, j)$ ,  $(i\pm 2, j)$ ,  $(i, j\pm 1)$ ,  $(i, j\pm 2)$ , and  $(i\pm 1, j\pm 1)$ . The periodicity required for the fast Fourier transformation is obtained by repeating the entire data matrix as shown in Figure B.1.

#### Fast Fourier Transformation

A fast Fourier transformation is performed on the data using a routine of Brenner (1968) after Cooley and Tukey (1965).

#### Filtering

Frequencies greater than the cutoff frequency are eliminated with a simple boxcar filter with a cosine bell taper. Tapering the filter reduces the amplitude of the secondary lobes when the spectral data is inversely transformed (Rayner, 1971). The filtering technique is described in detail by Pitts (1979).

#### Inverse Fast Fourier Transformation

The filtered frequency domain data is then inversely fast-Fourier transformed after the method of Cooley and Tukey (1965).

#### Retrending

The original trend is added back into the filtered data matrix.

#### Calculation of the Residual Anomaly

A value for the regional field at each data point is calculated using the method of Briggs (1974). The residual anomaly is

calculated as

$$\text{Resid}(\rho) = \text{CBA}(\rho) - \text{Reg}(\rho)$$

where  $\rho$  is the reduction density of the CBA.

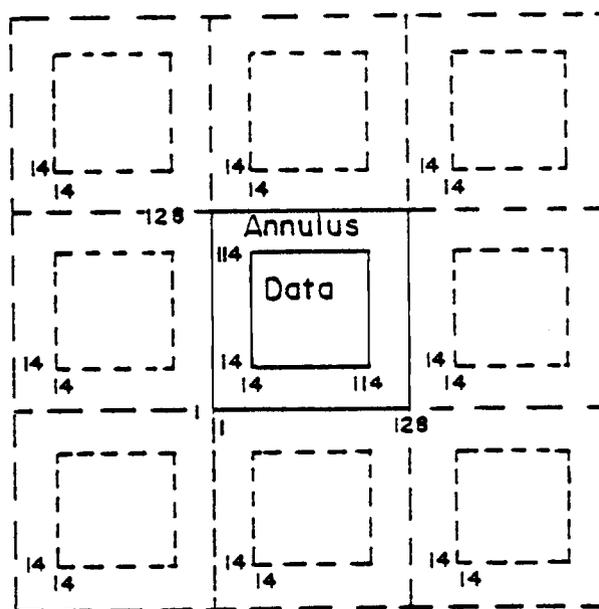


Figure B.1. Representation of the forced periodicity of the gridded gravity data.

## APPENDIX C

## BASE STATION DESCRIPTIONS

The base stations, described below, were established during October of 1979, and July and August of 1980. The Jackson Creek Guard Station and Thompson Reservoir base stations are tied to the OSU-PC base station (Berg and Thiruvathukal, 1965) through Silver Lake (PRB10; Pitts, 1979), Diamond Lake Junction (Blank, 1965), and Corvallis base station OSU-OC (Berg and Thiruvathukal, 1965). The Bonanza base station is tied to the OSU-PC base station through the Klamath Falls OIT base station (Berg and Thiruvathukal, 1965). The remaining base stations are tied to the Bonanza base station. The OSU-PC base station is tied to the base station at the Carnegie Institution in Washington, D.C. (Berg and Thiruvathukal, 1965).

Jackson Creek Guard Station

The Jackson Creek Guard Station base, SC79W001, is located at the entrance to the Jackson Creek guard station. The base plate was placed approximately 35 feet north of the center line of road 3037, on the west shoulder of road 3037E.

Observed gravity is  $980012.47 \pm .09$  mgals.

Thompson Reservoir

The base station near Thompson Reservoir, SC79W032, is located approximately one mile southwest of the reservoir at the junction of roads 5000 and 4000. The base plate was placed 12 feet north of a tree bearing road signs, east of the junction of the centerlines of

the roads.

Observed gravity is  $979984.43 \pm .17$  mgals.

#### Bonanza

Base station SC80W001 is located three feet northeast of the door to unit number two of the Hidden Pines Motel, Bonanza, Oregon. The base plate was placed directly against the wall of the motel.

Observed gravity is  $979993.18 \pm .10$  mgals.

#### Sprague River

Sprague River base station, SC80W009 is located approximately one mile east of the city of Sprague River on Sprague River Road. The base plate was placed atop Benchmark M15, 1920 which is located approximately ten feet north of the road and two feet north of a ditch.

Observed gravity is  $980001.45 \pm .16$  mgals.

#### Fuego Mountain

The Fuego Mountain base, SC80W041 is located on the south shoulder of road 4464. The base plate was placed atop a red boulder painted with a yellow 'X', approximately 12 feet northwest of and at the same elevation as benchmark 32 DRS, 1957.

Observed gravity is  $979968.46 \pm .16$  mgals.

#### Beatty

Base station SC80W068 is located atop benchmark Y350, 1943 in the Beatty Methodist churchyard.

Observed gravity is  $979985.72 \pm .16$  mgals.

Ivory Pine Mill

Base station SC80W108 is located on the west soulder of Silver Lake Road, four miles north of Highway 140. The base plate was placed on the southeast corner of a concrete platform on the shoulder, approximately 120 feet north of a bridge over the North Fork Sprague River.

Observed gravity is  $979968.60 \pm .16$  mgals.

Sycan Marsh

Station SC80W150 is located approximately 100 feet east of the main road from Yamsay Guard Station to Thompson Reservoir, approximately 50 feet south of a dirt road leading to the Sycan Fire Guard Station. The base plate was placed atop U.S. Forest Service benchmark TT-6, 1964, which is in a low rock just east of a line between two large pine trees.

Observed gravity is  $979944.63 \pm .16$  mgals.

Langell Valley Road

SC80W197 is located approximately 35 feet south of the centerline of Langell Valley Road approximately ten miles east of Bonanza, Oregon. The station is located on a flat rock painted yellow, four feet above the road and approximately 30 feet west of the northwest corner of a sheet metal building.

Observed gravity is  $979960.17 \pm .16$  mgals.