JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. B12, PAGES 19,439–19,451, NOVEMBER 10, 1990

Volcanism, Isostatic Residual Gravity, and Regional Tectonic Setting of the Cascade Volcanic Province

RICHARD J. BLAKELY AND ROBERT C. JACHENS

U.S. Geological Survey, Menlo Park, California

A technique to locate automatically boundaries between crustal blocks of disparate densities was applied to upward continued isostatic residual gravity data. The boundary analysis delineates a narrow gravitational trough that extends the length of the Pliocene and Quaternary volcanic arc from Mount Baker in northern Washington to Lassen Peak in California. Gravitational highs interrupt the trough at two localities: a northwest trending high in southern Washington and a northeast trending high between Mount Shasta and Lassen Peak. The latter anomaly is one of a set of northeast trending anomalies that, within the Quaternary arc, appear related to volcanic segmentation proposed previously on the basis of spatial and compositional distributions of volcanoes. These northeast trending anomalies extend hundreds of kilometers northeast of the arc, are caused by sources in the upper crust, and in some cases are related to exposed pre-Tertiary rocks. Segmentation models invoke geometric characteristics of the subducting plate as the primary factor controlling location and chemistry of volcanism, and these northeast trending gravity sources also may be a product of disturbance of the upper crust by the subduction process. More likely, the gravity sources may reflect upper crustal structures older than the High Cascades, possibly relicts from earlier accretionary events or more recent crustal deformation, that have actively influenced the spatial location of more recent volcanism. Much of the Pliocene and Quaternary volcanism of the Cascade arc has concentrated on or near contacts between crustal blocks of disparate density. These contacts may promote the ascension of magma to the Earth's surface.

INTRODUCTION

Volcanism associated with orogenic belts has been a part of the Pacific Northwest since at least the Mesozoic era, but the narrow Cascade volcanic arc of today, extending from northern California to British Columbia, is a relatively modern feature of the continental margin. The Cascade volcanic province is often divided into two parts on the basis of age and volcanic style. Calc-alkaline volcanic rocks of the Western Cascades (Figure 1) erupted from late Eocene to Miocene time in a broad zone across much of western Oregon and Washington. The volcanic arc narrowed markedly during Pliocene and Quaternary time to form the distinctive High Cascade volcanoes of today (Figure 1). The Pliocene and Quaternary arc, generally less than 75 km wide, extends over 1100 km from southeast of Lassen Peak in northern California to Mount Garibaldi in British Columbia. The Cascade volcanic province is clearly a consequence of subduction of the Juan de Fuca, Gorda, and Explorer plates beneath North America, as demonstrated by marine magnetic anomalies, [e.g., *Engebretson et al.*, 1985], deep focus earthquakes [*Ludwin et al.*, 1990], and geologic and tectonic constraints [e.g., *Taylor*, 1989].

The application of gravity measurements to understanding the structure of the Cascade volcanic province has had a long history [e.g., *Pakiser*, 1964; *LaFehr*, 1965; *Blank*, 1968; *Thiruvathukal et al.*, 1970; *Couch et al.*, 1981, 1982; *Williams and Finn*, 1985; *Blakely et al.*, 1985]. Variation in density between volcanic ejecta, flows, and underlying basement rocks causes distinctive regional gravity anomalies that can be used to learn about the distribution of mass in and beneath the volcanic terrane. Specifically, aspects of the structure of underlying basement rocks, the petrology and lithology within the volcanic terrane, and the tectonic setting of the entire province can be inferred from gravity data. Such studies are especially powerful when used concomitantly with other geophysical, geological, and geochemical information.

The Cascade volcanic province contains many regional structural features of sufficient size to be detected by gravity techniques. *Thayer* [1936], for example, proposed that an eastward facing, north trending scarp, which he termed the "Cascade fault," forms the structural boundary between the Western and High Cascades in Oregon. Movement along the Cascade fault raised the older Western Cascades at least 600 m relative to the eastern block and was followed by initiation of High Cascade volcanism to the east which largely buried the surface expression of the fault. *Allen* [1966] proposed a second north trending fault, downdropped to the west, parallel to and ≈30 km east of the Cascade fault. The resulting inferred graben includes Mount Hood, Mount Jefferson, Three Sisters, and Crater Lake; south of Crater Lake, the trend of the graben swings southeast to exclude Mount McLoughlin [*Allen*, 1966]. *Taylor* [1989] proposed that the tensional forces responsible for graben formation in the central Oregon Cascade Range are caused by circulating magma in contact with the bottom of High Cascades crust and generated by the descending lithosphere. *Couch et al.* [1981, 1982] examined residual gravity data from the Cascade Range and found a narrow, north trending gravitational minimum that extends from the Columbia River to nearly the Oregon–California border. They proposed that this minimum delineates a major fracture or brecciated zone. The gravitational minimum is generally coincident with the graben of *Allen* [1966], but it lies west of Mount Jefferson and Three Sisters.

The gravity field of the Pacific Northwest reflects significant crustal structures that have influenced the location of modern-day volcanic activity. It was noted earlier [*Blakely*

Paper number 90JB00605.

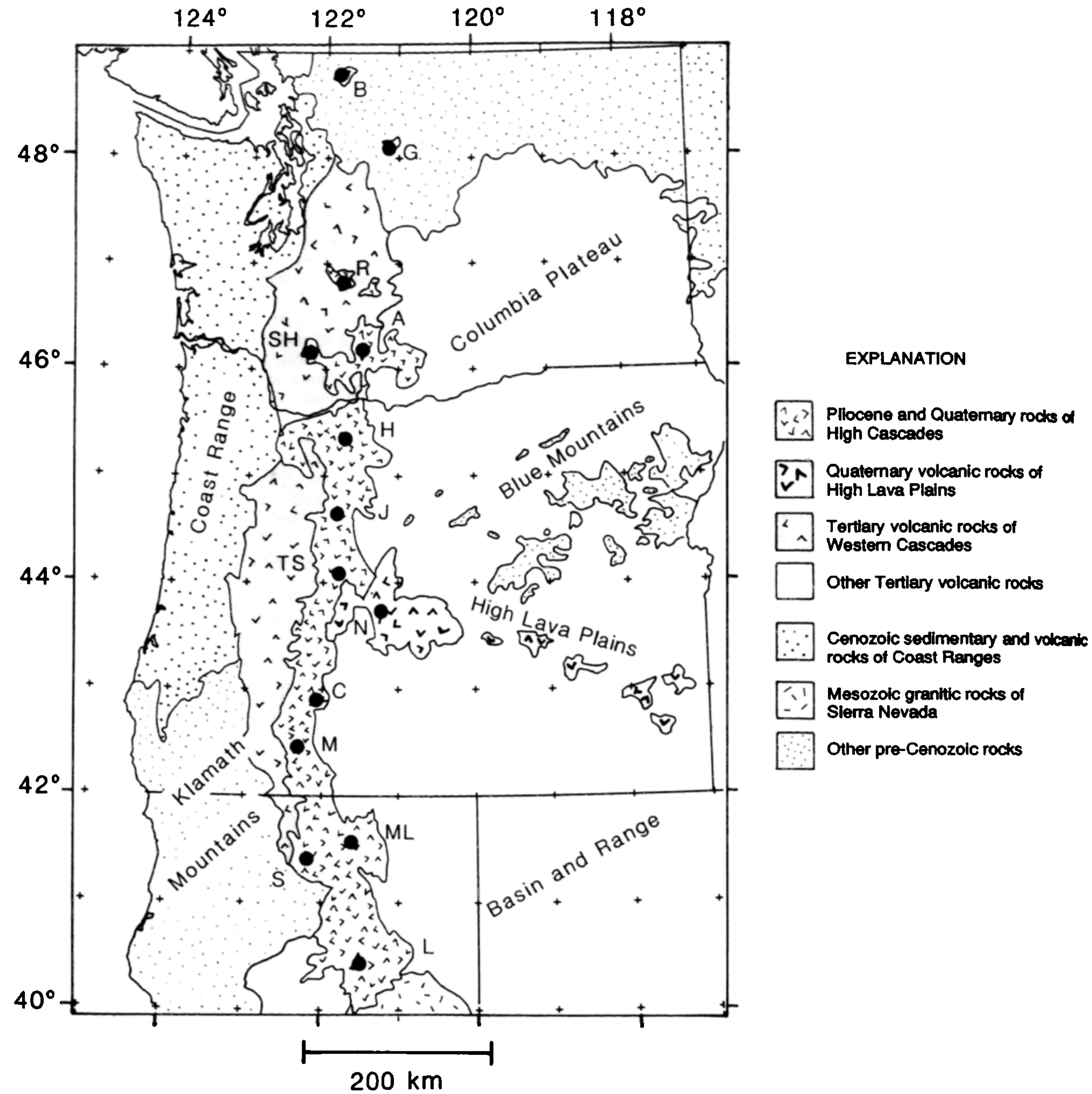

Fig. 1. Generalized geologic map of the Cascade volcanic province and surrounding areas of the Pacific Northwest within the United States. Modified from *Walker and King* [1969], *Weissenborn* [1969], and *Grommé et al.* [1986]. Letters refer to major volcanoes: B, Mount Baker; G, Glacier Peak; R, Mount Rainier; SH, Mount St. Helens; A, Mount Adams; H, Mount Hood; J, Mount Jefferson; TS, Three Sisters; N, Newberry Crater; C, Crater Lake; M, Mount McLoughlin; S, Mount Shasta; ML, Medicine Lake; L, Lassen Peak.

et al., 1985] that major volcanoes south of Mount Jefferson are located along the margins of regional gravity depressions. The gravity depressions were interpreted as reflecting structural depressions; volcanoes are focused near the edges of these depressions presumably because bounding faults and fractures have promoted ascension of magma to the surface. *Guffanti and Weaver* [1988] divided the Cascade arc into five segments on the basis of spatial, temporal, and compositional distributions of volcanoes. Boundaries between fundamental arc segments also should be reflected in gravity data. In this paper, we investigate the spatial relation between Pliocene and Quaternary volcanism and regional gravity data throughout the Cascade volcanic province in the United States and compare that relationship with arc segmentation and heat flow observations.

METHOD

The gravity method is well-established as a tool to delineate regional geologic features. In this paper, we are interested particularly in regional aspects of the middle and upper crust and, therefore, attempt to eliminate long-wavelength anomalies related to isostatic compensation of topographic loads and short-wavelength anomalies caused by local density variations. These problems are treated by an isostatic correction and by upward continuation, respectively.

Isostatic Residual

Bouguer anomalies include long-wavelength components caused by deep sources that isostatically support topographic loads. These regional anomalies are especially prominent in mountainous regions and in regions near continental borders and tend to obscure anomalies caused by lithotectonic variations in the crust. Regional anomalies can be removed by subtracting long-wavelength surfaces estimated from the Bouguer anomaly field. Regional fields are often calculated by polynomial fitting [*Coons et al.*, 1967] or by wavelength filtering [*Kane and Godson*, 1985] of Bouguer anomalies, but these techniques suffer from the fact that they eliminate all wavelengths longer than some threshold, whether or not they are related to topographic features. In particular, long-wavelength anomalies due entirely to lateral variations in crustal density will be eliminated by these techniques.

An isostatic correction is our prefered method for eliminating regional anomalies in the western United States [*Simpson et al.*, 1983, 1986]. Digital topographic models are used to calculate the shape of the crust-mantle interface consistent with the Airy-Heiskanen model for local isostatic compensation; the gravitational effect of this interface is calculated and subtracted from Bouguer anomaly values to produce isostatic residual anomalies. Isostatic residual anomalies used in this paper were calculated from the Gravity Anomaly Map of the United States [*Godson and Scheibe*, 1982; *Society of Exploration Geophysicists*, 1982]. These same data were used previously to prepare an isostatic residual map for the conterminous United States [*Simpson et al.*, 1986, Plate 1].

The Airy model assumes purely local isostatic compensation, which may not be entirely appropriate for areas of regional stress and distributed tectonic and thermal phenomena like those in the Pacific Northwest. Although the Airy model is undoubtedly oversimplified, the isostatic correction that it provides is very long in wavelength [*Simpson et al.*, 1986, Figure 6], and minor differences provided by other models will not greatly affect our conclusions. Moreover, *McNutt* [1980] studied the isostatic response of continental lithosphere to topographic loads and concluded that local compensation dominates regional compensation in the western United States.

Upward Continuation

Plate 1 shows isostatic residual gravity anomalies continued upward to 10 km above the Earth. Upward continuation is a transformation of anomalies measured at one level into those that would be observed at a higher level. Upward continuation tends to smooth all wavelengths, but shortest wavelengths are attenuated more rapidly than long wavelengths [*Blakely*, 1977]. Because anomalies increase in wavelength with increasing dimensions of and increasing distance from the source, upward continuation emphasizes anomalies due to regional, deep structures at the expense of local, shallower sources.

Consider, for example, an anomaly caused by a spherical mass located at depth z below the survey elevation. Upward continuation by height Δz attenuates the anomaly by a factor

$$A = \left[\frac{z}{z + \Delta z}\right]^2$$

and A is clearly dependent on the depth z of the mass. Upward continuation by 10 km attenuates the anomaly of a 1-km-deep sphere by a factor of 0.008 but attenuates the anomaly of an identical sphere at 10 km depth by only 0.250. A similar relation holds for more complicated masses: upward continuation attenuates anomalies due to shallow narrow sources more than anomalies due to deep sources or broad shallow sources.

Upward continuation requires no assumptions about the distribution of crustal densities beneath the survey area. However, assumptions are required about the manner in which crustal density continues beyond the limits of the gravity survey; incorrect assumptions can cause large errors in anomalies located near the edge of the survey. Our starting grid covers the entire conterminous United States. Therefore we were able to extend our "survey" well beyond the limits shown in Plate 1, perform the upward continuation, and then trim the survey back to the limits of Plate 1, virtually eliminating errors near the edges of our survey.

Boundary Analysis

A technique [*Blakely and Simpson*, 1986] for automatically locating the edges of gravity sources was applied to the upward continued isostatic residual gravity data. The method is a two-step procedure. First, the magnitude of maximum horizontal gradient is calculated. Anomaly gradients tend to be steepest over the edges of gravity sources. Consequently, the horizontal-gradient calculation transforms gravity anomalies into maxima that approximately overlie boundaries between regions with disparate density [*Cordell*, 1979]. Second, maxima in the horizontal gradient are automatically located and plotted [*Blakely and Simpson*, 1986], which results in sinuous sequences of dots that represent density boundaries. Figure 2 shows the application of this technique to the residual gravity data of Plate 1.

VOLCANOES

Various authors have noted systematic geological and geophysical variations along the length of the Cascade Range that presumably are due to interactions between the North American, Juan de Fuca, Gorda, and Explorer plates. *Rogers* [1985], for example, suggested that regional tectonism changes from slightly compressional in Washington to slightly extensional in Oregon because of the orientation of the convergent margin. *Hughes et al.* [1980] divided the Cascade Range into six segments based on spatial alignment of volcanoes. *Weaver and Michaelson* [1985] divided the northern Cascades into three segments based on distribution of earthquakes and Cenozoic volcanism. More recently, *Guffanti and Weaver* [1988] have studied the spatial, temporal, and compositional distribution of volcanic vents, including monogenetic and minor volcanoes, and proposed a five-segment model for the Cascade Range.

The distribution of volcanic vents can be a better indicator of regional volcanism than either the lateral extent of erup-

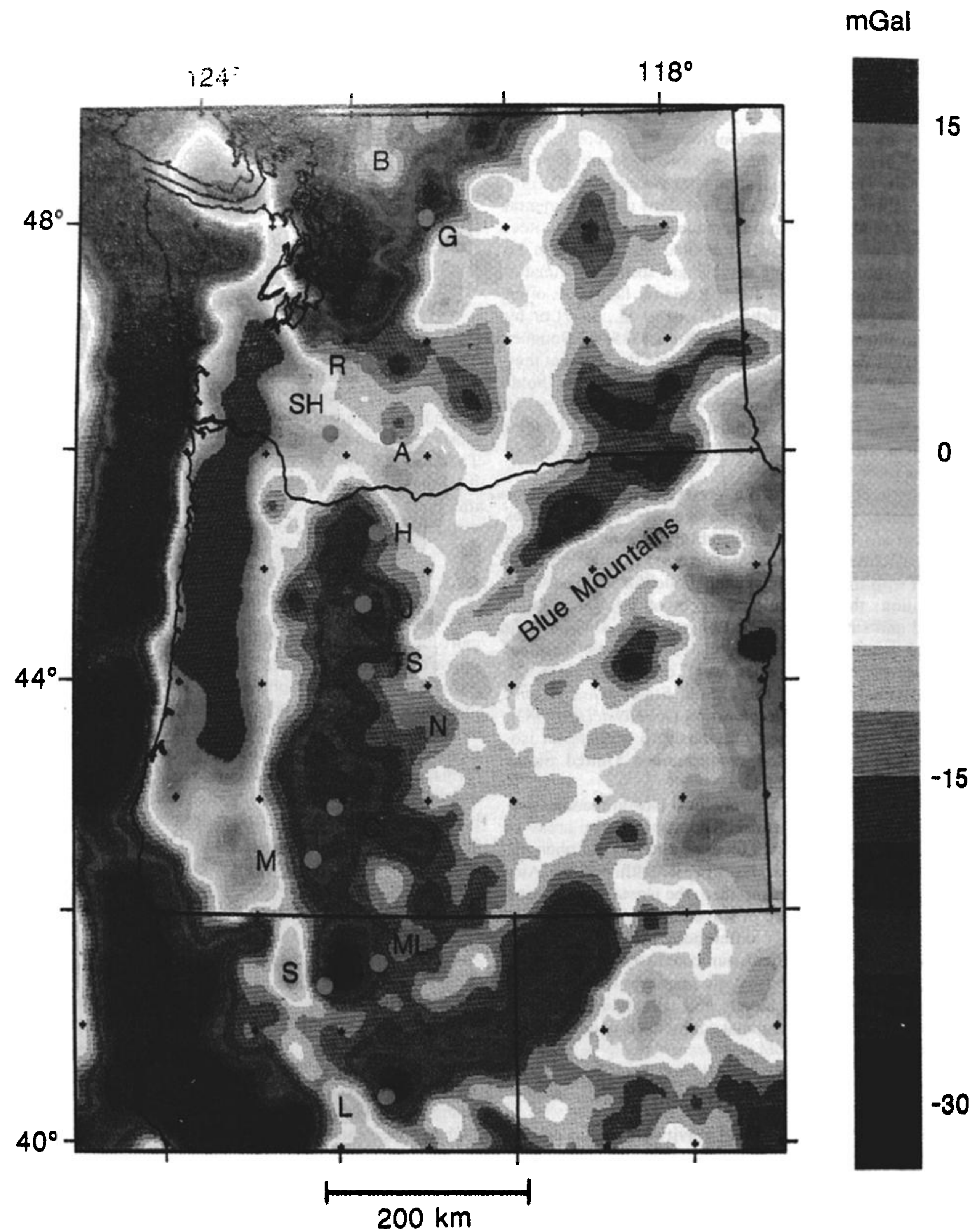

Plate 1. Isostatic residual gravity continued upward 10 km. Color contour interval 3 mGal. Dots indicate major volcanoes; see Figure 1 for definition of labels.

tive products or the distribution of major stratovolcanoes or composite centers [*Smith and Luedke*, 1984]. Vent location, composition, and age were digitized by *Guffanti and Weaver* [1988] from maps compiled by *Luedke and Smith* [1981, 1982]. Figure 3 shows the distribution of volcanoes in the Cascade Range calculated from digital vent locations.

Guffanti and Weaver [1988] discussed in detail the spatial, temporal, and compositional distribution of Cascade vents and

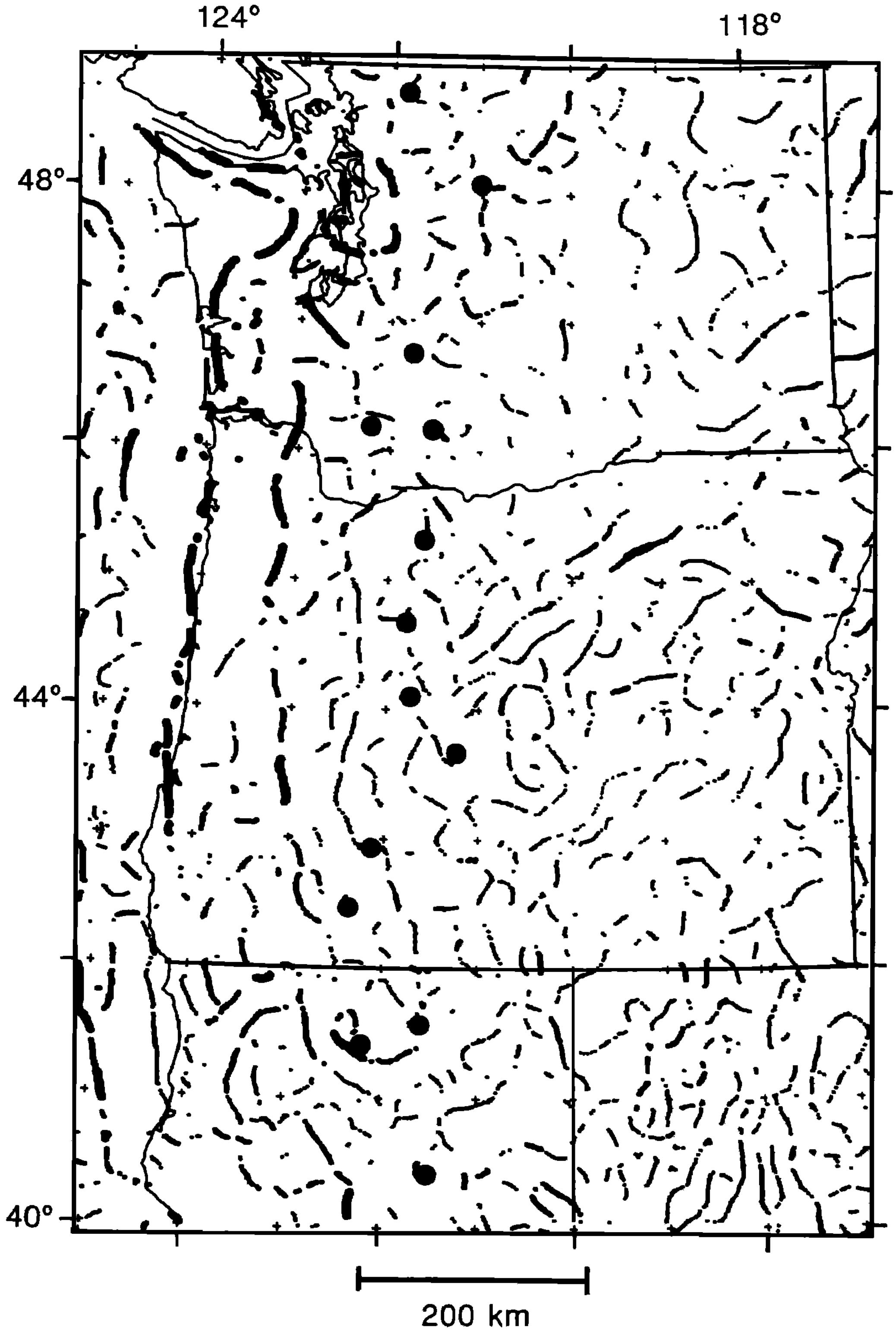

Fig. 2. Automatically calculated boundaries between mass densities. Size of dot represents steepness of horizontal gradient. Smallest dot, 0.2–0.5 mGal/km; medium-sized dot, 0.5–1.0 mGal/km; largest dot, >1.0 mGal/km. Very large dots indicate major volcanoes; see Figure 1 for labels.

divided them into five segments shown in Figure 3: (1) the isolated stratovolcanoes of northern Washington, (2) the wide zone of dominantly basaltic vents from Mount Rainier to Mount Hood, (3) the narrow zone of andesitic vents from south of Mount Hood to the Oregon–California border, (4) the broad zone that includes Mount Shasta and Medicine Lake volcano, and (5) the spatially isolated Lassen Peak area. The west-northwest trending belt of vents of the High Lava Plains (Figure 1) forms a sixth segment outside of the Cascade arc that is not discussed further. The relationship between isostatic residual gravity (Plate 1), volcanic vents (Figure 3), and proposed segmentation will be discussed subsequently.

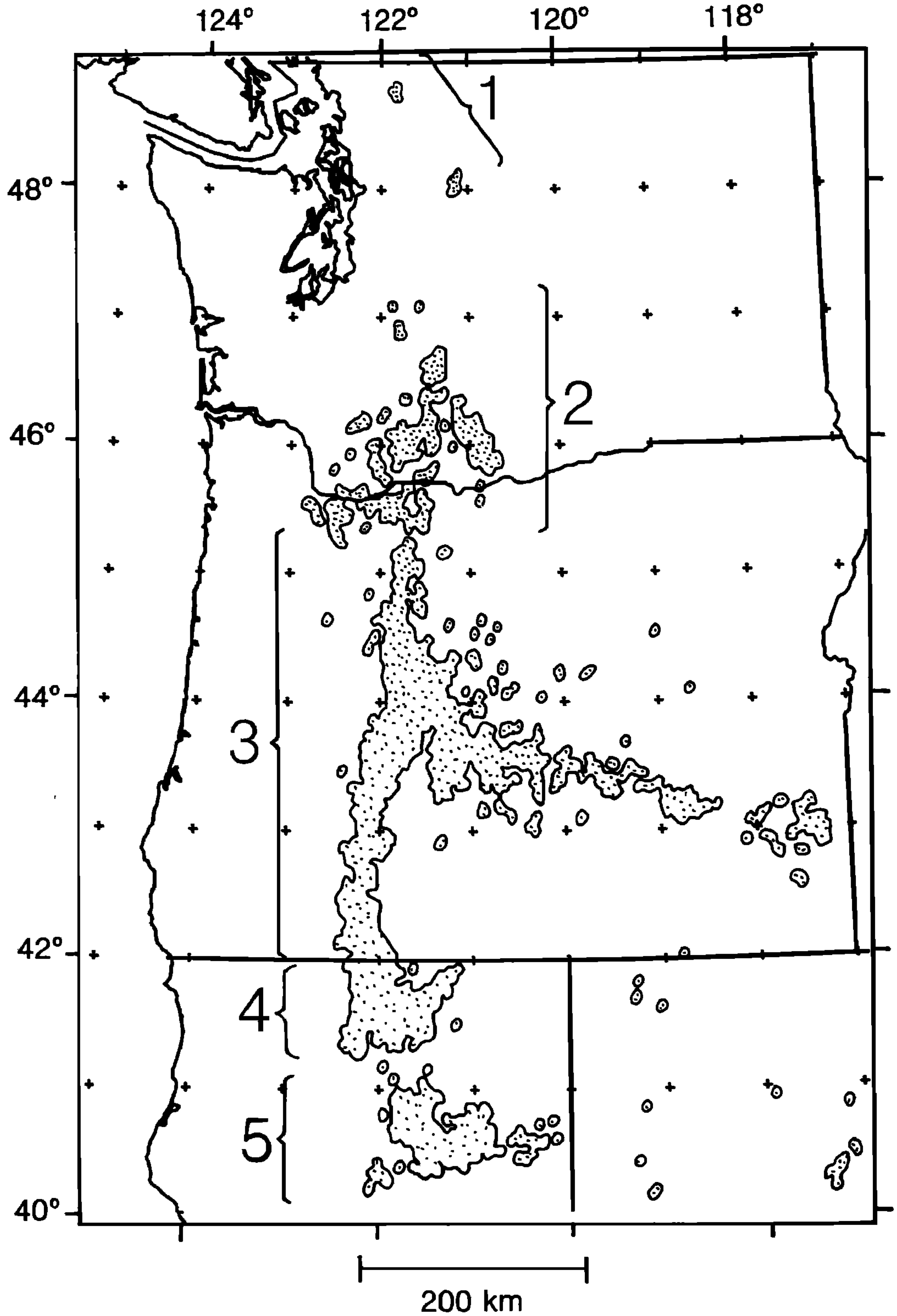

Fig. 3. Location of volcanoes younger than 5 Ma. Vents were summed in overlapping cells 0.5° on each side. Stippled area encloses cells with at least one vent. Numbers refer to segments discussed by *Guffanti and Weaver* [1988].

DISCUSSION

A prominent gravitational depression is visible along most of the Cascade Range (Plate 1). The trough extends from the Lassen Peak area to the Washington–Oregon border where it is interrupted by a northwest trending gravity ridge in southern Washington. The trough continues in northern Washington, although its relationship with the Cascade arc is not obvious. A less pronounced gravity ridge trends northeast and separates the Lassen Peak gravity low from the trough that extends from Mount Shasta to the Washington–

Oregon border. With the exception of one group of volcanoes, all Pliocene and younger vents of the Cascade Range (Figure 3) lie within or on the edge of the gravitational depression (Plate 1). The exception is the cluster of vents in southern Washington and extreme northern Oregon, including Mount St. Helens.

The gravitational depressions of the Cascade arc are bounded on the west by one of the most intense positive anomalies in North America [*Simpson et al.*, 1986]. This positive anomaly is caused in part by mafic igneous rocks of the Coast Ranges in Oregon and Washington [e.g., *Finn*, this issue] and by mafic and ultramafic rocks of the Klamath Mountains in southern Oregon and northern California [e.g., *Griscom*, 1980] (Figure 1), but part of the anomaly may be caused by isostatic effects. An isostatic residual gravity map for the whole of North America [*Simpson et al.* 1988] shows a broad positive anomaly west of the trench (and west of Plate 1) that corresponds with a foretrench bulge in bathymetric data. This offshore anomaly may indicate loading and flexing of the Juan de Fuca plate by the North American plate. Similar but larger bulges are seen at other subduction zones, such as south of the Aleutian Islands [*Watts et al.*, 1976] and west of Central America. If the offshore anomaly is caused by loading and flexing of the Juan de Fuca plate, then the plate probably has sufficient strength to support the overriding North American plate to some extent, thereby contributing to the intense positive anomaly over the Coast Ranges.

A broad region with generally subdued anomalies lies east of the gravitational depression. The region is interspersed with a series of northeast-trending anomalies. *Riddihough et al.* [1986] interpreted the most prominent of these northeast trending anomalies, the steep gradient trending northeast from central Oregon to extreme southeastern Washington (Plate 1), as reflecting a buried structural connection between pre-Tertiary rocks in the Blue Mountains with similar rocks in the Klamath Mountains; its present northeast orientation was interpreted to be the result of clockwise rotation of a Jurassic, north-south transform fault or continental margin.

The gravitational depression over the Cascade volcanic province is not an artifact of the data reduction. A density of 2.67 g/cm^3 was assumed for all rocks above sea level in order to compute both the Bouguer and isostatic correction, and this density may be too high for typical Cascade volcanic rocks [*Williams and Finn*, 1985]. We recomputed the upward continued, isostatic residual map using densities of 2.43 and 2.28 g/cm^3. The latter density is unreasonably small but provides a limiting case. The regional depression was preserved in both cases, and we conclude that the gravitational trough is not a result of an improperly selected density for the Cascade Range.

Spatial Relation of Density Boundaries and Volcanism

Lateral contrasts in density as determined by the automatic boundary analysis (Figure 2) were compared visually at identical scale with color-contour versions of the isostatic residual anomalies, both at ground level and continued upward (Plate 1). Density contrasts that we interpret as significant crustal features were transposed to Figure 4. Preferential attention was given to north trending features associated with the Cascade arc and northeast trending features subparallel to the Blue Mountain–Klamath Mountain lineament [*Riddihough et al.*, 1986].

The long, north-south boundary (Figure 4, location a) in western Oregon, southern Washington, and northern California lies near the western limit of the Western Cascades. It reflects the difference in density between the volcanic rocks of the Western Cascades and the more mafic igneous rocks of the Coast Ranges and Klamath Mountains. Although the Coast Ranges and Klamath Mountains have distinct geologic histories, they now form a rather continuous western boundary for the Cascade volcanic province in Oregon and California.

The Pliocene and Quaternary arc in Oregon and northern California (Figure 4) sinuates within and along the edge of the gravitational depression. From 43°30′ to 45°N, Pliocene and Quaternary volcanism has concentrated very close to the eastern edge of the trough. South of 43°30′N, Pliocene and Quaternary volcanism has concentrated near the center of the depression. Moreover, nearly all major volcanic centers lie near an interpreted gravitational boundary on Figure 4. Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, Mount Adams, Mount Hood, Mount Jefferson, Three Sisters, Crater Lake, Medicine Lake volcano, Mount Shasta, and Lassen Peak all lie within 10 km of a density boundary. Newberry Crater is the only major volcanic center of the Pliocene and Quaternary arc that is not within 20 km of a density boundary (Figure 4). Many gravity anomalies in the Cascade volcanic province reflect structural boundaries between blocks of disparate density; apparently, these boundaries are foci for the ascension of magma to the surface within the Pliocene and Quaternary arc [*Blakely et al.*, 1985].

Segmentation

Guffanti and Weaver [1988] proposed on the basis of spatial, temporal, and compositional distribution of volcanoes that the Cascade arc is divided into five segments (Figure 3). As summarized in Plate 2, the gravity data are consistent with much of their interpretation. The best agreement between gravity data and their proposed segmentation occurs in the Mount Shasta and Lassen Peak area. The residual gravity low over Lassen Peak is part of a regional northeast-trending depression (Plate 2, region A). Within the Pliocene and Quaternary arc, the southern boundary of region A agrees closely with the southern limit of segment 5 (Figure 3 and Figure 4, location b), but the gravity boundary extends nearly 400 km northeast of Lassen Peak, across the northwestern corner of Nevada and nearly into southeastern Oregon. It extends northeast well beyond the majority of young vents, although basaltic vents appear associated with the gravity boundary as far east as the Nevada–California border. The gradients of the anomaly indicate that its source is in the upper crust. In California, this abrupt gravity boundary corresponds with the boundary between pre-Cenozoic rocks of the Sierra Nevada province and younger rocks of the cascade province [*Jennings*, 1977]; in Nevada, the gravity boundary marks the northwestern limit of pre-Cenozoic rocks of the Basin and Range province [*McKee et al.*, 1990].

A northeast trending gravity high (Plate 2, region B) separates the gravitational depressions over Mount Shasta and Lassen Peak. Within the Pliocene and Quaternary arc,

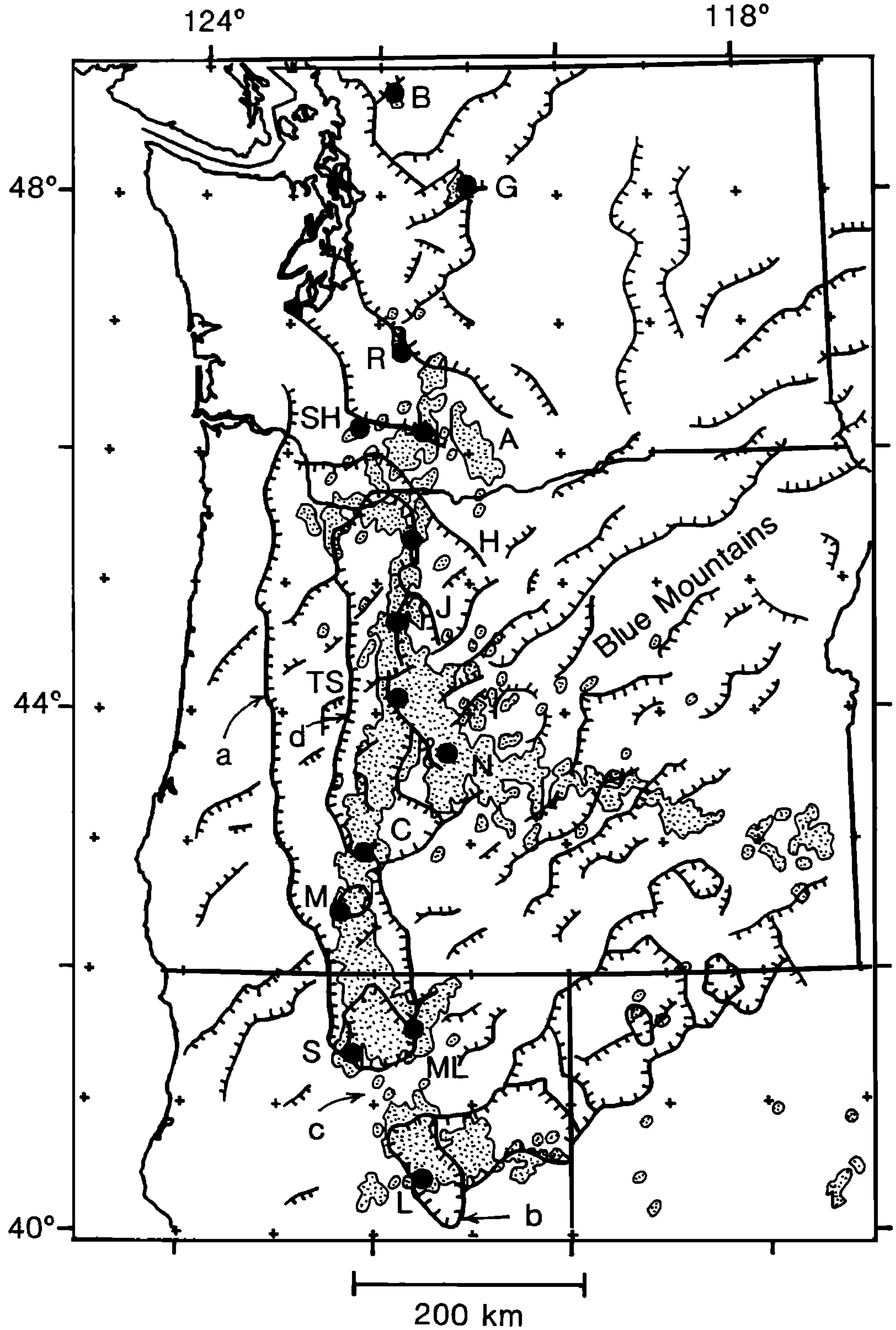

Fig. 4. Interpretation of boundary analysis. Bold, hachured lines indicate boundaries between regions of disparate density as interpreted from Plate 1 and Figure 2; hachures point toward less dense areas. Stippled area indicates lateral extent of Pliocene and Quaternary vents (Figure 3). Capital letters and associated dots are major volcanoes; see Figure 1 for volcano names. Lowercase letters indicate features discussed in text.

the gravity high corresponds closely with the boundary between segments 4 and 5 (Figure 3 and Figure 4, location c), but the gravity high extends over 400 km northeast of Mount Shasta. The steepness of the gravity gradients indicate that the source is located in the upper crust [*Griscom*, 1980; *Blakely et al.*, 1985]. Moreover, *Zucca et al.* [1986] interpreted a shallow "basement" high from seismic refraction data in the vicinity of Medicine Lake which corresponds spatially with region B (Plate 2). The basement high is approximately 40 km wide in the north-south direction and is

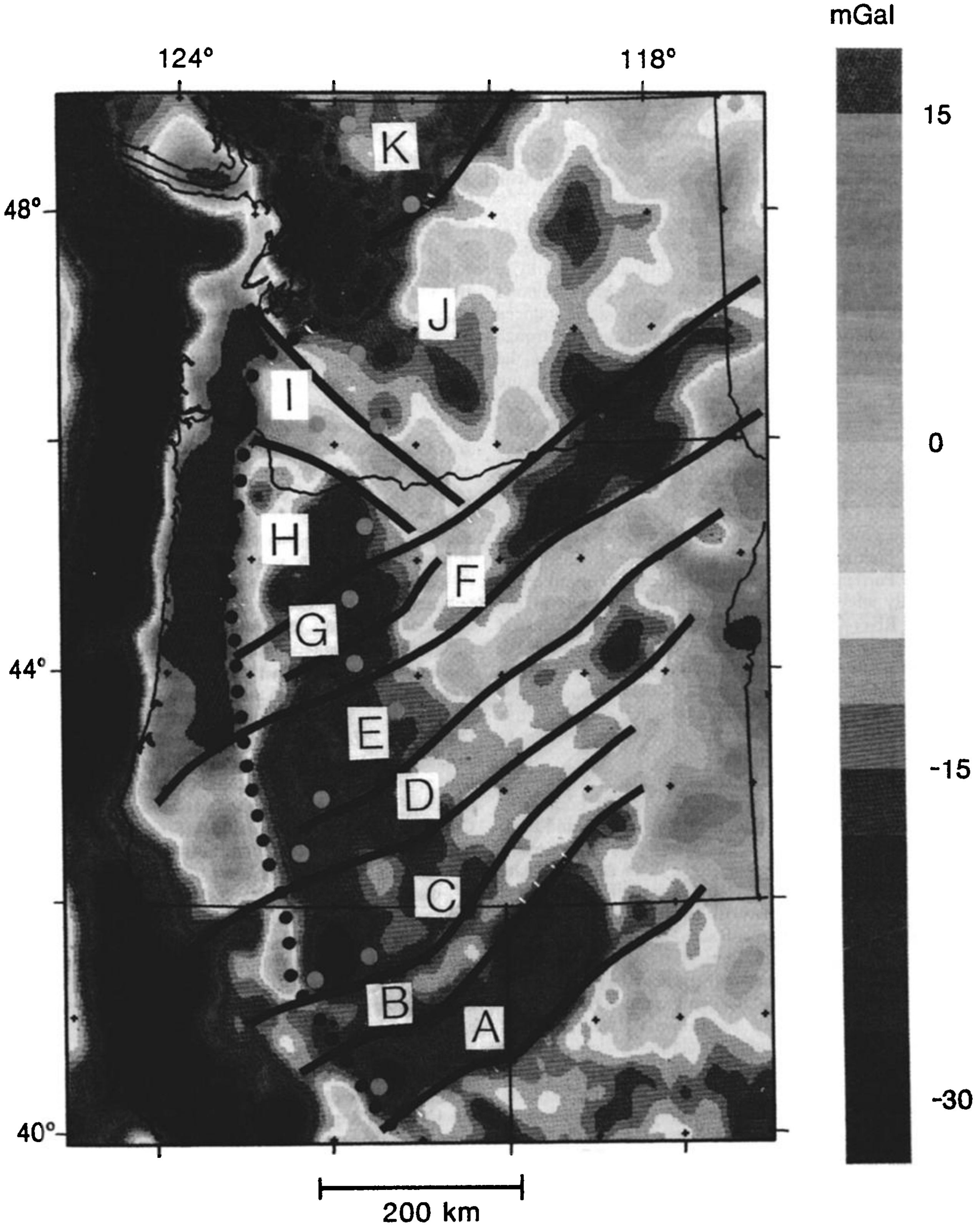

Plate 2. Relation between gravity boundaries and segmentation. Color contour interval 3 mGal. Bold lines are structural contacts interpreted from Plate 1 and Figures 2 and 4. Dotted line is the eastern edge gravitational expression of the Klamath Mountains, Coast Range, and Puget Sound. Pink dots indicate major volcanoes; compare with Plate 1 for volcano names.

buried approximately 1 km below sea level; the basement has a seismic velocity of 6.2 km/s.

Similar to region A, the gravity depression over Mount Shasta (Plate 2, region C) continues at least 400 km to the northeast. The northern limit of region C within the Pliocene and Quaternary arc is roughly 30 km north of the boundary between segments 3 and 4 (Figure 3), but this segment boundary is the least constrained of all their boundaries (M.

Guffanti, personal communication, 1988). It is based on a change in the ratio between andesitic and basaltic vents, as categorized by *Luedke and Smith* [1981, 1982], but the categorization was not based on published chemical analyses [*Sherrod and Smith*, 1989]. *Guffanti and Weaver* [1988] considered segment 3 to continue from the California-Oregon border to just south of Mount Hood. The gravity data suggest that segments (Plate 2, regions D, E, F, and G) may exist north and south of the Three Sisters on strike with the gravity lineations over the Blue Mountains.

A northwest trending gravity high (Plate 2, region I) is located within segment 2, includes many of the vents of segment 2, and separates the Oregon-California gravity depressions from other depressions in Washington. Region I is enigmatic for several reasons. It is the most pronounced high in an otherwise reasonably continuous gravity trough that extends the full length of the Cascade Range in the United States. It includes the only vents of the Cascade arc that do not lie within or near the edge of a gravitational depression. It trends northwest, whereas most gravitational features crossing the Cascade arc trend northeast. All crustal earthquakes greater than magnitude 5 in the Cascade Range have occurred within or near the edges of this enigmatic gravity feature [*Weaver*, 1989]. *Beeson and Tolan* [this issue] described a zone in the Portland area of dip-slip and dextral strike-slip faulting with north-northwest trend. This zone, called the Portland Hills-Clackamas River structural zone, significantly affected the westward flow of basalts of the Columbia River Group through a lowland in the ancestral Cascade Range [*Beeson and Tolan*, this issue]. Hence the north-northwest trending gravity anomaly in this vicinity (Plate 2, region I) may be related to the Portland Hills-Clackamas River structural zone, although the anomaly has a more westerly trend and is displaced tens of kilometers to the northeast of the structural zone.

The relation between volcanic activity and gravity anomalies is uncertain in northern Washington partly because of the very pronounced minimum over the Puget Sound area. This minimum probably is caused by thick accretionary deposits related to subduction of the Juan de Fuca plate [*Simpson et al.*, 1986]. *Stuart* [1961] estimated the thickness of the sedimentary deposits to be greater than 12 km assuming a density contrast with surrounding Eocene volcanic rocks of 0.2 g/cm^3. In spite of the complex gravity anomalies in this region, the southern boundary of segment 1 (Figure 3) corresponds closely with the southern boundary of region K (Plate 2). *Tabor and Crowder* [1969] proposed that a north-northeast trending structure, perhaps a deep fracture, was partly responsible for the location of Glacier Peak (Figure 1) and other volcanic and plutonic rocks of the Glacier Peak area. The northeast trending gravity boundary that separates regions K and J and passes through Glacier Peak (Plate 2) may be caused in part by the same crustal structure.

Northeast trending gravity anomalies in eastern Oregon, southeastern Washington, northeastern California, and northwestern Nevada appear related to segmentation of the Cascade arc proposed by *Guffanti and Weaver* [1988]. Segmentation at other convergent margins [e.g., *Carr et al.*, 1973, 1974] is defined by longitudinal changes in distribution of epicenters, dip of the Benioff zone, and distribution of andesitic volcanoes. These longitudinal changes are explained by fundamental structures of the descending lithosphere, such as tear faults that affect the dip of the subducting slab and shift the axis of volcanism perpendicular to the trench. The Cascade arc has less seismicity than other contemporary subduction zones, and *Guffanti and Weaver* [1988] relied primarily on the spatial and compositional distribution of volcanoes to define Cascade segmentation. Nevertheless, they were able to correlate volcanic segments with subducting plate geometry inferred from contours of subcrustal seismicity at a depth of 60 km.

The northeast trending gravity anomalies are approximately parallel to motion of the Farallon plate relative to North America [*Engebretson et al.*, 1985], but several factors argue against a direct subduction-related explanation for the anomalies. First, many of the gravity gradients are too steep to be caused by sources in the lower crust or below, and at least some of the gravity boundaries are caused in part by structural features that crop out. For example, the southern boundary of region A (Plate 2) is the northern limit of exposed pre-Tertiary basement [*Jennings*, 1977; *McKee et al.*, 1990], and *Riddihough et al.* [1986] interpreted the gravity anomaly that trends northeast from central Oregon to extreme southeastern Washington (Plate 1) to be caused in part by exposed pre-Cenozoic rocks of the Blue Mountains. Seismic refraction data indicate that region B is caused by sources within a few kilometers of the Earth's surface. It is difficult to imagine a causal connection between the emplacement of these upper crustal rocks and present-day subduction of the oceanic plate.

Second, geologic and paleomagnetic evidence indicates that rocks associated with the northeast trending gravity anomalies have been in their present orientation approximately since the end of the Eocene. The Blue Mountains province is an accreted island arc terrane of pre-Tertiary age [*Hamilton*, 1978; *Dickinson and Thayer*, 1978]. Late Jurassic to Early Cretaceous granitic and high-temperature metamorphic rocks within the Blue Mountains province have rotated 60° ± 29° clockwise relative to the stable craton [*Wilson and Cox*, 1980]. However, andesitic and volcaniclastic rocks of the nearby Clarno Formation, mostly of Eocene age, have rotated only 16° ± 10° clockwise [*Grommé et al.*, 1986], and the middle Miocene rocks of the Columbia River Basalt Group have not rotated significantly [*Choinere and Swanson*, 1979; *Hooper et al.*, 1979; *Rietman*, 1966; *Watkins and Baksi*, 1974]. Rotation of the Blue Mountains province, therefore, was largely completed prior to eruptions of the Clarno Formation and entirely completed by the end of eruptions of the Columbia River Basalt Group [*Grommé et al.*, 1986].

The foregoing discussion provides a maximum age for structures related to the northeast trending anomalies east of the Cascade Range. A minimum age can be established because of the juxtaposition of pre-Tertiary rocks associated with these structures with younger volcanic rocks. The steep gravity gradient along the northwest edge of the Blue Mountains is probably caused by relatively low-density rocks beneath the Columbia River Basalt Group ponded against rocks of the Blue Mountains uplift [*Swanson et al.*, 1979; *Mangan et al.*, 1986]. Because the Columbia River Basalt Group has not rotated, this northeast trending structure must have been in place by at least the middle Miocene. Similarly, the steep gravity gradient that forms the southern edge of region A (Plate 2) is related to volcanic rocks juxtaposed with older, pre-Cenozoic rocks to the southeast in northwestern Nevada. These volcanic rocks extruded 34–17 Ma and are in depositional contact with the older rocks [*Stewart and Carlson*, 1978], which implies the northeast trending structure was in place by at least 17 Ma. Consequently, the northeast trending gravity anomalies reflect structures that predate the Pliocene and Quaternary volcanism of the High Cascades.

The northeast trending gravity anomalies probably are not related to modern-day subduction of the Juan de Fuca plate, and their relationship with Cascade segmentation may be coincidental. More likely, segmentation of the Pliocene and Quaternary arc may be influenced by the upper crustal, pre-Tertiary structures that cause the northeast trending anomalies. These structures predate the Pliocene and Quaternary volcanism and may extend beneath the Pliocene and Quaternary arc. Thus the location of volcanism appears partially controlled by crustal structures that are reflected in gravity data, and Cascade segmentation may be influenced by similar effects.

Gravity and Heat Flow

Blackwell et al. [1982] noted a correlation between Bouguer gravity gradients and high conductive heat flow gradients roughly 35 km west of the Three Sisters at latitude 44°N. They interpreted the correspondence between Bouguer anomalies and heat flow in this region to reflect a widespread north-south zone of hot, partially molten material at a depth of about 10 km beneath the High Cascades and extending west well into the western Cascades and to the location of high heat flow and gravity gradients. However, part of the Bouguer gradient in this region is caused by proximity to the continental edge and by the presence of deep crustal masses that compensate the topographic edifice of the Cascade Range. Although Bouguer anomaly values do show a slight correlation with measured heat flow values, residual values, calculated by subtracting a regional field from the Bouguer anomaly, are not statistically correlated [*Ingebritsen et al.*, 1989*a*].

Ingebritsen et al. [1989*b*] suggested that anomalous heat flow in the Western Cascade Range near latitude 44°N is caused by a narrow, spatially variable intrusive zone and that the heat flow anomaly expands laterally at shallow depths due to groundwater flow. The Quaternary Cascade arc has virtually no conductive near-surface heat flow, whereas older rocks display anomalously high conductive and advective heat flow. The analysis of *Ingebritsen et al.* [1989*b*] indicated that anomalous near-surface heat flow arises from groundwater circulation that sweeps heat advectively from the young rocks to the old. They concluded that any deeper thermal anomaly is essentially confined to the Quaternary arc and that laterally extensive magmatic sources of the type envisioned by *Blackwell et al.* [1982] are not required.

Figure 4 (location d) shows a density boundary located roughly 40 km west of Three Sisters at 44°N. The location of the density boundary is based on isostatic residual anomalies rather than Bouguer anomalies and, therefore, is not directly influenced by steep gradients associated with the ocean-continent interface. The density boundary may reflect a geologic contact rather than a thermal discontinuity. The juxtaposition of rocks of disparate density along a north-south fault, as described in the same location by *Sherrod* [1986], may account for the gravitational gradient near 44°N. However, the coincidence of the density boundary with geothermal gradients supports the interpretation of *Blackwell et al.* [1982].

CONCLUSIONS

Many gradients in isostatic residual gravity data define structural boundaries between crustal blocks of disparate density that are related to the volcanic development of the Cascade Range. Our results are consistent with previous ideas about segmentation of the Cascade arc [*Guffanti and Weaver*, 1988], but deciphering the causal relationship between crustal density and segmentation is not straightforward.

Segmentation models commonly invoke geometric characteristics of the subducting plate as the primary factor controlling location and chemistry of upper crustal volcanism. Like volcanoes, the gravitational boundaries are upper crustal in origin, and perhaps they also are a product of disturbance of the crust by the subduction process. More likely, the density boundaries may reflect upper crustal structures that predate the Cascade arc and have influenced the spatial location of volcanism. The array of linear anomalies extending hundreds of kilometers northeast of the Cascade Range supports the latter hypothesis. At least one of these anomalies, extending northeast from central Oregon to southeastern Washington (Plate 1), appears related to segmentation within the Cascade arc but is caused by exposed pre-Tertiary rocks of the Blue Mountains province far from the arc. These rocks were in their present orientation by the middle Miocene and are not related to modern-day subduction of the Farallon plate. Moreover much of the Pliocene and Quaternary volcanism has concentrated on or near the contact between crustal blocks of disparate density. Apparently, these contacts promote the ascension of magma to the earth's surface.

Acknowledgments. We are grateful to Andy Griscom, Patrick Muffler, Dave Sherrod, Jim Smith, Jim Case, Tom Hildenbrand, and Marianne Guffanti for helpful comments and discussions. We also thank Marianne Guffanti and Craig Weaver for providing us with digital vent locations. This research was funded by the U.S. Geological Survey Geothermal Research Program.

REFERENCES

Allen, J. E., The Cascade Range volcano-tectonic depression of Oregon, in *Transactions of the Lunar Geological Field Conference, Bend, Oregon, August 1965*, pp. 21–23, State of Oregon Department of Geological and Mineral Industries, Portland, 1966.

Beeson, M. H., and T. L. Tolan, The Columbia River Basalt Group in the Cascade Range: A middle Miocene reference datum for structural analysis, *J. Geophys. Res.*, this issue.

Blackwell, D. D., R. G. Bowen, D. A. Hull, J. Riccio, and J. L. Steele, Heat flow, arc volcanism, and subduction in northern Oregon, *J. Geophys. Res.*, *87*, 8735–8754, 1982.

Blakely, R. J., Documentation for subroutine REDUC3, an algorithm for the linear filtering of gridded magnetic data, *U.S. Geol. Surv. Open File Rep.*, *77-784*, 27 pp., 1977.

Blakely, R. J., and R. W. Simpson, Approximating edges of source bodies from magnetic or gravity anomalies, *Geophysics*, *51*, 1494–1498, 1986.

Blakely, R. J., R. C. Jachens, R. W. Simpson, and R. W. Couch, Tectonic setting of the southern Cascade Range as interpreted from its magnetic and gravity fields, *Geol. Soc. Am. Bull.*, *96*, 43–48, 1985.

Blank, H. R., Aeromagnetic and gravity surveys of the Crater Lake region, Oregon, Andesite Conference Guidebook, edited by H. M. Dole, *Bull. Oreg. Dep. Geol. Miner. Ind.*, *62*, 42–52, 1968.

Carr, M. J., R. E. Stoiber, and C. L. Drake, Discontinuities in the deep seismic zones under the Japanese arcs, *Geol. Soc. Am. Bull.*, *84*, 2917–2930, 1973.

Carr, M. J., R. E. Stoiber, and C. L. Drake, The segmented nature of some continental margins, in *The Geology of Continental Margins*, edited by C. A. Burke and C. L. Drake, pp. 105–114, Springer-Verlag, New York, 1974.

Choinere, S. A., and D. A. Swanson, Magnetostratigraphy and correlation of Miocene basalts of the northern Oregon coast and Columbia plateau, southeast Washington, *Am. J. Sci.*, *279*, 755–777, 1979.

Coons, R. L., G. P. Woollard, and G. Hershey, Structural significance and analysis of mid-continent gravity high, *AAPG Bull.*, *51*, 2381–2399, 1967.

Cordell, L., Gravimetric expression of graben faulting in Sante Fe county and the Española basin, New Mexico, Guidebook to Santa Fe Country, edited by R. V. Ingersoll, *Field Conf. Guideb. N. M. Geol. Soc.*, *30th*, 59–64, 1979.

Couch, R. W., M. Gemperle, G. Connard, and G. S. Pitts, Structural and thermal implications of gravity and aeromagnetic measurements made in the Cascade volcanic arc, paper presented at Annual International Meeting, Soc. of Explor. Geophys., Los Angeles, Calif., 1981.

Couch, R. W., G. S. Pitts, M. Gemperle, D. E. Braman, and C. A. Veen, Gravity anomalies in the Cascade Range in Oregon: Structural and thermal implications, *Open File Rep. 0-82-9*, 66 pp., Oreg. Dep. of Geol. and Miner. Ind., Portland, 1982.

Dickinson, W. R., and T. P. Thayer, Paleogeographic and paleotectonic implications of Mesozoic stratigraphy and structure in the John Day inlier of central Oregon, in *Mesozoic Paleogeography of the Western United States*, edited by D. G. Howell and K. A. McDougall, pp. 147–161, Society of Economic Paleontologists and Mineralogists, Los Angeles, Calif., 1978.

Engebretson, D. C., A. Cox, and R. G. Gordon, Relative motions between oceanic and continental plates in the Pacific basin, *Geol. Soc. Am. Spec. Publ.*, *206*, 59 pp., 1985.

Finn, C., Structure of the convergent Washington margin, *U.S. Geol. Surv. Open File Rep.*, *89-178*, 291–317, 1989.

Finn, C., Geophysical constraints on Washington convergent margin structure, *J. Geophys. Res.*, this issue.

Godson, R. H., and D. M. Scheibe, Description of magnetic tape containing conterminous U.S. gravity data in gridded format, *Rep. PB82-254798*, magnetic tape with description, 5 pp., Natl. Tech. Inf. Serv., Springfield, Va., 1982.

Griscom, A., Klamath Mountains province, Interpretation of the Gravity Map of California and Its Continental Margin, edited by H. W. Oliver, *Bull. Calif. Div. Mines Geol.*, *205*, 34–36, 1980.

Grommé, C. S., M. E. Beck, Jr., R. E. Wells, and D. C. Engebretson, Paleomagnetism of the Tertiary Clarno Formation of central Oregon and its significance for the tectonic history of the Pacific Northwest, *J. Geophys. Res.*, *91*, 14,089–14,103, 1986.

Guffanti, M., and C. S. Weaver, Distribution of late Cenozoic volcanic vents in the Cascade Range: Volcanic arc segmentation and regional tectonic considerations, *J. Geophys. Res.*, *93*, 6513–6529, 1988.

Hamilton, W., Mesozoic tectonics of the western United States, in *Mesozoic Paleogeography of the Western United States*, edited by D. G. Howell and K. A. McDougall, pp. 33–70, Society of Economic Paleontologists and Mineralogists, Los Angeles, Calif., 1978.

Hooper, P. R., C. R. Knowles, and N. D. Watkins, Magnetostratigraphy of the Imnaha and Grande Ronde basalts in the southeast part of the Columbia Plateau, *Am J. Sci.*, *279*, 737–754, 1979.

Hughes, J. M., R. E. Stoiber, and M. J. Carr, Segmentation of the Cascade volcanic chain, *Geology*, *8*, 15–17, 1980.

Ingebritsen, S. E., D. R. Sherrod, and R. H. Mariner, Heat flow and hydrothermal circulation in the Cascade Range, north-central Oregon, *U.S. Geol. Surv. Open File Rep.*, *89-178*, 122–141, 1989*a*.

Ingebritsen, S. E., D. R. Sherrod, and R. H. Mariner, Heat flow and hydrothermal circulation in the Cascade Range, north-central Oregon, *Science*, *243*, 1458–1462, 1989*b*.

Jennings, C. W., Geologic map of California, *Geol. Map 2*, scale 1:750,000, Calif. Div. of Mines and Geol., Sacramento, 1977.

Kane, M. F., and R. H. Godson, Features of a pair of long-wavelength (>250 km) and short-wavelength (<250 km) Bouguer gravity maps of the United States, in *The Utility of Regional Gravity and Magnetic Anomaly Maps*, edited by W. J. Hinze, pp. 46–61, Society of Exploration Geophysicists, Tulsa, Okla., 1985.

LaFehr, T. R., Gravity, isostasy, and crustal structure in the southern Cascade Range, *J. Geophys. Res.*, *70*, 5581–5597, 1965.

Ludwin, R. S., C. S. Weaver, and R. S. Crosson, Seismicity of Washington and Oregon, in *The Geology of North America*, vol. CSMV-1, *Neotectonics of North America*, edited by D. B. Slemmons, E. R. Engdahl, D. Blackwell, and D. Schwartz, Geological Society of America, Boulder, Colo., in press, 1990.

Luedke, R. G., and R. L. Smith, Map showing distribution, composition, and age of late Cenozoic volcanic centers in California and Nevada, scale 1:1,000,000, *U.S. Geol. Surv. Misc. Invest. Ser.*, *Map I-1091-C*, 1981.

Luedke, R. G., and R. L. Smith, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Oregon and Washington, scale 1:1,000,000, *U.S. Geol. Surv. Misc. Invest. Ser.*, *Map I-1091-D*, 1982.

Mangan, M. T., T. L. Wright, D. A. Swanson, and G. R. Byerly, Regional correlation of Grande Ronde Basalt flows, Columbia River Basalt Group, Washington, Oregon, and Idaho, *Geol. Soc. Am. Bull.*, *97*, 1300–1318, 1986.

McKee, E. H., R. C. Jachens, and R. J. Blakely, Major crustal differences between the northwestern part of the Great Basin and other parts of the province (abstract), in *Geology and Ore Deposits of the Great Basin*, pp. 100–101, Geological Society of Nevada, Reno, 1990.

McNutt, M., Implications of regional gravity for state of stress in the Earth's crust and upper mantle, *J. Geophys. Res.*, *85*, 6377–6396, 1980.

Pakiser, L. C., Gravity, volcanism, and crustal structure in the southern Cascade Range, California, *Geol. Soc. Am. Bull.*, *75*, 611–620, 1964.

Riddihough, R., C. Finn, and R. Couch, Klamath-Blue Mountain lineament, Oregon, *Geology*, *14*, 528–531, 1986.

Rietman, J. D., Remanent magnetism of the Late Yakima basalt, Washington State, Ph.D. thesis, 114 pp., Stanford Univ., Stanford Calif., 1966.

Rogers, G. C., Variation in Cascade volcanism with margin orientation, *Geology*, *13*, 495–498, 1985.

Sherrod, D. R., Geology, petrology, and volcanic history of a portion of the Cascade Range between latitudes 43°–44°N, central Oregon, U.S.A., Ph.D. dissertation, 320 pp., Univ. of Calif., Santa Barbara, 1986.

Sherrod, D. R., and J. G. Smith, Quaternary extrusion rates from the Cascade Range, northwestern United States and British Columbia, *U.S. Geol. Surv. Open File Rep.*, *89-178*, 94–103, 1989.

Simpson, R. W., R. C. Jachens, and R. J. Blakely, AIRYROOT: A FORTRAN program for calculating the gravitational attraction of an Airy isostatic root out to 166.7 km, *U.S. Geol. Surv. Open File Rep.*, *83-883*, 66 pp., 1983.

Simpson, R. W., R. C. Jachens, R. J. Blakely, and R. W. Saltus, A new isostatic residual gravity map of the conterminous United States with a discussion on the significance of isostatic residual anomalies, *J. Geophys. Res.*, *91*, 8348–8372, 1986.

Simpson, R. W., T. G. Hildenbrand, R. C. Jachens, and D. F. Barnes, Geologic implications of a new isostatic residual gravity map of North America, *Geol. Soc. Am. Abstr. Programs*, *20*, A325, 1988.

Smith, R. L., and R. G. Luedke, Potentially active volcanic lineaments and loci in western conterminous United States, in *Explosive Volcanism: Inception, Evolution, Hazards*, pp. 47–66, National Academy Press, Washington, D. C., 1984.

Society of Exploration Geophysicists, Gravity anomaly map of the United States (exclusive of Alaska and Hawaii), scale 1:2,500,000, Tulsa, Okla., 1982.

Stewart, J. H., and J. E. Carlson, Geologic map of Nevada, scale 1:500,000, *U.S. Geol. Surv.*, Reston, Va., 1978.

Stuart, D. J., Gravity study of crustal structure in western Washington, *U.S. Geol. Surv. Prof. Pap.*, *424-C*, C273–C276, 1961.

Swanson, D. A., T. L. Wright, P. R. Hooper, and R. D. Bentley, Revisions in stratigraphic nomenclature of the Columbia River basalt Group, *U.S. Geol. Surv. Bull.*, *1457-G*, 59 pp., 1 plate, 1979.

Tabor, R. W., and D. F. Crowder, On bathliths and volcanoes—Intrusion and eruption of late Cenozoic magmas in the Glacier Peak area, North Cascades, Washington, *U.S. Geol. Surv. Prof. Pap.*, *604*, 67 pp., 1969.

Taylor, E. M., Volcanic history and tectonic development of the central High Cascade Range, Oregon, *U.S. Geol. Surv. Open File Rep.*, *89-178*, 369–394, 1989.

Thayer, T. P., Structure of the north Santiam River section of the Cascade Mountains in Oregon, *J. Geol.*, *44*, 701–716, 1936.

Thiruvathukal, J. V., J. W. Berg, and D. F. Heinrichs, Regional gravity of Oregon, *Geol. Soc. Am. Bull.*, *81*, 725–738, 1970.

Walker, G. W., and P. B. King, Geologic map of Oregon, scale 1:2,000,000, *U.S. Geol. Surv. Misc. Geol. Invest. Map*, *I-595*, 1969.

Watkins, N. D., and A. K. Baksi, Magnetostratigraphy and oroclinal folding of the Columbia River, Steens, and Owyhee basalts in Oregon, Washington, and Idaho, *Am. J. Sci.*, *274*, 148–189, 1974.

Watts, A. B., M. Talwani, and J. R. Cochran, Gravity field of the northwest Pacific ocean basin and its margin, in *The Geophysics of the Pacific Ocean Basin and Its Margin*, *Geophys. Monogr. Ser.*, vol. 19, edited by G. H. Sutton, M. H. Manghani, and R. Moberly, pp. 17–34, AGU, Washington, D. C., 1976.

Weaver, C. S., Seismicity of the Cascade Range and adjacent areas, *U.S. Geol. Surv. Open File Rep.*, *89-178*, 74–93, 1989.

Weaver, C. S., and C. A. Michaelson, Seismicity and volcanism in the Pacific Northwest: Evidence for the segmentation of the Juan de Fuca plate, *Geophys. Res. Lett.*, *12*, 215–218, 1985.

Weissenborn, A. E., Geologic map of Washington, scale 1:2,000,000, *U.S. Geol. Surv. Misc. Geol. Invest Map*, *I-583*, 1969.

Williams, D. L., and C. Finn, Analysis of gravity data in volcanic terrain and gravity anomalies and subvolcanic intrusions in the Cascade Range, U.S.A., and at other selected volcanoes, in *The Utility of Regional Gravity and Magnetic Anomaly Maps*, edited by W. J. Hinze, pp. 361–374, Society of Exploration Geophysicists, Tulsa, Okla., 1985.

Wilson, D., and A. Cox, Paleomagnetic evidence for tectonic rotation of Jurassic plutons in Blue Mountains, eastern Oregon, *J. Geophys. Res.*, *85*, 3681–3689, 1980.

Zucca, J. J., G. S. Fuis, B. Milkereit, W. D. Mooney, and R. D. Catchings, Crustal structure of northeastern California, *J. Geophys. Res.*, *91*, 7359–7382, 1986.

R. J. Blakely and R. C. Jachens, U.S. Geological Survey, 345 Middlefield Road, MS 989, Menlo Park, CA 94025.

(Received July 10, 1989;
revised March 9, 1990;
accepted October 4, 1989.)