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DEPOSITIONAL FEATURES OF RHYOLITIC AND ANDESITIC VOLCANICLASTIC ROCKS OF THE MINERAL KING SUBMARINE CALDERA COMPLEX, SIERRA NEVADA, CALIFORNIA

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ABSTRACT

Busby-Spera, C.J., 1986. Depositional features of rhyolitic and andesitic volcaniclastic rocks of the Mineral King submarine caldera complex, Sierra Nevada, California. *J. Volcanol. Geotherm. Res.*, 27: 43—76.

Rhyolitic and lesser andesitic pyroclastic rocks and lava flows are interstratified with marine sedimentary rocks deposited in shelf to basinal environm[illegible]d early Jurassic time. Voluminous (> 25 km^3) thick tabular sheets of rhyolitic ash-flow tuff accumulated within caldera collapse structures. Small (1—10 km^3) andesitic stratocones also formed. The andesitic units show abundant features typical of subaqueous deposition, including sorting, bedding, grading of single beds or overall grading of bedded sequences, and soft-sediment deformation. The rhyolite ash-flow tuffs show much less evidence of interaction with water during transport and deposition but are nonetheless believed to have been deposited subaqueously.

The andesite stratocones have a thick core facies of amygdaloidal lava flows, hyaloclastites, and massive tuff breccias and an apron facies of bedded and sorted lapilli tuffs, lahars, tuff turbidites and subaqueous fallout tuffs. The rhyolite ash-flow sheets, in contrast, consist dominantly of massive, unsorted, unbedded and pumiceous ash-flow tuffs which resemble subaerially deposited ash-flow tuffs; however, each ash-flow sheet passes gradationally upward and distally into a bedded facies which was sorted by water during deposition. The bedded facies composes only 5—15% of each ash-flow sheet The bedding is defined by: (1) discontinuous, crudely defined layers of blocks, lapilli, and ash within single flow units and (2) fallout layers and debris flow deposits interstratified with flow units at the distal end of each ash-flow tuff sheet. The former may be segregations that formed by shear between differentially flowing laminae within a single flow unit. The latter may have formed by settling and remobilization of material which was winnowed from the distal end of each flow unit during its subaqueous transport.

Turbulent mixing with the water column was important during small-volume pulsating andesitic eruptions, whereas silicic pyroclastics were deposited from highly concentrated plug or laminar flows fed by steady, voluminous eruptions.

INTRODUCTION

Triassic and early Jurassic volcanic rocks of the Mineral King area of the Sierra Nevada are part of a belt of calc-alkaline igneous rocks that extends

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from Canada through Mexico. These rocks record the onset of subduction-related arc volcanism that continued throughout Mesozoic time along the western edge of the North American continent. For at least 30 m.y., in a marine setting, large-volume rhyolitic ash-flows accumulated in calderas, and small-volume andesitic pyroclastic flows and lava flows formed small stratocones in the Mineral King area. Uranium-lead zircon dates on these volcanics have provided age controls for this poorly fossiliferous section, (Busby-Spera, 1983). The evolution of the caldera subsidence structures at Mineral King is described elsewhere (Busby-Spera, 1984b). Paleoenvironmental reconstructions of shallow to deep marine sedimentary rocks interstratified with the volcanic rocks are the topics of two other papers (Busby-Spera, 1984a, 1985). The purpose of this paper is to document sedimentary textures and structures of marine pyroclastic rocks at Mineral King, to construct facies models for subaqueously deposited pyroclastics, and to discuss the volcanic and hydrodynamic processes responsible for their formation. In particular, contrasting depositional features of small-volume marine andesites and large-volume marine rhyolites are described and interpreted. Mineral King is a particularly good place to study the products of submarine volcanism because the glaciated outcrops of the high Sierra provide nearly continuous exposure of lenticular and laterally variable volcanic strata.

Geologic setting

The lower Mesozoic volcanic and sedimentary rocks of the Mineral King area (Fig. 1) form a screen of metamorphic rock between adjacent younger plutons commonly called a 'roof pendant'. The strata of the roof pendant are vertically dipping and form an east-facing homocline that is locally complicated by folds and faults (Busby-Spera, 1983, 1984a). Although these strata have undergone regional metamorphism at upper greenschist grade, most primary textures and structures are well-preserved. For convenience, the prefix 'meta' will be dropped from such terms as 'metavolcanic' and 'metasedimentary'. Petrographic (Table 1) and whole-rock chemical analyses (Busby-Spera, 1983) show that metarhyolites and meta-andesites predominate, whereas metadacites and metabasalts are rare.

The three rhyolitic and three andesitic map units described in this paper are labelled with informal names used in the text (Fig. 1). Two more metavolcanic map units are not named or described further due to intense metamorphism of one and poor exposure of the other (Fig. 1). No formalized stratigraphy has been proposed at Mineral King because, in a fashion typical of many volcanic terranes, map units are lenticular and laterally variable, and strata cannot be directly correlated over the distance from one roof pendant to the next. Furthermore, some of the contacts that are not transitional over several meters of section may be unconformable or faulted (Fig. 1).

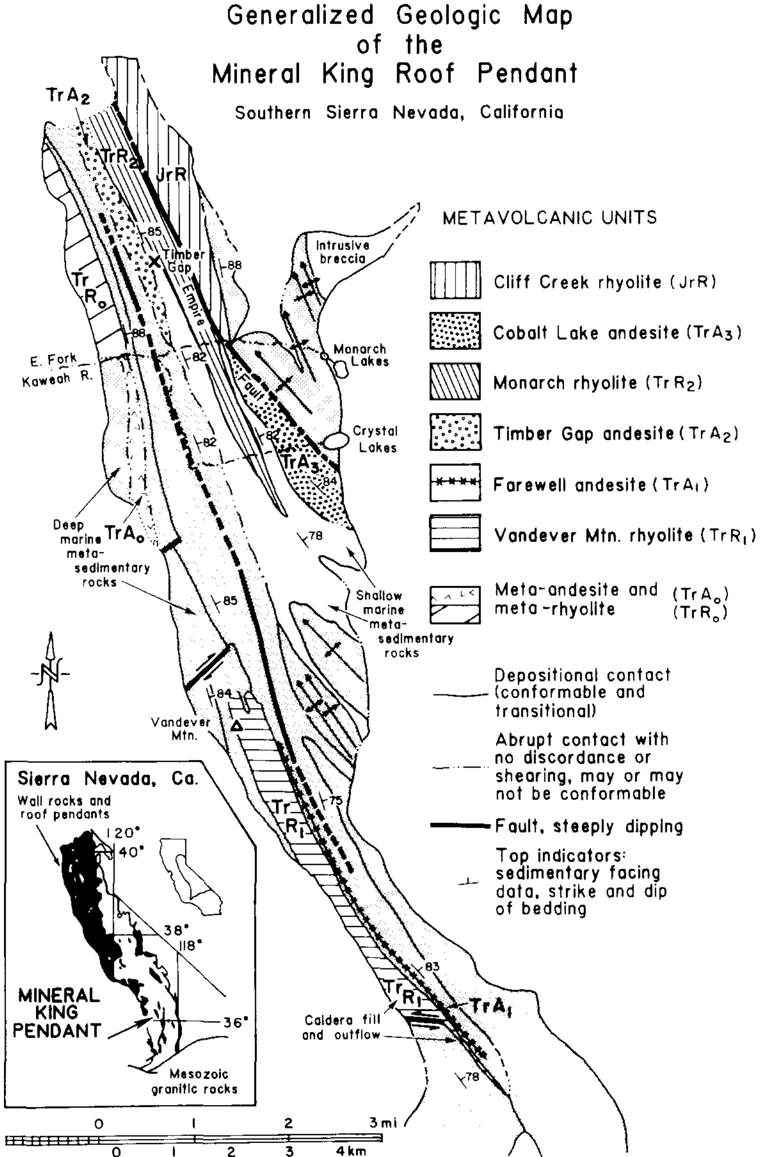


Fig. 1. Generalized geologic map of the Mineral King roof pendant, southern Sierra Nevada, California. Locality map included. Steeply dipping, dominantly east-facing Triassic and lower Jurassic metavolcanic and metasedimentary rocks form a screen between middle Cretaceous plutons. Six metavolcanic units are given names informally referred to in the text.

On the basis of detailed study of interstratified sedimentary rocks (Busby-Spera, 1983, 1984a), it is proposed that all of the volcanic map units were deposited below wave base in a marine environment. The Monarch ash-flow tuff (TrR_2) was deposited just below wave base in water depths of less than 200 to 300 m whereas the rest of the rhyolites and andesites were deposited in deeper water (Fig. 1).

Terminology of pyroclastic rocks

The term 'pyroclastic flow' has been used in a number of different ways. The definition that will be used here is "all fragmental flows or avalanches composed of pyroclastic material irrespective of temperature of emplacement" (Smith, in Aramaki and Yamasaki, 1963, p. 90). Pyroclastic flows may be classified according to the degree of vesiculation shown by essential fragments (Wright et al., 1981). At the highly vesiculated end of the spectrum lie ash-flow tuffs, also known as pumice flows or ignimbrites. Ash-flow tuffs are unsorted deposits of ash and block- and lapilli-sized pumice. Nonvesiculated juvenile lithic fragments are generally absent from ash-flow tuffs although a lesser percentage of accidental lithic fragments may be present. Block-and-ash flow deposits, in contrast, are composed of nonvesicular to poorly vesicular juvenile lithic fragments in an ash matrix. Subaerial pyroclastic flows are emplaced by laminar or plug flow (Sparks, 1976; Robool and Smith, 1982). Laminar flow occurs when layers or particles slide past one another and no significant turbulence develops. Plug flow is the flow of a high-concentration material in which the yield strength is such that the flow can only move along a basal shear layer; the rest of the flow moves as a rigid plug.

Subaqueous pyroclastic flows are "underwater flows of freshly erupted pyroclastic debris" (Fiske, 1963, p. 392). Freshly erupted pyroclastic debris is recognized by the presence of abundant pumice shreds, glass shards, accretionary lapilli, angular lithic fragments, or other delicate fragments (Fiske, 1963, p. 402). There is evidence that subaqueous pyroclastic flows can originate from eruptions on land which enter the sea (Tasse et al., 1978; Howells et al., 1979; Sparks et al., 1980), from submarine eruptions (Fiske and Matsuda, 1964) and by remobilization of pyroclastic material from steep submarine slopes (Fiske, 1963; Fisher, 1977). Deposits formed entirely of pyroclastic debris that show Bouma sequences will be referred to here as tuff turbidites. These are deposited from turbulent flows. Subaqueous fallout tuffs are accumulations of pyroclastic material that settled through water. Sorting is accentuated by this process (Fisher, 1964) and subaqueous fallout tuffs commonly are more distinctly stratified than airfall tuffs.

LARGE-VOLUME RHYOLITE CALDERAS AND SMALL-VOLUME ANDESITE STRATOCONES

An estimated 90 km^3 of rhyolitic and 10 km^3 of andesitic volcanic rocks are interstratified with marine sediments in the Mineral King roof pendant.

This estimation is made from the 2-dimensional cross-sectional map view of the volcanic units by assuming these large-volume intracaldera ash-flow tuffs were sheetlike rather than elongate. Each rhyolite map unit labelled on Fig. 1 is a voluminous, widespread sheet of homogeneous ash-flow tuff deposited during a single eruptive event. Each andesite unit, in contrast, records multiple, small-volume eruptive events of variable composition and effusive style.

Four different times at Mineral King, eruption of greater than 25—35 km^3 of rhyolite ash-flow tuff resulted in catastrophic caldera collapse and ponding of single, homogeneous ash-flow sheets to thicknesses greater than 0.5—0.8 km. The vertically dipping strata of the Mineral King pendant provide a rare opportunity to view rhyolitic calderas in cross-section. Eruption of the Vandever Mountain ash-flow tuff (TrR_1) was accompanied by piston-like subsidence of an intact cylinder of crust along high-angle normal faults (Fig. 1). A trap-door or hinge-like subsidence has been proposed for the Monarch and Cliff Creek calderas (Busby-Spera, 1984b). As discussed below, these two ash-flow sheets thicken and become more proximal in sedimentological character toward the north. The fault margin and vent region of these two asymmetrical calderas probably lay to the north of the Mineral King roof pendant, in an area now occupied by younger granites.

Each rhyolite unit at Mineral King is voluminous, widespread, compositionally homogeneous, and has only subtle textural variations along its length. There is no evidence of interruption during submarine emplacement of these sheets, i.e., no tuffaceous or sedimentary interbeds, so each unit is interpreted as the result of a single eruptive event. Each andesite unit, in contrast, is a small-volume deposit (1—8 km^3) which records several eruptive events. The Timber Gap (TrA_2) and Cobalt Lake (TrA_3) andesites are lenticular bodies that show rapid lateral and vertical variations in lithologic type and depositional structures. These heterogeneous bodies, referred to as andesitic stratocones, consist of a thick core facies of andesitic lava flows, hyaloclastites and block-and-ash flows that interfingers with a thinner apron facies of andesitic lapilli tuffs, tuff turbidites, subaqueous fallout tuffs, and lahars. The fourth andesite unit, The Farewell andesite (TrA_1) is more sheetlike and homogeneous in character, and is composed largely of laterally extensive block-and-ash-flow deposits.

Depositional features of andesitic rocks differ markedly from those of rhyolitic rocks at Mineral King, even though they were deposited in the same outer shelf to deep marine environment.

DEPOSITIONAL FEATURES AND MODES OF EMPLACEMENT OF MARINE PYROCLASTIC ROCKS

Subaqueous pyroclastic flows described in the literature can be divided into two basic types: (1) those that show evidence of turbulent mixing with water during emplacement, and (2) those that do not. Type (1) shows sorting, stratification and grading, and is deposited at low temperatures (Fiske and Matsuda, 1964; Bond, 1973; Yamada, 1973; Niem, 1977). Type (2) is predominately unsorted, unstratified and ungraded, and may show evidence of emplacement at high temperatures (Fernandez, 1969; Kato et al., 1971; Francis and Howells, 1973; Howells et al., 1979; Lowman and Bloxam, 1981). Type (2) closely resembles subaerially emplaced ash-flow tuffs. Andesitic pyroclastic rocks at Mineral King are type (1) whereas the rhyolitic pyroclastic rocks are type (2). The andesites are described first because features diagnostic of subaqueous deposition are much more abundant in these units than in the rhyolites, where such features are subtle and few.

Andesite pyroclastic rocks and lava flows

Farewell andesite (TrA_1)

The Farewell andesite consists of two monolithologic tuff breccias (Pf_1 and Pf_2) separated by 15 m of pyritic shale and thin-bedded turbidites. These tuff breccias form laterally extensive (length >7 km) relatively thin (Pf_1 = 15 m, Pf_2 = 30 m) sheet-like deposits (Fig. 1). Petrographic data are summarized in Table 1.

Pf_1 and Pf_2 are predominantly matrix-supported tuff breccias that are poorly sorted, unbedded and ungraded (Fig. 2A). Pf_1 and Pf_2 commonly contain less than 20% lithic fragments, but lithic-rich lenses with up to 60% clasts are present within Pf_1. Pf_1 also contains lenses up to 1 m thick of andesitic breccia supported in a massive limestone matrix, lenticular thin interbeds of siltstone, and medium to thin beds of felsic volcanic pebbly sandstone that is commonly well-graded. Pf_2 in contrast, is homogeneous and massive along most of its length except in the southernmost exposures, north of Pistol Creek (Fig. 1), where the unit thins slightly, becomes finer-grained, and develops normal grading and crude stratification. The basal contact of Pf_2 is extremely irregular, showing up to 4 m relief. In the northern outcrops of Pf_2 a graded felsic volcanic pebbly sandstone bed 0.3 m thick locally underlies the tuff breccia.

Although the lower tuff breccia horizon of the Farewell andesite (Pf_1) consists dominantly of unsorted massive block-and-ash flows deposited by a plug flow mechanism, lithic-rich lenses of winnowed fine material indicate that fluid turbulence locally played a role in its emplacement. Lenticular interbeds of pebbly sandstone, siltstone, and calcareous debris flows provide evidence that multiple flow units are included in Pf_1. Turbidite structures in the sandstones provide evidence for a subaqueous environment of deposition for Pf_1. The massive homogeneous upper tuff breccia (Pf_2) was probably deposited from a single block-and-ash flow by a plug flow mechanism. The basal contact of Pf_2 may be too irregular to be simply the result of scouring or loading. Perhaps it formed by fluidization of the underlying wet sediments due to expansion and explosion of water vapor below a hot

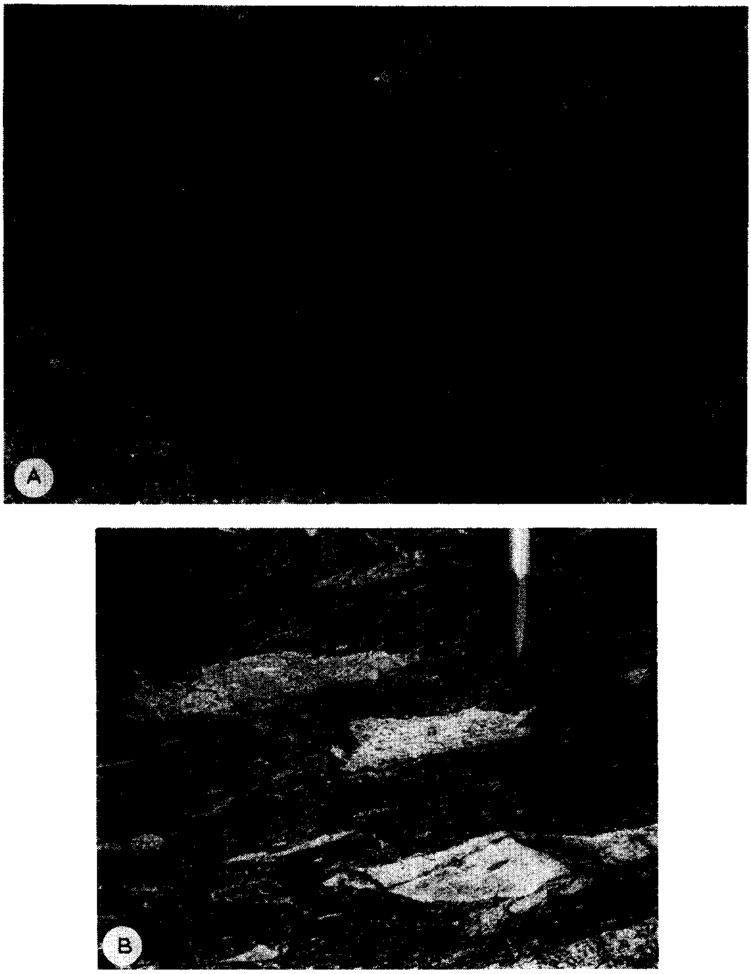


Fig. 2. Textures of meta-andesite block-and-ash flows and metarhyolite ash-flow tuffs in the Mineral King roof pendant. (A) Poorly vesiculated fragments in a tuff matrix of the same composition, Farewell andesite. (B) Pumice with ragged, wispy terminations, Vandever Mountain ash-flow tuff.

pyroclastic deposit, similar to those described by Kokelaar (1982). Irregular basal contacts have been cited as one of the criteria for recognition of subaqueous pyroclastic flows (Francis and Howells, 1973; Howells et al., 1979). The thinner, finer-grained graded and stratified part of Pf_2 near its southern termination probably represents a distal facies of these plug flows where progressive incorporation of water led to fluid turbulence in the flow. The turbidite sandstone beds under Pf_2 and in Pf_1, as well as the carbonate debris flows in Pf_1, may have been deposited by flows triggered by earthquake activity associated with the eruptions of Pf_1 and Pf_2, whereas the section of pyritic shale that overlies and underlies the Farewell andesite accumulated during a time of volcanic and seismic quiescence.

Timber Gap andesite stratocone (TrA_2)

The Timber Gap stratocone shows considerable variation in lithologic types and depositional structures (Fig. 3). It has a core of amygdaloidal andesitic lava flows, hyaloclastites and minor subaqueous fallout tuffs that interfingers laterally with andesitic block and ash flows, subaqueous lahars, laminated to thin-bedded subaqueous fallout tuffs, and tuff turbidites. The eruption of the andesitic volcanic rocks was preceded by a small-volume eruption of rhyolite ash-flow tuff, and a similar rhyolite ash-flow tuff was deposited on the northern flank of the stratocone after the andesitic eruptions ceased. The rhyolite ash-flow tuffs compose about one third of the preserved volume of the Timber Gap stratocone. No dikes or hydrothermal alteration zones have been recognized in the Timber Gap stratocone. Therefore, at the present level of erosion, an oblique slice near,

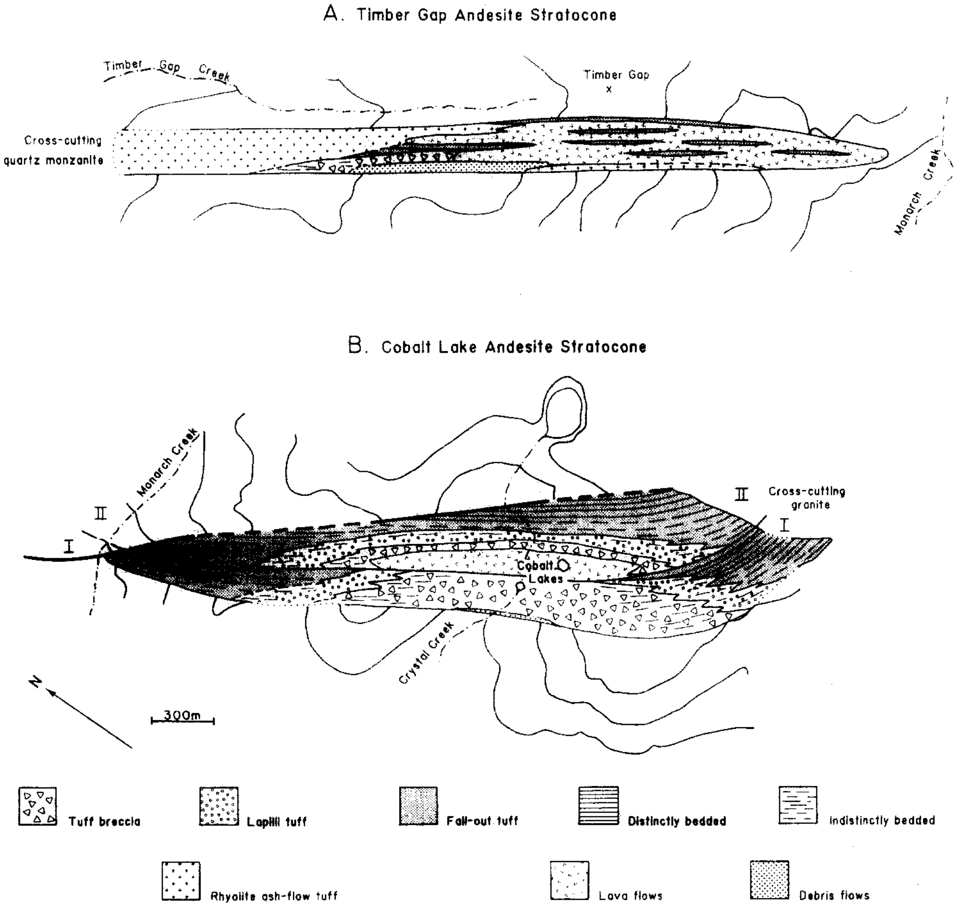


Fig. 3. Timber Gap and Cobalt Lake andesite stratocones. The map view provides a cross-section of these vertically dipping strata (Fig. 1).

rather than through, the core of an andesite stratocone may be exposed. Nonetheless, the abundance of andesite lava flows (Fig. 3) indicates proximity to the vent area of the stratocone.

The basal rhyolite ash-flow tuff contains large (up to 2 m) rip-up clasts of the underlying siltstones and thin-bedded turbidites. This depositional contact is locally obscured by shearing. The basal rhyolite ash-flow tuff is up to 20 m thick and is a massive, unsorted lapilli tuff. Due west of Timber Gap the rhyolite ash-flow tuff is overlain by an andesitic lava flow; 300 m to the north, however, the andesite lava flow ends and the ash-flow tuff is overlain by a 70-m-thick section of submarine lahars (Fig. 3). Progressively greater soft-sediment disruption of the rhyolite ash-flow tuff occurs along the base of the submarine laharic section for a strike distance of about 300 m to the north until the ash-flow tuff is totally disrupted and incorporated into the laharic deposit as clasts. This results in an irregular contact between the ash-flow tuff and the lahar section. The basal 0—20 m of the laharic section is interpreted as a slump deposit because it is choked with large (up to 8 m long), extremely irregularly shaped fragments of the rhyolite ash-flow tuff. Large siltstone intraclasts, presumably derived from below the ash-flow tuff, are also present where the laharic section directly overlies the siltstone (Fig. 3). The slump deposit is clast-supported by fragments of the white rhyolite tuff and has a brownish gray matrix of muddy andesitic tuff with a variety of lapilli-sized volcanic rock fragments. The slump deposit is overlain by massive andesitic lahars supported by matrix of the same composition, with wispy, irregularly shaped fragments of the rhyolite tuff up to 1 m long. The disorganized nature of these deposits and the preservation of delicate tuff fragments argue for a plug flow mechanism of deposition as debris flows. However, some internal motion of material must have occurred because the rhyolite tuff is thoroughly kneaded into the laharic matrix, in the debris flows as well as the slump deposits. The fluidal textures indicate that the rhyolite tuff was not lithified when the lahars were deposited. In the upper part of the laharic section, crude stratification and inverse to normal grading is locally developed. Here the rhyolite tuff fragments do not have wispy margins and are small, probably due to abrasion during transport. These data indicate deposition from a weakly turbulent debris flow. The upward progression toward greater fluid turbulence in the laharic section may reflect steepening of slopes due to contemporaneous build-up of volcanic material.

Andesitic lava flows accumulated contemporaneously with the lahars and overlie them (Fig. 3). The lava flows are amygdaloidal and indistinctly flow-banded, and are commonly brecciated around their margins. A block-and-ash flow lies at the northwestern termination of the lowest lava flow, and is petrographically similar to the lava flows (Table 1). Lenses of well-sorted thin-bedded tuff, crystal tuff, and lapilli tuff mark the contacts between successive lava flows of homogeneous composition (Fig. 3). These are more silicic than the lava flows or block-and-ash flows (Table 1).

Most of the tuffs and crystal tuffs are very well-sorted and distinctly parallel-laminated. These are interpreted to be subaqueous fallout tuffs. However, some thin beds grade from a lithic lapilli-rich or crystal-rich massive base to a laminated pumice- and ash-rich top (Fig. 4) and may be tuff turbidites.

A silicic ash-flow tuff laps onto the northern flank of the andesitic stratocone. The andesitic lava flows may have acted as a barrier to this ash-flow since it is not present on top of the lava flows or on the southern flank of the stratocone (Fig. 3). If ash flows did cross the stratocone, they must have left thin deposits that were entirely scoured away by the uppermost lava flow(s). Although exposures are poor in the northern third of the Timber Gap unit, this silicic ash-flow tuff is the dominant rock type in that area, although lahars are locally interstratified. It may have extended further north before the intrusion of the Eagle Lake pluton which truncates it to

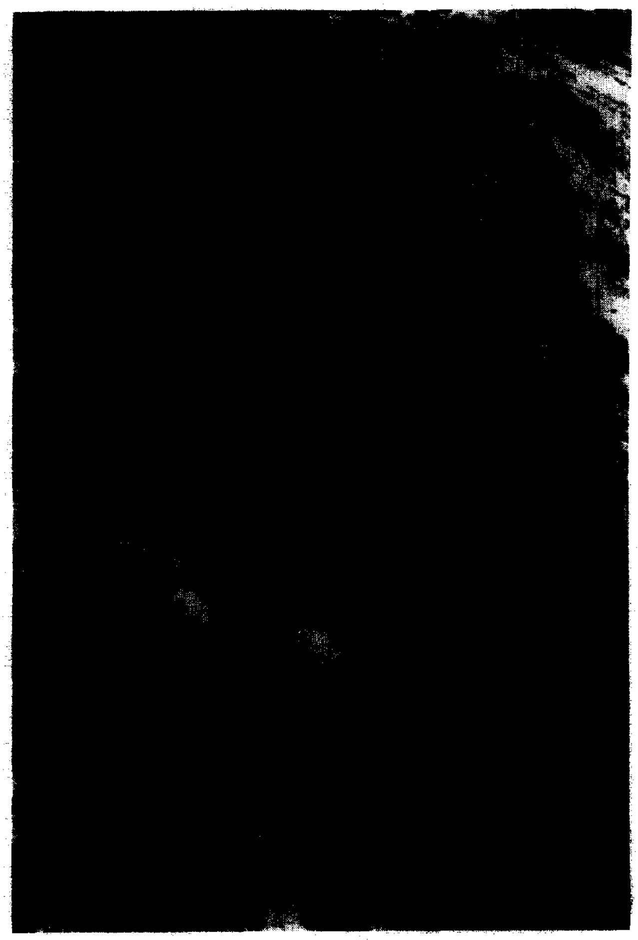


Fig. 4. Tuff turbidites and subaqueous fallout tuffs of the Timber Gap andesite stratocone.

the north (Fig. 1). This ash-flow tuff is petrographically very similar to the thinner rhyolite ash-flow tuff which underlies the andesite lava flow section.

In summary, the Timber Gap stratocone was built by many small-volume eruptions of lava and pyroclastic flows of andesitic and rhyolitic composition. Extensive interaction between pyroclastic flows and the water column as well as remobilization of unconsolidated pyroclastic debris resulted in deposition of subaqueous fall-out tuffs, tuff turbidites, and submarine lahars and slumps.

Cobalt Lake andesite stratocone (TrA_3)

The Cobalt Lake andesite stratocone has a thick core facies of andesitic lava flows, hyaloclastites, and tuff breccias that interfingers laterally with, and is mantled by, indistinctly to well-bedded andesitic lapilli tuffs, tuff breccias and subaqueous fallout tuffs (Fig. 3). The lava flows and pyroclastic rocks are petrographically and compositionally homogeneous (Table 1; Busby-Spera, 1983). The thick, coarse-grained core facies is centered over Crystal Creek (Fig. 1), and there is a rapid lateral decrease in maximum clast size and increase in amount of bedding and degree of sorting of pyroclastic material away from the core facies. Two distinct events are represented by the eruption of the Cobalt Lake andesite. Tuff breccias with cognate lithic fragments up to 2 m in size were deposited in the core facies during the first eruptive event. Lava flows and hyaloclastites as well as tuff breccias were deposited in the core facies during the second eruptive event. Dikes of intermediate to felsic composition are common in the core facies.

The first eruptive event was preceded by the deposition of 5—15 m of polymictic debris flows in the core facies of the stratocone (Fig. 3). About 180 m of massive unsorted monolithologic tuff breccia (Fig. 5A) was then deposited, probably very rapidly, since no subaqueous fallout tuffs occur within the breccia section. The basal contact of the tuff breccia is extremely irregular, with up to 15 m relief. The tuff breccia of the first eruptive unit passes gradationally upward into an unbedded, moderately well-sorted lithic lapilli tuff (Fig. 5B) 3—5 m thick. This winnowed lithic lapilli tuff grades upward into 3—6 m of indistinctly medium- to thin-bedded lapilli tuff and tuff which in turn grades upward into a 10-m-thick section of distinctly thin-bedded calcareous tuff and tuffaceous micrite.

From lower Cobalt Lake northward, the bedded sequence has been removed from the top of the first eruptive unit by scouring or 'bulldozing' at the base of the andesite lava flow (Fig. 3). This lava flow forms the base of the second eruptive unit in the core facies. Throughout its thickness, it is broken into angular polyhedral monolithologic blocks from a few centimeters to several meters in size with comminuted material of the same composition filling the cracks between blocks (Fig. 5C). Individual blocks are cracked internally. These blocks fit together in a jig-saw pattern and have not moved relative to each other, except at the top of the lava

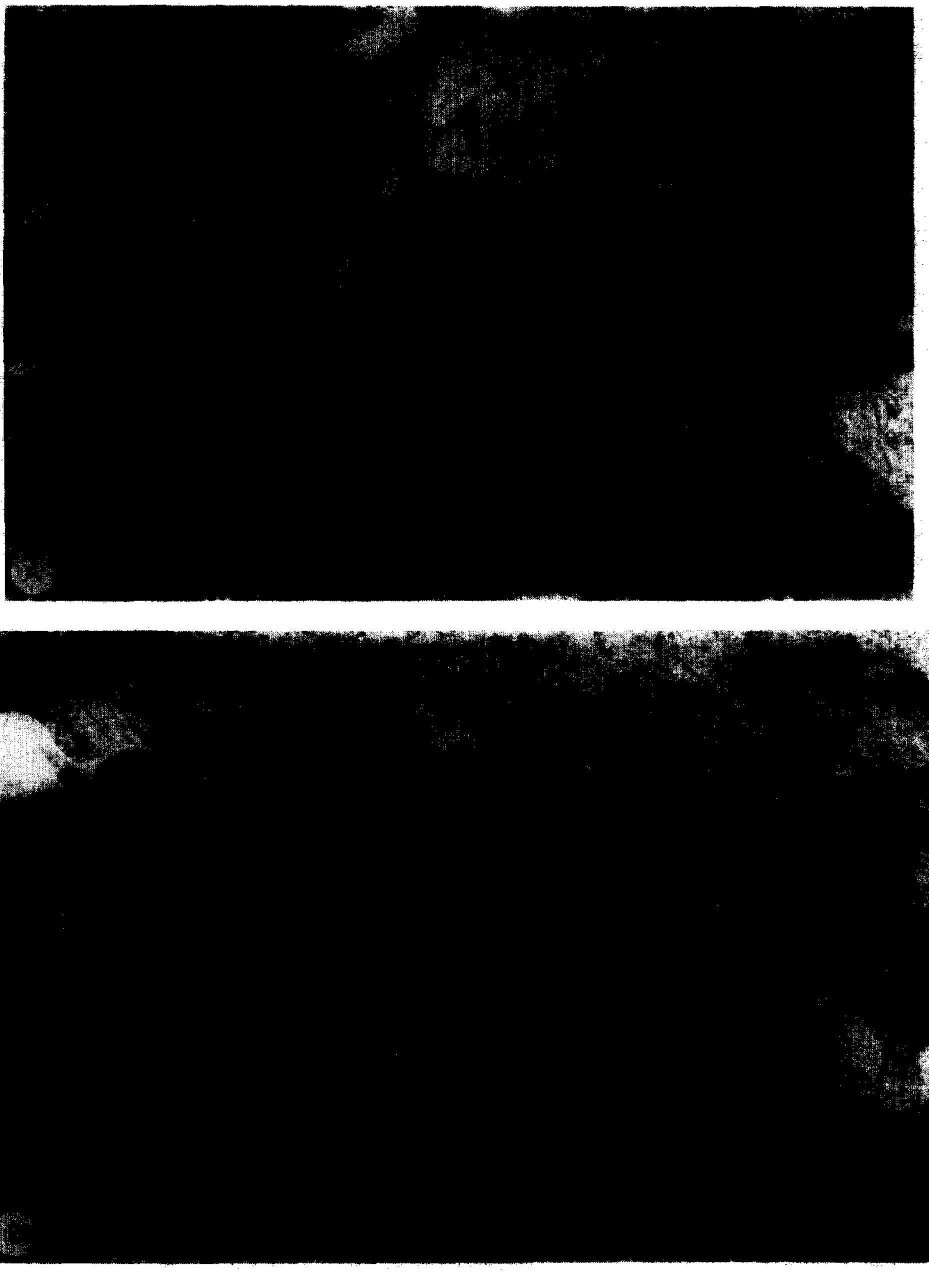
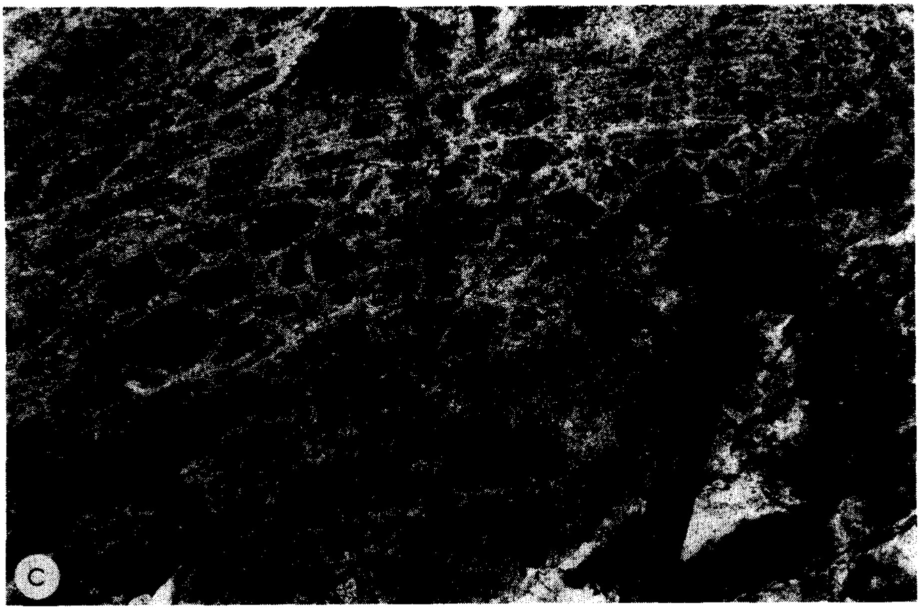


Fig. 5. Cobalt Lake andesite stratocone (Fig. 3). (A) Coarse, massive unsorted block-and-ash flow deposits; these pass gradationally upward into (B) moderately well-sorted lapilli tuffs that grade upward into thin-bedded tuffs and calcareous tuffs (not shown). (C) Hyaloclastite lava flows (see text).



flow near upper Cobalt Lake. This lava flow is mantled by and interfingers laterally with massive block-and-ash flow deposits (Fig. 3) that in turn are mantled by and interfingered with indistinctly to well-bedded lapilli tuffs. The upper and distal parts of the second eruptive unit are indistinctly bedded vitric tuffs and crystal tuffs that pass upward into laminated very well-sorted tuffs.

The debris flows that underlie the Cobalt Lake andesite stratocone may have been triggered by seismic activity preceding the first eruptive event. The irregular lower contact of the basal tuff breccia may indicate that it was emplaced hot and fluidized the underlying wet sediment. The andesite lava flow at the base of the second eruptive unit is shattered throughout, indicating subaqueous quenching such as that described by Kuno (1968). The two very thick thinning- and fining-upward sequences (200 m and 300 m, Fig. 3) are separated by calcareous tuffs and micrites that accumulated slowly, providing evidence that two eruptive events are represented by these deposits. The thick, coarse-grained, unsorted massive layer at the base of each fining-upward sequence was deposited very rapidly as highly concentrated mass flows, by a plug flow mechanism. These pass gradationally upward into indistinctly to well bedded, moderately sorted tuff breccias and lapilli tuffs that are ungraded and lenticular; this bedding may be the result of small subaqueous grain flows or slurry flows which immediately redistributed pyroclastic material until slopes became stabilized. These pass gradationally upward into indistinctly bedded tuffs that could have formed as subaqueous fallout that accumulated too rapidly to become very well-stratified, whereas the uppermost distinctly laminated tuffs and calcareous tuffs accumulated more slowly.

TABLE 1

Petrography of metavolcanic map units discussed in text

Map unit	Rock types	Phenocrysts	Groundmass (microcrystalline)	Fragments
Cobalt Lake Andesite (TrA_3)	Lava flows, tuff breccias, lapilli tuffs, tuffs	Plagioclase (epidotized) + biotite after amphibole (?)	Felsite + biotite	None in lava flows, same as groundmass in pyroclastics, unvesiculated to poorly vesiculated
Timber Gap Andesite (TrA_2)	Andesite lava flows, block-and-ash flows	Plagioclase, amphibole	Plagioclase microlites + interstitial felsite, amphibole, epidote	None in lava flows, same as groundmass in pyroclastics, unvesiculated to poorly vesiculated
	Rhyolite ash-flow tuff	Quartz, potassium feldspar, plagioclase	Felsite + sericite, lesser amphibole	Biotite after pumice
	Felsic thin-bedded tuffs	Plagioclase, potassium feldspar, embayed quartz	Felsite + sericite, lesser biotite	Felsic volcanic lithics, pumice
Farewell Andesite (TrA_1)	Andesite block-and-ash flows	Plagioclase, hornblende (locally replaced by biotite)	Felsite + amphibole ± biotite	Same as groundmass, unvesiculated to poorly vesiculated
Cliff Creek Rhyolite (JrR)	Ash-flow tuff	Potassium feldspar, plagioclase, quartz in lowest 100 m	Felsite, lesser biotite	Pumice, Volcanic lithics rare
Monarch Rhyolite (TrR_2)	Ash-flow tuff	Potassium feldspar, plagioclase, quartz	Felsite, lesser sericite	Pumice, up to 40% volcanic lithics
	Banded rhyolite sills	Potassium feldspar, plagioclase, ± quartz	Alternating coarser and finer bands of felsite	None
	Basaltic lava flows	Plagioclase + amphibole after pyroxene (?)	Plagioclase microlites + interstitial amphibole, epidote	None
Vandever Mountain Rhyolite (TrR_1)	Ash-flow tuff	Quartz plus potassium feldspar/plagioclase decrease upward	Felsite, sericite, lesser biotite	Pumice, volcanic lithics

To summarize, sedimentary structures and textures in volcanic rocks of the Cobalt Lake andesite stratocone suggest subaqueous accumulation of the entire 500-m thick section. If the core facies lay near the vent, it is likely that the vent was submarine as well. In that case, sorting of pyroclastic material in a submarine eruption column may have contributed to the overall thinning- and fining-upward pattern produced by each eruptive event.

Rhyolite pyroclastic rocks

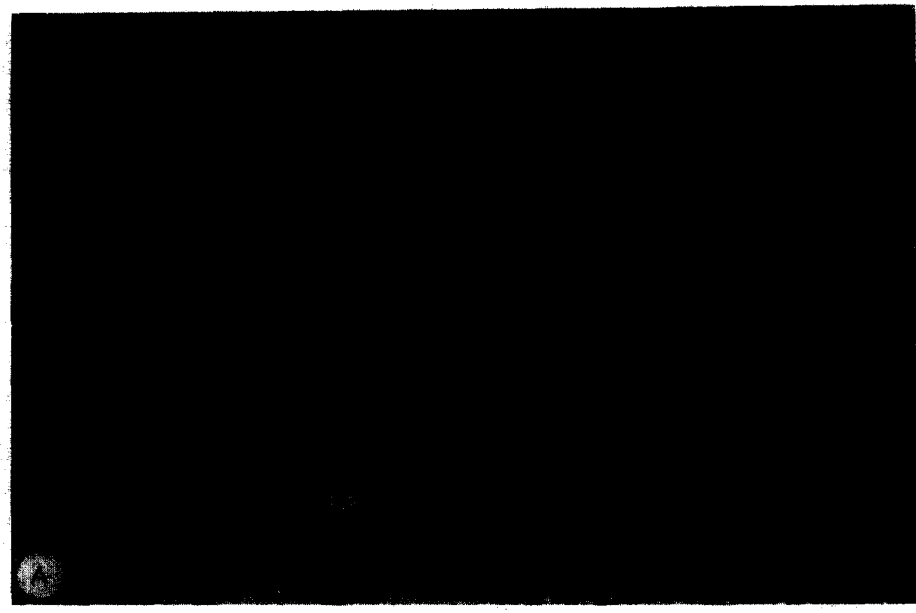
Vandever Mountain rhyolite ash-flow tuff (TrR_1)

The Vandever Mountain ash-flow tuff fills a caldera subsidence structure 7 km across and 480 m deep. A detailed reconstruction of events preceding and during this eruption is presented elsewhere (Busby-Spera, 1984b). Huge blocks up to 0.5 km long slid into the northern margin of the caldera as it subsided and filled with ash-flow tuff. Petrographic and whole-rock chemical data suggest that the ash-flow sheet is compositionally zoned (Busby-Spera, 1984b). A zone of intense sericitization emanates into the ash-flow tuff from the south fault margin of the caldera, where it is intruded by felsic dikes. Dikes and sills intrude the caldera floor and the lower half of the ash-flow sheet.

All but the uppermost 1—30 m of the Vandever Mountain ash-flow tuff is massive, unsorted lapilli tuff that lacks sedimentary or volcanic interbeds. These data suggest that the ash-flow tuff accumulated very rapidly during catastrophic subsidence of the caldera. The monotonously massive, unsorted lapilli tuff that composes 95% of the caldera fill resembles subaerially emplaced ash-flow tuffs. It cannot be determined if the massive interval was welded because shards were obliterated by the upper greenschist grade metamorphism. Other features normally used to infer a high temperature of emplacement, such as columnar jointing, pink coloration, or thermo-remanent magnetization, would also have been destroyed by deformation and metamorphism. However, it seems very likely that rapid accumulation of such a great thickness of massive nonsorted intracaldera tuff would result in welding. Only the uppermost 5% of the intracaldera tuff is bedded and shows textural evidence of subaqueous deposition. Yet the entire sheet must have been deposited subaqueously because it is underlain and overlain by deep marine sedimentary rocks (Busby-Spera, 1984a).

The bedded facies at the top of the Vandever Mountain ash-flow tuff can be divided into an upper, distinctly bedded interval 0—5 m thick and a lower, indistinctly layered interval up to 30 m thick.

The indistinctly layered facies is characterized by 2—30-cm-thick layers of lapilli tuff, tuff breccia, and tuff with extremely gradational upper and lower contacts (Fig. 6A). Sorting is moderate to poor and clasts are matrix-supported. Breccia layers can rarely be followed more than 3 m laterally, but tuff layers are more continuous. Layers terminate laterally by be-



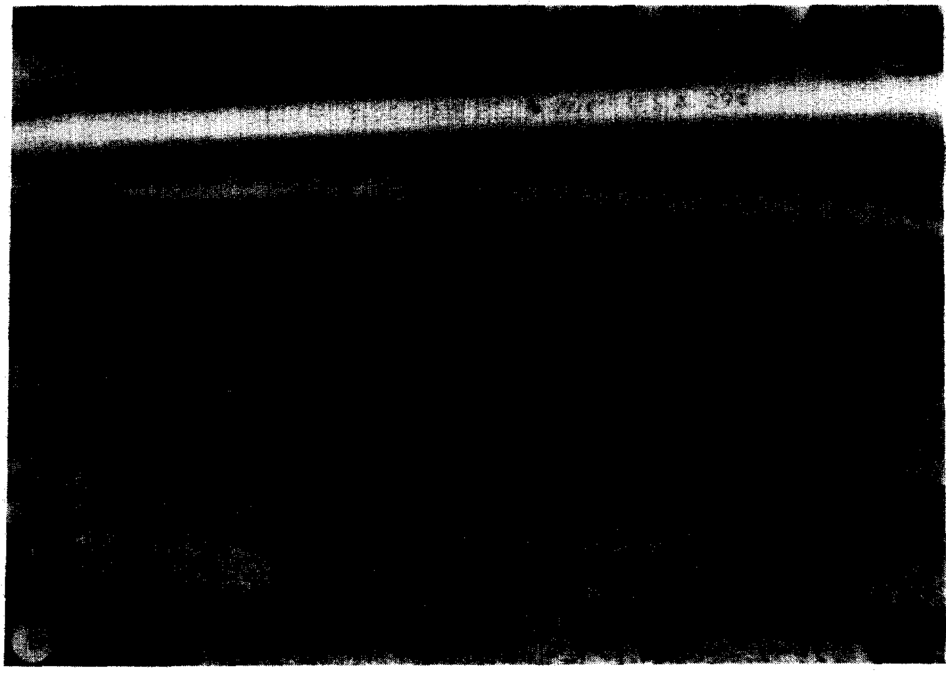


Fig. 6. Bedded facies at the top of the Vandever Mountain rhyolite ash-flow tuff. (A) Indistinct, discontinuous layers of pumice and lithic lapilli internal to pyroclastic flows (indistinctly layered facies). (B) Well-sorted, thin-bedded subaqueous tuffs that cap the ash-flow sheet (distinctly bedded-facies).

coming progressively less well-defined and thus do not appear to be scoured out. Layered areas interfinger with massive areas in the manner shown in Fig. 7. In some areas, tuff layers are absent but flat tuff clasts are abundant. No grading is present in the indistinctly layered facies. The indistinctly layered facies passes gradationally upward into the distinctly bedded facies in a 1—2-m upward-fining sequence of beds.

The distinctly bedded facies is thickest in the Little Kern River, thins to <1 m northward toward Vandever Mountain, and is absent to the south at the southern caldera margin. Well-sorted medium- to thin-bedded lapilli tuffs and coarse-grained tuffs alternate with thin-bedded laminated fine-grained tuffs (Fig. 6B). Many of the medium-bedded rocks are graded from lapilli tuff to coarse tuff, and these beds are commonly scoured into fine-grained tuff and contain abundant rip-ups at their bases. Thinner (2—3 cm thick) graded beds of crystal vitric tuff are interstratified with the laminated tuffs. Small pull-apart and slump structures are common. In some localities where the distinctly bedded facies is absent, abundant tuff clasts up to 30 cm long are enclosed in massive lapilli tuff, probably due to disruption of original bedding.

At the north end of the Vandever Mountain caldera, the ash-flow tuff is overlain by polymictic debris flows that interfinger with the uppermost part of the ash-flow sheet (Busby-Spera, 1984b). Elsewhere, the bedded facies of the ash-flow tuff passes gradationally upward into pyritic shales and lesser thin-bedded turbidites.

The massive, unsorted interval that dominates the Vandever Mountain ash-flow tuff accumulated too rapidly to allow ash to settle from the water column or be redistributed as turbidites or other mass flows. The distinctly bedded facies represents subaqueous fallout tuffs and small tuff turbidites that

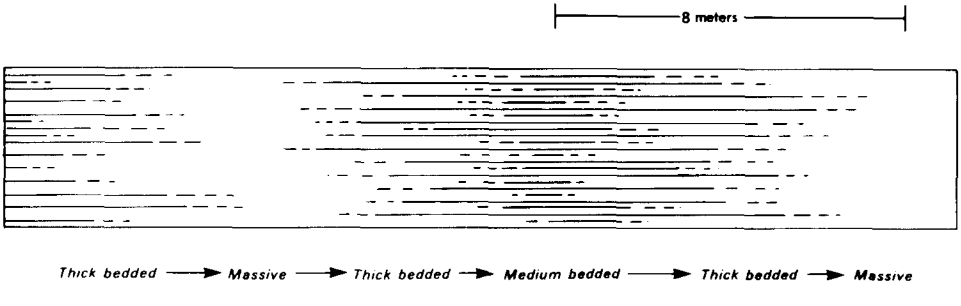


Fig. 7. Lateral variation shown by indistinct layering internal to some ash-flow tuffs at Mineral King. Traced laterally, a relatively well-defined internal layer becomes progressively less well-defined until it can no longer be seen (Fig. 12); this is accomplished by a decrease in the degree of sorting between layers. For example, a moderately well-sorted ash-rich layer between two moderately well-sorted lapilli-rich layers becomes more diffuse laterally until the three layers become an unsorted lapilli tuff layer. By this mechanism, a thin-layered region of an ash flow gradationally interfingers laterally into a region with layering of medium thickness, which in turn interfingers laterally to a thick-layered or massive area. Lateral transitions of this type commonly repeat many times along strike.

accumulated after the eruption, although local soft-sediment deformation of this facies suggests continued seismicity at this stage. The indistinctly layered facies may have formed by: (1) segregation of coarser and finer material by laminar shear or surging within the last flow units as the eruption waned or (2) local redistribution of material as thin grain-flows or slurry-flows after the eruption ended. The former is preferred because of the manner in which massive regions interfinger laterally with thick-bedded and medium-bedded regions of the ash-flow tuff (Fig. 7).

The Vandever Mountain ash-flow tuff fills a caldera that lies in a deep marine section, so it probably erupted subaqueously. Yet the tuff shows no sedimentological evidence suggestive of great amounts of mixing between a large eruption column and the ambient fluid. This suggests that hydrostatic pressure was great enough to suppress the eruption column, resulting in a 'boil-over' style of eruption, rather than a vertical column.

Monarch rhyolite ash-flow tuff (TrR_2)

The Monarch ash-flow tuff is well-exposed for an 8-km strike distance before it lenses out within the Mineral King pendant. Thus, it provides an excellent opportunity to compare the proximal and distal facies of a submarine ash-flow tuff.

The Monarch ash-flow tuff is thickest in the northernmost part of the map area (Fig. 1) where it reaches 600 m thickness. Although it has been subjected to tectonic flattening and may have originally been twice as thick, it is still much thicker than typical extracaldera tuffs (Busby-Spera, 1984b). The Monarch ash-flow tuff sheet lacks sedimentary interbeds, and it is dominantly massive, containing only minor subaqueous fallout tuffs and debris flow interbeds in its uppermost and distal parts (bedded facies, Fig. 8). On this evidence, the ash-flow tuff sheet was emplaced very rapidly. The source area presumably lay to the north because: (1) the size and frequency of lithic fragments decreases to the south (as they do in the distal parts of ash-flow tuffs elsewhere; Murai, 1961; Kuno et al., 1964; Sparks, 1976; Davies et al., 1978); and (2) the massive unsorted northern (proximal) part of the ash-flow tuff sheet passes gradationally into bedded, sorted tuffs to the south (distally). Furthermore, the Monarch ash-flow tuff thickens to the north and lenses out to the south (Fig. 1), possibly indicating that this very thick tuff was ponded in a hinge-like 'trap-door' caldera subsidence structure. Trap-door caldera subsidence and asymmetrical volcano-tectonic depressions have been recognized by numerous workers (Elston et al., 1975; Steven and Lipman, 1976; Toulmin, 1977; Greene, 1977; Burke and McKee, 1979; Erb, 1979). Because the Monarch ash-flow tuff thickens and becomes more proximal in sedimentologial character toward the north, the fault margin of this trap-door caldera probably lay to the north of the Mineral King roof pendant in an area occupied by younger granitoids.

Petrographic data from the Monarch rhyolite ash-flow tuff are sum-

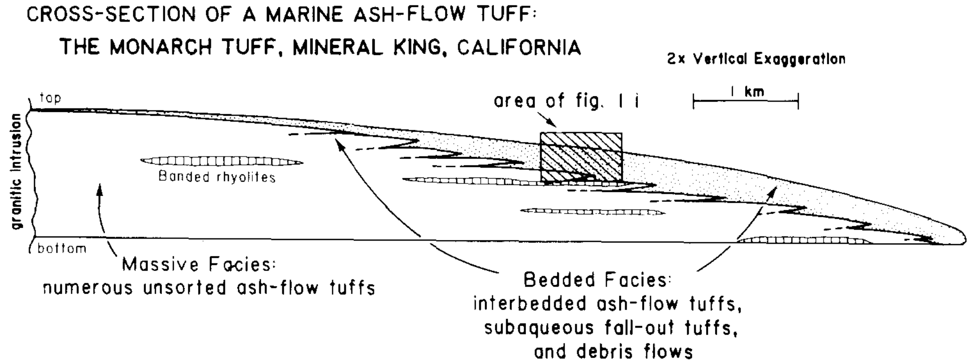
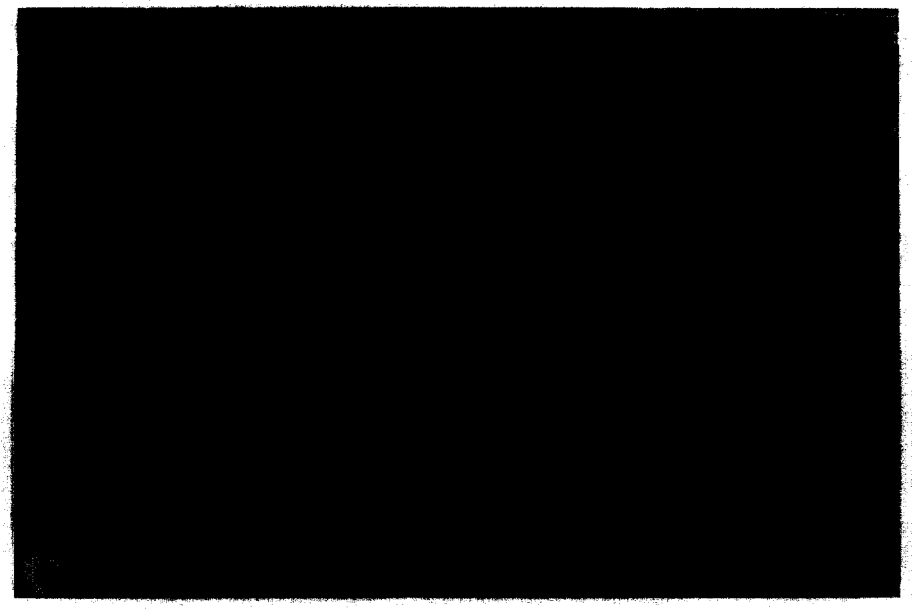


Fig. 8. Distribution of massive and bedded facies of the Monarch ash-flow tuff. The northern, proximal part of the ash-flow sheet is massive and unsorted. This passes gradationally upward and distally into alternating ash-flow tuffs and subaqueous fallout tuffs, referred to as the bedded facies. Thin (6—40 m) laterally continuous (1—2 km) banded rhyolite horizons shown.

Fig. 9. Photomicrograph of pumice with ragged, wispy terminations and vesicles preserved in the Monarch metarhyolite ash-flow tuff (field of view, 6 mm).

marized in Table 1. Lapilli-sized fragments are predominately pumice (Fig. 9) although lapilli- to block-sized accidental fragments are present. Banded rhyolite lithic fragments are common. These are petrographically identical to banded rhyolites interlayered with the ash-flow tuff. The origin of the banded rhyolites is uncertain. Some features suggest that they represent densely welded, rheomorphic zones in the ash-flow tuff, similar to those described by Schmincke and Swanson (1967). These features include the very thin, laterally continuous character of the banded rhyolites (Fig. 8), and the extremely consistent orientation of well-developed banding (Fig. 10A) and recumbent flow folds (Fig. 10B). However, the banded rhyolites



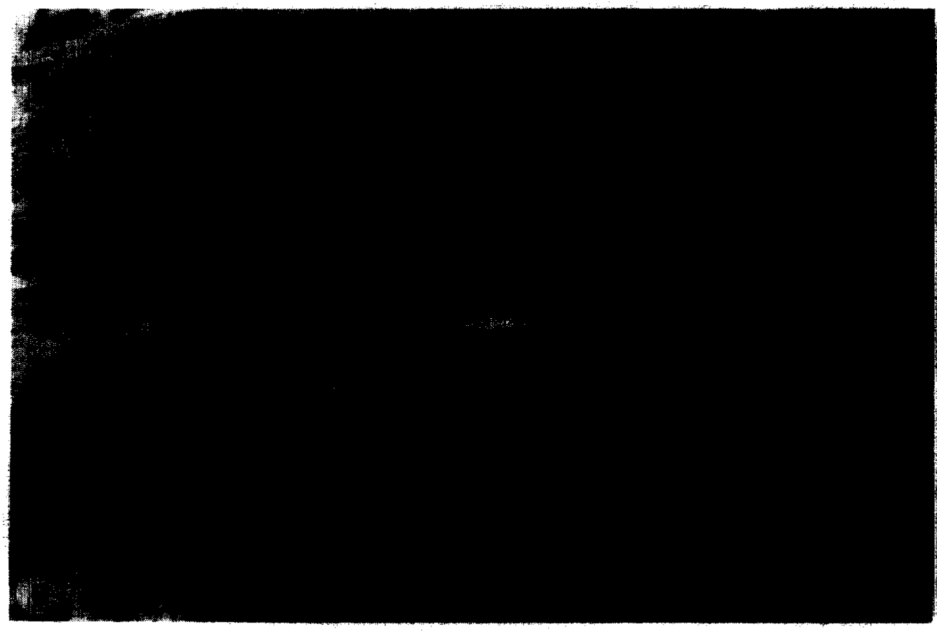


Fig. 10. Banded high-silica rhyolite layers in the Monarch rhyolite ash-flow tuff (see Fig. 8). Fragments of this rock type are abundant in the ash-flow tuff. (A) Lateral continuity of bands and even distribution of crystals. These bands lie parallel to regional bedding with remarkable consistency, or (B) are folded recumbently with axial planes parallel to bedding. Near the terminations of the layers parallel-banded zones alternate with zones where the banded rock is brecciated. (C) Fragments of the banded rhyolite in the Monarch ash-flow tuff indicate eruption of some banded rhyolites contemporaneous with the ash flow eruption.

have a higher SiO_2 and corresponding lower P_2O_5, Fe_2O_3 and MgO content than the ash-flow tuff (Busby-Spera, 1983). Furthermore, lithic fragments, common in the ash-flow tuff, are absent from the banded rhyolites. Last, crystals are more evenly distributed through the banded rhyolites than is typical of a pyroclastic rock (Fig. 10A). Therefore, the banded rhyolites are probably sills. The high-silica banded rhyolites must have breached the surface at some locality in order to be incorporated into the ash-flow tuff as fragments (Fig. 10C) possibly as lava flows or as sills exposed by slumping.

Late in the emplacement of the Monarch ash-flow sheet, a second chemically distinct magma was erupted. A basaltic lava flow is interstratified with pyroclastic flows and subaqueous fall-out tuffs of the bedded facies of the Monarch ash-flow tuff in Monarch Creek (Fig. 11). This basalt was shattered by submarine steam explosions, into a jig-saw pattern of angular fragments.

Most of the Monarch rhyolite ash-flow tuff is composed of massive nonsorted ash-flow tuffs that resemble subaerially emplaced ash-flow tuffs. However, the uppermost and distal part of the ash-flow tuff sheet is bedded and shows evidence (given below) of interaction with water, indicating that the entire sheet was emplaced subaqueously. Additionally, the ash-flow sheet is depositionally overlain and underlain by wave-rippled marine siltstones, limestones and sandstones interpreted to represent an outer shelf environment of deposition (Busby-Spera, 1983, 1984a). The bedded facies of the Monarch rhyolite ash-flow tuff consists of alternating ash flow tuffs and subaqueous fallout tuffs, with lesser diamictite debris flows and grain flows of remobilized rhyolite pyroclastic material.

The north-facing slope of Monarch Creek (Fig. 1) was chosen for detailed study of the bedded facies of the Monarch ash-flow tuff because exposure there is nearly complete. An aerial photograph shot by the author provided a base for tracing beds as thin as 1 m for the 0.4-km strike distance of the hillside. In addition, the section was measured at numerous localities. In Monarch Creek the upper 130 m of the Monarch ash-flow tuff is bedded and the lower 235 m is largely massive ash-flow tuff and banded rhyolite sills (Fig. 8). A map of the bedded section is presented in Fig. 11. Ash-flow tuffs are predominant in the lower part of the bedded section, whereas subaqueous fallout tuffs dominate the upper part. The ash-flow tuffs are nonsorted, massive to indistinctly layered pumiceous flows 6 to 23 m thick (Af_{1-6}, Fig. 11). The subaqueous fallout tuffs are very well-sorted, massive or thin-bedded tuffs, crystal tuffs, and fine-grained lapilli tuffs. These overlie each ash-flow tuff in a bed up to 2 m thick (T_{1-5}, T_7), and form the upper 29 m of the bedded section (T_8), with one exception. T_6 overlies a 12-m section of poorly sorted medium bedded lapilli tuffs (unit LT) emplaced as a series of small sediment gravity flows. Each map unit of the bedded facies is described in Table 2.

Ash-flow tuffs of the bedded facies are laterally continuous except for three relatively thin deposits ($Af_{3'}$, $Af_{4'}$, $Af_{4''}$) that occupy broad, shallow depressions (Fig. 11). Lower contacts are sharp whereas upper contacts are sharp to gradational (Table 2). Locally, the ash-flow tuffs show irregular basal scours cut into subaqueous fallout tuffs (T_1 to T_4, $T_{6'}$) and tuff rip-up clasts are commonly present near the base of each ash-flow tuff. The ash flows were capable of scouring out subaqueous fall-out tuffs up to 2 m thick but did not erode into other ash-flow tuffs. Gradational upper contacts are defined by normal grading in the uppermost 2—60 cm of an ash-flow tuff, but the overlying subaqueous fallout tuff is more commonly in sharp contact with unsorted, massive ash-flow tuff. Ash-flow tuffs of the bedded facies are largely massive and nonsorted, but indistinct layering is locally developed in ash-flow tuffs 1, 2, 3, 4′ and 4″. The layering is defined by 1—60-cm-thick segregations of moderately sorted ash, lapilli or blocks with gradational upper and lower contacts (Fig. 12). The layering is parallel planar but thicknesses of layers vary over lateral distances of less than a few meters in the manner shown in Fig. 7. Two of the thin, lenticular ash-flow tuffs ($Af_{4'}$ and $Af_{4''}$) pass laterally from massive deposits to indistinctly layered deposits near their terminations, accompanied by a decrease in abundance of large clasts (Fig. 11). The contact between Af_2 and Af_3 is not distinguishable in the field except at the north end of the area

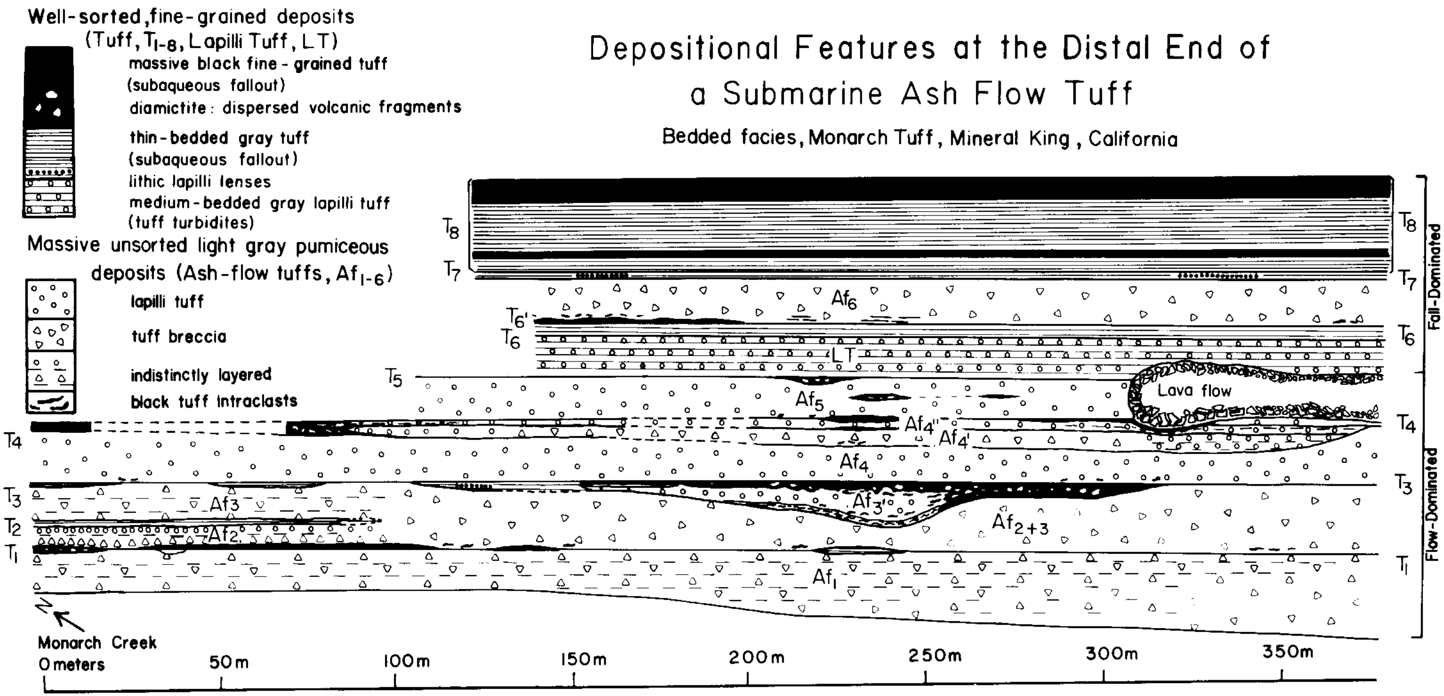


Fig. 11. The bedded facies of the Monarch rhyolite ash-flow tuff on the well-exposed mountainside south of Monarch Creek (Figs. 1 and 8).

mapped in Fig. 11, where a subaqueous fallout tuff intervenes (T_2) and Af_2 is layered. The thin beds of T_2 become progressively less distinct southward before it lenses out; this is accompanied by a progressive homogenization of Af_2 into massive tuff breccia (Fig. 11). Two lenses of tuff and diamictite lie 5 m from the base of Af_5, so it may have been emplaced as two ash flows of similar grain size characteristics. The uppermost ash-flow tuff (Af_6) has a significantly higher lithic clast content than the rest of the ash-flow tuffs (Table 2).

Subaqueous fallout tuffs of the bedded facies are discontinuous where overlain by ash-flow tuffs (see T_1-T_4 and $T_{6'}$, Fig. 11) and continuous where overlain by more subaqueous fallout tuffs or by grain flow deposits (see T_5-T_8, Fig. 11). T_4 is locally deformed by loading at the base of a basalt lava flow. In the lower, ash-flow dominated part of the bedded section, lenses of ash-flow tuff and diamictite are enclosed in subaqueous fallout tuff (Fig. 11). The diamictites are compositionally similar to the ash-flow tuffs but have distinctly bimodal grain size characteristics, with pumice and volcanic lithic fragments up to 15 cm in size widely dispersed in a well-sorted matrix of massive tuff. Diamictites occupy depressions cut into the tops of Af_1, and Af_{3-5}. Two of these depressions are so broad and shallow that they are only apparent on the map scale (see T_3 and T_4, Fig. 11). Both of these depressions are "lined" with subaqueous fallout tuff and filled with ash-flow tuff ($Af_{3'}$, $Af_{4'}$, $Af_{4''}$), diamictite, and subaqueous fallout tuff. Both the upper and lower contacts of $Af_{3'}$ are in ragged, wispy contact with enclosing tuffs and diamictites. Irregular patches and rip-up clasts of fine-grained tuff occur within the ash-flow tuff (Fig. 13), patches of ash-flow extend into the diamictites, and bedding in the subaqueous fallout tuff is extremely disrupted (Fig. 11). The contacts between $Af_{4'}$, $Af_{4''}$ and diamictites show similar evidence of soft-sediment mixing. In the upper, fallout dominated part of the bedded section, diamictites are absent. An overall density-graded sequence of beds passes from lithic lapilli tuffs (LT) to crystal tuffs (T_6) to pumiceous tuffs (T_7 and T_8), interrupted by the uppermost ash-flow tuff (Af_6). Medium beds in the lithic lapilli tuff (LT) are poorly sorted and structureless to faintly graded or convolute-laminated; these alternate with well-sorted thin-bedded tuffs. T_6 to T_8 are well-sorted, thin-bedded and parallel-laminated.

The following interpretations can be drawn from detailed study of the bedded facies of the Monarch ash-flow tuff:

(1) A subaqueous fallout tuff caps each ash flow unit in the distal part of the ash-flow sheet. Scour at the base of the succeeding ash flow resulted in lateral discontinuity of most of the caps; only those overlain by a section of fallout tuffs or small grain flow deposits are continuous. Most of the ash-flow tuffs in the bedded section are laterally continuous. Individual ash-flow units can be traced into the proximal part of the sheet where contacts between flow units become difficult or impossible to detect, due to a total lack of intervening subaqueous fallout tuff. Because the caps of subaqueous

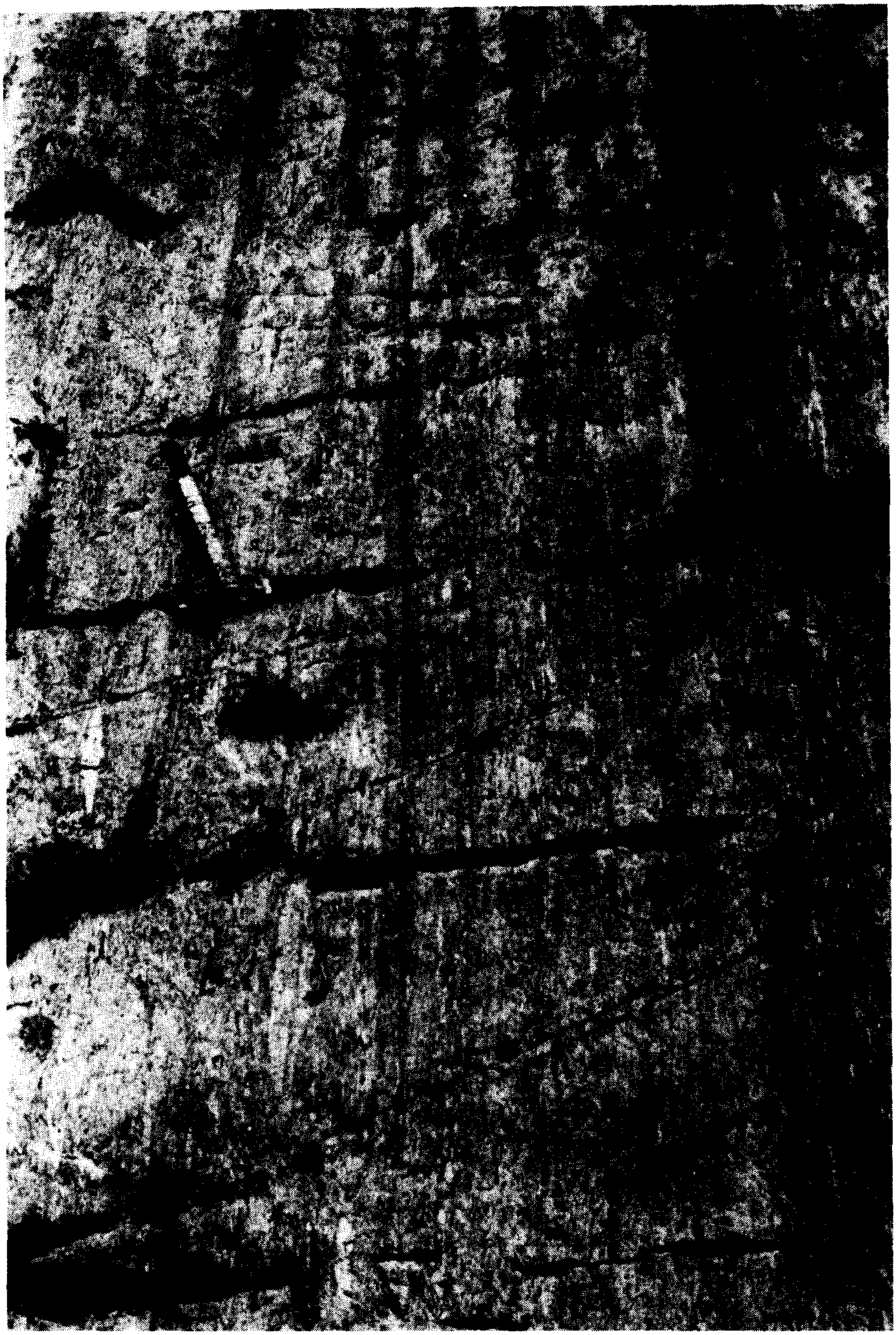


Fig. 12. Indistinct, discontinuous bedding internal to ash-flow unit 1 of the bedded facies of the Monarch tuff (Fig. 11). Beds terminate laterally by becoming progressively less distinct, as exhibited by the bed under the hammer and two more to the right of it. In this fashion, medium-bedded, thick-bedded and massive zones interfinger and alternate (Fig. 7).

TABLE 2

Features of ash-flow tuffs and interstratified subaqueous fallout tuffs in the bedded facies of the Monarch ash-flow tuff (see Fig. 11)

Map Unit	Grain size	Thickness	Bedding plane properties	Layer properties	Special features
T_8	Tuff and lapilli tuff	27 m	Passes gradationally upward into calcareous sediment	Massive or thin-bedded parallel laminated, well-sorted	Laterally continuous. Minor vertical fluctuations in grain size, bedding thickness
			gradational		
T_7	Tuff, lapilli tuff	1.8 m		Parallel-planar, laterally continuous laminated thin beds, well-sorted	Laterally continuous. Rare lenses of volcanic lithic lapillistone
			gradational		
Af_6	Tuff breccia	12 m		Massive with very indistinct lithic-rich horizons, unsorted. Basal 0.7—2 m is lapilli tuff with a few thin tuff interbeds	High (30—40%) lithic content relative to other ash flow tuffs in section (<20%)
			sharp and planar to irregular		
$T_{6'}$	Tuff	0—0.1 m		Massive, well-sorted	Discontinuous
			sharp and planar		
T_6	Crystal tuff	3.3 m		Thin bedded parallel-laminated, well-sorted	Laterally continuous
			sharp and planar		
LT	Lapilli tuff + tuff	12 m		Medium-bedded lapilli tuffs (poorly sorted) thin-bedded laminated tuffs (well-sorted); some grading; convolute lamination, load structures	Laterally continuous
			sharp and planar		
T_5	Tuff	1.0—1.5 m		Laminated and massive, well-sorted; one massive lense of diamictite	Lowest laterally continuous tuff in section
			gradational		
Af_5	Lapilli tuff	9 m		Massive, unsorted	1 extremely discontinuous, slumped horizon of diamictite and tuff 5 m from base
			sharp; planar, locally scoured by Af_5, locally deformed by lava flow		
T_4 ($+Af_{4',4''}$)	Tuff with lenses of lapilli tuff, tuff breccia, diamictite	4.5—8 m		Tuff: massive or laminated, well-sorted Lenses: massive tuff breccia ($Af_{4'}$) and lapilli tuff ($Af_{4''}$) with finer-grained, indistinctly bedded margins	The lenses of ash-flow tuff and diamictite occupy a very broad shallow depression (8 × 300 m)
			sharp and planar (erosive on map scale)		

TABLE 2 continued

Af_4	Lapilli tuff	7—15 m		Massive, unsorted	
			sharp; planar, locally irregular		
T_3 (+$Af_{3'}$)	Tuff with lenses of lapilli tuff, diamictite, lapillistone	0.01—0.6 m 0.3—10 m	Extensive soft-sediment mixing between tuffs, diamictites and ash flow tuff: mixed zones, slumps, rip-up clasts, flames	Tuff: massive or with parallel or disrupted laminae, well-sorted. Lenses: Lapilli tuff—massive, unsorted ($Af_{3'}$) Diamictite—massive **Lapillistone—thin, wel-sorted** lenses (rare)	T_3 is discontinuous. The lenses of ash-flow tuff, diamictite and lapillistone occupy a broad shallow depression (10 × 200 m)
			sharp and planar (erosive on map scale)		
Af_3	Tuff breccia	0—9 m		Massive to indistinctly layered; block-rich layers thicker than in Af_1 (up to 300 cm thick)	Completely removed by slump scarp or scour in region of x = 250 m
			gradational		
T_2	Tuff: fine- to coarse-grained	0.3—0.6 m		Thin-bedded, parallel-planar. Bedding progressively less distinct toward south	T_2 is discontinuous (only present from x = 0—97 m)
			gradational		
Af_2	Lapilli tuff and tuff breccia	6 m		Where overlain by T_2: 5 m moderately sorted tuff breccia gradationally overlain by 1 m lapilli tuff Where overlain by Af_3: 6 m massive unsorted lapilli tuff breccia	
			sharp and planar; local diffuse mixed zones with abundant rip-up clasts		
T_1	Tuff, fine- to coarse-grained; lesser diamictite	0—2 m		Dominately massive fine-grained black tuff; lesser black and gray fine- and coarse-grained tuff with parallel to disrupted laminae. Diamictites are massive.	T_1 is extremely discontinuous. Diamictites (<20% volcanic lithic fragments and pumice up to 15 cm dispersed in massive fine-grained tuff) occupy broad scours into Af_1
			sharp and planar		
Af_1	Lapilli tuff breccia	12—23 m		Indistinct layering: 4—60-cm-thick planar parallel segregations of moderately sorted coarse ash, lapilli and blocks, discontinuous (<5—10 m along strike)	Small (1.8 × 7 m) channel cut into top of Af_1 is filled with massive tuff breccia with load structures and flames at base (at x = 40 m)
			sharp and planar		

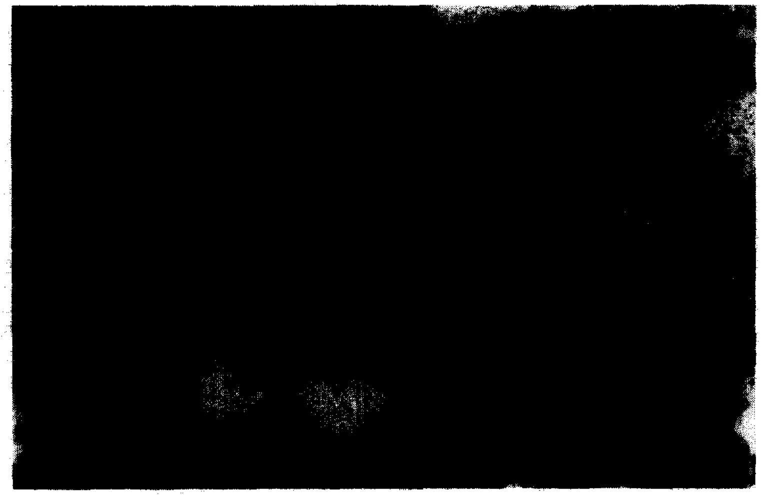


Fig. 13. Soft-sediment mixing of ash-flow tuff (light gray, unsorted) and fine-grained tuff (black) to form diamictite debris flows interstratified with ash flows, distal Monarch tuff.

fallout tuff only occur on the distal reaches of each ash flow unit, it is inferred that they were derived from the ash flows themselves (Fig. 14). These deposits are similar in some ways to those of initially turbulent flows that were segregated by gravity into dense underflows and overlying dilute flows at Mt. Pelee (Fisher and Heiken, 1982). In the marine environment at Mineral King, flows of initially high concentration were progressively diluted by incorporation of water as they traveled. This, combined with the effects of frictional drag of the overlying water column, resulted in mixing of ash into the water column from the flow.

(2) Diamictites of the bedded facies formed by local remobilization of subaqueous fallout ash into mudflows that picked up pumice and lithic fragments from underlying ash-flow tuffs. Remobilization was triggered by seismic activity contemporaneous with ash flow eruptions. Lack of stratification or grading suggests deposition from highly concentrated plug flows.

(3) Excellent exposure of the bedded facies permits recognition of two small submarine slide scarps within the Monarch ash-flow tuff (T_3 and T_4, (Fig. 11). These scarps were cut into underlying ash-flow tuffs, showered with ash, and filled with remobilized pyroclastic debris (diamictites and variably contaminated ash-flow tuffs) that in turn slumped after deposition. Deposition of the ash-flow tuff on a steep slope is not necessarily implied, however, because submarine slumps occur on slopes of only 1° (Lewis, 1971).

(4) Most ash-flow units in both the distal and proximal part of the ash-flow sheet are internally massive and unsorted, and were deposited from highly concentrated plug flows (Fig. 14). However, some ash-flow units

MARINE EMPLACEMENT OF LARGE VOLUME ASH-FLOW TUFF

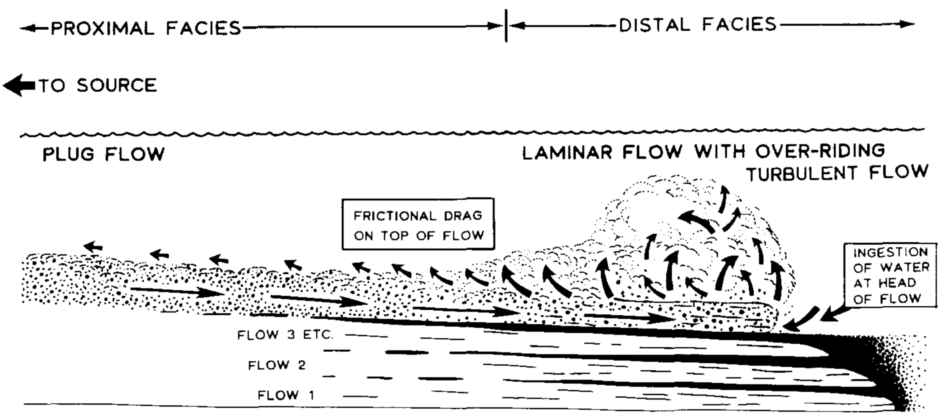


Fig. 14. Steady, voluminous pyroclastic flows, such as those associated with large-volume caldera-forming eruptions, exhibit minimal evidence of interaction with the water column during subaqueous transport and deposition. Only minor dilution of the flow occurs, accomplished by ingestion of water at the head. Dilution of the flow results in a "flow transformation" (Fisher, 1983) from plug flow to laminar flow. This, combined with frictional drag on the top of the flow, results in limited winnowing of ash in the distal reaches, some of which settles prior to emplacement of the succeeding flow units.

in the distal part of the sheet show indistinct internal layering. These formed by laminar shear segregation of coarser and finer material along differentially flowing layers throughout the thickness of an individual ash flow, or by surging or pulsing of the ash flow (Fig. 14). Pumice-rich layers locally developed within flow units at the distal end of Bishop Tuff may have a similar origin (Sheridan, 1979, p. 134). Diffuse, discontinuous layers, similar to some of those in the Monarch tuff (pers. observation, 1982) are present in the upper parts of marine ash-flow tuffs in the Ordovician Welsh basin but are absent from nonmarine equivalents (Howells et al., 1979). Perhaps shearing or surging of a subaqueous ash-flow tuff is enhanced by frictional drag of water in its upper surface and/or by progressive incorporation of water as it travels. Indistinct layering at the ends of two small ash-flow tuffs ($Af_{4'}$ and $Af_{4''}$, Fig. 11) provides evidence that laminar shear segregation or surging may become important along the relatively thin margins or terminus of a plug flow.

(5) The ash-flow-dominated part of the bedded facies must have accumulated in a very short time (hours? days?) because no volcanic or sedimentary interbeds are present in the proximal part of the ash-flow sheet. In contrast, the density-graded sequence of lithic lapilli tuffs, crystal tuffs, and pumice lapilli tuffs in the upper part of the bedded section record slow (months? years?) accumulation of pyroclastic debris after the ash flow eruptions ceased. Small grain flows and turbidites of lithic lapilli tuff record remobilization of pyroclastic material until slopes stabilized, fol-

lowed by settling of crystals, then pumice and ash, through the water column. This process was briefly interrupted by the emplacement of an ash-flow tuff (Af_6, Fig. 11). This ash-flow tuff cannot be traced laterally into the proximal part of the ash-flow sheet, and its unusually high lithic clast content, suggestive of winnowing, provides evidence that it represents material remobilized long after the eruption ceased. The lack of diamictites or slumps in the fallout-dominated part of the bedded facies may signify that eruptive activity and associated seismicity had generally ceased. Tuffs and pumiceous tuffs at the top of the bedded facies pass gradationally upward into calcareous sediments deposited in an outer shelf environment (Busby-Spera, 1984a).

In summary, subaqueous fallout tuffs that cap each flow unit in the distal Monarch ash-flow tuff consist of material winnowed from the underlying flow unit during its subaqueous transport. These tuffs began to settle, were locally remobilized, and were immediately buried by the succeeding ash-flow unit. The transport mechanism of the ash flows also changed distally, from highly concentrated plug flows to somewhat more dilute laminar flows or surging flows, due to incorporation of water and/or frictional drag of the overlying water column at the relatively thin terminus of each flow unit as it slowed to a halt. The bedded facies of the Monarch ash-flow tuff migrated sourceward as the ash-flow sheet accumulated (Fig. 8). Therefore, winnowing of ash flows must have been more effective at sites progressively closer to the source as the eruption continued. This may reflect a progressive decrease in eruptive volumes with time, resulting in less voluminous ash flows that were more easily diluted and sheared as they traveled subaqueously.

The Monarch ash-flow tuff fills a trap-door caldera interstratified with shallow marine sedimentary rocks; therefore, it was probably erupted in shallow water or on land. If the eruption was shallow marine, minimal mixing took place between the eruption column and the ambient water, possibly because the eruption column was large. If the eruption was nonmarine, the rate of supply of pyroclastic material must have surpassed the rate of ablation by phreatomagmatic explosions as the ash flows crossed the shoreline. Whether the eruption was marine or nonmarine, the flows were dense enough to move beneath water along the bottom (see Sparks, 1976 and Sparks et al., 1978 for a discussion of the density of ash flows). Such flows may possibly have been hot, particularly in the proximal part of the sheet, but features that can be used to determine temperature of emplacement were obliterated by metamorphism.

Cliff Creek rhyolite ash-flow tuff (JrR)

The western and southern margins of the lower Jurassic Cliff Creek ash-flow tuff are bounded by the Empire fault (Fig. 1), which cuts out upper Triassic sedimentary and volcanic rocks that depositionally overlie the Monarch ash-flow tuff (Busby-Spera, 1983, 1984a). Thus, the basal and distal part of the Cliff Creek tuff (as inferred from textures and facies below) may have been tectonically removed.

The Cliff Creek ash-flow tuff is similar to the Monarch ash-flow tuff in that: (1) the size and frequency of lithic fragments decreases to the south; (2) the ash-flow sheet contains subaqueous fallout tuffs in its uppermost (eastern) part; and (3) the southern part of the sheet shows more of the effects of sorting by water than the northern part (Fig. 1). It is inferred that the source lay to the north of the Mineral King pendant, as it did for the Monarch ash-flow tuff. Its great thickness (up to 800 m) is also suggestive of ponding in a caldera (Busby-Spera, 1984b).

The northern proximal part of the Cliff Creek ash-flow tuff is massive and nonsorted and contains no intercalations of subaqueous fallout tuff. The ash-flow sheet is overlain by about 70 m of subaqueous fallout tuffs and lesser ash-flow tuffs. Exposures are not continuous, but southeast of Timber Gap (Fig. 1) the ash flows appear to become better sorted and subaqueous fallout tuffs increase in abundance southward.

CONCLUSIONS

The strata of the Mineral King roof pendant provide an opportunity to study depositional processes in a marine volcanic field now well-exposed in the high Sierra. Subaqueous pyroclastic flows described here and elsewhere can be divided into two types: (1) those that show evidence of turbulent mixing with water during emplacement and (2) those emplaced as nonturbulent high concentration mass flows. Fluid turbulence played a larger role in the submarine emplacement of the andesitic pyroclastic material at Mineral King than it did in the rhyolitic pyroclastic material, which was largely deposited from highly concentrated laminar or plug flows. The andesitic pyroclastic rocks show abundant sorting, bedding, grading of single beds or overall grading of bedded sequences. The rhyolite ash-flow tuff sheets, in contrast, are largely nonbedded and nonsorted. Bedding in the rhyolite ash-flow tuffs is restricted to the upper and distal 5—15% of each sheet and consists of: (1) indistinct, discontinuous layers of coarse and fine debris within flow units; and (2) subaqueous fallout tuffs interstratified with individual flow units. The indistinct layers may have formed by laminar shear segregation within flows. The subaqueous fallout tuffs were winnowed from the distal part of each flow unit and deposited prior to the emplacement of succeeding flow units.

The more turbulent nature of the andesitic pyroclastic flows may be due in part to local topographic relief on the flanks of the andesitic stratocones; on lower slopes these flows would have moved at a lower velocity and would have then been less turbulent. This interpretation is consistent with the fact that the upper block-and-ash flow of the Farewell andesite, which was deposited over a broad surface of low relief, shows somewhat less evidence of turbulent flow than other andesite pyroclastic flows at

Mineral King. Eruptive volumes, however, probably had a stronger influence on depositional processes. The rhyolite ash-flow tuffs were probably deposited during steady voluminous eruptions whereas pulsating or intermittent small-volume eruptions were typical of the andesitic units. Steady flow of eruptive material may have led to a minimum of interaction with water during subaqueous transport (and possibly eruption) of the rhyolite ash-flow tuffs. The resulting deposit could be easily confused with a subaerially emplaced ash-flow tuff without thorough examination.

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