VOLCANIC HAZARD POTENTIAL IN THE CALIFORNIA CASCADES

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ABSTRACT

The Cascade Range, which extends 200 km into northern California, includes three long-lived compound volcanoes or volcanic systems capable of eruption. Eruptions should also be expected from other, short-lived volcanoes in the Cascade Range.

Mount Shasta, the most voluminous andesite-dacite stratovolcano of the Cascades, has been constructed, primarily in four major cone-building episodes, since about 450,000 years. B.P. During the past 10 000 years, it has erupted at least once every 600-800 years. Many of the eruptions produced debris flows, and some produced pyroclastic flows. Although Mount Shasta has not erupted voluminous lavas or pumice in about the past 2,000 years, small eruptions have continued to within the past 200 years. Eruptions that could be expected in the future range from small events high on the cone that would have little surrounding effect to pyroclastic eruptions that could produce destructive ash flows. Such a large, long-lived stratovolcano that has been through several thousand years of relative quiescence could even produce a catastrophic caldera-forming pyroclastic eruption, although nothing specific in Mount Shasta's recent history indicates that it is evolving toward such an eruption.

The Medicine Lake volcano, a broad shield with a shallow caldera, may have evolved for more than a million years. Most of the exposed shield-forming lavas, some as young as Holocene, are andesite or basalt. Two ash-flow eruptions have produced tuff sheets with volumes of several cubic kilometers: a silicic tuff on the order of one million years old is exposed to the north, and a widely exposed upper Pleistocene andesitic tuff was erupted from the summit area. Holocene eruptions, some as recent as 1,000 years B.P., produced either basalt or rhyolite to dacite and affected mainly the shield itself. Almost all Holocene lavas high on the shield are silicic; low on the flanks, only mafic lavas have erupted. This distribution suggests that a large silicic magma chamber could exist beneath the central area of the volcano. Such a chamber might be capable of producing voluminous ash flows and caldera subsidence.

Lassen Peak is one of a cluster of dacitic domes and flows formed within the past 250,000 years on the northeast flank of a deeply eroded 500,000-year-old stratocone. Lassen Peak itself is a large 11,000-year-old dome; the adjacent Chaos Crags domes were emplaced only about 1,100 years B.P. There are more than a dozen other domes, flows, and related fallout deposits, some of which are associated with pumiceous ash flows. The 1914-1915 eruptions began with steam-blast eruptions near the summit of Lassen Peak but later produced minor dacitic lava and pumice; the most vigorous eruptions produced mudflows that extended more than 30 km down the valley of Hat Creek. The historic eruptions and the numerous young dacitic centers, considered together with the active hydrothermal systems of the region and active seismicity, indicate an active silicic magma body. The possible locations of vents for future silicic, possibly explosive, eruptions anywhere in the dacitic field make this potentially one of the most dangerous volcanic areas of the Cascades.

Besides these three major volcanic systems, there are many smaller edifices,

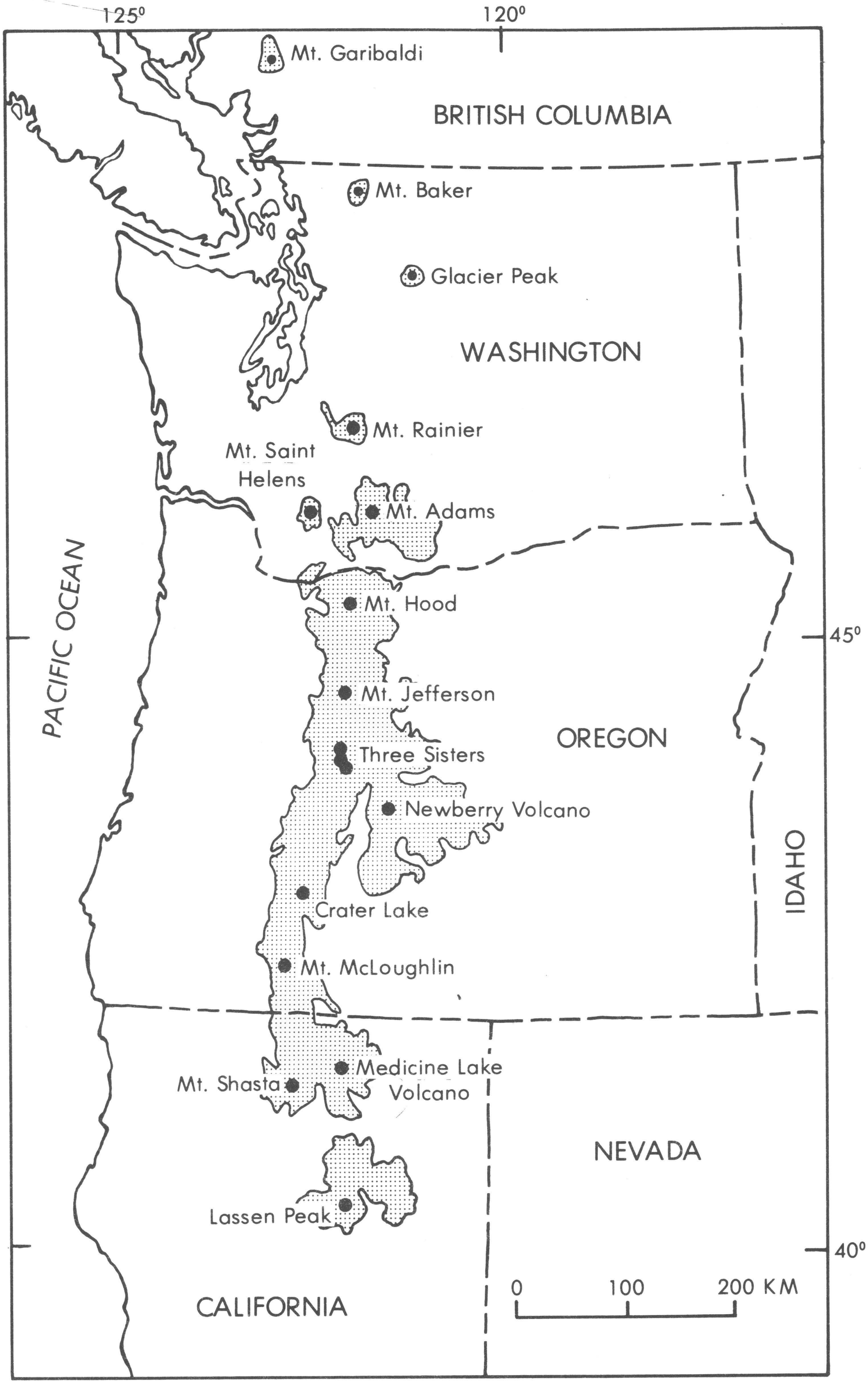

Figure 1. Index map showing Pliocene and Quaternary volcanic rocks of Cascade Range.

from small shields to single-eruption cinder-and-lava fields. The latest eruption of one of these smaller volcanoes was in 1850-1851 at Cinder Cone in Lassen Volcanic National Park. Similar future eruptions should be expected; their sites probably would not be known long in advance and are more likely to be at new vents than at existing ones. Swarm seismicity like that of recent years near Stephens Pass and Tennant could precede such a mafic eruption.

INTRODUCTION

The Cascade Range includes a generally north-trending chain of Quaternary volcanoes that extends from northern California through Oregon and Washington into southern British Columbia (Figure 1). In the northernmost part of the range, Quaternary volcanic activity generally has been isolated and centered around a few large stratovolcanoes. From southern Washington southward, cover by Quaternary volcanic rocks becomes more continuous and vents more abundant, especially through most of Oregon. In California, the Quaternary volcanic products are less continuous than in Oregon, and young volcanoes mostly cluster around major centers.

The southern part of the Cascade volcanic chain extends about 200 km into northern California and is marked by two discrete areas of Pliocene and Quaternary volcanism that contain three major long-lived volcanic systems. The northern area includes Mount Shasta, the Medicine Lake Highland, and numerous small volcanoes between and around the two major centers as well as along a northwest- to north-trending axis of volcanic vents between them. The southern area includes Lassen Peak and closely associated vents, as well as another group of volcanoes along a northwest- trending axis. A topographic map (Figure 2) accentuates these two regions of Quaternary volcanism, which are separated both topographically and geologically. The map (Figure 2) also shows the close topographic relation between Mount Shasta and the Medicine Lake Highland, each of which lies to one side of the Cascade axis. Another conspicuous regional volcanic feature, mainly of Tertiary age, is the Modoc Plateau, which stands at a relatively consistent level east of the Cascade Range, below the Cascades but higher than the Sacramento and Shasta Valleys that lie west of the range.

Volcanic hazards in the Cascades and a rationale for assessment of hazards at specific volcanoes were discussed comprehensively by Crandell and others (1979). In this report, I do not attempt to duplicate that type of analysis, but rather I present a brief overview of Quaternary volcanism in the California Cascades, with emphasis on the kinds of future volcanic activity that might be expected, the possible localities of future eruptions, and the significance of the similarities and differences among the several types of volcanic systems that make up the California Cascades. Such a broad overview cannot take the place of specific hazards assessments at individual volcanoes, such as that for Mount Shasta by Miller (1980) or that now underway for the Lassen Peak area by L.J.P. Muffler and others (1982), but it can provide a perspective and a point of departure for broad considerations of volcanic hazards in this active region.

MOUNT SHASTA

Mount Shasta is the most voluminous Quaternary stratovolcano of the Cascades. It is a typical andesite-dacite composite volcano (Williams, 1934) that may serve as a good model for how such stratocones are built and for some of the types of activity that can be expected from them in the future. It is worth noting that, although Mount Shasta conforms to the commonly held but simplistic image of a volcano, in some senses it might better be termed a "volcanic system." In this report, I use that term for a large volcano that has numerous vents, has evolved complexly over a long time (more than 100,000 years), and has changed its style of activity over time. Defined this way, a volcanic system is the expression of an even larger magmatic system that includes the subvolcanic and plutonic roots of the volcanic system as well as zones of magma generation and related transformations of the crust and upper mantle.

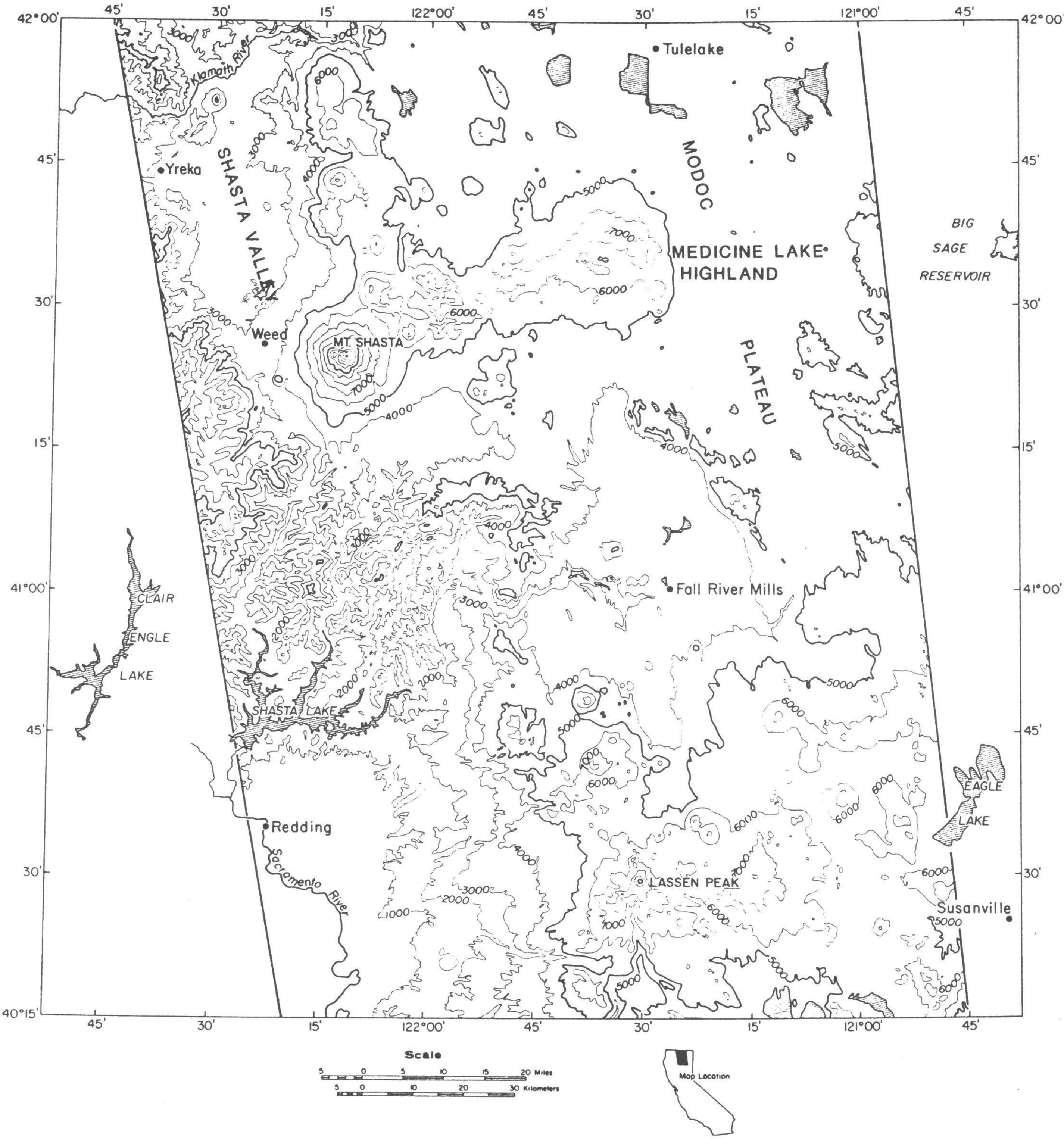

Figure 2. Topographic map of Cascade Range and nearby areas in northern California. Contour interval, 1,000 feet (after R. Couch, Oregon State University, unpublished data, 1981).

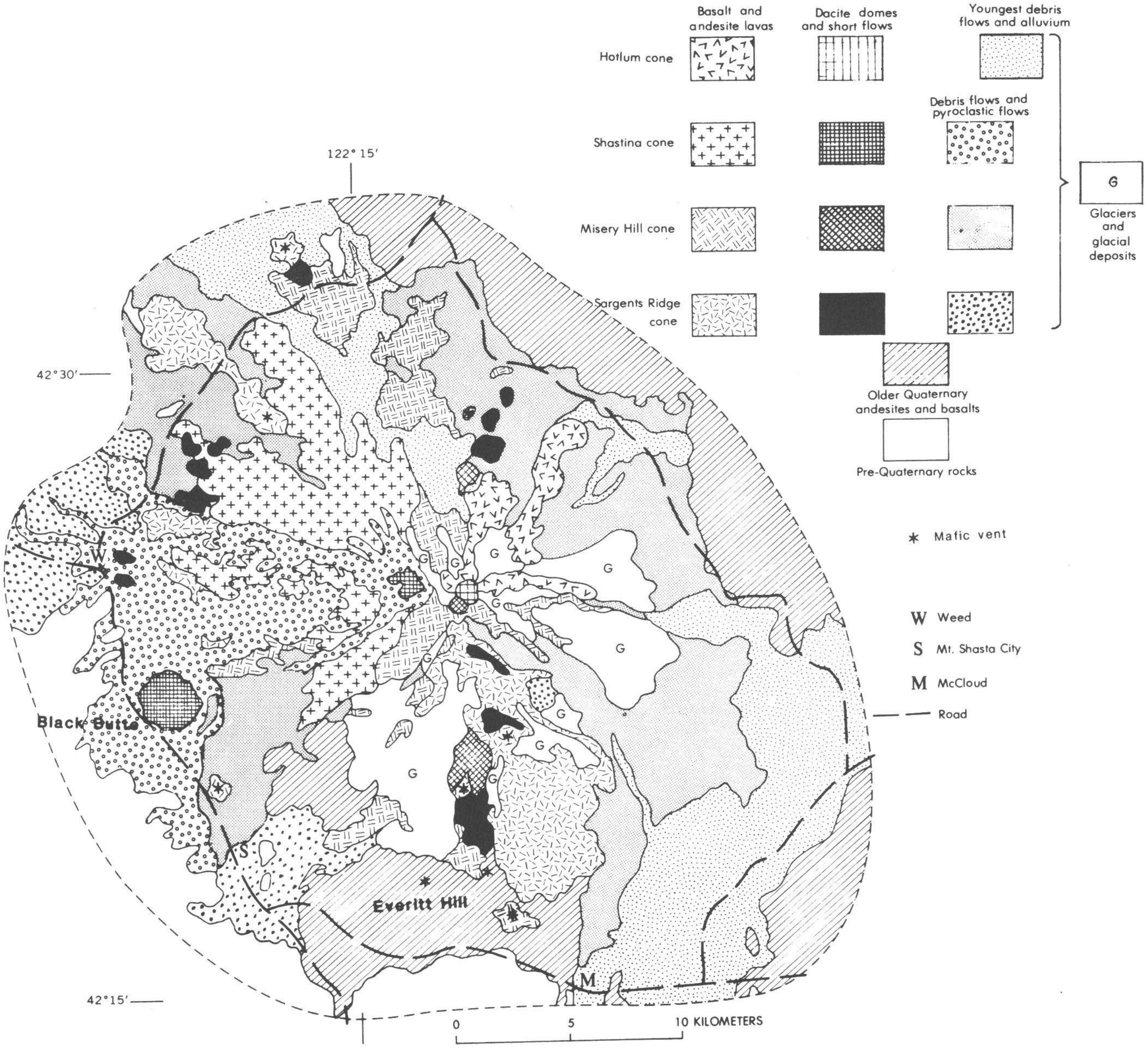

Figure 3. Geologic map of Mount Shasta (after Christiansen and others, 1977).

The Compound Cone

In recent collaborative work (Christiansen and Miller, 1976; Christiansen and others, 1977), we have recognized four major cone-building episodes that have constructed most of the Shasta volcanic edifice. Each of the four cones of Mount Shasta is more or less uniform in chemical and mineralogic composition, and each cone was little eroded during its major growth. Nearly 90 percent of the volume of the stratocone probably consists of two-pyroxene andesitic lavas that were erupted from the four central vents during rather brief episodes -- probably lasting only a few thousand years or less -- separated by relatively longer periods of erosion and more varied but commonly smaller eruptions.

The Sargents Ridge cone, the oldest of the four, grew around a central vent high on the south side of present Mount Shasta (Figure 3). Growth of the cone began sometime after about 450,000 years B.P., as shown by K-Ar dates on the underlying Everitt Hill shield (G.B. Dalrymple, unpublished data, 1979). Relations with older till deposits indicate that the Sargents Ridge cone grew mainly before at least part of a major glaciation of pre-Tioga age. A large area (nearly 350 km^2) of unusual hummocky topography northwest of Mount Shasta appears to be the partly buried deposit of a very large avalanche-landslide that catastrophically disrupted the Sargents Ridge or a predecessor cone in an episode perhaps similar to the May 18, 1980, eruption of Mount St. Helens, Washington (Christiansen and Peterson, 1981).

The Misery Hill cone was formed by lavas that were erupted from just south of the present summit, burying much of the north flank of the Sargents Ridge cone and partly filling deep erosional valleys in it. This cone was built before the major glacial advance during the Tioga glaciation, probably 15,000 or 20,000 years ago, and its summit crater was partly filled by the dacite dome of Misery Hill.

Shastina, a conspicuous peak on the west side of Mount Shasta, stands somewhat apart from the other three cones and would be one of the major stratovolcanoes of the Cascades if it stood by itself. It is the best dated of Shasta's four cones. Shastina overlies the widespread pumice of Red Banks, dated at about 9,700 ^{14}C years (Miller, 1980), and the last eruptions of Shastina produced dacitic domes and pyroclastic flows about 9,400 years B.P. (Miller, 1978). Such short eruptive episodes, of only a few hundred to perhaps a few thousand years, may have been typical of the growth of each of Shasta's four major cones and perhaps of many other Cascade stratocones.

Probably the youngest of the four cones is the Hotlum, which forms the present summit and northeast flank of Mount Shasta (Figure 3). The Hotlum cone is less well dated than Shastina but probably largely postdates it, as shown by its relations to Neoglacial deposits.

In contrast to the four brief episodes of major cone building, intervening periods were relatively long, commonly tens of thousands to hundreds of thousands of years. Erosion was predominant as lavas accumulated slowly. Eruptions during these periods commonly occurred from flank vents, and the compositions of the lavas were more varied than those of the main cones, ranging from basalt to rhyodacite. During each of these periods, dacitic domes were emplaced in the summit crater of the preceding cone and commonly on the flanks as well. The positions of all the flank vents, either within an approximately north-trending broadly arcuate zone through the summit or west of that line, indicates structural control of the volcanism.

Fragmental Deposits

A large proportion of Shasta's eruptions have produced fragmental deposits. As seen in the deep valley of Mud Creek that exposes the Sargents Ridge cone, about half the volume of volcanic materials forming the compound cone consists of fragmental deposits. Many were deposited as debris flows that were mobilized either by the melting of ice and snow during eruptions or by external sources of water in noneruptive processes, such as occurred in climatically induced mudflows during 1924 and 1977 (Hill and Egenhoff, 1976; Miller, 1980). Some of these debris-flow deposits extend more than 10 km onto and beyond the volcano's lower flanks.

Many eruptions also have produced pyroclastic flows, some of which extended more than 20 km from their vents. These pyroclastic flows are particularly well displayed around Shastina and Black Butte, a dome low on its west flank (Miller, 1978). Most are lithic pyroclastic flows, possibly related to the explosive disruption or collapse and avalanching of hot volcanic domes or lava flows; some pumiceous ash flows also formed during pyroclastic eruptions. Relative to some other large Cascade stratocones, however, a proportionately smaller amount of pumiceous ash has been erupted, and distal fallout deposits are sparse.

Potential Hazards

Miller (1980) considered factors in the evolution of Mount Shasta as well as a detailed analysis of the stratigraphy of its Holocene deposits, to designate several zones of volcanic hazard potential. The zones of greatest risk are around the major central vents; risks decrease radially outward. Beyond the volcano's immediate flanks, the effects of local topography become important in controlling the distribution of far-traveled debris flows and pyroclastic flows.

Mount Shasta has erupted at least once every 600-800 years for the past 10,000 years (Miller, 1980). The last voluminous lava or pumice associated with a major eruption are older than about 2,000 years, but Mount Shasta has produced numerous smaller, more recent eruptions. It erupted at least as recently as about 200 years B.P. and may have been witnessed in eruption from sea by the explorer, LaPerouse, in 1786 (Finch, 1930). A small event is reported to have occurred in 1855 (Eichorn, 1954), but its nature is uncertain.

Expectable future volcanic activity from Mount Shasta could range from small vulcanian eruptions high on the cone, which would have little effect on surrounding areas, to large pyroclastic eruptions that could produce ash flows to 20 km or farther. Because the volcano has evolved complexly over a long time and because each cone-building episode was both preceded and followed by silicic eruptions, the Mount Shasta magmatic system probably has generated a rather large subvolcanic silicic intrusion through the course of its evolution; part of this body may still exist as an eruptible volume beneath the stratocone. From a large, long-lived andesitic to dacitic volcano that has been relatively quiescent for several thousand years, as Mount Shasta has, even a voluminous caldera-forming pyroclastic eruption is within the range of possible behavior. Although no specific data at hand indicate that Mount Shasta is evolving toward a catastrophic eruption like that of Mount Mazama about 6,850 years B.P. (Williams, 1942; Bacon, 1982), such behavior should be considered among Shasta's potential long-term hazards.

MEDICINE LAKE VOLCANO

Whereas Mount Shasta lies just west of the axis of the Cascade Range, the Medicine Lake Highland is east of that axis and nearly symmetrically opposite (Figure 2). The more or less symmetrical positions of these two volcanic systems, as well as a large negative gravity anomaly that includes both of them (LaFehr, 1965), suggest that they are parts of an even larger magmatic system that dominates this part of the Cascades. Despite this possible relation, the Medicine Lake Highland comprises a quite different volcanic system -- a large shield-like edifice with a shallow caldera. The Medicine Lake lavas typically include both more mafic and more silicic types than are common in large stratocones like Mount Shasta. Although no individual long-lived major central vents are obvious on the highland, its flanks are dotted with numerous monogenetic vents. Nevertheless, like Mount Shasta, the Medicine Lake volcano is an edifice built by a closely related long-lived group of eruptive vents that has evolved complexly and systematically (Anderson, 1941; Donnelly-Nolan and others, 1981).

The Volcanic Shield

The highland probably has grown over a period of more than a million years. Most of the exposed lavas that appear to be parts of the shield edifice (Figure 4) range in composition from basalt to andesite; the summit area is also underlain by rhyolite that now occurs only as inclusions in the more mafic lavas. Some of the shield-forming lavas are as young as Holocene. J.M. Donnelly-Nolan (unpublished data, 1982) has shown that two ash-flow sheets with volumes of at least several cubic kilometers erupted from the Medicine Lake volcano. A rhyolitic or dacitic tuff exposed to the north has reverse paleomagnetic polarity (D. Champion, unpublished data, 1982) and, thus, probably is older than about 700,000 years; an andesitic tuff exposed mostly on the flanks of the shield, but also in the caldera, was associated with late Pleistocene summit eruptions.

Holocene eruptions from the Medicine Lake volcano generally have produced either basalt or rhyolite to dacite, and some single eruptive sequences have produced both. On the upper parts of the shield, including the caldera area, the Holocene lavas are generally silicic or are composites that incorporated basaltic magma blebs into rhyolitic magma (Eichelberger, 1975). Low on the north and south flanks, high-alumina basaltic lavas dominate. The most recent eruptions, both basaltic and silicic, occurred about 1,000 or 1,100 years B.P. to form rhyolite to dacite domes and flows near the east and west rims of the caldera -- Glass Mountain and Little Glass Mountain -- and basaltic lavas on the north and south flanks (Heiken, 1978). Fallout deposits of rhyolitic pumice related to these recent eruptions are thick in the vicinity of the caldera.

Potential Hazards

Expectable eruptions from the Medicine Lake volcano are most likely to produce basaltic or mafic-andesitic lavas and cinder cones or rhyolitic to dacitic lavas and fallout deposits. Although they could have significant effects on parts of the highland, even to its lowest flanks, only falls of pumice or ash from such eruptions would be likely to affect areas much beyond the shield itself. The distribution of silicic Holocene lavas on the upper part of the shield, however, and the eruption of only mafic lavas on the flanks suggest that a moderately large silicic intrusion could exist beneath the caldera. If much of this body remains molten, the possibility exists that the volcano could produce a voluminous silicic ash-flow eruption, perhaps associated with caldera subsidence, and the occurrence of two such pre-Holocene eruptions should be considered in hazards analysis.

LASSEN DOME FIELD

Because of its early-20th-century eruptive activity, as well as its local topographic prominence, Lassen Peak has been the focus of attention for possible future volcanic activity in the California Cascades. Lassen Peak itself, however, is only one of a cluster of dacitic domes and flows that has formed during about the past 250,000 years (G.B. Dalrymple, unpublished data, 1982) and that, like Mount Shasta and the Medicine Lake volcanoes, probably should be considered a volcanic system (Figure 5). These domes all lie on the deeply eroded northeast flank of a 500,000-year-old stratocone, called either Mount Tehama or the Brokeoff cone (Williams, 1932; Fountain, 1979). Williams (1932) suggested that a caldera collapse formed the present topographic depression within this old stratocone, but later workers have generally regarded the depression as erosional (Bowen, 1978; Kane, 1980, p. 85; L.J.P. Muffler and M.A. Clynne, unpublished data, 1982).

The Dome Field

Lassen Peak is a very large dacitic dome, formed about 11,000 years B.P. (Crandell, 1972). Most volcanic domes are single-eruption features that formed in a few hours to a few days or complexes of individual eruptive domes and flows that accumulated in rather short eruptive episodes lasting a few decades at most. The eruptions of 1914-1915 -- tailing off with milder eruptions for another two years and vigorous

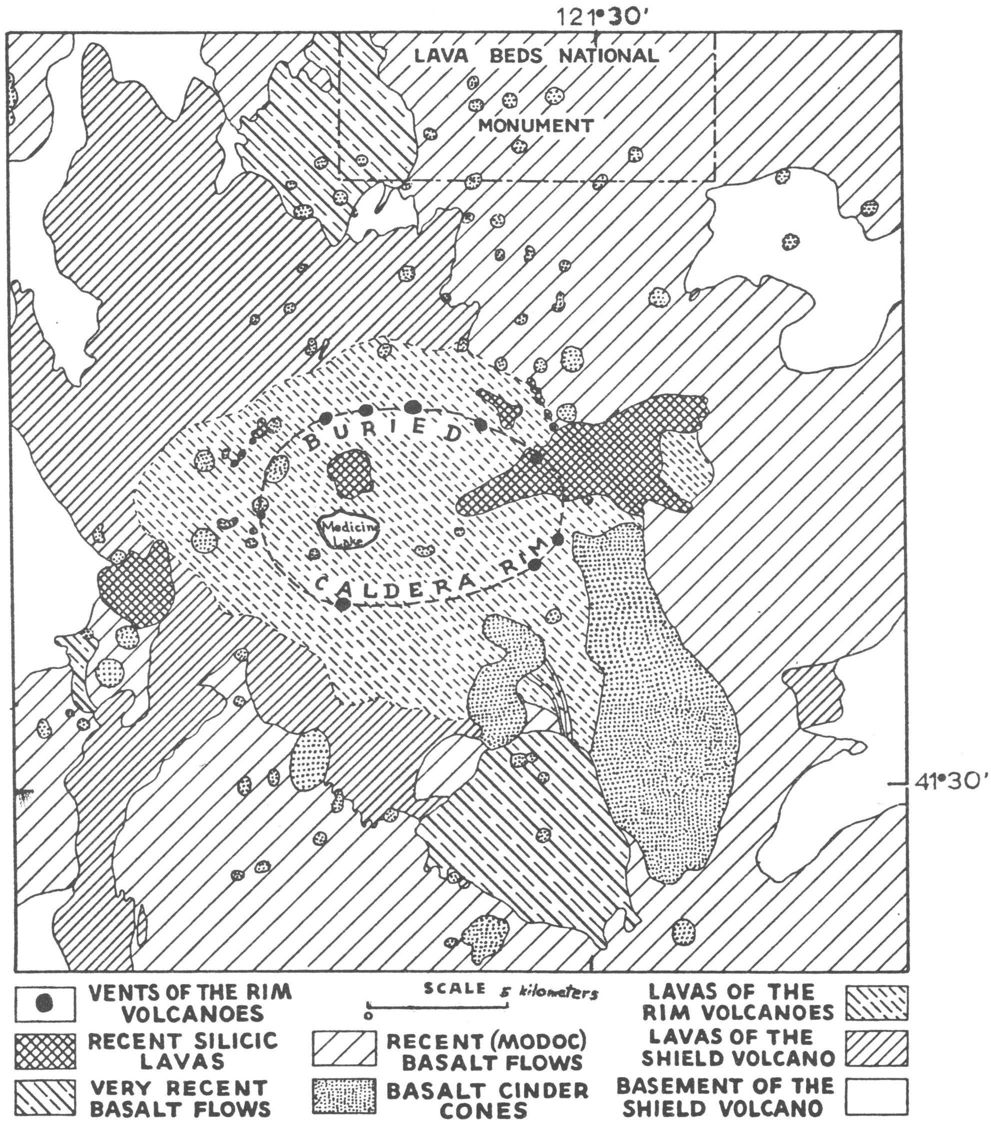

Figure 4. Geologic map of Medicine Lake volcano (after Anderson, 1941).

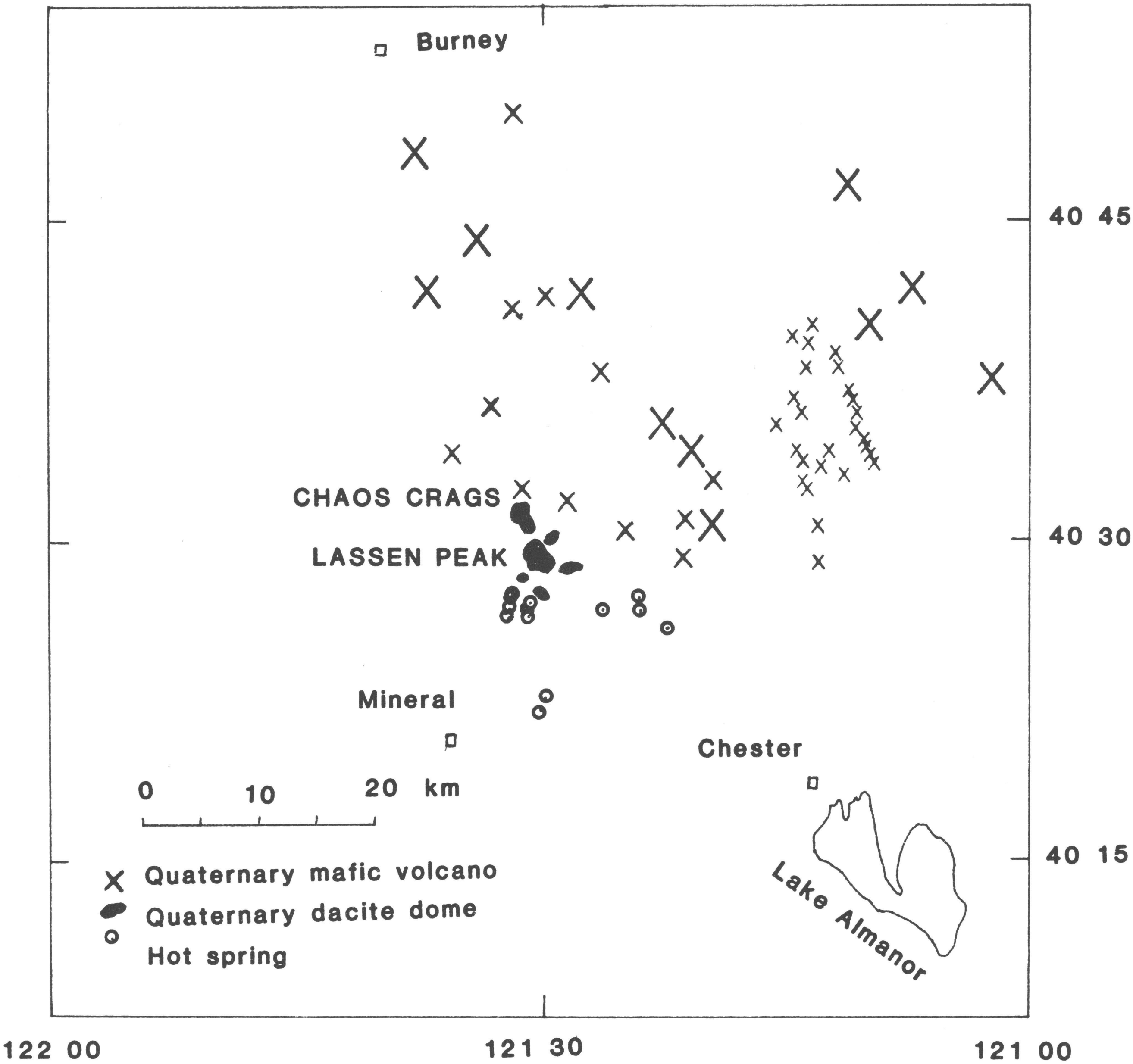

Figure 5. Youngest volcanic and tectonic features of Lassen Peak area (after Lydon and others, 1960; Heiken and Eichelberger, 1980).

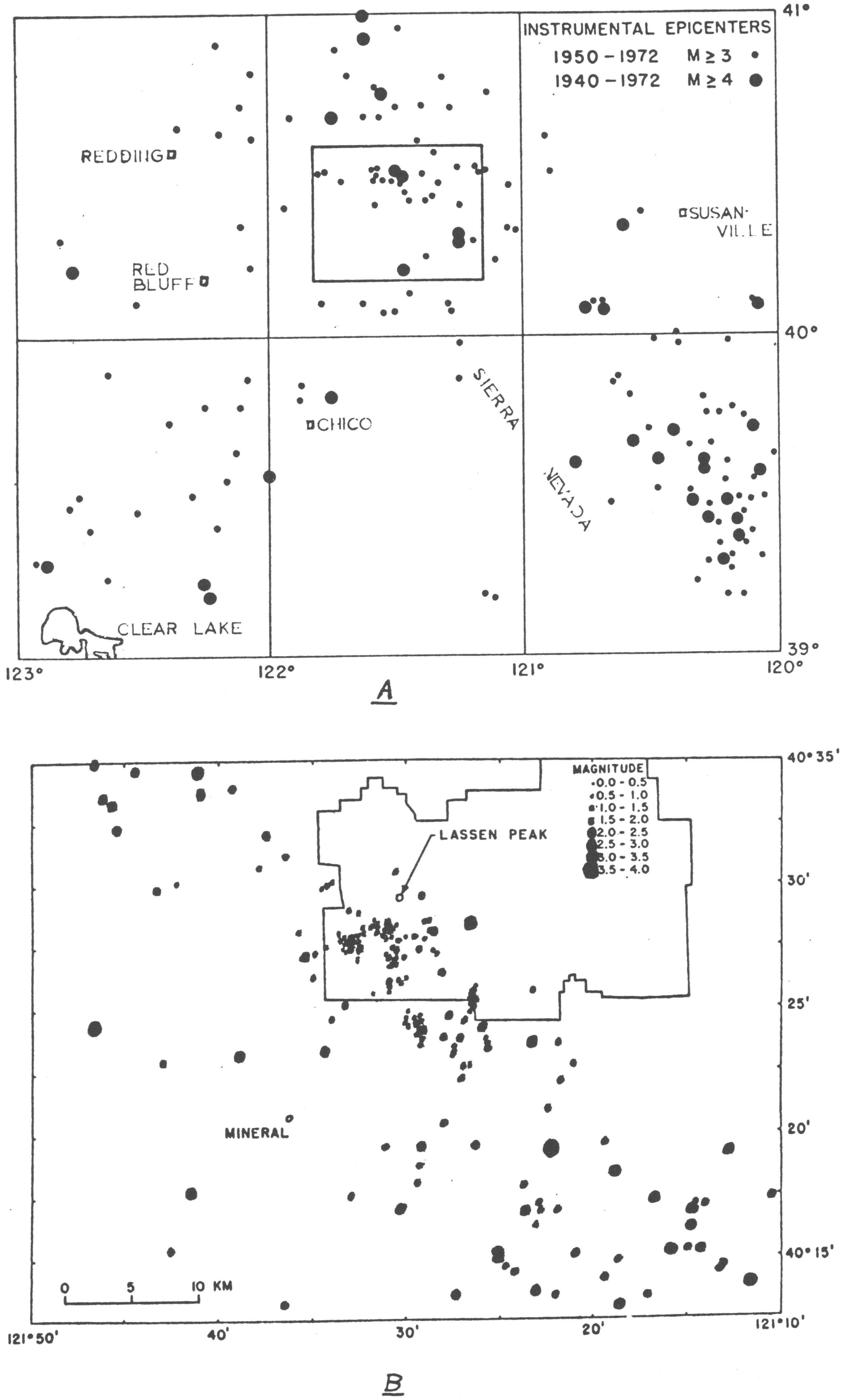

Figure 6. Seismicity of Lassen Peak region. A, Epicenters of earthquakes recorded in 1940-72 of magnitude 3 and larger; rectangle encloses area of fig. 6B. B, Epicenters of earthquakes recorded in January 1977-February 1978 of magnitude 0 and larger; irregular outline encloses area of Lassen Volcanic National Park (after Klein, 1979).

fumarolic and minor explosive activity until about 1921 -- may or may not have been directly related to the magma that formed the dome of Lassen Peak near the end of Pleistocene time.

The 1914-1915 eruptions (Day and Allen, 1925; Loomis, 1926; Finch, 1927) were characterized by a series of explosive blasts from the summit area. The earliest were steam-blast eruptions that formed a small crater near the summit, probably caused by the emplacement of magma into a water-saturated volcanic edifice. A similar mechanism operated during the first two months of eruptive activity in 1980 at Mount St. Helens before its climactic blast and magmatic eruption of May 18 (Christiansen and Peterson, 1981). The most important later eruptions of Lassen Peak, which occurred in May 1915, were associated with the emplacement of a dacitic lava flow and pumiceous ejecta. The most vigorous of these eruptions produced large mudflows down the slopes of the peak. One especially large mudflow down the northeast side of the volcano on May 20 swept more than 30 km down the valley of Hat Creek to the north and was followed two days later by a lateral blast that devastated an area of several square kilometers on the east side of the peak.

Besides the historical eruption from Lassen Peak, the youngest major event in the Lassen dome field was the emplacement of the Chaos Crags domes, probably about 1,100 years B.P. (Crandell and others, 1974; Heiken and Eichelberger, 1980). In addition to the domes, the Chaos Crags eruptions formed pumice cones around the vents and moderately extensive pumiceous pyroclastic flows. It is not known whether a group of devastating rockfall-avalanches that fell from Chaos Crags to produce Chaos Jumbles about 300 years B.P. (Crandell and others, 1974) were associated with renewed eruptive activity. Chaos Crags was reported to be steaming as late as the 1850s, and that steaming might have indicated residual heat from somewhat earlier eruptive activity.

There are more than a dozen older dacitic domes, flows, and related pyroclastic deposits in the Lassen field, some of which were associated with pumiceous ash flows that extended considerably beyond the eruptive vents.

Seismicity

A plot of recent earthquake epicenters in the vicinity of Lassen Peak (Figure 6B) reveals a linear pattern trending northwest through the dome field (Klein, 1979). A regional plot (Figure 6A) appears to show an intersection of seismic zones in the Lassen area: one zone extends northwestward from the frontal fault system of the Sierra Nevada, and the other trends northeast through the vicinity of Chico. The most frequent earthquakes in the region are those that occur as swarms centered in the Lassen volcanic and hydrothermal area.

Potential Hazards

The Lassen dome field is the center of a system of vigorous hydrothermal activity, the hottest part of which is centered on the southwest side of the dome cluster (Muffler and others, 1982). Together, this hydrothermal system, the early-20th-century eruption, the continuing seismicity, and the numerous clustered young dacitic centers (Figure 5) indicate an active silicic magmatic system. This system lies within a large negative gravity anomaly (LaFehr, 1965) somewhat analogous to what encloses both Mount Shasta and the Medicine Lake Highland, and some studies have suggested that this anomaly relates to a plutonic body which might sustain a larger Lassen-region magmatic system (Heiken, 1976; Heiken and Eichelberger, 1980). Future eruptions from the Lassen group of volcanoes would be likely to produce not only dacitic domes or lava flows but also pumiceous fallout deposits and, possibly, voluminous pyroclastic flows. Pumiceous ash flows could devastate areas many tens of kilometers from their eruptive vents. Vents for future eruptions could be not only at Lassen Peak or Chaos Crags but also virtually anywhere within the field of dacitic domes. Consequently, the Lassen dome field should be regarded as one of the principal candidates in the Cascade Range for future silicic, probably explosive eruptions:

potentially, this could be one of the most dangerous volcanic areas of the Cascade Range.

OTHER VOLCANOES

In addition to the three major volcanic systems described above, which command most of the attention for volcanic hazards in the California Cascades, hundreds of smaller volcanic edifices (Figure 7; see Luedke and Smith, 1981) range from small commonly monogenetic shields to cinder-cone/lava-flow fields that formed in single short eruptive episodes (for example, Williams, 1949). These volcanoes generally are basaltic to andesitic. It is important that large areas of past eruptive activity also be considered for their potential volcanic hazards.

Although the localities of future outbreaks of this type of volcano probably could not be determined long in advance, such eruptions should be expected in the future. The latest was that of 1850-1851 (Finch and Anderson, 1930) at Cinder Cone in Lassen Volcanic National Park (Figure 5). Although it is difficult or impossible to forecast where the next eruption from one of these small volcanoes might be, more such eruptions certainly will occur and are probably even more likely to occur through new vents than from existing ones.

Such eruptions might be expected to begin along northwest- to north-trending fissures, subparallel to regional normal-fault trends, and to produce mafic lavas or cinders; if activity were to persist for more than a few hours or days, it would be likely to centralize to form one or a few cinder cones. Persistent swarm-type seismic activity is likely to precede eruptions although seismicity might be recognized as a precursor to volcanic activity only shortly before an eruption -- or, even, only in hindsight.

Earthquake-swarm activity has occurred intermittently in the past few years near Stephens Pass and Tennant, in the area of the Cascade axis about midway between Mount Shasta and the Medicine Lake Highland (Figure 8). In 1978, earthquake swarms were centered in the vicinity of Stephens Pass (Bennett and others, 1979). They were not mainshock and aftershock sequences like those typically associated with tectonic strain release; instead, the earthquakes occurred in swarms similar to those commonly associated with hydrothermal or volcanic activity. The 1978 swarm occurred intermittently over a period of a few months and included several events of magnitude 3 and greater. Activity ceased until January 1981, when another swarm occurred about 10 km north near the town of Tennant. Surface breaks were associated with the 1978 activity, although the earthquake magnitudes were smaller than those that typically produce surface displacements. The breaks consisted of open ground cracks and small discontinuous grabens with no predominant sense of offset, similar to features associated with earthquake swarms along the volcanic rift zones of Kilauea, Hawaii, and the neovolcanic zone of Iceland. One possible, though tentative, explanation for these events near Stephens Pass and Tennant is that they reflected the injection of dikes to high levels in the crust. Although the data at hand do not specifically suggest the likelihood of basaltic eruptions in the area in the near future, an intrusive model can be considered as one possible working hypothesis for the 1978 and 1981 activity.

DISCUSSION, Christiansen and Kilbourne

Question: Is there any indication of seismic swarm activity in the area between Shasta and Medicine Lake in the 50 years or so prior to the 1978 swarm?

Christiansen: We know of no such seismic swarms in that area. However, seismic instrumentation has been very sparse in the region, and it's only been in the last few years that we have had anything like a comprehensive seismic network. Events like this would have been marginally detectable with previously existing seismic nets, and the swarm-like character would probably not have been detectable even if individual events had been recorded. The area has had

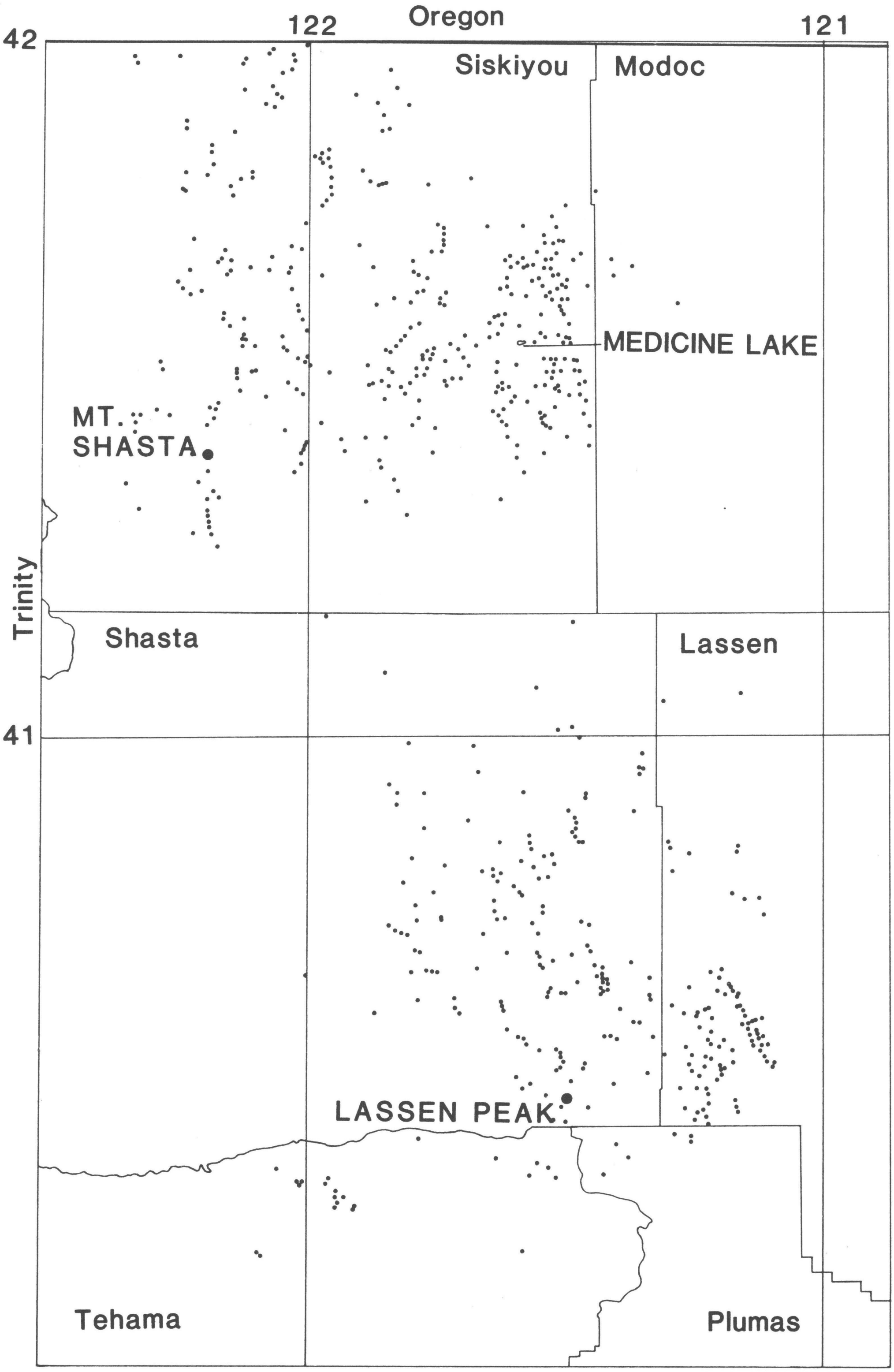

Figure 7. Volcanic vents of Pliocene and Quaternary age in Cascade Range of northern California. County boundaries are shown for reference (after Luedke and Smith, 1981).

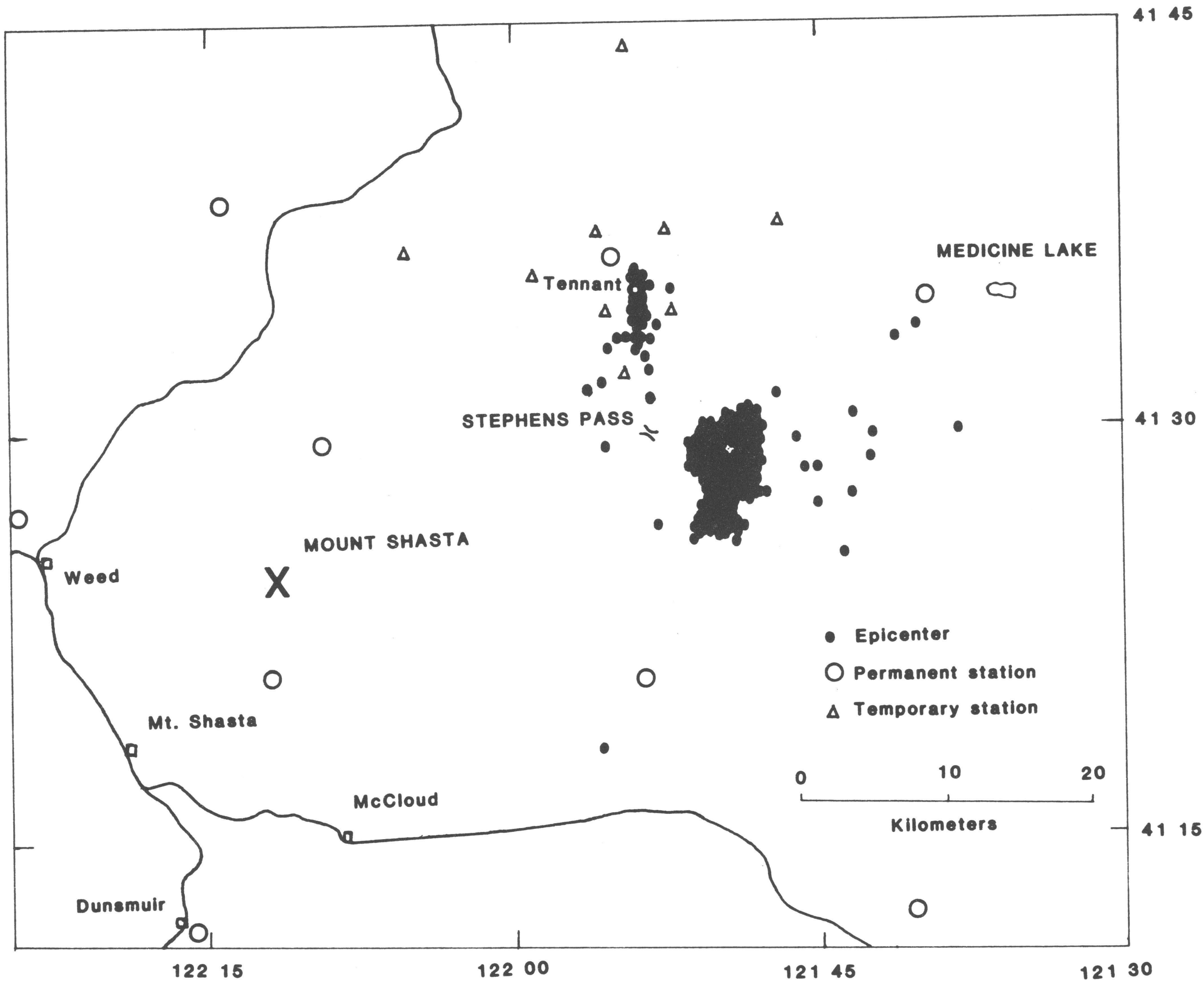

Figure 8. Epicenters of Stephens Pass and Tennant earthquake swarms of 1978 (southern cluster of epicenters) and 1981 (northern cluster), (after R. Cockerham, U. S. Geological Survey, unpublished data, 1982.)

some sporadic earthquake activity over the years. It is on the northern boundary of one of California's major seismic zones.

Question: Has there been any attempt to make volumetric determinations of magma outpourings with respect to time?

Christiansen: Yes; that attempt is going on just now. A point I would like to make in the talk is that for the California Cascades, until about the last five or six years, we have been entirely dependent upon data that was obtained in the 1920s and 1930s by a very few people. Some real pioneering work was done by Howel Williams and Charlie Anderson and a few others, supplemented, of course, by some specific locality studies, but, really, all of our comprehensive data came from those early studies, and we are just now re-examining these areas and getting the kind of data you're asking about. I think that is one of the very important things for us to do; that is, gathering quantitative information such as volumes of eruptions.

Question: On the definition of "active volcano," if we have development of fumarolic or hydrothermal activity on a volcano, but no eruptions in the past two-thousand years, would you consider it an active volcano?

Kilbourne: If the only activity that has been documented is that of an active fumarole, no, I would not call that an active volcano.

Question: What is Bob's opinion?

Christiansen: Well, I really have trouble with this term, "active volcano," and I am not sure it is a terribly useful term. Quite honestly, I think that we tell ourselves more if we say, "a volcano that has erupted in the last two-thousand years" or "an active fumarole field," or whatever, than we do by arbitrarily defining a term like "active volcano" and then trying to apply it. I think it is very likely that there are many volcanoes that erupted in the last two-thousand years that will never erupt again. And I think that there are volcanic systems that have not erupted in the last two-thousand years that are very likely to erupt in the future. I am worried that use of the term "active volcano" may fool us sometimes. I'd rather be more specific when categorizing volcanos.

Kilbourne: I realize what you're saying about "active volcano" being a poorly understood term, or a potentially dangerous term. On the other hand, the public does understand the term "active" as meaning dangerous in the case of a volcano, and since we sometimes deal with the public in crisis situations, I'm proposing that we as scientists standardize our definition. I am not aware of many volcanos or volcanic regions that have not erupted in the last two-thousand years that have somehow suddenly become active. The eruptions of Paracutin in Mexico (1943) and Surtsey in Iceland (1964) are often cited as surprise eruptions, but even these occurred in active volcanic terrains as I would have us define them, with the 2,000-year datum. I don't think anyone could name a volcano that has erupted in the last two-thousand years that they would swear would not erupt again; so, therefore, I would like to use this term only in this fashion; i.e., with a rigid definition of eruption in the last 2,000 years.

Question: Would you elaborate on your statement that Mount Shasta was like Mount Mazama in its nature?

Christiansen: The point I was trying to make is one that I think many other people have made: that volcanic systems are of different types, and that some seem to have a capability of evolving in the direction of a climactic sort of pyroclastic eruption and caldera collapse related to it. The reason I think Shasta could be in that class is because it: 1) has evolved in a rather complex manner for a long period of time indicating that there is a substantial, active heat source that is continuing to evolve magma beneath that region; 2) eruptions have repeatedly evolved to silicic compositions, as seems to be typical of most such volcanoes that erupt large volumes of pyroclastic materials; and 3) the volcano has had a long period of relative quiescence. "Silicic," in this case, is also a fairly loose term, but I mean more silicic than the typical sort of mafic andesites or basaltic andesites that we see a lot of. This complexity of evolution and diversity of lava compositions is the principal thing that suggests that this may be a volcano like Mazama was before it entered its climactic episode.

Question: Isn't there some aeromagnetic evidence that there is magma within the Shasta Volcano?

Christiansen: There has been some interpretation based upon the aeromagnetic data that is consistent with the main cone of Mount Shasta being the hottest part of the volcanic edifice. As you are aware, this is an ambiguous type of data. It is only a consistency argument and not really what I would regard as evidence for magma.

Question: Dr. Kilbourne, one of your slides dealt with the source of the Carbon-14 of a lava flow and it shows 280° and 500° isotherms. Is that in Fahrenheit or Centigrade?

Kilbourne: It is Centigrade. The significance is that above 500°C, wood burns to ash in the presence of oxygen. The wood is preserved for us to use in age-dating if the temperature does not go above 500°C. Above 280°C, wood will char, and in a closed environment, turn to charcoal.

Question: Dr. Christiansen, you identified the Lassen area as potentially one of the most dangerous in the Cascades. Has the USGS or the state increased their monitoring of this area recently?

Christiansen: What I said is a value judgment of a sort. Nevertheless, most people would regard Lassen as a dangerous part of the Cascades and one of the most dangerous. The USGS in recent years has augmented the seismic network there, and just last summer the first set of measurements of a geodetic network were undertaken. These will be used as the basis for comparison with future data. These are very skeletal efforts, and, certainly, more is called for. In addition, there is an ongoing study of the geology and volcanic hazards of Lassen Park by Mike Clynne and Patrick Muffler. That work has just begun and will be continuing for the next few seasons, and I hope to be able to participate in it too. These efforts are aimed at hazard assessment, but, again, in terms of monitoring specifically, the USGS effort is skeletal or minimal.

McBirney: In looking at the geologic record in a large mature volcano and trying to piece together the past history, do you think we get an unbiased representation of the different types of activity that that volcano has gone through, due to the fact that the large ash eruptions are usually less likely to be preserved and they produce material which the geochronologist usually doesn't want to fool with?

Christiansen: I think the answer is implicit in the question. Indeed, we do get a biased view of the evolution of a volcanic system like this. This points out something that I personally have found useful in my own work in the last few years, and I think has been borne out in a number of instances, including, specifically, Mount St. Helens. There are different complementary approaches that ought to be utilized in looking at the geologic record as a basis for hazards analysis. One is the sort of traditional mapping and evolutionary study of a volcano such as I am attempting to undertake at Mount Shasta. The complementary aspect is the stratigraphic approach: looking at the record of what has happened on the flanks of the volcano, and also looking for the record of even the small events that would be represented, perhaps indirectly, by things such as mudflows. This is the approach Dan Miller is taking at Mount Shasta, and I think that both of us feel that by working closely together between a stratigraphic/soils/

surficial-geology approach and a volcanic-evolution/petrology/geophysical approach, we get much more information than either approach by itself possibly could.

Kilbourne: I think we get a good representation of the hazardous types of eruptions. The larger eruptions are the ones we're really worried about. Small things like the 1951 mud-volcano event in Surprise Valley or the small 1910 eruption in the Medicine Lake Highlands area don't leave any record; unless they're observed, they aren't dated.

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