Evolution of a multi-vent volcanic complex within a subsiding arc graben depression: Mount Wrightson Formation, Arizona

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ABSTRACT

The Mount Wrightson Formation in the Santa Rita Mountains south of Tucson, Arizona, is a homoclinally dipping section of Lower Jurassic volcanic, subvolcanic hypabyssal, and lesser sedimentary rocks that is 4.5 km thick and crops out over a strike length of 25 km. The nature and distribution of volcanic lithofacies in the Mount Wrightson Formation are interpreted to record the evolution of a multi-vent volcanic complex that formed within a subsiding cratonal intra-arc graben. These lithofacies are grouped into the following facies assemblages: (1) the near-vent facies assemblage, consisting of silicic to intermediate hypabyssal intrusive bodies and peperites and dacite lava flows; (2) the proximal facies assemblage, containing intermediate lava flows, ignimbrites, and debris-flow deposits; (3) the medial facies assemblage, comprising ignimbrites, debris-flow deposits, and reworked pyroclastic deposits; and (4) the distal facies assemblage, including nonwelded ignimbrites and fluvial deposits. These facies assemblages are characteristic of stratovolcano complexes; in the Mount Wrightson Formation, however, the paucity of debris-flow deposits and the burial of near-vent facies assemblages by ignimbrites suggest that the formation was deposited in a low-relief multi-vent complex with no high-standing central edifice. Some of the thickest, most densely welded ignimbrites in the Mount Wrightson Formation probably represent outflow from a more distant caldera or calderas within the intra-arc graben, rather than being products of volcanism within the multi-vent complex.

Intra-arc subsidence resulted in a complex juxtaposition of vent, proximal, medial, and distal facies as vent areas were repeatedly buried by debris derived from adjacent vents in the multi-vent complex and, to a lesser extent, by debris from calderas outside the complex. This subsidence resulted in accumulation and preservation of a thick section of terrestrial volcanic and sedimentary rocks.

The Mount Wrightson complex evolved from predominantly effusive (lower member) to predominantly explosive (middle member), followed by waning volcanism (upper member). Rapid intra-arc subsidence resulted in burial of vent areas by craton-derived eolian quartz arenites correlative with either the Wingate or Navajo Sandstones on the Colorado Plateau; this was particularly important as volcanism waned.

INTRODUCTION

The analysis of volcanic sequences is critical to understanding the paleogeography and tectonic evolution of magmatic arcs. Stratigraphic and petrographic analysis of volcanic and sedimentary sequences permits interpretation of whether the arc was extensional, neutral, or contractional and whether it was high or low standing. Volcanic arcs may be dominated by large stratovolcanoes, many smaller cones, caldera complexes, ignimbrite plateaus, or a combination of these features; they may be deeply incised or maintain an even topographic profile. Analysis of volcanic sequences is frequently complicated, however, by incomplete preservation due to syn- and post-eruptive erosion of the volcanic edifice, metamorphism, or structural dismemberment. Even more difficult is the interpretation of complexly juxtaposed facies resulting from the superposition of more than one volcanic edifice.

We report herein on the Mount Wrightson Formation (Drewes, 1968), an unmetamorphosed, diverse assemblage of Lower Jurassic volcanic rocks, interstratified quartz arenites, and associated subvolcanic intrusive rocks exposed in the Santa Rita Mountains south of Tucson, Arizona (Fig. 1). The Mount Wrightson Formation represents a multi-vent volcanic complex deposited in a subsiding intra-arc basin that was part of an early Mesozoic Cordilleran arc graben depression (Busby-Spera, 1988). By documenting the distribution of hypabyssal, volcanic, and sedimentary lithofacies in the Mount Wrightson Formation, we are able to infer that parts of the Early Jurassic magmatic arc in southern Arizona were low standing and extensional in character, similar to the modern Central American arc rather than a high-standing "Andean" arc.

REGIONAL GEOLOGIC SETTING

The Late Triassic–Middle Jurassic magmatic arc in southern Arizona was established across a basement of 1.8–1.4 Ga supracrustal and plutonic rocks (Anderson and Silver, 1976; Silver, 1978) overlain by a Paleozoic cratonic sequence representing stable-margin sedimentation. Subduction-related volcanic and plutonic activity began in Late Triassic or Early Jurassic time across eastern California and into southern Arizona (Dickin-

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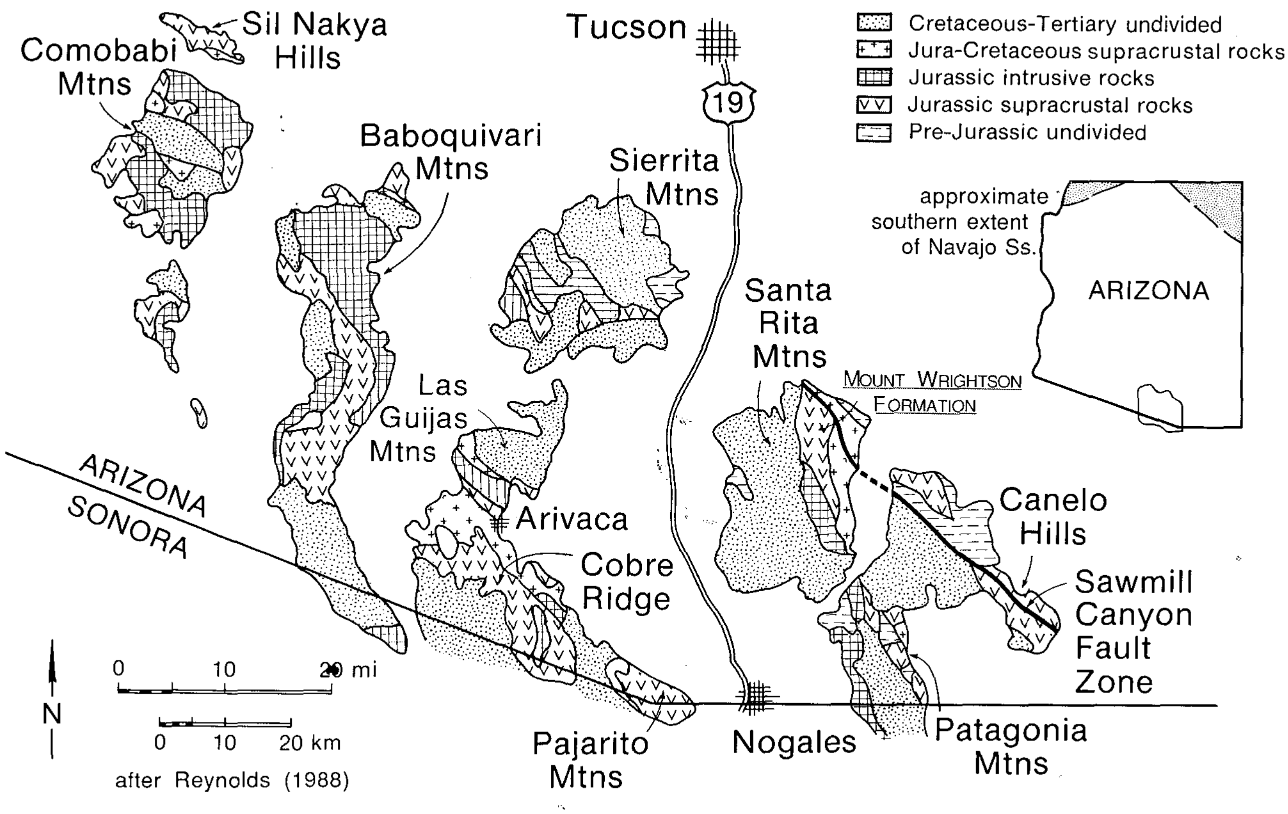


Figure 1. Generalized lithostratigraphic map of southern Arizona, after Reynolds (1988).

son, 1981; Walker, 1987; Tosdal and others, 1989) and northern Sonora (Anderson and Silver, 1978, 1979).

Sedimentary rocks that underlie Mesozoic volcanic rocks in the eastern Mojave Desert region (for example, Hewett, 1956; Grose, 1959; Marzolf, 1980, 1982; Walker, 1985, 1987), and that are interstratified with volcanic rocks in southern Arizona (for example, Cooper, 1971; Drewes, 1971c; Bilodeau and Keith, 1981, 1986; Tosdal and others, 1989), have been litho- and biostratigraphically correlated with Triassic and Jurassic strata on the Colorado Plateau. Drewes (1968, 1971c) assigned a Late Triassic age to interstratified volcanic rock–eolianite sequences in the Santa Rita Mountains, based on Pb-alpha ages on the volcanic rocks, and noted that these ages corroborated stratigraphic correlation of the eolian quartz arenites with Mesozoic eolian sandstone on the Colorado Plateau 250 km to the north.

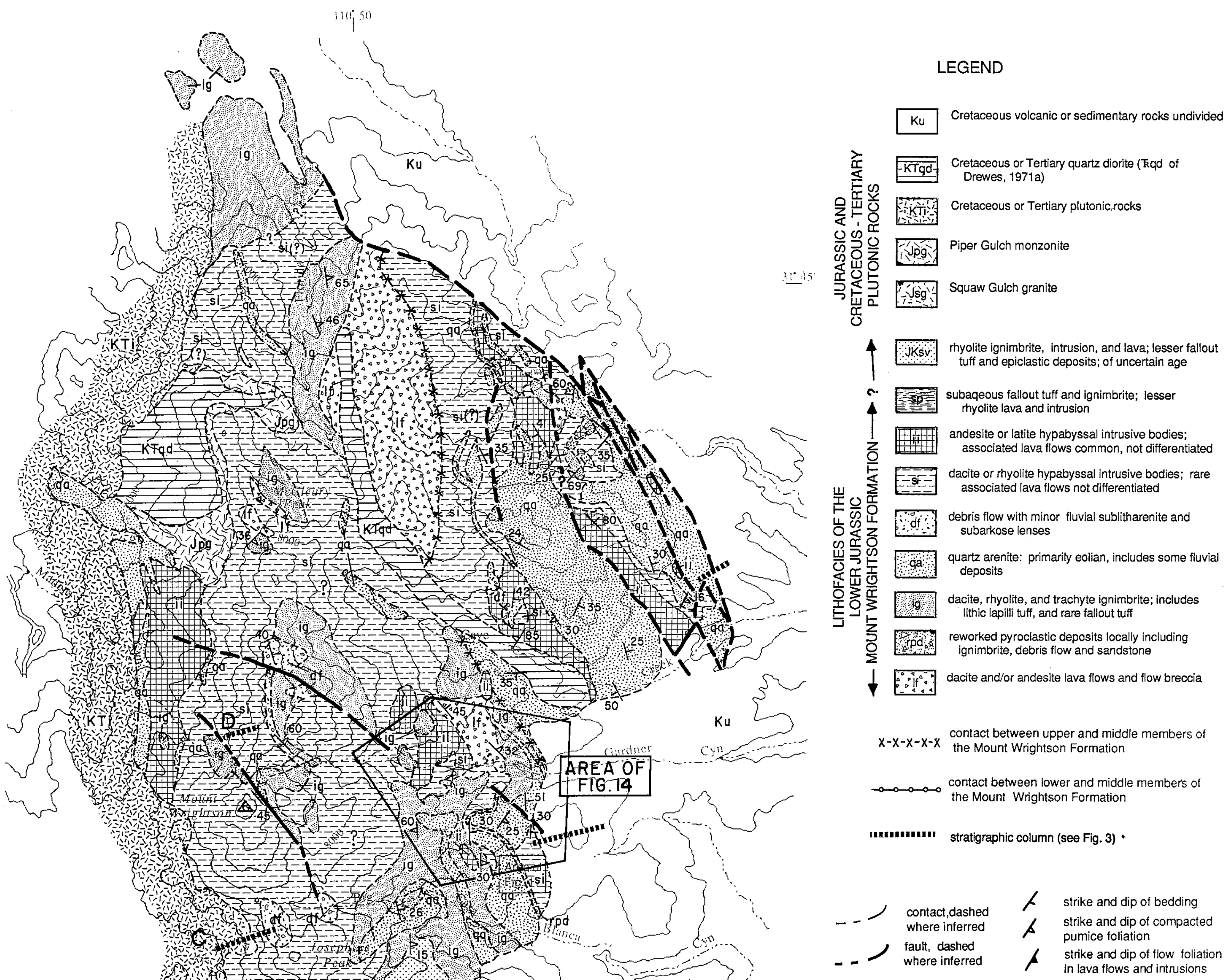
Early Jurassic arc magmatism in southern Arizona is characterized primarily by volcanic and shallow subvolcanic intrusive rocks with few mesozonal equivalents. The Mount Wrightson Formation is probably among the oldest preserved arc-related sequences in southern Arizona. Known Early Jurassic plutonic rocks are confined to the Piper Gulch Monzonite in the Santa Rita Mountains, dated by Asmerom (1988) and Asmerom and others (1988) at 188 ± 2 Ma, and possibly the Harris Ranch Monzonite in the Sierrita Mountains (Cooper, 1971) (Fig. 1).

Late Jurassic through early Tertiary tectonism in southern Arizona may have formed structural boundaries of the Mount Wrightson Formation (for example, Sawmill Canyon fault zone; Fig. 1) but affected the formation itself very little. Late Jurassic and Late Cretaceous to early Tertiary plutonism probably caused potassic metasomatism apparent in the Mount Wrightson Formation volcanic rocks (Drewes, 1971c; Table 1) and elsewhere in southern Arizona (Haxel and others, 1985; Riggs, 1985, 1987; Krebs and Ruiz, 1987). Recent Basin and Range faulting has shaped the present-day topography of southern Arizona.

GEOLOGIC OVERVIEW OF THE MOUNT WRIGHTSON FORMATION

Stratigraphy

The present thickness of the Mount Wrightson Formation is approximately 4.6 km, of which approximately 2.5 km consists of supracrustal strata and the remainder penecontemporaneous hypabyssal intrusive bodies. The formation was first studied by Drewes (1968, 1971a, 1971b, 1971c), who divided it into lower, middle, and upper members. This study supports Drewes' tripartite division and elaborates upon his stratigraphic analysis (Figs. 2 and 3). The lower member consists largely of dacite and andesite lava flows and flow breccias and latite ignimbrite and reworked ignimbrite, with lesser fluvial conglomerate and sandstone, and possibly eolian sandstone. These strata are intruded by andesite, latite, and lesser dacite. The middle member comprises dacite to rhyolite ignimbrite, eolian quartz arenite, lesser andesite and dacite lava flows, and minor andesite and trachyte ignimbrite and debris-flow deposits. This member is also multiply intruded by intermediate to silicic rocks. The upper member is made up of subequal parts eolian sandstone and andesite to dacite intrusions, with minor andesite lava and flow breccia, silicic ignimbrite, and debris-flow deposits (Figs. 2 and 3). The lithofacies analysis of this diverse assemblage provides a descriptive basis for understanding the paleotectonic and paleogeographic setting of the Mount Wrightson Formation.


LEGEND
Ku Cretaceous volcanic or sedimentary rocks undivided
KTqd Cretaceous or Tertiary quartz diorite (Tqd of Drewes, 1971a)
KTi Cretaceous or Tertiary plutonic rocks
Jpg Piper Gulch monzonite
Jsg Squaw Gulch granite
JURASSIC AND CRETACEOUS - TERTIARY PLUTONIC ROCKS
JKsv rhyolite ignimbrite, intrusion, and lava; lesser fallout tuff and epiclastic deposits; of uncertain age
sp subaqeous fallout tuff and ignimbrite; lesser rhyolite lava and intrusion
ii andesite or latite hypabyssal intrusive bodies; associated lava flows common, not differentiated
si dacite or rhyolite hypabyssal intrusive bodies; rare associated lava flows not differentiated
df debris flow with minor fluvial sublitharenite and subarkose lenses
qa quartz arenite: primarily eolian, includes some fluvial deposits
ig dacite, rhyolite, and trachyte ignimbrite; includes lithic lapilli tuff, and rare fallout tuff
rpd reworked pyroclastic deposits locally including ignimbrite, debris flow and sandstone
lf dacite and/or andesite lava flows and flow breccia
LITHOFACIES OF THE LOWER JURASSIC MOUNT WRIGHTSON FORMATION
X-X-X-X-X contact between upper and middle members of the Mount Wrightson Formation
contact between lower and middle members of the Mount Wrightson Formation
stratigraphic column (see Fig. 3)
contact, dashed where inferred
fault, dashed where inferred
strike and dip of bedding
strike and dip of compacted pumice foliation
strike and dip of flow foliation in lava flows and intrusions
110° 50'
31° 45'
Ku
KTi
KTqd
Jpg
AREA OF FIG. 14
Gardner Cyn
Mount Wrightson
Josephine Peak
Blanca Cyn
C
D

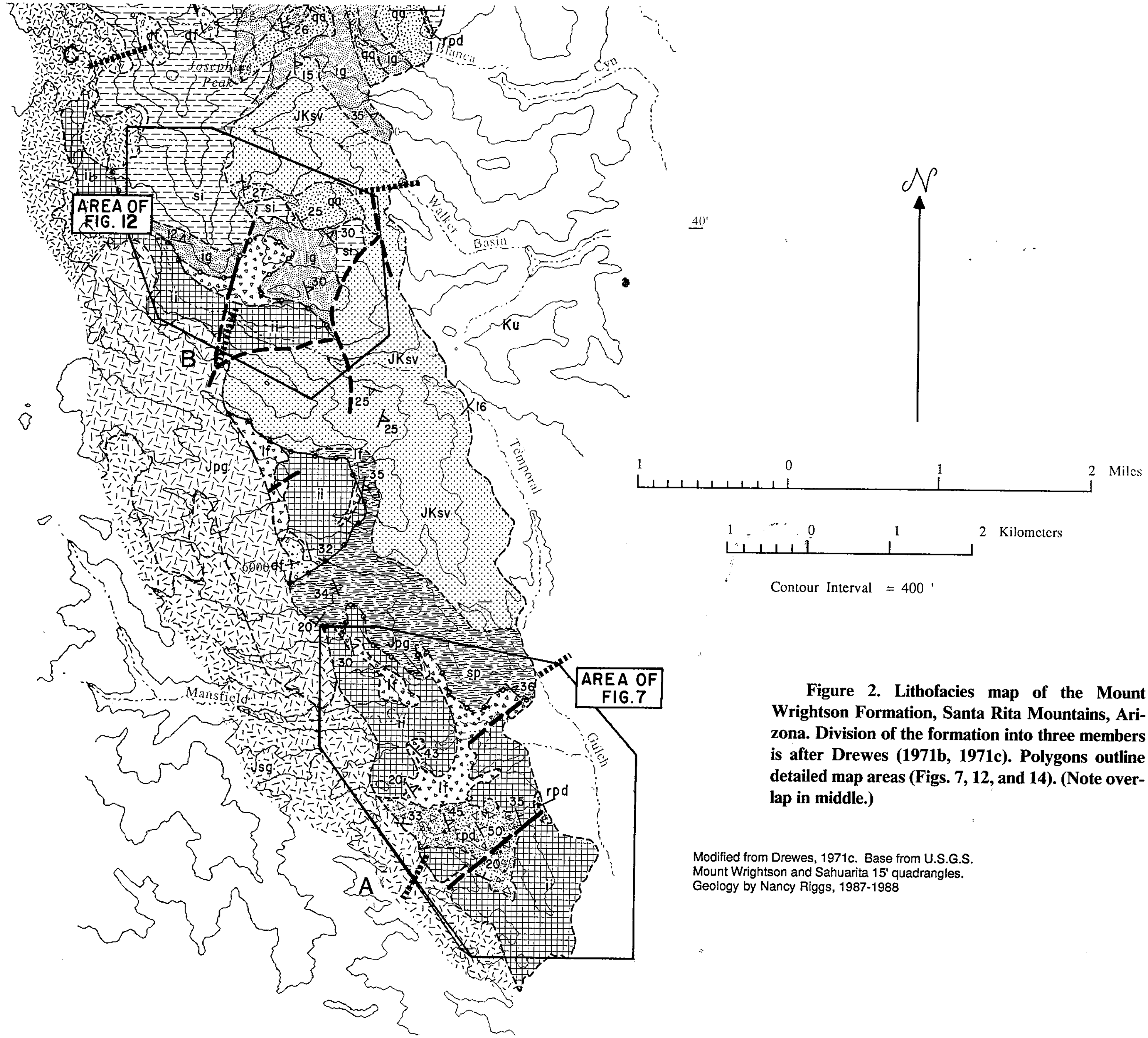


Figure 2. Lithofacies map of the Mount Wrightson Formation, Santa Rita Mountains, Arizona. Division of the formation into three members is after Drewes (1971b, 1971c). Polygons outline detailed map areas (Figs. 7, 12, and 14). (Note overlap in middle.)

Modified from Drewes, 1971c. Base from U.S.G.S. Mount Wrightson and Sahuarita 15' quadrangles. Geology by Nancy Riggs, 1987-1988

Structure and Metamorphism

The Mount Wrightson Formation crops out as a homocline dipping an average of 35° to the northeast, except in the upper member, where attitudes are more variable (Fig. 2). The formation is intruded everywhere along its base by Early Jurassic through Late Cretaceous plutons (ages from Drewes, 1968, 1971c; Asmerom, 1988) and is unconformably overlain over most of its length by Jurassic-Cretaceous and Cretaceous sedimentary and volcanic rocks (Drewes, 1968, 1971a, 1971b, 1971c). The upper member is truncated to the northeast by the Sawmill Canyon fault zone (Fig. 2), which is a major regional northwest-trending discontinuity postulated to have been episodically active since Precambrian time (Titley,

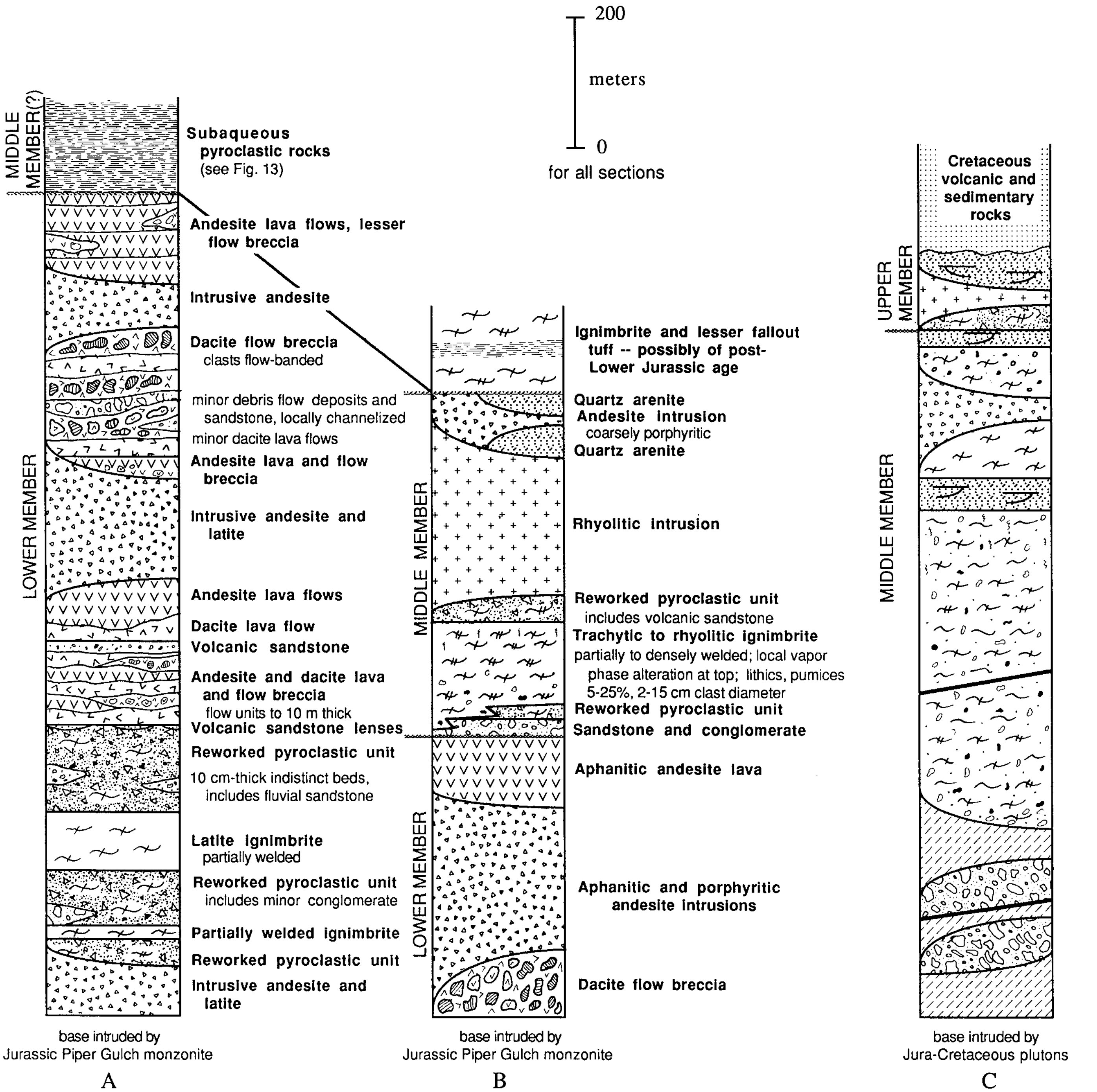


Figure 3. Stratigraphic sections through the Mount Wrightson Formation. Locations of section lines are shown in Figure 2. (Note overlap in center.)

1976; Davis, 1981; Kluth, 1983). Strata of the Mount Wrightson Formation are cut by northwest- to northeast-trending high-angle faults (Fig. 2) of uncertain age, with no apparent major repetition of section.

The effects of post-depositional magmatism and tectonism on the Mount Wrightson Formation are minor. Metamorphism is generally subgreenschist grade and is confined to hornfelsic alteration with concomitant obliteration of sedimentary and volcanic textures within 50 m of intrusive contacts. Deformational fabrics are absent, and volcanic and sedimentary textures and structures are commonly excellently preserved. Hydrothermal alteration is common (see Table 1).

Age

Interpretation of the age of the Mount Wrightson Formation is constrained by U-Pb zircon analyses by Riggs and others (1986; N. R. Riggs, unpub. data) and Asmerom (1988) and Asmerom and others (1988). Asmerom (1988) and Asmerom and others (1988) reported a "concordant" age of 212 ± 3 Ma for one fraction of zircons from the lower member. Three other fractions are quite discordant, however, and this discordancy, together with low $^{206}Pb/^{204}Pb$ values averaging 250, suggests that the error assignment may be optimistically small (compare with Mattinson, 1984). These workers also suggest a minimum age of 184 ± 2 Ma for the middle member of the Mount Wrightson Formation, based apparently on a statistical average of the $^{206}Pb^{*}/^{238}U$ ages obtained on six fractions.

Our geochronologic work (Riggs and others, 1986) suggests that the middle member of the Mount Wrightson Formation is 206 ± 9 Ma, and

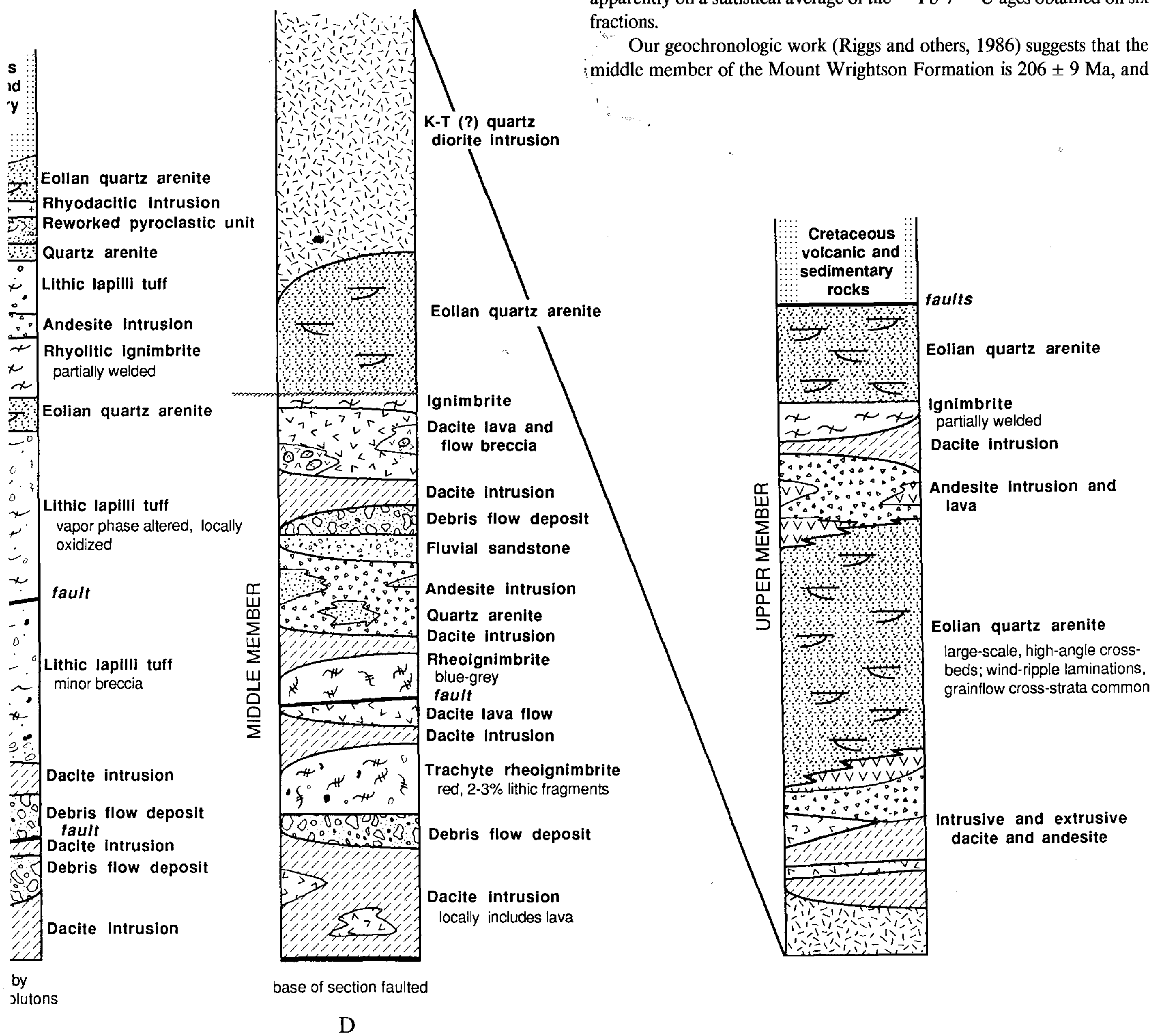


Figure 3. (*Continued*).

TABLE 1. PETROGRAPHIC AND TEXTURAL CHARACTERISTICS OF MAP UNITS IN THE MOUNT WRIGHTSON FORMATION

Map unit	Phenocryst and groundmass mineralogy of igneous units	Lithic fragments	Alteration
lf: lava flows: Dacitic and andesitic lava flow and flow breccia, flows as much as 5 m thick, locally associated with thin fluvial sandstone, pebbly sandstone, and siltstone. Lava flows commonly massive; flow breccia clasts flow banded, as much as 30 cm diameter	Plagioclase 5% (An_{20}); 1%–2% opacitized hornblende; tr. quartz; tr. zircon and/or monazite as crystallization phase with magnetite. Groundmass K-feldspar and quartz, devitrified glass. Andesite: see ii	Rare felsitic aphanite. Clots of zircon and/or monazite with opaques ± feldspar may be crystallization phase, cognate inclusion, or xenolithic phase	Plag to sericite or clay locally; hbd to opacite; secondary quartz veins. Groundmass takes Ksp stain
ii: intermediate hypabyssal intrusive and extrusive rocks: Andesitic and latitic hypabyssal rocks. Associated lava flows not differentiated except in lower member; flow breccias common. Shape, lateral extent, and thickness variable, from one to several tens of meters	Andesite: Lower member hypabyssal intrusions and lava flows: Commonly porphyritic; plagioclase 2%–50%, An_{20-37}, 0.75–4 mm; primary mafic pigeonite or augite(?) 1%–5%, or hornblende 1%–5%, commonly opacitized; magnetite grains 0%–5%. Groundmass pilotaxitic to hyalopilitic or coarsely recrystallized; composed of plag crystals, opaque grains, and secondary K-fdsp. Middle-upper member hypabyssal intrusions and lava flows: Porphyritic; plag 1%–20%, An_{19-26} (one An_{65-80}); cpx 2%–5%, or opacitized hbd tr.–6%, mgt tr.–8%. Groundmass commonly recrystallized; rarely trachytic. Latite (lower member only) Porphyritic; phenocrysts K-feldspar 5% ≤5 mm; plagioclase 3%, An_{10-27}, ≤2.5 mm; opacitized hornblend tr.; magnetite 1%; groundmass primarily plag microlites with lesser Ksp crystals. Local alkali fdsp rims on plagioclase	None	And: cpx to uralite ± calcite; opx ubiquitous to chlorite ± sphene/leucoxene; plag to clay or calcite locally; hbd to opacite or rarely chlorite; epidote as secondary veins and variable replacement of all minerals. Groundmass rarely takes Ksp stain. Lat: Calcite veinlets, cc also in groundmass, spotty epi; opx(?) to leucoxene + sph; cavities filled with secondary epidote + quartz. Groundmass locally takes Ksp stain
si: silicic intrusive and extrusive rocks: Dacitic to rhyolitic(?) hypabyssal intrusive bodies, locally including lava flows. Units variable in lateral extent and thickness, as much as 2 km	Porphyritic to aphanitic; plag 1%–7%, An_{20-28}; Ksp 1%–5%, locally partially albitized; biotite tr.–2%; zircon tr. Groundmass commonly devitrified or recrystallized glass, now quartz and Ksp	Rare fine-grained plutonic fragments. Inclusions of zircon and/or monazite associated with opaques ± feldspar (compare with lf dacite)	Ubiquitous devitrification of groundmass; calcite veinlets common; plag to cl/ser. Groundmass takes Ksp stain
qa: quartz arenite: Eolian and fluvially reworked eolian deposits, includes lesser primarily volcanogenic fluvial deposits. Eolian set thickness as much as several meters; fluvial deposits commonly <2 m thick		Intermediate to silicic volcanic rock fragments	Overgrowths on qtz grains common; local alteration of matrix to calcite; minor veinlets filled with clay or sericite. Matrix does not take Ksp stain
ig: pyroclastic deposits: Andesitic, dacitic, trachytic, and rhyolitic nonwelded to densely welded ignimbrite and minor rheoignimbrite, deep pink to deep purple in color, locally lithic rich. Individual flows as much as 30 m thick; complex cooling units as much as 300 m thick	Rhyolite: qtz 1%–3%; plag 2%–15%, An_{20-35}; Ksp tr.–3%; hbd tr.–3%; bio tr.–5%. Dacite: see si. Trachyte: plag tr.–1%, An_{20-35}; Ksp up to 10%; bio tr.–2%; hbd tr.–3%. Zircon and/or monazite as crystallization phase with magnetite; groundmass devitrified ash, now quartz, plag, secondary(?) K-feldspar, clay. Excellent preservation of pumice fragments and, locally, shards	Predominantly nonvesicular porphyritic and aphanitic andesite and aphanitic dacite similar to lower member types; also silicic ignimbrite. Recognizable basement xenoliths of Continental Granodiorite (1.4 Ga, Drewes, 1971b) confined to rare fragments	Clay and/or sericite ± opaques in veinlets; sparse chlorite common; local bio to ser, opaques on cleavage surfaces; plag to clay ± calcite. Groundmass takes Ksp stain
rpd: reworked pyroclastic deposits: Pyroclastic detritus with as much as 50% sand grains; mud-ash matrix 5%–50%. Commonly as 5- to 15-cm-thick beds. Locally includes volcanic sandstone and/or conglomerate	As for primary pyroclastic deposits (ig)	As for primary pyroclastic deposits (ig)	As for ig. Ksp stain on groundmass indicates ash matrix; no stain indicates clastic groundmass
df: debris-flow deposits: Matrix-supported, massive, unsorted polymict volcanic breccia; also includes volcanogenic sandstone locally. Deposits as much as 10 m thick. Matrix commonly mud with variable sand component, locally minor ash		As for primary pyroclastic deposits (ig); clasts of Continental Granodiorite somewhat more common. Local clasts of quartz arenite	Clay and ser ± chl(?) in veinlets; qtz veins within clasts indicate syn-volcanic alteration; plag to ser/cl on cleavage surfaces. Variable groundmass Ksp stain as for rpd
sp: subaqueous pyroclastic rocks: Includes fallout tuff and nonwelded ignimbrite containing pumice blocks as much as 0.5 m in diameter. Possibly post–Early Jurassic in age. Age differentiation from JKsv (see below) based on intrusive contact with 188 Ma Piper Gulch pluton (Asmerom, 1988)	Quartz 2%–5%; sanidine to 2%; plag to 2%; bio to 2%; groundmass devitrified ash or glass now altered. Minor preservation of pyroclastic textures in thin section	Contains rare clasts of all rock types found in Mount Wrightson Formation; quartz arenite locally common	Phyllic/argillic alteration. Groundmass takes Ksp stain
JKsv: silicic volcanic, volcaniclastic, and hypabyssal units of possible Jurassic-Cretaceous age or belonging to an as-yet-undefined Jurassic-age formation: Rhyolitic nonwelded tuff, lithic lapilli tuff, lava, subaqueous(?) fallout tuff, debris-flow deposits, and hypabyssal bodies, not differentiated	As for subaqueous pyroclastic rocks (sp)	All rock types from Mount Wrightson Formation; quartz arenite locally common	Phyllic/argillic alteration locally pervasive. Secondary quartz in vugs and veinlets. Groundmass takes Ksp stain. Epiclastic units generally less altered

the lower intercept of a two-fraction chord on an ignimbrite from the upper member (N. R. Riggs, unpub. data) gives a minimum crystallization age of 181 Ma. These geochronologic data allow the interpretation that deposition of the Mount Wrightson Formation occurred over as much as 30 m.y. (212–181 Ma). By analogy, volcanism of different episodes has occurred in the Western Cascade and High Cascade chain over the past approximately 40 m.y. (McBirney, 1978; Lux, 1982), over the past 20 m.y. on the island of Martinique (Cas and Wright, 1987), and over 7 m.y. in the basal formation of the Marysvale volcanic district (Cunningham and Steven, 1979). We assume that the age obtained by Asmerom (1988) and Asmerom and others (1988) for the lower member is accurate, perhaps within larger error margins, and our data suggest that the middle member is approximately the same age. The nature of the contact between the middle and upper members, discussed below, suggests that these two members are nearly equivalent in age. We infer, therefore, that deposition of the Mount Wrightson Formation occurred within far less than 30 m.y. and suggest that accumulation of the entire formation occurred within less than 10 m.y.

Eolian quartz arenite in southern Arizona and eastern California has traditionally been correlated with the Lower Jurassic Navajo Sandstone of the Colorado Plateau (Hewett, 1956; Grose, 1959; Marzolf, 1980, 1982; Bilodeau and Keith, 1981, 1986). U-Pb dates of 190 ± 10 Ma on volcanic rocks interstratified with eolian quartz arenite in the Baboquivari Mountains and Sil Nakya Hills in southern Arizona support this correlation (Fig. 1; Wright and others, 1981). Bilodeau and Keith (1981, 1986) further inferred that eolian sandstones throughout southern Arizona are distal equivalents of the Navajo Formation. Our U-Pb zircon data permit correlation of eolian quartz arenite in the Mount Wrightson Formation with either the Wingate Sandstone and/or the Navajo Formation on the Colorado Plateau (time scale of Harland and others, 1982).

TERMINOLOGY

The variable use of certain terms to describe pyroclastic rocks necessitates definition of the terms used in this report. "Ignimbrite" is used to describe a rock that is "composed predominantly of vesiculated juvenile material (pumice and shards) . . . whether welded or not" (Sparks and others, 1973, p. 115) and that is interpreted to be the deposit of pyroclastic flow. Pyroclastic deposits that contain fragments 2–64 mm in size and 25%–75% ash are here called "lapilli tuff" (Fisher and Schmincke, 1984); "pumice" or "lithic" preceding a term describes the primary fragment type. "Tuff breccia" contains 25%–75% fragments greater than 64 mm. In general, ignimbrites in the Mount Wrightson Formation consist of as much as 95% ash and pumice lapilli, and lithic lapilli tuff contains <10% pumice fragments. Ignimbrite flow units represent single depositional events (Smith, 1960) and in the Mount Wrightson Formation are distinguished from other flow units by characteristics such as mineralogy, grain size, color, and pumice concentrations. Simple cooling units are defined by a single zone of welding that may comprise multiple flow units (Smith, 1960). Compound cooling units are more common in the Mount Wrightson Formation and may have formed when the cooling process was disrupted by continued emplacement of hot flows that disturbed the welding zonation. Size-grade scales used are those of Wentworth (1922).

VOLCANIC AND SEDIMENTARY LITHOFACIES

The Mount Wrightson Formation is a heterogeneous mixture of hypabyssal intrusive rocks, lava flows and flow breccias, ignimbrites, reworked pyroclastic deposits, quartz arenite, and debris-flow deposits, with rapid lateral and vertical changes in lithofacies (Figs. 2 and 3). With few exceptions, each of these lithofacies occurs within each of the three members; the formation as a whole, however, records an upsection evolution from primarily intermediate effusive volcanism to primarily silicic explosive volcanism, with increasing sand deposition and probable waning volcanism at the top of the formation. The distribution and petrology of these lithofacies and complex interstratification of the facies assemblages indicate that deposition of the Mount Wrightson Formation occurred within an actively subsiding basin that was the site of a multi-vent volcanic complex.

We present herein a volcanic facies model of the Mount Wrightson multi-vent complex (Fig. 4). This model incorporates near-vent, proximal, medial, and distal facies assemblages used in traditional stratovolcano facies models (Williams and McBirney, 1979; Vessell and Davies, 1981; Cas and Wright, 1987). The stratovolcano model, shown in Figure 4A, provides a reference for understanding the physical distribution of lithofacies and facies assemblages in the Mount Wrightson Formation, summarized in Figure 4B.

The near-vent facies assemblage (less than 2 km from central vents) in a typical stratovolcano facies model includes feeder intrusive bodies, domes, coarse ejecta, thick silicic and thin mafic lava flows, and mass-flow deposits; of these, the Mount Wrightson Formation contains intrusive bodies and peperites, and silicic lava flows and domes. The proximal facies assemblage (as much as 5–15 km from central vents) traditionally comprises thick intermediate or mafic lava flows, debris-flow deposits, and welded ignimbrites; all of these lithofacies are present in the Mount Wrightson Formation, although debris-flow deposits are not common. The medial facies assemblage (as much as 25–35 km from central vents) consists of moderately to nonwelded ignimbrites, debris-flow deposits, thin fallout deposits, minor lava flows, and coarse-grained epiclastic units; the Mount Wrightson Formation contains all of these lithofacies, although debris-flow deposits, as mentioned, are rare. The distal facies assemblage (>35–50 km from central vents) contains abundant epiclastic deposits, minor lava flows and pyroclastic deposits, and thin fallout deposits; of these, only some of the fluvial deposits and pyroclastic or reworked pyroclastic deposits in the Mount Wrightson Formation may be analogous to the distal facies assemblage of a stratovolcano.

The Mount Wrightson Formation contains most of the lithofacies present in a classic stratovolcano model but lacks abundant debris-flow deposits characteristic of stratovolcanoes. In addition, examples of burial of near-vent facies by other volcanic products are common in the Mount Wrightson Formation. We therefore propose that despite lithologic similarities with stratovolcano facies models, the Mount Wrightson Formation was deposited in an area of low relief rather than in proximity to a large central stratovolcano (Fig. 4B). Geologic evidence presented below indicates that multiple vents were commonly active penecontemporaneously. Thick densely welded ignimbrites that are locally common in the Mount Wrightson Formation may have been derived from a caldera or calderas outside the Mount Wrightson Formation depocenter, and thus caldera-complex facies models (Cas and Wright, 1987) are incorporated into the model of the depositional setting of the Mount Wrightson Formation (Fig. 4B).

Hypabyssal Intrusions (including Peperites)

Description. Irregular hypabyssal intrusions of andesite, dacite, rhyolite, latite, and trachyte (units ii and si, Table 1) occur throughout the Mount Wrightson Formation. Lateral continuity is highly variable; some dacite intrusions, for example, are exposed for 1 km or more along the strike of the formation and are as much as 900 m thick (for example, south of Josephine Peak, Figs. 2 and 3). Andesitic intrusives, in contrast, commonly occur as plugs or dikes as small as a few meters wide or thick (for example, lower Gardner Canyon, Fig. 2).

Interpretation. The commonly aphanitic nature of the groundmass of the hypabyssal bodies suggests shallow levels of intrusion (Buddington, 1959); in addition, miarolitic cavities and vesicles in andesite and dacite indicate depths of crystallization of 2 km or less (Williams and McBirney, 1979). Brecciated silicic material and steeply inclined flow-banded blocky material may represent endogenous lavas and volcanic domes.

We interpret the hypabyssal intrusions as vent related. Peperitic margins found on some intrusions (see below) indicate a shallow depth of emplacement; some of these shallow hypabyssal bodies vented at the surface and fed lava flows.

Age. The contemporaneity of hypabyssal intrusions and volcanism and sedimentation in the Mount Wrightson Formation is demonstrated by petrographic and field characteristics in the lower member and by peperitic margins on intrusions in the middle and upper members (see below). In the lower member of the Mount Wrightson Formation, intrusive ande-

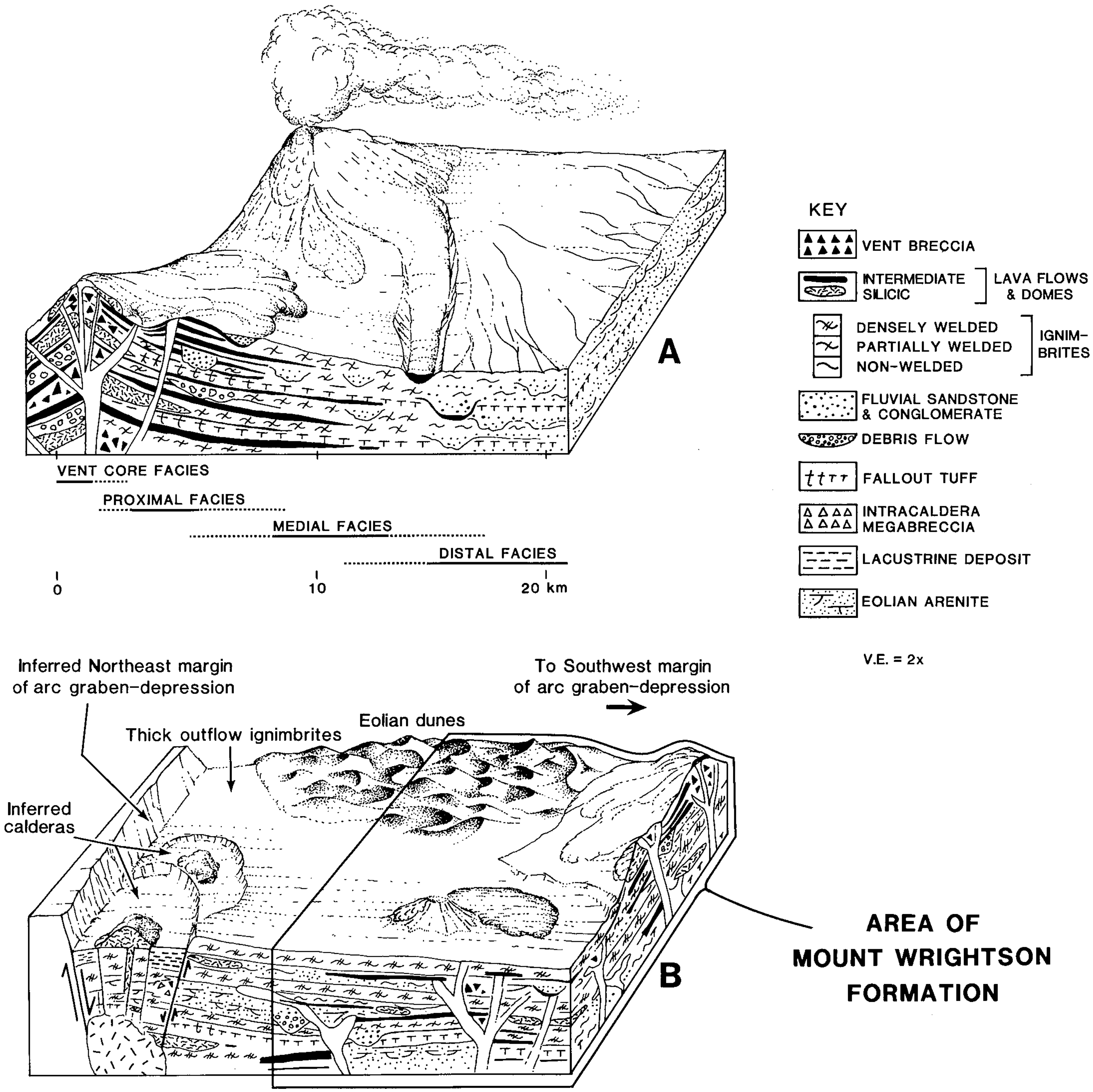


Figure 4. A. Facies model of a stratovolcano, adapted, in part, from Williams and McBirney (1979), Vessell and Davies (1981), and Cas and Wright (1987). B. Model of the paleogeography and volcanic setting of the Mount Wrightson Formation. Eolian dunes derived from the north or northwest are interstratified with the products of active and inactive effusive vents and more distal caldera complexes, within an intra-arc graben. Active subsidence during deposition enhances preservation potential of this multi-vent complex.

site is petrographically identical to andesite lava flows and flow breccias (Table 1). The petrology of intrusive latite strongly resembles the groundmass petrology of the basal pyroclastic unit. Latite and andesite intrusions commingle in one outcrop.

Peperitic margins on hypabyssal intrusions are common in the middle and upper members of the Mount Wrightson Formation but have not been observed in the lower member. Peperitic intrusions, most commonly andesitic in composition, show mixing of magma and quartz arenite on scales ranging from centimeters to single grains (Fig. 5), over zones several centimeters to 0.5 m wide. The fragments of andesite within sandstone, and vice versa, are highly irregular in shape, and locally show millimeter-thick zones in which sandstone is darkened, andesite is bleached, and individual crystals are indistinguishable. These zones may represent preservation of the water-vapor film developed during peperite formation (Kokelaar, 1982).

Peperites are formed when magma or lava intrudes or mixes with wet unconsolidated sediment and are extremely useful in demonstrating contemporaneity of sedimentation and magmatism. Peperites form when conditions of temperature and pressure allow steam to form and wet sediment to "fluidize." Under conditions of lithostatic load (that is, wet sediment), this corresponds to a maximum depth of approximately 1.5 km (Kokelaar, 1982), although pore waters are more commonly expelled at shallower depths. In the Mount Wrightson Formation, peperitic margins indicate that the quartz arenites were wet and unlithified when andesite intrusions were emplaced, demonstrating penecontemporaneity of quartz sand deposition and much of the intrusive activity.

Figure 5. Drawing of a rock slab, showing a peperitic margin along an andesite intrusion (black) into quartz arenite (white) from the upper member, Mount Wrightson Formation.

Dacite Lava and Flow Breccia

Description. Dacite in the Mount Wrightson Formation (unit lf, Table 1) forms lavas and flow breccias (Fig. 6), in units as much as 10 m thick. Outcrops of dacite lava and flow breccia are most common in the lower member in the Mansfield Canyon area (Figs. 2 and 7) but occur elsewhere in the formation. The relative amounts of massive lava and flow breccia in a flow unit are highly variable, although flow breccia is in general more common than massive lava, and in places entire flow units are brecciated. The lavas and flow breccias locally show a crude stratification and, in the Mansfield Canyon area (Fig. 2), are intercalated with andesite lava flows and flow breccias or volcanic-pebble sandstone or conglomerate. Intercalated sandstone lenses, primarily confined to lower member outcrops of dacite lava and flow breccia, are as much as 10 cm thick and exhibit normal grading and minor channeling.

Interpretation. Dacite lava flows are interpreted as near-vent facies deposits (see Fig. 4). Although dacite lava has been reported from Chao, Chile, as far as 12 km from its recognized vent (Guest and Sanchez, 1969),

Figure 6. Dacite flow breccia from the Mansfield Canyon area, lower member of the Mount Wrightson Formation. Note well-developed flow banding. Scale 15 cm long.

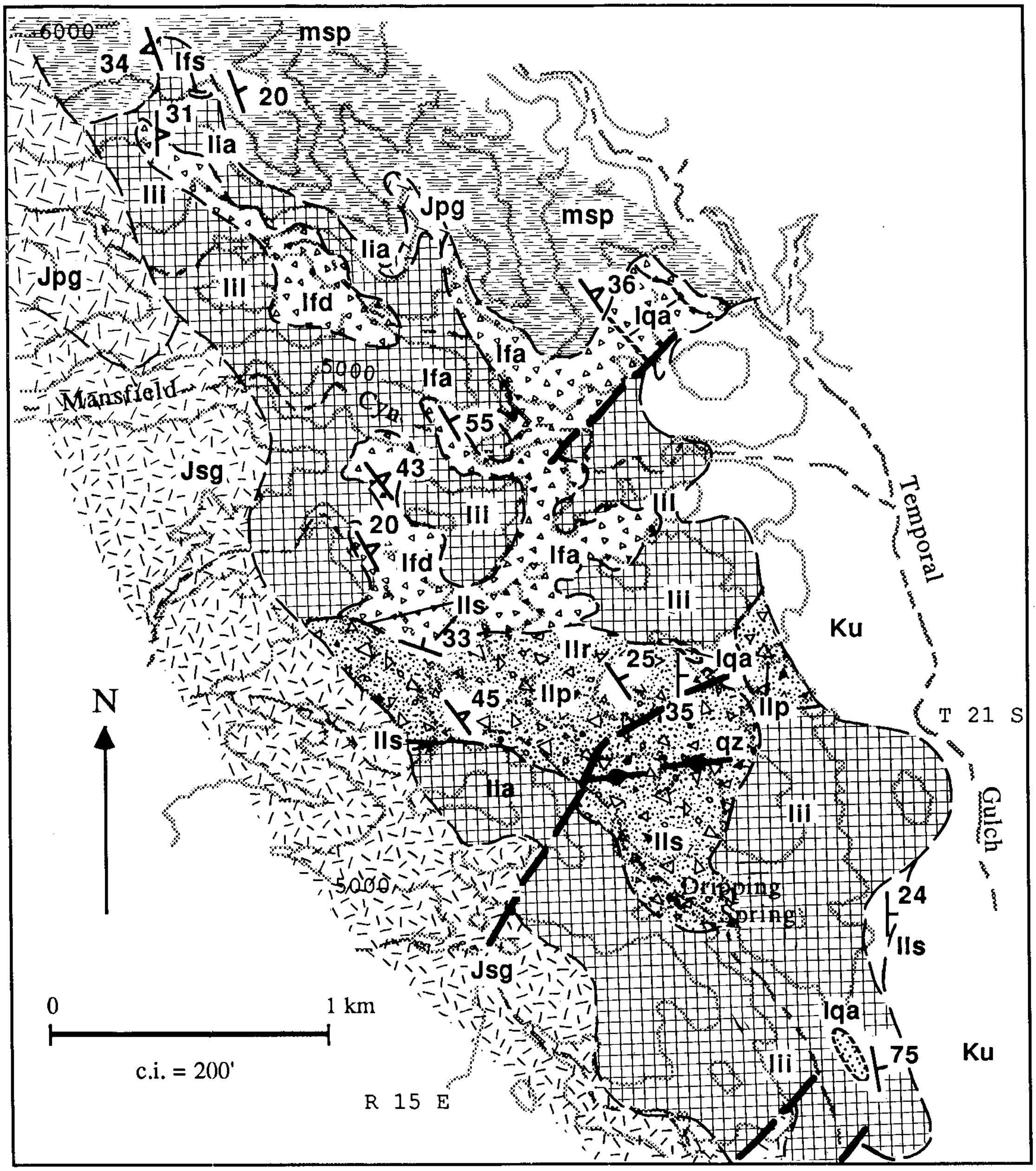


Figure 7. Geologic map of the lower member of the Mount Wrightson Formation in the Mansfield Canyon area, southern Santa Rita Mountains (locality shown in Fig. 2).

LEGEND

qz — quartz vein

Ku — Cretaceous strata undifferentiated

Jsg — Squaw Gulch granite

Jpg — Piper Gulch monzonite

MOUNT WRIGHTSON FORMATION

MIDDLE MEMBER

msp — Silicic subaqueous fallout tuff and ignimbrite, possibly not part of the Mount Wrightson Formation

LOWER MEMBER

li — Intermediate intrusion: andesite (a), latite (l), undifferentiated (i), dacite locally near Dripping Spring; includes minor extrusive andesite

lqa — Quartz arenite

lf — Lava and flow breccia unit, includes dacite (d), andesite (a), and polylithologic breccia and sandstone (s)

ll — Latitic reworked pyroclastic (r) and pyroclastic (p) unit, includes volcanogenic sandstone and breccia (s) dacitic lavas in general are found within 3 km of a vent (Williams and McBirney, 1979). Associated sandstones are interpreted as fluvial deposits in small rills and channels.

Andesite Lava and Flow Breccia

Description. Andesite lavas and lesser flow breccia (unit lf, Table 1) form units as much as 5 m thick in the Mount Wrightson Formation. Andesitic lava is difficult to distinguish from hypabyssal andesite; in general, however, lava is less resistant to erosion than are intrusions. In the McCleary Peak area (Fig. 2), andesite lava shows crystal alignment and, in one place, an oxidized flow top.

Interpretation. Andesite lavas and flow breccias may have traveled considerable distances from source vents; intermediate-composition nonviscous flows are commonly found tens of kilometers from vents (Cas and Wright, 1987). The nearly ubiquitous spatial association of andesite lava flows with dacite lava flows and flow breccias, especially in the lower member of the Mount Wrightson Formation, suggests that many of the andesite flows and flow breccias are near-vent or proximal facies deposits (Fig. 4).

Pyroclastic Rocks

Description. Pyroclastic rocks in the Mount Wrightson Formation include nonwelded, partially welded, and densely welded ignimbrite comprising andesitic, dacitic, trachytic, and rhyolitic pumice lapilli tuff, lithic lapilli tuff, and minor rheoignimbrite (units ig, rpd, and sp, Table 1). Fallout tuff is rare. Pumice and lithic fragments are nearly always less than 5–7 cm in diameter. Pyroclastic deposits range from a few tens of centimeters thick to compound cooling units 300 m thick; lateral continuity varies from a few meters to a few hundreds of meters along strike, owing to paleotopographic relief or disruption by hypabyssal intrusions. Variations in welding apparent in outcrop (Fig. 8A) are confirmed by thin-section textures (Fig. 8B), which indicate that flattening of pumice occurred by sintering during deposition rather than by later tectonic deformation.

Pyroclastic rocks exposed along the lower/middle member contact in the Mansfield Canyon area (Figs. 2 and 7) represent the only accumulation of subaqueous tuff in the Mount Wrightson Formation. These rocks are described in detail below.

Locally, deposits in the Mount Wrightson Formation that have an ash matrix also contain as much as 25% rounded to well-rounded or oblate

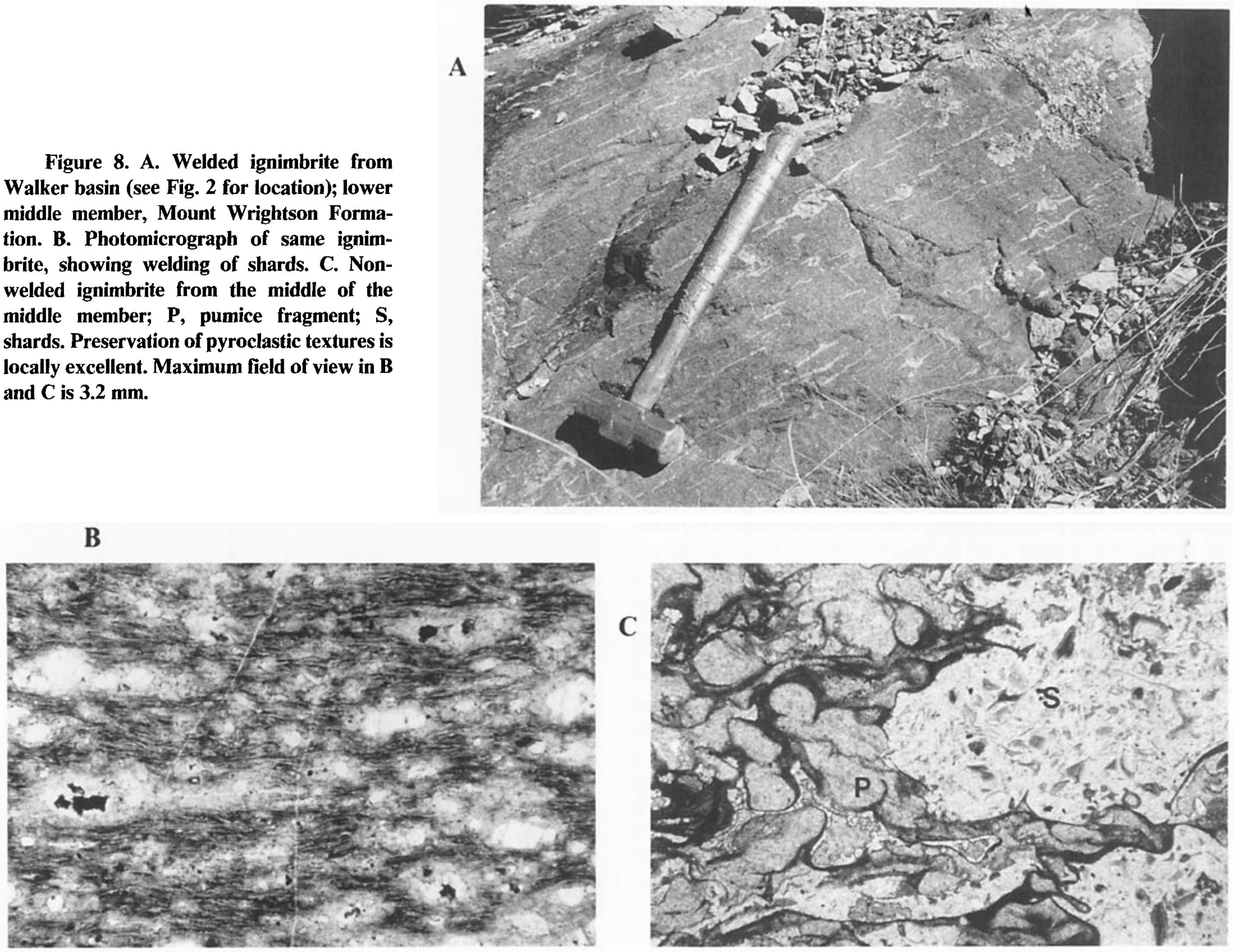


Figure 8. A. Welded ignimbrite from Walker basin (see Fig. 2 for location); lower middle member, Mount Wrightson Formation. B. Photomicrograph of same ignimbrite, showing welding of shards. C. Nonwelded ignimbrite from the middle of the middle member; P, pumice fragment; S, shards. Preservation of pyroclastic textures is locally excellent. Maximum field of view in B and C is 3.2 mm.

Figure 9. Photomicrograph of mixed eolian sand grains and glass shards in plain light. This unit occurs as a discontinuous intruded horizon near the top of the lower member and may record the inception of pyroclastic activity that was predominant in middle member time. Field of view is 6.4 mm.

quartz grains that are 0.1–0.3 mm in diameter. These deposits, which are stratified on a 5- to 25-cm scale, locally cross-stratified, and poorly sorted, are frequently in gradational contact with conglomerate and/or channelized or cross-stratified sandstone.

Interpretation. The origin of pyroclastic rocks in the Mount Wrightson Formation is problematic. Dense welding and local rheomorphic textures, together with thickness of compound cooling units as much as 300 m, suggest large-volume, possibly caldera-related sources for some of the ignimbrite sequences. Alternatively, some of these thick sequences may represent small-volume eruptive products of small composite cones, which were ponded in canyons to thickness sufficient to cause welding. Other intracanyon deposits, however, such as debris-flow deposits or fluvial sequences, are absent in nearly all cases, and we assume that the terrain was not deeply eroded. We interpret thin or nonwelded pyroclastic flows as being derived from vents within the multi-vent complex and suggest that some of the thickest compound cooling units were derived from more distant calderas.

Cross-stratified deposits that contain bubble-wall shards, pyrogenic minerals, and/or pumice fragments and as much as 25% well-rounded sand grains are interpreted as fluvially reworked unconsolidated pyroclastic material (for example, Fig. 9). Quartz grains in these deposits are identical in modality of size and shape to grains in the eolian sandstones and are inferred to have eolian origin.

Debris-Flow Deposits

Description. Massive, unsorted, mud-matrix–supported breccias 2–15 m thick are referred to herein as "debris-flow deposits." Clasts constitute as much as 40% of the debris-flow deposits and are primarily a heterogeneous mixture of volcanic rocks, although they are in some cases confined to one or two clast types (unit df, Table 1). Volcanic rock fragments are predominantly intermediate lavas and silicic ignimbrites typical of the Mount Wrightson Formation. Rare quartz arenite and Precambrian granite clasts are present. The matrix locally contains as much as 50% quartz sand.

Debris-flow deposits in the Mount Wrightson Formation are associated primarily with fluvially reworked ignimbrites and sandstones or with andesitic lava flows and, to a lesser extent, with ignimbrites. Debris-flow deposits constitute a small proportion of the Mount Wrightson Formation (Fig. 2).

Interpretation. The paucity of debris-flow deposits in the Mount Wrightson Formation is noteworthy. Although many of the lithofacies in the Mount Wrightson Formation are easily ascribed to stratovolcano facies assemblages (Fig. 4A), stratovolcanoes commonly have a much higher proportion of debris-flow deposits, resulting from remobilization of unconsolidated volcanic material on the steep sides of a major constructional edifice. Sparse evidence of debris-flow deposits within the Mount Wrightson Formation may indicate that relief within the multi-vent complex was low. Alternatively, or simultaneously, a hyperarid climate may have caused only rare thunderstorms, thus limiting the remobilization of volcanic material. By analogy with the stratovolcano model, we consider the debris-flow deposits to be proximal or medial facies deposits.

Eolian Quartz Arenite

Drewes (1971c) first interpreted quartz arenite in the Mount Wrightson Formation as eolian deposits and correlated them with Mesozoic sandstones on the Colorado Plateau. This interpretation was corroborated

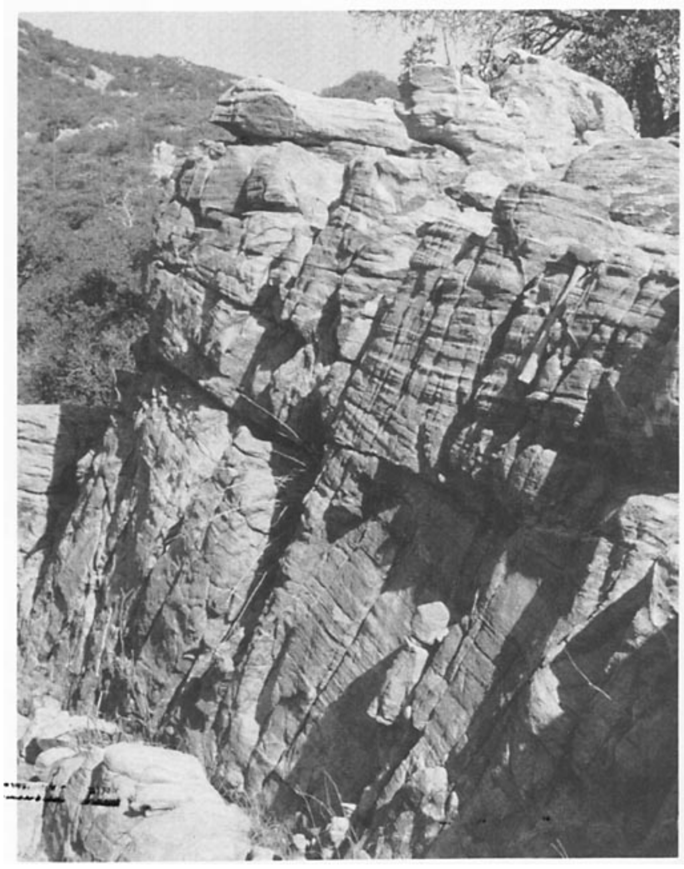


Figure 10. High-angle large-scale cross-stratification in quartz arenite in the upper member of the Mount Wrightson Formation; set heights are locally as much as 10 m.

by Bilodeau and Keith (1981, 1986), who recognized large-scale trough and wedge-planar cross-stratification, well-sorted sandstone, and frosted grains, supporting an eolian interpretation. These authors also measured paleo–wind directions on the cross-stratified quartz arenites and proposed that primary wind direction was from the northeast.

Description. Quartz-arenite horizons are 0.5–250 m in thickness (unit qa, Table 1). Strata thicker than approximately 3 m locally have large-scale tabular and trough cross-beds (Fig. 10), with set heights rarely as much as 10 m. Small-scale sedimentary structures present in quartz-arenite horizons in the Mount Wrightson Formation that are considered characteristic of eolian processes (Hunter, 1977, 1981; Kocurek and Dott, 1981) include wind-ripple lamination sets as much as 25 cm thick and, more rarely, 1- to 2-cm-thick grainflow cross-strata.

Petrographic study of 19 quartz-arenite samples from the Mount Wrightson Formation, summarized in Figure 11 and Table 2, indicates that sandstone beds in the Mount Wrightson Formation, referred to herein collectively as quartz arenite, include quartz arenite, sublitharenite, and subarkose (classification of Folk, 1968). Detrital tourmaline, present in amounts as much as 1%, is a common accessory mineral in the Lower Jurassic Wingate and Navajo Sandstones on the Colorado Plateau (High and Picard, 1975; Picard, 1977; Uygur and Picard, 1980) and is much less common, by contrast, in the Upper Jurassic Entrada Sandstone (Otto and Picard, 1977). In addition, Paleozoic sedimentary rock grains of southern Arizona provenance, such as carbonate or quartz sandstone with prominent quartz overgrowths, are absent. Chert, which in large quantities could

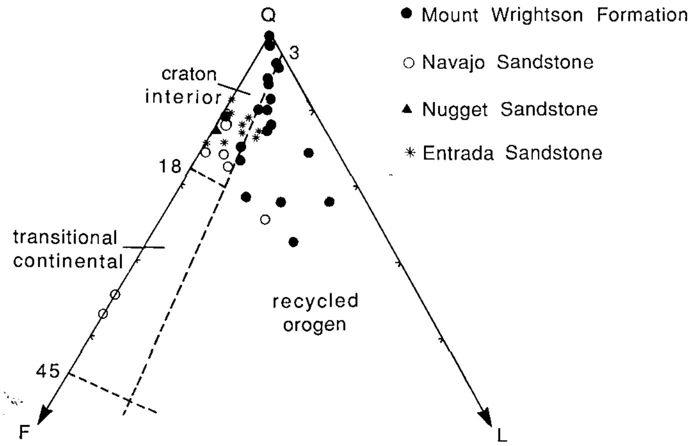


Figure 11. Sandstones of the Mount Wrightson Formation plotted on Q–F–L diagram (after Dickinson and Suczek, 1979; Dickinson and others, 1983). Arenites from the Mount Wrightson Formation lie primarily within the craton-interior, recycled-orogen, and quartzose-recycled fields. Lithic fragments are nearly exclusively volcanic and probably locally derived; these tend to bring the rocks out of the craton-interior field. Published point-count data from the Navajo, Nugget, and Aztec Sandstones (High and Picard, 1975; Picard, 1977; Uygur and Picard, 1980) are included for comparison.

TABLE 2. POINT COUNTS OF SANDSTONES IN THE MOUNT WRIGHTSON FORMATION

Sample number	Mono xtln round qtz	Mono xtln ang'lr qtz	Poly xtln qtz	Volc. qtz	Matrix	Overgrowth	Interstitial qtz*	Volc. frags	Plag	Holes	Other
Lower member											
1215-11	46.3%	5.5%	1.2%	—	14.4%	16.9%	11.2%	0.4%	—	4.1%	ch, 4.9%; opq, tr.
Middle member											
MtW-4	15.1%	3.1%	0.5%	1.0%	52.3%	0.7%	4.6%	5.3%	11.5%	1.9%	ch, tr.; trm, 0.7; Ksp, 2.9; bio, tr.
MtW-5	16.1	13.2	1.1	1.6	36.7	8.6	11.1	1.1	0.9	7.7	ch, 1.0; opq, 1.2; epi, tr.; Ksp, tr.
MtW-8	27.4	16.4	2.5	1.6	24.0	5.5	13.7	0.5	0.2	7.1	ch, 1.2; opq, tr.; calcite replaces cement
MtW-1	30.0	14.4	2.5	2.2	25.6	2.0	1.5	3.7	2.7	0.5	opq, 0.5; Ksp, tr.
0128-4B	31.8	8.8	3.0	5.2	33.6	1.0	1.2	11.4	2.2	0.5	opq, 0.7; ch, 0.5
0129-6A	26.5	15.9	1.0	2.0	27.0	10.7	10.9	1.5	0.7	3.0	ch, 3.1; opq, 0.5; extr. rextl
0129-6B	17.1	15.1	1.5	—	31.7	9.4	19.0	2.0	2.2	1.0	ch, tr.; trm, 0.5; epi, tr.; rextlized
0205-5A	22.1	9.2	2.6	1.7	35.5	9.2	10.2	2.6	2.2	3.2	ch, 1.0; opq, tr.; Ksp, tr.
0205-5B	30.8	14.4	3.6	5.6	31.6	1.7	4.4	2.7	2.2	1.0	ch, tr.; opq, tr.; Ksp, tr.
0205-5C	21.5	10.7	2.4	5.6	30.8	1.5	10.9	6.8	4.1	2.7	ch, 0.75; opq, 0.75; bio, 0.5
Upper member											
0325-1C	28.7%	2.0%	0.7%	4.0%	22.2%	9.5%	22.0%	5.2%	1.2%	4.2%	ch, 0.5; rextlized
0325-1B	38.1	4.7	1.5	3.0	15.6	10.1	16.0	5.7	2.2	1.7	ch, 0.5; trm, tr.; opq, tr.; epi, tr.; Ksp, 1.0
1216-10	25.9	5.2	1.6	1.0	41.4	4.2	7.8	6.1	4.8	0	opq, tr.; detr. wh. mica, tr.
1218-5	39.8	17.4	4.2	3.4	18.2	1.0	6.4	2.0	2.2	3.7	ch, tr.; opq, tr.
1219-1B	44.5	2.5	2.2	0.7	4.2	18.5	17.2	3.5	6.0	0.5	tourm, 0.5; opq, 1.2; epi, tr.
1218-2	43.0	6.8	1.7	2.2	21.6	9.0	4.6	6.6	1.7	1.2	ch, tr.; opq, 0.8; Ksp, 1.2
1218-13	42.7	1.4	1.4	tr	9.4	12.8	19.4	2.8	2.6	5.4	ch, tr.; tourm, tr.; grain boundaries resutured
0326-1	39.0	8.7	2.5	2.5	24.2	6.5	12.5	2.0	0.5	1.5	ch, tr.; rextlized

*Indicates between-grain quartz not associated with other quartz grains, that is, not overgrowth; probably recrystallization of matrix.

also be indicative of erosion of local Paleozoic sediments, is present only in trace quantities to rarely as much as 3% (Table 2), similar to the amount of chert found in the Wingate and Navajo Sandstones (High and Picard, 1975; Picard, 1977; Uygur and Picard, 1980).

Quartz arenites of the Mount Wrightson Formation plot in the craton-interior and recycled-orogen fields of Dickinson and Suczek (1979) and Dickinson and others (1983) (Fig. 11), rather than showing a large component of dissected arc provenance. Volcanic-lithic grains are present in amounts commonly less than 7% and rarely as much as 11% (Table 2). In addition, pyrogenic crystals, such as would be expected from the weathering and erosion of ignimbrites, are extremely rare.

Interpretation. An eolian origin for quartz arenites in the Mount Wrightson Formation is indicated by eolian sedimentary structures such as wind-ripple strata and grainflow cross-strata and by the petrology of the sandstones (Table 2). Post-depositional subgreenschist-grade metamorphism(?) has masked small-scale sedimentary structures in many of the arenite horizons, however, and the environment of deposition of these beds is inferred to be eolian, based on structures preserved in over- and underlying strata. On the basis of the proportionality of thickness of grainflow cross-strata to slip-face height (G. Kocurek, unpub. data, and 1989, personal commun.), dunes were probably 10–20 m in height. Wind-ripple laminae indicate that the dunes were transverse, and a dune slip face preserved in the upper member of the Mount Wrightson Formation indicates that dunes were crescentic in form.

Busby-Spera and others (1987) and Busby-Spera (1988) have suggested that eolian sands impinged on a low-standing magmatic arc in the area of eastern California, based on the proximity of the arc in that area to cratonal exposures of eolian sandstone, and have inferred that sands were funneled northwest- and southeastward along the length of the arc. The paucity of volcanic detritus, and absence of plutonic detritus (Fig. 11, Table 2), however, suggests that eolian sand in the Mount Wrightson Formation interacted very little with the magmatic arc prior to deposition. Paleowind indicators suggesting southward wind direction in the Mount Wrightson Formation (Bilodeau and Keith, 1981, 1986), together with the lack of arc-related detritus in the sandstones, suggest that the eolian sand was derived directly from the Colorado Plateau to the north. In any case, petrographic data indicate that the sands were not locally derived.

Fluvial Sandstones

Description. Some sandstone lenses in the Mount Wrightson Formation are less than 5 m thick, range from a few meters to tens of meters in lateral extent, and are locally red in color. These sandstones are subarkose, sublitharenite, lithic arkose, and feldspathic litharenite and typically are poorly sorted, normally graded, and fine to coarse grained and contain intercalated pebble conglomerate beds as much as 10 cm thick. Rarely, pumice clasts as much as 15 mm in diameter are present in both sandstone and pebble conglomerate beds. Channels and small-scale, low-angle cross-bedding are common.

Interpretation. Sandstone lenses are interpreted to be fluvial deposits, based on small lateral extent and on sedimentary structures. A noneo-

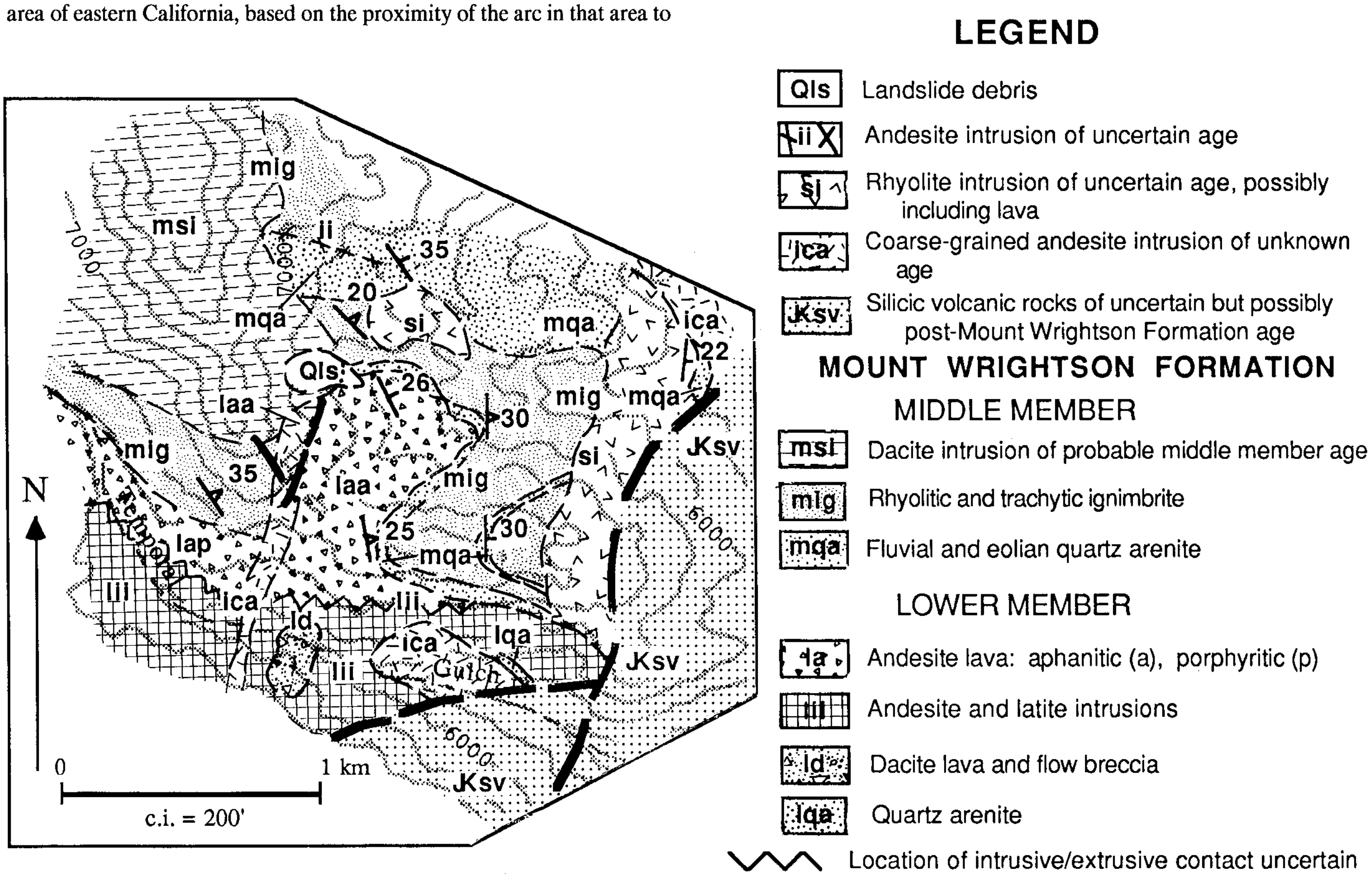


Figure 12. Geologic map of the upper Temporal Gulch area, southern Santa Rita Mountains, showing the contact between the lower and middle members of the Mount Wrightson Formation (locality shown in Fig. 2).

lian origin is suggested by local coarse grain size and normal grading, as well as, in contrast to the eolian deposits, a high detrital volcanic component. Red color suggests subaerial oxidation and reduction of iron minerals. The fluvial sandstones are commonly associated with eolian deposits or reworked pyroclastic deposits.

DISTRIBUTION OF LITHOFACIES

Although nearly all of the lithofacies described above occur in each of the members of the Mount Wrightson Formation, the formation as a whole is characterized by a transition from primarily near-vent and proximal effusive lithofacies in the lower member to predominantly proximal and medial facies explosive deposits in the middle and upper members (Fig. 3). The thickness and abundance of eolian quartz arenite increases upsection through the middle and upper members and is paralleled in the upper member by a decrease in explosive volcanic deposits.

Lower Member

The lower member of the Mount Wrightson Formation occurs in the southeastern Santa Rita Mountains (Fig. 2). Exposures in the Madera Canyon area of the west-central Santa Rita Mountains, considered by Drewes (1971b, 1971c) to be part of the lower member, are reassigned here to the middle member (Fig. 2). The lower member is everywhere intruded at its base by Jurassic and younger plutons.

The best-exposed section through the lower member occurs in the Mansfield Canyon area (Figs. 2, 3A, and 7) and is representative of the evolution of the lower member from a base of reworked pyroclastic deposits and ignimbrites upward to an effusive vent complex. Similar vent deposits along the approximately 10-km strike length of the lower member indicate that multiple vents were active early in the depositional history of the Mount Wrightson Formation.

The basal reworked pyroclastic and ignimbrite unit includes minor sandstone and conglomerate horizons near the base (Figs. 3A and 7), indicating that the terrain was being dissected in lower member time. These conglomerates contain clasts of unmetamorphosed ignimbrite and andesite and dacite lava. The presence of these volcanic clasts indicates that although the Mount Wrightson Formation contains the oldest precisely dated Mesozoic rocks in southern Arizona, the formation as presently preserved postdates the inception of volcanism in southern Arizona.

The intermediate effusive complex that overlies the basal reworked pyroclastic and ignimbrite unit comprises dacite and andesite lava flows and flow breccias with lesser fluvial sandstone (Figs. 3 and 7), intruded by andesite and latite hypabyssal bodies. Andesite lava flows commonly pass gradationally into intrusions. No pyroclastic deposits are present in this lava and intrusive complex, suggesting either that the basal reworked pyroclastic and ignimbrite unit was a small-volume, short-lived event during a time of predominantly effusive volcanism, or that some relief developed in the area of effusive volcanism, precluding the accumulation of pyroclastic products.

Quartz arenites in the lower member occur primarily within the basal reworked pyroclastic and ignimbrite unit. Beds are commonly less than 100 m in lateral extent and less than 1.5 m in thickness and lack eolian structures common in many of the quartz arenites in the middle and upper members. The sandstones are petrographically identical to quartz arenites elsewhere in the Mount Wrightson Formation (Table 2), however, and they lack the cross-lamination and channelization typical of fluvial sandstones in the lower member. The small lateral extent and relative thinness of the lenses may indicate that regional wind patterns that later brought abundant sand into the area were not yet established.

A distinctive reworked pyroclastic unit discontinuously intruded near the top of the lower member may record the onset of explosive volcanism typical of the middle member. The unit is a mixture of light-colored slightly abraded bubble-wall shards and well-rounded eolian sand grains (Fig. 9).

Lower Member/Middle Member Contact

The contact between the lower and middle members of the Mount Wrightson Formation, exposed in upper Temporal Canyon (Figs. 2 and 12), and in the Mansfield Canyon area (Figs. 2, 7, and 13), records the transition from predominantly effusive volcanism of the lower member to predominantly explosive volcanism, which lasted through the remainder of the Mount Wrightson Formation.

The contact between the lower and middle members in upper Temporal Gulch (Figs. 2 and 12) records valley fill after an erosional hiatus between lower and middle member volcanism. Relief along the contact may have been as much as 30 m (Fig. 3B). Low areas in porphyritic and aphanitic andesite lava flows of the lower member were filled by fluvial sandstone and conglomerate. These basal sediments are overlain by as much as 200 m of welded to nonwelded trachytic and dacitic ignimbrite (Fig. 12). Eolian sandstone lenses along the contact are rare and as much as 5 m in strike length. Paleocurrent measurements taken on the basal 50 m of the sedimentary/pyroclastic sequence suggest that paleoflow may have shifted from channel controlled to reflecting paleoflow directly away from a vent.

A lacustrine basin-fill sequence comprising as much as 100 m of subaqueous fallout tuff and interstratified ignimbrites (unit sp, Table 1) depositionally overlies the extrusive and intrusive andesites of the lower member in the Mansfield Canyon area (Figs. 2, 7, and 13). The base of the sequence consists of a polylithologic lithic tuff breccia (heterolithologic breccia of Fig. 13), which may represent the products of the earliest stages of explosive volcanism. This is overlain by nonwelded ignimbrites, with as much as 40% pumice blocks (tuff breccia of Fig. 13) and thin-bedded, laminated crystal and vitric tuffs (Fig. 13). Lesser rhyolitic lava flows and hypabyssal intrusions are also part of the lacustrine basin-fill sequence. Subaqueous deposition and remobilization of the tuffs and ignimbrites are indicated by excellent sorting and rhythmic interstratification of thinly laminated coarse- and fine-grained tuff beds (compare with Fisher and Schmincke, 1984; Busby-Spera, 1986), as well as slump and flame structures in the fallout tuff beds, and fallout tuff intraclasts in the ignimbrites (Fig. 13). Ignimbrites are nonstratified and contain pumice blocks as much as 0.5 m in diameter supported in an unsorted, nonwelded ash matrix. Texturally, the ignimbrites resemble subaerially emplaced pyroclastic flow deposits, but they are intimately interstratified with the subaqueous fallout tuffs, indicating that they were emplaced as high-density bottom-hugging pyroclastic flows that did not mix with the overlying water column.

The lacustrine basin-fill sequence is intruded by the Piper Gulch pluton, dated by Asmerom (1988) and Asmerom and others (1988) as 188 ± 2 Ma, but is, however, nowhere in contact with the upper Temporal Canyon valley-fill sequence described above. The lacustrine basin-fill unit is very distinctive compared to the rest of the Mount Wrightson Formation owing to its environment of deposition, ubiquitous quartz (Table 2), and light color. These pyroclastic rocks may represent an areally restricted subaqueous facies association not present elsewhere within the Mount Wrightson Formation. Alternatively, they may represent a formation younger than the ~205 Ma Mount Wrightson Formation but older than the 188 Ma Piper Gulch pluton. Subaerially deposited pyroclastic rocks (unit JKsv, Table 1) similar in mineralogy and appearance to the lacustrine basin-fill sequence overlie and are in fault contact with the upper

Temporal Gulch valley-fill sequence. These subaerial pyroclastic rocks, however, locally overlie conglomerates containing clasts of probable Late Jurassic granite and hypabyssal andesite that intrudes the Piper Gulch pluton (unit ica, Fig. 12); thus these pyroclastic rocks may not be coeval with the lacustrine sequence.

Middle Member

The middle member of the Mount Wrightson Formation is dominated by silicic pyroclastic deposits (Figs. 3B, 3C, and 3D), indicating that explosive volcanism was at a maximum during this time. Effusive and intrusive activity continued, and eolian sand deposition became more common through middle member time. Evidence of erosion and dissection of the volcanic terrain, seen in the Temporal Gulch contact area (Figs. 3B and 7) and elsewhere throughout the member, includes lenticularity of ignimbrites and the presence of minor debris-flow deposits and fluvial deposits. The sharp change in eruptive style between the lower and middle members is paralleled by a transition to more-silicic volcanism that is marked by generally lighter rock color and a pronounced decrease in crystal content (Table 1).

The middle member of the Mount Wrightson Formation is exposed in the central part of the Santa Rita Mountains (Fig. 2) and consists of laterally discontinuous dacitic, trachytic, and rhyolitic ignimbrite and local rheoignimbrite, andesitic to rhyolitic hypabyssal intrusives and lavas, eolian and lesser fluvial quartz arenite, andesitic ignimbrite, and minor debris-flow deposits (Figs. 3B, 3C, and 3D). Variation in composition between ignimbrites (Table 1) may be due to many different source vents erupting different-composition magmas penecontemporaneously (compare with Cunningham and Steven, 1979; Wright and others, 1984; Henry and McDowell, 1986).

A sequence of interstratified medial-facies-association pyroclastic rocks and near-vent– and proximal-facies-association effusive rocks and eolian sandstone in lower Gardner Canyon (Figs. 2 and 14) illustrates in detail the difficulty in interpreting the superposed effects of erosional dissection of a volcanic terrain and complex juxtaposition of facies associations in a multi-vent complex.

The Gardner Canyon sequence contains nonwelded to densely welded ignimbrites interstratified with eolian quartz arenite, interrupted by the eruption and erosion of a small andesite vent. Eolian dune deposits (mqa$_2$ in Figs. 14 and 15) may have formed a topographic barrier to the flow of a stream or streams that reworked pyroclastic material (unit mrp, Fig. 15A). Following deposition of the reworked pyroclastic unit and overlying eolian deposit, a valley or canyon was cut into these units, and a small andesitic vent (unit miv) developed, within or on the sides of the valley (Fig. 15B). This vent unit includes volcaniclastic sandstone, andesite lava and flow breccia, a debris-flow deposit of 10- to 20-cm-diameter

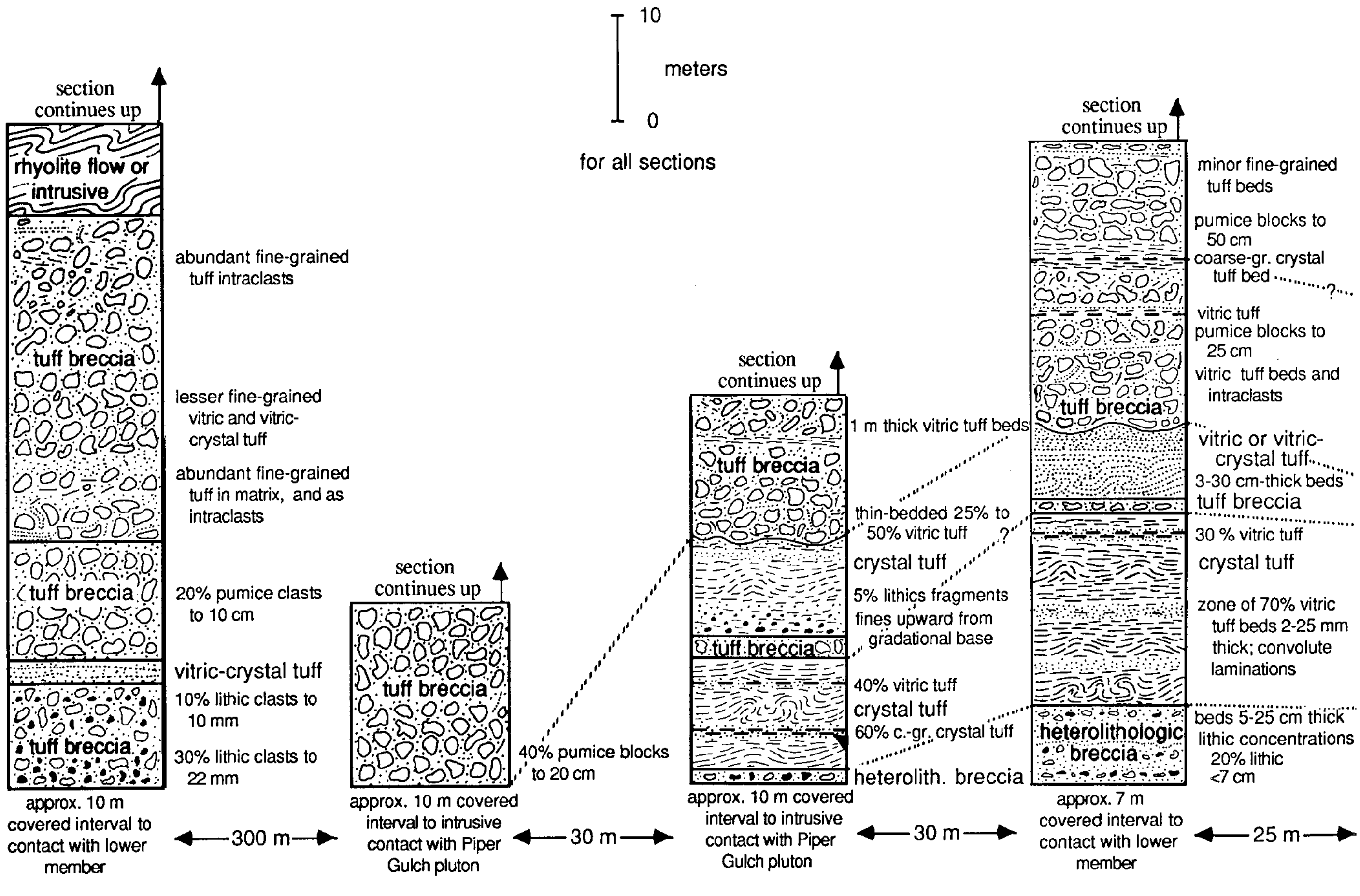


Figure 13. Measured sections of the lacustrine basin-fill pyroclastic sequence that overlies the lower member of the Mount Wrightson Formation in the Mansfield Canyon area (see also Fig. 7). The fine- to coarse-grained tuffs represent subaqueous fallout, and the tuff breccias are subaqueously emplaced ignimbrites.

primarily andesite clasts in a sandstone matrix, and minor intrusive andesite. Renewal of pyroclastic activity brought ignimbrites (uig_1) into the canyon, and the andesite vent was at least partially buried (Fig. 15C). During a hiatus in pyroclastic activity, eolian quartz arenite (uqa_2) was deposited. The quartz-arenite lens (uqa_3) that overlies this interbedded ignimbrite/sandstone sequence contains granules of andesite that may represent debris eroding from the still-emergent andesite vent.

The predominance of explosive activity was coupled with lesser activity from effusive centers in middle member time. Intermediate lava flows and possibly endogenous domes are common in the northern part of the middle member outcrop belt near McCleary Peak (Fig. 2). Dacitic and andesitic domes and probable vents are scattered throughout the member, indicating that intrusive and effusive activity was occurring as ignimbrites were being deposited. Eolian sand deposition became more common upward through the middle member, indicating either increased sand availability or incipient waning volcanism.

Upper Member

The upper member of the Mount Wrightson Formation, exposed in the northeast part of the study area (Fig. 2), documents the waning of volcanism in the multi-vent complex, coupled with an increase in sand supply (Fig. 3D). The contact between the members is transitional; lithology and composition of the volcanic and hypabyssal rocks do not change between the middle and upper members, and many of the contacts between the two members drawn by Drewes (1971c) are intrusive contacts between quartz arenite and dacite or trachyte.

The upper member is marked by a dramatic increase in the amount of eolian quartz arenite relative to volcanic rock, estimated at approximately 50% of exposed rock (Drewes, 1971b, 1971c), with a concomitant decrease in pyroclastic deposits (Fig. 3D). Primary rock types aside from quartz arenite include andesitic to rhyolitic hypabyssal intrusives, andesitic lava, and minor ignimbrites and debris-flow deposits. Peperitic margins characterize many contacts between intrusions and quartz arenites (Fig. 5), indicating that sedimentation and intrusive activity were penecontemporaneous.

FACIES MODEL OF THE MOUNT WRIGHTSON FORMATION

Certain major problems must be addressed in stratigraphic analysis of volcanic sequences and presentation of a facies model (Ayres, 1977). These include (1) determination of the nature of the volcano, whether shield, stratovolcano, dome complex, caldera, or a combination; (2) determination of the size and shape of individual volcanoes represented by the sequence; (3) recognition of the nature of vents, whether single or multiple, and central or flank; (4) recognition of vent, proximal, and distal facies; (5) history of the volcano; and (6) interrelationship between adjacent volcanoes or multiple vents. Through the recognition of volcanic facies assemblages as described above, many of these problems can be addressed concerning the Mount Wrightson Formation.

Nature of the Volcano

The Mount Wrightson Formation contains products commonly associated with stratovolcanoes, including andesitic to dacitic hypabyssal intrusions, lava flows, and domes, as well as ignimbrites and minor debris-flow deposits. Thick densely welded ignimbrites may represent the eruptive products of large silicic vents (calderas) that lay outside of the Mount Wrightson Formation depocenter. These ignimbrites commonly buried vents (for example, Fig. 15) within the Mount Wrightson Formation

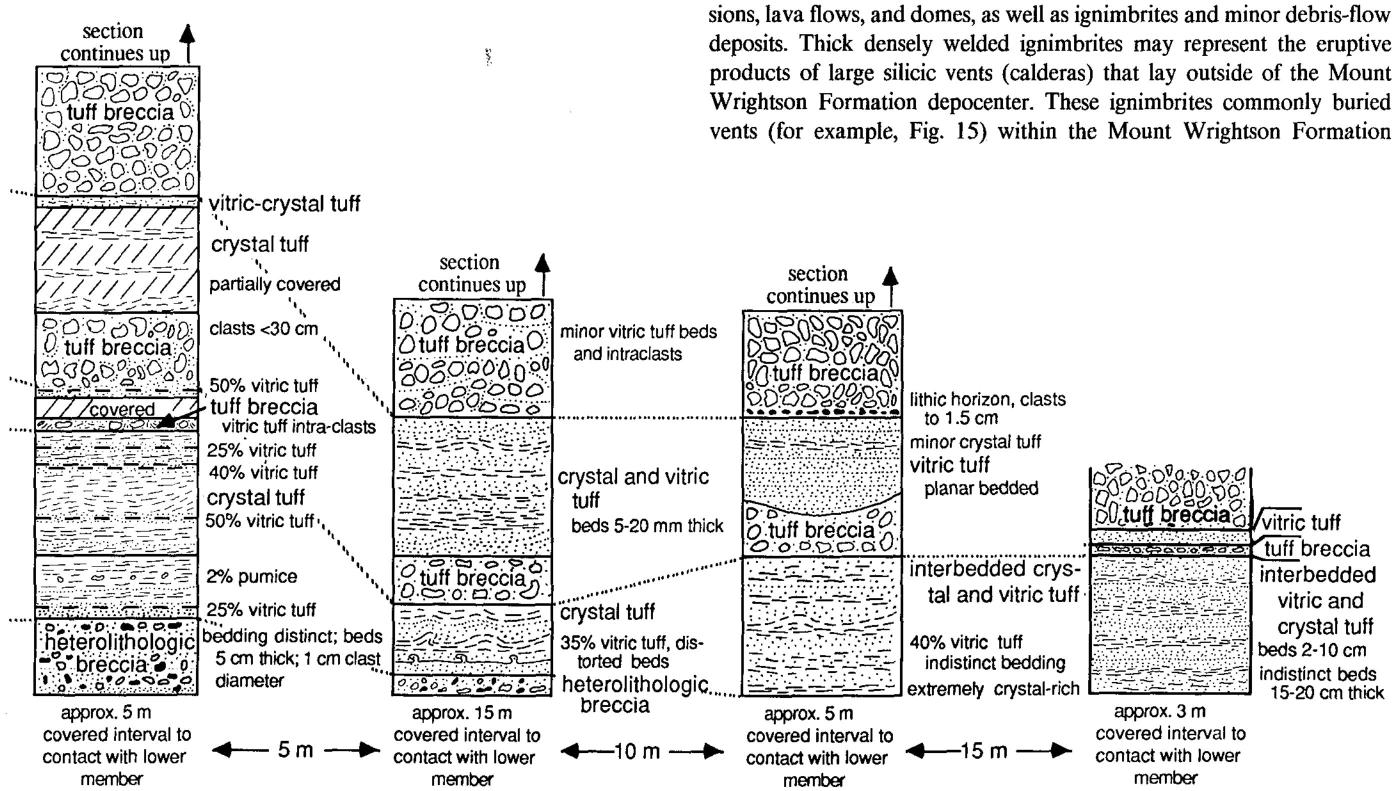


Figure 13. (*Continued*).

depocenter, which, together with the paucity of debris-flow deposits, suggests that the Mount Wrightson Formation represents a low-relief volcanic complex rather than a steep-sided, high-standing central cone.

Size of Volcano(es)

Although the precise sizes of the edifices, the products of which constitute the Mount Wrightson Formation, cannot be determined, certain estimates can be made. Source vents for intermediate lava flows were small edifices, as the mass-flow deposits characteristic of large central composite cones are rare. The thickness of some of the ignimbrite compound cooling units (≤300 m) suggests that they were derived from sources large enough to produce large-volume eruptions. Although many of the smaller ignimbrites may have been erupted from small vents within the depocenter, some were possibly derived from one or more large-volume silicic (caldera) sources not preserved in the Mount Wrightson Formation (Fig. 4B).

Single or Multiple Vents; Proximal or Distal Facies

Multiple source vents in the Mount Wrightson depocenter are indicated by complex interstratification of near-vent domes, proximal lava flows, medial ignimbrites and debris-flow deposits, and distal(?) reworked ignimbrites (Figs. 3 and 4). All of these facies associations are intruded by vent-related hypabyssal bodies throughout the formation.

History of the Volcano; Relationship between Multiple Vents

As described in earlier sections, the Mount Wrightson Formation represents the evolution of a multi-vent complex from an intermediate effusive phase to a silicic explosive phase and then to a phase of waning volcanism. Our facies model of the Mount Wrightson Formation (Fig. 4B) illustrates the activity of multiple vents within the depocenter, and the contributions likely from a more distant caldera or calderas. Smaller vents may have been within a few kilometers of one another.

Examples of sequences erupted from multiple vents have been described both from the geologic record (for example, Rubel, 1971;

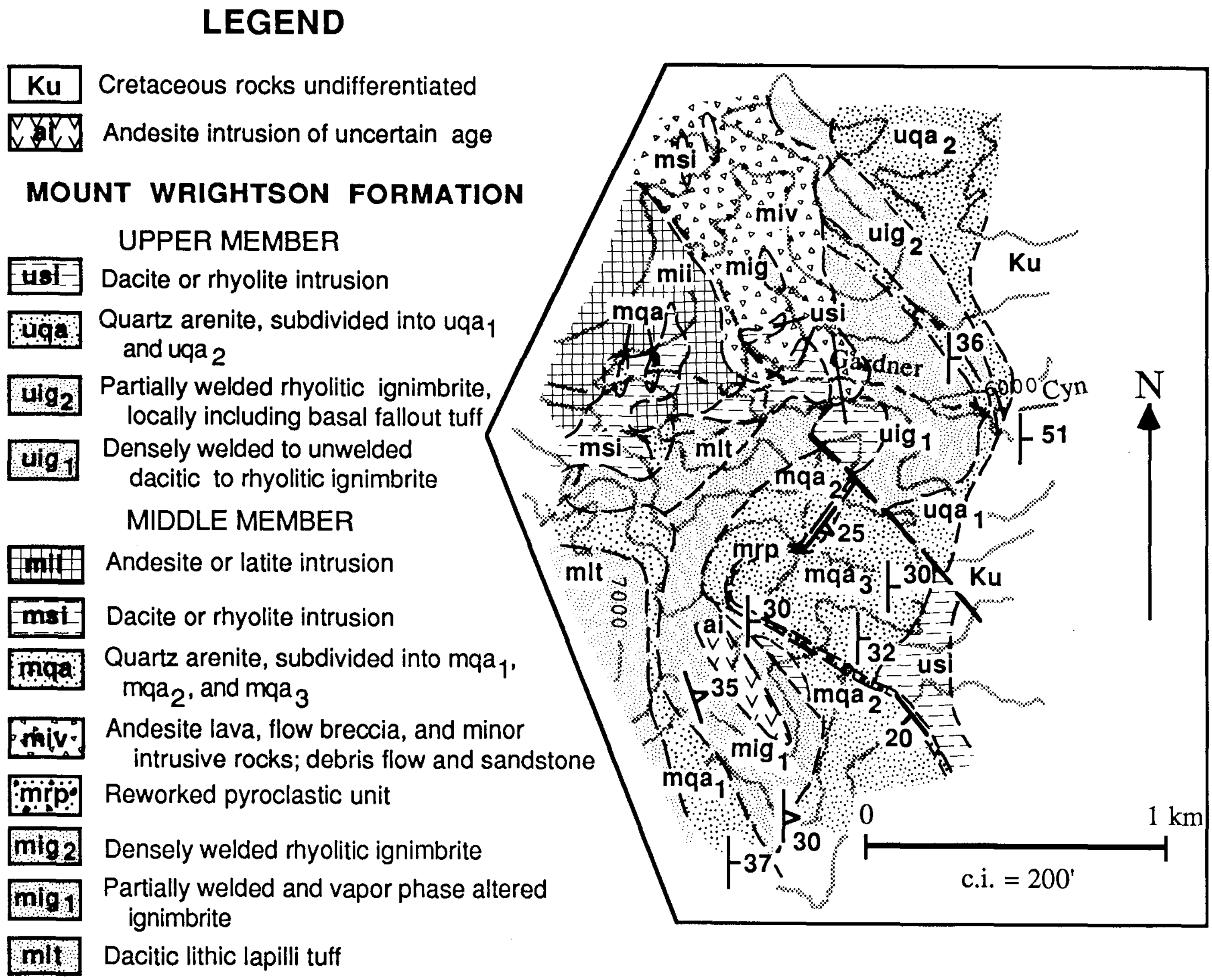


Figure 14. Geologic map of the middle member of the Mount Wrightson Formation, in the Gardner Canyon area (locality shown in Fig. 2).

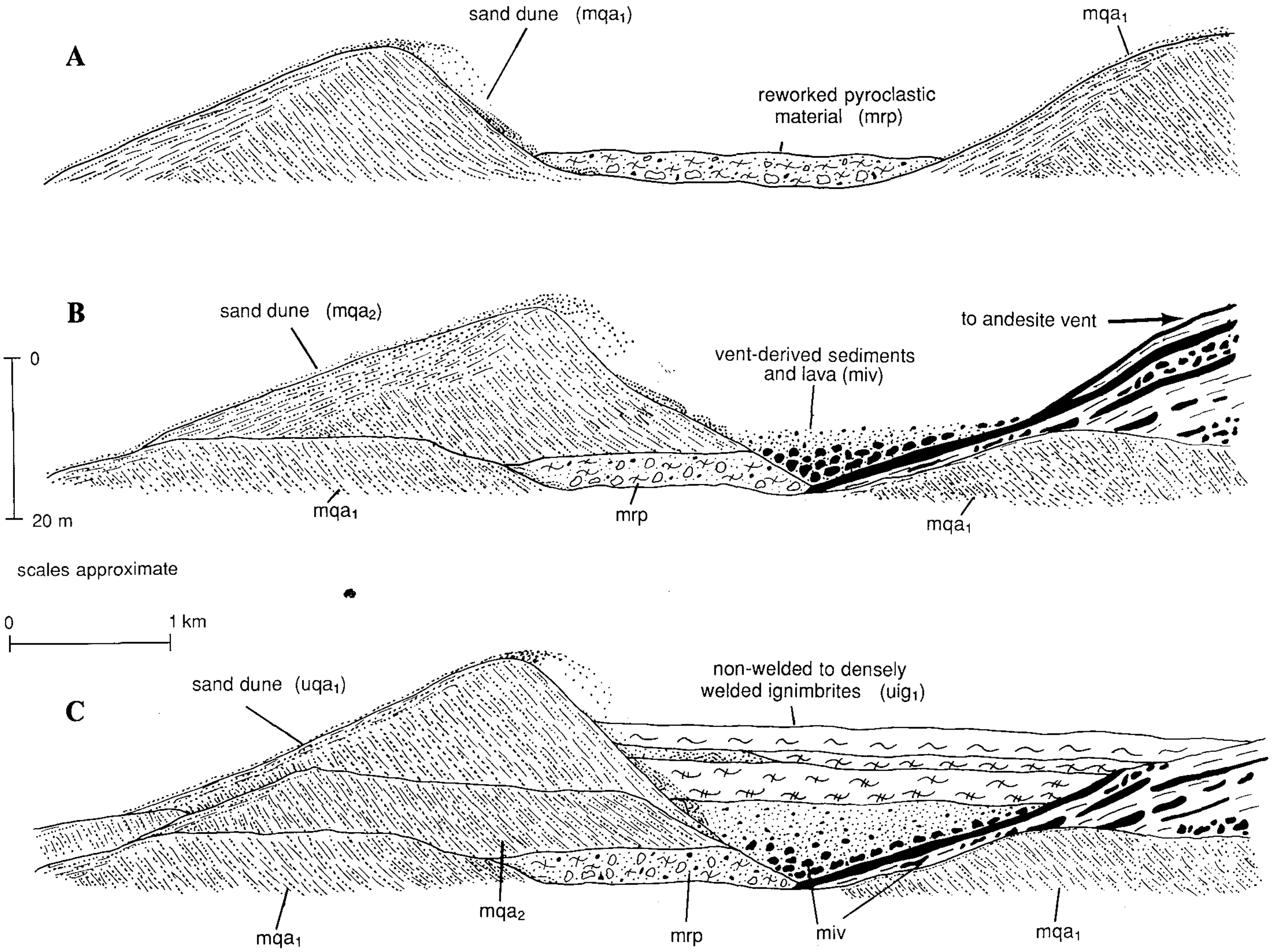


Figure 15. Schematic reconstruction of the stratigraphic evolution of the middle member of the Mount Wrightson Formation in the Gardner Canyon area, in cross-sectional view. A. Reworked pyroclastic debris is funneled by ephemeral streams between sand dunes. B. Following deposition of more eolian deposits, a valley is eroded into the eolian and reworked pyroclastic deposits; a small andesitic vent complex forms within the valley. C. Ignimbrites fill the valley and partially cover the vent complex.

Cunningham and Steven, 1979; Sherrod, 1986) and in modern settings (for example, Wolfe and Self, 1983; Wright and others, 1984). In the Marysvale, Utah, mid-Tertiary volcanic district, for example, Cunningham and Steven (1979) documented near-vent and proximal facies intermediate-composition lava flows and volcanic breccias from multiple vents (Bullion Canyon Volcanics) that interfinger with ignimbrites (Needles Range Formation, Three Creeks Tuff Member, Delano Peak Tuff Member, and other unnamed units) derived locally and from sources far to the west; volcanic and subvolcanic intrusive activity occurred over approximately 7 m.y. Major and satellite cones are interspersed within very small distances (400 km^2) in southwest Luzon, Philippines (Wolfe and Self, 1983), and on St. Lucia, West Indies (Wright and others, 1984). The Taupo volcanic zone is an excellent example of a modern multiple-vent setting within a subsiding extensional arc. Andesitic centers (for example, Tongariro) are interspersed with major silicic centers (for example, Taupo, Rotorua) (Cole, 1981, 1984), and the deposits of these and other major centers are probably interstratified within the >2-km-thick volcanic section that fills the Taupo-Rotorua depression (Cole, 1984).

CONCLUSIONS

The effects of subsidence on the accumulation of volcanic and volcaniclastic deposits are illustrated by the stratigraphy of the Mount Wrightson Formation. We suggest that subsidence and deposition were commonly in equilibrium throughout deposition of the formation, resulting in continuous burial of small constructional edifices (Figs. 14 and 15). Evidence of erosional hiatuses elsewhere between units, such as debris-flow deposits, development of pronounced soil horizons, or deep canyons, is rare. Deposition of at least 300 m of eolian quartz arenite in the upper member of the Mount Wrightson Formation (Figs. 2 and 3D) indicates that subsidence was active at this time. Although sand dunes may form on any surface, net deposition will occur only when the dune is trapped in a basin or against a significant topographic barrier and interacts with the water table. For reasons enumerated above, we do not believe that large topographic barriers were present in the Mount Wrightson Formation depocenter.

We propose that the Mount Wrightson Formation multi-vent complex was active within a subsiding arc graben depression, similar to the modern Taupo volcanic zone (Cole, 1981, 1984), the Central American arc (Stoiber and Carr, 1973; Burkart and Self, 1985), the Trans-Mexican volcanic belt (Surbet and Cebull, 1984; Luhr and others, 1985; Allan and others, 1990), and the Kamchatka arc (Erlich, 1979). Busby-Spera (1988) proposed that this arc graben depression dominated the structural setting of the early Mesozoic magmatic arc in southeastern California and western and southern Arizona. Evidence of subsidence in the Early Jurassic magmatic arc is present in the Baboquivari Mountains approximately 75 km to the west of the Santa Rita Mountains (Fig. 1). Geologic mapping and geochronology (Haxel and others, 1980a, 1980b, 1982, 1985; Wright and others, 1981; Tosdal and others, 1989) indicate that as much as 8 km of volcanic and sedimentary material, including alkali basalts and rhyolites, accumulated in less than 10 m.y., suggesting a high rate of subsidence and deposition of volcanogenic material within an arc. Elsewhere within the early to middle Mesozoic Cordilleran magmatic arc, Busby-Spera (1986) has documented minimum rates of subsidence of 200 m/m.y. Subsidence documented in the Mount Wrightson depocenter supports the interpretation of an extensional arc in southern Arizona in Early Jurassic time.

We propose here a model of a subsiding basin containing a multi-vent volcanic complex to explain the complex stratification of effusive, explosive, and hypabyssal intrusive rocks in the Mount Wrightson Formation. This model is supported by the following observations concerning the geology and evolution of the Mount Wrightson Formation.

(1) The Mount Wrightson Formation represents the evolution of a multi-vent volcanic complex from intermediate primarily effusive volcanism to intermediate to silicic primarily explosive volcanism, and finally to waning volcanism. The predominance of effusive volcanic rocks within the lower member (Figs. 3A and 7) may indicate that the rapid accumulation of lava flows provided modest topographic relief that precluded the accumulation of pyroclastic flows from other sources. In middle member time, the rate of explosive volcanism was high relative to effusive volcanism, and pyroclastic flows, possibly erupted in part from vents outside the Mount Wrightson Formation depocenter, buried effusive source vents. Multiple pulses of magma within vents in the depocenter only locally reached surface and primarily crystallized as hypabyssal bodies. In upper member time, waning volcanism and increased sand supply allowed the accumulation of thick eolian deposits.

(2) The interstratification of near-vent facies hypabyssal intrusions, domes, and silicic lava flows with proximal and medial facies ignimbrites, intermediate lava flows and flow breccias, and debris-flow deposits, plus lesser distal facies reworked pyroclastic deposits and fluvial sandstones, indicates that the depocenter for the formation included multiple vents. In addition, the paucity of debris-flow deposits and other epiclastic sediments suggests that relief in the multi-vent complex was low and was not dominated by a large central-vent stratovolcano.

(3) Eolian quartz arenites and ignimbrites commonly buried vents within the Mount Wrightson Formation depocenter. This repeated burial of vents, together with the preserved thickness of the terrestrial volcanic and volcaniclastic section, indicates that subsidence was ongoing throughout the evolution of the Mount Wrightson Formation and suggests that in southern Arizona, the Early Jurassic magmatic arc was extensional in character.

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