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Magmatic History of the East Tintic Mountains, Utah

By

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CONTENTS

ILLUSTRATIONS

TABLE

Introduction

The East Tintic Mountains of west-central Utah (fig. 1) (all figures are at end of report) are noted for the highly productive Tintic mining district centered on the town of Eureka. Genesis of the ore deposits in the district apparently was related to Oligocene magmatism which produced a thick volcanic/plutonic sequence in the central part of the mountain range. Morris (1975) proposed that eruption of large volumes of quartz latite, now represented by the Packard and Fernow Quartz Latites, resulted in collapse of a 14-km-diameter caldera, centered south of the mining district (fig. 2), and herein referred to as the Tintic caldera. According to Morris, the caldera was subsequently filled and overtopped by voluminous latite tuffs, flows, and breccias, and intruded by numerous monzonitic stocks, sills, and dikes. Morris' arguments for the existence of the Tintic caldera were based on three principal observations: (1) lack of Paleozoic outcrops in a circular area; (2) a major, circular, positive magnetic anomaly (more than 700 gammas above that of surrounding areas) centered over his proposed caldera; and (3) drill-hole evidence for more than 1 km of volcanic fill.

Although new detailed mapping (fig. 3 and pl. 1) provides strong evidence for the existence of a Tintic caldera, the location of the margin and the lithologic units related to caldera collapse differ from those proposed by Morris (1975). Our revised volcanic stratigraphy and lithologic descriptions reveal the magmatic history and structural development of the largely concealed caldera first insinuated by Morris' insightful observations. Conclusions presented here are based solely on field observations supplemented by examination of selected thin sections. Geochemical analyses and $^{40}Ar/^{39}Ar$ dating are underway, and will certainly lead to refinements in the proposed magmatic history.

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Tertiary Stratigraphy in the East Tintic Mountains

Morris and Lovering (1979) separated the Tertiary igneous rocks into three groups: (1) the early Packard and Fernow Quartz Latites; (2) the Tintic Mountain Volcanic Group (Copperopolis Latite and Latite Ridge Latite); and (3) the late Laguna Springs Volcanic Group (fig. 4). We propose revisions of the internal stratigraphy of the Copperopolis Latite and define informal lithologic sequences produced during six magmatic episodes (fig. 3): (1) construction of a dome field and eruption of one or more widely dispersed ash flows (Packard and Fernow Quartz Latites); (2) growth of small stratocones comprising intermediate flows and heterolithic breccias (lower flow sequence); (3) two phases of explosive volcanism and caldera collapse, which produced a semicircular depression filled with at least 1 km of tuff and lacustrine siltstone (lower and upper pyroclastic sequences); (4) eruption of post-caldera latite tuff, possibly during an early episode of resurgence (Latite Ridge Latite); (5) extensive post-caldera magmatism producing intrusions both within and along margins of the caldera (Sunrise Peak Monzonite Porphyry, Silver City stock, and other intrusions); and (6) eruption of post-resurgent(?) latite flows and tuffs (upper flow sequence and Laguna Springs Volcanic Group).

Episode 1: Packard and Fernow Quartz Latites

Eruptions of the Packard and Fernow Quartz Latites, both deposited entirely outside the caldera proposed here, were apparently unrelated to caldera formation. The Packard Quartz Latite is a thick section of overlapping flows that formed an extensive dome field north of the caldera. Morris and Lovering (1979) cited drill-hole evidence for a total thickness in excess of 1000 m near the eastern margin of the Packard outcrop area adjacent to Goshen Valley. Morris and Anderson (1962) mapped the paleorelief at the base of the Packard, and defined a deep valley draining highlands to the south and west. Packard flows typically display pink to white color layers, layers of stretched vesicles, and platy jointing that define folded flow layering. Textural and structural variations, along with discordant flow folding, mark multiple flow units within the Packard Quartz Latite, with some younger flows ramping over or butting against older flows.

Zones of dense black vitrophyre mark vent areas where temperatures were locally higher. One such area, near the Silver Shield dike (Morris and Lovering, 1979) in the northeastern part of the Eureka Quadrangle, has a vertical flow-foliation in a central black vitrophyre which flattens as the glassy rocks grade outward to more typical pink quartz latite porphyry. Thin deposits of unwelded tuff occur locally near the base of the unit; these contain broken crystals of plagioclase, sanidine, quartz, and biotite in a matrix of glass shards. Petrographic evidence for a pyroclastic origin is absent, however, from most other parts of the Packard Quartz Latite.

The possibility that the ubiquitous flow foliation formed by rheomorphism from a pyroclastic deposit must be considered. Several arguments against a remobilized pyroclastic origin are: (1) exceedingly sparse preservation of pyroclastic textures, (2) complete lack of welding in the thin interlayered pyroclastic units, (3) no gradation between unwelded tuffs, layered flow rocks, and vitrophyres, and (4) limited outcrop area and abrupt thinning of the lithosome from several thousand feet thick to nothing in only a few miles. Morris and Lovering (1979) described an upper vitrophyre layer, which we have not yet examined, which is intercalated with lapilli tuffs and may be of pyroclastic origin. Delineation and correlation of this upper unit is an important problem for future work.

The Fernow Quartz Latite, exposed south of the caldera, is a widespread ash-flow sheet, whose source remains undiscovered. Though the phenocryst assemblage is identical to that of the Packard Quartz Latite, coarse, smoky, beta-quartz and clear sanidine are far more abundant in the Fernow tuff. Eutaxitic textures are widespread; partial welding and a distinct compaction foliation are evident in most exposures. Thin sections display abundant shattered crystals, heavily oxidized biotite flakes, and beautifully preserved glass shards. The tuff is draped over paleotopography similar to the present day relief (fig. 5), with highlands to the north and west. The total thickness is unknown, as the top of the unit is nowhere exposed and the base is highly irregular; exposed thicknesses do not exceed about 150 meters.

Both the Packard and Fernow Quartz Latites appear to underlie pre-caldera latite flows (lower flow sequence, figs. 3 and 6). Reconnaissance mapping in the Eureka Quadrangle reveals dense, black, pyroxene-phyric flows lithologically identical to the lower flow sequence overlying the Packard Quartz Latite. Morris and Lovering (1979) also correlate these flows with those in Copperopolis Canyon. Where the base of the Packard is exposed, the flows rest depositionally on Paleozoic sedimentary rocks or on the Apex Conglomerate, a thin layer of erosional rubble derived from the Paleozoic section. There is no evidence for pre-Packard volcanism.

The Fernow Quartz Latite is similarly bracketed stratigraphically by the Paleozoic rocks and the lower flow sequence at one locality near the western margin of the Tintic Mountain Quadrangle at 47°30"N latitude (fig. 6). South of the study area, however, in exposures along Utah state highway 132, the Fernow Quartz Latite overlies a conglomerate of volcanic cobbles of uncertain origin. Morris (1977) interpreted the conglomerate as a younger unit which lapped up on the flanks of a hill of Fernow Quartz Latite. This interpretation requires extreme relief and does not account for a thin baked zone in the conglomerate just below the tuff. In addition, buff to reddish volcanic lithic fragments are widespread in the Fernow Quartz Latite particularly near the base. A source for volcanic material apparently existed prior to eruption of the Fernow tuff.

The Packard Quartz Latite reaches its greatest thickness several miles outside the Tintic caldera and has not been recognized within the caldera. It seems unlikely, therefore, that its eruption was directly linked to caldera collapse. The Fernow Quartz Latite could have been erupted from a source to the north and may have induced collapse of the caldera. In support of this scenario, exposures of quartz latite tuff north of Chimney Rock Pass in the Allens Ranch Quadrangle north of Eureka (Proctor, 1956) are lithologically identical to the Fernow Quartz Latite, suggesting a broad outflow sheet both north and south of the Tintic caldera. It is surprising, however, that no quartz-bearing, crystal-rich tuff has been observed within the caldera, even in drill holes reaching depths of 1000 meters. If the Fernow tuff is related to the caldera, it must have been a very early, more silicic eruptive phase that preceded caldera collapse. Further efforts to locate the source of the Fernow Quartz Latite and to date both the tuff and intracaldera rocks should help to resolve this ambiguity.

Episode 2: Lower flow sequence

Black to dark-brown, plagioclase- and pyroxene-phyric massive flows characterize the pre-caldera lower flow sequence. The flows dominate the western flank of the East Tintic Mountains south of the Tintic caldera (fig. 6). Although correlation remains tentative, similar flows are observed north of the caldera, notably on east-trending ridges 1 mile south-southeast of

Latite Ridge and also north of Gold Bond Spring along the Silver Pass Road (flow member of the Copperopolis Latite of Morris and Lovering, 1979). Four flow units are herein defined on the bases of varied groundmass color and texture, size and abundance of phenocrysts, and style of jointing (pl. 1). The oldest of the four are intercalated with coarse breccias in Copperopolis Canyon near the southern boundary of the caldera, suggesting a source or volcanic edifice in that area. Irregular contacts between the flow units define moderate topographic relief at the time of deposition. The chaotic distribution of the units is most pronounced in the north, again suggesting greater relief and a possible source in that area.

The stratigraphic position of the lower flow sequence is somewhat ambiguous. At one locality noted above, the flows clearly post-date quartz latite correlated with the Fernow Quartz Latite. The correlative(?) flows north of the caldera overlie the Packard Quartz Latite. Very limited contacts with the caldera fill along the southern margin of the caldera are largely obscured by intrusive bodies and associated alteration. The only certainty is that the oldest unit in the lower flow sequence underlies tuff breccia at the base of the lower pyroclastic sequence. The relative ages of younger units in the lower flow sequence and younger units in the pyroclastic sequences cannot be determined from contact relationships. Because of the restricted outcrop area of the flows and the fundamental change in magmatic style in the lower pyroclastic sequence, we assume that the entire lower flow sequence pre-dates the caldera.

Episode 3: Lower and upper pyroclastic sequences

The lower and upper pyroclastic sequences are exposed in a semi-circular area between Silver Pass and Copperopolis Canyon, and represent caldera fill (figs. 3 and 6, and pl. 1). The predominant units in the lower flow sequence are a basal tuff breccia and a thick welded lithic crystal tuff, both with abundant foreign clasts including Paleozoic sedimentary rocks. These pyroclastic units are overlain by several small flow units. The upper pyroclastic sequence is characterized by a thick section of lapilli tuff overlain by lacustrine deposits of tuffaceous siltstone.

The tuff breccia at the base of the lower pyroclastic sequence documents a violent pyroclastic eruption accompanied by collapse. The breccia is heterolithic and clast size varies from lapilli to house-sized slide blocks. Although the exposures are at least a mile from known Paleozoic outcrops, clasts of quartzite, shale, and carbonate are ubiquitous. Conspicuous megablocks of white quartzite at the west end of Volcano Ridge are visible from Highway 6. The blocks float in a matrix of pale- to dark-green crystal lithic lapilli tuff with abundant plagioclase and lapilli of flattened, chloritized pumice, other volcanic fragments, and Paleozoic sedimentary rocks. The strike belt of Cambrian Tintic Quartzite projects under this locality. On the northwest flank of Volcano Ridge, chaotically distributed clasts of varied size and lithology in a tuff matrix attest to violent collapse. None of the volcanic clasts have been positively correlated with specific units in the lower flow sequence, but many are dark, massive pyroxene-bearing porphyry.

The tuff breccia is overlain by welded crystal lithic lapilli tuff of similar composition. Crystals, comprising as much as 20 percent of the rock, include abundant blocky plagioclase, chloritized biotite, and rare quartz. As in the tuff breccia, lithic fragments include volcanic detritus and Paleozoic sedimentary rocks, ranging in size from granules to pebbles and rare boulders. The large, bold outcrops of olive-green welded tuff are characterized by a well-defined, northeast-dipping compaction foliation. The tuff breccia and green welded tuff have a combined thickness of as much as 530 m, and were deposited in the proposed source area for the lower flow sequence. Collapse, indicated by the megabreccia, seems necessary to accommodate the great depositional thickness in an area of formerly positive relief.

Three small flow units of plagioclase-pyroxene porphyry overlie the pyroclastic rocks of the Volcano Ridge sequence. Non-horizontal and non-planar basal contacts indicate that the flows were extruded onto an irregular topography. These units document a hiatus prior to renewed pyroclastic activity which produced the lapilli tuff of the upper pyroclastic sequence.

The second major pyroclastic event produced more than 300 m of crystal vitric lapilli tuff. Unlike the tuffs in the lower pyroclastic sequence, lithic fragments are rare. The lapilli are flattened, chloritized pumice chunks that lend the rock a mottled pale blue-green to green color. Crystals, predominantly of opaque white plagioclase with lesser biotite and rare quartz, locally comprise up to 50 percent of the rock. Varied grain size and repeated graded sequences suggest multiple eruptive pulses. Fine-grained tuff near the top of the section grades into well-indurated blue-green siltstone. The siltstone is very poorly exposed, but bedding surfaces on rare outcrops and abundant float reveal plant debris, mudcracks, and small, low-amplitude ripples. Layers of fine, pale green ash and lenses of darker green volcanogenic sandstone occur sporadically within the siltstone. Thin limestone lenses are intercalated with the siltstones in Government Canyon, and are discontinuously present in the uppermost part of the unit on the western flank. These features suggest that the silt was derived from the blue-green lapilli tuff and accumulated in a shallow lake which occupied the center of the Tintic caldera. Alternatively, the lacustrine rocks may represent a western promontory of the Oligocene Goldens Ranch Formation which records lacustrine deposition east of the East Tintic Mountains (Muessig, 1951; Meibos, 1983; Jeffrey D. Keith, written commn., 1988). Nevertheless, the lacustrine rocks demonstrate that the area remained a topographic basin even after deposition of at least 800 m of tuff, providing further evidence of caldera collapse.

The total thickness of pyroclastic material within the Tintic caldera cannot be determined. Core from drill holes in Diamond Gulch reveal crystal lapilli tuff as much as 1000 m below the surface (Welsh, 1985). These rocks have been dropped down an unknown amount, however, by normal movement on the Diamond Gulch Fault. Nevertheless, continuous exposure in drill core and surface outcrops indicate a minimum of 1 km of pyroclastic fill, and suggest much greater thicknesses.

Episode 4: Latite Ridge Latite

The Latite Ridge Latite, named by Morris and Lovering (1979) for exposures in the Eureka Quadrangle, is a distinctive brick-red, welded, crystal vitric tuff, widely exposed both north and south of the Tintic caldera. A characteristic lithologic sequence is observed at several localities. The base is typically marked by an unwelded tuff, up to 30 m thick, that commonly displays cross-beds, scours, and both normal and reversed grading suggestive of a surge deposit. The unwelded tuff grades through a few meters into a dense black vitrophyre. Above the vitrophyre, black glassy streaks are progressively thinner and less abundant as the vitrophyre grades into the typical brick-red welded tuff with undulous black streaks. At least two additional vitrophyre layers at 10 to 20 m intervals within the welded tuff suggest several ash-flow pulses, each marked by a vitrophyre near its base. The brick-red welded tuff is overlain by a weakly welded, purple-blue to pink, plagioclase-rich lapilli tuff and tuff breccia. This upper subunit is particularly well exposed along the Silver Pass road, notably at the benchmark at the top of the pass and along roadcuts north of the pass. Color variations are, in part, a result of hydrothermal alteration. West of Silver Pass, for example, where the tuff is adjacent to or overlies apophyses of the Silver City stock, it is strongly argillized and cut by pebble dikes.

The Latite Ridge Latite contains crystals of plagioclase, oxidized biotite, minor sanidine, and rare pyroxene and quartz. Lapilli of exotic volcanic fragments are common near the base of the unit, decreasing in abundance up section. Morris (1975) proposes that the latite porphyry of Burnt Hollow (pl. 1), in the center of the Tintic caldera, is the source for the Latite Ridge Latite. The phenocryst population is similar and it is centrally located with respect to the distribution of Latite Ridge Latite outcrops. Firm evidence, however, from geochemical or geochronological studies, is not yet available.

The stratigraphic position of the Latite Ridge Latite cannot be completely constrained. It clearly overlies the Packard and Fernow Quartz Latites and the lower flow sequence, and it is intruded and altered by the Silver City stock. However, it is nowhere in contact with the pyroclastic rocks which fill the Tintic caldera; their relative ages cannot be determined on the basis of field relationships. Petrographic similarity of the Latite Ridge Latite to post-caldera rocks suggests that the stratigraphic position assigned by Morris (1975) is correct. Unlike the Latite Ridge Latite, the majority of the intracaldera rocks are biotite-free or biotite-poor, whereas the post-caldera flows (upper flow sequence) are generally biotite-rich. In addition, a dike of brick-red biotite latite, remarkably similar to the Latite Ridge Latite, cuts intracaldera rocks in Government Canyon. Again, results of geochemical and geochronological studies in progress will help resolve these uncertainties.

Episode 5: Post-caldera intrusive rocks

Four stages of intrusive activity followed and possibly accompanied caldera collapse. The stratigraphic positions shown on plate 1 indicate maximum ages, based on the youngest unit known to be cut by a member of each intrusive suite. Intrusive bodies which occupy the center of the caldera are relatively fresh monzonites that have not significantly altered their host rocks. Those which intruded along the caldera margin, on the other hand, consistently show pervasive alteration, including strongly argillized halos. One exception to this generalization is the widespread argillic and pyritic alteration in Government Canyon, apparently associated with a dike swarm correlated with the intracaldera Sunrise Peak Monzonite Porphyry (Kim, 1988; Jeffrey D. Keith, personal commun., 1987).

The apparently oldest intrusive bodies, including the breccia pipe, do not cut rocks younger than the lower pyroclastic sequence. The three intrusive types in this group, the mottled green intrusion, the breccia pipe, and the gray-brown intrusions, are exposed predominantly in Copperopolis Canyon. The breccia pipe contains abundant blocks of fractured quartzite, up to 100 m in diameter, and smaller clasts of carbonate and volcanic rocks in a strongly argillized igneous matrix. The pipe is an elongate body with vertical contacts parallel to the contact between caldera fill and the lower flow sequence and parallel to a high-angle fault between the two pyroclastic sequences. We propose that the pipe was emplaced along a fracture system related to caldera collapse.

The middle intrusive bodies, includes the Latite Porphyry of Burnt Hollow (defined by Morris, 1975) and a swarm of small cliff-forming dikes and plugs. These intrusions cut the upper pyroclastic sequence, but not the overlying upper flow sequence. The relative ages of the Burnt Hollow and cliff-forming intrusions cannot be determined.

The Latite Porphyry of Burnt Hollow of Morris (1975), includes a large, elongate stock roughly 1.3 by 2.5 km, and several small satellite plugs. Intense argillic and local silicic alteration has obliterated much of the original texture of the stock; ghosts of coarse plagioclase laths, oxidized biotite, and relict quartz are visible in a matrix of white kaolinitic clays. Alteration diminishes northward, revealing an aphanitic to microcrystalline red-purple groundmass. Separation into altered and unaltered subunits on plate I is based on recognition of the red-purple groundmass; the contact is in fact gradational.

The cliff-forming intrusions comprise one small, irregular plug and a cluster of short, north-trending dikes. The intrusions form bold, vertical cliffs and free-standing ridges up to 40 m high. Phenocrysts of fine, clear plagioclase, abundant biotite, and sparse pyroxene occupy a dark-green microcrystalline groundmass. Little alteration is associated with this intracaldera intrusive suite.

The youngest intrusive bodies include the Monzonite Porphyry of Sunrise Peak and its numerous satellite intrusions, dark-green pyroxene porphyry, and steel-gray plagioclase porphyry intrusions of approximately the same age. The Sunrise Peak intrusions contain coarse, blocky, white plagioclase, biotite, and minor pyroxene in a microcrystalline green groundmass. Some of the intrusions may have been feeders for the lithologically identical flows of Sunrise Peak in the upper flow sequence. Many dikes and plugs of Sunrise Peak porphyry in the Volcano Ridge and Copperopolis Canyon areas show a strong preferred orientation parallel to northeast-trending normal faults. Although the intrusions are not significantly altered, they are associated with northeast-trending quartz veins, many of which have been prospected for copper and gold. Some of the quartz veins cut the Sunrise Peak intrusions, however, suggesting that both followed the same structural weakness, but may have been genetically unrelated.

Many small plugs and dikes of plagioclase-pyroxene porphyry with a dense steel-gray groundmass of fine, felted plagioclase laths comprise the steel-gray intrusions. Like the Sunrise Peak intrusions, these are lithologically identical to a flow unit in the upper flow sequence, and may, in part, represent feeders. Although the steel-gray flows overlie the flows of Sunrise Peak, complex, mutually cross-cutting relationships between the two intrusive units suggests that they are essentially coeval.

The Silver City stock and its many small satellite intrusions were emplaced during the youngest magmatic event associated with the Tintic caldera. Dikes and plugs of Silver City monzonite cut intrusive rocks of the

Sunrise Peak Monzonite Porphyry (Jeffrey D. Keith, written commun., 1988). The biotite- and amphibole-bearing quartz monzonite of the main stock is intensely altered; it hosts fissure veins mined for gold and copper, including the discovery site for the Tintic mining district. All of the major deposits of the Main and East Tintic districts are spatially associated with Silver City stock or its equivalents. Broad halos of phyllic or argillic alteration invariably surround Silver City intrusions. No intracaldera rocks occur north or west of the main Silver City stock; it appears to have intruded the northern margin of the caldera. Surface exposures of the satellite intrusions define a strong north-northeast lineament, probably following Sevier (Cretaceous) structures in the Paleozoic sedimentary rocks.

A blind intrusion of monzonite porphyry, informally termed the "alfalfa field porphyry" but here named the Southwest Tintic Monzonite Porphyry, underlies the western edge of Diamond Gulch. Its existence is evinced in surface outcrops by well-defined, concentric phyllic and propylitic alteration zones (Norman, 1983). An inner potassic alteration zone is revealed by drill core from Diamond Gulch. Two drill holes intersected the porphyry at 150 to 600 meters below the surface (SWT-32 and 33, Welsh, 1985). It is a biotite hornblende quartz monzonite characterized by sparse orthoclase phenocrysts as much as 4 cm long. The porphyry intrudes latite flows and pyroclastic rocks which host stockwork chalcopyrite and molybdenite veins with an estimated average grade of 0.2 percent copper at depths greater than 370 to 920 m. Ten drill holes also intersected a chalcocite enrichment blanket at depths of 30 to 125 meters, yielding average grades of 0.1 to 0.2 percent copper (Welsh, 1985). Thick sections of pyroclastic rock are intersected by the drill holes extending to at least 1000 meters below the surface; hence, the margin of the caldera must be near or west of the Southwest Tintic porphyry.

Episode 6: Late latite tuffs and flows: upper flow sequence and the Laguna Springs Volcanic Group

Post-caldera flows and tuffs comprise two major groups: (1) the upper flow sequence, which dominates the highest peaks and eastern flank of the East Tintic Mountains (pl. 1 and fig. 6), and (2) the Laguna Springs Volcanic Group of Morris and Lovering (1979), which overlies the Packard Quartz Latite and Latite Ridge Latite east and north of Eureka. The flows of the upper flow sequence are mostly plagioclase-rich, biotite- and pyroxene-bearing porphyries. Their continuous, north-trending, gently east-dipping outcrop belts reflect deposition on subdued topography shaped by the caldera fill. The flows are cut by few intrusions and show little alteration. That is, they either post-date the caldera-related intrusive activity of Episode 5, or are spatially removed from it.

The relatively simple outcrop pattern of units in the upper flow sequence is disrupted somewhat in the vicinity of the cliff-forming intrusions, where the flows overlie one of several talus or erosional breccias (pl. 1). Two of these breccias, the Buckhorn Mountain and Burnt Hollow breccias, are spatially associated with the cliff-forming and Burnt Hollow intrusions, respectively. The breccias each contain clasts of the associated intrusive body. The matrix supported, heterolithic breccias probably originated as debris flows and rock falls from topographic highs and tectonic activity related to emplacement of the intrusions. A third breccia, the breccia of Volcano Ridge, is not associated with any single intrusive body.

It contains a wide variety of clasts, including samples of the Sunrise Peak and steel-gray flows or plugs, but was deposited down-slope to the west; it rests unconformably on members of the lower and upper pyroclastic sequences, as well as the normal fault which separates the two sequences.

The flows and tuffs of the Laguna Springs Volcanic Group (Morris and Lovering, 1979) characteristically contain hornblende in addition to the ever-present plagioclase and varied amounts of biotite, augite, and sanidine. Morris and Lovering (1979) suggested that the latites are the extrusive equivalent of the Silver City quartz monzonite. They reported moderate argillization and pyritization of the tuffs and flows, however, which indicates that they pre-date the latest of the Silver City intrusions, or that there is some later, yet unidentified heat source for hydrothermal alteration. The temporal relationship between the Laguna Springs Volcanic Group and the upper flow sequence cannot be determined, as they are nowhere in contact. They are mineralogically dissimilar, however, and probably not correlative.

The Silver Shield Quartz Latite of Morris and Lovering (1979), which overlies the Laguna Springs Volcanic Group on the far east side of the East Tintic Mountains, is a coarsely porphyritic quartz latite with characteristic large sanidine and plagioclase phenocrysts. K-Ar ages of about 18 Ma (Miocene) indicate that they post-date other igneous rocks of the Tintic volcanic field by ten to twenty million years (Laughlin and others, 1969). The composition is unusual for Miocene rocks in this part of the Basin and Range; most Miocene and younger rocks are part of the extension-related bimodal suite: either basalts or high-silica rhyolites.

History of the Tintic Caldera

Four lines of evidence strongly support the existence of a caldera in the Tintic area. First, early flows and breccias of the Southern Flow sequence are overlain by at least 1 km of tuff breccia, lapilli tuff and lacustrine siltstone, which define a 20 km^2 crudely circular outcrop pattern (fig. 3). Second, the basal tuff breccia contains widespread clasts and blocks of Paleozoic basement rocks. Massive blocks, some exceeding 100 m in diameter, indicate collapse or slides from basement highlands, such as a caldera roof or margin, into a basin that was being filled simultaneously by pyroclastic debris. Third, a series of shallow intrusions, including the Burnt Hollow intrusion, the elongate breccia pipe, the Southwest Tintic intrusion (buried under pyroclastic deposits in Diamond Gulch), and the Silver City stock, crudely define a semicircular rim around exposures of pyroclastic and lacustrine caldera fill. These late intrusions may have been localized along a complex ring fracture system. Fourth, an extreme positive magnetic anomaly defines a striking bull's-eye centered directly on the caldera as originally proposed by Morris (1975) reaching a maximum over 800 gammas higher than that in surrounding Paleozoic sedimentary rocks (Mabey and Morris, 1967; David Campbell, personal commun., 1987).

The first three lines of evidence are clear from the description of map units given above. The fourth requires some elaboration. The magnetic anomaly apparently results from an extensive intrusive body underlying the pyroclastic caldera fill and from surface exposures of high susceptibility rocks of the Southern Flow sequence. Mabey and Morris (1969) pointed out that the magnetic anomalies in the Tintic area are not readily explained by the extrusive rocks exposed at the surface. Known thick masses of volcanic material are, in some areas, directly correlated with positive anomalies; in other areas, there is little expression of thick accumulations. For example, a magnetic high extends smoothly from exposures of the Silver City stock east toward Silver Pass, where relatively low-susceptibility altered tuffs dominate surface exposures; thus, the Silver City quartz monzonite, exposed as minor intrusive bodies in the Silver Pass area, must connect at depth with the main Silver City stock. Similarly, the magnetic susceptibility of the caldera fill is more than an order of magnitude lower than that of the Southern flows (about 1 X 10^{-4} and 3 to 5 X 10^{-3} cgs units, respectively). Yet the anomaly declines smoothly to the south across that contact. The intrusive rocks yield the highest susceptibility measurements, typically about 5 X 10^{-3} cgs units. The Diamond Gulch area underlies a saddle in the East Tintic Mountains magnetic high, perhaps the result of destruction of magnetic minerals by extensive alteration in and around the Southwest Tintic intrusion. The poor correlation of the anomaly with susceptibilities of surface exposures strongly suggests that high susceptibility, unaltered intrusive rocks underlie the center of the Tintic caldera.

The history of the Tintic caldera is presented as a series of cross-sections along section B-B' of plate 1 (fig. 7). Changes from one section to the next include one or more tectonic and (or) magmatic events plus reasonable erosion. The geometries of the resulting rock units are otherwise unchanged. The final section is a true cross-section through the present topography and surface exposures.

The margins of the Tintic caldera have proven remarkably elusive. We were unable to map with certainty any ring fractures or collapse breccias in contact with wall rocks. Figure 8 demonstrates that these features are largely obscured by post-caldera events. A simplified caldera with two stages of collapse, as suggested by the historical reconstruction, is intruded along ring fractures by late plugs and dikes (resurgent magmatism?), buried by younger flows (upper flow sequence), and cut by a major normal fault (the Tintic Valley Basin-and-Range fault). Subsequent erosion has exposed the caldera fill only in the southwestern quadrant of the caldera and in a small window in Government Canyon. The ring fractures are either obliterated by later intrusive activity or buried under younger flows and late Tertiary basin fill.

Geochronologic Constraints

A middle Eocene fossil age for Tertiary volcanism in the East Tintic Mountains (Muessig, 1951) was accepted until potassium-argon (K/Ar) ages of 27.8 to 38.7 were reported (table 1). Morris and Lovering (1979) argued that Early Oligocene ages clustering around 32 Ma are correct for most East Tintic volcanism. Recently, however, slightly older ages have been suggested for the East Tintic volcanic section and possibly correlative rocks in adjacent mountain ranges. These apparently conflicting data indicate a need to review known age relations and recommend additional radiometric age determinations.

The first age information for volcanic rocks of the East Tintic Mountains came from correlative(?) rocks to the southeast in the Goldens Ranch Formation on Long Ridge. The Goldens Ranch Formation comprises three members: the lower Chicken Creek Tuff Member, the middle Hall Canyon Conglomerate Member, and the upper Sage Valley Limestone (Meibos, 1983). The limestone contains plant debris identified as middle Eocene by Roland W. Brown, and the

Table 1. Summary of published K/Ar ages for volcanic rocks in the East Tintic Mountains and adjacent areas

Unit	Quadrangle	Mineral	Age (Ma)	Reference
Silver Shield Dike	Eureka	biotite	17.9 +/- 0.5	1
Silver Shield Quartz Latite	Eureka	sanidine #1	18.3 +/- 0.5	1
		sanidine #2	15.9 +/- 2.6	1
Tintic Delmar Quartz Latite	Eureka	biotite	32.2 +/- 1.0	2
		hornblende	32.3 +/- 1.0	2
Pinyon Queen Latite	Eureka	sanidine	27.8 +/- 0.8	1
Big Canyon Latite	Eureka	whole rock	35.3 +/- 1.4	2
Silver City Quartz Monzonite	Eureka			
sample 1		biotite	34.1 +/- 1.0	1
sample 2		biotite	32.1 +/- 0.9	1
		hornblende	38.7 +/- 1.9	1
sample 3 (main stock)		biotite	31.5 +/- 0.9	1
Hydrothermal biotite from stockwork ore	Eureka	biotite	31.4 +/- 0.5	2
Southwest Tintic stock SWT-32, 1644-1690'	McIntyre	biotite	34.4 +/- 1.2	3
Burnt Hollow stock	Tintic Mtn.	sanidine	36.2 +/- 1.5	3
Pristine Black flows	Tintic Mtn.	whole rock	35.1 +/- 1.7	3
Packard Quartz Latite	Eureka	biotite	32.8 +/- 1.0	1
		sanidine	32.7 +/- 1.0	1
Fernow(?) Quartz Latite	Champlin Pk.	whole rock	37.1 +/- 1.8	4
Chicken Creek tuff Goldens Ranch Formation	Nephi NW	biotite	33.2	5
Chicken Creek sill	Nephi SW(?)	biotite	34.1 +/- 1.7	6
		whole rock	38.9 +/- 1.9	6
Moroni Volcanics	Moroni NE(?)			
sample 1 (upper?)		whole rock	24.6 +/- 1.2	6
sample 2 (lower?)		whole rock	38.3 +/- 1.9	6

References:
(1) Laughlin and others, 1969.
(2) Morris and Lovering, 1979.
(3) Welsh, J.E., 1971, unpublished Kennecott memorandum, received from H.T. Morris, written communication, 1988; data from Geochron Laboratories.
(4) Villien, 1984; correlation based on Higgins, 1982.
(5) Everenden and James, 1964.
(6) LeVot, 1984; precise locations and stratigraphic positions unknown.

underlying conglomerate grades laterally to the northwest into volcanic breccias possibly correlative with the Laguna Springs Volcanic Group of theEast Tintic Mountains (Muessig, 1951). As the Green River Formation, which underlies the entire Goldens Ranch Formation, is lower to middle Eocene, Muessig concluded that the East Tintic volcanism must also be middle Eocene.

A 33.2 Ma K/Ar age for the Chicken Creek Tuff, however, suggests that the Eocene age assignment for the Sage Valley Limestone is incorrect (Evernden and James, 1964). Subsequent K/Ar geochronology supports this conclusion. H.D. MacGintie, cited in Evernden and James (1964), believes the limited flora in the Sage Valley Limestone are indeterminate and could range from middle Eocene to upper Oligocene. Witkind and Marvin (1989) reported new K/Ar data for the Goldens Ranch and Moroni Formations that range from 30 to 39 Ma. On the basis of overlapping ages and similar stratigraphy, the authors correlated the two geographically distinct formations. They proposed that the upper volcanic sections of both formations correlate broadly with the volcanic rocks of the East Tintic Mountains. The varied ages are not necessarily in agreement with stratigraphic positions and, thus, constrain the age of the volcanism only to late Eocene to early Oligocene.

One additional type of age information is available for the volcanic section in the East tintic Mountains. Using samples collected by Jeffrey D. Keith (University of Georgia), Bart Kowallis (Brigham Young University) has determined fission-track ages of about 37 Ma for detrital apatite from two limy siltstone units in Government Canyon (Kim, 1988). The lacustrine sedimentary rocks overlie crystal tuff of the Copperopolis pyroclastic sequence and are cut by dikes petrographically similar to the Sunrise Peak stock. Though these data indicate only the age of the apatite, rather than the age of the sedimentary rocks, the implied latest Eocene age is slightly older than that commonly accepted for East Tintic Mountains volcanism.

The data in table 1 are listed in the stratigraphic order determined from field relationships. As with the data of Witkind and Marvin (1989), the relative ages do not agree with the observed stratigraphic sequence, suggesting that the K/Ar dating technique lacks sufficient precision to resolve stratigraphic ambiguities. The discrepancies in age determinations may be explained in several ways: (1) incorporation of excess argon (especially in volcanic glass), loss of potassium during alteration, or assimilation of older xenoliths to produce too high an age; (2) loss of argon during alteration or hydration of glass to produce too low an age; or (3) incorrect stratigraphic correlations. We lack sufficient details on sample petrography, analytical procedures, and, in some cases, sample locations, to choose among these alternatives. A renewed effort to date the units, with carefully selected samples and modern ^{40}Ar/^{39}Ar incremental heating techniques, is underway to establish with certainty the age(s) of volcanism and mineralization in the East Tintic Mountains.

An added dilemma arises from the limited control on the stratigraphic positions of the Fernow and Packard quartz latites. Meibos (1983) described a thin quartz latite unit overlying the Sage Valley Limestone. On the basis of striking petrographic similarity, he correlates it with the Fernow Quartz Latite. Other workers, however, have correlated volcanic members of the Goldens Ranch Formation with parts of the Tintic Mountain volcanic field, which apparently overlie the Fernow Quartz Latite. As noted above, however, we have observed a volcanic cobble conglomerate underlying the Fernow Quartz Latite. This conglomerate matches descriptions of the Hall Canyon

Conglomerate Member of the Goldens Ranch Formation. Thus, it is possible that the Fernow (and Packard?) Quartz Latite post-dates the Goldens Ranch Formation. If so, other proposed correlations with the Goldens Ranch Formation, such as the lacustrine rocks of Government Canyon (Jeffrey D. Keith, personal commun., 1987; Kim, 1988), or the Tintic Mountain and Laguna Springs volcanic groups (Witkind and Marvin, 1989) must be reconsidered.

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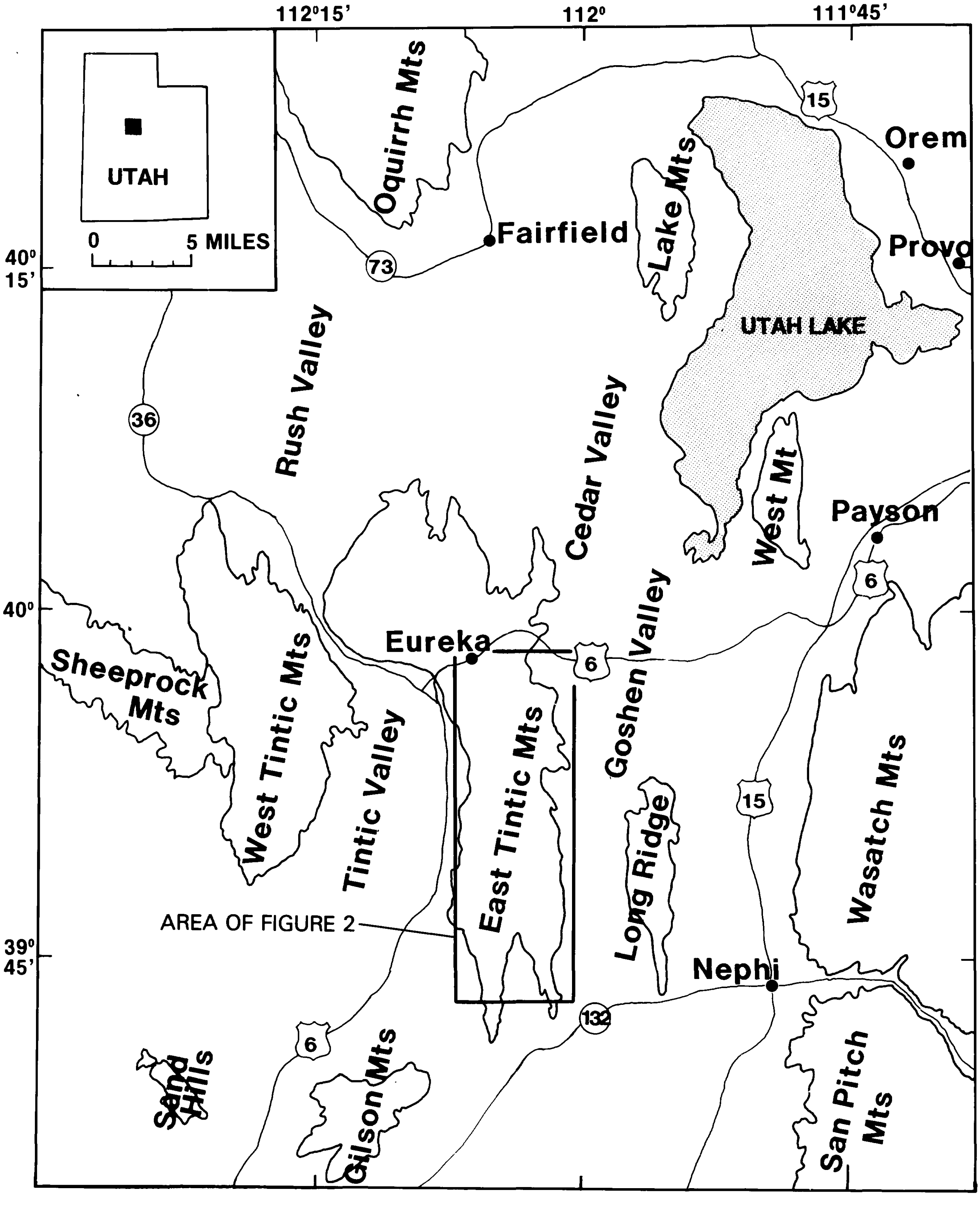


Figure 1. Location of map area in the East Tintic Mountains.

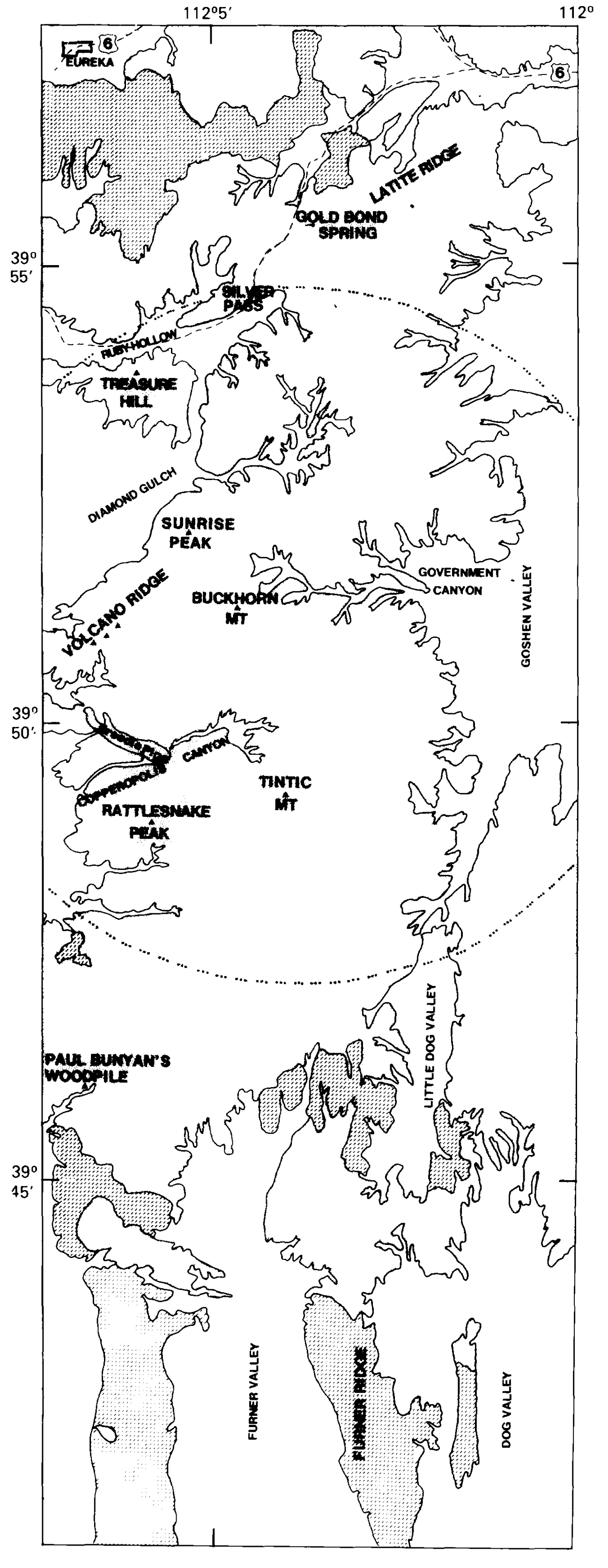


Figure 2. Generalized geologic map of the East Tintic Mountains showing the outline of the caldera proposed by Morris (1975) and principal geographic features.

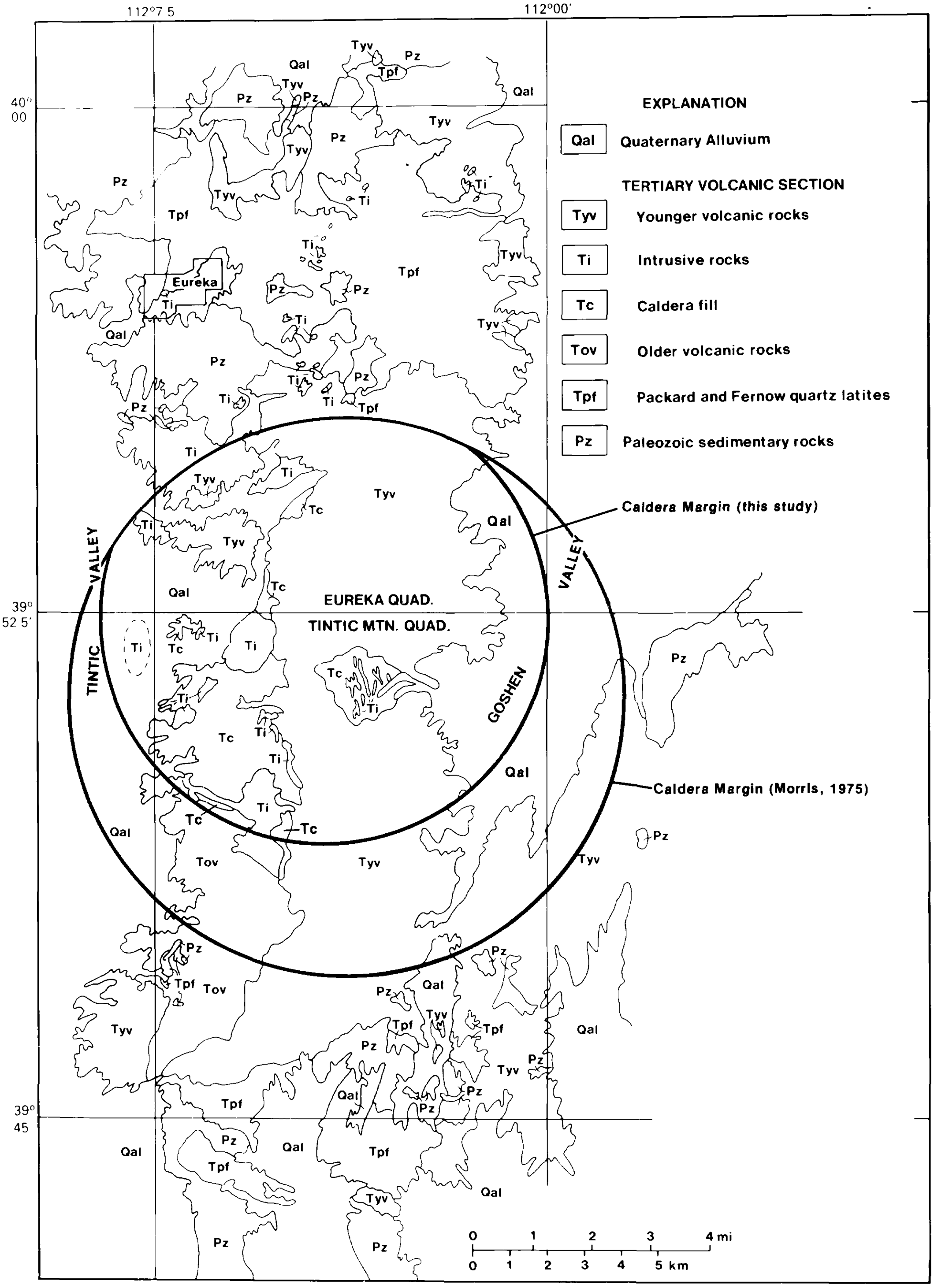
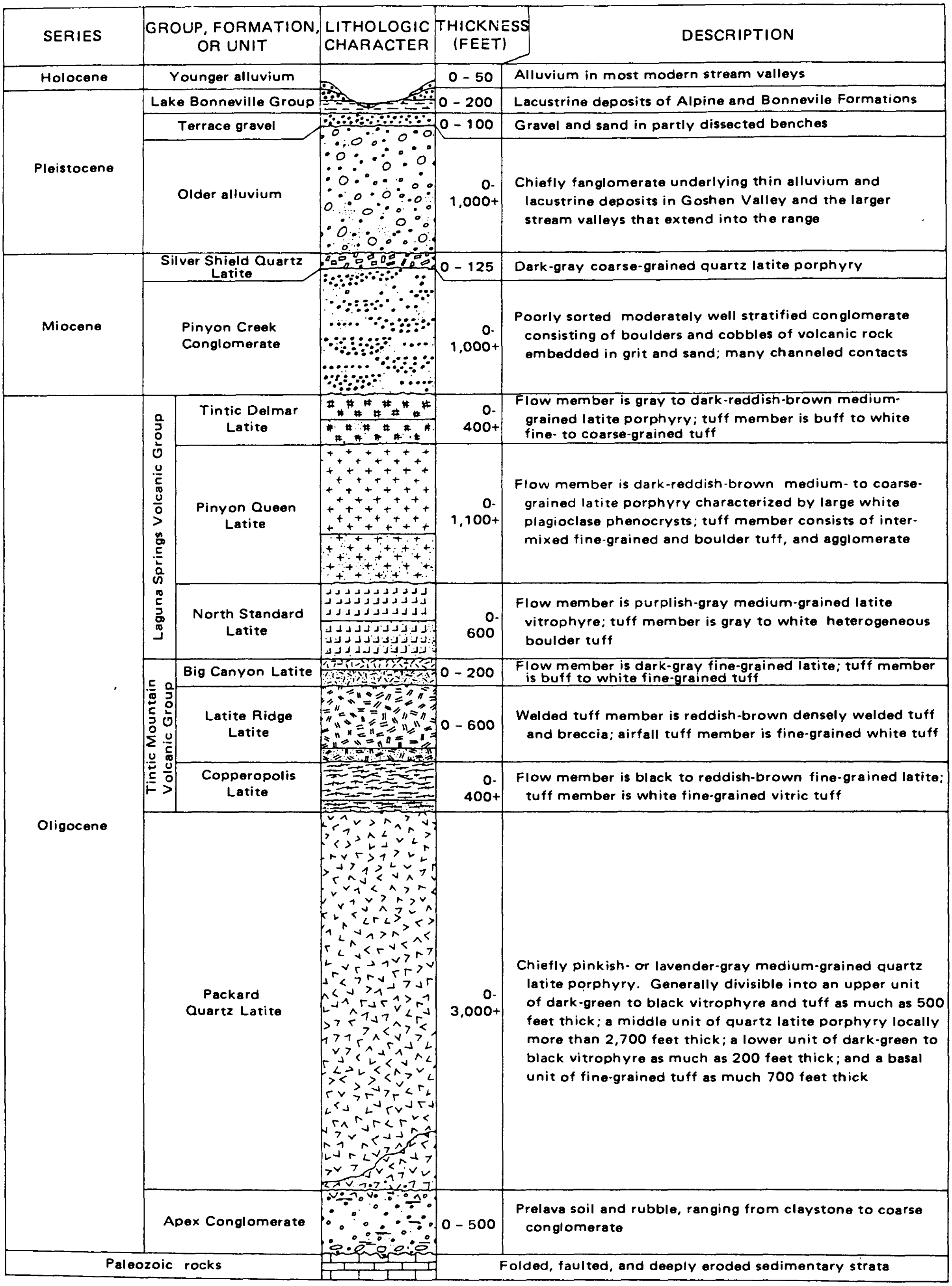


Figure 3. Regional geologic relationships, East Tintic Mountains, modified from Morris (1975). The approximate extent of the Tintic caldera is indicated by the distribution of caldera fill (pyroclastic and lacustrine rocks) and intrusive rocks. Note that mapping is incomplete in the southern third of the Eureka Quadrangle and the southeastern quarter of the Tintic Mountain Quadrangle. Some pre-caldera volcanic rocks may exist in areas shown here as post-caldera rocks; e.g., reconnaissance reveals pyroxene-phyric flows in the Eureka Quadrangle that probably correlate with the pre-caldera lower flow sequence.



SERIES	GROUP, FORMATION, OR UNIT		LITHOLOGIC CHARACTER	THICKNESS (FEET)	DESCRIPTION
Holocene	Younger alluvium			0 - 50	Alluvium in most modern stream valleys
Pleistocene	Lake Bonneville Group			0 - 200	Lacustrine deposits of Alpine and Bonnevile Formations
	Terrace gravel			0 - 100	Gravel and sand in partly dissected benches
	Older alluvium			0-1,000+	Chiefly fanglomerate underlying thin alluvium and lacustrine deposits in Goshen Valley and the larger stream valleys that extend into the range
Miocene	Silver Shield Quartz Latite			0 - 125	Dark-gray coarse-grained quartz latite porphyry
	Pinyon Creek Conglomerate			0-1,000+	Poorly sorted moderately well stratified conglomerate consisting of boulders and cobbles of volcanic rock embedded in grit and sand; many channeled contacts
Oligocene	Laguna Springs Volcanic Group	Tintic Delmar Latite		0-400+	Flow member is gray to dark-reddish-brown medium-grained latite porphyry; tuff member is buff to white fine- to coarse-grained tuff
		Pinyon Queen Latite		0-1,100+	Flow member is dark-reddish-brown medium- to coarse-grained latite porphyry characterized by large white plagioclase phenocrysts; tuff member consists of intermixed fine-grained and boulder tuff, and agglomerate
		North Standard Latite		0-600	Flow member is purplish-gray medium-grained latite vitrophyre; tuff member is gray to white heterogeneous boulder tuff
	Tintic Mountain Volcanic Group	Big Canyon Latite		0 - 200	Flow member is dark-gray fine-grained latite; tuff member is buff to white fine-grained tuff
		Latite Ridge Latite		0 - 600	Welded tuff member is reddish-brown densely welded tuff and breccia; airfall tuff member is fine-grained white tuff
		Copperopolis Latite		0-400+	Flow member is black to reddish-brown fine-grained latite; tuff member is white fine-grained vitric tuff
	Packard Quartz Latite			0-3,000+	Chiefly pinkish- or lavender-gray medium-grained quartz latite porphyry. Generally divisible into an upper unit of dark-green to black vitrophyre and tuff as much as 500 feet thick; a middle unit of quartz latite porphyry locally more than 2,700 feet thick; a lower unit of dark-green to black vitrophyre as much as 200 feet thick; and a basal unit of fine-grained tuff as much 700 feet thick
	Apex Conglomerate			0 - 500	Prelava soil and rubble, ranging from claystone to coarse conglomerate
Paleozoic rocks					Folded, faulted, and deeply eroded sedimentary strata

Figure 4. Columnar section of Cenozoic rocks in the East Tintic mining district. Eureka Qudrangle (from Morris and Lovering, 1979).

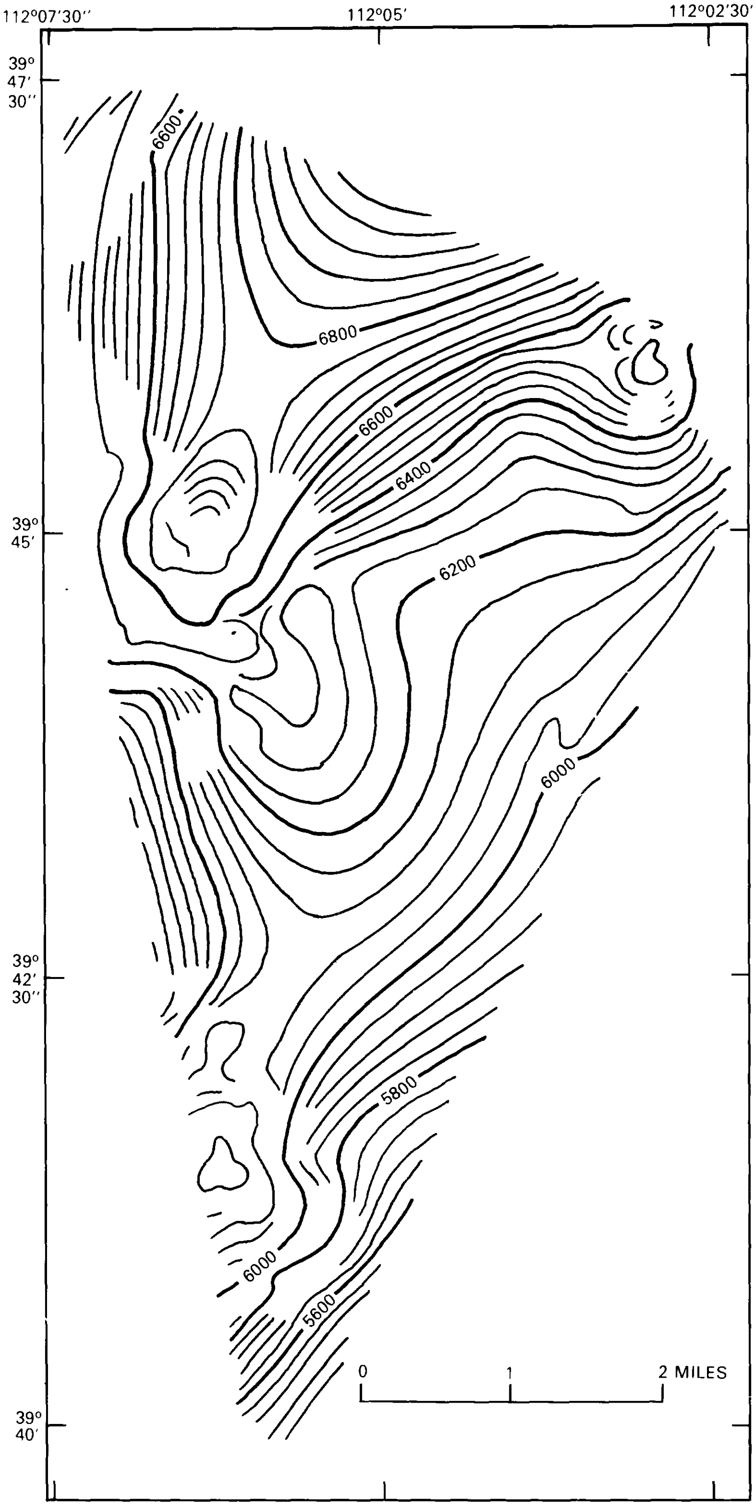


Figure 5. Paleotopography defined by computer-generated contours on the base of the Fernow Quartz Latite in the southern East Tintic Mountains. The map provides generalized image of the topography at the time of eruption of the Fernow. Lack of data points over broad areas limits the map's reliability; most data points are at the corners of the triangular area and the midpoint of the western boundary. Produced by Nancy Nelson with the assistance of Gregory N. Green of the U.S. Geological Survey.

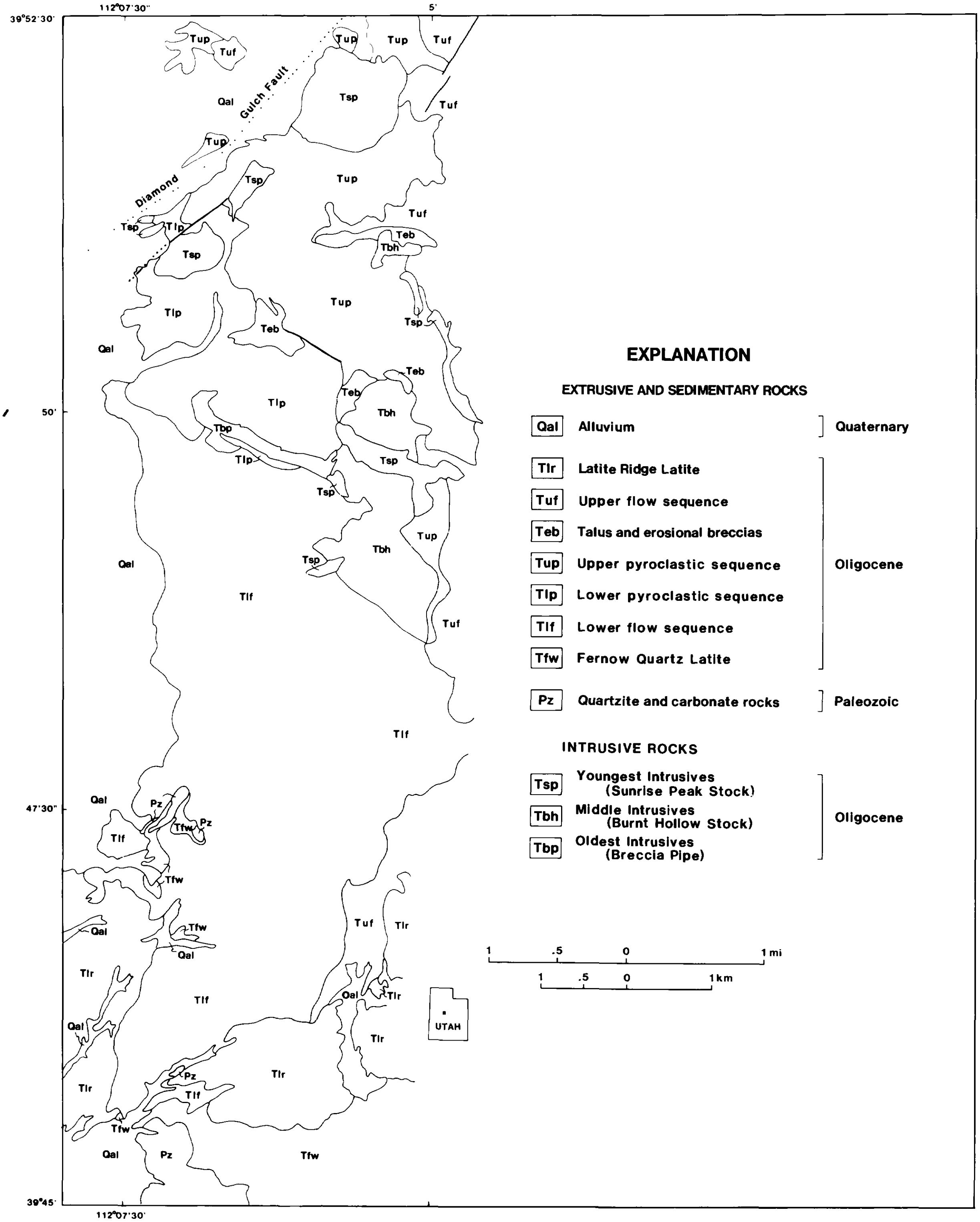
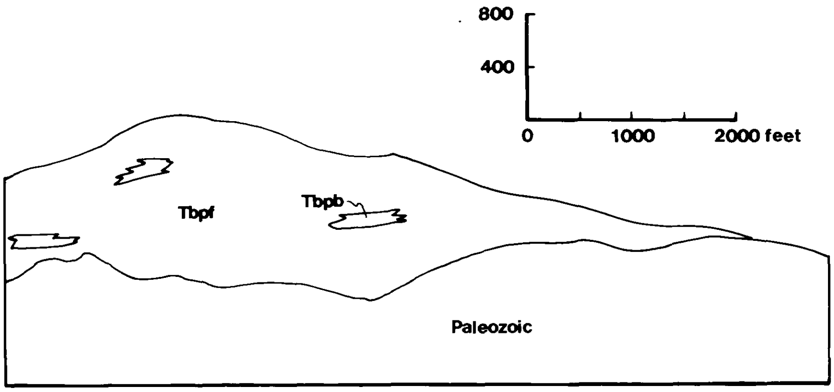
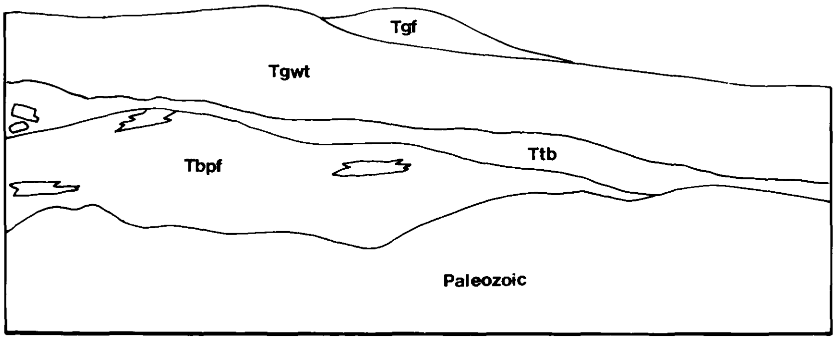


Figure 6. Simplified geologic map of west flank of the East Tintic Mountains, showing the distribution of the principal volcanic sequences and intrusive groups.

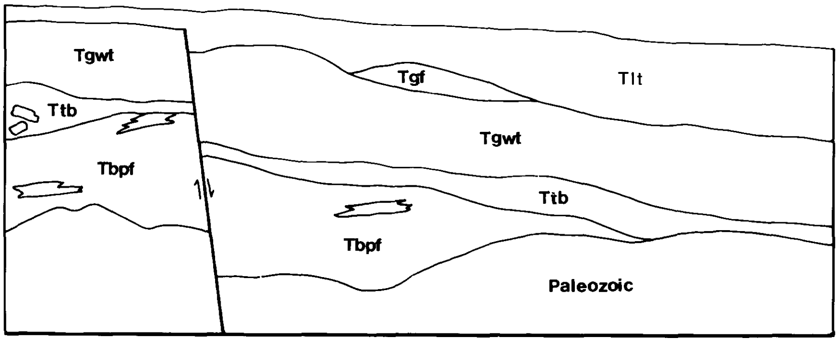
(p. 22 follows)



(1) Flows and breccias of the lower flow sequence are deposited on irregular topography of the Paleozoic basement rocks.

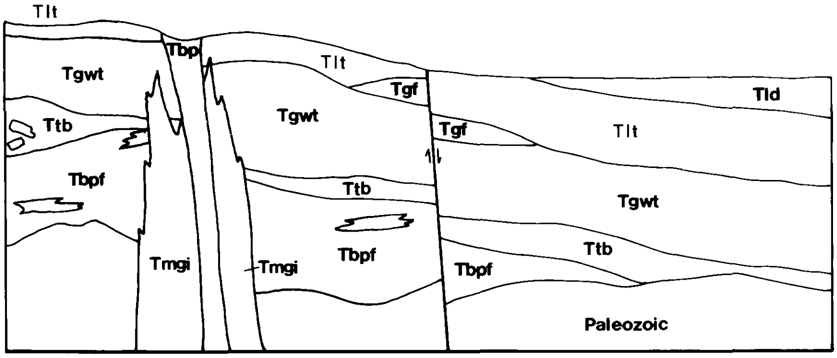


(2) Major pyroclastic eruption results in collapse and deposition of tuff breccia and welded tuff (lower pyroclastic sequence). Unexposed cauldron boundary lies west of section in the present-day Tintic Valley. Massive slide blocks of basement rocks and volcanic clasts from the lower flow sequence are emplaced in lower part of pyroclastic section. Pyroclastic rocks are overlain by additional lava flows.

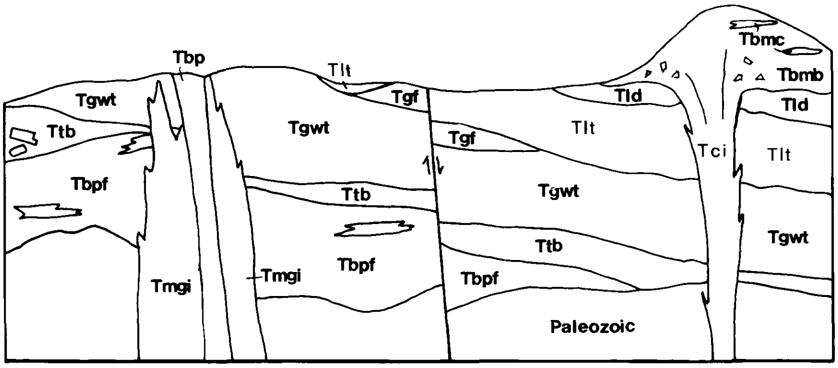


(3) Second major pyroclastic eruption, accompanied by additional collapse, deposits lapilli tuff (upper pyroclastic sequence).

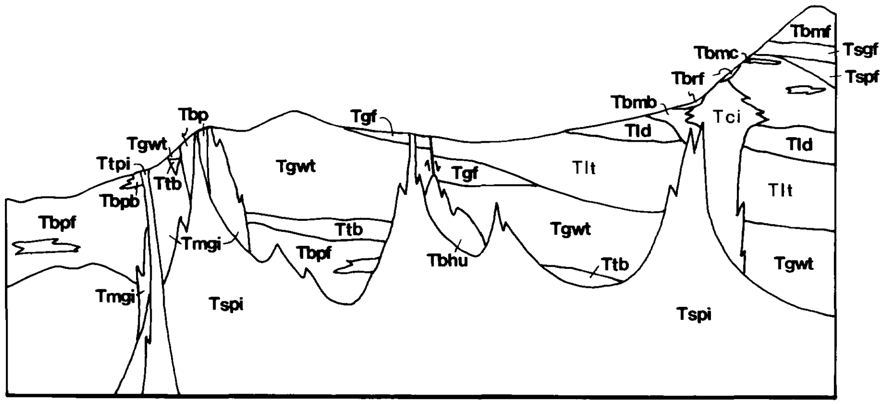
Figure 7. Reconstructed sections illustrating the magmatic history of the East Tintic Mountains volcanic field and the development of the Tintic caldera. Drawn west-east through Copperopolis Canyon (Section B-B', pl. 1). In each successive section, the geometry of the rock units is changed only by faulting, magmatic events, or erosion. The final section (#6) is true to the present topography and surface exposures. Symbols are as used in plate 1.



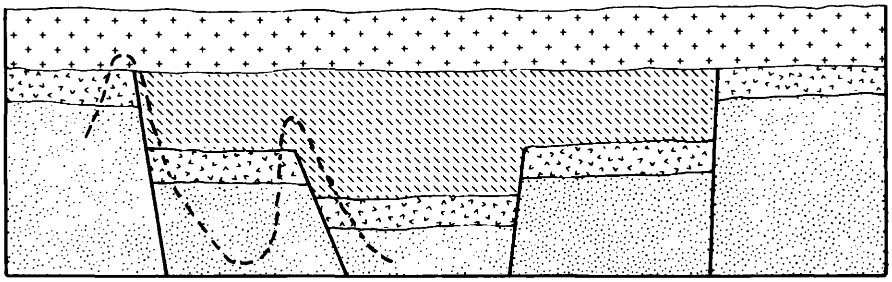
(4) Additional normal faulting, possibly coincident with eruption, offsets lapilli tuff. Intrusions, including a breccia pipe, invade earlier fracture systems. Lacustrine deposits accumulate in the basin.



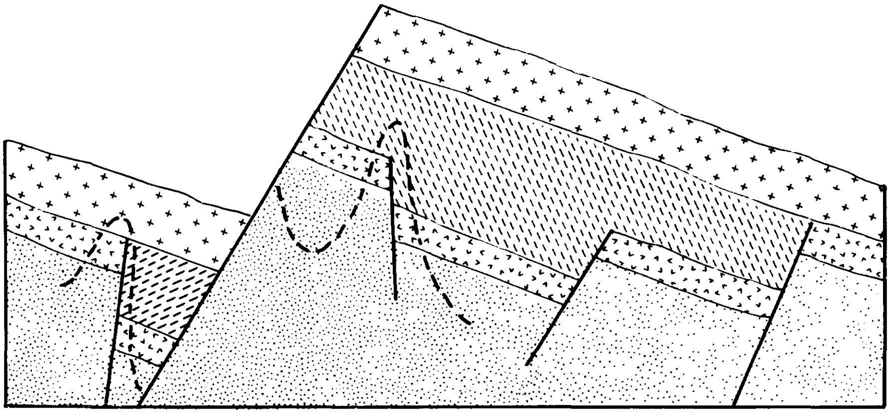
(5) Cliff-forming intrusions emplaced during early episode of resurgent magmatism (upper flow sequence). Breccias develop adjacent to intrusions by spalling and local extrusion of magma. Carbonates intercalated with breccias may have formed in local hot springs.



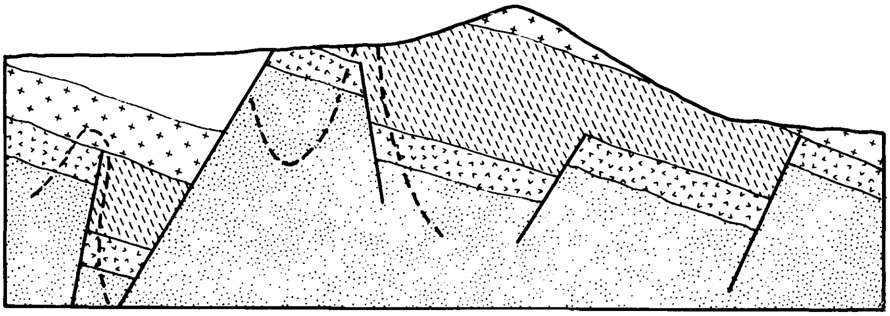
(6) Additional resurgent activity produces Burnt Hollow, Sunrise Peak, and smaller intrusions as well as related flows. Upper flows and breccias of upper flow sequence are deposited.



(1) Generalized cross-section of caldera with two stages of collapse; outflow tuff largely removed by erosion prior to post-caldera flows. Stipple: Paleozoic sedimentary rocks. V-pattern: pre-caldera lava flows. Dash pattern: pyroclastic rocks. Crosses: post-caldera lava flows. Heavy solid lines: faults. Heavy dashed line: possible location of resurgent intrusions.



(2) Basin and Range faulting produces the East Tintic Mountains and adjacent Tintic Valley, offsets the caldera, and tilts all units to the east.



(3) Erosion exposes part of the caldera fill. Ring fractures remain covered, either by post-caldera lava flows or recent valley fill. This figure is a highly simplified, but accurate rendition of cross-section B-B'.

Figure 8. Schematic geometry of the Tintic caldera illustrating the relationship of the caldera margins to the present topography in a west-east cross-section through the East Tintic Mountains.