Cauldron Subsidence of Oligocene Age At Mount Lewis, Northern Shoshone Range, Nevada

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CAULDRON SUBSIDENCE OF OLIGOCENE AGE AT MOUNT LEWIS, NORTHERN SHOSHONE RANGE, NEVADA

By Chester T. Wrucke and Miles L. Silberman

ABSTRACT

In the Shoshone Range of north-central Nevada, a ring fault that dips vertically to 65° inward outlines a deeply eroded cauldron 16 km in diameter. Thrust faults of Early Mississippian and early Mesozoic age that cut Paleozoic and Mesozoic strata in the cauldron have been deformed by the subsidence and dip inward, steeply near the ring fault, more gently in the interior, where they form a concentric pattern around a centrally located cluster of plugs and breccia pipes.

The plugs and breccia pipes are the largest intrusive bodies in the subsided block. Plugs of quartz monzonite, rhyolite porphyry, and pumiceous vitrophyre occupy central positions in each of three breccia pipes; a dacite plug and two rhyolite plugs occur several kilometers from the pipes. Other intrusive bodies include a subhorizontal mass of quartz latite breccia at the summit of Mount Lewis, many dikes in the western part of the cauldron, and an intrusive breccia in the ring fault. The intrusive deposits, some of which have been studied in detail by Gilluly and Gates, contribute only a few percent of the exposed rocks in the cauldron.

Extrusive rocks in the vicinity of Mount Lewis are preserved mainly within the cauldron. One sequence of extrusive and interlayered volcaniclastic rocks crops out at the summit, on a few spurs that extend out from the summit, and in lowland east of the mountain. This sequence is composed of altered tuffs, dacite lava flows and agglomerate, rhyolite welded tuffs, conglomerate, and sandstone. There is another sequence at the north margin of the cauldron and in an extensive volcano-tectonic depression centered 25 km south of Mount Lewis. It consists of andesite lava flows and rhyolite welded ash-flow tuff of the Caetano Tuff.

K-Ar dates and field relations provide a basis for determining only the general chronology of igneous events related to cauldron subsidence at Mount Lewis. Collapse occurred after the ring fault cut a 35.1-m.y.-old granodiorite pluton and before the fault was invaded by 33.2-m.y.-old intrusion breccia. Age determinations of 34.4 m.y. from the dacite plug and 34.7 and 33.2 m.y. from the quartz latite intrusion breccia record volcanism interpreted as occurring before collapse. Subsidence is thought to have resulted from eruption of some of the 33–31-m.y.-old Caetano Tuff from the Mount Lewis cauldron. Uplift of volcanic and sedimentary rocks in the center of the cauldron 850 m relative to deposits near the ring fault, and the dips away from the summit in patches of these rocks on spurs flanking the mountain may result from mild resurgent doming.

Volcanic activity in the northern Shoshone Range during an igneous cycle that existed from 38 to 31 m.y. ago began with intrusions of small granodiorite and quartz monzonite plutons, continued with emplacement of plugs and presubsidence tuffs at Mount Lewis, and ended with eruption of the Caetano Tuff from the volcano-tectonic depression and the Mount Lewis cauldron. The cauldron thus formed differs from many cauldrons in the western United States and from igneous ring complexes in Great Britain, New England, Nigeria, and Norway by exposing only a small percentage of intrusive rocks, probably because the subjacent pluton at Mount Lewis did not rise to high levels during resurgent doming as in most ring complexes and cauldrons.

INTRODUCTION

One of the most prominent structural features of the Shoshone Range in north-central Nevada (fig. 1) is a ring fault 16 km in diameter (fig. 2). On the deeply incised flanks of Mount Lewis, the highest peak at the northern end of the range, this fault bounds Paleozoic and Mesozoic stratified rocks that foundered during volcanic collapse. Within the subsided mass, breccia pipes, plugs, and dikes, together with remnants of tuffs and volcaniclastic deposits, record an episode of Oligocene volcanism. The collapse structure, here named the Mount Lewis cauldron, is one of the oldest Tertiary volcanic centers in Nevada. It is relatively deeply eroded, as the greater part of the rocks exposed lie well below the base of the original volcanic edifice.

Our interest in the subsidence structure was aroused when we noticed on the geologic map of the northern Shoshone Range by Gilluly and Gates (1965), a fault pattern strikingly concentric about the volcanic center at Mount Lewis and markedly different from the structural grain of the surrounding area. In order to determine the significance of the fault pattern, Wrucke spent several weeks examining structural, stratigraphic, and igneous features in and around the subsided mass and made a geologic sketch map (fig. 4) of a key area at the cauldron margin. Silberman obtained K-AR dates (tables 2, 3) that helped establish the sequence of igneous and structural events. Together we visited many localities and collected samples for isotopic dating. Although this paper documents critical episodes in the history of volcanism at Mount Lewis, we recognize that the area is structurally far too complex to be fully understood from reconnaissance examinations. Our interpretations have benefited greatly from progress made in the understanding of cauldrons and calderas since Gilluly and Gates completed fieldwork in the Shoshone Range in 1959.

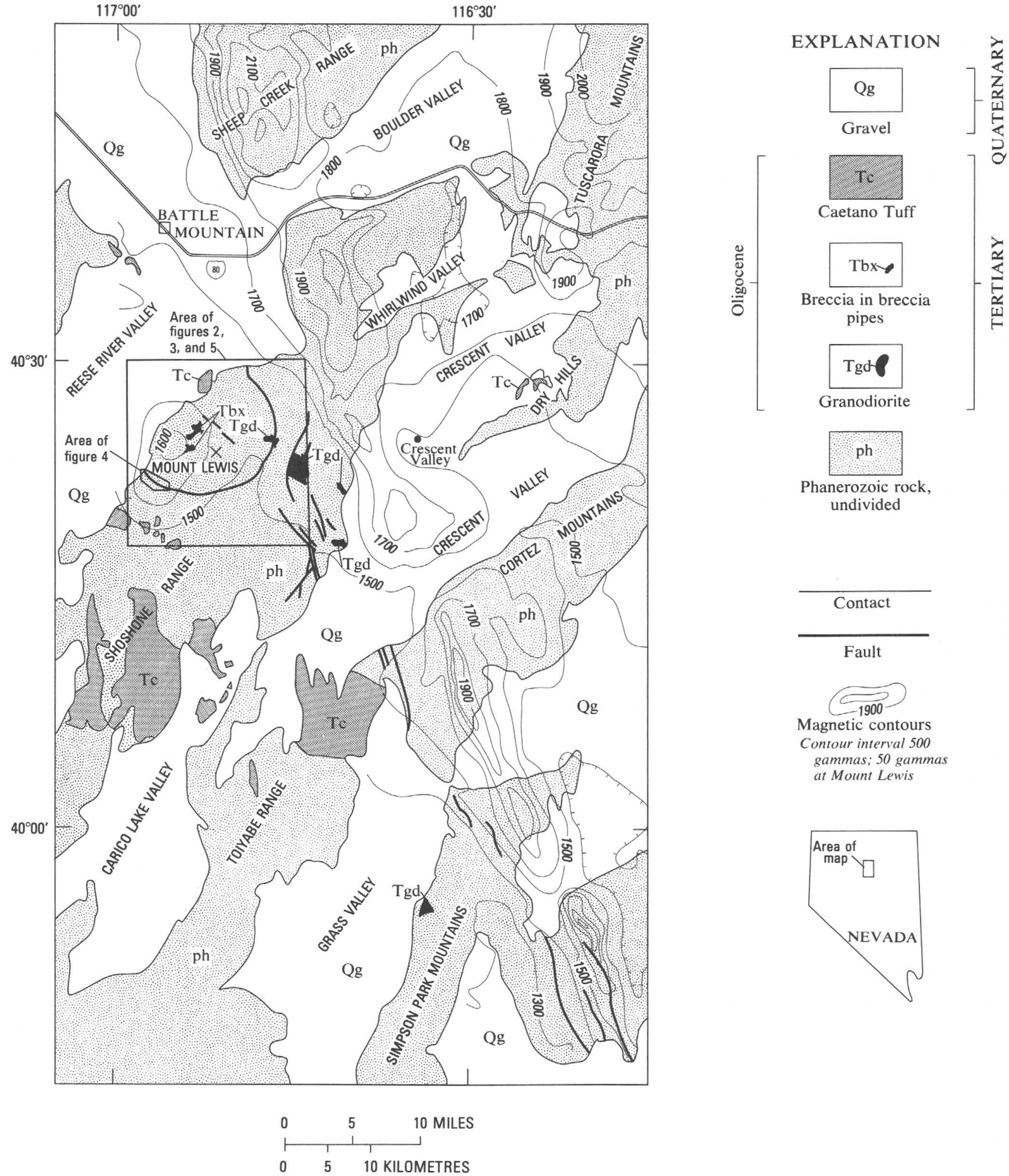


FIGURE 1.—Generalized geologic map of part of north-central Nevada showing location of the Mount Lewis cauldron, selected lithologic units, faults (after Gilluly and Gates, 1965; Roberts and others, 1967; Stewart and McKee, unpub. data; and this report), and aeromagnetic contours (after Philbin and others, 1963).

The principal results of our study include recognition of the ring fault and the character of the rocks emplaced in it, structures developed in the downdropped pile, timing of subsidence relative to igneous events elsewhere in the range, and the effects of a preexisting pluton on the collapsed mass. Features critical to the history of subsidence have been found in structural and stratigraphic relations in Paleozoic rocks at the southwest margin of the cauldron.

Our study has benefited from enlightening discussions of cauldron subsidence with R. A. Bailey, E. H. McKee, and D. C. Noble, the last two in the field and in the office; and we are grateful to T. E. Mullens and J. H. Stewart for sharing with us observations on the stratigraphy of Paleozoic strata southwest of Mount Lewis.

GEOLOGIC SETTING

The Shoshone Range is a northeast-trending, eastward-tilted fault block in the northwestern part of the Great Basin. In this region, the oldest formations exposed consist of miogeosynclinal rocks of Cambrian to Mississippian age in the lower plate of the Roberts Mountains thrust and eugeosynclinal strata of about the same age range in the upper plate of the thrust. Thrusting during the Antler orogeny, which culminated in Early Mississippian time, juxtaposed these plates. Upper Paleozoic rocks are sparse in the region, as are Mesozoic rocks, remnants of which rest on thrust faults of Mesozoic age. Cenozoic volcanic rocks cover large areas of some ranges.

In the vicinity of the Mount Lewis cauldron, bedrock consists principally of siliceous sedimentary rocks of Ordovician, Silurian, and Devonian age in numerous thin thrust slices above the Roberts Mountains thrust (fig. 2). Carbonaceous strata of Cambrian to Silurian age below the thrust crop out in a window immediately south of the ring fault. It is significant that all but one remnant of upper Paleozoic rock and the only scraps of Mesozoic strata in the northern 60 km of the range occur within the cauldron, some at relatively low altitudes.

Overlying the older rocks are lava flows, welded tuffs, water-laid tuffs, and sedimentary rocks of Oligocene age. Some of these rocks are scattered, unnamed deposits in the cauldron, but most rocks of this age in the northern Shoshone Range belong to the Caetano Tuff, a composite sheet of welded ash flows that crops out extensively 20–35 km south of Mount Lewis and in adjacent ranges (fig. 1). The relation of the Caetano Tuff and the unnamed deposits to the Mount Lewis cauldron is discussed in a later section.

The Mount Lewis cauldron lies along a narrow zone of steep faults, small plutons, and numerous mineral deposits that trend northwest across the range. Many of the steep faults are cut by plutons of Oligocene age. About 35 km southeast of Mount Lewis, this zone merges with a strikingly linear north-northwest-trending zone that extends from the Simpson Park Mountains at least to the Sheep Creek Range (fig. 1) and consists of strong magnetic anomalies (Philbin and others, 1963; Robinson, 1970) that follow a swarm of diabase dikes of Miocene age and a system of faults as young as Pliocene. The northwest-trending zone that crosses the Shoshone Range and that part of the north-northwest-trending zone southeast to the Cortez Mountains form much of the Battle Mountain-Eureka mineral belt of Roberts (1966). These belts seem to be deep-seated features that have been the locus of considerable igneous activity; the zone crossing the Shoshone Range may have controlled the ascent of magma in the Mount Lewis area. Although no belt of comparable length containing high-angle faults is known to intersect the northwest-trending zone in the vicinity of Mount Lewis, the numerous north-trending dikes west and southwest of the summit (fig. 2) may follow structures that were important in localizing the cauldron.

Only the southeastern half of the cauldron is exposed. The northwestern half is downfaulted and buried beneath a thick cover of valley fill west of the steep Basin and Range faults that border the Shoshone Range.

BOUNDARY FAULT

The fault that encircles the subsided mass at Mount Lewis traces a smooth curve for 29 km around the south and east flanks of the mountain (fig. 2). It is a typical ring fault in that it bounds a nearly perfect semicircular area that forms the exposed southeastern half of a circular subsidence structure. The fault is covered by alluvium around the western perimeter of the cauldron. Along the southern margin, the fault has been invaded by dikes for 5.6 km of its extent; at the east edge of the cauldron, the fault is interrupted by a pluton. Elsewhere it is a well-defined single fault that dips 90°–65° inward.

The ring fault, composed of several segments, was mapped by Gilluly and Gates (1965) as separate faults of different origins. The Trout Creek fault they interpreted to be a tear fault in the upper plate of the Roberts Mountains thrust along the south margin of the cauldron. The Hilltop and Bateman faults were considered by them to be two thrusts in the upper plate along the east margin of the cauldron (fig. 3). A critical element of their interpretation is that these faults originated by processes unrelated to volcanism.

The tear-fault concept was devised by Gilluly (1960;

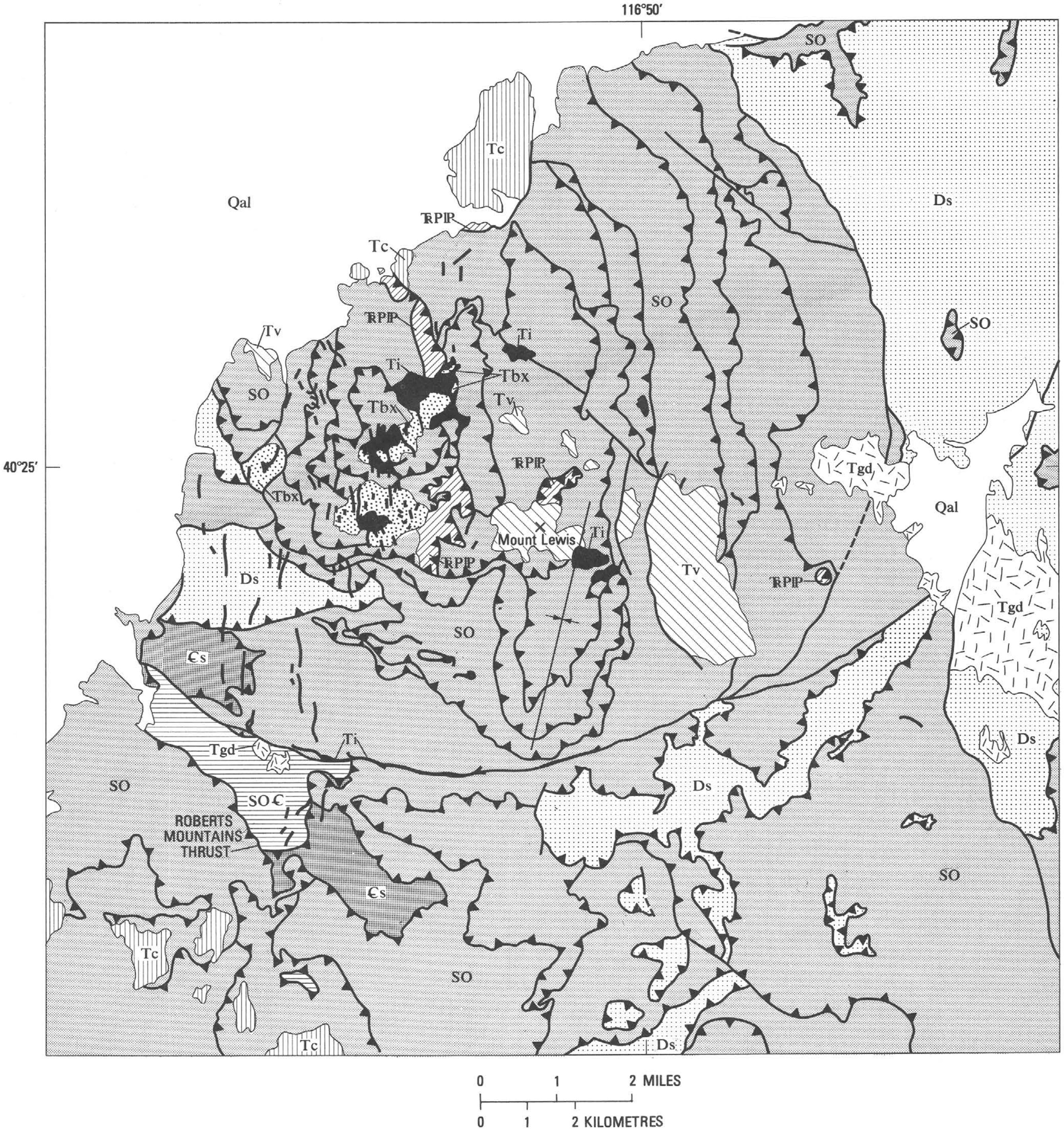
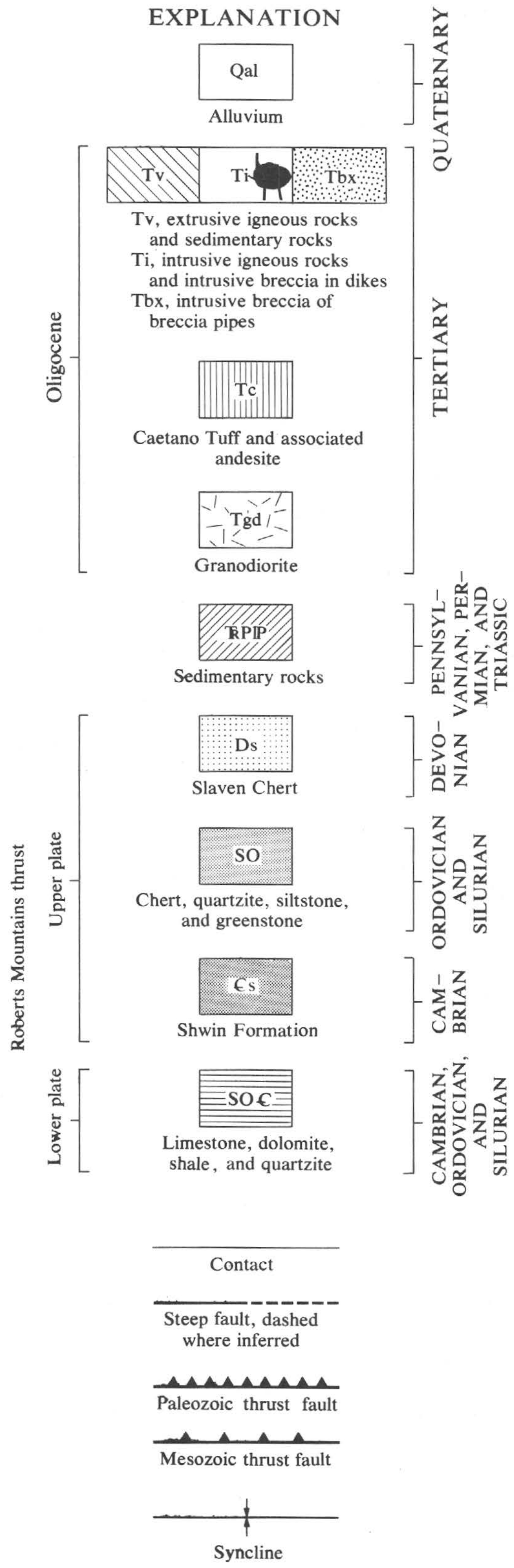


FIGURE 2.—Geologic map of the Mount Lewis area, showing the ring fault. Modified from Gilluly and Gates (1965). Location shown in figure 1.

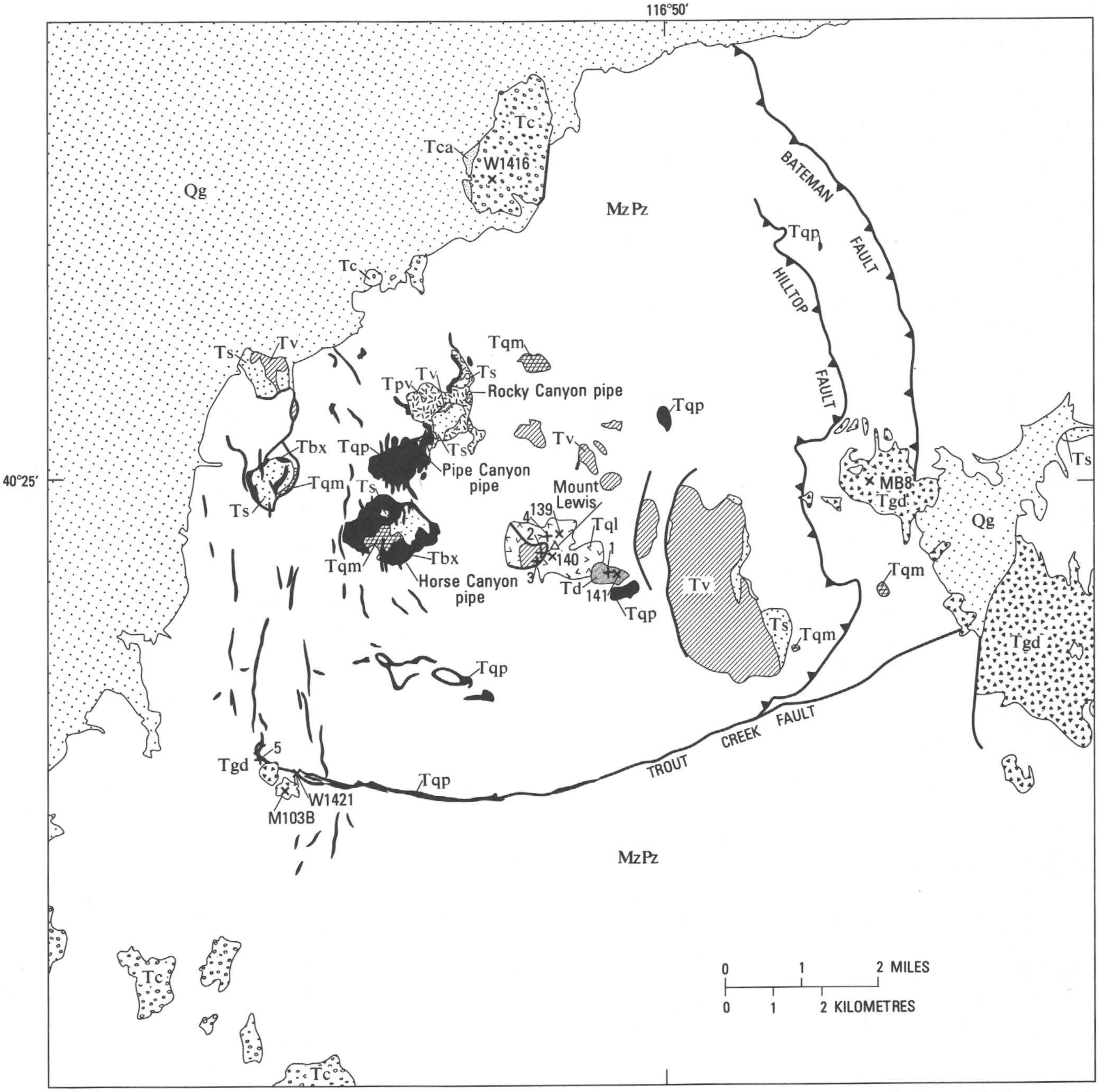
see also Gilluly and Gates, 1965, p. 98–100) to explain the development of folds and an overturn in the Roberts Mountains thrust near the mouth of Trout Creek, 8 km south-southwest of Mount Lewis. They assumed that in the Trout Creek area the Roberts Mountains thrust separated rocks of Cambrian age in the lower plate from rocks of Ordovician age in the upper plate (fig. 4*A*). However, the Ordovician rocks have been found by us to underlie as well as overlie the Cambrian strata on the northwest-trending ridge north of the ring fault, as illustrated in figure 4*B*. Specifically, the contact of the southeast-trending prong of the Cambrian rocks of that ridge was found to be the basal contact of those rocks dipping west slightly steeper than the slope of the ridge



crest that they cap; that is, the contact forms a somewhat rounded V that points upridge. Because the Cambrian rocks rest on upper-plate Ordovician strata, they must belong in the upper plate: they form a thrust slice torn from the lower plate during thrust faulting and interleaved with wedges of upper plate formations. A limestone sliver of Silurian Roberts Mountains Formation, a short distance southeast of the Cambrian rocks and immediately north of the Trout Creek fault, has a similar origin, for it, too, is of lower-plate lithology but is now interleaved with upper-plate rocks. The Roberts Mountains thrust is not exposed north of the ring fault. Slices of rocks originally in the lower plate, but now incorporated within upper-plate rocks of the Roberts Mountains thrust, occur adjacent to the Gold Acres window (Wrucke and Armbrustmacher, 1969) on the east flank of the range. Since the Cambrian and adjacent rocks north of the Trout Creek fault are part of the upper plate, the structural relations between them need not be explained by folding of the thrust or by movements related to tear faulting, so the Trout Creek fault may be interpreted as a normal rather than a tear fault. As discussed below, we interpret this normal fault to be a segment of the ring fault bounding the Mount Lewis cauldron.

The structural break originally mapped as a tear fault is shown by Gilluly and Gates (1965) as beginning 8 km east of the range front and extending eastward (fig. 3). We believe, however, that the Trout Creek fault extends to the west edge of the range, as shown in figures 2 and 4*B*. Near the mountain front, the boundary fault dips steeply northeast into the cauldron, separating stratigraphic units of different structural blocks.

Our geologic sketch map (fig. 4*B*) of the area near the mountain front differs from the geologic map of Gilluly and Gates (reproduced as our figure 4*A*) in the identification of some of the formations and in the existence of thrust faults as well as in the extent of the Trout Creek fault. In particular, rocks labeled Hanson Creek Formation or the Roberts Mountains Formation in the lower plate of the Roberts Mountains thrust south of Trout Creek in figure 4*A* are identified as quartzite, shale-quartzite-limestone, and limestone in figure 4*B*. We believe that the Roberts Mountains Formation does not crop out adjacent to the Trout Creek fault in this part of the area, although it crops out farther south as shown in figure 4*B*. The limestone that we mapped with rocks designated Cambrian(?) and Ordovician(?) resembles the Bullwhacker Member of the Windfall Formation at Eureka, Nev. (Nolan and others, 1956; T. E. Mullens, oral commun., 1972), but the identity of the quartzite and the shale-quartzite-limestone units remains uncertain. The shale-quartzite-limestone unit is

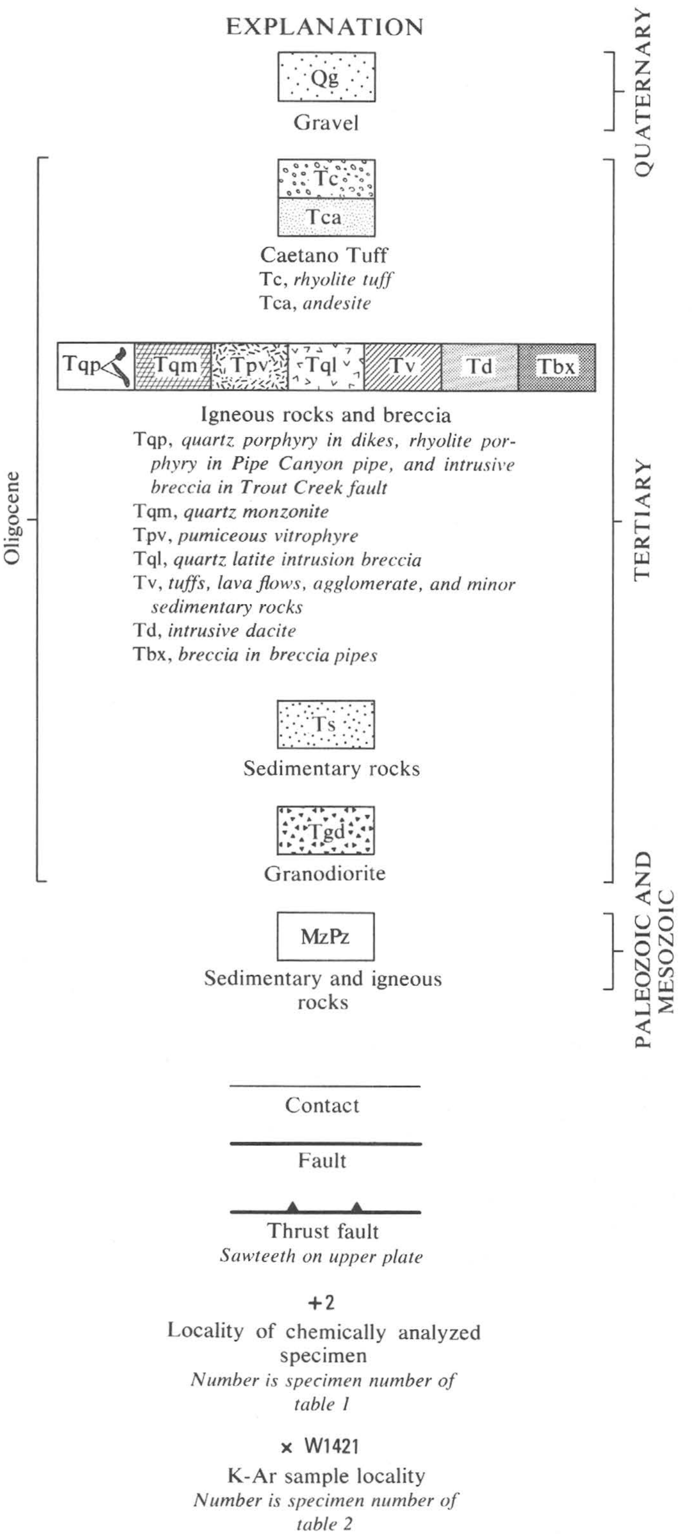


Geology modified from Gilluly and Gates (1965)

FIGURE 3.—Map of the Mount Lewis area showing Tertiary igneous rocks, selected faults, and the location of chemically analyzed samples and samples dated by K-Ar methods. Location shown in figure 1.

mostly dark-gray to black, sandy, phyllitic shale and dark-brownish-gray phyllitic sandstone with subordinate light-gray quartzite and thin-bedded dark-blue-gray limestone. The geology of the lower plate of the Roberts Mountains thrust south of the Trout Creek fault is more complex than the geology of the upper plate immediately north of that fault and will not be understood until studied in detail.

Other critical relations that involve the Trout Creek fault at the south edge of the cauldron can be observed at the small granodiorite body 3½ km east of the mountain front (figs. 2, 3). Although the contact at the north edge of this granodiorite is not exposed, the pluton crops out boldly as far north as the projection of the ring fault, suggesting that the granitic mass ends there. Furthermore, the northern 30 m of the body is crossed by



numerous fractures that parallel the fault, dip 75° N., and produce a strong sheeted appearance in the granodiorite. These fractures probably formed during development of the ring fault. If this is true, this pluton, dated at 35.1 m.y. (table 2, sample M103B), predates the ring fault.

The most problematic feature along the ring fault is the granodiorite intrusion at the east margin of the cauldron (figs. 2, 3). As mapped by Gilluly and Gates (1965, pl. 1), this pluton seems to cut across the Bateman segment of the ring fault as though it were younger. Indeed, we have found no evidence that the Bateman fault crosses the pluton. The isotopic dates discussed below, however, show that the granodiorite predates the volcanism at Mount Lewis; rocks in the cauldron must, therefore, have subsided around the pluton. The contact of the pluton and host rocks is so poorly exposed that it is not possible to determine if it is brecciated. Gilluly and Gates (1965) show that strata around the granitic mass tend to follow the outline of the body as though they were draped around it. This area warrants further examination, but we believe that the interpretation presented here is correct.

A modification of the draping theory was suggested to us by Roy A. Bailey (written commun., 1973) of the U.S. Geological Survey: Because of the rigidity of the granodiorite, the ring fault may have split into two faults around the pluton—the Hilltop fault and the Bateman fault (fig. 3). The Hilltop fault formed as the Trout Creek fault turned northward and, with decreasing displacement, passed west of the pluton and died out 8 km northeast of Mount Lewis. Segments of the Hilltop fault appear to be nearly vertical, suggesting that it may be a normal fault rather than a reverse fault. Along the steep, west-dipping Bateman fault to the east, displacement decreased southward and died out at the north edge of the granodiorite pluton. The combined effect of decreasing displacement in opposite directions on these faults produced an unbroken arcuate ramp-like structure leading from the caldera rim to the floor—a feature that Bailey states (written commun., 1973) is not uncommon in calderas.

Evidence that the Bateman fault forms a segment of the ring fault is that the Bateman fault dips steeply west and follows the arcuate trend of the Trout Creek fault and the southern part of the Hilltop fault. Juxtaposition of stratigraphic units of different structural masses on opposite sides of the fault could be explained as easily by normal as by reverse movements.

Evidence favoring the ring-fault hypothesis include the curved trace of the Trout Creek, Hilltop, and Bateman fault segments roughly concentric about the intrusive centers at Mount Lewis and the difference in stratigraphy and the contrasting styles of the structure on opposite sides of the ring fault. Inside the cauldron, thrust sheets dip toward the interior and strike approximately parallel to the ring fault; outside the cauldron, thrusts are subhorizontal.

In summary, the ring fracture can be traced as a single fault around the exposed part of the cauldron

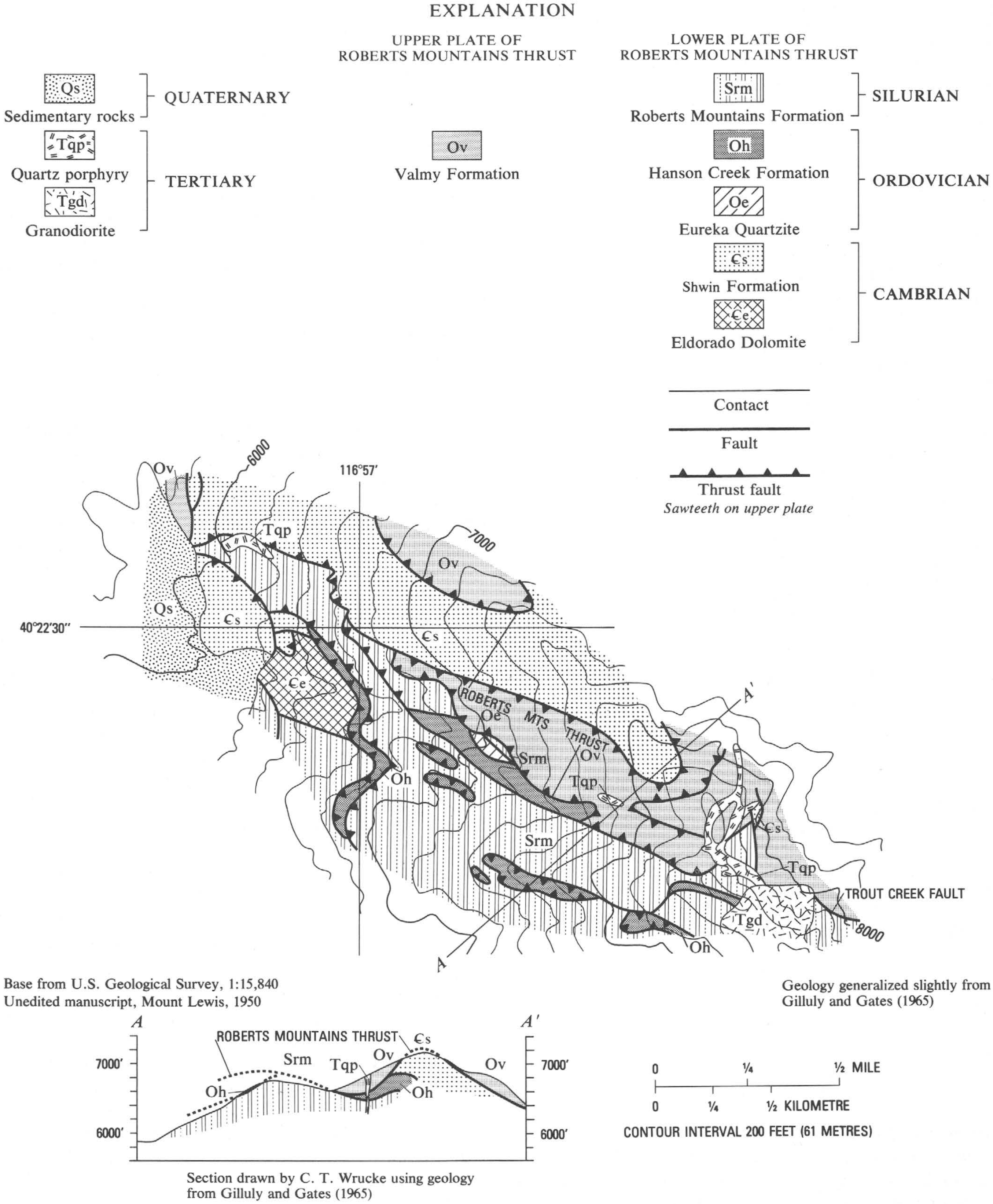
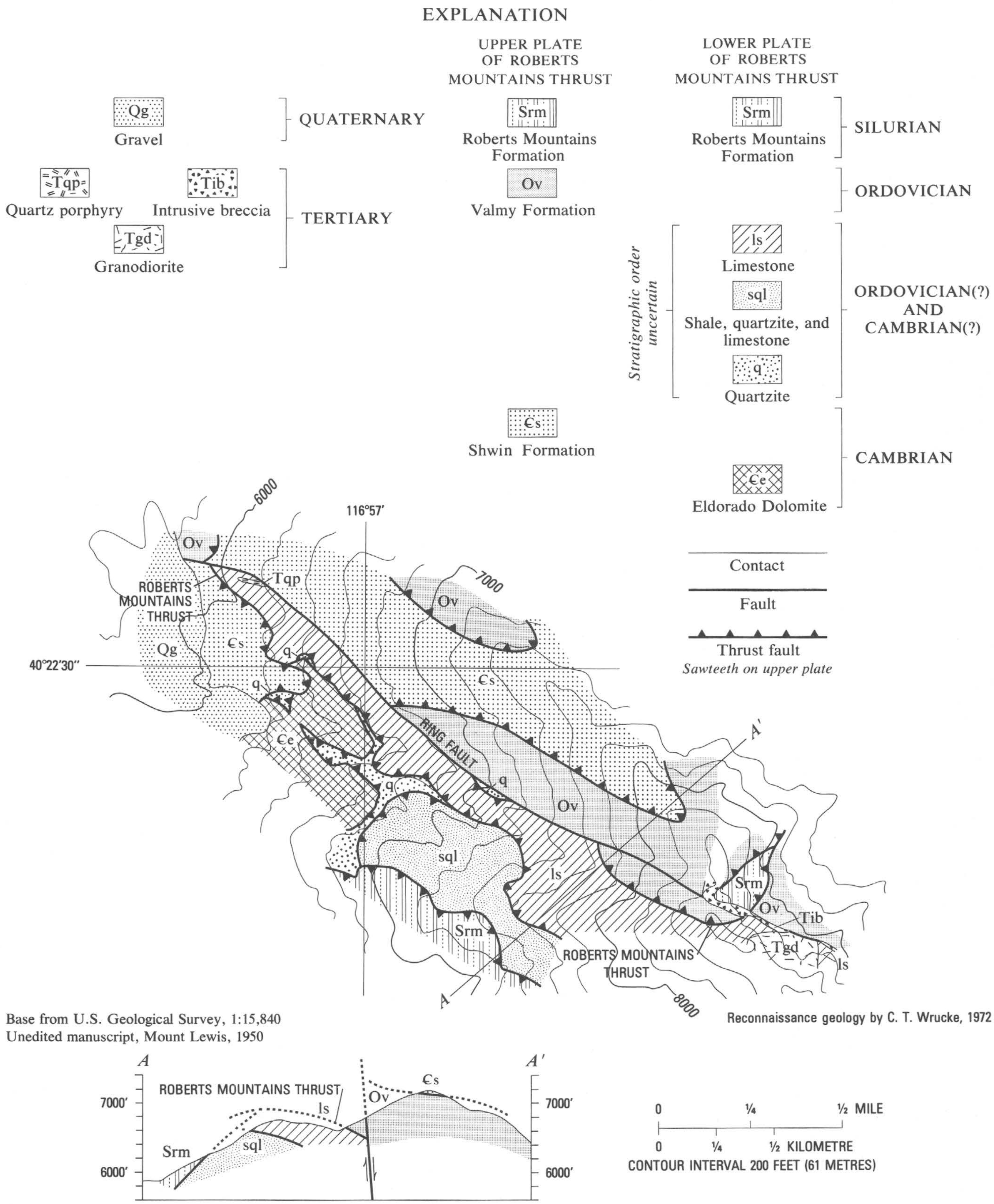


FIGURE 4.—Geologic maps and sections of the southern margin of the Mount Lewis area. *A*, as mapped



by Gilluly and Gates (1965, pl. 1). *B*, as sketched for this report. Location shown in figure 1.

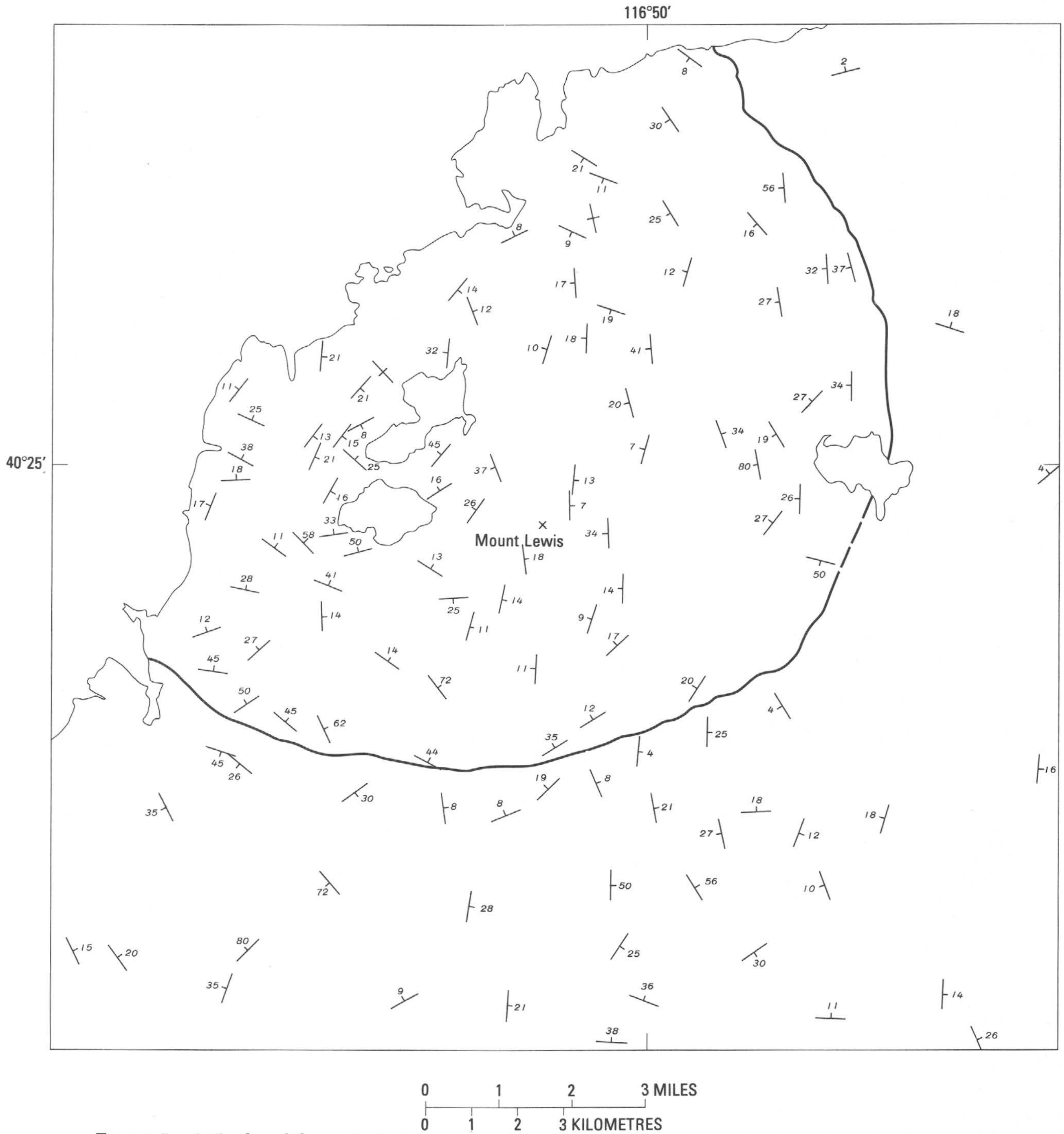


FIGURE 5.—Attitudes of thrust faults in and around the Mount Lewis cauldron. Location shown in figure 1.

except for the segment occupied by the granodiorite on the east side. It dips vertically to 65° inward and separates rocks of such differing structural styles that the internal structure of the subsided mass must offer additional clues to its origin.

INTERNAL STRUCTURE

Thrust faults provide the best reference surfaces for study of the internal structure of the subsided mass because they are the prevolcanic features most likely to have been subhorizontal before subsidence. In contrast, bedding or other planar structures within thrust sheets commonly are highly contorted as a result of deformation during thrusting. This is especially true of chert and argillite strata; quartzite beds generally retain the attitude of overlying and underlying thrusts. Most thrusts in the Shoshone Range are warped and some have been folded sharply; most thrust faults outside the cauldron are inclined at angles less than 30°. The approximate attitudes of thrusts within the subsided mass have been calculated using the three-point method and the relation of the trace of the faults across the land surface as shown on Gilluly and Gates' map (1965, pl. 1). The results, illustrated in figure 5, show clearly that the thrusts in the downdropped mass tend to parallel the boundary fault and to dip inward toward the breccia pipes.

Thrusts tend to dip more steeply near the boundary fault than in the central part of the downdropped pile. Within the outer kilometer of the cauldron, thrusts have an average dip of 38°; in the remainder of the cauldron interior and in the area of figure 5 outside the cauldron, the average dip of the thrusts is 24°. This basining effect strongly suggests that the boundary fault dips generally inward and that the internal mass collapsed into increasingly more restricted space downward, uptilting the peripheral layers into generally steep attitudes along the cauldron margin. Direct or indirect evidence of an inward-dipping boundary fault has been found at many other cauldrons, including the Paresis igneous complex of South Africa (Siedner, 1965), Ossipee cauldron, New Hampshire (Kingsley, 1931), Oslo region (Oftedahl, 1953), and Glen Coe, Scotland (Taubeneck, 1967; Reynolds, 1956).

Some thrust faults in the subsided mass diverge from the general inward dip. At the west edge of the range, a few thrusts have probably been affected by drag along Basin and Range faults. In the western part of the southeast quadrant of the cauldron, the attitudes shown in figure 5 define a north-northeast-trending synform that probably formed during thrusting prior to volcanism. The few aberrant attitudes detract only slightly from the general symmetry of the inward dips.

Attitudes of thrust faults outside the cauldron show little conformity to the boundary fault. They record a vague northerly strike common to rocks in the upper plate of the Roberts Mountains thrust in the northern Shoshone Range. Evidence that the rocks dip outward from the boundary fault as a result of tumescence from rising magma was not found. Considering the variation in strike and dip of thrust faults outside the cauldron, the degree to which the attitudes parallel the boundary fault within the subsided mass is all the more remarkable.

The structural complexities at the southwest margin of the cauldron suggest that the downdropped block subsided at least 950 m in that area. This conclusion is based on the observation that the Roberts Mountains thrust crosses the high ridge south of Trout Creek fault but is not exposed along Trout Creek, which lies in the first deep canyon north of the fault. However, the Cambrian and Silurian formations that interleave with typical upper plate Ordovician rocks just inside the cauldron form a sequence that probably lies only a short distance above the Roberts Mountains thrust, for the same Cambrian and Silurian rocks are here interpreted as occurring respectively immediately above or immediately below the thrust south of the boundary fault (figs. 2, 4*B*). Therefore, the amount of subsidence may not have been much more than 950 m. In the northeastern part of the cauldron, the thrust contact between the Ordovician rocks and the underlying Devonian chert is not exposed, but rocks outside the ring fault are Devonian; consequently, the subsidence in that part of the cauldron must have been greater than the 335 m maximum topographic relief in the Ordovician rocks, as measured in a section normal to the ring fault. Mesozoic rocks exposed within the cauldron, some at relatively low altitudes, are preserved as a result of the downdropping; rocks of this age do not crop out for many kilometres outside the structure. The absence of a Mesozoic reference plane outside the fault prevents an estimate of subsidence of these rocks. The presence of a simple ring fault rather than a complicated zone of boundary faults and the relatively unbroken pattern of thrusts in the subsided mass suggest that the cauldron subsided more or less as a single intact block.

Resurgent doming at Mount Lewis is suggested by late Paleozoic and early Mesozoic rocks and by Tertiary volcanic rocks that in general are topographically high at the summit of Mount Lewis and dip toward topographically lower areas nearer the ring fault. The difference in elevation between the late Paleozoic and Mesozoic rocks at the summit and rocks of the same age 5.6 km northwest is about 850 m, between the volcanic rocks on Mount Lewis and the tuffs in Indian Creek Valley 4 km east about 800 m. These values are not much less than the 3,500–5,000 foot (1,065–1,520 m) probable range of structural relief that Smith and Bailey (1968) report for resurgent domes. Positive evidence of an igneous mass that might have caused the doming suggested here has not been found, but the pattern of magnetic contours shown on figure 1 is suggestive of a buried pluton. An aeromagnetic map by Philbin, Meuschke, and McCaslin (1963) shows that in the northern Shoshone Range there is a strong association between positive magnetic anomalies and known granitic plutons (see Wrucke and others, 1968, fig. 1). Possibly the subjacent magma chamber beneath Mount Lewis is relatively deep.

INTRUSIVE ROCKS

Within the block here interpreted to be downfaulted by volcanic subsidence, Gilluly and Gates (1965) mapped three breccia pipes, many small bodies of quartz monzonite, a dacite plug, three rhyolite plugs, a tabular mass of intrusive breccia, and innumerable dikes (fig. 3). Most of the intrusive centers are slightly elliptical in plan; the largest is a pipe 1.3×2 km, but no single body dominates as a major intrusive center. Paleozoic and Mesozoic country rock separate the larger intrusive bodies, although a narrow neck of intrusive breccia connects two of the pipes. The pipes and plugs are clustered in an area about 7 km across slightly southwest of the center of the cauldron. Together the intrusive rocks, exclusive of the tabular mass of breccia at the summit, constitute only about 3 percent of the area exposed within the cauldron. A positive magnetic anomaly (Philbin and others, 1963) that may be related to a larger subjacent intrusive body lies only a short distance west of the pipes (fig. 1).

PIPES AND PLUGS

The breccia pipes, named the Horse Canyon, Pipe Canyon, and Rocky Canyon breccia pipe (fig. 3) by Gilluly and Gates (1965, p. 66–73), contain two varieties of breccia, foundered blocks of sedimentary rocks, and plugs of Tertiary igneous rocks. Around the margin of each pipe are discontinuous patches of coarse breccia composed of angular fragments ranging in size from microscopic chips to blocks as much as 100 feet long of wall rock and sparse pieces of Tertiary porphyries. This breccia is interpreted as having formed by slumping and landsliding of the sides of the pipes. Intruded into the coarse breccia as dikes and veinlets and as masses occupying much of the inner part of the Horse Canyon pipe and the southern and eastern parts of the Pipe Canyon pipe is fine breccia composed of angular to rounded fragments ranging in size from microscopic to about 3 cm across. One-half to two-thirds of this breccia is a thorough mixture of Paleozoic rock types, the remainder, clasts of Tertiary igneous rocks and chips of quartz, plagioclase, biotite, and hornblende crystals. Fragments of pumice, tuff, and glass occur in the fine breccia of the Pipe Canyon pipe; the matrix is a dense siliceous, isotropic to devitrified glassy mass containing mineral fragments and rock flour. As interpreted by Gates (1959) and Gilluly and Gates (1965), this breccia formed by volatiles rising from a cupola of magma, penetrated the overlying rock and brecciated it, causing turbulence that resulted in abrasion and mixing of the fragments. Steam generated from ground water percolating into the fragmented rock may have aided the process of brecciation; the brecciation could have occurred in several pulses followed by periods of rock bursting and collapse stoping. Magma intruding the rock debris fragmented as it congealed, adding crystal fragments and pieces of igneous material to the breccia. A conglomerate consisting chiefly of pebbles of Paleozoic sedimentary rocks and Tertiary volcanic rocks occurs in the Horse Canyon pipe and probably formed close to the vent from fine breccia reworked by running water before subsiding into the pipe.

The pipes, as described by Gates (1959) and Gilluly and Gates (1965), contain plugs intrusive into the breccias—a plug of quartz monzonite porphyry in the Horse Canyon pipe, a rhyolite porphyry in the Pipe Canyon pipe, and a plug of pumiceous vitrophyre in the Rocky Canyon pipe. The pumiceous vitrophyre is a vesicular, locally fragmental rock composed of altered and devitrified glass that Gilluly and Gates (1965) interpret as having been a viscous gas-charged magma which on reaching the surface may have formed a welded tuff. Lenses of block agglomerate and several varieties of tuff incorporated in the vitrophyre record eruptions older than the vitrophyre. There is no firm evidence that the quartz monzonite of the Horse Canyon pipe breached the surface. However, the abundance of shards and fragments of collapsed pumice in the fine breccia of the Pipe Canyon pipe suggest that explosive eruptions may have occurred at the vent, although this is not specifically mentioned by Gilluly and Gates. All the plugs described here are altered, and none of them has been chemically analyzed.

A dacite plug and a rhyolite plug occur on the east slope of Mount Lewis, outside the breccia pipes (fig. 5). As described by Gilluly and Gates (1965), both plugs have a zone of intrusive breccia at the contact, and both are flow banded. A specimen of the dacite collected for this study consists of plagioclase, biotite, and hornblende phenocrysts in a purplish-gray aphanitic matrix. In thin section the dacite is seen to be devitrified glass containing numerous small grains and pools of late quartz. According to the chemical analysis (table 1, column 1) this rock is a dacite. Gilluly and Gates (1965) propose that the dacite and rhyolite plugs may have fed explosive eruptions and could have been the roots of domes.

INTRUSIVE QUARTZ LATITE BRECCIA OF GILLULY AND GATES

The volcanic rock at the summit of Mount Lewis (fig. 3) is described by Gilluly and Gates (1965) as a subhorizontal mass of intrusive quartz latite breccia emplaced along the unconformity between Paleozoic rocks and an overlying sequence of Tertiary extrusive and sedimentary rocks. The breccia, which shows evidence of having been subjected to great turbulence during deposition, is described as being composed of fragments of quartz latite porphyry, glass, Paleozoic rocks, and of broken crystals of plagioclase, hornblende, biotite, and quartz. The rock fragments commonly are 1–10 mm in diameter, but

TABLE 1.—*Chemical analyses, norms, and semiquantitative spectrographic analyses of Tertiary igneous rocks, Mount Lewis area and vicinity, Nevada*

[Methods used are those described in Shapiro and Brannock (1962). Supplemented by atomic absorption. Analysts: P. Elmore, L. Artis, G. Chloe, H. Smith, J. Kelsey, and J. Glenn. Semiquantitative spectrographic analysis. Results are to be identified with geometric brackets whose boundaries are 1.2, 0.03, 0.56, 0.38, 0.26, 0.18, 0.12 . . . ., but are reported arbitrarily as midpoints of those brackets, 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, ... The precision of a reported value is approximately plus or minus 1 bracket at 68 percent or 2 brackets at 95 percent confidence. Analysts: C. Heropoulos and R. Mays]

Specimen No.	1	2	3	4	5
Chemical analyses (weight percent)					
SiO_2	67.6	63.6	66.2	68.3	70.2
Al_2O_3	14.1	16.7	16.5	15.0	15.3
Fe_2O_3	2.1	3.1	3.6	2.3	1.2
FeO	1.2	.44	.08	.72	1.3
MgO	.88	.89	1.0	1.0	.59
CaO	3.2	2.9	1.4	2.0	1.2
Na_2O	2.8	4.1	4.6	3.6	3.2
K_2O	3.3	4.1	4.2	3.1	4.8
H_2O+	1.6	1.2	1.2	1.5	1.2
H_2O-	.85	1.2	.45	.87	.16
TiO_2	.41	.50	.48	.44	.37
P_2O_5	.15	.15	.18	.12	.16
MnO	.05	.04	.05	.04	.02
CO_2	1.7	1.0	<.05	1.0	.32
Sum	100	100	100	100	100
C.I.P.W. norms					
Q	35.60	19.69	19.40	32.79	30.71
or	19.51	24.25	24.83	18.32	28.36
ab	23.71	34.72	38.95	30.47	27.07
an	4.15	7.09	5.77	2.82	2.88
en	2.19	2.22	2.49	2.49	1.47
fs	----	----	----	----	.82
mt	2.84	.10	----	1.18	1.74
hm	.14	3.03	3.60	1.49	----
il	.78	.95	.28	.84	.70
ru	----	----	.34	----	----
ap	.36	.36	.43	.28	.38
cc	3.87	2.28	----	2.27	.73
C	4.40	2.93	2.27	4.69	3.78
Semiquantitative spectrographic analyses (in parts per million)					
B	7	----	----	----	----
Ba	1,000	1,500	1,000	2,000	1,500
Be	----	1.5	----	----	----
Co	3	5	3	5	----
Cr	1.5	5	2	10	----
Cu	3	3	1	3	15
La	----	50	----	50	----
Mn	200	300	200	500	100
Mo	----	----	----	----	----
Nb	----	10	----	10	----
Ni	----	----	----	2	----
Pb	15	20	15	20	15
Sc	5	7	5	5	2
Sr	200	700	300	1,000	200
V	20	50	15	30	15
Y	10	15	10	15	10
Zr	100	150	100	100	100

Description of analyzed samples; locations shown in figure 3.
1. Biotite dacite from plug, contains late quartz.
2. Biotite dacite from lava flow in volcanic rocks (unit Tv of Gilluly and Gates, 1965, pl. 1) on Mount Lewis.
3. Biotite rhyodacite from lava flow in volcanic rocks (unit Tv of Gilluly and Gates, 1965, pl. 1) on Mount Lewis.
4. Quartz latite from quartz latite intrusion breccia (unit Tg of Gilluly and Gates, 1965, pl. 1) on Mount Lewis.
5. Rhyolite porphyry, devitrified from dike in intrusive breccia of ring fault.

a few rounded clasts of granitic rock resembling the granodiorite at Granite Mountain reach cobble size. The fragmental material is set in a groundmass of glass shards, dustlike opaque minerals, and fine-grained isotropic to faintly birefringent grains. According to Gilluly and Gates (1965), this groundmass resembles the matrix of the fine breccia in the Horse Canyon and Pipe Canyon pipes. One sample of the breccia that was chemically analyzed (table 1, column 4) is a quartz latite. The geologic map of Gilluly and Gates (1965) shows that the intrusive breccia is at least 240 m thick. Although Gilluly and Gates (1965) present detailed discussions of the intrusive origin of the unit, we have found that the unit contains rocks with abundant flattened pumice lapilli; and these rocks closely resemble welded ash flows. Moreover, the presence of granitic cobbles and the great thickness of the unit lead us to speculate that the unit might have been formed of rocks deposited subaerially; subsequently these rocks may have been jumbled and thickened during mass sliding.

DIKES

The dikes are the youngest intrusive rocks in the cauldron. Many of them form a north-trending swarm that extends from south of the boundary fault into the subsided block and across the Horse Canyon and Pipe Canyon pipes (fig. 3). According to Gates (1959) and Gilluly and Gates (1965), the dikes range in composition from andesite to rhyolite; many are quartz latite and quartz monzonite. Because many of the dikes are altered, Gilluly and Gates (1965) found that it was not always practicable to distinguish the various kinds. They designated many of them quartz porphyry. Most of the dikes shown in figures 3 and 4, regardless of composition, are labeled quartz porphyry.

Our observations show that the eastern dike along the Trout Creek fault is a quartz porphyry and that the western dike and at least the western 500 m of the middle dike, beginning at sample locality W1241 (fig. 3), are intrusive breccia locally intruded by rhyolite porphyry. The western dike also extends north into the cauldron. These breccia dikes are 0.3–35 m wide; those in the Trout Creek fault dip vertically to 65° toward the center of the cauldron.

The intrusive breccia of the dikes contains 15–25 percent unsorted angular mineral grains and 1–25 percent angular rock fragments set in a dense, siliceous, nearly isotropic groundmass. One sample contains about 25 percent shards and collapsed pumice fragments. Most mineral grains are quartz, plagioclase, and biotite, but sanidine occurs locally; all range in size from a few millimeters to pieces barely discernible through a hand lens. Rock fragments consits of chert, argillite, and porphyries, and their lengths are as great as several centimetres.

The most distinctive feature of the intrusive breccia is a layering parallel to the walls of the dikes. This feature is well developed in the western dike in the Trout Creek fault and it occurs locally in the middle dike. The layers are light to very dark gray, sharply defined, and commonly 2–30 mm wide. In detail, contacts between layers are irregular; the layers interfinger at all scales from

TABLE 2.—*Summary of K-Ar ages of igneous rocks from Mount Lewis and vicinity*

Specimen No.	Location	Mineral	Age[1] (m.y.)	Average age[2] (m.y.)	Reference	Rock Type
W1416	West-central sec. 14, T. 30 N., R. 45 E., 40°28′12″ N., 116°52′19″ W.	Biotite Sanidine	32.1±1.0 32.8±1.0	32.4±0.5	This work.	Rhyolite welded ashflow tuff from the Caetano Tuff within cauldron.
W1421	SW cor. sec. 21, T. 29 N., R. 45 E., 40°21′52″ N., 116°55′34″ W.	Biotite Sanidine	33.6±1.0 32.8±1.0	33.2±0.6	do	Intrusive breccia in ring fracture at south margin of cauldron.
141	SW¼NW¼ sec. 7, T. 29 N., R. 46 E., 116°50′49″ W., 40°23′57″ N.	Biotite	34.4±0.7	34.4±0.7	McKee and others, 1971, p. 40	Dacite plug, southeast flank of Mount Lewis.
139	NE¼NW¼ sec. 12, T. 29 N., R. 45 E., 40°24′14″ N., 116°51′42″ W.	do	34.7±1.4	34.7±1.4	do	Quartz latite intrusion breccia of Gilluly and Gates (1965) from summit of Mount Lewis.
140	NE¼NW¼ sec. 12, T. 29 N., R. 45 E., 40°24′09″ N., 116°51′43″ W.	do	33.2±0.7	33.2±0.7	do	Do.
M103B	NW¼ sec. 28, T. 29 N., R. 45 E., 40°21′39″ N., 116°55′25″ W.	do	35.1±0.7	35.1±0.7	Silberman and McKee, 1971, p. 24.	Biotite-granodiorite stock, precauldron intrusive from south margin of cauldron.
MB8	North-central sec. 3, T. 29, N., R. 46 E. 40°24′55″ N., 116°46′56″ W. (incorrectly located in the published reference).	Hornblende	38.1±0.8	38.1±0.8	do	Hornblende granodiorite, precauldron intrusive from east margin of cauldron.
Granite Mountain pluton	Sec. 13 and parts of 11, 12, 14, and 24, T. 29 N., R. 46 E.	Biotite Hornblende Biotite Hornblende	38.0 36.7 37.0 36.0	37.0±0.6 Average of four mineral ages on two samples.	McKee and Silberman, 1970, p. 2324, no. 5.6, table 4.	Biotite, hornblende, granodiorite of Granite Mountain, 14 km east of Mount Lewis.
Tenabo pluton	Southern parts of secs. 8 and 9, T. 28 N., R. 47 E.	Biotite Hornblende Biotite	37.4 38.2 [3]37.2	37.6±0.4 Average of three mineral ages from two samples.	McKee and Silberman, 1970, p. 2324, no. 2.3, table 4.	Biotite, hornblende, granodiorite of Tenabo pluton. 18 km southeast of Mount Lewis.
Caetano Tuff	Regional distribution in Shoshone, Toiyabe Ranges, Fish Creek Mountains, and Battle Mountain.	Various minerals and mineral pairs from 11 separate samples.	33.5 30.6 31.2 31.5 33.6 31.2 33.5 32.3 32.7 [4]33.0 [4]34.1 32.0	Range 34.1–30.6[5] (33.6–30.6) for K-Ar ages alone. Average 32.5.	J. H. Steward and E. H. McKee (unpub. data)	Rhyolite welded tuff.

[1]Plus-minus represents estimated analytical uncertainty at one standard deviation (68 percent confidence level) and is based on statistical analysis of a large number of replicate potassium and duplicate argon analyses (Silberman, 1971).
[2]Plus-minus represents standard deviation calculated from ages of different minerals and from one or more samples.
[3]Incorrectly reported as 38.2 m.y. by Silberman and McKee (1971).
[4]Fission track ages.
[5]Includes fission track ages of note 4 above.

the widest layers down to the thinnest ones, many of which taper gradually though irregularly to a fine point. The dark layers are intrusive breccia. Most of the light-gray layers are rhyolite porphyry composed of quartz, plagioclase, sanidine, and biotite phenocrysts set in a matrix of devitrified glass, but some are bleached breccia. A chemical analysis of the rhyolite porphyry is given in table 1, column 5.

Evidently the rhyolite porphyry invaded the rising intrusive breccia and was itself brecciated. Volatiles streaming through the layers promoted devitrification of the rhyolite and altered some of the breccia. Most of the breccia and invading rhyolite moved by flowage parallel to the dike walls to produce the well-defined layers.

INTRUSIVE SEQUENCE

The order in which the various intrusive bodies were emplaced in the cauldron can be determined only in part from intrusive relations. Following and in part contemporaneously with development of the pipe breccias, the plugs were intruded into the pipes. None of the plugs are in contact with other pipes. The dacite plug, however, probably formed before the pumiceous vitrophyre, for the vitrophyre engulfed dacite agglomerate thought to have come from the dacite plug (Gilluly and Gates, 1965). The dacite plug is likely of presubsidence origin, as the dacite agglomerate is thought to have been emplaced before cauldron collapse. The intrusive quartz latite breccia of Gilluly and Gates contains fragments of the dacite plug and is therefore younger than the plug despite map relations that suggest the converse as discussed by Gilluly and Gates (1965), but the age of the breccia relative to the other intrusive rocks and to subsidence is uncertain. The rhyolite porphyry plug is probably a relatively late intrusive rock at Mount Lewis because it closely resembles the rhyolite dikes.

Clearly most of the dikes are younger than the plugs. The dikes show no evidence of having been faulted, therefore, they probably formed after the cauldron collapsed. Because the breccia and rhyolite dikes in the Trout Creek fault occur in a structural feature interpreted to have resulted from subsidence, they must have been emplaced during or after subsidence. A few dikes of andesite cut dikes of quartz latite and rhyodacite porphyry and seem to be the youngest intrusives in the Mount Lewis cauldron.

The sequence of intrusive events cannot be deciphered entirely by the isotopic ages. With the exception of the breccia in the ring fault (tables 2, 3, sample W1421) and the dacite plug on the southeast spur of

TABLE 3.—*Analytical data for new K-Ar ages of igneous rocks from Mount Lewis*

[Potassium analyses were done by flame photometer using lithium metaborate fusion, on lithium serving as an internal standard. Analyst: Lois Schlocker. Argon analyses were made by standard isotope dilution procedures (Dalrymple and Lanphere, 1969). A Neir-type, 60°, 6-inch mass spectrometer operated in the static mode was used for the mass analysis. Analyst: M. L. Silberman]

Sample No.	Mineral	K_2O	Ar^{40}_{rad} mol/g	Ar^{40}_{rad} / Ar^{40}_{total} (percent)	Age (m.y.)
W–1416	Biotite	8.40	4.009×10^{-10}	80.5	32.1±1.0
	Do	8.37			
	Sanidine	11.17	5.459×10^{-10}	90.1	32.8±1.0
	Do	11.20			
W–1421	Biotite	8.64	4.303×10^{-10}	88.9	33.6±1.0
	Do	8.54			
	Sanidine	12.47	6.093×10^{-10}	76.1	32.8±1.0
	Do	12.45			

Constants used: $\lambda_e = 0.585 \times 10^{-10} yr^{-1}$, $\lambda_B = 4.72 \times 10^{-10} yr^{-1}$, K^{40}/K total = 1.22×10^{-4} g/g.

Mount Lewis (table 2, sample 141), the intrusive igneous rocks are hydrothermally altered and do not yield samples suitable for K-Ar age determination.

EXTRUSIVE AND SEDIMENTARY ROCKS

In the vicinity of Mount Lewis, remnants of sedimentary deposits, tuffs, and lava flows cap the summit, crown high ridges, and make up exposures in low areas near the edge of the subsided mass (fig. 2). Most of these deposits occur within the ring fault. The original areal extent of the deposits is not known, but some of the tuffs, as discussed below, probably blanketed large areas.

DEPOSITS ON MOUNT LEWIS AND IN INDIAN CREEK VALLEY

The oldest layered rocks of Tertiary age in the Mount Lewis cauldron are conglomerate and impure coal that crop out in Indian Creek Valley east of Mount Lewis. These rocks, mapped as Tertiary sedimentary rocks by Gilluly and Gates (1965, pl. 1), are included in the unit designated Tertiary extrusive igneous rocks and sedimentary rocks in figure 2 but are shown separately in figure 3. An important feature of the conglomerate, which consists of well-rounded pebbles and cobbles chiefly of Paleozoic sedimentary rocks, is that it contains clasts of granodiorite derived from the stock at Granite Mountain, 9 km east of Mount Lewis. These granitic clasts indicate that the streams depositing them drained areas outside the cauldron; furthermore, the streams must have existed before eruptions at Mount Lewis because the conglomerate lacks volcanic debris.

Other sedimentary rocks in the unit mapped as Tertiary sedimentary rocks by Gilluly and Gates (1965, pl. 1) are younger than the conglomerate in Indian Creek Valley. They include reworked breccia in the Horse Canyon pipe and water-deposited tuff in the Rocky Canyon pipe. Sedimentary rocks that crop out west of the mouth of Pipe Canyon are not described by Gilluly and Gates (1965).

According to Gilluly and Gates (1965), dacite block agglomerate, tuff, siltstone, mudstone, and conglomerate overlie the conglomerate and coal in Indian Creek Valley. These rocks crop out in several patches that differ in stratigraphy from place to place because of lensing and pinching out of layers. Gilluly and Gates (1965, p. 61) state that the block agglomerate is the dominant Tertiary rock in Indian Creek Valley. This observation may be correct, but we have found that the largest remnant of Tertiary rock in the valley consists principally of massive, poorly consolidated, altered tuffs, and conglomerates containing clasts of plagioclase-rich latite and rhyodacite porphyries. We estimate the sequence of extrusive and sedimentary rocks above the basal coal and conglomerate to be 100—150 m thick.

The volcanic rocks lying on the intrusive breccia at the summit of Mount Lewis, according to Gilluly and Gates (1965), consist of tuffaceous lake beds, rhyolite tuff, mud-flow breccia, arkose, and dacite block agglomerate. We have found, in addition, rhyolite welded tuff, a rhyodacite lava flow (table 1, column 3), and a dacite lava flow (table 1, column 2) on this unit. On the geologic map of Gilluly and Gates, the remnant of this unit exposed on Mount Lewis is shown to be about 50 m thick.

The tuffs and sedimentary rocks on Mount Lewis and in Indian Creek Valley may be approximately contemporaneous. Fresh rocks in both areas are similar in composition, and the altered rocks of these areas are similar in appearance. Moreover, Gilluly and Gates (1965) report dacite block agglomerate in both areas.

CAETANO TUFF

Welded rhyolite tuff and andesite flows here interpreted to be part of the Caetano Tuff crop out at the north edge of the cauldron, in a few small areas southwest of the cauldron, and in patches along the mountain front northwest of Mount Lewis (figs. 2, 3). The tuff in the northern part of the cauldron is chiefly medium gray, locally bleached light gray to white, and structureless to weakly layered. It is composed of about 30 percent subhedral and broken crystals of quartz, sanidine, plagioclase, and biotite in a devitrified matrix of shards and trains of glassy clasts that tend to be wrapped around phenocrysts. A chemical analysis (Gilluly and Gates, 1965, p. 85, column 13) shows that the rock is rhyolite and that it resembles the Caetano Tuff of the type locality, Caetano Ranch, 42 km southeast (Gilluly and Masursky, 1965, p. 77). As mapped by Gilluly and Gates (1965), the tuff at the north end of the cauldron is at least 180 m thick. It appears to overlie, rather than underlie, the andesite, which is about 60 m thick.

DEPOSITIONAL SEQUENCE

The relative ages of the layered rocks in the cauldron, inferred from a few isotopic dates and from the intrusive order of dikes and plugs, indicate that the tuffs in Indian Creek Valley and those at the summit of Mount Lewis formed before the Caetano Tuff. An isotopic age of 34.4 m.y. for the dacite plug, assumed to be the source of the dacite agglomerate, indicates that these rocks, and presumably the extrusive rocks at Mount Lewis, formed only a short time before deposition of the 32.4-m.y.-old Caetano Tuff exposed in the cauldron (table 2). The relation of the volcanic rocks to cauldron subsidence at Mount Lewis is discussed in the next section.

HISTORY OF VOLCANISM

Field relations supplemented by K-Ar dates (tables 2, 3) provide at present only a sketchy account of volcanism in the Mount Lewis cauldron. The isotopic dates cannot be used to establish a detailed sequence of events for several reasons. Many of the rocks, particularly the intrusives but also some of the extrusives, are too altered hydrothermally to provide suitable samples for K-Ar dating. Moreover, the uncertainty of the K-Ar dating method as applied to rocks of this age is of the order of 3 percent for a single age determination (McKee and Silberman, 1970). This uncertainty for rocks of Oligocene age is approximately 1 m.y., a time interval that is long compared with the duration of cauldron-forming events such as ash-flow eruption and cauldron subsidence (Smith and Bailey, 1968). Finally, data available are not sufficient for a detailed account of the relation of all volcanic rocks in the region to events that occurred at Mount Lewis. Nevertheless, K-Ar ages provide an overall time framework for the igneous and structural events at Mount Lewis and nearby areas in the Shoshone Range.

Volcanism and subsidence of the Mount Lewis cauldron were preceded by an episode of granitic intrusive activity along the northwest-trending mineral belt that crosses the range in the vicinity of the cauldron. This activity, which occurred from about 38 to 35 m.y. ago (latest Eocene–early Oligocene), resulted in emplacement of five small plutons that range in composition from granodiorite to quartz monzonite, all medium to coarse grained. These magmatic bodies probably did not breach the surface, as extrusive rocks of this age are unknown in the region. The oldest of these plutons is the 38.1 m.y. (table 2, sample MB8) body that interrupts the ring fault at the east edge of the cauldron (figs. 2, 3), the one around which strata in the cauldron appear to have been draped during collapse. The youngest of these plutons, which lies adjacent to the cauldron at the south margin, has been cut by the ring fault. The clasts of granodiorite from Granite Mountain in the basal conglomerate of Indian Creek Valley indicate an episode of deep erosion before volcanism at Mount Lewis.

Volcanism in the Mount Lewis area began about 35 m.y. ago as recorded by K-Ar dating (table 2). The oldest ages obtained from volcanic rocks are 34.4 m.y. from the dacite plug on the east spur of the mountain and 34.7 m.y. from a sample of the quartz latite intrusion breccia of Gilluly and Gates (1965). The 34.7-m.y. date has a large analytical uncertainty due to high atmospheric contamination and is therefore less reliable than a 33.2-m.y. date from another sample of the intrusion breccia. The quartz latite intrusion breccia may be younger than the sequence of volcanic and sedimentary rocks correlated with the dacite plug as Gilluly and Gates (1965) imply. The breccia and the volcanic and sedimentary rocks are interpreted as forming before subsidence because they are older than the regionally extensive Caetano Tuff. The tuff is thought to have initiated the volcanic collapse.

The youngest dated rock within the subsided block is a 32.4-m.y.-old rhyolite ash flow from the Caetano Tuff near the north edge of the cauldron. Rhyolite intrusive breccia from the Trout Creek fault was dated at 33.2 m.y. This breccia and associated rhyolite in this fault could have fed some of the eruptions that represent parts of the Caetano Tuff.

Volcanic collapse at Mount Lewis began after emplacement of the 35.1-m.y. granodiorite that is faulted at the south margin of the cauldron and before the rhyolite breccia and associated dike rock invaded the ring fault about 33.2 m.y. ago. Subsidence could have been contemporaneous with or earlier than emplacement of the breccia and dikes in the ring fault. Presumably the pumiceous vitrophyre of the Rocky Canyon pipe, the rhyolite plug of the Pipe Canyon pipe, and the late rhyolite dikes within the cauldron could have occupied conduits that fed eruptions during or after collapse, but none of these rocks has been dated radiometrically. The andesite dikes could have breached the surface during or following subsidence to feed lava flows associated with rhyolite of the Caetano Tuff at the north edge of the cauldron. A chart, figure 6, represents graphically our proposed sequence of structural and igneous events in the Mount Lewis area.

Meager evidence of resurgent doming in the Mount Lewis cauldron includes the 850-m displacement of the extrusive and sedimentary rocks at the summit relative to the sequence in Indian Creek Valley; the tilting away from the summit of small patches of similar rocks on the north and northeast spurs of the mountain; and the dip of late Paleozoic and early Mesozoic rocks close to the summit of Mount Lewis toward topographically low areas near the ring fault. In a general way, volcanic rocks in the center of the cauldron are structurally high, those near the ring fault are low.

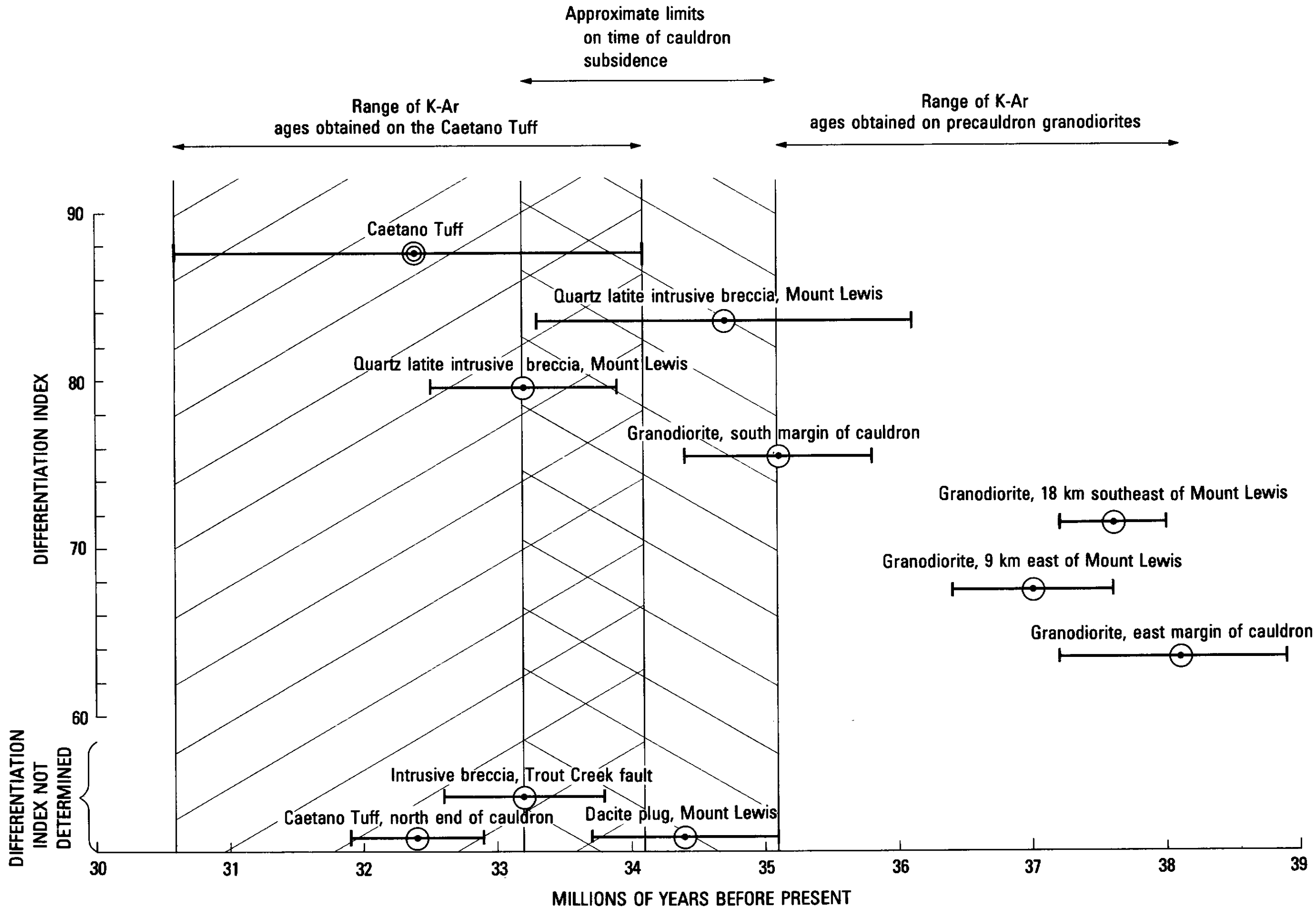


FIGURE 6.—Sequence and duration of events at Mount Lewis and vicinity and differentiation index as a function of age of igneous rocks.

CAETANO TUFF AND THE MOUNT LEWIS CAULDRON

The Caetano Tuff was named by Gilluly and Masursky (1965, p. 73–78) for a thick sequence of welded ash flows and associated water-laid tuffs, sandstones, and conglomerates in the northern Toiyabe Range. Masursky (1960) writes that the formation lies mainly in an east-west-trending volcano-tectonic depression that Burke and McKee (1973) report to be 8–16 km wide and 115 km long. The depression extends from the northern Toiyabe Range across the Shoshone Range south of the Mount Lewis cauldron. Isolated areas of Caetano Tuff occur east and northwest of the cauldron (fig. 1). J. H. Steward and E. H. McKee (unpub. data) suggest that the tuff erupted from the volcano-tectonic depression and point out that the formation is at least 2,400 m thick in the eastern part of the depression and less than 150 m thick in most outliers near Mount Lewis. E. H. McKee (oral commun., 1973) believes, moreover, that the source lies in the part of the depression that crosses the Shoshone Range 18–35 km south of Mount Lewis because the tuff in that area is thicker than elsewhere, has not developed horizontal to subhorizontal layering typical of thinner outliers, is pervasively altered, contains large zones of breccia, and includes many more xenoliths than elsewhere. We suggest, however, that at least part of the Caetano Tuff was erupted from Mount Lewis.

K-Ar ages shown by the histogram, figure 7, suggest that the Caetano Tuff is early Oligocene in age. These ages were obtained from stratigraphically uncorrelated samples collected at widely scattered localities, mainly in the volcano-tectonic depression. An age of 32.4 m.y. from a sample obtained at the north edge of the Mount Lewis cauldron lies within the range of ages reported for the Caetano Tuff.

The histogram (figure 7) suggests that tuffs identified as part of the Caetano Tuff were emplaced during an interval perhaps as long as 3.5 m.y. Although there is no way of knowing if the Caetano Tuff erupted more or less continuously as the data suggest, the 3.5-m.y. interval seems long for eruptions from one volcanic center. Smith and Bailey (1968) indicate that a major ash flow may be emplaced during a period of 10 years or less. We

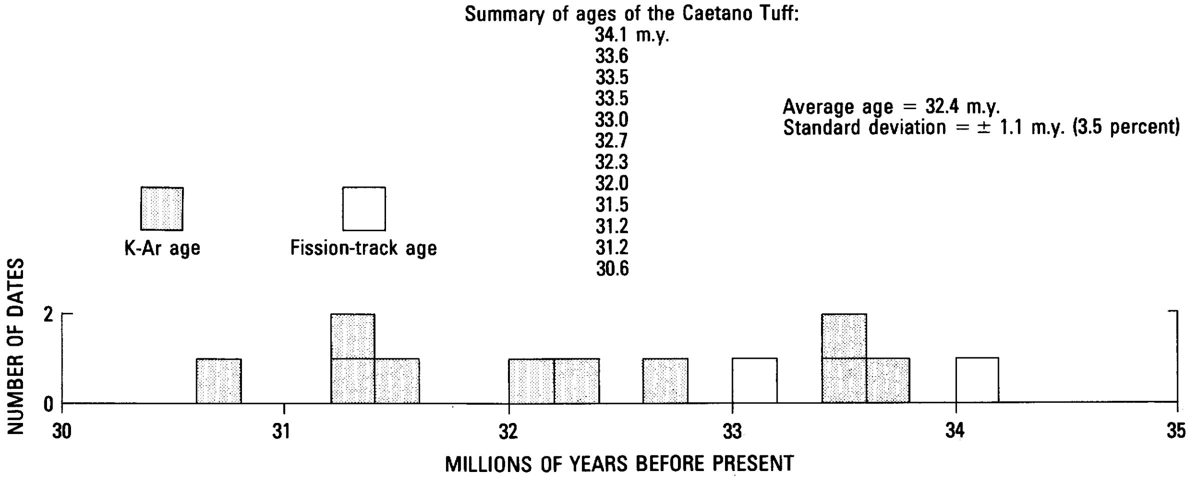


FIGURE 7.—Histogram of K-Ar and fission-track ages of the Caetano Tuff (After J. H. Stewart and E. H. McKee, unpub. data, 1972), grouped in 0.2-m.y. intervals.

suggest that the Caetano Tuff is a complex unit that may have several different source areas.

Eruption of at least some of the Caetano Tuff from the Mount Lewis cauldron is suggested by the overlap of the K-Ar ages with the limits of cauldron subsidence at Mount Lewis (fig. 6); the distribution of the formation east, south, and northwest of the mountain; and the relatively structureless altered deposit of the tuff at the north edge of the cauldron. Further work is needed to determine the location of eruptive vents of the Caetano Tuff, but it is the only tuff of regional extent and appropriate age that could have caused subsidence at the Mount Lewis cauldron.

Chemical and age data suggest that eruption of the Caetano Tuff was the final event in a single cycle of igneous activity in the northern Shoshone Range. The cycle began with emplacement of small granodiorite plutons, mainly east and southeast of Mount Lewis, and continued after an interval of erosion and dissection of these early granitic rocks with intrusion of dacite and quartz monzonite plugs and contemporaneous eruption of dacite lavas and quartz latite breccias and tuffs in the Mount Lewis area. This magmatic cycle ended with emplacement of andesite lava flows and rhyolite ash flows of the Caetano Tuff. The chemical progression of the rocks thus formed is summarized in a chart, figure 6, that shows a plot of the differentiation index (Thornton and Tuttle, 1960) of analyzed rocks as a function of their age.

The evolution of igneous rocks in the northern Shoshone Range is typical of the general history of igneous activity in central Nevada, where Tertiary igneous activity began abruptly about 38 m.y. ago with eruption of andesitic to dacitic lavas from numerous centers scattered over the region. These lavas were accompanied by or preceded by emplacement of small granodiorite to quartz monzonite plutons at shallow crustal levels (McKee and Silberman, 1970; McKee and others, 1971). About 33 m.y. ago, local andesitic and dacitic volcanism was followed by eruption of widespread quartz latitic to rhyolitic ash flows that blanketed large parts of the region. Small amounts of andesite occur with these silicic rocks (Burke and McKee, 1973). Ash-flow volcanism continued for 10–12 m.y. (McKee and Silberman, 1970; McKee and others, 1971), characterized by differentiation of more primitive intermediate magmas (McKee and Silberman, 1970; Noble, 1972). In the northern Shoshone Range, the andesite flows and rhyolite tuffs of the Caetano Tuff and the quartz latite breccias and tuffs of Mount Lewis represent the later period of generally silicic volcanism.

COMPARISON OF THE MOUNT LEWIS AND OTHER CAULDRONS

The Mount Lewis cauldron differs from most other cauldrons of Cenozoic age in the western United States in being deeply eroded below the original volcanic pile; it differs from many ring complexes of the world in exposing only a small percentage of intrusive rocks. Within the cauldron, the base of the layered volcanic rocks is exposed at a high elevation on the summit of Mount Lewis; below the summit, the cauldron is exposed by erosion to depths as great as 1,100 m. No vestige of the original Oligocene topography remains. In contrast, cauldrons such as the Valles (Smith and others, 1961; Smith and Bailey, 1968), of Pleistocene age in New Mexico, the Timber Mountain (Christiansen and others, 1965; Carr and Quinlivan, 1968; Byers and others, 1968), of Miocene age in Nevada, and the Creede (Steven and Ratté, 1965; Lipman and others, 1970), of Oligocene age in Colorado, retain original topographic elements of their central resurgent domes, the surrounding moats, and the caldera walls. The Phanerozoic and Precambrian host rocks are exposed at the San Juan-Silverton cauldron complex of Oligocene age in Colorado (Burbank and Luedke, 1969; Luedke and Burbank, 1968), but detailed maps of the area have not been published. Because of the deep level of exposure at Mount Lewis, it seems reasonable to compare the Mount Lewis cauldron with igneous ring structures, as they, too, are eroded below the original topographic features.

In contrast to the 3 percent of igneous rocks that crop out in the exposed part of the Mount Lewis cauldron, igneous ring complexes commonly consist of 30–100 percent intrusive rocks. This is true of ring structures in New Hampshire (Kingsley, 1931; Billings, 1956), Nigeria (Jacobson and others, 1958; Turner, 1963, 1968), Norway (Oftedahl, 1953), and Queensland (Branch, 1966). Ring complexes in these areas contain a central pluton as well as ring intrusions. Most of the ring complexes preserve downdropped volcanic rocks and only small amounts of prevolcanic host rocks.

Magma reached high structural levels at all these ring complexes. Smith and Bailey (1968) have interpreted the central plutons in some of the ring complexes of Nigeria, Norway, and New Hampshire as subvolcanic analogs of resurgent domes. Considering this interpretation and the high percentage of subvolcanic host rocks enclosed by the ring fault at Mount Lewis, we conclude that any resurgence at Mount Lewis was small, possibly because the subjacent pluton did not rise to high levels as in most ring complexes or possibly because it was much smaller than the plutons causing resurgence in the other complexes discussed.

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