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Gravity anomalies, Quaternary vents, and Quaternary faults in the southern Cascade Range, Oregon and California: Implications for arc and backarc evolution

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Abstract. Isostatic residual gravity anomalies in the southern Cascade Range of northern California and southern Oregon are spatially correlated with broad zones of Quaternary magmatism as reflected by the total volume of Quaternary volcanic products, the distribution of Quaternary vents, and the anomalously low teleseismic *P* wave velocities in the upper 30 km of crust. The orientation of Quaternary faults also appears to be related to gravity anomalies and volcanism in this area, trending generally north-south within the magmatic regions and northwest-southeast as they enter the neighboring amagmatic zones to the north and south. The relationship between gravity anomalies, vent density, and fault orientations may indicate in a broad sense the strength of the middle and upper crust. The southern Cascade Range occupies a transition zone where horizontal stress is transferred from the northwest-southeast dextral shear of the Walker Lane belt to the east-west extension characteristic of the Cascade arc in central Oregon. Faulting along north-south strikes in the volcanically active areas indicates the east-west extensional stresses in thermally weakened crust, whereas northwest faulting between the volcanically active areas reflects the northwest trending, right lateral shear strain of the Walker Lane belt. The segmentation of the arc reflected in Quaternary magmatism may be caused by differential extension behind crustal blocks of the forearc rotating clockwise with respect to North America. In this view the volcanic centers at Mount Shasta, Medicine Lake volcano, and Lassen Peak in northern California are situated along the southern parts of the trailing edges of two distinct segments of the forearc where additional extension is implied by their differential clockwise rotation.

1. Introduction

The southern Cascade Range in southern Oregon and northern California occupies a tectonically complex part of the Pacific Northwest. Although clearly part of the active volcanic arc associated with subduction of the Juan de Fuca and Gorda plates beneath North America, the southern Cascade Range is also influenced by interactions with the Basin and Range province, the Mendocino triple junction, and the San Andreas fault system (Figure 1). Although the Juan de Fuca and Gorda plates are converging with North America at an oblique angle, the maximum horizontal stress behind the arc is oriented generally north-south [*Zoback*, 1992]. *Zoback and Zoback* [1985] suggested that transform motion between the Pacific and North American plates along the San Andreas fault system, rather than convergence between the Juan de Fuca and North American plates, is the dominant factor in controlling regional stress throughout a broad region of the Pacific Northwest, a region which includes the southern Cascade Range.

Residual gravity anomalies are common over volcanoes and volcanic centers, reflecting the relatively low density of volcanic products, the geothermal conditions of the crust, and the structural and magmatic underpinnings of the volcanism. This relationship is particularly well displayed in northern California where a well-defined gravity anomaly over the volcanic centers at Mount Shasta and Medicine Lake volcano is distinctly isolated from a similar anomaly over the Lassen volcanic center to the south and from gravity anomalies to the north over the Oregon High Cascades. In this paper we examine this part of the Cascade arc, focusing on the spatial relationship between gravity anomalies and the distributions of Quaternary vents, Quaternary faults, crustal earthquakes, seismic velocity structure, and other crustal manifestations of stress, tectonism, and geothermal conditions. The spatial correlations among these various observations reflect dynamic properties of the crust and upper mantle and provide clues concerning the Tertiary and Quaternary evolution of the Cascade arc within the complexly evolving western margin of the North American plate.

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2. Data and Observations

2.1. Gravity Anomalies

The southern part of the Cascade volcanic arc lies within a broad, north-south depression in isostatic residual gravity [*Simpson et al.*, 1986] extending more than 600 km from north of the Columbia River to south of Lassen Peak (Plate 1). The abrupt western margin of this north-south gravity trough is caused principally by lithologic contrasts between arc-related rocks of the Cascade Range and forearc-accreted terranes of the Oregon Coast Range and Klamath Mountains [*Couch et al.*, 1982; *Blakely*, 1994]. The eastern margin of the trough is

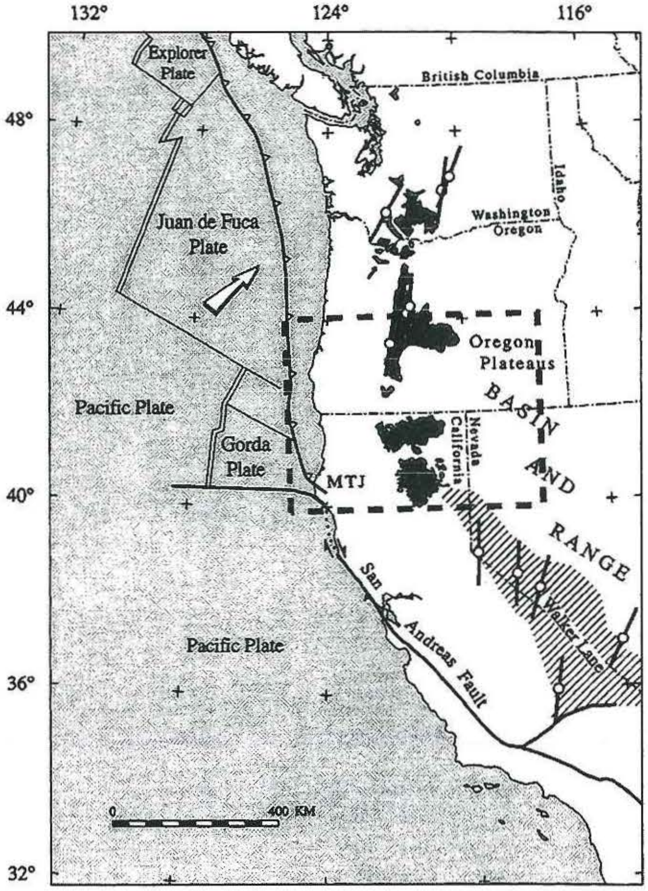

Figure 1. Regional tectonic setting of the southern Cascade Range. Darkly shaded pattern represents Quaternary rocks of the Cascade Range, and the lined pattern is the Walker Lane belt. Line-circle symbols indicate orientation of maximum horizontal stress [*Zoback*, 1992] in the arc and backarc of Oregon and Washington and in the Walker Lane (only quality "A" determinations are shown; see *Zoback* [1992] for an explanation). Arrow indicates direction of convergence between the Juan de Fuca and North American plates. Dashed box shows the area of Figures 3, 4, 6–8, 10, and 11.

less well defined gravitationally, reflecting a complex boundary between the arc and backarc regions. As discussed subsequently, the complexity in gravity anomalies results both from the configuration of the base of Tertiary volcanic rocks and from structures in the underlying basement.

The north-south gravity trough, although relatively continuous from the Columbia River to Lassen Peak, is pockmarked with several local gravity lows spatially associated with major volcanic centers. The best examples occur in the southernmost part of the Cascade arc, where a broad gravity low enclosing Mount Shasta and the Medicine Lake volcano is separated spatially from a gravity low enclosing the Lassen volcanic center (Plate 1) [*Pakiser*, 1964; *LaFehr*, 1965]. *LaFehr* [1965] concluded that the gravity lows over the volcanic centers at Mount Shasta and Lassen Peak are caused primarily by lithologic variations in the upper 10 km of crust.

In the following discussion we will make a distinction between the roughly equidimensional gravity lows discussed above and the gravity lineaments (labeled MGL, SGL, and LGL on the figures) that extend northeastward from the Cascades. For example, the gravity low over the Lassen volcanic center is at the southwestern end of a broad, linear gravity depression, referred to here as the Lassen gravity lineament, extending northeastward 300 km into northwestern Nevada and southeastern Oregon (LGL on Plate 1 and subsequent figures). Similarly, the Mount Shasta-Medicine Lake gravity low lies at the southwestern end of another linear gravity depression, referred to as the Shasta gravity lineament (Plate 1, SGL), less well defined than the Lassen gravity lineament but extending northeastward a similar distance. A third gravity lineament, referred to here as the McLoughlin gravity lineament, extends northeastward from Mount McLoughlin in southern Oregon (Plate 1, MGL).

Trends other than those shown in Plate 1 can be found, to be sure. The roughly north-south pattern of normal fault blocks related to basin-range extension produces numerous gravity anomalies. These and other local structures strongly modify the northeast striking pattern throughout the backarc region, but the northeast pattern remains evident in the broader anomalies. Figure 2 shows two maps derived from the gravity data of Plate 1. Figure 2a shows the locations of maximum horizontal gradients of the gravity field with trends between 0° and 90°E, calculated using the method of *Blakely and Simpson* [1986]. Maxima in the horizontal gradient tend to indicate abrupt density contrasts in the middle and upper crust. These calculations were used along with the isostatic residual gravity anomalies and other data discussed subsequently to interpret the boundaries surrounding the gravity lows and lineations shown in Plate 1 and discussed subsequently.

Figure 2b shows the gravity anomalies of Plate 1 analytically continued upward 10 km in order to emphasize deeper parts of the crust [*Blakely and Jachens*, 1990]. The Lassen gravity lineament and, to a lesser extent, the other gravity lineaments are reflected in the upward continued anomalies, implying that they originate from the upper and middle crust.

The Shasta and Lassen gravity lineaments (Plates 1 and 2) are separated by a northeast-trending chain of gravity highs, which *Chapman and Bishop* [1968] and *Griscom* [1980b] suggested could be caused by structures within the basement underlying the Modoc Plateau. The westernmost anomaly of this chain (Plate 1, T1) lies over a salient of the Eastern Klamath belt of pre-Tertiary rocks [*Irwin*, 1966] exposed south of Mount Shasta and northwest of Lassen Peak. *Griscom* [1980a] concluded that this gravity high is caused by mafic and ultramafic rocks of the Trinity ophiolite complex, an early Paleozoic assemblage within the Eastern Klamath belt. The Trinity complex is also exposed west and southwest of Mount Shasta, where it produces a pronounced gravity anomaly [*LaFehr*, 1965; *Griscom*, 1977, 1980a] (Plate 1, T2). Aeromagnetic [*Blakely et al.*, 1985] and seismic refraction [*Fuis et al.*, 1987; *Zucca et al.*, 1986] data suggest that the Trinity complex extends eastward with shallow dip and may lie at a depth of ~5 km beneath Mount Shasta.

The Lassen, Shasta, and McLoughlin gravity lineaments are part of a northeast trending "fabric" of gravity anomalies throughout central and eastern Oregon, northeastern California, and northwestern Nevada, which we refer to here as the Oregon Plateaus gravity province. This region is bounded on the south by the northern limit of pre-Tertiary exposures in the Basin and Range province and northern Sierra Nevada and on the north by pre-Tertiary exposures of the Blue Mountains uplift. The most notable gravity anomaly of the region lies along a northeast trending line from the Klamath Mountains in southwestern Oregon to the Blue Mountains in northeastern

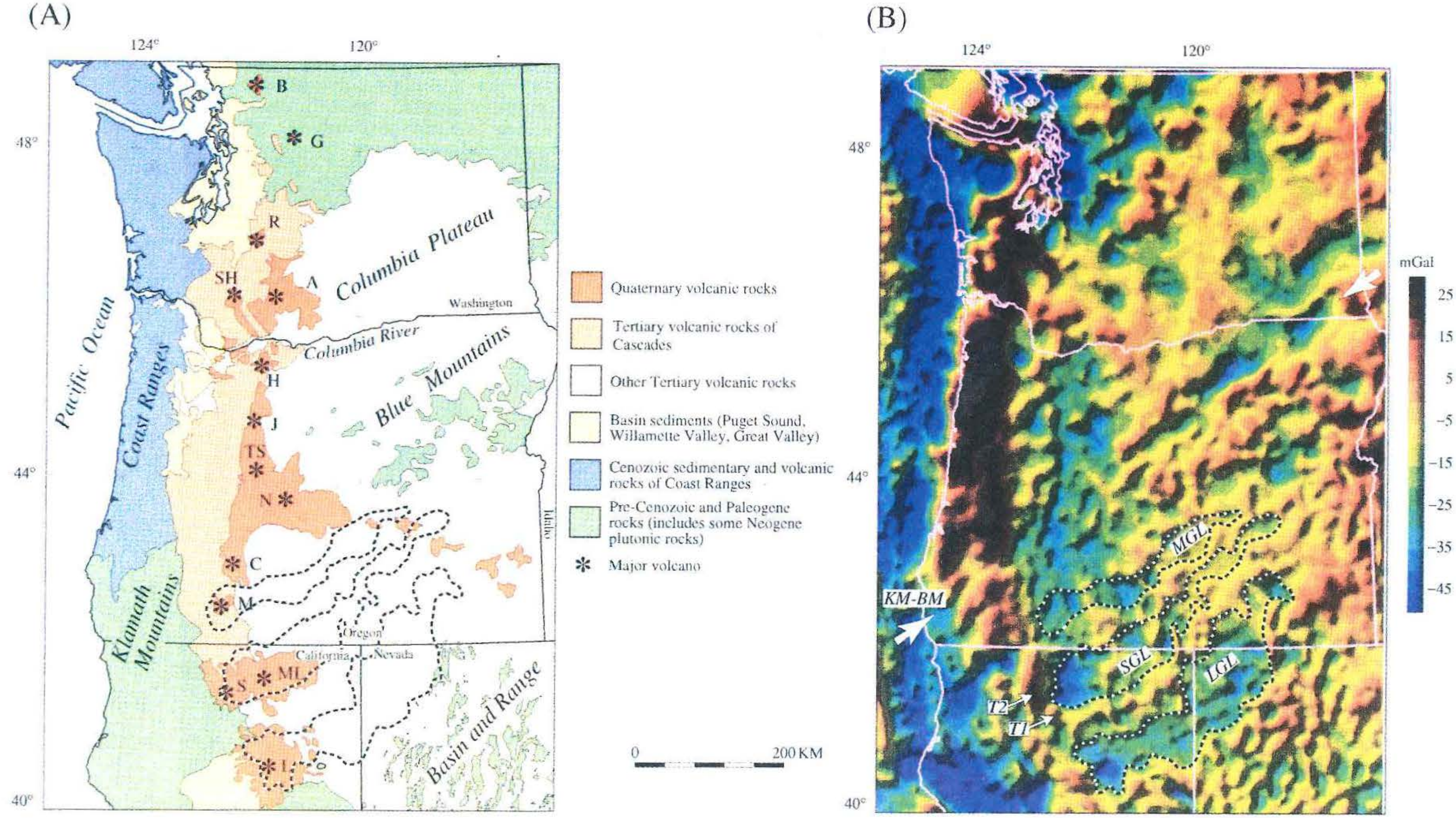

Plate 1. (a) Generalized geologic map of the Cascade Range and surrounding region. Letters refer to major volcanoes: B, Mount Baker; G, Glacier Peak; R, Mount Rainier; SH, Mount St. Helens; A, Mount Adams; H, Mount Hood; J, Mount Jefferson; TS, Three Sisters; N, Newberry Crater; C, Crater Lake; M, Mount McLoughlin; S, Mount Shasta; ML, Medicine Lake; and L, Lassen Peak. (b) Isostatic residual gravity [*Simpson et al.*, 1986] of the Cascade Range and surrounding region, shown as colored, shaded relief with illumination from the northwest. Anomalies have been corrected for the effects of terrain. Dashed lines outline gravity lineaments discussed in text: MGL, McLoughlin gravity lineament; SGL, Shasta gravity lineament; and LGL, Lassen gravity lineament. The eastern parts of these linear anomalies are lower in amplitude and less well defined than their western counterparts, but they have consistently lower values of gravity than areas immediately north and south. The shapes of the anomalies are strongly modified by the oblique grain of basin-range structures trending more nearly north-south. T1 and T2 are anomalies caused by the Trinity ophiolite assemblage as discussed in the text. KM-BM and accompanying arrows indicate gravity lineament at the northern edge of the Klamath Mountains-Blue Mountains zone.

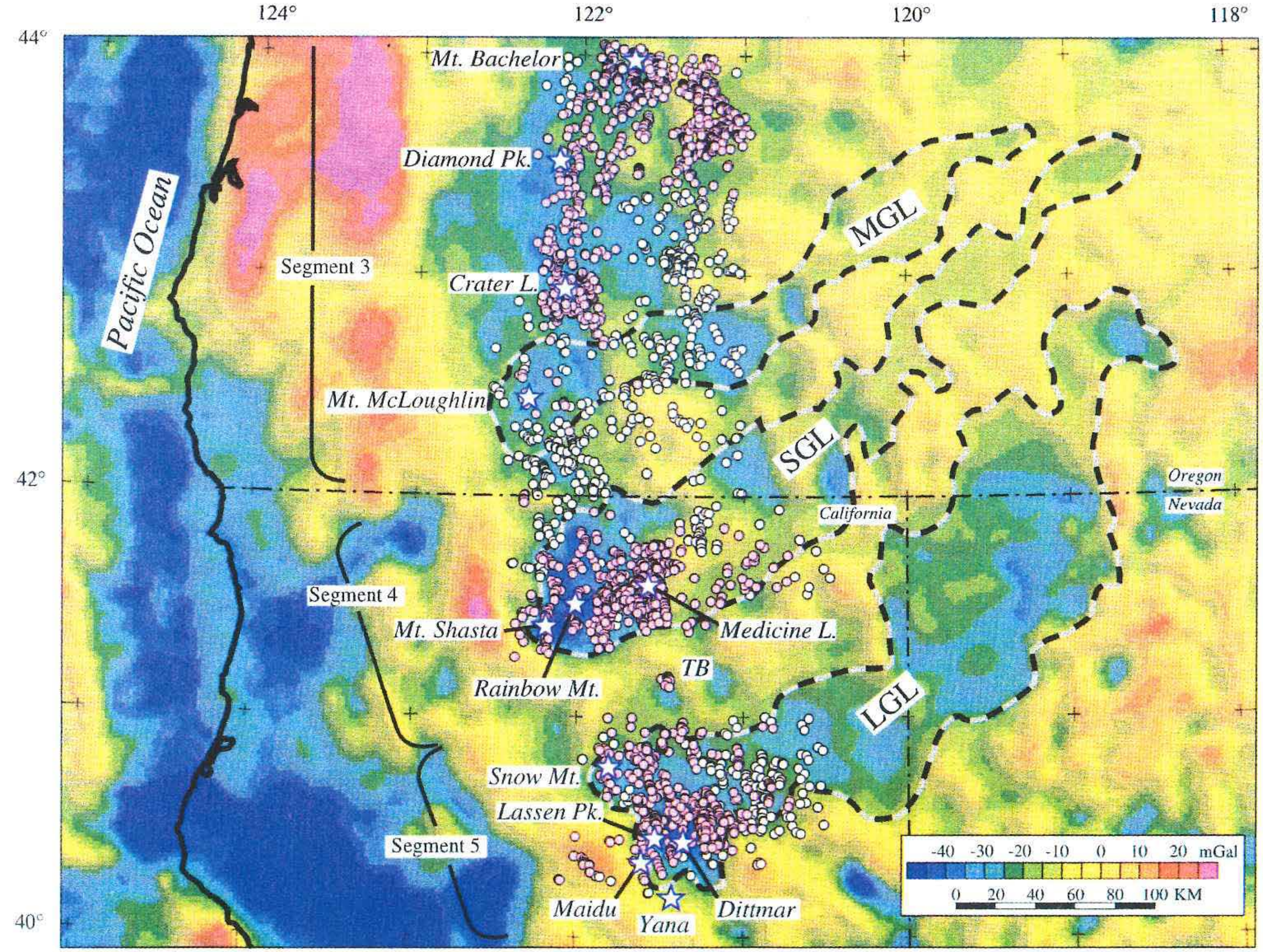

Plate 2. Volcanoes of northern California and southern Oregon. Pink dots indicate 0–2 Ma, and white dots indicate 2–7 Ma. Color map is isostatic residual gravity. Dashed lines outline gravity lineaments discussed in text: MGL, McLoughlin gravity lineament; SGL, Shasta gravity lineament; LGL, Lassen gravity lineament; and TB, Brushy Butte and Timbered Crater. Stars show locations of major volcanoes as named. Brackets indicate segments of the Cascade arc, as described by *Guffanti and Weaver* [1988].

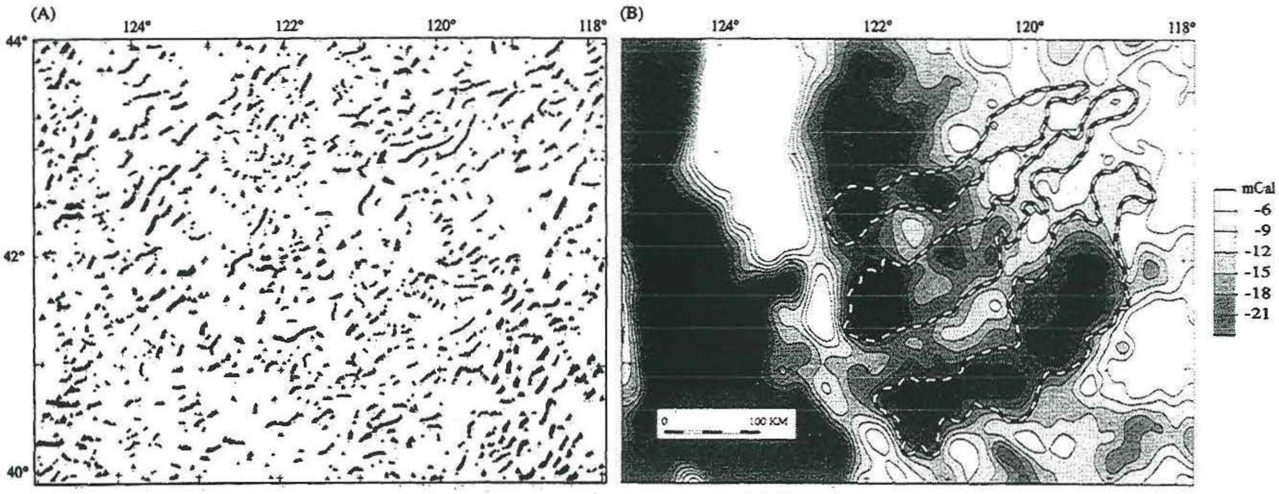

Figure 2. (a) Maximum horizontal gradient of isostatic residual gravity anomalies with trends between 0° and 90°E, calculated with the method of *Blakely and Simpson* [1986]. (b) Isostatic residual gravity continued upward 10 km. Dashed lines outline gravity lineaments discussed in text.

Oregon (Plate 1, KM-BM). The association of this gravity anomaly with pre-Tertiary rocks at each of its ends led *Riddihough et al.* [1986] to propose that the anomaly reflects a pre-Tertiary continental margin, now mostly concealed beneath younger rocks, a conclusion with which we concur. *McKee et al.* [1990] suggested that the southern edge of the Lassen gravity lineament (Plate 1, LGL) marks a major change in crustal composition in the Great Basin, with little or no sialic crust northward, although that tectonic interpretation is less well supported. Other northeast trending gravity anomalies in the Oregon Plateaus gravity province probably also are caused, at least in part, by structural features in the pre-Tertiary basement [*Blakely and Jachens*, 1990].

It might be expected that major volcanic centers would tend to lie near the centers of gravity lows, reflecting the thickest sections of low-density eruptive products and the symmetry of underlying geothermal conditions. On the contrary, some of the major recent volcanic centers of the Cascade arc (e.g., Mount Shasta, Medicine Lake volcano, and Lassen Peak) (Plate 2) lie along the edges of gravity lows [*Blakely et al.*, 1985; *Christiansen*, 1985]. This is particularly evident at the southern end of the Cascade arc, where Mount Shasta and Medicine Lake volcano lie on the west and east margins, respectively, of their gravity low, and Lassen Peak lies on the west margin of its gravity low. These volcanic centers may have developed along perimeter faults that surround much larger tectonomagmatic structural depressions [*Heiken*, 1976; *Dzurisin et al.*, 1991], the lower density of the materials that both fill and underlie the depressions causing the equidimensional gravity anomalies. We are unaware, however, of any specific evidence that these perimeter gradients are caused by faults.

2.2. Inverse Gravity Model

Figure 3 shows a three-dimensional model of the southern Cascade Range and surrounding regions based on gravity data, geologic mapping, topography, and seismic refraction interpretations. The model was constructed with a method described by *Jachens and Moring* [1990], which assumes that residual gravity anomalies originate from two principal sources: Tertiary and younger volcanic and sedimentary deposits atop a pre-Tertiary basement surface. The density of the overlying deposits increases with depth according to prescribed density-depth relations, whereas the density of the underlying basement is free to vary in horizontal directions. The density-depth relations for the sedimentary and volcanic sections are the same as used by *Jachens and Moring* [1990] in their study of the Basin and Range province.

Our model is constrained by mapped exposures of pre-Tertiary basement, such as those that occur in the Klamath Mountains and in various ranges within Nevada, but such exposures are rare throughout most of our study area. To further constrain the model, we also used interpretations of seismic refraction data discussed by *Zucca et al.* [1986] and *Fuis et al.* [1987]. We assumed that the basement surface corresponds to depths where velocity abruptly increases to >5 km s^{-1}. Depths were selected at the 8 shot points located east of the Klamath Mountains and at two additional locations discussed by *Zucca et al.* [1986].

With the understanding that any model based on gravity data is nonunique we can draw some interesting conclusions from Figure 3. First, the model indicates significant basement relief beneath the Cascade Range and Modoc Plateau, especially in the vicinity of the Mount Shasta-Medicine Lake and Lassen Peak gravity anomalies (Figure 3b). Indeed, much of the residual gravity can be explained by undulations of this basement surface. The model supports our contention that the major volcanic centers (Mount Shasta, Medicine Lake volcano, and Lassen Peak) are located near the edges of two tectonomagmatic structural depressions. The narrow, northeast striking region between the Shasta and Lassen gravity lineaments is relatively smooth and elevated, an observation to be discussed subsequently.

The basement gravity map (Figure 3c) includes a high-amplitude anomaly centered about 5 km west of Mount Shasta caused by the Trinity ophiolite exposed in this region. This anomaly extends eastward to include Mount Shasta, indicating that ophiolitic rocks underlie the Mount Shasta volcanic center. A broad, northwest striking lineament passes midway between Mount Shasta and Medicine Lake volcano. This anomaly is approximately coincident with the midcrustal suture between accreted terranes of the Klamath Mountains and the

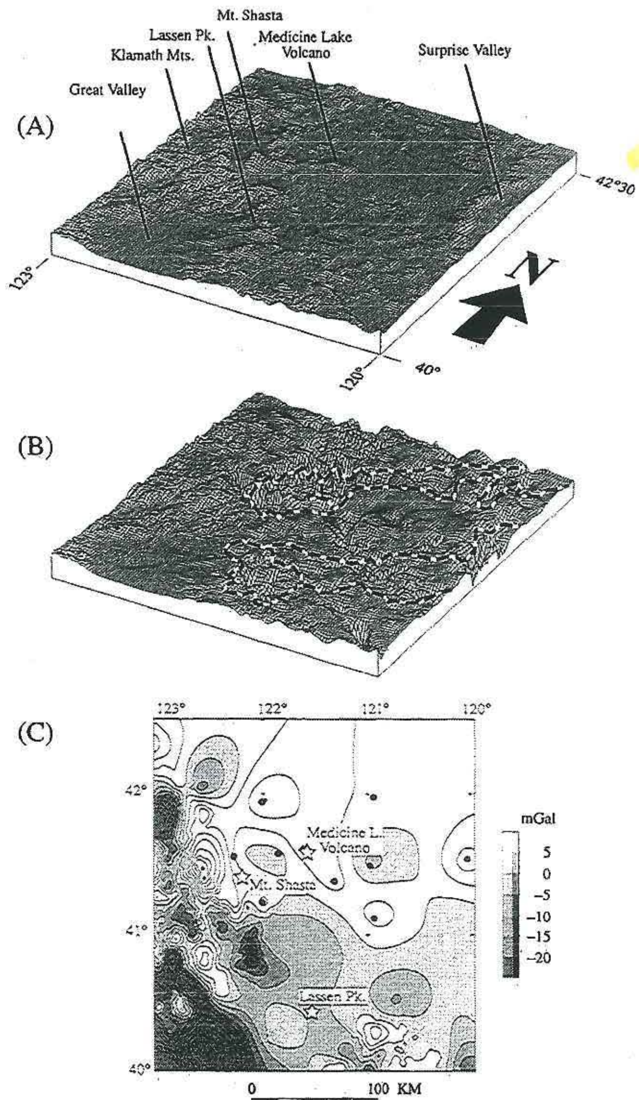

Figure 3. Three-dimensional model of the southern Cascade Range and surrounding regions. Model was constructed with the method described by *Jachens and Moring* [1990]; it assumes that gravity anomalies originate from a relatively low density sedimentary and volcanic section situated atop a basement surface. See text for details of assumptions and caveats. Figure 3a shows the topographic surface. Figure 3b shows the basement surface relative to the topographic surface, with the same vertical exaggeration. Dashed lines indicate Shasta and Lassen gravity lineaments shown on Plate 2 and other figures. Figure 3c shows basement gravity. Dots indicate location of constraining depths selected from seismic refraction interpretations [*Zucca et al.*, 1986; *Fuis et al.*, 1987].

granitic and metamorphic rocks of the Sierra Nevada proposed to exist on the basis of seismic refraction data [*Fuis et al.*, 1987].

2.3. Volcanic Vents

Long-lived (durations $>10^5$ years) Quaternary volcanism in northeastern California is distributed among three major areas with distinctive volcanic styles and vent patterns. Mount Shasta is a large andesitic to dacitic stratovolcano built within the past 600,000 years [*Christiansen*, 1985; *Christiansen and Miller*, 1989]. It consists of at least five overlapping cones with satellitic flank vents. A north-south trend of vent alignments at Mount Shasta indicates east-west extension in its underlying crust. Medicine Lake volcano, east of the main Cascade axis at the margin of the basin-range region, is a large shield complex built over about the past 500,000 years by hundreds of predominantly mafic flows, although silicic lavas have erupted throughout the history of the volcano, including Holocene rhyolitic flows vented near the summit caldera [*Donnelly-Nolan*, 1988]. Vent alignments at Medicine Lake volcano are dominantly north-south, indicating east-west extension, as at Mount Shasta. In an area between Mount Shasta and Medicine Lake volcano, however, some Quaternary vent alignments trend northeast at high angles to regional basin-range trends, perhaps reflecting a local reorientation of crustal stress due to growth of the two large centers [*Christiansen*, 1996]. The Lassen Peak region comprises hundreds of small, mostly mafic volcanoes that surround a few larger, long-lived, andesitic to rhyodacitic volcanic centers, the youngest of which is the Lassen volcanic center, with earliest activity dating from about 650,000 years ago and the site of the 1914–1917 eruptions at Lassen Peak [*Muffler et al.*, 1989]. North-northwest vent alignments here indicate east-northeast extension, characteristic of the adjacent basin-range region [*Guffanti et al.*, 1990a].

Volcanism along the length of the Cascade arc is nonuniform, both temporally and spatially. *Guffanti and Weaver* [1988] divided the Cascade arc into five segments on the basis of spatial, temporal, and compositional distributions of volcanic vents. Mount Shasta and Medicine Lake volcano lie within one arc segment, about 75 km long in the north-south direction. Volcanism in this segment during the past 7 m.y. has been spatially isolated from the 50 km long arc segment to the south that includes Lassen Peak. *Guffanti and Weaver* [1988] distinguished the Mount Shasta-Medicine Lake segment from the segment to the north in Oregon on the basis of geochemical observations, the Mount Shasta-Medicine Lake segment having a markedly decreased ratio of andesitic to basaltic volcanism. Other geologic, geophysical, tectonic, and geothermal indicators have since been noted which support this pattern of segmentation of the Cascade arc [*Guffanti et al.*, 1990b; *Blakely and Jachens*, 1990; R. E. Wells et al., Tectonic segmentation of Cascadia, manuscript in preparation, 1997 (hereinafter referred to as R. E. Wells et al., 1997)].

Plate 2 shows an updated database of Quaternary volcanic vents in northern California and southern Oregon. Only vents west of longitude 120°W are shown, although Quaternary vents do exist farther east. Vents in Oregon were digitized from a 1:500,000-scale geologic compilation [*Sherrod and Smith*, 1989], supplemented in the Crater Lake area by detailed map information (C. R. Bacon, written communication, 1995). In California, vents were taken from *Luedke and Smith* [1981], supplemented by extensive geologic mapping by many of the authors of the present paper and supported by geochemical analyses of rock compositions and radiometric age data, primarily using the K-Ar method. Vent locations are useful in our analysis because they demarcate the overall area of regional volcanism, indicate zones of crustal weakness, and can be compared readily to gravity and other spatially based data. Our vent data do not include the volume of rock erupted from each vent, and thus volcanic productivity at large polygenetic centers is underrepresented.

The segmentation of the southern Cascade arc discussed by *Guffanti and Weaver* [1988] is reflected clearly in Plate 2. Significant volcanic activity during the past 7 m.y. is evident in both the Mount Shasta-Medicine Lake segment and the Las-

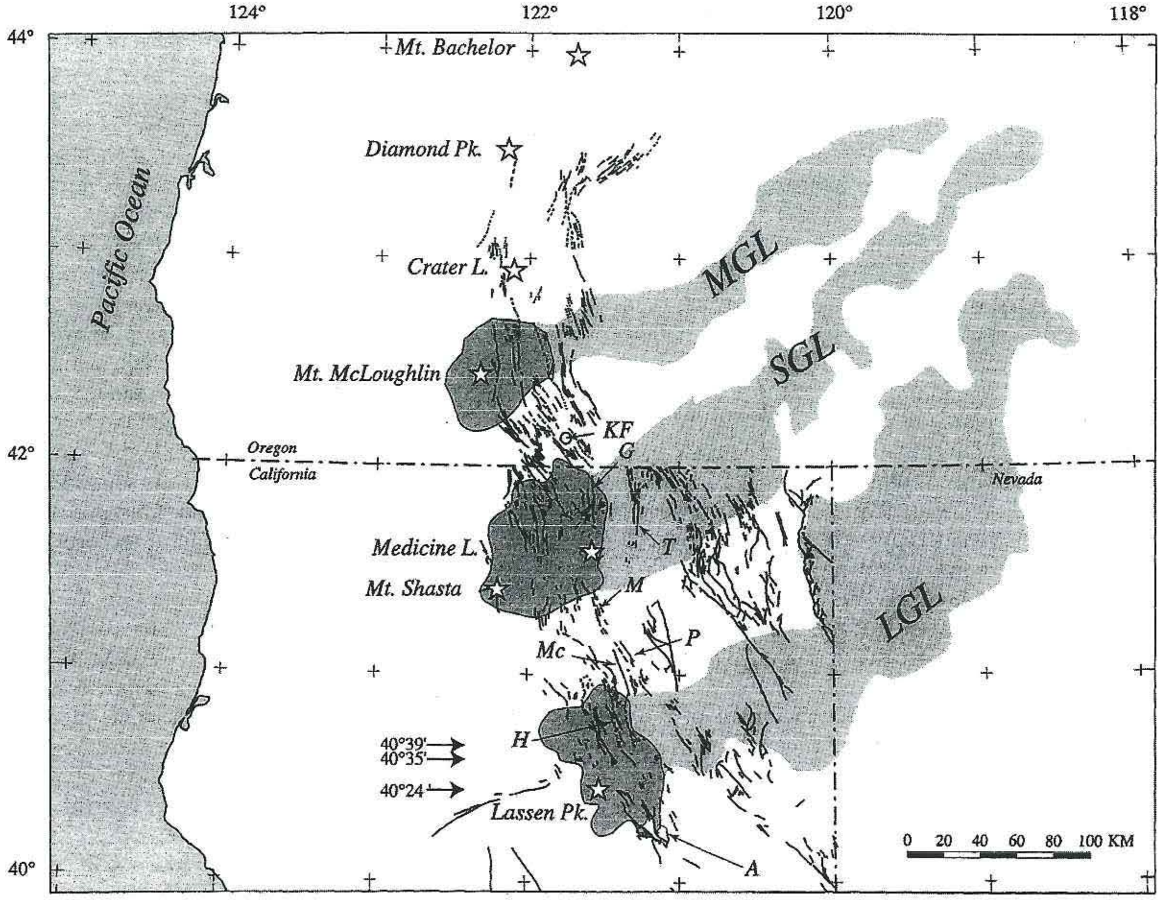

Figure 4. Quaternary faults of northern California and southern Oregon. Faults in California are from the statewide compilation of *Jennings* [1994] supplemented by more recent geologic mapping (Muffler et al., unpublished mapping, 1996); faults in Oregon are from the Cascade geologic map of *Sherrod and Smith* [1989], supplemented by additional information from D. R. Sherrod (written communication, 1995) and C. R. Bacon (written communication, 1995). Faults are not shown in Nevada and in eastern Oregon east of longitude 121°W. G is the Gillem fault; T is the fault along the east margin of Tule Lake graben; M is the Mayfield fault; Mc is the McArthur fault zone; P is the Pittville fault; H is the Hat Creek fault; and A is the Almanor fault. Outlined patterns indicate gravity lows at Mount McLoughlin, Mount Shasta-Medicine Lake, and Lassen Peak. Light patterns without outline represent gravity lineaments discussed in text: MGL, McLoughlin gravity lineament; SGL, Shasta gravity lineament; and LGL, Lassen gravity lineament. Stars show locations of major volcanoes as named (see captions to Plate 1 and 2).

sen segment, but an intervening gap, about 35 km across in the north-south direction, is nearly devoid of vents of these ages. The primary exception is an isolated cluster of low-K basaltic vents situated along a Holocene fault system that extends between the two volcanic regions, discussed subsequently. During the Quaternary the Mount Shasta-Medicine Lake segment has been isolated from the Cascade arc to the north as well; very few vents younger than 2 Ma occur between the Mount Shasta-Medicine Lake segment and Mount McLoughlin (Plate 2). The volcanic gaps north and south of the Mount Shasta-Medicine Lake segment also are evident in estimates of the total volume of Quaternary volcanic rocks erupted in the area [*Sherrod and Smith*, 1990].

Plate 2 also shows the known older major volcanic centers of the Mount Shasta-Medicine Lake and Lassen areas: Yana (3.1–2.7 Ma), Maidu (2.4–1.2 Ma) [*Muffler et al.*, 1989], Dittmar (2.1–1.4 Ma) [*Clynne*, 1984, 1985], Snow Mountain (2.7–1.1 Ma) (J. G. Smith, unpublished data, 1995), and Rainbow Mountain (about 1 Ma) (R. L. Christiansen, unpublished mapping, 1995) (age data from *Chesterman and Saucedo* [1984]). All of these older volcanic centers fall within either the Mount Shasta-Medicine Lake or Lassen gravity lows, except for Yana that lies about 7 km outside the Lassen gravity lineament. It is of interest to note that like the younger volcanic centers at Mount Shasta, Medicine Lake, and Lassen Peak most of these older centers (Yana, Maidu, and Snow Mountain) are situated very near the edges of the roughly equidimensional gravity lows.

2.4. Quaternary Faults

A band of late Quaternary, extension-related normal faults stretches from south of the Lassen Peak region to north of Medicine Lake volcano and structurally connects the major volcanic areas along the western edge of this part of the Basin and Range province. Figure 4 shows these Quaternary faults in and adjacent to the southern Cascade Range and their spatial relationship to the gravity lows at Mount Shasta-Medicine Lake and Lassen Peak. The faults in California were digitized from a statewide compilation by *Jennings* [1994] supplemented by more recent geologic mapping in the Lassen area (L. J. P. Muffler et al., unpublished mapping, 1996); faults in Oregon were digitized from the Cascade geologic compilation of *Sherrod and Smith* [1989], supplemented by information provided by D. R. Sherrod (written communication, 1995) and C. R. Bacon (written communication, 1995). (Faults of similar age in the Basin and Range province farther east are not shown.)

The orientation of Quaternary faults in and adjacent to the southern Cascade Range appears spatially related to gravity anomalies and to the density of Quaternary vents. Faults within the Mount Shasta-Medicine Lake gravity low are dominated by nearly north-south trends (Figure 4). The Gillem fault (Figure 4, G), for example, projects into Medicine Lake volcano from the north with a north-south trend a distance of about 22 km [*Donnelly-Nolan and Champion*, 1987]. From its exposed southern end the Gillem fault is inferred on the basis of vent alignments to continue southward another 35 km with NNW-SSE trend [*Donnelly-Nolan*, 1983]. At Mount Shasta a north-south alignment of Quaternary vents (Plate 2) probably represents north-south extensional fractures. The north striking fault along the east margin of the Tule Lake graben (Figure 4, T) lies east of the main gravity low and appears to be the eastern extent of extensive north-south faulting within the Shasta gravity lineament.

In contrast to the nearly north-south alignment of faults within the Mount Shasta-Medicine Lake gravity low, Quaternary faults to both the north and south have, generally, more northwesterly trends. To the north of the gravity low, faults trend northwestward, the bend occurring approximately at the northern edge of the gravity anomaly, and maintain this orientation to the southern edge of the McLoughlin gravity lineament, where they change back to a more northerly strike.

The relationship between fault orientation and gravity anomalies is less clear south of Mount Shasta. Here faults typically have a northwesterly orientation, the change in orientation occurring approximately along the line of steepest gravity gradient at the south edge of the Mount Shasta-Medicine Lake gravity low. Specific faults in this region include the Mayfield fault, the Pittville fault, and the McArthur fault zone (Figure 4), all of which have experienced displacement during the Holocene [*Wills*, 1991]. Farther to the south, in and adjacent to the northern part of the Lassen Peak gravity low, the fault orientation is again north-south, an orientation well displayed by the northern and central part of the Holocene Hat Creek fault zone (Figure 4, H) [*Wills*, 1991; *Muffler et al.*, 1994]. This north-south trend continues southward to latitude 40°39′N, where the Hat Creek fault zone bends back to a dominantly northwesterly strike. South of latitude 40°35′N, the fault zone (albeit obscure) trends N10°W, linking up at 40°24′N with a prominent set of northwest trending faults that bound the northeast and southwest shores of Lake Almanor (Figure 4, A).

Thus Quaternary faults in this region appear to bend as they pass in and out of regions of relatively low gravity and high vent density. Figure 5 shows a stylized view of the "zed" pattern that we observe. In general terms, Quaternary faults strike north-south in the low-gravity, magmatic regions and northwest-southeast in the intervening amagmatic regions. This relationship is best displayed from the Mount McLoughlin gravity low southward to the northern part of the Lassen Peak gravity low. The relationship is less convincing farther north and south. Together this system of Quaternary normal faults, which shows Holocene displacement on the Almanor, Hat Creek, McArthur, Pittville, Mayfield, and possibly other faults, extends a distance of over 200 km from south of Lassen Peak to north of Mount McLoughlin. This regionally extensive fault zone, which we informally refer to here as the Fall River fault zone [*Guffanti et al.*, 1994], is part of a larger regional structural alignment termed the Tahoe-Medicine Lake trough [*Page et al.*, 1993], a 400 km long series of right-stepping en echelon tectonic depressions that form the eastern edge of the Sierra Nevada province and southern Cascade Range.

Because various faults discussed above have Holocene and younger displacements [*Wills*, 1991; *Muffler et al.*, 1994], we might expect to see a spatial relationship between gravity anomalies and the trends of earthquake alignments or trends of earthquake first motions. A dramatic example occurred in 1993 about 25 km northwest of Klamath Falls, Oregon (Figure 4), where three earthquakes of magnitude 5.4–6.0 and aftershocks up to magnitude 4.8 occurred at the southern boundary of the McLoughlin gravity lineament. This series of earthquakes will be discussed in more detail in the next section.

3. Discussion

Isostatic residual gravity anomalies are caused by density variations in the middle and upper crust [*Simpson et al.*, 1986], and the spatial correlations between isostatic anomalies, the distribution of Quaternary vents, and the orientation of Quaternary faults in the southern Cascade Range likely reflect a history of lateral variations in physical properties and magmatic conditions in the crust, now manifested as three-dimensional variations in density. The roughly equidimensional gravity anomalies of about 50–80 km diameter over Mount Shasta-Medicine Lake and over Lassen volcanic center may point, for example, to structures in the pre-Tertiary basement beneath this part of the Cascade arc that relate directly to the distribution of magmatism. This view is supported by the spatial link between these roughly equidimensional anomalies and the northeasterly trend of the McLoughlin, Shasta, and Lassen gravity lineaments and to the general fabric of the entire Oregon Plateaus gravity province. Some of these northeast trending anomalies may be associated with pre-Tertiary structures, particularly the Klamath Mountains-Blue Mountains gravity lineament [*Riddihough et al.*, 1986] and perhaps the southern edge of the Lassen gravity lineament [*McKee et al.*, 1990] (Plate 1), and it seems likely that other northeast trending anomalies in the Oregon Plateaus gravity province are related to concealed structures in pre-Tertiary rocks.

The northeast trending chain of gravity highs between the Shasta and Lassen gravity lineaments may be a specific example of a causal relationship between basement structure and volcanism. Plate 2 illustrates a clear correlation between the density of Quaternary volcanic vents and the broad, equidimensional gravity lows associated with the Mount Shasta-Medicine Lake and Lassen Peak areas. Vents less than 2 Ma are predominantly restricted to the two low-gravity regions, and the intervening volcanic gap corresponds to the northeast trending chain of positive gravity anomalies that at its western end, overlies a salient of the pre-Tertiary Eastern Klamath belt. The high gravity between Mount Shasta-Medicine Lake and Lassen volcanic centers probably indicates a concealed, structurally elevated block of pre-Tertiary crust that extends northeastward from the Eastern Klamath belt. Perhaps the strength and density of this high standing block, distinct relative to crust to the north and south, have inhibited in some way

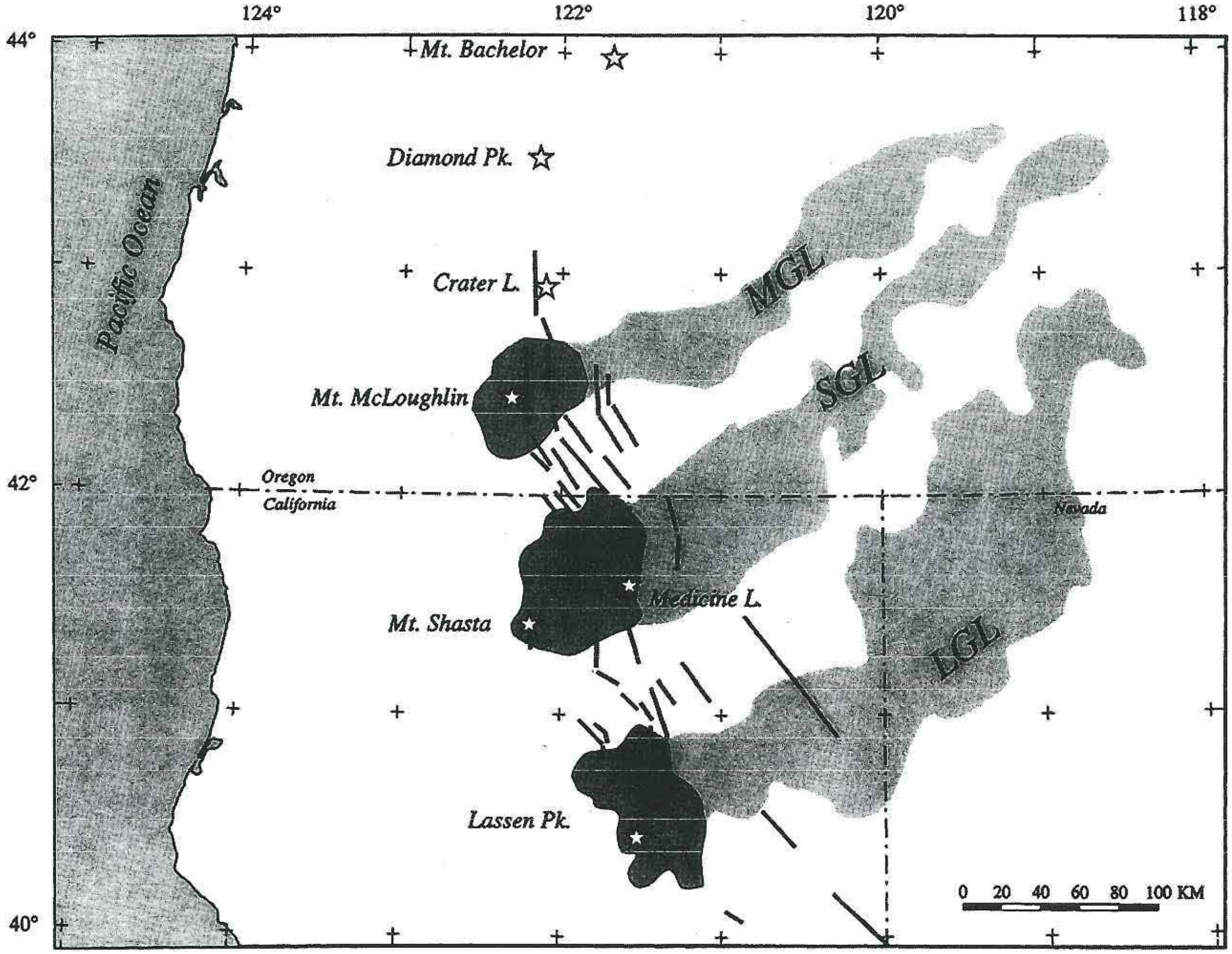

Figure 5. Stylized interpretation of fault patterns in northern California and southern Oregon, shown by bold lines. See Figure 4 for an explanation of other patterns and symbols.

the storage or vertical transport of magma in this region. As time progressed, the discontinuous magmatic activity north and south of the block served to further enhance its anomalous characteristics. Thus this block, characterized by distinct physical properties, may have restricted the formation and rise of magma from the mantle and lower crust to areas north and south of the block.

The relationship between gravity anomalies and the volcanic gap north of Mount Shasta is less clear. The Quaternary volcanic gap here is also associated with a region of positive gravity anomalies between the McLoughlin and Shasta gravity lineaments, although it is much less pronounced than in the volcanic gap south of Mount Shasta.

A spatial relationship between gravity anomalies, vent distribution, and magma accumulation should be reflected in crustal heat flow. Regional heat flow maps for Oregon [e.g., *Blackwell et al.*, 1990, Figure 1] show a pattern typical of arc regions, namely, elevated heat flow in the backarc and anomalously low heat flow in the forearc, although the data in the backarc south of 44°N latitude either are absent over large areas or are clustered in areas of known hydrothermal convection (e.g., Klamath Falls). These regional data do not indicate a pattern of alternating high and low heat flow along the length of the arc in southern Oregon, as might have been predicted from the gravity anomalies and vent distribution.

The picture is complicated even further in northeastern California, where *Mase et al.* [1982] showed that the heat flow is dominated by circulation of groundwater and that this convective effect masks conductive transfer of heat. Heat flow measurements in this area were made in shallow (<200 m) holes, in permeable volcanic rocks, and in an area of high average precipitation [*Mase et al.*, 1982]. The resulting heat flow pattern in northeastern California forms an extensive dumbbell-shaped low unequivocally related to massive near-surface flow of cold water south from the Medicine Lake Highlands and north from the Lassen Highlands [*Mase et al.*, 1982, Figure 2].

It is important to note that the major young volcanic centers at Mount Shasta, Medicine Lake volcano, and Lassen Peak all lie near the edges of their respective, roughly equidimensional gravity lows, indicating that these centers are located vertically above abrupt density contrasts in the middle to upper crust. This is demonstrated by the inverse model (Figure 3), which shows these volcanic centers located near the edges of depressions in the pre-Tertiary basement. The same is true of several older (3–1 Ma) volcanic centers at Maidu, Yana, and Snow Mountain. The density contrasts may reflect fundamental crustal structures 3 Ma old or older that have promoted the rise of magma to the surface [*Blakely et al.*, 1985; *Christiansen*, 1985]. Crustal structures seem to have played an important role in focusing volcanism elsewhere in the region as well. Brushy Butte and Timbered Crater (Plate 2, TB), for example, are colocated about 50 km south of Medicine Lake and 80 km

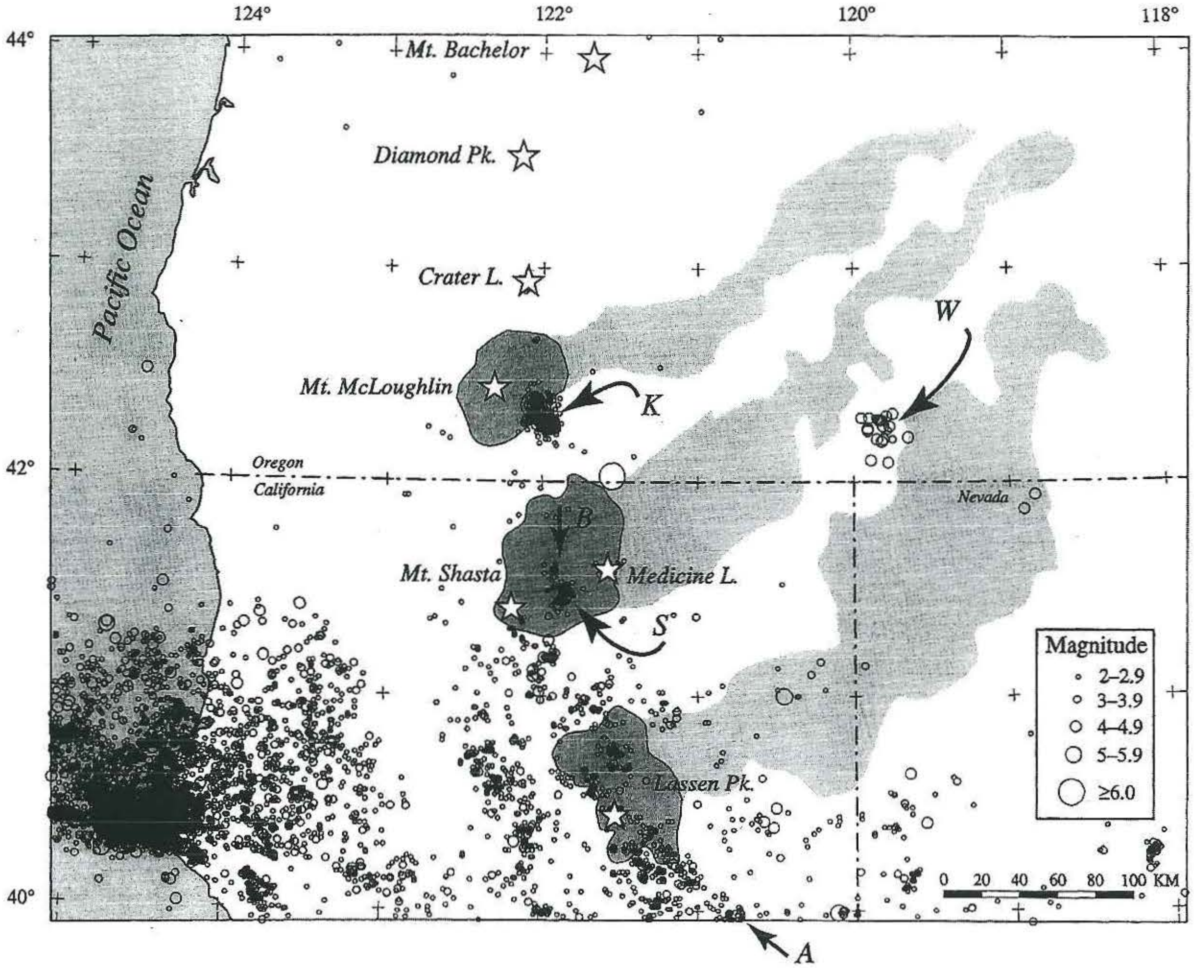

Figure 6. Earthquake epicenters in southern Oregon and northern California. Earthquakes occurred from 1973 to present and had magnitudes 2 and greater: K, Klamath Falls earthquakes of 1993; S, Stephens Pass earthquakes of 1978; W, location of 1968 earthquake swarm near Warner Valley, Oregon, 1968. A and B indicate epicenter alignments discussed in text. Except for the Warner Valley earthquakes (W) the size of the symbol indicates earthquake magnitudes. Sources are the U.S. Geological Survey for earthquakes in California and the University of Washington for earthquakes in Oregon. See Figure 4 for an explanation of other patterns and symbols.

north of Lassen Peak in the dominantly amagmatic area. During Quaternary time these vents erupted basalt essentially devoid of evolved products or obvious crustal interaction, suggesting that magma traveled to the surface through fractures in cold brittle crust.

Tomographic inversions of teleseismic data [*Benz et al.*, 1992] indicate the presence of zones of anomalously low *P* wave velocities in the upper 30 km of the crust in both the Mount Shasta-Medicine Lake and the Lassen Peak areas. The low-velocity zone at Lassen Peak is approximately coincident with the Lassen Peak gravity anomaly, and the Lassen volcanic center lies above the western edge of the low-velocity zone. This low-velocity zone is spatially separated from the low-velocity zone at Mount Shasta-Medicine Lake by a zone of normal velocities in the upper crust. The correspondence between gravity and low-velocity anomalies is less clear at Mount Shasta-Medicine Lake, but Mount Shasta lies near the western edge of the zone of low velocity. The anomalously low *P* wave velocities may represent elevated crustal temperatures or lithologic effects, in general agreement with the spatial distribution of Quaternary vents.

Mooney and Weaver [1989] have summarized seismic results bearing on the crustal thickness of the Pacific Northwest. Only one seismic investigation has been conducted in the southern Cascade region, consisting of five refraction profiles in the Mount Shasta-Medicine Lake area [*Zucca et al.*, 1986; *Fuis et al.*, 1987] discussed previously. Two other studies outside of the southern Cascade Range are of interest: An east-west profile in central Oregon east of Newberry volcano [*Catchings and Mooney*, 1988] and a northwest-southeast profile in northwestern Nevada [*Catchings et al.*, 1988]. Taking all three of these studies together, they indicate a relatively uniform crustal thickness east of the southern Cascade volcanic arc, ranging from 37 km at Newberry volcano to 38 km east of Medicine Lake to 34 km in northwestern Nevada [*Mooney and Weaver*, 1989]. The broad spatial separation of these studies precludes conclusions regarding small-scale variations in crustal thickness in our study area. In regional terms, however, the uniformity of crustal thickness throughout the study area suggests that the same crust-forming processes were at work throughout the area.

The gravity lows reflect a longer history of volcanism than

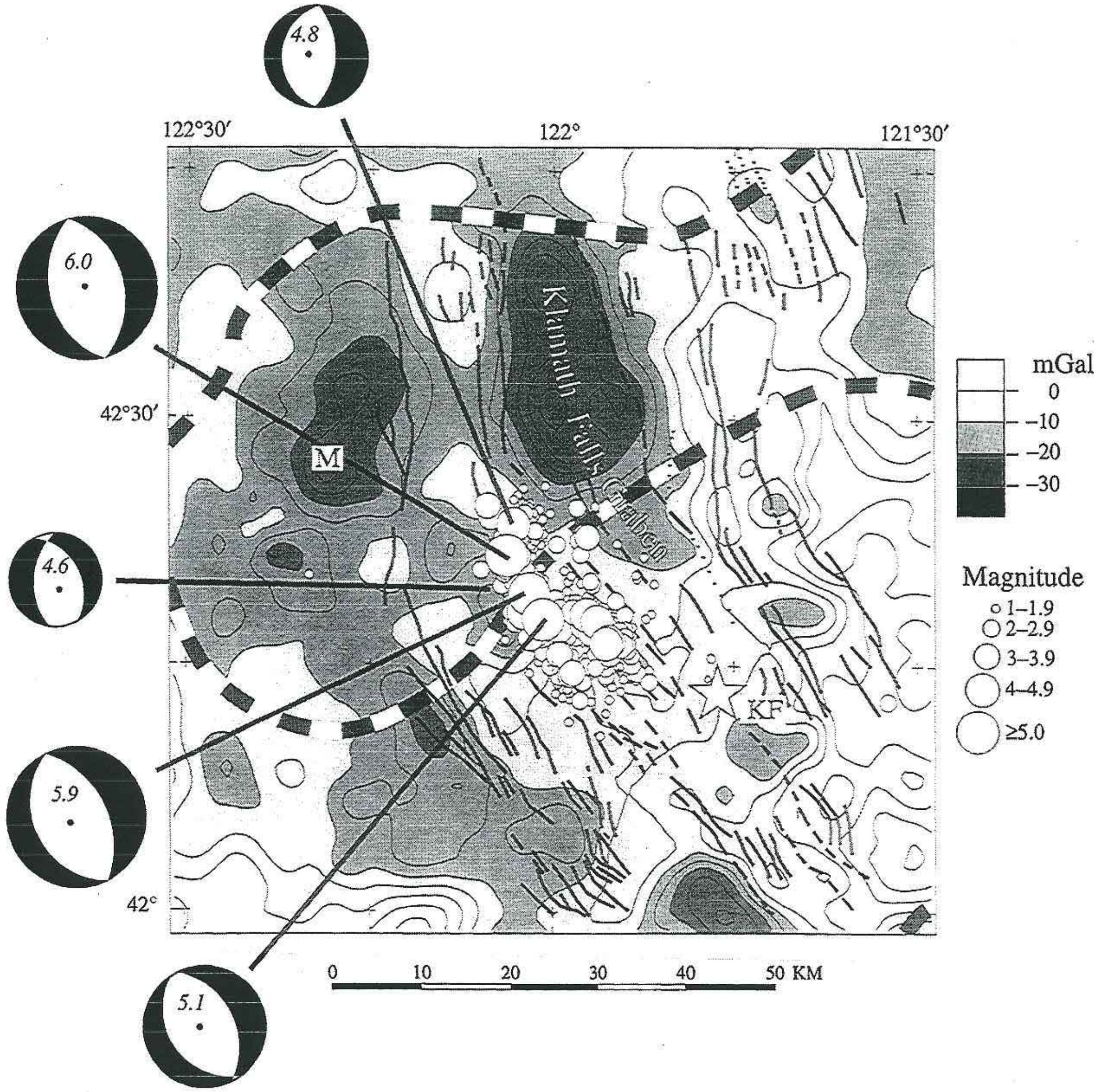

Figure 7. Isostatic residual gravity, faults, and recent seismicity in the Klamath Falls area. Shaded contours are isostatic residual gravity anomalies [*Simpson et al.*, 1986]; the shade interval represents 10 mGal; the line contour interval represents 5 mGal. Faults shown by bold lines are from *Sherrod and Smith* [1989] and from D. R. Sherrod (written communication, 1995). Heavy dashed line is the margin of the McLoughlin gravity lineament, as shown on Plate 1 and subsequent figures. First-motion solutions are shown for the five largest earthquakes [*Dreger et al.*, 1995]. KF is the city of Klamath Falls; M is Mount McLoughlin. The southern margin of the McLoughlin gravity lineament separates regions to the north and south with consistent fault orientation and epicentral alignment and, in the epicentral region, corresponds approximately with line D of *Blakely and Jachens* [1990, Plate 2].

that represented by the modern major volcanic centers at Mount Shasta, Medicine Lake volcano, and Lassen Peak. These modern centers are located along the edges of the gravity lows, as described above, but not all the earlier major centers were. Precursors of the Mount Shasta and perhaps the Medicine Lake volcanic centers were located more nearly on the main axis of arc volcanism, as represented by the Rainbow Mountain center (Plate 2). Similarly, the older Dittmar center near Lassen Peak is closer to the center of its gravity low, and regional volcanism in the Lassen area has contracted westward from a relatively broad zone of volcanism during the Miocene into its present narrow zone located at the western margin of Miocene volcanism [*Grose and McKee*, 1982; *Guffanti et al.*, 1990a]. The gravity lows thus also may have migrated with time, as new low-density material was emplaced at the margins of active volcanism.

Isostatic gravity anomalies in the southern Cascade Range apparently reflect in a broad sense the strength of the middle and upper crust. Zones of north trending faults seem to correlate with areas of low gravity between elongate, northeast trending gravity highs, whereas northwest trending faults occupy intervening areas where the fault pattern crosses the

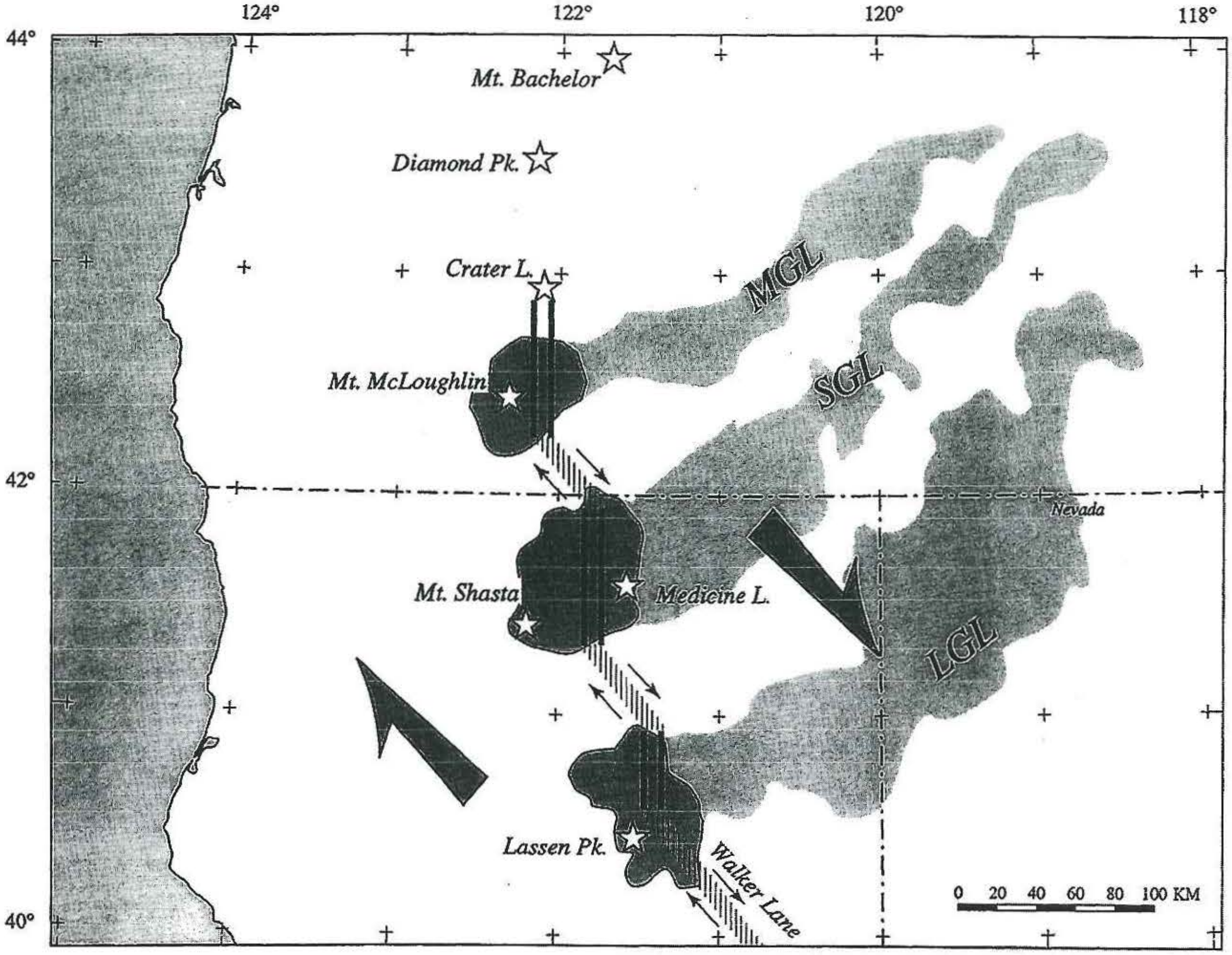

Figure 8. The southern Cascade Range as a transitional zone where horizontal stress is transferred from northwest-southeast dextral shear of the Walker Lane to the south to dominantly east-west extension of the Cascade Range to the north. Strike slip and extensional strain are partitioned among domains in the southern Cascades that are distinguished by their gravity anomalies. See Figure 4 for an explanation of patterns and symbols.

gravity highs. These relationships are best represented at the south edge of the Mount McLoughlin gravity low and the north edge of the Mount Shasta-Medicine Lake gravity low. Similarly, the distribution of Quaternary Cascade volcanic vents correlates with the gravity lows; vents are much less abundant on the northeast trending gravity highs at about latitudes 41°N and 42°N. Thus the crust of the high-gravity regions, which has experienced little magmatism during the Quaternary, may be cooler and possess greater elastic strength than the contrasting crust of the neighboring low-gravity regions that display abundant young volcanism.

This lateral variation in crustal strength is reflected in the distribution of earthquake epicenters. Figure 6 shows earthquakes greater than magnitude 2 occurring in this region since 1973. A belt of magnitude 2–4 epicenters extends northwestward from the southern edge of the study area (Figure 6, A) to Lassen Peak and perhaps beyond. A second belt may extend southward from the Shasta gravity low (Figure 6, B), where it includes the swarm of earthquakes that occurred near Stephens Pass, California, in 1978 (Figure 6, S), and continues southward to about latitude 41°N, longitude 122°W. Between these two belts, epicenters are broadly distributed and show no clear alignments.

The Klamath Falls earthquakes of September 1993, however, are of particular interest. These earthquakes occurred at an inflection point in the trend of normal faults bounding the Klamath Falls graben (Figure 7). South of the epicentral region, the graben trends about N40°W and maintains this trend to near the California-Oregon border; to the north the graben trends about N15°W toward Crater Lake. This change in fault trend is mirrored in both the focal mechanisms of the largest earthquakes [*Dreger et al.*, 1995] and in the pronounced curvature of the aftershock distribution [*Qamar and Meagher*, 1993]. This change in fault orientation coincides with the southern margin of the McLoughlin gravity lineament (Figure 7, dashed line), a gravity boundary previously noted by *Blakely and Jachens* [1990] as one of a series of northeast trending lineations crossing the Cascade arc and northwestern Basin and Range province between the Klamath Mountains and the Blue Mountains of northeastern Oregon [*Blakely and Jachens*, 1990, Plate 2, D]. This lineation intersects the Quaternary arc just south of Mount McLoughlin, corresponding to one of the segmentation boundaries of *Guffanti and Weaver* [1988] and to the northern edge of a zone of negligible volcanic activity during the past 2 m.y. (Plate 2).

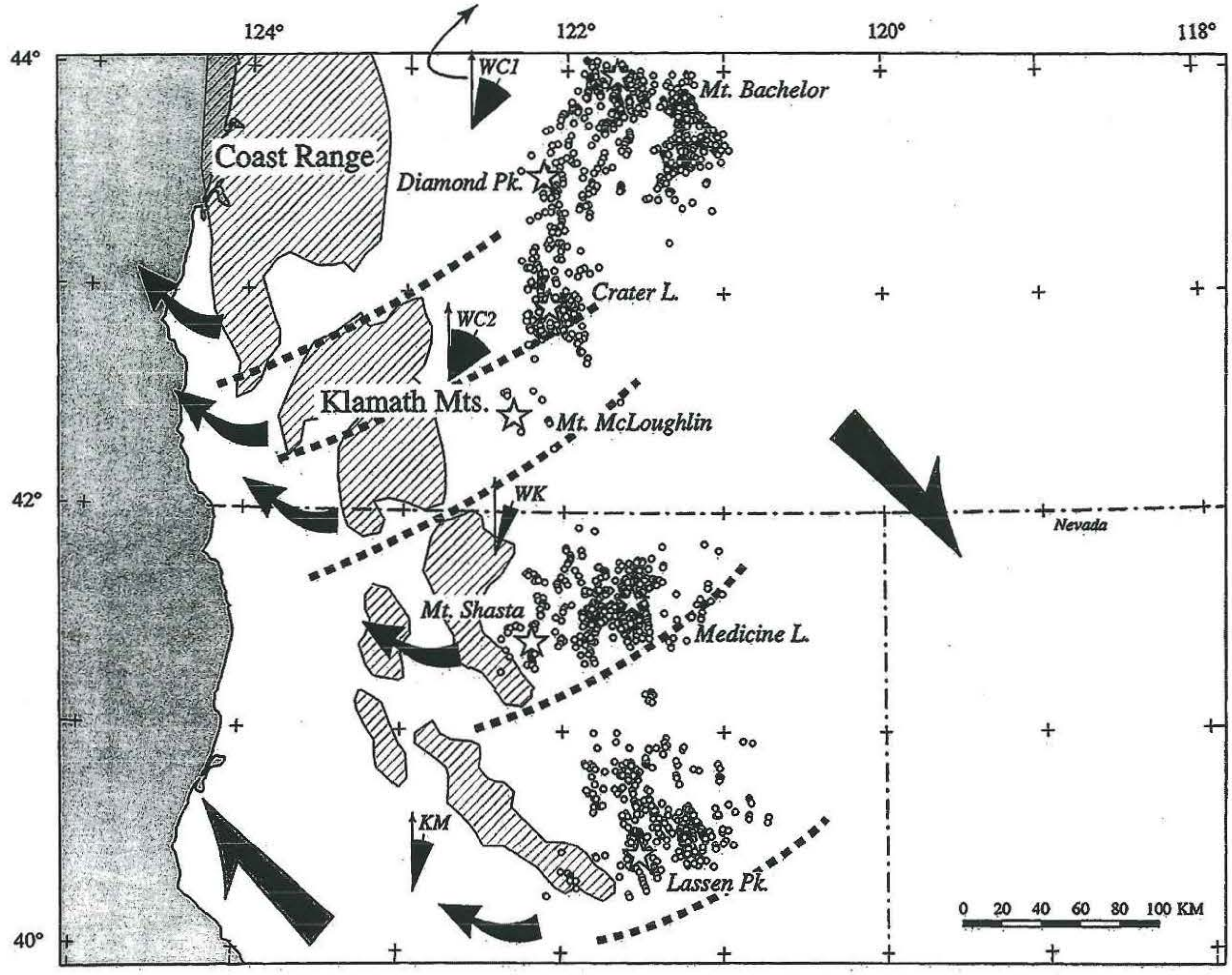

Figure 9. Interpretational model for the nonhomogeneous focusing of volcanism along the southern Cascade arc. Striped pattern indicates regions of positive gravity anomalies in the forearc interpreted to reflect coherent crustal blocks. Open circles are volcanoes with ages less than 2 Ma. Solid arrows indicate Cenozoic clockwise rotation of forearc segments along zones of accommodation (dashed lines); these zones are not left-lateral faults but rather areas of enhanced east-west extension. Solid sectors indicate 95% confidence limits on rotations determined from paleomagnetic studies: WC1 and WC2 from *Magill and Cox* [1980]; WK from *Beck et al.* [1986]; and KM from *Mankinen and Irwin* [1982].

4. Regional Interpretation

The southern Cascade Range is apparently acting as a transition zone between the Walker Lane to the south and the continuous volcanic arc of the Cascades to the north. Maximum horizontal stress in both regions is oriented generally north-south (Figure 1) [*Zoback*, 1992]. This regional stress apparently is accommodated differently in the two regions. The western margin of the Basin and Range province including the Walker Lane, is characterized by spatial or temporal alternations between right lateral strike slip and normal faulting controlled by variations in the magnitude of the maximum horizontal stress relative to other components of stress [*Zoback and Zoback*, 1989; *Zoback*, 1989] or by partitioning of strain between domains [*Jones and Wesnousky*, 1992; *Wesnousky and Jones*, 1994]. The Cascade arc in central Oregon, north of our study area, is dominated by east-west extension [*Priest*, 1990; *Weaver and Michaelson*, 1985]. Strain, apparently, is partitioned in the southern Cascade Range as it transfers one style of accommodation to the other. This transition occurs discontinuously through a series of step overs (Figure 8), which are reflected by the Mount McLoughlin, Mount Shasta-Medicine Lake, and Lassen Peak gravity lows and their corresponding Quaternary volcanism and north trending Quaternary faults. We suggest that the location of the step overs and thus the distribution of volcanism are controlled, in part, by preexisting structures within the underlying pre-Tertiary basement, structures manifested by the northeast trending gravity lineaments of the Oregon Plateaus gravity province.

The correlation between fault orientation and gravity boundaries is excellent at the south edge of the Mount McLoughlin gravity low and the north edge of the Mount Shasta-Medicine Lake gravity low and less so at the south edge of the Mount Shasta-Medicine Lake gravity low and north edge of the Lassen Peak gravity low (Figure 4). The correlation breaks down entirely farther to the south, where northwest trending faults dominate the southern half of the Lassen gravity low. The Walker Lane probably exerts a greater influence on the southern part of the transition zone, and the lack of correlation between fault orientation and gravity boundaries at and south of Lassen Peak may be related simply to its relative proximity to the Walker Lane.

It is interesting to note that the northwest trending faults in the amagmatic regions are roughly normal to the margins of the northeast trending gravity lineaments which lie over the magmatic regions (Figure 4). This is especially apparent in the region between the McLoughlin and Shasta gravity lineaments (Figures 4 and 7). The margin of the gravity lineaments could correspond to discontinuities in average crustal strength, crust in the magmatic regions being thermally weakened relative to crust in the intervening amagmatic regions. The northwest trend of faults in the stronger crust may be a "minimum energy" configuration in which faults tend to align normal to the discontinuity. The north trending faults, on the other hand, are responding to east-west extension of the continuous extensional arc farther north.

If our analysis is correct, the Klamath Falls earthquakes occurred on the northern edge of a zone of relatively strong crust and propagated northward into relatively weak, volcanically active crust (Figure 7). It is possible that earthquakes in this region may preferentially occur in the northeast trending gravity highs, while extensional strain in the gravity lows is taken up partly by magmatic intrusion, following the rationale of *Bursik and Sieh* [1989], *Parsons and Thompson* [1992], and *Dzurisin et al.* [1991]. Large-magnitude earthquakes are rare in this region, and the seismic record is inadequate to test this hypothesis on a regional scale. We note, however, that the earthquake swarm that occurred at Warner Valley near Adel, Oregon, in 1968, also was located within a northeast trending gravity high (Figure 6, W) [*Blakely and Jachens*, 1990, Plate 2, B].

A complex interplay between oblique subduction of the Gorda and Juan de Fuca plates, distributed extension in the backarc, transform motion along the San Andreas fault system, and strike slip on the Walker Lane belt [*Zoback and Zoback*, 1989; *Dilles and Gans*, 1995] is the engine that drives arc segmentation and ultimately produces inhomogeneities in the distribution of Quaternary volcanism and the orientation of crustal strain. Gravity anomalies and other geophysical data indicate that the forearc in central and northern Oregon is a relatively continuous block, whereas the forearc to the north in Washington and to the south in southern Oregon and northern California is broken into segments (Figure 9). Paleomagnetic data (summarized by *Grommé et al.* [1986] and *Wells* [1990]) indicate that with respect to North America during the Cenozoic the central Oregon forearc block and, to a lesser extent, the southern forearc segments in southern Oregon and northern California have rotated clockwise while simultaneously undergoing northwestward transport (R. E. Wells et al., 1997). If that rotation is continuing today, simultaneous clockwise rotation and translation of the various segments of the forearc would imply nonhomogeneous extension along the trailing edges of the forearc blocks. Specifically, maximum translational velocity must occur at the southern ends of each forearc segment to accommodate the clockwise rotation, and this extra velocity must be accommodated by increased extension, magmatism, and volcanism in the wake of each rotating segment (Figure 9). According to this view, the Mount Shasta-Medicine Lake, and Lassen volcanic centers are located along the southern part of the trailing edges of two rotating forearc segments. This model implies sinistral slip between the forearc blocks; i.e., along the dashed lines on Figure 9. We are not aware of any evidence to support zones of left lateral faults in these regions, and deformation is more likely accommodated by enhanced east-west extension.

The scenarios illustrated in Figures 8 and 9 are not necessarily competing interpretations. Both strain partitioning and differential rotation of forearc blocks could contribute to the segmented pattern of gravity anomalies, volcanism, and faulting in the southern Cascade arc.

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