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Crustal Subsidence, Seismicity, and Structure Near Medicine Lake Volcano, California

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The pattern of historical ground deformation, seismicity, and crustal structure near Medicine Lake volcano illustrates a close relation between magmatism and tectonism near the margin of the Cascade volcanic chain and the Basin and Range tectonic province. Between leveling surveys in 1954 and 1989 the summit of Medicine Lake volcano subsided 389 ± 43 mm with respect to a reference bench mark 40 km to the southwest (average rate = 11.1 ± 1.2 mm/yr). A smaller survey across the summit caldera in 1988 suggests that the subsidence rate was 15–28 mm/yr during 1988–1989. Swarms of shallow earthquakes ($M \leq 4.6$) occurred in the region during August 1978, January–February 1981, and September 1988. Except for the 1988 swarm, which occurred beneath Medicine Lake caldera, most historical earthquakes were located at least 25 km from the summit. The spatial relation between subsidence and seismicity indicates (1) radially symmetric downwarping of the volcano's summit and flanks centered near the caldera and (2) downfaulting of the entire edifice along regional faults located 25–30 km from the summit. We propose that contemporary subsidence, seismicity, and faulting are caused by (1) loading of the crust by more than 600 km^3 of erupted products plus a large volume of mafic intrusives; (2) east-west extension in the western Basin and Range province; and, to a lesser extent, (3) crystallization or withdrawal of magma beneath the volcano. Thermal weakening of the subvolcanic crust by mafic intrusions facilitates subsidence and influences the distribution of earthquakes. Subsidence occurs mainly by aseismic creep within 25 km of the summit, where the crust has been heated and weakened by intrusions, and by normal faulting during episodic earthquake swarms in surrounding, cooler terrain.

INTRODUCTION AND SCOPE

The Medicine Lake region in northeastern California, located near the margin of the Cascades volcanic chain and the Basin and Range tectonic province, provides an excellent opportunity to study the relation between tectonism and magmatism near a convergent plate margin. The region is seismically active, and earthquakes have been monitored for several decades. Extensive leveling surveys were conducted throughout the region in 1954, and they can be repeated to determine vertical strain rates. In addition, Medicine Lake volcano's recent eruptive history is well known, and the regional crustal structure has been studied using various geophysical techniques. Our study combines results from repeat leveling surveys, earthquake monitoring, and measurements of crustal structure to develop a model that explains most aspects of contemporary ground deformation and seismicity.

GEOLOGIC SETTING AND ERUPTIVE HISTORY

Medicine Lake volcano is a Pleistocene-Holocene shield volcano located about 50 km east-northeast of Mount Shasta, between the crest of the Cascade Range to the west and the Basin and Range tectonic province to the east (Figure 1). The Medicine Lake shield rises about 1200 m above the Modoc Plateau to an elevation of 2376 m. Lavas from Medicine Lake volcano cover nearly 2000 km^2, and their volume is estimated to be at least 600 km^3, making it the largest volcano by volume in the Cascade Range. Medicine Lake volcano began to grow about 1 m.y. ago, following eruption of a large volume of tholeiitic high-alumina basalt. Similar high-alumina basalt has continued to erupt around the volcano throughout its history. Although mafic lavas predominate on the volcano's flanks, all lava compositions from basalt to rhyolite have erupted during Pleistocene time. The lower flanks consist of mostly basaltic and some andesitic lavas. Basalt is mostly absent at higher elevations, where andesite dominates and rhyolite and small volumes of dacite are present [*Donnelly-Nolan*, 1988].

During the past 11,000 years, eruptive activity at Medicine Lake volcano has been episodic. Eight eruptions produced about 5.3 km^3 of basaltic lava during a time interval of a few hundred years about 10,500 years ago. That eruptive episode was followed by a hiatus that ended with a small andesitic eruption about 4300 years ago. During the most recent eruptive episode between 3000 and 900 years ago, eight eruptions produced approximately 2.5 km^3 of lava ranging in composition from basalt to rhyolite. Late Holocene lava compositions include basalt and andesite, but silicic lavas dominate [*Donnelly-Nolan et al.*, 1989].

Medicine Lake caldera is a 7 × 12 km depression in the summit area of the volcano. *Anderson* [1941] suggested that the caldera formed by collapse after a large volume of andesite was erupted from vents along the caldera rim. However, the distribution of late Pleistocene vents, mostly concentrated along the rim, suggests that ring faults already existed when most of the andesite erupted [*Donnelly-Nolan*, 1988]. No single large eruption has been related to caldera

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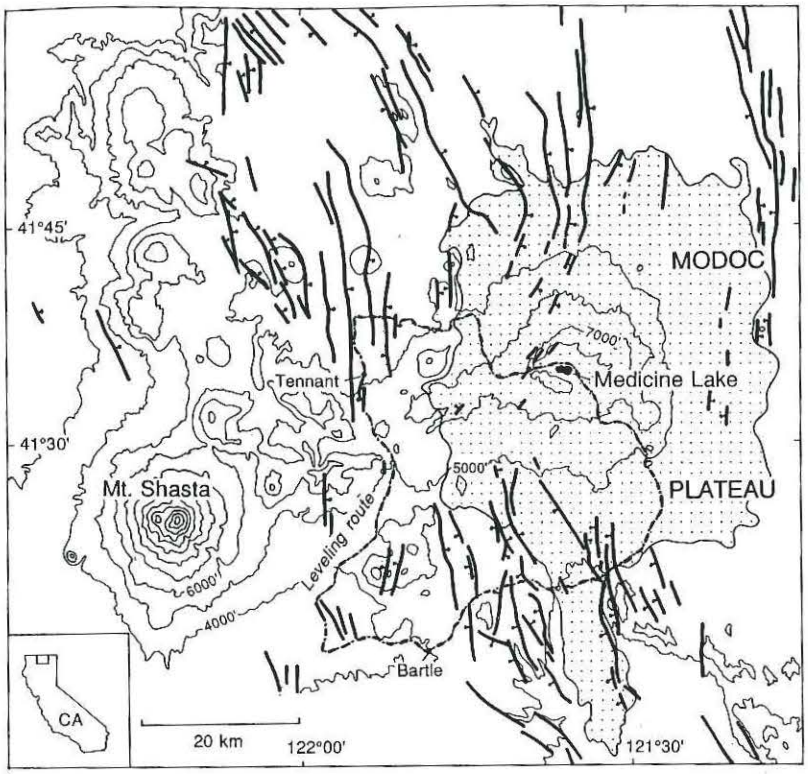

Fig. 1. Location map showing the Medicine Lake volcano–Mount Shasta area of the southern Cascade Range, northern California. Pattern indicates extent of lavas of Medicine Lake volcano. Heavy lines are faults, with bar and ball on downthrown side (*Gay and Aune* [1958] and air photograph interpretation). Heavy dotted-dashed line represents the 1954–1989 leveling route. Contour interval is 1000 feet (305 m).

formation. The only eruption recognized to have produced ash flow tuff occurred in late Pleistocene time, and this eruption was too small to account for formation of the caldera [*Donnelly-Nolan and Nolan*, 1986]. *Donnelly-Nolan* [1988] concluded that Medicine Lake caldera formed by collapse in response to repeated extrusions of mostly mafic lava beginning early in the history of the volcano (perhaps in a manner similar to the formation of Kilauea caldera, Hawaii). She hypothesized several small differentiated magma bodies fed by and interspersed among a plexus of dikes and sills. In her model, late Holocene andesitic to rhyolitic lavas were derived by fractionation, assimilation, and mixing from high-alumina basalt parental magma.

CRUSTAL STRUCTURE

The crustal structure beneath Medicine Lake volcano is dominated by a roughly columnar region, approximately 40 km thick and 50 km in diameter, consisting of mostly high-velocity material superposed on what has been interpreted as either (1) a transition zone from Klamath terrain to basement equivalent to Sierran batholith [*Fuis et al.*, 1987] or (2) an underplated Basin and Range structure in a back arc setting [*McKee et al.*, 1983; *Catchings*, 1987]. Seismic refraction measurements indicate that a high-velocity basement underlies 3–5 km of low-velocity material, which presumably consists of lava flows from Medicine Lake volcano plus interbedded lava flows and sediment of the Modoc Plateau. Schlumberger soundings in the area detected a "geoelectric basement" with a resistivity greater than 200 ohm m at a depth of 1.5 km beneath Medicine Lake caldera [*Zohdy and Bisdorf*, 1990], near the contact between the base of the volcano and the underlying Modoc Plateau.

Various lines of evidence suggest that virtually the entire crustal column beneath Medicine Lake volcano has been intruded by mafic dikes, is still hot, and may be locally molten. The low-velocity layer near the surface is underlain at the volcano by a high-velocity, high-density lens that extends from about 1 km to at least 3 km below the caldera (from about 1 km above to 1 km below sea level; Figure 9*a*). This feature has been interpreted as a complex of mafic-to-silicic material intruded into Modoc Plateau materials [*Finn and Williams*, 1982; *Zucca et al.*, 1986; *Evans and Zucca*, 1988]. An active source seismic tomography experiment indicated that seismic wave fronts are steepened by a radially symmetric, high-velocity anomaly 5–10 km beneath the volcano [*Evans and Zucca*, 1988]. This high-velocity root extends to even greater depths, as shown by inversion of teleseismic travel time data. The inversion indicates that the lower crust, upper mantle, and possibly the middle crust are 2–4% faster than surrounding material. In addition, the upper and middle crust beneath the volcano may be seismically attenuating, on the basis of interpretation of a seismic refraction study [*Catchings*, 1983].

At Newberry volcano, a shield volcano in central Oregon that is geologically similar to Medicine Lake volcano, *Stauber et al.* [1988] used teleseismic data to image a columnar high-velocity feature that extends from within 10 km of the surface to about 25 km depth. They interpreted this feature as a largely subsolidus mafic intrusive complex. On the basis of the surface geology and seismic data from

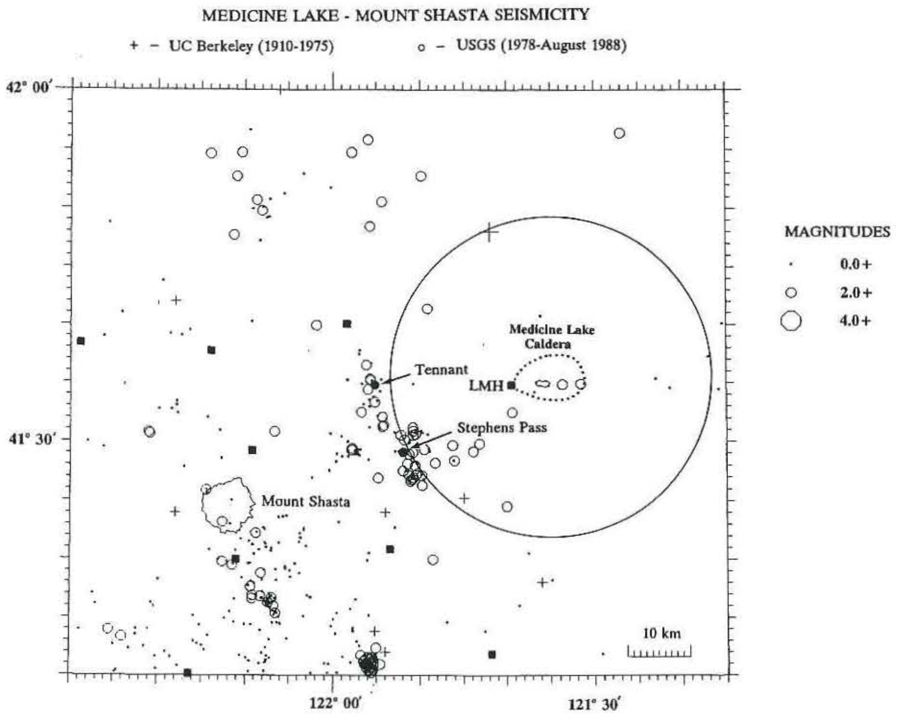

Fig. 2. Seismicity in the Medicine Lake–Mount Shasta region for the period from 1910 to August 1988. Solid squares represent seismographs of the USGS Mount Shasta network, including Little Mount Hoffman (LMH) on the west rim of Medicine Lake caldera. Large circle encloses a relatively aseismic area within 25 km of the summit of Medicine Lake volcano. Clusters of earthquakes near Tennant and Stephens Pass occurred during swarms in 1981 and 1978, respectively [from *Bolt and Miller*, 1975; USGS, unpublished data, 1991].

Medicine Lake volcano, and by analogy to Newberry volcano, we conclude that the lower and possibly middle crusts beneath Medicine Lake volcano consist of silicic rocks intruded by numerous dikes and sills that contain gabbro and diabase (slowly cooled equivalents of mafic melts), perhaps with variable amounts of basalt melt. In the upper mantle the high-velocity anomaly may represent ultramafic residuum left by removal of this basalt. This conclusion is consistent with (1) geochemical evidence suggesting that generation of intermediate and silicic melts from basaltic melts by fractionation and assimilation occurs in the upper crust [*Grove and Baker*, 1984; *Grove and Donnelly-Nolan*, 1986; *Grove et al.*, 1988] and (2) the eruption of primitive mantle-derived basalt throughout the history of Medicine Lake volcano [*Donnelly-Nolan*, 1988].

The high-resolution active seismic tomography experiment mentioned above detected a low-velocity, low-Q region in the upper crust beneath Medicine Lake caldera [*Evans and Zucca*, 1988]. The anomalous feature, which extends from about 1 to 3 km below sea level (i.e., 3–5 km beneath the caldera), has a diameter of about 3 km and a volume of the order of 10 km^3. It is interpreted as a small silicic magma body, on the basis of its distinctive seismic signature, its association with an active magmatic system, and various geologic, geochemical, and geophysical considerations [*Evans and Zucca*, 1988; *Evans and Walter*, 1989]. No other magma bodies were suggested by the experiment, which had a spatial resolution of 1–2 km in the upper 5–7 km of the crust beneath the caldera and most of the shield.

SEISMICITY

Prior to the first seismograph records in 1909, there were various reports of seismic activity in the Medicine Lake region. G. W. Courtright, a local rancher and trapper, felt numerous earthquakes and saw "flames" and ground cracks near Glass Mountain in January and February 1910 [*Finch*, 1928]. Finch also reported that "earthquakes originating in the mountain and accompanied by rattling noises have been noted by Forest Service officials for at least 15 years." He added, "Similar noises and shakes have been observed by Mr. Courtright for a much longer period."

Seismic records collected by the University of California Berkeley Seismographic Stations starting in 1909 show no earthquakes in the Medicine Lake–Mount Shasta region prior to 1950 [*Bolt and Miller*, 1975]. However, instrumental coverage during that interval was such that events smaller than M 4 probably would not have been located. As additional stations were added in the 1950s, earthquakes as small as M 3.0 began to be located in the Mount Shasta area. Still, no events were detected near Medicine Lake volcano through 1975 (Figure 2).

In 1980 the U.S. Geological Survey (USGS) extended its northern California seismic network by installing nine short-period, vertical seismometers around Mount Shasta. The new stations included one on the western edge of Medicine Lake caldera at Little Mount Hoffman (LMH, Figure 3*a*). Seismic signals are telemetered by a combination of radio and telephone lines to the USGS office in Menlo Park,

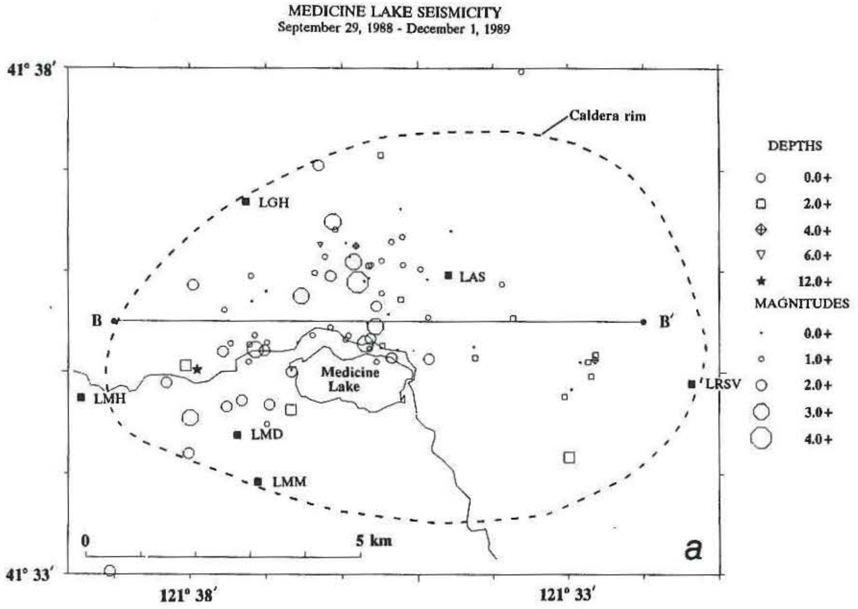

Fig. 3*a*. Located earthquakes of the 1988 Medicine Lake swarm and its aftershocks. Epicenters are shown as open symbols, and seismographs of the USGS Medicine Lake network, installed in October 1988, are shown as solid squares. Solid line at lower left represents the main road across the caldera that was leveled in 1954, 1988, and 1989; dashed line represents the caldera rim. The star about 2 km west of the west end of Medicine Lake marks the location of a long-period earthquake that occurred at 15 km depth on December 1, 1989. Line B-B′ shows the orientation of the cross section shown in Figure 3*b*.

California, where they are recorded and earthquakes are identified, timed, and located. Earthquakes are located with HYPOINVERSE [*Klein*, 1989] using a homogeneous layered crustal model determined from refraction studies [*Catchings*, 1983, 1987]. For a full discussion of instrumentation and data processing, see *Lester and Meagher* [1978] and *Stewart and O'Neill* [1980].

Between 1980 and the September 1988 swarm (see below), only three earthquakes were located in the vicinity of Medicine Lake caldera. Two of these events occurred in the eastern part of the caldera, in an area active after the 1988 swarm. The third event was a long-period earthquake that occurred on October 14, 1986. An approximate location for this event places it about 13 km beneath the western edge of the caldera, close to the hypocenter of a well-located long-period earthquake that occurred on December 1, 1989 (see the 1988 Medicine Lake swarm, Figure 3).

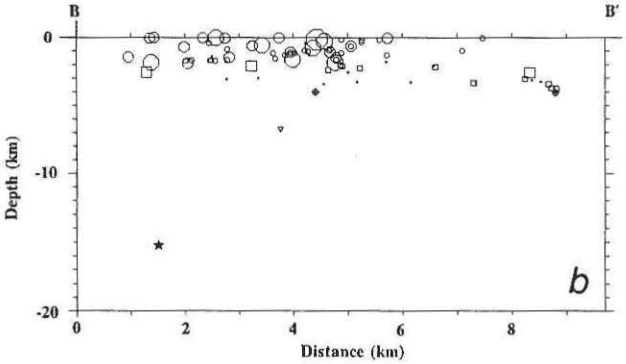

Fig. 3*b*. Cross section shows depths of the earthquakes that occurred during the 1988 swarm. All epicenters shown in Figure 3*a* were projected onto a vertical plane through B-B′. Star at about 15 km depth represents the same long-period earthquake as in Figure 3*a*.

1978 Stephens Pass Swarm

The apparent seismic quiescence near Medicine Lake volcano was broken by an intense swarm of shallow earthquakes that began with a *M* 4.6 event on August 1, 1978. The initial shock was followed within the next 90 min by six events of *M* 3.5–4.5 and within 24 hours by 100–200 events of $M \geq 2$ [*Cramer*, 1978; *Bennett et al.*, 1979]. The epicentral area was centered 15 km south of the town of Tennant and 5 km south of Stephens Pass, approximately midway between Medicine Lake volcano and Mount Shasta (Figure 2). A second flurry of activity began with a *M* 4.3 event on August 12. On August 14, U.S. Forest Service personnel reported large fissures across Stephens Pass Road 5 km south of Stephens Pass.

Subsequent field observations documented a 2-km-long, 75-m-wide zone of tensional fractures, grabens, and circular depressions ("sink holes") within the grabens. The zone trended north-south through the epicentral area (Figure 4). Vertical displacements were as large as 1 m in the grabens and 1.5 m in the circular depressions [*Cramer*, 1978; *Bennett et al.*, 1979]. An 8-km-long aftershock zone dips eastward away from the ground breakage; focal depths increase eastward to a maximum of about 4 km. Focal mechanisms suggest east-west extension on a north striking fault dipping 35°–45° east [*Cramer*, 1978], consistent with the pattern of north striking normal faults in the region.

1981 Tennant Swarm

Another swarm of shallow earthquakes occurred during January–February 1981, in this case almost directly beneath

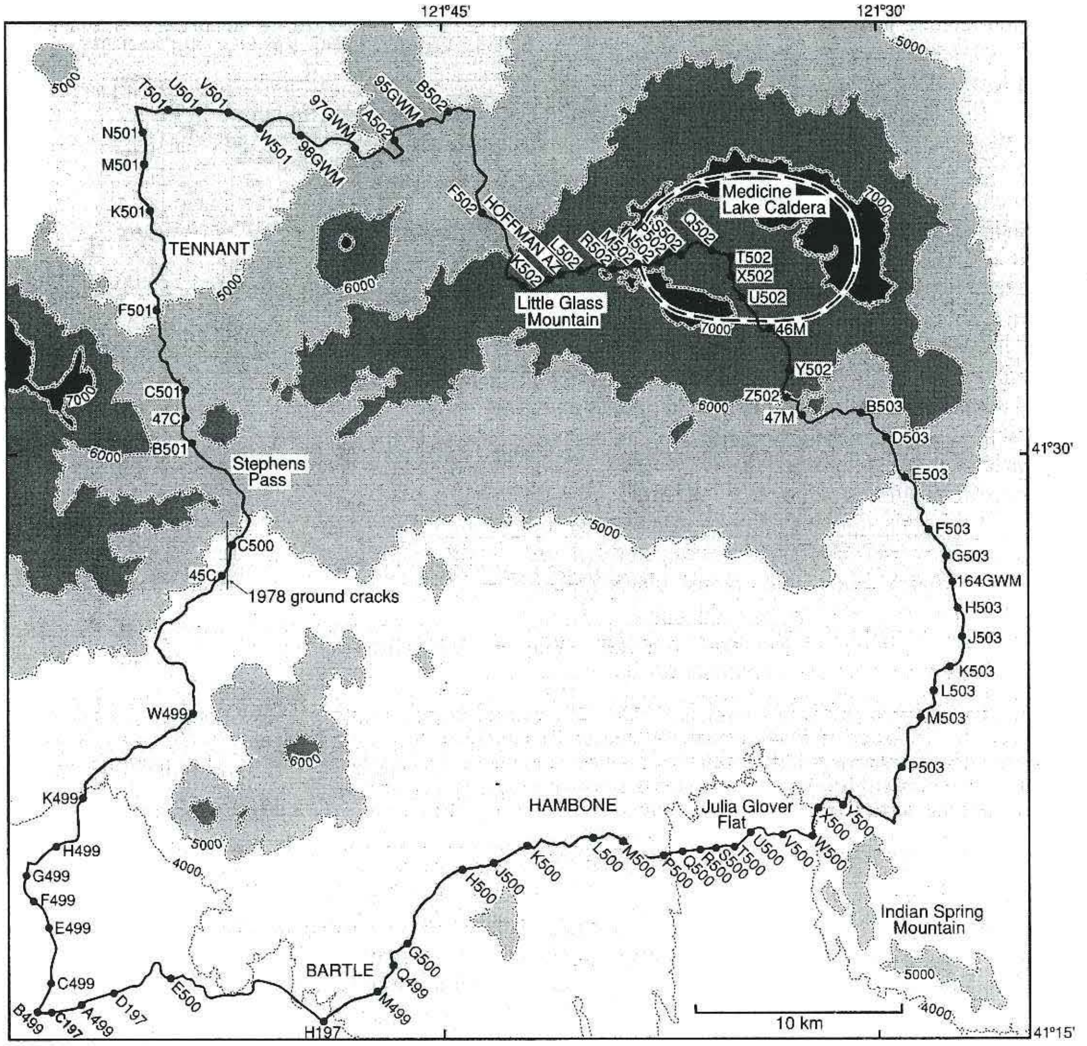

Fig. 4. Locations of bench marks along the 193-m leveling circuit across Medicine Lake volcano and Stephens Pass. Also shown are the locations of Bartle, Hambone, Tennant, and several features mentioned in the text. Stippling indicates five elevation ranges, from less than 4000 feet (1220 m) above sea level (no stippling) to more than 7000 feet above sea level (2130 m) (the heaviest stippling); contour interval is 1000 feet (305 m). Throughout the text, stadia distances are measured counterclockwise from H197, the southernmost mark in the circuit, near Bartle. Dashed line marks the boundary of Medicine Lake caldera; solid line between bench marks C500 and 45C near Stephens Pass indicates the area of ground breakage associated with the 1978 Stephens Pass earthquake swarm [from *Bennett et al.*, 1979].

the small town of Tennant, about 10 km north of Stephens Pass. The activity began on January 1, 1981, with an earthquake that was felt by residents of Tennant (A. M. Allison, personal communication, 1981). Several dozen additional events, all of $M < 3.0$, were recorded on seismographs of the Mount Shasta network from January 5 to January 8. Activity increased abruptly early on January 9 with a M 4.1 earthquake, the largest of the sequence, followed by 26 events of $M \geq 2.0$ within the next 24 hours, including 11 events of $M \geq 3.0$. Seismicity declined markedly over the next several weeks, with several flurries of small events ($2.0 \leq M \leq 3.0$) on January 12 and again in early February.

Temporary seismic stations were installed by January 15, after the main part of the sequence had ended. Well-determined focal depths for aftershocks recorded by the temporary stations all are very shallow, generally less than 2 km. The aftershock zone is about 10 km long and elongate in a north-south direction, suggesting movement on a north striking fault aligned with the regional structural pattern (Figures 1 and 2). Despite the large extent of the aftershock zone and the shallowness of the seismicity, no ground breakage was reported. However, minor ground breakage could have been obscured by a thin layer of snow covering the ground at the time (J. Coakley, personal communication, 1990).

1988 Medicine Lake Swarm

The Medicine Lake swarm began on the morning of September 29, 1988, with a flurry of some 20 small events, the largest of M 3.3. The swarm peaked in the late afternoon with more than 80 earthquakes recorded in 1 hour, including two M 3.5 events and one M 4.1 event, the largest of the

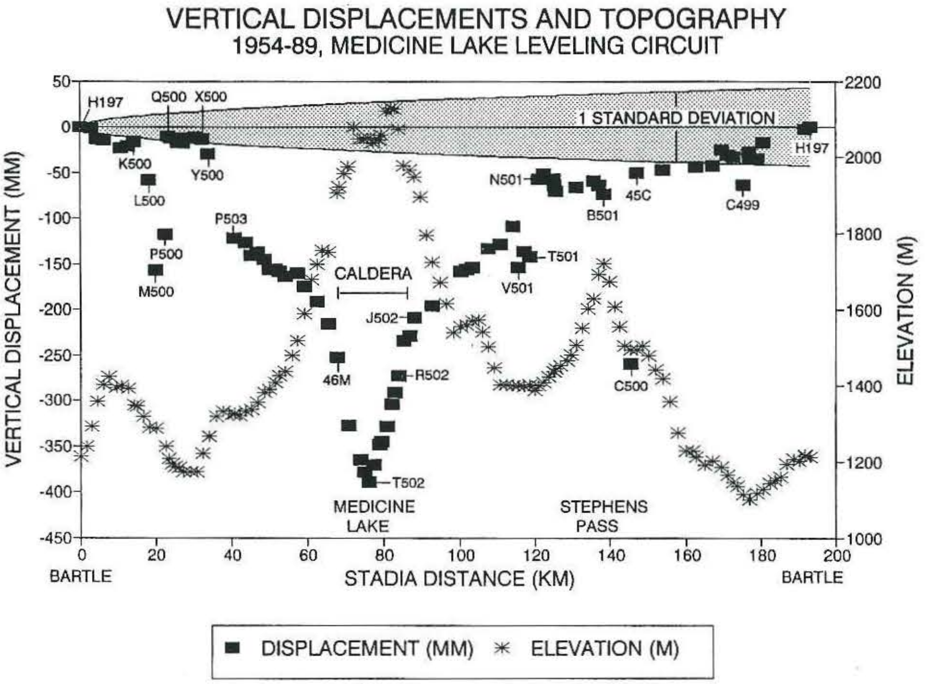

Fig. 5. Topographic profile (asterisks) and 1954–1989 vertical displacements (squares) along the Medicine Lake–Stephens Pass leveling circuit. Stadia distance is measured counterclockwise from H197 near Bartle, which is held fixed (see Figure 4). Stippled area indicates 1 standard deviation in the vertical displacements, based on published standards for second-order, class II leveling surveys (1954) and first-order, class II surveys (1989) [*Vanicek et al.*, 1980]. At any stadia distance the vertical dimension of the stippled area indicates the height of the 1-sigma error bar at that distance.

sequence. Activity declined rapidly with 90 earthquakes recorded in the next 24 hours, several events per day during October 1988, and several events per week during the remainder of 1988. Several additional seismographs were installed around Medicine Lake caldera in late October 1988 (Figure 3). Sporadic flurries of small events ($M \leq 3.1$) occurred beneath Medicine Lake caldera throughout 1989 [*Walter and Dzurisin*, 1989].

All 1988–1989 earthquakes occurred beneath Medicine Lake caldera, primarily north or west of Medicine Lake (Figure 3*a*) and within about 2 km of the surface (Figure 3*b*). A small cluster of events occurred in April 1989 at depths of 3–4 km beneath the eastern part of the caldera. With one exception, all 1988–1989 earthquakes were short-period, tectonic-type events. A long-period event of M 2.7 occurred about 15 km beneath the western part of the caldera on December 1, 1989. Similar long-period events have been recorded (1) beneath Kilauea and Mauna Loa volcanoes in Hawaii; (2) beneath Long Valley caldera, the Lassen volcanic center, and near the Geysers/Clear Lake area, all in California; and (3) at Yellowstone caldera in Wyoming. The significance of such long-period events may not be the same at every volcano, but their association with young magmatic systems suggests that they record movement of mafic magma or other fluids within the crust [e.g., *Koyanagi et al.*, 1987; *Chouet et al.*, 1987].

LEVELING RESULTS

A 193-km leveling circuit across Medicine Lake volcano and Stephens Pass via the towns of Tennant and Bartle (Figure 4) was first measured in 1954 by the National Geodetic Survey (NGS) using second-order, class II procedures. The circuit was remeasured in 1989 by the USGS Cascades Volcano Observatory (CVO), using first-order, class II procedures. CVO also measured a 20-km segment of the same circuit, from bench mark J502 near Little Glass Mountain eastward across Medicine Lake caldera via T502 to 46 M, in August 1988 and October 1988. All appropriate corrections specified by NGS [*Schomaker and Berry*, 1981; *Balazs and Young*, 1982] were applied to the measurements, including rod scale corrections based on calibrations performed at the National Bureau of Standards and refraction corrections based on measured temperatures. Misclosures for the 193-km circuit were 5.4 mm in 1954 and 19.7 mm in 1989, compared to NGS specifications of 111 mm (8 mm/km$^{1/2}$ $L^{1/2}$ for second-order, class II surveys) and 69 mm (5 mm/km$^{1/2}$ $L^{1/2}$ for first-order, class II surveys [*Vanicek et al.*, 1980]), respectively. An analysis of random and systematic errors in the surveys is given in the Appendix.

Vertical Displacements, 1954–1989

Figures 4–6 show bench mark locations, topography, and vertical displacements during 1954–1989 along the Medicine Lake leveling circuit. Displacements are relative to bench mark H197 near Bartle, which was held fixed as a reference. A broad area of subsidence centered at Medicine Lake caldera and extending across the entire volcano is evident in Figures 5 and 6. The maximum measured subsidence was 389 ± 43 mm at T502, which corresponds to an average annual rate of 11.1 ± 1.2 mm/yr during the 35-year interval spanned by the surveys. T502 is the bench mark nearest to the center of the caldera.

Between 1954 and 1989, large local displacements occurred south of Medicine Lake caldera near M500 (east of

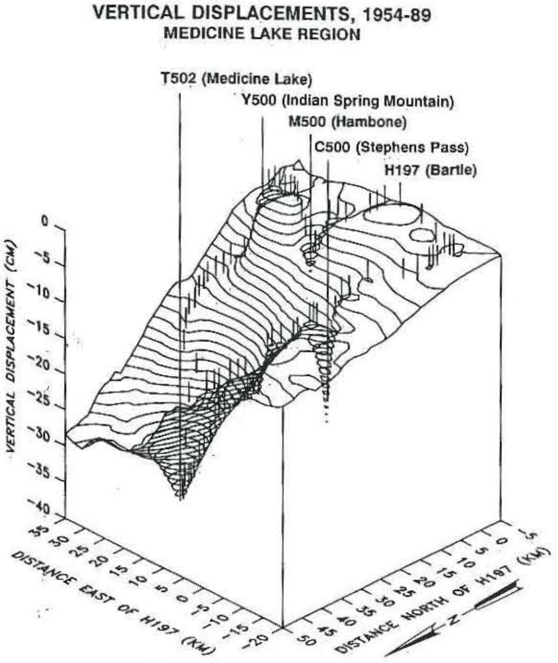

Fig. 6. Three-dimensional representation of the 1954–1989 vertical displacements in the Medicine Lake region. Curved lines represent contours of relative vertical displacement (contour interval = 10 mm). Locations of bench marks along the leveling route are indicated by small vertical lines. View is from the northwest. Displacements are known accurately only at the marks; elsewhere they were extrapolated using a gridding program with an inverse square weighting scheme. Fault displacements near M500 (Hambone), Y500 (Julia Glover Flat), and C500 (Stephens Pass) are not portrayed accurately because the leveling traverse did not sample those areas in detail.

Hambone) and Y500 (northeast end of Indian Spring Mountain), and also west of the caldera near V501 and N501 (north of Tennant) and C500 (Stephens Pass) (Figures 4–6). C500 is located within the epicentral area of the 1978 Stephens Pass earthquake swarm, near the southern end of a zone of ground cracks that formed during the swarm [*Bennett et al.*, 1979]. C500 is on the east (downthrown) side of the surface cracks, while nearby marks are on the west side. We attribute the anomalous movement of C500 to the effects of the 1978 swarm. V501 and N501 are located near the northern margin of the epicentral area associated with the 1981 Tennant earthquake swarm, near a prominent north striking regional fault (Figures 1 and 4). We suspect that the anomalous movements of V501, N501, and two intervening marks occurred during the 1981 swarm. M500 and Y500 are located near prominent, young-looking normal faults that bound Indian Spring Mountain and Julia Glover Flat in horst-and-graben terrain about 30 km south of Medicine Lake caldera (Figure 4). One fault forms the eastern boundary of Julia Glover Flat and offsets by about 10 m a basalt flow dated 10,600 years B.P. [*Donnelly-Nolan et al.*, 1989]. The large displacements of marks near M500 and Y500 indicate that some of these faults have been active since 1954. A search of regional seismic records for the period from 1911 to 1989 turned up only one earthquake larger than M 2.0 in the area; a M 3.2 event on February 16, 1959, located about 10 km east-southeast of Hambone, beneath Julia Glover Flat. However, the records are incomplete for events of $M \leq 4.5$ prior to about 1950 and of $M \leq 3.5$ during 1950–1980. Therefore a swarm of smaller earthquakes could have gone undetected, as evidenced by the absence of recorded earthquakes near Glass Mountain associated with the 1910 swarm reported by *Finch* [1928].

Inspection of Figures 4 and 5 suggests that historical faulting has downdropped Medicine Lake volcano by 5–10 cm with respect to the surrounding plateau (i.e., P503 relative to Y500 and T501 relative N501; Figure 5). Owing to the configuration of the leveling route, it is unclear whether this subsidence is bounded by a north striking graben or a basin centered at Medicine Lake caldera. The existence of a circular subsidence feature nested within a major north striking graben encompassing both Medicine Lake volcano and Mount Shasta has been proposed on the basis of regional magnetic and gravity anomalies [*Blakely et al.*, 1985; *Blakely and Jachens*, 1990], but those anomalies are considerably larger than the area of subsidence surrounding Medicine Lake caldera.

It is surprising that Julia Glover Flat, a young-looking graben that the leveling route crosses between Q500 and X500, was stable during 1954–1989 while adjacent areas to the west and northeast subsided 10–15 cm (Figure 5). This sense of movement is opposite to what has prevailed over longer time scales, as indicated by the current topography and by large Holocene movements on faults that bound the graben. Thus Julia Glover Flat seems particularly prone to faulting and subsidence in the future.

Vertical Displacements, 1988–1989

Any relation between the subsidence during 1988–1989 and the September 1988 earthquake swarm is difficult to demonstrate, because movements were barely larger than measurement error. Vertical displacements within Medicine Lake caldera from August 1988 to August 1989 are mostly less than 2 standard deviations of the measurements and therefore of marginal significance. However, the measured displacements suggest that the intracaldera subsidence rate was at least as high during 1988–1989 as during 1954–1989. The average subsidence rate at T502 with respect to J502 was 13.8 ± 3.5 mm during 1988–1989 compared to 5.2 ± 0.2 mm/yr during 1954–1989. The amount of movement at T502 during 1988–1989 seems anomalous relative to nearby bench marks (Figure 7), but even at adjacent marks the 1988–1989 subsidence rates were higher than the 1954–1989 rates (e.g., at X502, 7.6 ± 4.0 mm/yr during 1988–1989 compared to 4.8 ± 0.3 mm/yr during 1954–1989). The 1988 and 1989 surveys did not include H197, so subsidence rates with respect to H197 can only be estimated by comparison with the 1954–1989 results. From 1954 to 1989 the amount of subsidence at T502 with respect to J502 was about half the amount at T502 with respect to H197 (Figure 5). Assuming the subsidence pattern did not change, we doubled the 1988–1989 subsidence rates with respect to J502 to estimate the rates with respect to H197. Thus we estimate that the center of Medicine Lake caldera subsided 15 mm/yr (X502) to 28 mm/yr (T502) with respect to H197 during 1988–1989, compared to 11.1 ± 1.2 mm/yr at T502 during 1954–1989.

SUBSIDENCE MECHANISMS

Mechanisms that might cause subsidence of Medicine Lake volcano and sporadic earthquake swarms in the sur-

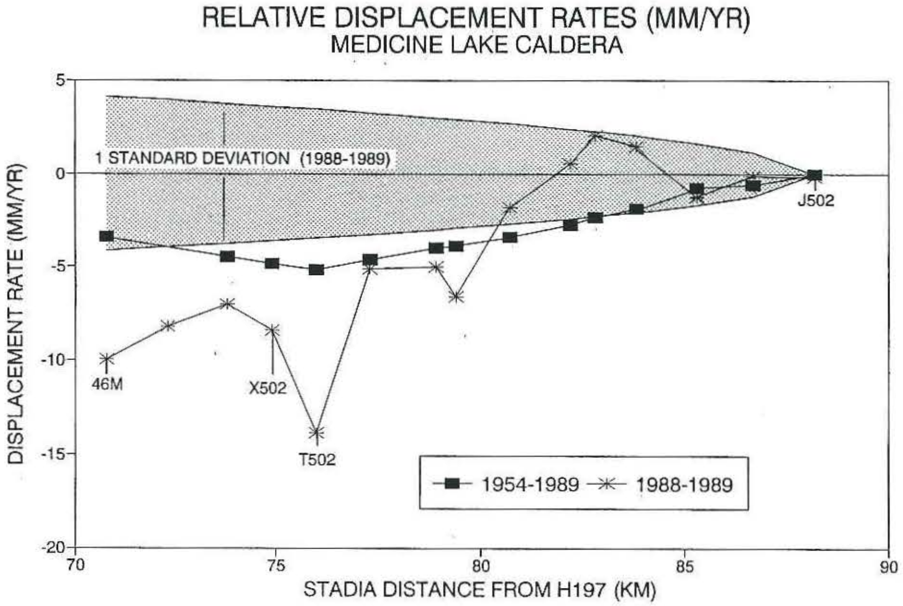

Fig. 7. Annual vertical displacement rates relative to J502 for the periods 1954–1989 (squares) and August 1988 to August 1989 (asterisks) along a 20-km leveling traverse across Medicine Lake caldera. Stippled area indicates 1 standard deviation in the 1988–1989 displacement rates. At any stadia distance the vertical dimension of the stippled area indicates the height of the 1-sigma error bar for the 1988–1989 measurements at that distance. See Figure 4 for locations of bench marks.

rounding area include (1) crustal thinning caused by extension in the western Basin and Range province, (2) loading of the crust by the weight of the volcano and its subvolcanic intrusive complex, (3) densification during cooling and crystallization of magma, and (4) deflation caused by magma withdrawal. We propose that mechanisms 1 and 2 are primarily responsible for historical subsidence and that mechanisms 3 and 4 may contribute over longer time scales.

Crustal Extension

Several lines of evidence indicate that an important mechanism for historical subsidence at Medicine Lake volcano is thinning and bending of the crust in response to regional tectonic extension. Although the contemporary extension rate has yet to be measured, structural and geologic evidence indicates that Medicine Lake volcano lies in a region of east-west extension that has been active at least through late Holocene time. Seismic and leveling data show that extension and faulting have continued to the present. The Medicine Lake area is cut by numerous north striking normal faults with up to a few hundred meters of displacement. Others may be partially or completely buried by young lava flows. Open ground cracks, common on and around Medicine Lake volcano, have N30°W to N30°E orientations and east-west opening directions consistent with the extensional direction indicated by regional faults [*Donnelly-Nolan*, 1988]. The same is true for cracks that formed during the 1978 Stephens Pass earthquakes, which had focal mechanisms indicating east-west extension on a north striking fault [*Cramer*, 1978].

If the mechanical response of the crust in the Medicine Lake region were laterally homogeneous, east-west extension would cause grabens and fissures to form along a north striking axis, creating a north trending trough. That is not the pattern observed at Medicine Lake volcano, where the known subsidence is more or less symmetric about the center of Medicine Lake caldera. However, could such a pattern result from east-west extension if the crust beneath the volcano is mechanically weaker than its surroundings? Using a finite element model of the crust and upper mantle beneath the Yellowstone region, *Meertens* [1987] demonstrated the reverse process, i.e., that regional compressive strain can cause doming of mechanically weak crust. He proposed that such weakness is a consequence of elevated temperatures and fracturing associated with the Yellowstone magmatic and hydrothermal systems. If similar conditions prevail beneath Medicine Lake volcano (as indicated by interpretation of seismic data), then subsidence of weak subvolcanic crust could be a result of Basin and Range extension.

Crustal Loading

Another mechanism that may contribute to subsidence at Medicine Lake volcano is crustal loading by the volcanic edifice and dense mafic intrusions. A similar mechanism has been proposed to account for subsidence of the Hawaiian Islands [*Moore*, 1970]. The dimension over which the crust is loaded, which determines the response depth, is an order of magnitude larger in Hawaii (400 km) than at Medicine Lake volcano (40 km). Therefore a classical isostatic response of the asthenosphere is unlikely at Medicine Lake volcano. However, a similar response might occur within the upper lithosphere, because is has been heated and weakened by numerous mafic intrusions.

Studies of samples from eight drill holes located on the upper flanks of Medicine Lake volcano indicate that five of the holes penetrated the entire volcanic pile. In drill cores from each of those holes, fresh aphyric lavas of Medicine Lake volcano abruptly give way to altered flows, sediments, and/or porphyritic lavas, some of which are petrographically unlike Medicine Lake lavas [*Donnelly-Nolan*, 1990]. One hole on the west flank reached a highland of pre–Medicine Lake volcano vents and flows (at 4600 feet, 1402 m elevation) that connects westward to Mount Shasta. The other four holes penetrated the base of Medicine Lake volcano at elevations of 2487–3365 feet (758–1026 m), well below the level of the surrounding Modoc Plateau (1250 m). The possibility that a circular basin 0.5 km deep may have existed at the location where Medicine Lake volcano was built is thought to be unlikely. No thick sequences of sediment are present in any of the drill holes, nor do the underlying basalt flows show signs of eruption into water. We conclude that the crust under the volcano has been downwarped approximately 0.5 km relative to the surrounding plateau, at least partly as a result of crustal loading.

The downwarped part of the volcanic edifice does not contribute significantly to the isostatic load, because it displaces rocks of similar density [*Zucca et al.*, 1986]. However, the drill core observations indicate the large magnitude of subsidence that has occurred over geologic time scales, and it is likely that at least part of the historical subsidence is caused by this mechanism. More subsidence may have occurred deeper in the crustal column if magmatic intrusion caused unrecorded uplift, which seems likely on the basis of seismic evidence for dense intrusive material throughout the crustal column. One consequence of the downwarping is that the volume of the volcano may be significantly greater than the previous estimate of 600 km^3. The volume of Medicine Lake volcano that has been downwarped below 1250 m elevation is approximately 150 km^3, so the total volume of the volcanic pile is estimated to be 750 km^3.

The long-term subsidence rate calculated from the amount of downwarping can be compared to the historical subsidence rate determined from measured displacements. Geologic mapping shows that Medicine Lake volcano had attained essentially its current configuration by about 150,000 years B.P., so the current subsidence rate can be estimated as $0.5\ km/1.5 \times 10^5$ years = 3 mm/yr (assuming that the entire load was emplaced 150,000 years ago). This estimate is of the same order as, but almost a factor of 4 less than, the subsidence rate during 1954–1989 measured by leveling (11.1 ± 1.2 mm/yr). The implication is that the effect of crustal loading has increased through time to account for the current subsidence rate or, more likely, that crustal loading is not the dominant cause of contemporary subsidence.

Cooling and Crystallization of Magma

Subsidence may also result from densification in response to fluid loss during cooling and crystallization of magma. Even for a large rhyolitic system with a vigorous hydrothermal system such as Yellowstone, the thermal contraction caused by cooling of crystalline rock is negligible. However, if heat is extracted from the crustal column by cooling and crystallization of magma, the amount of contraction is appreciable. At Yellowstone, crystallization of rhyolite initially containing 2 wt % water results in a 7% decrease in volume, assuming that all of the released aqueous fluid escapes to the shallow, hydrostatically pressured part of the hydrothermal system [*Fournier*, 1989; *Dzurisin et al.*, 1990]. The amount of contraction would be somewhat less for silicic magmas, which typically contain less water. Note that this mechanism causes both horizontal contraction and subsidence, owing to the net decrease in volume.

Although there is scant surface evidence for a significant hydrothermal system beneath Medicine lake volcano, high vertical temperature gradients in three drill holes suggest that a considerable amount of heat may be available in the shallow subsurface [*Donnelly-Nolan et al.*, 1989]. The most likely heat sources are the low-velocity, low-Q zone beneath the caldera or an underlying zone of mafic intrusions. If the heat is derived from crystallizing magma in either of these zones, resulting fluid loss may account for part of the historical subsidence. If so, the thermal and chemical signature of the magma is greatly attenuated at the surface, possibly by flushing through the shallow groundwater system.

Magma Withdrawal

Evans and Walter [1989] proposed that deflation of the shallow magma chamber identified by a seismic tomography experiment [*Evans and Zucca*, 1988] caused the floor of Medicine Lake caldera to bow downward and eventually fail under bending stresses during the September 1988 earthquake swarm (Figure 9*a*). Although deflation of this chamber might contribute to subsidence, the leveling observations and modeling results (see the section on source models) show that the chamber is too small and shallow to account for the full extent of the 1954–1989 subsidence. Two long-period earthquakes have occurred recently in the depth range 13–15 km beneath Medicine Lake caldera, but their relation to the 1954–1989 subsidence is uncertain. Perhaps intruding mafic magma accumulates temporarily at 10–15 km depth, cools, densifies, and then sinks while still fluid to cause subsidence. Withdrawal of silicic magma from shallower depth seems less likely, owing to its lower density and greater effective viscosity. In either case, magma withdrawal probably is of secondary importance except during eruptive or intrusive episodes, when large volumes of magma move rapidly to the surface or into the rift zones.

SOURCE MODELS

A realistic model of the 1954–1989 subsidence would include both viscoelastic and brittle deformation (i.e., downsagging and faulting) and would be constrained by both horizontal and vertical displacement data. Lacking horizontal data, we used a simple point source elastic model [*Mogi*, 1958] to estimate the depth of the deformation source (i.e., volume decrease) from the measured vertical displacements. Although the model assumes that the crust is homogeneous and elastic, the effects of faulting and tectonic strain can be factored in qualitatively to explore the range of likely source depths. First, we consider all of the observations except for several marks obviously affected by faulting. Then we consider only those marks within 25 km of T502, where the subsidence profile is smooth and no faulting is indicated. In each case the volume change in the source region is adjusted to match the observed subsidence at T502.

Using a single deformation source, the best fit is obtained for a source depth of 15 km and a volume decrease of $550 \times 10^6\ m^3$ (Figure 8*a*). A slightly better fit results from including two sources: one at 15 km depth (volume decrease of 450 ×

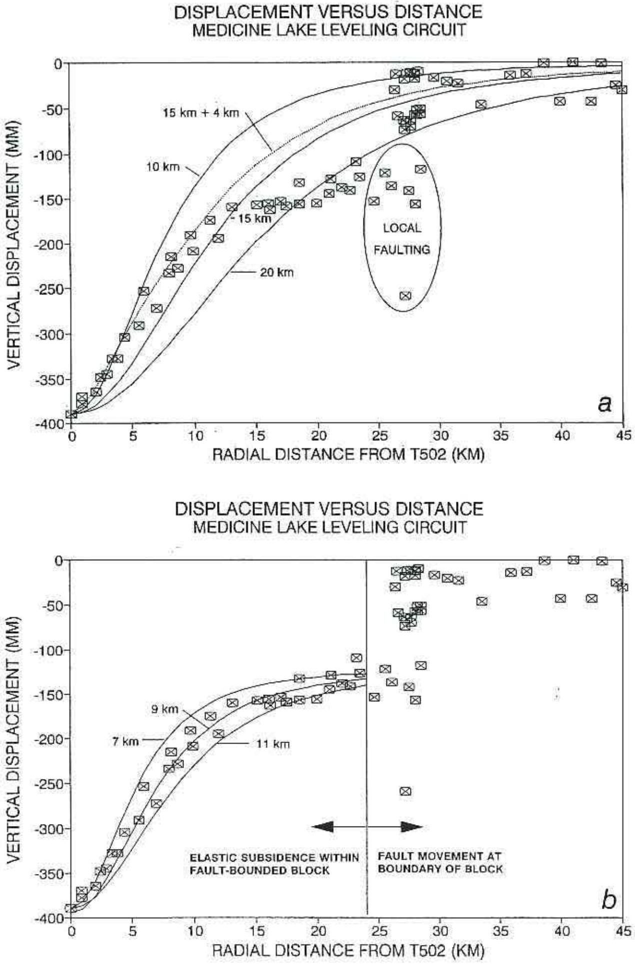

Fig. 8. Vertical displacement during 1954–1989 versus radial distance from bench mark T502 (near the center of Medicine Lake caldera) from leveling (squares) and from point source elastic models of bodies at the indicated depths (curved lines). (*a*) Attempt to fit all of the observations except those obviously affected by faulting. Solid lines represent effects of single sources centered at depths of 10, 15, and 20 km; dashed line represents the combined effect of two sources, one at 4 km depth and one at 15 km depth. The source volume decreases required to produce the indicated subsidence for sources at various depths are (in units of 10^6 m^3) 980 (depth = 20 km), 550 (15 km), 245 (10 km), and 450 + 7 (15 + 4 km). Each model was fit to the data by inspection; other combinations of depth and source volume change are possible. Ellipse encloses seven marks affected by local faulting (V501, U501, T501, C500, P503, M500, and P500) which were ignored when fitting the curves to the data. (*b*) Attempt to fit only those observations within 25 km of T502, assuming that more distant points are affected by faulting. The required source volume changes are (in units of 10^6 m^3) 205 (11 km), 140 (9 km), and 83 (7 km). Vertical line separates marks within 25 km of T502, where the subsidence profile is smooth, from those farther away and subject to faulting. Only marks to the left of the line were considered for the model.

10^6 m^3) and another at 4 km depth (volume decrease of 7 × 10^6 m^3). The deeper source corresponds to the approximate locations of two long-period earthquakes that might indicate a magma storage zone, and the upper source corresponds to the low-velocity, low-Q anomaly interpreted by *Evans and Zucca* [1988] as a silicic magma body beneath Medicine Lake caldera. The addition of a second source improves the fit slightly, but the improvement may simply reflect the increased degrees of freedom in the model.

An alternative model is illustrated in Figure 8*b*. The shape of the subsidence profile in Figure 5 and the offset near a radial distance of 25 km in Figure 8*a* suggest that the entire volcano, including the downwarped area centered at T502, has been downfaulted 5–10 cm relative to the surrounding plateau. This is illustrated in Figure 5 by the relative displacements of X500 and P503 near a stadia distance of 40 km and of N501 and T501 near a stadia distance of 120 km. To exclude the effect of faulting from the second model, we considered only those marks located within 25 km of T502. A volume decrease of 140 × 10^6 m^3 centered at 9 km depth yields the best fit. This model probably underestimates the true source depth by ignoring the far-field deformation, while the previous model may overestimate the depth slightly by ignoring the effect of faulting. A possible advantage of the second model, in view of the lack of a single large magma body beneath Medicine Lake caldera, is that smaller subsurface volume changes are needed to explain the amount of historical subsidence.

We suspect that the source is actually a vertically extended plexus of dikes with subsidiary magma storage zones at depths of 10–15 km and 3–5 km. This interpretation is based on (1) regional geophysical measurements that suggest the presence of mafic intrusions throughout the crust; (2) the occurrence of long-period earthquakes, suggesting magma movement, at 10–15 km depth; (3) seismic tomography measurements that indicate a small magma chamber at 3–5 km depth; and (4) the geodetic modeling results described above.

CONCEPTUAL MODEL

Our preferred model of the Medicine Lake magmatic system is illustrated in Figure 9. The dominant causes of subsidence are (1) crustal loading by the volcano plus dense subvolcanic intrusions and (2) crustal thinning due to Basin and Range extension. Both processes are facilitated by heat-induced crustal weakening; indeed, without such weakening, the load probably would be supported by an elastic upper lithosphere. A roughly columnar region beneath the edifice has been intruded extensively by basalt, most of which has solidified, thereby heating and weakening the crustal column (Figure 9*c*). An unknown fraction of this melt has differentiated to more silicic material that has intruded the upper crust and erupted at the surface, as has some of the parental basalt. Addition of mass and heat causes the volcano and underlying crust to subside. At the same time, Basin and Range extension thins the weakened crust, causing it to subside further. Possible subsidiary causes of surface subsidence include fluid loss during crystallization of magma and withdrawal of magma as a result of cooling or eruptions.

Earthquakes are largely absent from the heated crustal column but occur around its periphery. Historical earthquake swarms and faulting episodes mark the transition from relatively warm crust near the volcano to cooler crust 25 km or more from the summit. The inner zone deforms more steadily and mostly aseismically, while the outer zone deforms episodically by brittle failure. The pattern of subsidence is roughly symmetric about Medicine Lake caldera, except possibly for north-south elongation caused by east-west tectonic extension.

In the summit area, most tectonic strain is released by

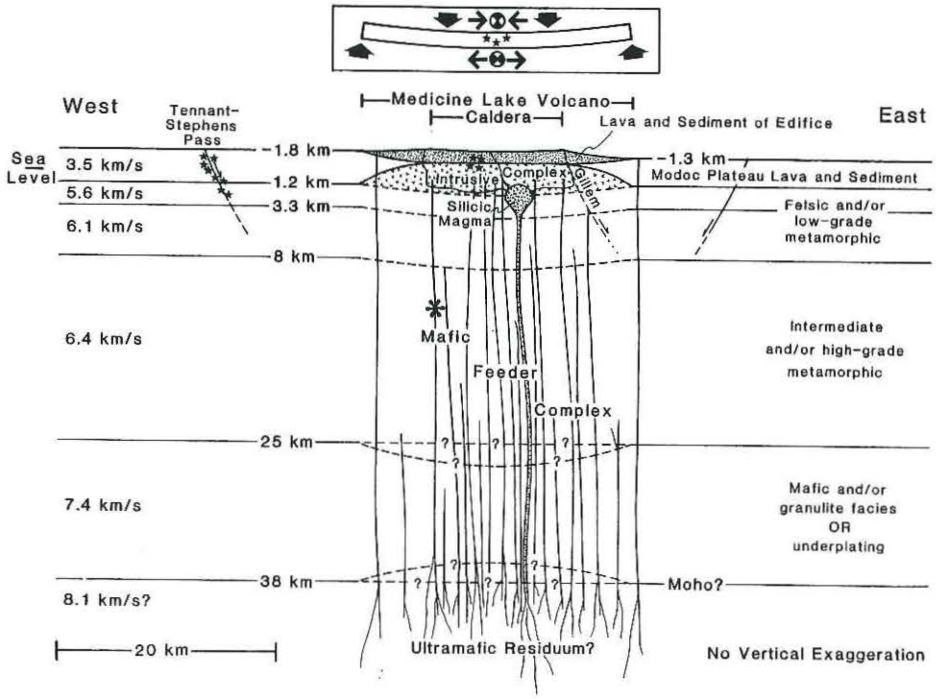

Fig. 9*a*. Conceptual model for Medicine Lake volcano. Many details are abstracted or rendered in schematic. East-west cross section through the volcano, showing major volcano-tectonic features plus the bending moment mechanism believed to be responsible for a shallow earthquake swarm in the summit region. Large arrows indicate load; small arrows, stars, and "focal spheres" indicate response. Velocity structure and rock types are abstracted from a seismic refraction study by *Zucca et al.* [1986]. Asterisk represents a relatively deep, long-period earthquake like those which occurred beneath the volcano on October 14, 1986, and December 12, 1989.

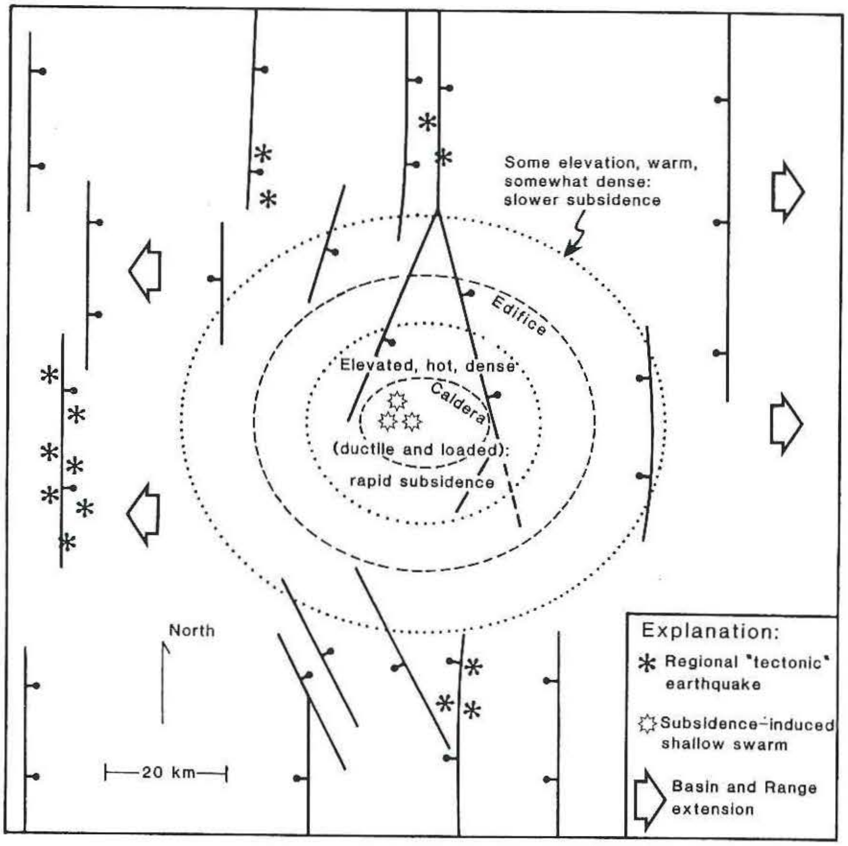

Fig. 9*b*. Plan view schematic of regional structure and loading stresses. "Tectonic" earthquakes (stars) are rare or absent in the heated crust beneath the volcano, except for shallow earthquake swarms that occur in the relatively cool, brittle lavas and sediment of the volcanic edifice.

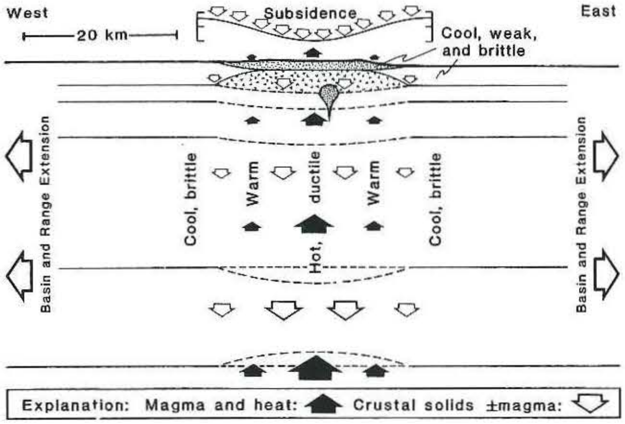

Fig. 9*c*. Cross section showing mass and heat transfer in the crustal column beneath the volcano. Both the edifice and a column of relatively dense, mafic intrusive material load the column. Heating by intrusions weakens the column, so it subsides in response to the load and to Basin and Range extension. It is unclear whether deeper boundaries would suffer net upward or downward deflections (dashed lines). Episodic withdrawal of magma and fluid loss during crystallization also may also contribute to subsidence.

thermally augmented creep and subsidence. Episodic swarms of shallow earthquakes are caused by subsidence-induced bending of a weak, brittle surface layer consisting of lava flows and related sediment, i.e., the volcanic edifice and possibly some underlying Modoc Plateau rocks (Figure 9*a*). In theory this layer fails under compression near the surface and under extension near its base. At Medicine Lake caldera, there is weak evidence from earthquake focal mechanisms for compression near the surface and extension a few kilometers deeper. Most earthquakes in the 1988–1989 swarm occurred near the center of bending, i.e., at the center of the caldera near T502.

The dominant control on the pattern of seismicity in the Medicine Lake region is the system of north striking normal faults formed by crustal extension at the western edge of the Basin and Range province. For this reason, seismic activity over geologic time scales presumably reflects the pervasive north-south structural grain in the region. The historical record is too short for this pattern to assert itself fully, but the character of earthquake swarms such as those near Stephens Pass in 1978 and Tennant in 1981 is consistent with normal faulting along north striking faults. An important secondary control on regional seismicity is the transition from warm to cool crust about 25 km from the summit of Medicine Lake caldera.

Tectonism and volcanism appear to be linked at Medicine Lake volcano to the extent that ground breakage in the context of regional crustal extension sometimes is accompanied by eruption of lava to the surface. A set of northeast striking, east-west opening ground cracks formed during the Little Glass Mountain eruption about 1000 years ago on the upper west flank of the volcano [*Fink and Pollard*, 1983]. This fracturing was accompanied by emplacement of rhyolite domes at about 10 sites along a 7.5-km-long N30°E alignment. Other vents also are located along inferred faults and fissures, and most vents form alignments oriented between N30°W and N30°E (similar to regional fault trends). Magma movement probably occurs more commonly along north striking dikes than central conduits, although the latter may occur under Medicine Lake caldera where small differentiated magma bodies may be present [*Donnelly-Nolan*, 1988; *Evans and Zucca*, 1988].

This model can be tested by repeated geodetic measurements across the inferred transition from aseismic subsidence to episodic normal faulting. The Global Positioning System (GPS) of satellite geodesy is capable of measuring vertical and horizontal displacements to an accuracy of about 1 cm over horizontal distances of at least 200 km [*Davis et al.*, 1989; *Prescott et al.*, 1989] and thus is well suited to this task. USGS established a regional network of GPS stations in the Mount Shasta–Medicine Lake region during July 1990. The network will be remeasured in 3–5 years to determine the contemporary strain rate and to characterize further the relation between tectonism and magmatism in this transitional zone between the Cascades and the Basin and Range.

APPENDIX: ANALYSIS OF LEVELING ERRORS

Random Error

The magnitude of random error in leveling surveys can be estimated by closing a circuit, double running all or part of a traverse or assuming that the error is typical of other surveys of the same order and class. On the basis of several decades of NGS experience the standard deviation σ of an observed elevation difference h measured by leveling is given by

$$\sigma(h) = \beta(L)^{1/2}$$

where β, in units of mm/km$^{1/2}$, is a constant for each order and class of leveling and L is the distance along the traverse. The standard deviation of a vertical displacement (i.e., change in an observed elevation difference between surveys) is given by

$$\sigma(\Delta h) = [\sigma_1(h)^2 + \sigma_2(h)^2]^{1/2}$$

where σ_1 and σ_2 are the standard deviations of the observed elevation differences from the first and second surveys, respectively. The contemporary value of β is 0.7 mm/km$^{1/2}$ for first-order, class II surveys and 1.3 mm/km$^{1/2}$ for second-order, class II surveys. However, NGS experience indicates that the value of β for second-order surveys during 1917–1955 (including the 1954 survey at Medicine Lake) was about 3 mm/km$^{1/2}$ [*Vanicek et al.*, 1980]. Thus the standard deviation of vertical displacements measured between the 1988 and the 1989 surveys is taken as 1 mm/km$^{1/2}$ $L^{1/2}$, and the standard deviation of vertical displacements measured between the 1954 and the 1989 surveys is taken as 3.1 mm/km$^{1/2}$ $L^{1/2}$. This corresponds to an accumulated 1-σ uncertainty of ±4.5 mm along the 1988–1989 traverse and ±43 mm around the 1954–1989 circuit.

Systematic Error

Inspection of the 1954–1989 leveling results suggests an inverse correlation between elevation and vertical displacement or, in other words, between slope and tilt (Figure 5). Such a correlation could be a consequence of (1) volcano-tectonic processes responsible for subsidence or (2) systematic leveling errors that accumulate with elevation (e.g., rod scale or refraction error) and are not completely removed by corrections. The mean slope along the leveling circuit varies

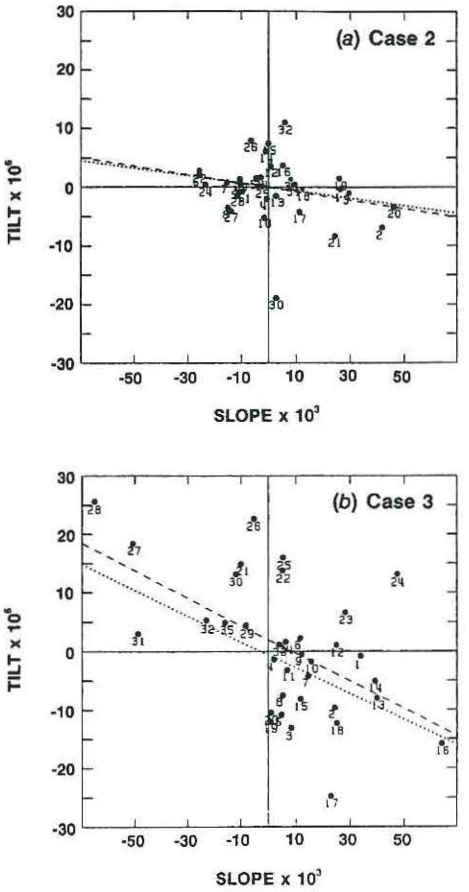

Fig. A1. Tilt versus slope plots and regression lines (*a*) for sections of the leveling circuit located off Medicine Lake volcano (case 2) and (*b*) for sections located on the volcano (case 3). Dashed regression lines are for the unweighted case; dotted lines are for the weighted case. Numbers denote bench mark pairs (i.e., sections) that differ in the two plots. See the Appendix for details.

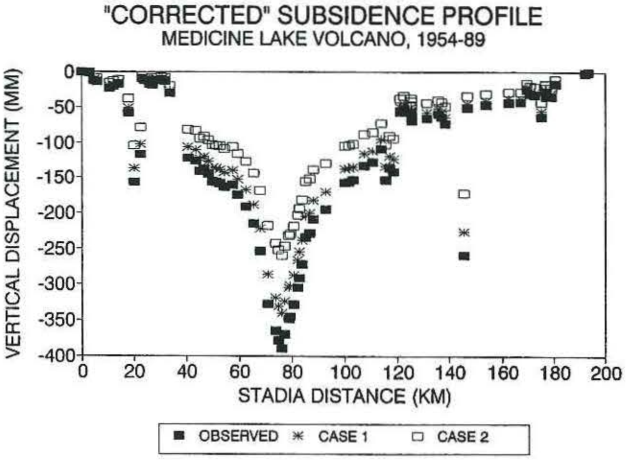

Fig. A2. Observed and "corrected" subsidence profiles showing the effect of removing the tilt-slope correlation determined in cases 1 and 2. In each case the linear regression coefficient m was used to adjust the observed values to $m = 0$.

from almost zero near Tennant to about 2% on the flanks of Medicine Lake volcano and near Stephens Pass (Figure 5). Accumulation of systematic error is possible in such terrain, but the largest cumulative correction applied to either the 1954 or the 1989 data was only 43 mm (K. Koepsell, personal communication, 1990; CVO, unpublished data, 1991). Therefore barring a serious flaw in the corrections, any residual error is likely to be much smaller than the maximum subsidence during 1954–1989 (389 ± 43 mm). We verified that conclusion in two ways. First, we applied linear regression analysis to the 1954–1989 results to determine the magnitude of any slope-dependent error [*Stein*, 1981]. Next, we analyzed a 1958 leveling survey in Virginia for evidence of slope-dependent error. The same rods were used for the 1958 Virginia survey and the 1954 Medicine Lake survey, so any rod calibration error should be common to both surveys.

To assess the significance of the apparent correlation between tilt and slope, we calculated regression coefficients m, Y intercepts b, and correlation coefficients r for the equation $\tau = m\theta + b$, where τ and θ represent tilt and slope, respectively, for each section along the leveling circuit. Two weighting functions were used: (1) equal weight for all data points (hereafter referred to as "unweighted") and (2) $1/\sigma^2$, where σ is the standard deviation from random leveling error for each section ("weighted"). The latter approach takes account of the fact that tilt is better determined for long sections than for short sections.

Three cases were evaluated in detail. Case 1 included 70 of the 81 sections measured in 1989. Twelve benchmarks were excluded for the following reasons: (1) their displacements were anomalous relative to adjacent marks, and they are judged to be unstable (Z502, C499); (2) their displacements were large and probably caused by faulting (L500, M500, P500, V501, U501, T501, C500); or (3) they formed unusually short sections ($L \leq 0.3$ km) for which tilt was poorly determined (TENNANT, TENNANT AZ). Inclusion of these marks in the regression analysis yielded ambiguous results (i.e., the unweighted and weighted fits were much different), because sections involving these marks were conspicuous outliers on plots of tilt versus slope. Such outliers strongly influence the least squares fit if data points are unweighted. Case 2 included only those sections from case 3 that are located off Medicine Lake volcano (i.e., zero to 30 km or 110–193 km from H197, measured counterclockwise along the leveling circuit; $N = 35$). Conversely, case 3 included only those sections from case 1 that are located on the volcano (30–110 km from H197; $N = 35$). Results of the regression analysis are given in Figures A1 and A2 and Table A1, along with the critical values of r for various levels of significance α (i.e., $\pm r_c(\alpha)$). Two variables are correlated at the 1-α confidence level if $r \leq -r_c(\alpha)$ (inverse correlation) or $r \geq +r_c(\alpha)$ (direct correlation).

For case 1, both unweighted and weighted values of r indicate that tilt and slope are linearly correlated at the >99% confidence level, consistent with the inference drawn earlier from inspection of Figure 5. However, when only marks located off Medicine Lake volcano are included in the regression analysis (case 2), the correlation between tilt and slope is either not significant (unweighted) or barely significant (weighted) at the 92% confidence level. Conversely, if only marks located on the volcano are included (case 3), the correlation is significant even at the 99% level (Table A1). These results can be verified by closer inspection of Figure 5: tilt and slope are inversely related on Medicine Lake volcano, but not near Stephens Pass, where steep topogra-

TABLE A1. Linear Regression Statistics

	Case 1	Case 2	Case 3
Number of sections N	70	35	35
Regression coefficient, m*	$-1.771 \pm 0.415 \times 10^{-4}$	$-0.727 \pm 0.488 \times 10^{-4}$	$-2.348 \pm 0.621 \times 10^{-4}$
	$(-1.594 \pm 0.350 \times 10^{-4})$	$(-0.640 \pm 0.369 \times 10^{-4})$	$(-2.200 \pm 0.549 \times 10^{-4})$
Y intercept b*	$+8.075 \pm 9.482 \times 10^{-4}$	$-8.645 \pm 85.284 \times 10^{-5}$	$+1.988 \pm 1.688 \times 10^{-3}$
	(0)	(0)	$(-6.311 \pm 14.895 \times 10^{-4})$
Correlation coefficient r*	−0.455	−0.247	−0.539
	(−0.478)	(−0.285)	(−0.561)
Critical values of r, $\pm r_c(\alpha = 0.10)$	±0.195	±0.279	±0.275
Critical values of r, $\pm r_c(\alpha = 0.05)$	±0.232	±0.330	±0.325
Critical values of r, $\pm r_c(\alpha = 0.02)$	±0.274	±0.387	±0.381
Critical values of r, $\pm r_c(\alpha = 0.01)$	±0.302	±0.424	±0.418

*Values that are not in parentheses are unweighted. Values that are in parentheses are weighted.

phy similar to that at the volcano is not reflected in the subsidence profile. We conclude that the strong correlation between tilt and slope is spatially associated with the volcano, presumably because the subsidence mechanism is volcanogenic. A corollary of this interpretation is that cases 1 and 3 overestimate the importance of slope-dependent error, while case 2 may be representative.

To calculate an upper bound for the magnitude of slope-dependent error in the Medicine Lake data, we "corrected" the 1954–1989 subsidence profile using the regression coefficients determined for cases 1 and 2 (Figure A2). Removal of the case 2 regression line reduces the maximum subsidence during 1954–1989 by about 13% to 340 mm. The corresponding values are 33%, to 260 mm, if the case 1 regression line is used. The possibility of nonlinear errors cannot be excluded, but lacking evidence to the contrary, we conclude that slope-dependent error accounts for less than one third of the 1954–1989 subsidence at Medicine Lake volcano.

This conclusion is supported by analysis of leveling observations in 1958 and 1985 along a 40-km traverse from Talcott, West Virginia, to Glenlyn, Virginia. First-order, class II procedures were followed for both surveys. The 1958 survey used the same pair of rods that was used for the 1954 survey at Medicine Lake; the 1985 survey used NGS rods 121176, 132181, 270711, and 277921 (K. Koepsell, personal communication, 1990). Assuming that the rods used in 1985 and 1989 were properly calibrated, any rod scale error associated with the rods used in 1954 and 1958 should be present in both the 1958–1985 (Virginia) and the 1954–1989 (Medicine Lake) data sets.

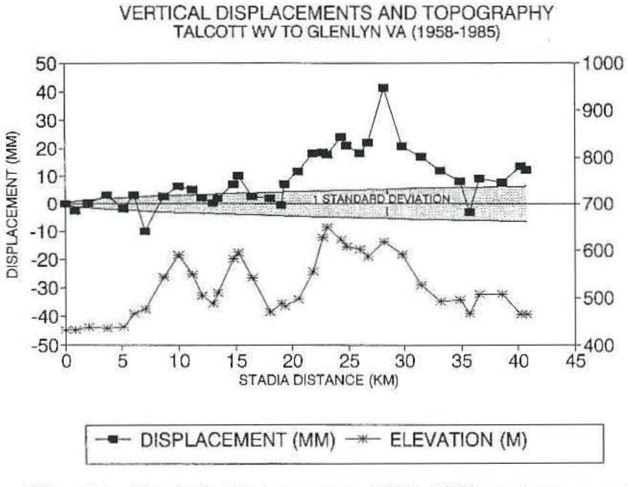

Fig. A3. Vertical displacements (1958–1985) and topography along a 40-km leveling traverse from Talcott, West Virginia, to Glenlyn, Virginia. Procedures for first-order, class II leveling were followed for both surveys. NGS data were provided by K. Koepsell (personal communication, 1990). Stippled area indicates 1 standard deviation in the leveling measurements. At any stadia distance the vertical dimension of the stippled area indicates the height of the 1-sigma error bar at that distance.

Vertical displacements and topography are apparently correlated in the Virginia data set (Figure A3), but the magnitude of the correlation is smaller than for the Medicine Lake case and is of opposite sign. In the Virginia case, approximately 20 mm of apparent uplift accumulates over 200 m of vertical relief, suggesting the possibility of a rod scale error of about 100 parts per million (ppm). At Medicine Lake, 389 mm of subsidence accumulates over 1000 m of relief, which would require a rod scale error of almost 400 ppm in the opposite sense. Clearly, both cases cannot be explained by the same rod scale error in the 1954/1958 rods; a combination of errors in at least two rod pairs would be required. Errors of such magnitude would be unprecedented for calibrated USGS or NGS rods. *Strange* [1980] showed that the largest apparent scale difference between any two sets of rods used for 64 repeat surveys over 17 profiles in southern California with topographic relief ranging from about 600 m to 2200 m was less than 160 ppm. Therefore we conclude that any rod scale error in the 1954–1989 results is small compared to the amount of real subsidence: less than 33% and probably less than 13%.

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